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Development of a Production Scheduling Model in a Hybrid MTO/MTS Production System Considering the Demand for Spare Parts

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Abstract

In this paper, a new mathematical model for production scheduling in hybrid Make-to-Order (MTO)/Make-to-Stock (MTS) systems is presented, incorporating the possibility of selling semi-finished parts. This research aims to develop an optimization method that reduces production time and operational costs while providing precise scheduling of start/end times for each machine's tasks and machine utilization durations throughout the process. The proposed model is formulated as a Mixed-Integer Linear Programming (MILP) framework and enhances system efficiency by simultaneously managing MTO order demands, MTS demands, and independent demands for semi-finished parts in both MTO and MTS systems, while minimizing resource wastage. Simulation and sensitivity analysis results demonstrate that the model can significantly improve scheduling accuracy and optimize equipment utilization. The evaluation of the model was conducted using simulated data. This approach has broad applications in industries such as automotive and electronics and can support strategic decision-making in production management.

Keywords: Production scheduling, Hybrid MTO/MTS system, Spare parts.

1 | Introduction

Hybrid Make-to-Order/Make-to-Stock (MTO/MTS) production systems have attracted increasing attention from industry and the scientific community in recent years as a solution to the challenges of managing variable demand and reducing inventory costs. In these systems, standard products are manufactured based on demand forecasts MTS, while customized products are manufactured based on customer orders MTO. This combination provides greater flexibility compared with traditional production systems. However, one of the key challenges in these environments is optimizing production scheduling so that production resources, such as machinery and raw materials, are utilized as efficiently and effectively as possible. This challenge becomes

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more complex in systems involving demand for semi-finished components, as these components are not only used in the production of final products but may also have independent demand. Failure to manage this flexibility can lead to resource waste or missed revenue-generating opportunities. Although numerous studies have been conducted on production scheduling in MTO and MTS systems, most of them have focused solely on optimizing the production process of final products and have not considered the possibility of selling semi-finished components in a hybrid environment. This research gap provides an opportunity to develop a mathematical model that can simultaneously manage this flexibility in hybrid systems. This paper aims to develop a production scheduling model that, in addition to reducing production time and operating costs, provides accurate planning of production machine activities. The proposed model in this paper is a Mixed-Integer Linear Programming (MILP) framework that addresses the optimization of production scheduling in a hybrid MTO/MTS environment. The main novelty of this model lies in integrating flexibility into the decision-making process, such that semi-finished components not only serve as intermediates in the production of final products but can also be sold independently when separate demand exists. The model incorporates this flexibility by simultaneously optimizing total production time and operating costs, including setup costs, machine idle costs, and inventory holding costs, and ultimately provides detailed operational outputs, such as the start and completion times of operations on each production machine. This innovative approach has broad applications in industries such as automotive and electronics, where the multiple-use management of semi-finished components can improve resource utilization, reduce costs, and increase revenue through the direct sale of components. For example, in an automotive factory, a semi-finished engine can either be used in the production of a customized vehicle (MTO) or sold as an independent component when market demand exists, thereby providing significant operational and revenue flexibility.

2 | Literature Review

Hybrid MTO/MTS production systems have been widely recognized in both industry and the research literature over recent decades as a response to the challenges of managing variable demand and reducing inventory costs. By combining the advantages of MTS and MTO production strategies, these systems provide greater flexibility and efficiency compared with traditional production systems. Existing research has primarily focused on three main areas: production strategy design, inventory control, and production scheduling. In a systematic review, Peters and van Oijen [1] proposed a framework for classifying hybrid systems and identified three main types of production control: sequential, parallel, and floating. This classification provided an important foundation for understanding the different structures of these systems. Rafiei and Rabbani [2] also addressed capacity coordination in hybrid production environments and highlighted the importance of decision-making regarding the Customer Order Decoupling Point (CODP). In inventory control and production planning, numerous studies have investigated optimal policies. Beemsterboer, Land, and Teunter [3], in an exploratory study, examined hybrid MTO/MTS production planning and proposed various strategies for simultaneously managing MTO and MTS demands. Subsequently, Beemsterboer et al. [4] investigated the optimization of production batch sizes in hybrid MTO/MTS systems. This study addressed the problem of determining batch sizes for products in both customized and standard production systems. By focusing on flexibility in batch sizes, they demonstrated that the use of hybrid approaches can increase production efficiency while reducing inventory costs, and that flexibility in batch sizes under uncertain conditions can contribute to improved productivity. This paper primarily considered systems comprising only one MTO product and one MTS product and focused on a model that incorporates flexibility in production batch sizes under fixed and predefined conditions; therefore, the current model may not be able to adapt to larger market fluctuations and unforeseen changes in demand. Kuthambalayan and Bera [5] also developed a zero-one integer nonlinear programming model for managing product variety in hybrid systems, in which decisions regarding the production mode (MTS or MTO) and the inventory level of semi-finished components are made at the first stage. In the area of production scheduling, various models have been proposed to optimize the performance of hybrid systems. Kusuma et al. [6] proposed a hybrid MTO/MTS scheduling model for multi-product systems and demonstrated that the hybrid (s,Q)-SPT model performs better in reducing lead time and inventory levels compared with traditional models.

Furthermore, Altendorfer and Minner [7] showed that hybrid MTO/MTS systems generally outperform pure MTS or MTO strategies under most conditions and can serve as an optimal solution. The choice between these two strategies is significantly dependent on system parameters; specifically, the MTO system is more desirable when inventory holding costs are high, customer lead times are longer, or the production rate increases. In contrast, the MTS system performs better under conditions of high demand rates and short lead times. In other studies, Beemsterboer et al. [8] specifically addressed the operational aspects and production scheduling in job-shop environments and the management of workflow. However, a careful review of the existing literature reveals two important research gaps that the present study addresses. The first gap is the lack of attention to the direct sale of semi-finished components. Although several studies have addressed the management of semi-finished components in hybrid systems, such as Tiagarajan and Kothambalayan [5], none has explicitly considered the possibility of selling these components directly as an independent revenue-generating option, separate from their internal use in the production of final products. This aspect, which is common in industries such as automotive and electronics, represents an overlooked opportunity for improving strategic decision-making and increasing profitability. The second gap is the limitation of existing models in managing complex multi-product systems. Many studies, particularly earlier studies or those focusing on simpler systems, consider MTS systems with a limited number of products. This assumption limits the applicability of these models to real-world industries that deal with a high variety of products and components. Therefore, the present study is conducted to address these research gaps by developing a production scheduling framework that considers both the direct sale of semi-finished components and the complexity of multi-product hybrid MTO/MTS production environments.

3 | Problem Definition

In this section, the modeling framework for the production scheduling problem in a hybrid MTO/MTS environment is first presented in detail, and its key challenges are examined. Subsequently, a mathematical model is developed to formulate the key decisions, including production scheduling, batch size determination, and decision-making regarding the destination of semi-finished components. Finally, the efficiency and validity of the proposed model are evaluated by analyzing numerical results under several scenarios.

3.1 | Problem Statement

In modern production environments, the integration of MTO and MTS production systems creates significant challenges in production scheduling. These challenges become more complex when semi-finished components are considered, as they can either be consumed internally within the organization for the production of final products or sold independently in the market. This dual-use capability creates a unique optimization opportunity that has not been adequately addressed in the existing literature [9], [10].

The problem addressed in this paper involves determining an optimal production schedule that simultaneously manages the following:

- I. MTO customer orders with predetermined demands.
- II. MTS production based on demand forecasts.
- III. Independent demand for semi-finished components that can be sold directly.
- IV. Machine setup and inventory holding requirements.
- V. Precedence relationships among components in the production process.

The primary objective is to minimize total operating costs while satisfying all demand requirements and meeting the system's constraints. Due to the simultaneous consideration of multiple types of demand and complex scheduling constraints, this problem is considered a complex combinatorial optimization problem.

In traditional MTO/MTS systems, production decisions are generally made separately for each production type. However, in the proposed approach, flexibility in using semi-finished components enables integrated

optimization. This flexibility means that, at any point in time, the system can determine whether a semi-finished component should be retained for internal production or sold independently. This flexible decision-making approach has the potential to reduce costs and increase revenue.

3.2 | Mathematical Model

The proposed mathematical model is formulated as a MILP problem. The notation used in the model is presented below.

Indices

i, j : Indices of components, representing each component in the set of components.

t : Index of time periods, representing each time period in the planning horizon.

m : Index of machines, representing each machine in the set of machines.

k : Index of precedence relationships, used to define precedence relationships for components in the workshop.

Sets

J : Set of components.

T : Set of time periods.

M : Set of machines.

K : Set of precedence relationships.

Parameters

b_j : Processing time of component $j \in J$.

CAP_q : Warehouse capacity.

$d_{j,t}$: Demand for component $j \in J$ in time period $t \in T$.

$assigned_{mj}$: Equals 1 if component $j \in J$ is assigned to machine $m \in M$; otherwise, it equals 0.

$Setupcost_{mj}$: Setup cost of machine $m \in M$ for component $j \in J$.

$From_k$: The number of the prerequisite component in precedence relationship $k \in K$.

To_k : The number of the subsequent component in precedence relationship $k \in K$.

CR_k : Consumption coefficient of component To_k for producing component $From_k$.

Hq_j : Holding cost of component $j \in J$.

CW : Cost per unit of machine idle time.

CZ : Cost per unit of machine tardiness time.

$Policy_j$: Equals 1 if component $j \in J$ is produced under the MTS policy; otherwise, it equals 0, indicating MTO production.

Variables

$x_{j,t}$: Start time of production for component $j \in J$ in time period $t \in T$.

$q_{j,t}$: Production quantity of component $j \in J$ in time period $t \in T$ (integer).

$invq_{j,t}$: Inventory level of component $j \in J$ in time period $t \in T$.

$Setupflag_{mj,t}$: Equals 1 if machine $m \in M$ is set up to produce component $j \in J$ in time period $t \in T$; otherwise, it equals 0. This variable determines the machine setup decisions.

$y_{i,j,t}$: Equals 1 if component $i \in J$ is produced before component $j \in J$ on the same machine; otherwise, it equals 0. This variable determines the production sequence of components.

$Usage_{j,t}$: Auxiliary variable representing the amount of component $j \in J$ used in time period $t \in T$.

$SM_{m,t}$: Start time of machine $m \in M$ in time period $t \in T$.

$FM_{m,t}$: Completion time of machine $m \in M$ in time period $t \in T$.

$idle_{m,t}$: Idle time of machine $m \in M$ in time period $t \in T$. This variable calculates the duration for which the machine remains inactive.

Z_t : Latest delivery time of completed components in time period $t \in T$. This variable represents the completion time of jobs in each period.

The proposed mathematical model, based on the aforementioned notation, consists of an objective function, a set of constraints, and the variable domains, as described below:

$$\begin{aligned} \text{Min CW. } & \sum_{m \in M} \sum_{t \in T} + \sum_{m \in M} \sum_{j \in J} \sum_{t \in T} \text{setupcost}_{m,j} \cdot \text{setupflag}_{m,j,t} \\ & + \text{CZ. } \sum_{t \in T} Z_t + \sum_{j \in J} \sum_{t \in T} Hq_j \cdot \text{inv}q_{j,t}, \end{aligned} \quad (1)$$

$$q_{i,t} \leq M \cdot \text{setupflag}_{m,j,t}, \quad \forall m \in M, j \in J \mid \text{assigned}_{m,j} = 1, \quad \forall t \in T, \quad (2)$$

$$\text{setupflag}_{m,j,t} \leq \text{assigned}_{m,j}, \quad \forall m \in M, j \in J, t \in T, \quad (3)$$

$$x_{\text{from}_k,t} + b_{\text{from}_k} \cdot q_{\text{from}_k,t} \leq x_{\text{to}_k,t}, \quad \forall k \in K, \forall t \in T, \quad (4)$$

$$x_{j,t} + b_j \cdot q_{j,t} \leq x_{i,t} + M(1 - y_{i,j,t}), \quad \forall i, j \in J \mid 1, \text{assigned}_{m,i} = 1, \text{assigned}_{m,j} = 1, \quad (5)$$

$$x_{j,t} + b_j \cdot q_{j,t} \leq x_{i,t} + M \cdot y_{i,j,t}, \quad \forall i, j \in J \mid 1, \text{assigned}_{m,i} = 1, \text{assigned}_{m,j} = 1, \quad (6)$$

$$\text{usage}_{j,t} = \sum_{k \in K \mid \text{from}_k = j} CR_k \cdot q(\text{to}_k,t), \quad \forall j \in J, \quad \forall t \in T, \quad (7)$$

$$\text{inv}q_{j,t} = q_{j,t} - \text{usage}_{j,t} - d_{j,t}, \quad \forall j \in J, \quad t = 1, \quad (8)$$

$$\text{inv}q_{j,t} = \text{inv}q_{j,t} + q_{j,t} - \text{usage}_{j,t} - d_{j,t}, \quad \forall j \in J, \forall t \in T \mid t > 1, \quad (9)$$

$$\text{inv}q_{j,t} = 0, \quad \forall j \in J \mid \text{policy}_j = 0, \quad t = T, \quad (10)$$

$$SM_{m,t} \leq x_{j,t}, \quad \forall m \in M, \forall j \in J \mid \text{assigned}_{m,j} = 1, \forall t \in T, \quad (11)$$

$$FM_{m,t} \geq x_{j,t} + b_j \cdot q_{j,t}, \quad \forall m \in M, \forall j \in J \mid \text{assigned}_{m,j} = 1, \forall t \in T, \quad (12)$$

$$\text{idle}_{m,t} = FM_{m,t} - SM_{m,t} - \sum_{j \in J \mid \text{assigned}_{m,j} = 1} b_j \cdot q_{j,t}, \quad \forall m \in M, \quad \forall t \in T, \quad (13)$$

$$Z_t \geq x_{j,t} + b_j \cdot q_{j,t}, \quad \forall j \in J, \forall t \in T, \quad (14)$$

$$\sum_{j \in J} \text{inv}q_{j,t} \leq \text{CAP}q, \quad \forall t \in T, \quad (15)$$

$$q_{j,t} \in \mathbb{Z}^+, \quad \forall j \in J, \forall t \in T, \quad (16)$$

$$x_{j,t} \geq 0, \quad \forall j \in J, \forall t \in T, \quad (17)$$

$$\text{inv}q_{j,t} \geq 0, \quad \forall j \in J, \forall t \in T, \quad (18)$$

$$\text{setupflag}_{m,j,t} \in \{0,1\}, \quad \forall j \in J, \forall t \in T, \forall m \in M, \quad (19)$$

$$y_{i,j,t} \in \{0,1\}, \quad \forall i, j \in J \mid i \neq j, \quad \forall t \in T, \quad (20)$$

$$SM_{m,t}, FM_{m,t}, \text{idle}_{m,t} \geq 0, \quad \forall t \in T, \forall m \in M, \quad (21)$$

$$Z_t \geq 0, \quad \forall t \in T. \quad (22)$$

Objective *Function (1)* aims to minimize machine idle time, which indicates the optimal utilization of production capacity, while simultaneously reducing MTO order delivery delays by controlling setup and inventory holding costs. This multi-objective approach is particularly suitable for hybrid MTO/MTS systems,

as it simultaneously considers the conflicting requirements of the two systems: rapid responsiveness to MTO orders versus efficient inventory management in MTS.

Constraints (2) and (3) ensure that production takes place only when the machine has been set up to produce the respective component, and that setup operations are performed only for components assigned to the machine. Precedence *Constraints (4)* enforce the precedence relationships among components, ensuring that prerequisite components are produced before the production of subsequent components begins. Non-overlapping *Constraints (5) and (6)* determine the production sequence of components on each machine using binary sequencing variables to prevent overlap in production times. Consumption calculation *Constraints (7)* define the consumption relationships of semi-finished components in the production of other components, while inventory balance *Constraints (8) and (9)* control the material flow within the system and require zero inventory for MTO components in the final period, *Constraint (10)*. Machine scheduling *Constraints (11) and (12)* define the start and completion times of machine activities and calculate machine idle time *Constraint (13)*, while the tardiness *Constraint (14)* ensures that the completion time of each order is recorded within the specified time. Finally, the warehouse capacity *Constraint (15)* ensures that the total inventory level in each period does not exceed the warehouse capacity. The variable domain (*Constraints (16) to (22)*) defines that the decision variables must take positive integer values (*Constraint (16)*), non-negative values (*Constraints (17) and (18)*), or binary values (*Constraints (19) and (20)*). This comprehensive set of constraints enables the model to simultaneously manage MTO, MTS, and independent demand for semi-finished components while providing detailed production scheduling.

3.3 | Verification and Validation of the Proposed Model

To comprehensively evaluate the performance of the model, a systematic three-stage approach is adopted. First, the production network structure, including precedence relationships, MTO/MTS policies, and the possibility of selling semi-finished components, is introduced. Subsequently, several numerical examples with diverse parameters are defined to simulate the behavior of the model under different operating conditions. Finally, the results obtained from solving these examples are analyzed to verify the mathematical correctness of the model, compliance with all constraints, and its effectiveness in generating optimal and feasible production schedules.

3.3.1 | Production System Structure

The production network shown in Figure 1 represents the structure of the production system of the proposed model using a directed graph.

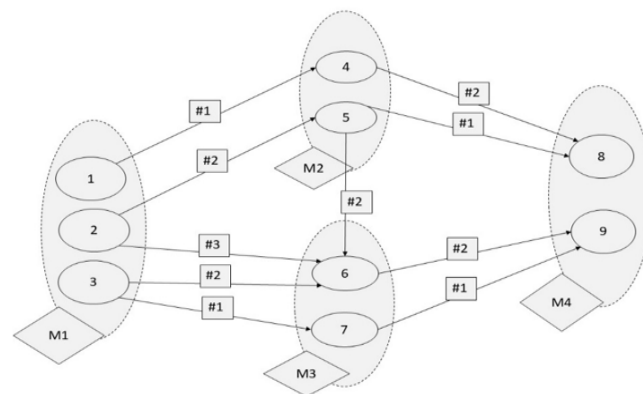


Fig. 1. Directed graph representation of the hybrid MTO/MTS production system with the possibility of selling semi-finished components

The edges of this graph are defined based on the precedence relationships specified in the input data, such that the directed edges point from prerequisite components to subsequent components. For example, the

directed edge from node 1 to node 4 with a weight of 1 (the consumption coefficient, denoted by #) indicates that one unit of component 1 is required to produce each unit of component 4. Figure 1 shows that the production system is designed as a hierarchical production line, in which the initial components (1, 2, and 3) are produced on the initial machines and then used as inputs for the production of intermediate components (4, 5, 6, and 7), and finally, the final components (8 and 9). Each component can be produced under either the MTO or MTS policy. This graphical structure clearly illustrates the dependency relationships among components and the flow of materials within the system and is highly useful for analyzing production scheduling and managing semi-finished components.

3.3.2 | Input data

The model input data are organized into three structured tables. *Table 1* includes the periodic demand for components and the production policy (MTO/MTS) associated with each component and is used as the basis for production planning and inventory management. *Table 2* includes the processing time, holding cost, and setup cost of each component, which play a key role in scheduling and cost evaluation. *Table 3* defines system parameters such as the weighting coefficients for operating costs (setup, machine idle time, and machine tardiness) and the overall warehouse capacity. This transparent structure ensures the reproducibility of the model and enables a detailed analysis of its performance.

Table 1. Component parameters.

j	d in Scenario 1				d in Scenario 2				d in Scenario 3				d in Scenario 4			
	t1	t2	t3	Policy	t1	t2	t3	Policy	t1	t2	t3	Policy	t1	t2	t3	Policy
part1	2	15	4	1	16	16	17	1	19	19	6	1	13	17	1	1
part 2	10	4	6	1	20	20	3	1	7	9	0	0	2	0	18	0
part 3	6	8	3	1	9	2	10	0	9	9	6	1	5	5	9	1
part 4	7	4	12	0	5	15	4	1	9	16	16	1	9	46	16	1
part 5	3	5	10	1	18	14	2	1	1	10	19	0	17	0	5	0
part 6	6	6	11	1	15	10	11	1	11	12	8	1	6	13	9	1
part 7	2	7	5	0	7	4	11	1	16	15	14	1	9	12	11	1
part 8	9	5	7	0	14	17	19	1	19	18	19	0	17	12	14	0
part 9	8	10	5	1	5	1	19	0	6	13	19	1	1	0	18	1

Table 2. Machine Parameters.

j	b	hq	M1	M2	M3	M4
part 1	10	1.1	70	—	—	—
part 2	12	2	20	—	—	—
part 3	9	0.7	10	—	—	—
part 4	15	1	—	120	—	—
part 5	9	0.5	—	80	—	—
part 6	11	1	—	—	20	—
part 7	13	1	—	—	30	—
part 8	14	1.2	—	—	—	100
part 9	8	0.8	—	—	—	60

Table 3. System parameters.

	CAPq	CW	CZ
Scenario 1	50	0.9	0.8
Scenario 2	300	0.45	1
Scenario 3	1000	0.05	0.2
Scenario 4	2000	0.7	0.7

3.3.3 | Model implementation and solution results

The proposed mathematical model was implemented using LINGO version 18.0. In this process, the input data were read from Excel files, and the obtained results were also written back to the same files. To evaluate

the performance of the proposed model, four numerical scenarios with different combinations of cost parameters, inventory policies, and capacity levels were defined and solved. The results obtained are summarized in *Table 4*, which includes the total cost and its components (setup, tardiness, holding, and machine idle costs) for each scenario.

Table 4. Comparison of total costs and their components across four numerical scenarios.

	$CZ \times \sum Z$	$\sum hq^{invq}$	Setup Cost	$CW \times \sum idle$	Total Cost
Scenario 1	8416	84.6	990	0	9490.6
Scenario 2	14618	283.2	710	148.5	15759.7
Scenario 3	3041.6	240.2	570	0	3851.8
Scenario 4	8435	297.5	670	0	9402.5

4 | Analysis of the Results

The analysis of the results in *Table 4* shows that the model intelligently balances competing costs (setup, holding, and tardiness). Scenario 2, with the highest tardiness cost ($CZ=1$), has the highest total cost (15759.7), whereas Scenario 3, with the lowest CW and CZ and the highest warehouse capacity, achieves the lowest total cost (3851.8). The proposed model effectively manages hybrid MTO/MTS production policies. For MTS components, considering setup and holding costs, the model determines whether production should take place before demand or not. For MTO components, the model flexibly utilizes inventories of semi-finished components and final components. This capability makes it possible to generate additional revenue from semi-finished components and creates added value in the production system. In Scenario 1, with limited warehouse capacity ($CAP=50$), the model is required to manage inventory very carefully. This constraint results in production being carried out approximately in proportion to demand, and the holding cost (84.6 units) reaches its minimum possible level. However, this strategy requires frequent production, which increases the setup cost to 990 units. In addition, to prevent tardiness, the model schedules production such that the production of initial components (such as component 2) begins at the beginning of the first period ($x_{2,1}=0$), so that the production chain of dependent components (5, 6, and 8) is not delayed.

In contrast, Scenario 4, with the highest warehouse capacity ($CAP=2000$) and a more balanced combination of CW and CZ costs, adopts a different strategy. In this scenario, by utilizing the abundant warehouse space, the model moves toward mass production and reduces the number of setups, resulting in a setup cost of 670 units. For example, component 2, which has low demand in the first period, is produced in the second period ($x_{2,2}=0$) and its inventory is held for the third period, demonstrating the model's focus on reducing setup costs and utilizing warehouse capacity. This comparison shows that the model dynamically responds to changes in system capacity and determines the optimal production strategy based on resource constraints. Finally, the comparison of the scenarios shows that reducing tardiness costs and increasing warehouse capacity can lead to a significant reduction in total cost, even if this results in increased inventory. Overall, the model is capable of effectively and intelligently balancing the competing objectives of production, inventory management, and scheduling. These results highlight that the proposed model has successfully satisfied demand, such that all MTO and MTS demands have been fulfilled on time, no machine has remained idle in any period, and the production resources have been fully optimized. Inventory levels have been optimally managed and holding costs have been controlled; furthermore, all precedence and scheduling constraints have been successfully satisfied. These findings clearly demonstrate that the developed mathematical model is capable of solving real-world problems with considerable complexity and providing precise and applicable operational outputs for production management decision-making.

5 | Conclusion

In this study, a novel mathematical model was developed for production scheduling in hybrid MTO/MTS environments that integrally incorporates the possibility of directly selling semi-finished components as a

strategic decision-making option. The main innovation of this model is the modeling of flexibility in determining the final destination of semi-finished components, which is introduced for the first time in the production management literature as an integrated optimization problem. This approach enables intelligent decision-making between using components as intermediates in the production of final products or selling them as independent products. The proposed model simultaneously optimizes total production time, operating costs (including setup, machine idle time, and inventory holding costs), and revenue from the sale of semi-finished components by combining multi-objective optimization. Numerical results under four different scenarios show that the model is capable of satisfying all MTO, MTS, and semi-finished component demands without delay, minimizing the total system cost, and providing detailed planning of machine scheduling. These outputs are highly applicable to the operational implementation of production. The practical applications of this model are extensive in industries such as automotive, electronics, and industrial machinery, where intelligent management of semi-finished components can lead to improved resource utilization, cost reduction, and the generation of additional revenue. This approach not only enables production managers to make better strategic decisions but also increases organizational profitability through value creation. However, this study has certain limitations that can shape future research directions: 1) the uncertainty in demand and processing times is not considered, which can be addressed using stochastic or robust models, 2) the model is limited to a single-job-shop environment, 3) there is a need to develop metaheuristic algorithms for solving large-scale problems, and 4) operational parameters such as quality and maintenance scheduling are not considered. This research confirms that integrating flexibility in the sale of semi-finished components can lead to improved efficiency of hybrid production systems and create added value for them.

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Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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