Scientia Iranica E (2014) 21(6), 2315–2325

SCIENTIA IRANICA

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Scientia Iranica
Transactions E: Industrial Engineering
www.scientiairanica.com

Capacity coordination under demand uncertainty in a hybrid make-to-stock/make-to-order environment: A system dynamics approach

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Received 27 July 2012; received in revised form 17 August 2013; accepted 28 October 2013

KEYWORDS
MTS/MTO;
System dynamics;
Capacity coordination;
Demand uncertainty;
Production planning.

Abstract. Hybrid Make-To-Stock (MTS)/Make-To-Order (MTO) production systems have recently attracted the interest of practitioners and academicians in the field of operations management, since these systems benefit from both stock-based and order-driven strategies. In this paper, capacity coordination dynamics of a hybrid MTS/MTO production system is addressed, whose continuous production line is comprised of three workstations. Also, the product portfolio of the considered system includes three kinds of product; pure MTS, pure MTO, and hybrid MTS/MTO. In the developed model, system performance is explored and assessed in terms of system delivery lead time. To do so, three capacity coordination rules are studied; simple average of expected demands, weighted average of expected demands, and the dynamic mechanism for the difference between target and actual delivery lead times. Moreover, the effects of demand uncertainty are taken into account.

1. Introduction

Today's competitive business environment has forced manufacturers to focus on customer rather than technical requirements, resulting in rapid evolution of Make-To-Order (MTO) production systems. In such systems, the production process is not triggered unless a real order is received from a customer. Hence, all production activities are performed after the receipt of the order, resulting in low holding costs and high flexibility, which are the main characteristics of these systems. The main performance criteria of MTO systems include average response time, average order delay, delivery lead-time, due-date adherence, etc. [1]. In contrast with MTO production systems, Make-To-Stock (MTS) production systems are based upon demand forecasts, and products are processed regarding higher fill rate, demand forecast, lot sizes and average work-in-process [2,3]. Moreover, MTS systems are the most compatible systems for producing inexpensive standard products, whilst customized products with relatively long delivery lead times are commonly processed in MTO systems [4-6]. Considering the benefits and pitfalls of both the above-mentioned systems, a hybrid MTS/MTO has recently attracted the attention of practitioners and academicians, which takes advantage of both pure MTS and pure MTO systems simultaneously. Since two conflicting principles are augmented in hybrid systems, production planning in such systems is a challenging issue. If a firm adopts customer orders more flexibly, more production fluctuations are inevitable, leading to several undesirable, cost-increasing issues, such as longer deliveries, higher order rejection rate, and more overtime capacity, etc. On the

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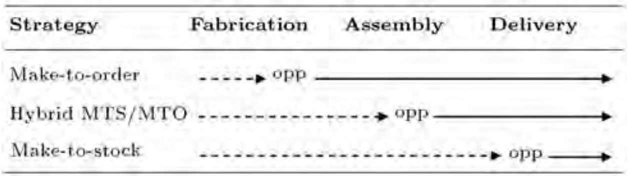

Figure 1. Different production strategies. Dotted and solid lines represent forecast-driven and customer-order-driven activities, respectively [1].

other hand, shifting production towards forecast-based activities results in other issues, such as overstocking, opportunity costs and market shrinkage. From another point of view, production systems are categorized with respect to the Order Penetration Point (OPP). OPP is the point of the production streamline at which the customer order enters the line and, henceforth, production activities are performed upon the order [7-9]. Figure 1 shows where the OPP is located in MTS, MTO, and MTS/MTO production systems.

The main decision complexity of hybrid MTS/MTO systems might be related to two different push and pull mechanisms that are active in a common production line with conflicting signaling directions in such systems. To cope with this complexity issue, dynamic relations of different components of the system should be modeled and analyzed. In this regard, a system dynamics approach [10] is adopted. Using this approach, the scope of the study is assessed using a systematic point of view, whose focus is on the cause-effect relationships among internal/external components of the system. Therefore, results of the different decision mechanisms could be analyzed through a continuous-time model, and, therefore, a hybrid MTS/MTO continuous production system is considered in which three categories of products; MTS, MTO and MTS/MTO, are processed. A novel system dynamics model is developed in order to study interactions of the production system to capacity planning issues for the three kinds of products under demand uncertainty. In this regard, performances of different capacity coordination mechanisms are assessed in terms of their delivery lead times. The remainder of the paper is as follows; Section 2 reviews the literature body of MTS/MTO production systems and production planning via a system dynamics approach. Afterwards, the developed model is presented in Section 3, whilst Section 4 is comprised of simulation results and discussion. Finally, conclusions and future research directions are provided in Section 5.

2. Literature review

In this section, the literature body of MTS/MTO production planning is elaborated on from two points of view. First, research trends of MTS/MTO production planning are evaluated and, next, the role of system dynamics is reviewed in the field of production/inventory planning. To do so, the two following sections are presented.

2.1. Hybrid MTS/MTO production systems

Although hybrid MTS/MTO production systems have been of interest to practitioners and academicians since nearly two decades ago, only a handful of research instances have been devoted to the different issues involved. The first academic research towards hybrid MTS/MTO is related to the one by Williams [11]. He considered a single-stage system with stochastic demands and interactions between demands and capacity, and answered several questions using the queuing theory. The considered questions were related to the inventory control policy, acceptance/rejection of MTS and MTO products, and the effects of accepting MTO products on the performance criteria of MTS products. Adan and van der Wal [12] studied the effects of combining pure MTS and pure MTO production strategies to compare lead time with cases before combination. In order to model the system as a Markovian process, the authors assumed processing times and the times between coming orders as exponential. Arreola-Risa and DeCroix [13] evaluated the optimality condition for choosing MTS or MTO production system for manufacturing facilities with multiple products and random demands with respect to holding and backlog costs. Another similar research is presented by Federgruen and Katalan [14] in which four criteria (inventory level, waiting time distribution, average setup time and cost, holding and backlog cost), were assessed in a manufacturing firm with one MTO item and several MTS items. The authors examined the performance criteria under each of the production strategies and concluded the steady conditions of the strategies. In Tsubone et al. [15], one MTS item and multiple MTO items were considered for which the unfilled rate for the MTS item and manufacturing lead time for MTO items were assessed. The MTS item is processed through an m-stage flow line, while different pre-defined process routes are assumed for MTO items. Gupta and Benjaafar [16] called the hybrid system delayed differentiation, and attempted to answer under what conditions each strategy was suitable. They tackled the question in a two-stage production facility with load-dependent lead times, while other assumptions were comprised of capacity constraints, no setups and no priorities of products (first-in, first-out).

In addition to the above-mentioned mathematical approaches, a new trend of qualitative research has been devoted to different issues in hybrid MTS/MTO systems since nearly a decade ago. Two seminal papers in this field are those by van Donk [8] and Olhager [9]. van Donk [8] related the concept of production strategies with the OPP by introducing eight criteria in two categories; process and stock, product and market. Moreover, he studied how the defined criteria was influenced by shifting the OPP location. Similarly, Olhager [9] presented an extension of van Donk's proposed model by defining more criteria. However, the turning point in this trend might be the hierarchical production planning structure proposed by Soman et al. [3]. They proposed a three-level decision structure, whose levels correspond to strategic, tactical and operational decisions. To cope with the issues introduced by Soman et al. [3], three papers were published by Rafiei and his colleagues [1,17,18]. In the first paper, they attempted to tackle order partitioning and determining OPP location using a fuzzy analytic network process model. Then, they addressed the capacity coordination problem in hybrid MTS/MTO systems with three products; MTS, MTO and MTS/MTO. The considered problem is comprised of order acceptance/rejection, due date setting, overtime planning and product lot sizing. Their third paper was devoted to the third level of scheduling. Henceforth, they developed an integrated framework towards scheduling using the decisions made in the first (strategic) and second (tactical) levels.

2.2. System dynamics in the field production/inventory planning

Numerous system dynamics models are developed to study the dynamics of an inventory management problem. In this regard, readers are referred to Bijulal and Venkateswaran [19], Poles and Cheong [20], and Yasarcan [21]. However, the research papers which have been published at the business level are quite limited. Michaloudis and Georgiadis [22] proposed a model to study the efficiency of different feedforward policies in the field of production/inventory. They evaluated four control mechanisms (constant proportion clearing function, capacitated constant proportion clearing function, concave saturating clearing function, and variable capacity utilization) in an MTO production line with three capacity-constrained stations. In their study, three kinds of demand rate were considered; constant, impulse, and upward step demands. In 2005, a multi-product batch-wise system was evaluated through a system-dynamics model, by Verwater-Lukszo and Christina [23], to facilitate inventory management activities in a chemical plant producing resins in different quality degrees. The authors considered different sources of uncertainty; external, such as order estimation, and internal, such as system response upon which the most suitable policy was selected with respect to two decision criteria; inventory level and service level (ratio of order accomplished). Another inventory planning model was developed by Al-Refaie et al. [24] to manage the inventory of an airplane fuel system. In this regard, a two-stage production system was modeled, the most important component of which was forecasting, which took into account short-time fluctuations as well as the long-run trend. Finally, the authors concluded with the best possible policies to respond to different demand structures. Gonçalves et al. [25] considered the feedback between supply chain performance and customer demand variability in a push-pull system of a semiconductor manufacturer. In other words, they modeled demands as endogenous parameters instead of exogenous ones, as are mostly studied in the literature. Their results show supply chain destabilization with lower average performance due to its sensitivity to supply chain responsiveness. Diehl [26] proposed a system dynamics approach to assess the dynamics of the short-run production/inventory fluctuations. Also, it was studied how fluctuations in one component of the model affect the performance of other components. The authors concluded that the most important factor leading to fluctuations is lack of proper information feedback.

Overall, as concluded from the literature, evaluation of MTS/MTO production dynamics is an ultimately challenging issue from several aspects. As induced from Section 2.1, in the field of hybrid MTS/MTO, no research paper has addressed the dynamics of such systems so far, since these dynamics determine the outputs of the system and the level of performance criteria the system attains. Some instances of these dynamics include those belonging to capacity coordination, acceptance/rejection and labor and capacity development. Moreover, system dynamics might be the most appropriate approach towards MTS/MTO production planning, since MTS/MTO systems embody both material flow and information signals to control the flow in a complex environment. In this regard, a system dynamic model is developed in order to evaluate the effects of different capacity coordination mechanisms on system performance through its delivery lead time.

3. The proposed system dynamics model

In this section, first, an introduction to system dynamics concepts and symbols is provided for those readers who are not familiar with this approach. Next, the developed model is elaborated upon.

3.1. System dynamics

System dynamics is an approach towards the modeling and analysis of system behavior and is a strong apparatus for overcoming different complexities involved in a variety of fields, from socio-economic policy making

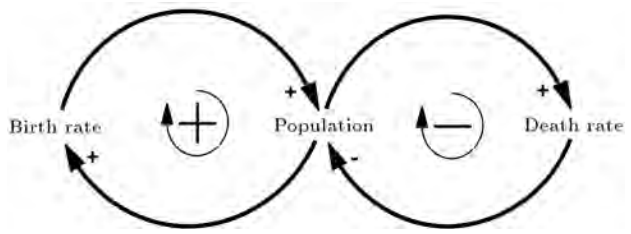

Figure 2. Causal relation between elements "Birth Rate" and "Population" [10].

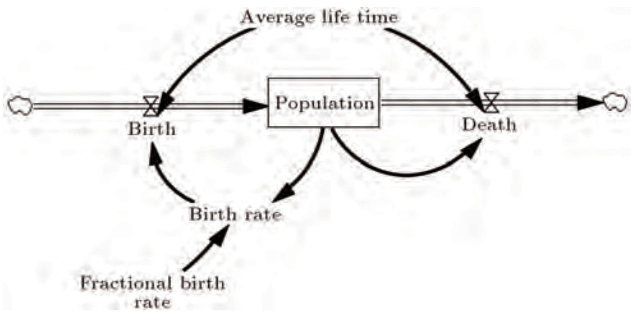

Figure 3. Level (Population) and rates (Birth and Death) of a social system [10].

to supply chain inventory management. This approach was firstly introduced by J. W. Forester in the 1960s at the Massachusetts Institute of Technology, using fundamentals from areas of electronic circuits, and servo-mechanism and feedback control theories [27]. In order to provide a brief insight into system dynamics, two components are explained herein: 1) causality and feedback, and 2) level and rate.

In order to show any causal relation between two elements of a model, an arrow is used, as depicted in Figure 2. Moreover, a polarity of positive/negative is applied to the relation to indicate same/reverse directions between the elements. For instance, as shown in Figure 2, "Population" moves in the same direction as "Birth Rate" (i.e. $\partial(\text{Population})/\partial(\text{Birth Rate}) > 0$). In other words, as "Birth Rate" increases, "Population" increases.

Feedback is the reverse relation between two system components. For example, as "Population" increases, "Birth Rate" increases too. The resulted structure is called a loop, which is the closed path of the relations between the elements.

Two main elements of systems are the components indicating level and rate. The level shows the state of the system at any point of time, while the rate measures its change. For example, an inventory of a factory and a production rate shows the level and rate of the inventory system of the factory. In other words, the system level is calculated upon in-flow and out-flow rates. A schematic view is presented in Figure 3.

In Figure 3, the net value of the population is determined by birth, death, average life time, and birth rate.

3.2. Model description

The considered hybrid MTS/MTO system is comprised of three types of demand (MTO, MTS, and MTS/MTO products) in a continuous production environment. Some examples of the products in the field of continuous processing include Bitumen-4050 and Polypropylene-TCS, which are produced solely upon received orders (MTO), whilst Bitumen-6070 and Fuel Oil-300 cSt are delivered from the stock (MTS) and Bitumen-85100 is produced from Bitumen-6070 at the middle stages of the process (MTS/MTO). Demands are partitioned upon their corresponding OPPs. Also, production capacity is supposed to be constant during the planning horizon of the study; therefore, it should be coordinated to meet three types of demands. The production system is a multi-level system; the MTS production process is completed after four workstations and the MTS/MTO and MTO production processes are completed after three workstations (hence, the forth workstation is just utilized for MTS production). The OPP for MTS/MTO production is located between Workstations 2 and 3.

It is supposed that the capacity of workstations is limited to 25 units per day. Moreover, due to workforce constraints, and the volume of contracts with suppliers and retailers, administrative processes, and transportation capacity, etc., the release capacity as well as raw material purchasing capacity is limited to 25.

In this research, demands for MTS, MTS/MTO and MTO products are considered, respectively, as follows:

$$10+\text{RANDOM UNIFORM}(0,2,0) * \text{SIN}(1 * \text{Time}), \tag{1}$$

$$\text{RANDOM NORMAL}(3,9,6,2,0) +2 * \text{SIN}(0.3 * \text{Time}), \tag{2}$$

$$\text{RANDOM NORMAL}(2.5,9,5,3,0) +2.5 * \text{SIN}(2 * \text{Time}). \tag{3}$$

As shown in Figure 4, the demand of the MTS product is more predictable with the lowest fluctuation and the highest average in quantity. The MTS/MTO demand faces more fluctuation, although the demand average is less than that of MTS. In contrast with MTS, the MTO demand is less predictable, with the highest fluctuation and the lowest average in quantity.

In the remainder of this section, different parts of the model are described. The MTS production process is started with expectations of its demand. The following equation describes the forecasting formula in the model.

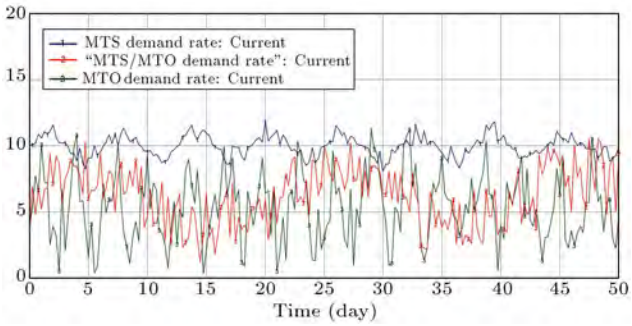

Figure 4. Different demands for MTS, MTS/MTO and MTO products.

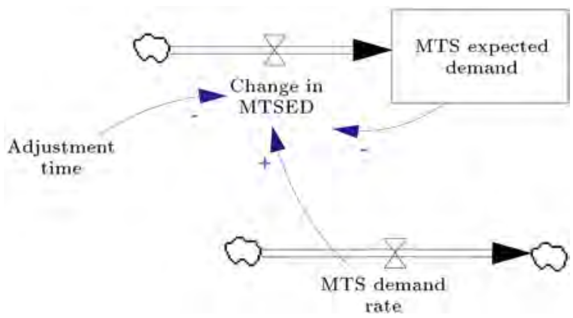

Figure 5. The structure of forecasting in the model.

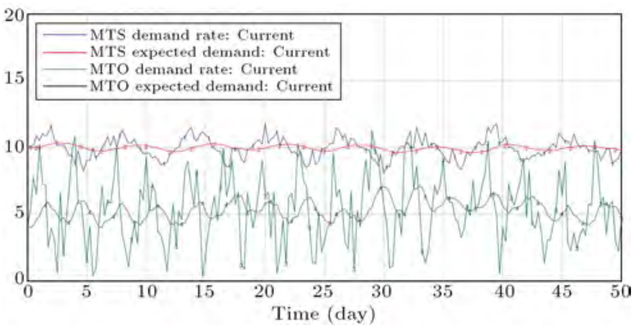

Figure 6. Demand vs. expected demand for MTS and MTO products.

$$\text{Expected Demand} = \int (\text{Demand Rate} - \text{Expected Demand})/\text{Adjust Time})dt + \text{Initial Expected Demand}. \quad (4)$$

As an instance, Figure 5 shows the structure of the forecasting module for MTS demand in the developed model.

Figure 6 shows demand vs. expected demand for MTS and MTO products in the model.

To model the raw material supply rate, the structure shown in Figure 7 is developed. The rate is determined through Eq. (5) using the difference between total expected demand and raw material inventory, that is, if the difference is positive, there will be a demand for raw materials (T01 represents supplier

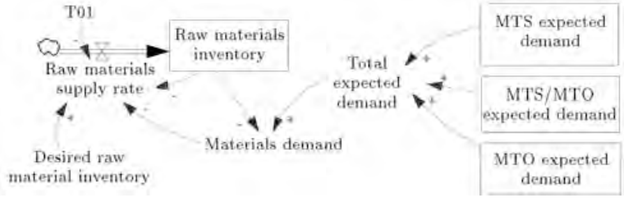

Figure 7. The structure of raw material delivery in the model.

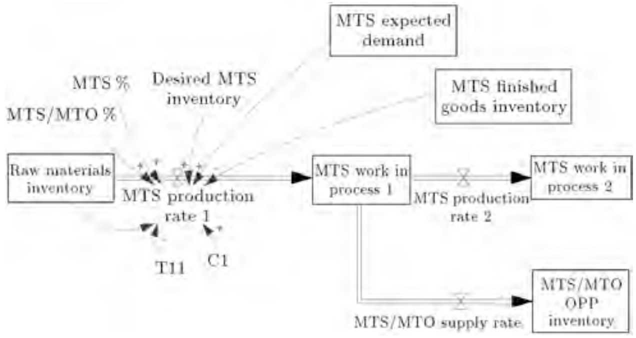

Figure 8. The structure of MTS production rate in Workstation 1.

lead time):

$$\text{Raw Materials Supply Rate}_t = \text{MAX}((\text{Material Demand}_t + \text{Desired Raw Materials Inventory} - \text{Raw Materials Inventory}_t), 0)/\text{T01}. \quad (5)$$

Capacity assignment and production rate are the most important modules in the developed model. In the base run, capacity assignment is determined through a simple averaging method, as in Eq. (6):

$$\text{Capacity share of workstations} = \text{Product's Expected Demand}/\text{Total Expected Demand}. \quad (6)$$

For instance, MTS production rate in Workstation 1 is taken into account, as shown in Figure 8, by using Eq. (7) (C1 demonstrates capacity of Workstation 1):

$$\textbf{MIN}(\text{MIN}((\text{MTS Expected Demand} + \text{Desired MTS Inventory} - \text{MTS Finished Goods Inventory}), \text{Raw Materials Inventory}), (\text{MTS \%+MTS/MTO \%})\text{*C1})/\text{T11}. \quad (7)$$

In Eq. (7), first, the demand for production is restrained with the availability of raw materials. Second, it is also restrained with the share of capacity dedicated to the MTS and MTS/MTO products (since OPP point is located between Workstations 2 and 3). Finally, the production lead time is considered through T11.

For the MTO product in Workstation 1 (and the MTS/MTO product after its OPP), production rate is calculated by means of demand rate, availability of raw materials, and availability of capacity (Eq. (8)).

$$\textbf{MIN}(\text{MIN}(\text{MTO Demand Rate}, \quad \text{Raw Materials Inventory}),\ \text{MTO }\%{*}\text{C1})/\text{T12}. \quad (8)$$

Production rate in subsequent workstations is determined via the availability of work in process inventories and the capacity share dedicated to the workstation.

If delivery lead time exceeds a threshold for MTO and MTS/MTO products, new orders are rejected (or customers will give up their purchase in MTS product). The mentioned threshold is assumed 5, 6, and 8 for MTS, MTS/MTO, and MTO products, respectively. Overall, Figure 9 demonstrates a Stock Flow Diagram (SFD) of the developed model including the integrated structure of the above-explained segments.

4. Simulation results and discussion

4.1. Simulation results

Figure 10 presents the results of the simulation for demand rate, shipment rate and give up rate for the MTS product. Although the production rate fairly satisfies the demand, in some periods, purchases are given up by customers due to intolerable delivery delay.

MTS/MTO and MTO simulation results are demonstrated in Figure 11. In this case, some orders are rejected in order to control the delivery lead time much closer to its target value when the demand is not satisfied completely within the acceptable range of delivery lead time.

With respect to the delivery lead time, Figure 12 shows the result of simulation. Delivery lead time for the MTS product is, to some extent, reasonable, whilst delivery lead times for two other kinds of product do not satisfy the threshold defined in the previous section.

The behavior of delivery lead time is a useful indicator of policy performance for further analysis. As shown in Figures 12 and 13, the system could not respond to demands properly since there is a considerable gap between total demand and shipment rate, with respect to the capacity of 25 for the production system as well as the thresholds of 5, 6, and 8 for MTS, MTS/MTO, and MTO products, respectively; therefore, in the following, delivery lead time will be used to design a better decision rule for the capacity coordination problem.

4.2. Discussion

In capacity coordination, a key point to be taken into account is that the value and priority of MTS, MTO, and MTS/MTO products are different for the manufacturer, i.e.:

MTO priority>MTS/MTO priority>MTS priority.

In order to cover this issue, a weighted average of the products' expected demand is adopted as the capacity coordination rule instead of Eq. (6). To do so, weights of 4, 2, and 1 are applied for MTO, MTS/MTO, and MTS products, respectively. As seen in Figure 14, although the delivery lead time for MTO and MTS/MTO products rises slower in comparison with the previous situation, the final result at the end of the simulation time is the same.

Although considering the prioritization of products in capacity coordination brings in some improvements, it is not sufficient regarding the fact that delivery lead times could not satisfy the defined thresholds. Hence, the amount of delivery lead time for each product should be considered endogenously in decision rules. Thus, after calculating the production rate of products in each workstation, the remaining capacity is used to meet delivery lead time goals in the system; for example, the MTO production rate of Workstation 2 is determined through the following formula:

$$\begin{aligned}&\text{IF THEN ELSE (MTO Delivery lead Time}>8,\\&\quad \text{MIN(MTO Work in Process 1, MTO}\%{*}\text{C2)/T23}\\&\qquad +\text{DELAY1I(MTO}\%{*}\text{(C2}\\&\qquad -\text{Total Production in Workstation 2), 1, 5)},\\&\qquad \text{MIN(MTO Work in Process 1, MTO}\%{*}\text{C2)}\\&\qquad \text{/T23).}\end{aligned} \quad (9)$$

As shown in Figure 15, this information feedback creates a significant change in the behavior of the delivery lead time. In fact, the delivery lead time seeks to reach its goal because of two information flows; the feedback from delivery lead time and the remaining capacity assigned to each workstation. It is noted that the delivery lead time oscillates around its goal due to system delay and noise.

Next, the system response is assessed towards demand uncertainty. Here, two types of change in demand are executed; ramp (linear) increase and step increase. For instance, Eqs. (10) and (11) are used to generate MTS demand:

$$10+\text{RANDOM UNIFORM}(0,2,0) \quad *\,\text{SIN}(1*\text{Time})+\text{RAMP}(0.15,0,50), \quad (10)$$

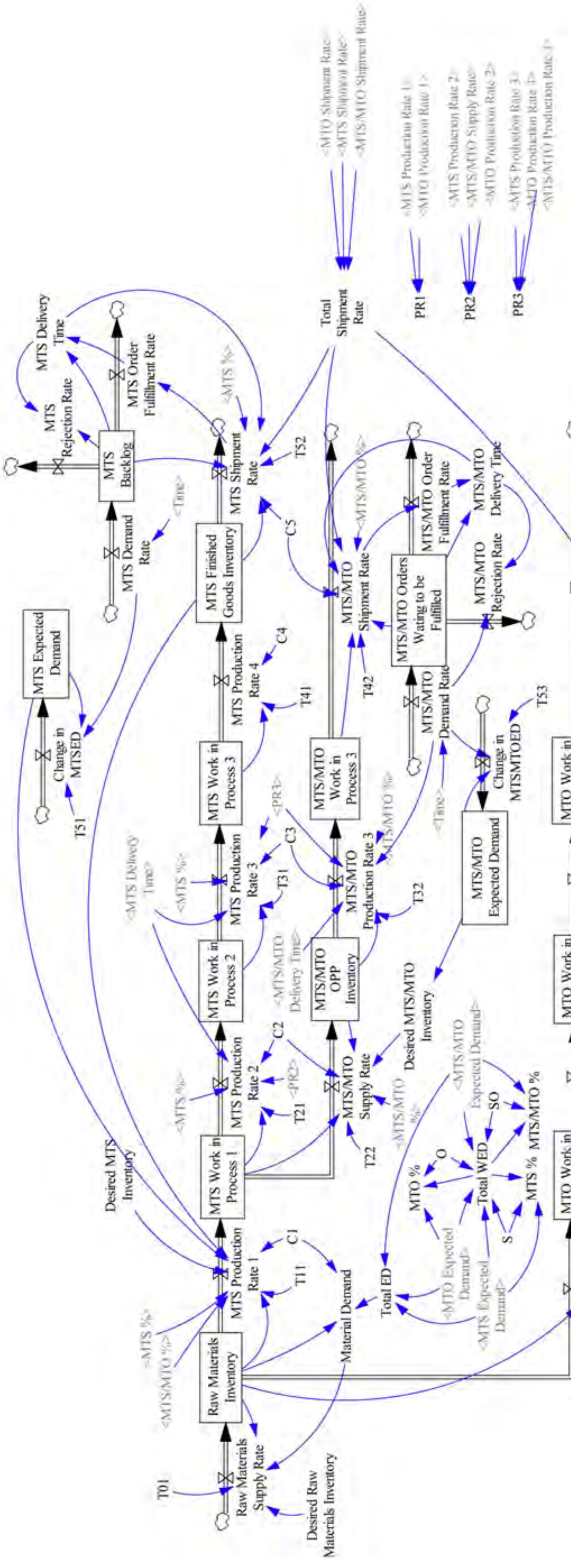

Figure 9. The SDF of the developed model.

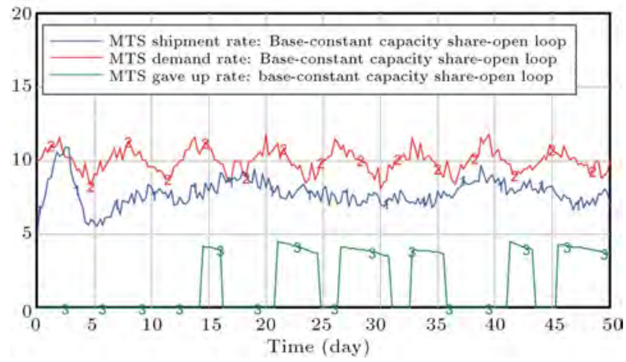

Figure 10. Simulation results for MTS product in base run.

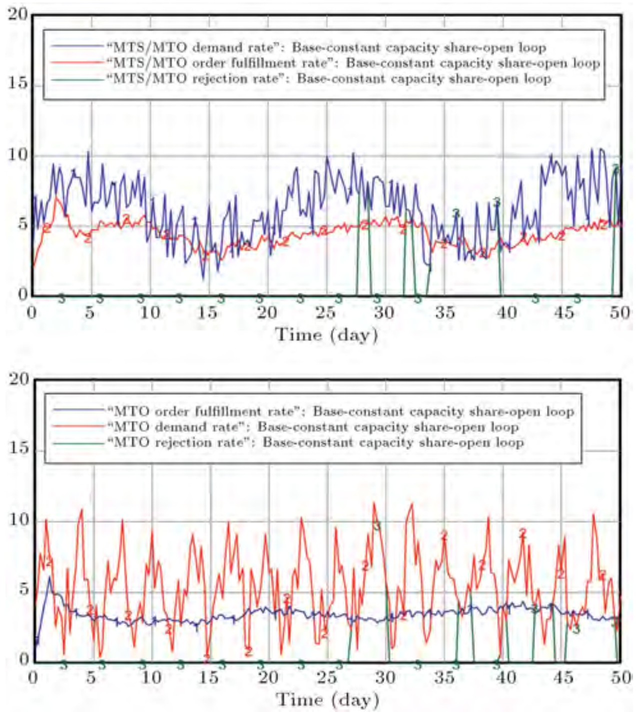

Figure 11. Simulation results for MTS/MTO and MTO products in base run.

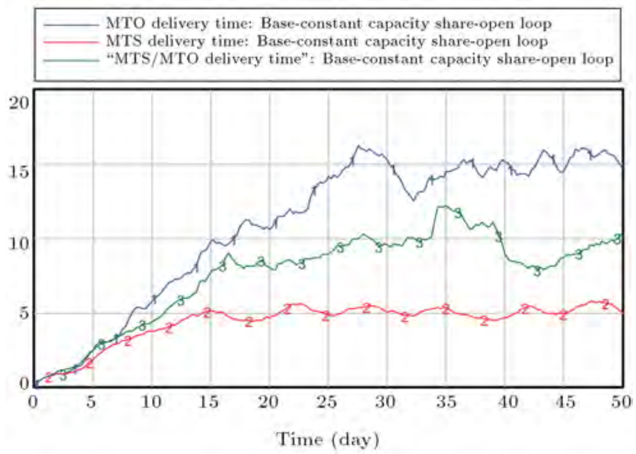

Figure 12. Simulation results for delivery lead times in base run.

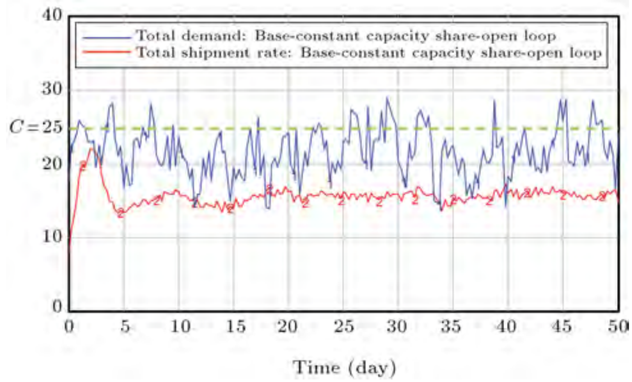

Figure 13. Simulation results for total demand and shipment rate.

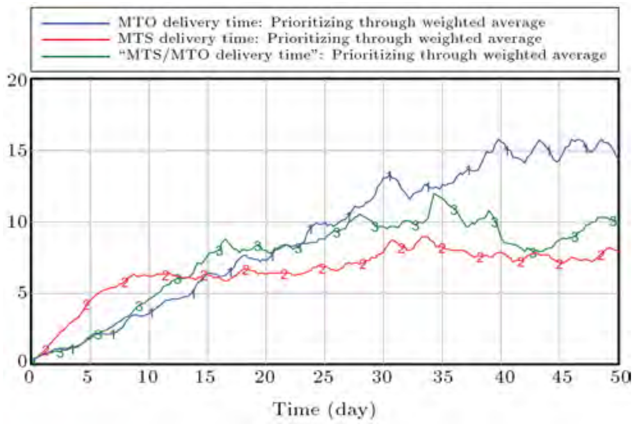

Figure 14. Simulation results for delivery lead time after considering the prioritization of products.

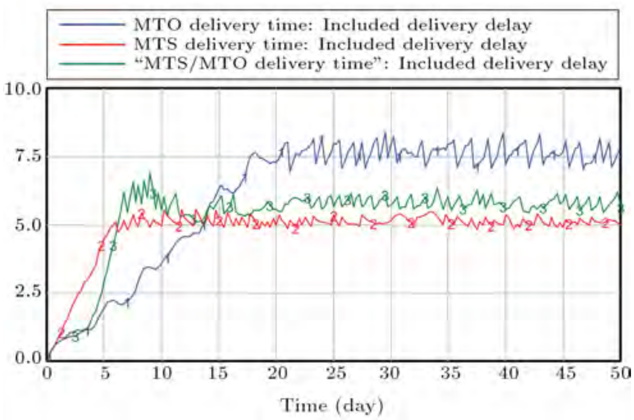

Figure 15. Simulation results for delivery lead time after considering the delivery lead time endogenously.

$$10 + \text{RANDOM UNIFORM}(0, 2, 0)$$

$$* \, \text{SIN}(1 * \text{Time}) + \text{STEP}(5, 20). \tag{11}$$

Having demand uncertainties applied to system responses is shown in Figures 16 and 17, in terms of delivery lead times for MTS and MTO products, respectively. Due to the lowest priority among the

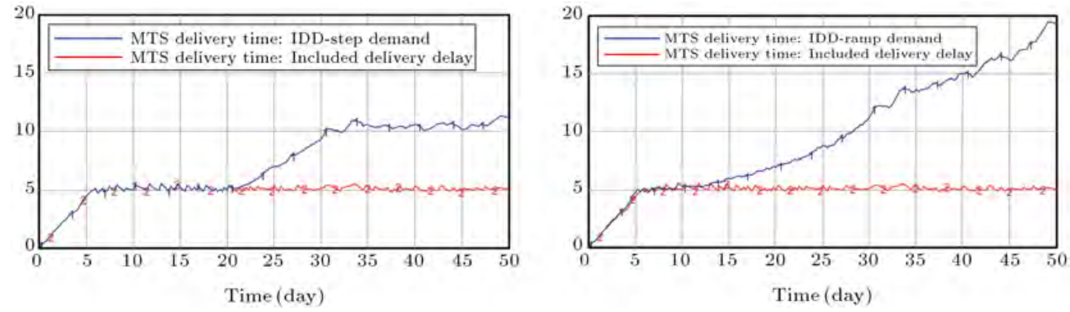

Figure 16. Simulation results under demand uncertainty for MTS delivery lead time.

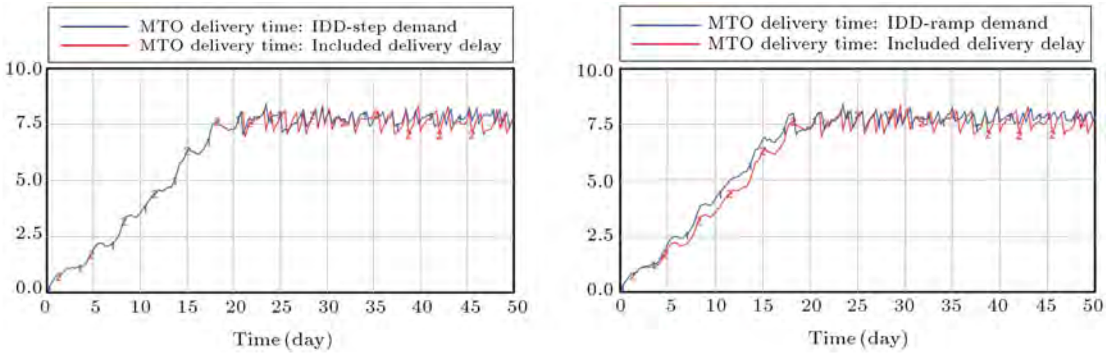

Figure 17. Simulation results under demand uncertainty for MTO delivery lead time.

products, MTS delivery lead time increases stepwise and linearly when the demand increases; however, the delivery lead time for the MTO product does not change considerably due to its high priority (but order rejection rate increases!). Admittedly, the system sacrifices the MTS market to gain more added-value from order-based products. The last discussion emphasizes the importance of prioritizing products in a company portfolio, as well as capacity coordinating rules, in a limited capacity production system.

5. Conclusions and future research directions

Capacity coordination might be the most challenging issue to have arisen in the field of hybrid MTS/MTO production planning, since the performance of such systems is directly influenced by the way the capacity is coordinated. Hence, a hybrid MTS/MTO production system is modeled upon system dynamics disciplines by which capacity coordination rules are studied in terms of delivery lead time. In this regard, three mechanisms were examined; simple average of expected demands, weighted average of expected demands, and the mechanism by which coordination was conducted upon the difference between target and resulted delivery lead times. Results of the simulation indicate that the performance criteria should be considered endogenously in capacity coordination decisions (as delivery lead time in this paper). Additionally, demand uncertainty was added to the developed model in order to assess the robustness of the developed capacity coordination decision rules. Upon the obtained results, the last decision rule was capable of controlling the delivery lead time of the higher priority orders in an acceptable range, with respect to their target values.

In order to continue the research direction of this paper, suggestions are threefold. First, it is highly suggested to develop the model in this paper in order to cover more characteristics of the capacity coordination of hybrid systems, such as pricing and profit maximization. Second, a stability analysis of such a system is useful to study the effects of the decision rules in capturing and damping system fluctuations. Based upon the results, the best policy might be selected with the least harmful implications. Also, this analysis provides some mathematical viewpoints of the system. Last but not the least, it is recommended to extend the developed model in this paper into a hierarchical production planning structure with two decision levels in which an integration of system dynamics and mathematical programming is adopted. To this aim, a business-level model is developed using system dynamics to cover diverse complex internal/external dynamics in a long-term manner upon which a mathematical model is developed at the operational level, such as scheduling. This integrated approach yields a synergy in covering all different issues at different levels of decision making.

Acknowledgment

The authors would like to acknowledge the financial support of the University of Tehran for this research under grant number 8109002/1/09. Also, they are grateful to the reviewers for their valuable, constructive comments.

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