Optimizing Hybrid Assembly Strategies in Supply Networks: Evaluation of Make-to-Stock and Make-to-Order Models

by

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ABSTRACT

This Capstone developed an optimization-based framework to support production planning decisions in supply networks that operate with both make-to-stock (MTS) and make-to-order (MTO) strategies. Many manufacturing firms face the challenge of deciding which products should be produced in advance and which should be produced only after receiving customer orders. These decisions become more complex in networks with multiple products, factories, and customers, where demand variability, capacity limits, lead times, and transportation distances interact.

The proposed model evaluated MTS and MTO decisions at the product–factory–customer level, allowing the same product to be produced to stock for some customers and to order for others, reflecting realistic hybrid production environments. The model maximized total profit by jointly considering revenue, production, transportation, and inventory holding costs. Demand decay captured lost revenue under MTO due to long lead times, while safety stock costs were modeled using pooled demand variability to represent inventory risk under MTS production.

The framework was applied to a dataset based on real operational data provided by a company and extended to enable a comprehensive analysis. The network included multiple products, customers, and factories. Results showed that the optimal strategy was inherently hybrid, with MTS and MTO allocations driven by a balance of demand variability, holding cost, customer distance, factory capacity, and lead-time sensitivity rather than any single factor.

Sensitivity analyses further demonstrated how changes in demand variability, holding cost, lead time, and demand decay affect the MTS–MTO mix. Overall, hybrid strategies consistently outperformed pure MTS or pure MTO approaches, illustrating the framework's value as a scalable decision-support tool for improving profitability and supply network resilience.

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# 1. Introduction

## Background

This Capstone project is proposed and sponsored by the Center for Transportation & Logistics (CTL) Intelligent Logistics Systems (ILS) Lab at Massachusetts Institute of Technology (MIT). The project is inspired by real-world challenges faced by global manufacturing firms that operate across distributed networks of factories, warehouses, and suppliers. These firms face the manufacturing scenario where they need to decide whether to assemble products in advance, also known as make-to-stock (MTS) or in response to customer demand, also known as make-to-order (MTO), balancing cost efficiency with responsiveness and customization.

MTS is suited for standardized, high-volume products with stable demand, enabling quick delivery but risking excess inventory and obsolescence. MTO, on the other hand, is ideal for customized or low-volume products, minimizing inventory costs but often resulting in longer lead times and planning complexity. In some production settings, traditional MTS and MTO approaches cannot achieve the Key Performance Indicator (KPI) requirements imposed by a company or its customers (Peeters et al., 2020). Consequently, many firms now adopt hybrid MTS/MTO models, producing high-volume items ahead of demand while manufacturing low-volume or configurable items to order (Thoma, 2016). Hybrid strategies improve responsiveness, reduce inventory risk, and support mass customization, making them increasingly relevant in multi-product environments.

## 1.1 Motivation

Although MTS and MTO strategies have been widely studied, modern supply networks introduce new complexities related to product diversity, multi-factory operations, and demand uncertainty. This Capstone aimed to develop a practical, optimization-based methodology for determining MTS/MTO allocation across a real-world complex supply network. Key drivers of complexity include:

A. Variations in unit holding costs and production time variability, which influence whether products are better suited for MTS, MTO, or hybrid production decisions.
B. Customer-specific lead times and demand decay effects, which reduce realized revenue under MTO production.
C. MTS and MTO assignments that are specific to products and customers, including partial splits for the same product, requiring an integrated approach that balances cost, service, and variability tradeoffs.

Applying the optimized hybrid strategy developed in this Capstone enables firms to reduce unnecessary inventory, improve production and distribution decisions, lower transportation and holding costs, and enhance overall profitability and operational resilience.

## 1.2 Problem Statement and Key Questions

The central question examined in this Capstone is: How can manufacturing firms effectively evaluate and select between pure MTS, MTO, or hybrid MTS/MTO production strategies to optimize operational performance and customer satisfaction across multi-factory, multi-product networks?

To investigate this, the Capstone is guided by three key questions:

A. How do MTS and MTO decisions affect overall profit when considering selling price, lead-time-driven revenue decay, production cost, transportation cost, and safety stock holding cost?
B. How do factory-specific constraints, such as production capacity shape the assignment of products to MTS or MTO?
C. How can optimization modeling and scenario analysis be used to identify the most effective mix of MTS and MTO strategies across products, factories, and customers?

To address these questions, this Capstone applies a structured analytical approach that combined exploratory analysis of demand and lead-time behavior with the development of a mathematical optimization model that incorporates factory level cost structures and operational parameters to quantify the trade-offs between MTS and MTO decisions.

### 1.3 Project Goals

Manufacturers operating across multiple factories must balance responsiveness, cost, capacity, and demand uncertainty. This Capstone proposes a data-driven framework to allocate MTS and MTO assignments across the network with an aim to:

A. Develop a systematic framework for determining when products should be fulfilled through MTS, MTO, or hybrid configurations at the product, factory, and customer level.
B. Design an optimization-based decision model that evaluates the profitability of alternative fulfillment strategies by jointly accounting for demand variability, lead-time sensitivity, and key cost drivers.
C. Generate managerial insights through scenario and sensitivity analyses that identify conditions under which hybrid MTS/MTO strategies outperform pure approaches and enhance resilience under uncertainty.

Overall, this work provides strategic guidance for aligning fulfillment decisions with broader business objectives, enabling more profitable, flexible, and resilient supply network operations.

### 1.4 Expected Outcomes

This Capstone is expected to deliver practical, data-driven decision support for MTS/MTO planning in multi-product, multi-facility manufacturing environments. Expected outcomes include:

A. An optimization-based tool for identifying MTS, MTO, and hybrid assignments.
B. Quantitative insights into cost, demand, and lead-time trade-offs.
C. A final report and presentation summarizing the framework, results, and recommended strategies.

## 2. State of the Practice

Production planning and control (PPC) plays a central role in determining how manufacturing systems balance cost efficiency, responsiveness, and service performance. Among PPC decisions, the choice between MTS, MTO, or hybrid production strategies is particularly critical in multi-product, multi-facility environments where demand uncertainty, capacity constraints, and lead-time requirements coexist. Although much of the discussion in this section draws on academic research, these studies reflect practical challenges faced by manufacturers in configuring fulfillment strategies across complex production networks. This section reviews current industry practices and academic research on MTS, MTO, and hybrid production systems, with a focus on strategic structures and analytical insights that directly inform the development of this Capstone's proposed optimization-based MTS/MTO allocation model.

### 2.1 Production Planning Strategies: MTS, MTO, and Hybrid Systems

Early production planning approaches typically relied on MTS for forecast-driven environments and MTO for order-driven fulfillment. However, as manufacturing systems have become more complex, research and practice have increasingly shifted toward hybrid strategies that combine elements of both MTS and MTO to improve flexibility and cost efficiency. This evolution has been examined extensively in studies seeking to define suitable configurations for MTS, MTO, and assemble-to-order (ATO) systems. Peeters et al., (2020) provide a comprehensive review of hybrid MTS/MTO production control literature published between 1984 and 2018 (Figure 1). They classify hybrid MTS/MTO systems into sequential, parallel, and floating categories, which describe alternative structural implementations of MTS and MTO integration. These categories are used to characterize the distribution of hybrid system types examined in prior research. Peeters et al. (2020) also note that, despite the breadth of their review, the surveyed literature cannot be guaranteed to be fully complete.

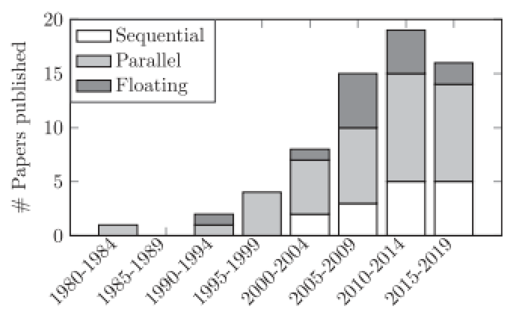


*Figure 1 Number of Hybrid MTS/MTO Production Control Articles Published From 1984 to 2018.*

Sequential hybrids apply MTS and MTO stages in sequence for a single product. The customer order decoupling point (CODP) determines where production transitions from forecast-driven to order-driven operations. Parallel hybrids manage shared resources for MTS and MTO products simultaneously, requiring sophisticated scheduling and prioritization rules. Floating hybrids allow CODP to shift dynamically under real-time production control, often leveraging advanced information systems for adaptability. Across these system types, prior studies consistently find hybrid configurations to outperform pure MTS or pure MTO strategies in terms of cost, lead time, and service performance, particularly under volatile demand and tight delivery requirements. (Peeters et al., 2020).

Building on this literature, this Capstone focuses specifically on hybrid MTS/MTO strategies as a repsonse to the fundamental trade-off between inventory risk and responsiveness. Forecast-driven MTS systems, offer shorter delivery times but incur high inventory holding costs, while MTO systems reduce inventory exposure at the expense of longer lead times (Peeters et al., 2020).

In addition to structural hybrid configurations, optimization-based studies evaluate MTS and MTO decisions at the network level and consistently find hybrid strategies to outperform pure approaches under demand variability and delivery constraints (Sun et al., 2008). Shah (1993) models inventory availability as an exponential decay process, where delays in time reduce the effective quantity available to satisfy demand, implying that the proportion of realizable demand decreases continuously as a function of elapsed time. Complementing this work, other strands of the literature emphasize demand pooling effects that reduce variability and safety stock requirements in MTS systems (Simchi-Levi et al., 2008). Together, these perspectives motivate the modeling approach adopted in the next section.

## 2.2 Modeling Approaches

Modeling approaches for MTS/MTO systems vary widely, including mixed-integer programming (Rajagopalan, 2002), queuing theory (Gupta and Benjaafar, 2004), dynamic programming (Akinc et al., 2009), and simulation (Brabazon, 2006). Modeling choices differ across the literature depending on the production environment and planning horizon considered. This Capstone adopts an optimization-based approach, which is widely used to study integrated production and inventory decisions in hybrid MTS/MTO systems. In optimization-based models, the MTS/MTO choice is most often represented as a binary variable, where each item is either produced to stock or to order. For example, Rajagopalan (2002) and Beemsterboer et al. (2016) employ mixed-integer programming formulation in which $z_i$=1 denotes MTS and $z_i$=0 denotes MTO, often combined with batch-size decisions for MTS items. Conversely, recent research explores continuous or dynamic representations of MTS/MTO decisions. Chen et al. (2014), for instance, model hybrid systems using Markov decision processes (MDPs) in which production and pricing decisions depend on system states such as inventory levels and backlogs rather than fixed binary assignments.

Objective functions in these models typically aim to minimize total cost or maximize service performance, incorporating components such as setup costs, inventory holding costs, stock-out penalties, and asset specificity costs. Sun et al. (2008) characterize total cost as the sum of:

**Total Cost = Set-Up Cost + Inventory Holding Costs + Stock-Out Costs + Asset Specificity Costs**

Inventory cost modeling is central to these frameworks and is commonly expressed as a function of the expected inventory levels:

**Inventory Cost = *h* X E[Inventory],**

where *h* denotes the unit holding cost. Expected inventory levels are typically derived from base-stock policies and demand distributions. Safety stock requirements are determined by demand variability and service-level targets. Budget constraints are often imposed to prevent excessive inventory investment resulting from service-level improvements (Shao et al., 2012).

Hybrid MTS/MTO models also adopt different approaches to representing unmet demand and stock-out effects. Lee (1996) introduces service-based inventory models in which unmet demand is indirectly reflected through response-time and reliability measures rather than explicit shortage costs. Rajagopalan (2002) embeds stockout considerations through probabilistic lead-time satisfaction requirements, where unmet demand arises when customer demand exceeds available inventory.

Beyond cost minimization, several studies adopt profit-maximization objectives that integrate revenue with production, holding, stockout, and overtime costs (Ervural et al. 2024), while others focus on service-level optimization under inventory budgets (Shao et al., 2012). Consistent with these approaches, this Capstone adopts a profit-maximization framework, which is tied to economic objectives of a company in contrast to cost reduction metrics, for evaluating hybrid MTS/MTO decisions.

Across these studies, key performance indicators include inventory cost, fill rate, lead time, and customer satisfaction. Industry applications such as Amazon's print-on-demand operations (Thoma, 2016) and Dell's postponement strategies (Peeters et al., 2020) further underscore the practical relevance of hybrid MTS/MTO systems in complex manufacturing environments.

Building on these insights, the modeling framework developed in this Capstone integrates lead-time-dependent revenue effects and inventory risk considerations within a unified optimization formulation, enabling systematic evaluation of hybrid MTS/MTO decisions without revisiting structural configuration choices.

## 3. Methodology

The key objective of this Capstone was to establish a methodology for optimizing MTS and MTO decisions across a multi-factory, multi-product supply network. The proposed approach considered customer-specific demand and lead-time considerations that affect revenue realization and associated costs, while ensuring that production assignments remain feasible given available factory capacity. The methodology employed an optimization-based model to maximize total profit by jointly accounting for revenue, production costs, transportation costs, and inventory holding cost while determining the optimal MTS or MTO fulfillment mode for each product-factory-customer combination.

### 3.1 Methodology Selection

The methodology adopted in this study combined quantitative optimization modeling with hybrid production theory. In contrast to models that assign a single production strategy to an entire product line, this formulation evaluates MTS and MTO decisions at the product-factory-customer level, allowing the same product to be produced to stock for some customers and to order for others. Consistent with the final computational model, MTS and MTO decisions were represented as binary variables, where each product-customer demand is served through exactly one fulfillment mode and one factory.

This structure reflected hybrid production environments in which customer requirements and lead-time sensitivity influence fulfillment decisions (Gupta & Benjaafar, 2004).

The model integrated customer-specific demand, production lead times, and transportation costs, with factory capacity included to ensure feasible allocations rather than to drive trade-off decisions. Revenue was generated from customer orders fulfilled either through MTS or MTO, where MTO revenue was adjusted by a demand-decay factor reflecting lead-time sensitivity.

Inventory holding costs arose from safety stock maintained for MTS production and were calculated using pooled demand variability and lead-time based protection intervals, consistent with standard safety stock formulations. Production and transportation costs were explicitly modeled for both MTS and MTO flows, ensuring that trade-offs across fulfillment strategies were fully captured. By incorporating these cost and revenue components directly into a unified profit-maximization objective, the methodology provided a robust foundation for analyzing hybrid MTS/MTO production policies.

### Model Assumptions

The following assumptions defined the scope and limitations of the proposed model:

A. MTS and MTO decisions were binary and made at the product–factory–customer level, with each demand served by exactly one factory and one fulfillment mode.
B. Demand quantities were deterministic and known in advance and demand uncertainty was accounted for only through safety stock calculations for MTS production.
C. A single-stage manufacturing process was assumed at each factory.
D. Lead time affected MTO demand fulfillment through a decay factor and was not treated as a decision variable.
E. Inventory holding costs applied only to safety stock associated with MTS production.
F. Production capacity at each factory was assumed to be sufficient to meet assigned demand and was included solely to ensure feasibility of production allocations.

These assumptions simplified the modeling framework while capturing the key economic and operational trade-offs relevant to hybrid MTS/MTO systems.

## 3.2 Model Details and Preparation

This section presents the formal specification of the proposed hybrid MTS/MTO optimization model, including the sets, parameters, decision variables, objective function, and constraints, as summarized in Tables 1–5. The model was instantiated using operational data provided by a partner company and represents a global manufacturing and distribution network comprising 4,884 SKUs, 84 customers, and 24 factories. Product data included item characteristics such as weight and category, while factory data capture geographic locations and production capacities. Additional factors such as customer demand, pricing, production costs, holding costs, lead times, and transportation distances were also integrated to reflect realistic end-to-end supply chain decisions.

| Set | Description |
|---|---|
| P | Set of products, indexed by i. Each element represents a distinct finished product. |
| F | Set of factories, indexed by j. Each factory has finite production capacity. |
| C | Set of customers, indexed by k. Customer-specific demand and lead-time sensitivity are explicitly modeled. |

*Table 1 Sets*

| Parameters | Description |
|---|---|
| $D_{ik}$ | Demand for product i from customer k (units) |
| $s_i$ | Selling price of product i |
| $S_i$ | Unit production cost of product i |
| $h_i$ | Inventory holding cost per unit of product i |
| $c_{ijk}$ | Transportation cost per unit of product i shipped from factory j to customer k |
| $C_j$ | Production capacity available at factory j |
| $L_i$ | Production lead time of product i |
| $p_{ik}$ | Demand survival factor for product i and customer k under MTO fulfillment |
| $F$ | Safety factor used for safety stock calculation |
| $V_{ik}$ | Demand variability for product i from customer k (units) |
| β | Demand decay factor |

*Table 2: Parameters*

| Decision Variable | Description |
|---|---|
| $x_{ijk}^{MTS} \in \{0,1\}$ | Equals 1 if demand for product i from customer k is supplied from factory j using MTS; 0 otherwise. |
| $x_{ijk}^{MTO} \in \{0,1\}$ | Equals 1 if demand for product i from customer k is supplied from factory j using MTO; 0 otherwise. |
| $z_{ij} \geq 0$ | Pooled demand standard deviation for product i is held as make-to-stock at factory j. |

*Table 3 Decision Variables*

| Component | Mathematical Expression | Description |
|---|---|---|
| Profit | maxΠ=R−PC−TC−HC (1) | Total profit maximization objective |
| Revenue (R) | $R = \sum_{i,j,k} \left[ s_i D_{ik} x_{ijk}^{MTS} + s_i D_{ik} p_{Lik} x_{ijk}^{MTO} \right]$ | Revenue from fulfilled MTS and decay-adjusted MTO demand |

|  |  |  |
|---|---|---|
| Production Cost (PC) | $PC = \sum_{i,j,k} \mathrm{S}_i \, D_{ik}(x_{ijk}^{MTS} + p_{ik} x_{ijk}^{MTO})$ | Production cost for assigned demand |
| Transportation Cost (TC) | $TC = \sum_{i,j,k} c_{ijk} \, D_{ik}(x_{ijk}^{MTS} + p_{Lik} x_{ijk}^{MTO})$ | Transportation cost for shipped demand |
| Holding Cost (HC) | $HC = \sum_{i,j} h_i \times \mathrm{F} \times z_{ij} \times \sqrt{L_i}$ | Safety stock holding cost for MTS inventory |

*Table 4 Objective Function*

| Constraint | Mathematical Expression | Description |
|---|---|---|
| Profit | $\sum_{j \in F} (x_{ijk}^{MTS} + x_{ijk}^{MTO}) = 1 \forall i \in P,\ k \in C$ *(2)* | Each product–customer demand is served by exactly one factory and one mode. |
| Revenue (R) | $\sum_{i \in P} \sum_{k \in C} D_{ik} \left(x_{ijk}^{MTS} + x_{ijk}^{MTO}\right) \leq C_j \forall j \in F$ *(3)* | Total demand assigned to each factory cannot exceed capacity. |
| Production Cost (PC) | $\left(z_{ij}\right)^2 = \sum_{k \in C} V_{ik}^2 \ x_{ijk}^{\mathrm{MTS}} \forall i \in P,\ j \in F$ *(4)* | Pooled demand variance is calculated for MTS assignments. |

*Table 5 Constraints*

**Equation (1**) maximizes total profit by jointly accounting for revenue from fulfilled customer demand and the associated production, transportation, and inventory holding costs. Therefore, it captures the economic trade-offs between MTS and MTO fulfillment.

**Equation (2)** enforces the assignment constraint by ensuring that each product–customer pair is served by exactly one factory and one fulfillment mode. This results in a unique and feasible production decision for every demand instance.

**Equation (3)** enforces factory-level feasibility by ensuring that the total demand assigned to each factory does not exceed available production capacity, thereby preventing infeasible allocations.

**Equation (4)** defines the demand variance pooling constraint used for safety stock estimation. It specifies that the pooled demand variance for each product–factory pair equals the sum of customer-specific demand variances associated with MTS assignments. This quadratic constraint captures risk-pooling effects and links MTS decisions directly to safety stock holding costs without introducing explicit inventory balance constraints.

The demand survival factor is expressed as $p_{ik} = e^{-\beta L_i}$.

Together, these equations established an optimization framework that integrates profit maximization, feasibility constraints, and demand variance pooling to support lead-time-sensitive hybrid MTS/MTO fulfillment decisions.

### 3.3 Application of Methodology

The model captured the hybrid nature of production planning by allowing MTS and MTO decisions to coexist across customers and factories. While each customer's demand is fulfilled by a single factory and production mode, the system as a whole may follow a mixed strategy depending on lead-time sensitivity, capacity availability, and cost tradeoffs.

The profit-maximization objective internalized revenue decay under MTO, safety stock investment under MTS, and operational costs associated with production and transportation. The constraints ensured feasible assignments and capacity feasibility, enabling comparative analysis of how customer demand allocation and lead-time sensitivity influence optimal hybrid production strategies. This formulation provided a decision-support framework that is consistent with industry practices observed in hybrid MTS/MTO production environments.

## 4. Results and Discussion

Using the dataset described in Section 3.2 (Model Details and Preparation), this section presents and interprets the baseline model results and sensitivity results of the hybrid MTS/MTO optimization model. Figure 2 presents a geographic visualization of the baseline optimization results for a selected subset of the manufacturing and distribution network. Under the baseline solution, the model selects 15 SKUs, five factories, and 10 customers, with factory capacities scaled to 1.2 times the baseline demand requirements to ensure feasibility. The map highlights the spatial distribution of the factories and customers involved in the optimal MTS/MTO allocation, providing context for how geography, lead-time sensitivity, and cost tradeoffs influence fulfillment decisions under baseline conditions


*Figure 2: Baseline Supply Chain Network*

## 4.1 Results

### 4.1.1 Baseline Optimization Results

The baseline run used demand decay factor of 0.01 and a safety factor of 2.05. Other parameters were per the dataset. With the chosen dataset, total demand is 1,176 units and total adjusted capacity is 1,411 units.

The baseline model produced 31 MTS allocations and 18 MTO allocations. High-demand variability and the elimination of safety stock costs were primary drivers for MTO assignments. Conversely, MTS was favored for items with lower demand variability and more manageable holding costs. The model optimized assignments by balancing production, transportation, and safety stock costs to minimize overall expenditures for each SKU. Table 6 presents SKU-level baseline results from the hybrid MTS/MTO optimization model, summarizing how fulfillment decisions vary with demand characteristics, cost factors, and geographic considerations. For each selected SKU, the table reports total demand, the percentage split between MTS and MTO fulfillment, average customer distance, holding cost per unit, and demand variability. It shows that SKUs with higher demand variability are predominantly assigned to MTO, particularly when holding costs are relatively low, thereby limiting inventory exposure. In contrast, SKUs with stable demand patterns are allocated to MTS or hybrid strategies, even when holding costs are high, as demand predictability reduces inventory risk under the baseline optimization. These outcomes should be interpreted as the result of non-linear interaction of multiple factors, including demand levels, holding costs, customer distance, and variability, and not as the result of any single parameter in isolation.

| SKU | SKU Demand | % MTS | % MTO | Customer distance (km) | Unit holding cost (USD) | Demand Variability |
|---|---|---|---|---|---|---|
| 02463 | 269 | 0 | 100 | 5,006 | 121.97 | 2.01 |
| 00614 | 58 | 0 | 100 | 3,376 | 199.51 | 2.19 |
| 02461 | 86 | 0 | 100 | 3,332 | 88.32 | 2.52 |
| 02087 | 42 | 0 | 100 | 2,482 | 82.49 | 1.73 |
| 00840 | 87 | 50 | 50 | 3,294 | 277.11 | 1.4 |
| 00352 | 91 | 66.67 | 33.33 | 2,944 | 373.94 | 1.6 |
| 00386 | 81 | 66.67 | 33.33 | 2,094 | 427.51 | 2.5 |
| 01037 | 25 | 66.67 | 33.33 | 2,076 | 677.76 | 1.02 |
| 01914 | 85 | 80 | 20 | 1,503 | 348.08 | 1.16 |
| 00915 | 59 | 100 | 0 | 3,530 | 744.86 | 1.15 |
| 01861 | 48 | 100 | 0 | 2,502 | 622.65 | 1 |
| 01063 | 108 | 100 | 0 | 2,397 | 434.97 | 1.12 |
| 00857 | 28 | 100 | 0 | 1,316 | 696.54 | 1.04 |
| 01676 | 74 | 100 | 0 | 1,316 | 564.04 | 1 |
| 02509 | 35 | 100 | 0 | 1,040 | 451.64 | 1.2 |

*Table 6 Baseline SKU-Level MTS/MTO Allocation Results*

Figure 3 presents the baseline capacity utilization of factories selected in the optimal solution, highlighting variation in resource usage across the manufacturing network.

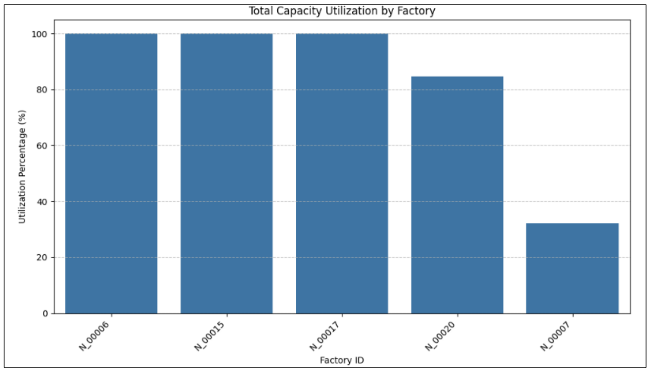


*Figure 3: Capacity Utilization*

Table 7 summarizes optimal profit, revenue, cost breakdowns, and MTS/MTO assignment counts across the hybrid, MTS-only, and MTO-only scenarios, providing a quantitative basis for the profitability comparison. The baseline hybrid scenario demonstrated superior profitability, yielding a 3.43% improvement in optimal profit when compared to an exclusive MTS strategy and an even more significant 7.92% improvement in optimal profit over an exclusive MTO strategy.

| Scenario | Optimal Profit | Total Revenue | Production Cost | Transportation Cost | Safety Stock Cost | MTS Assignments | MTO Assignments |
|---|---|---|---|---|---|---|---|
| Baseline (Hybrid) | $1,427,389 | $2,558,138 | $565,052 | $445,294 | $120,404 | 31 | 18 |
| MTS Only | $1,380,089 | $2,617,325 | $599,949 | $490,410 | $146,877 | 49 | 0 |
| MTO Only | $1,322,697 | $2,247,806 | $515,584 | $409,526 | $0 | 0 | 49 |

*Table 7 Profit and Cost Comparison Across Hybrid, MTS-Only, and MTO-Only Scenarios*

Overall, the baseline results confirmed that a hybrid MTS/MTO strategy effectively balances inventory risk and responsiveness while delivering superior profitability compared to pure fulfillment strategies.

## 4.2 Sensitivity Analyses

Sensitivity analysis was used to assess the robustness of the hybrid MTS/MTO model by examining how changes in key parameters affect fulfillment decisions and profitability. The analysis evaluated the impact of variations in demand-decay factor (β), demand variability (σ), holding cost (h), and production lead time (L) on MTS/MTO assignments, optimal profit, safety stock cost, and MTO revenue.

### 4.2.1 Sensitivity to Demand Decay Factor

This subsection analyzes effects of variations in demand decay factors in fulfillment decisions and profitability in a hybrid MTS/MTO model. This factor was evaluated across five levels, taking values of 0.001, 0.005, 0.01 (baseline), 0.015, and 0.02. Table 8 summarizes the variation impact on optimal profit, MTS/MTO assignment decisions, and the relative shares of production, transportation, and safety stock costs within total cost.

| β | Profit | MTS Assignments | MTO Assignments | Production Cost % | Transportation Cost % | Safety Stock Cost % |
|---|---|---|---|---|---|---|
| 0.001 | +6.31% | 0 | 49 | 55.73 | 44.27 | 0.00 |
| 0.005 | +1.22% | 13 | 36 | 53.65 | 42.72 | 3.63 |
| 0.01 | $ 1,427,388 | 31 | 18 | 49.97 | 39.38 | 10.65 |
| 0.015 | +0.60% | 33 | 16 | 49.93 | 38.57 | 11.50 |
| 0.02 | +1.19% | 33 | 16 | 50.05 | 38.15 | 11.79 |

*Table 8 Decay Factory Sensitivity to MTS/MTO Assignments and Profit*

Figure 4 illustrates how changes in demand decay factor affect the optimal profit obtained from the hybrid MTS/MTO model, highlighting the sensitivity of overall profitability to customer lead-time sensitivity. Figure 5 shows how variations in demand decay factor influence the allocation of MTS and MTO assignments, illustrating the shift in fulfillment strategy as demand decay increases.

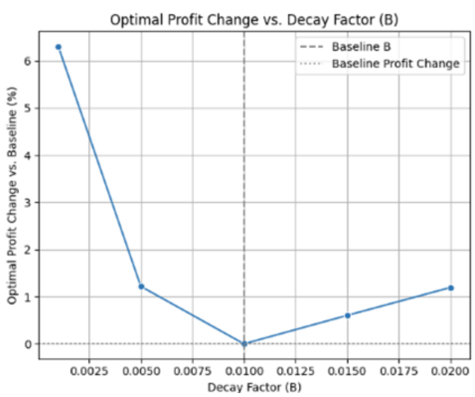


*Figure 4 Impact of decay factor on optimal profit*

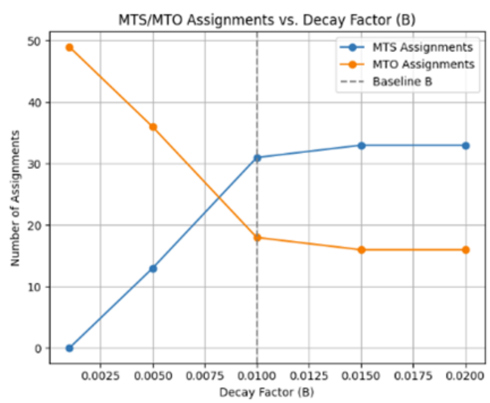


*Figure 5 Effect of decay factor on MTS/MTO assignments*

Key Insights:

A. As demand decay factor increased, MTO fulfillment became less attractive, leading to a shift toward greater MTS adoption.
B. Overall profitability remains largely stable across decay levels, showing only small and non-linear and non-monotonic deviations from the baseline.
C. Safety stock costs increased as more SKUs transition to MTS fulfillment, reflecting higher inventory investment associated with reduced responsiveness.

These results highlighted the robustness of the hybrid MTS/MTO strategy to changes in demand decay behavior.

### 4.2.2 Sensitivity to Demand Variability

This subsection analyzes the effects of variations in demand variability on fulfillment decisions and profitability within the hybrid MTS/MTO model. Demand variability was adjusted using multiplicative factors of 0.5, 0.75, 1.0 (baseline), 1.25, and 1.5, while all other parameters were held constant. Table 9 summarizes the impact of these variations on optimal profit, MTS/MTO assignment decisions, and the relative shares of production, transportation, and safety stock costs within total cost.

| Demand Variability Factor | Profit | MTS assignments | MTO assignments | Production Cost % | Transportation Cost | Safety Stock Cost % |
|---|---|---|---|---|---|---|
| 0.5 | +4.45% | 33 | 16 | 52.76 | 41.31 | 5.93 |
| 0.75 | +2.21% | 33 | 16 | 51.24 | 40.12 | 8.64 |
| 1.0 | $ 1,427,389 | 31 | 18 | 49.97 | 39.38 | 10.65 |
| 1.25 | -1.76% | 24 | 25 | 50.66 | 40.20 | 9.15 |
| 1.5 | -3.16% | 24 | 25 | 49.75 | 39.48 | 10.78 |

*Table 9 Impact of Demand Variability Factor on Profit and MTS/MTO Assignments*

Figure 6 illustrates how changes in demand variability affect the optimal profit obtained from the hybrid MTS/MTO model, highlighting the sensitivity of overall profitability to increased uncertainty in demand.
Figure 7 shows how variations in demand variability influence the allocation between MTS and MTO assignments, illustrating a shift in fulfillment strategy toward MTO as safety stock requirements increase.

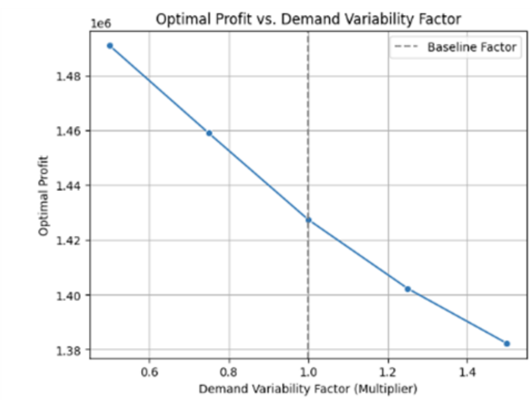


*Figure 6: Impact of Demand Variability Factor on Optimal Profit*

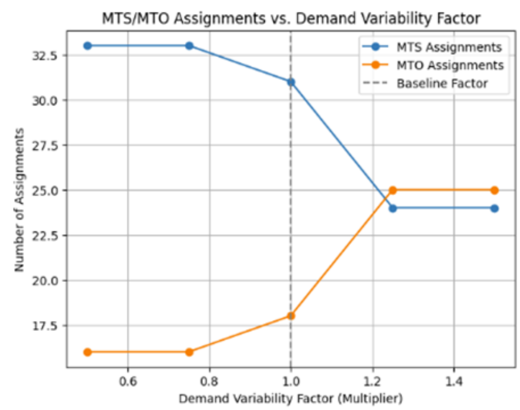


*Figure 7: Impact of Demand Variability Factor on MTS/MTO Assignments*

Key Insights:

A. As demand variability increased, higher pooled variance raises safety stock costs, leading to a shift from MTS toward greater MTO adoption.
B. Lower values of demand variability substantially increased MTS usage, as reduced variability lowered safety stock requirements and inventory costs.
C. Profitability declined as demand variability rose, driven by the nonlinear increase in safety stock costs associated with higher variability.

These findings highlighted demand variability as a critical determinant of both fulfillment mix and profitability in hybrid MTS/MTO systems.

### 4.2.3 Sensitivity to Holding Cost (*h*)

This subsection analyzes the effects of variations in holding cost (*h*) on fulfillment decisions and profitability within the hybrid MTS/MTO model. Holding cost was adjusted as a percentage of the SKU selling price, using values corresponding to 7.5%, 10% (baseline), 20%, 30% and 40%, while all other model parameters were held constant. Table 10 summarizes the impact of these variations on optimal profit, MTS/MTO assignment decisions, and the relative shares of production, transportation, and safety stock costs within total cost.

| Holding Cost % | Profit | MTS assignments | MTO assignments | Production Cost % | Transportation Cost % | Safety Stock Cost % |
|---|---|---|---|---|---|---|
| 0.075 | +4.45% | 33 | 16 | 52.76 | 41.31 | 5.93 |
| 0.100 | $ 1,469,531 | 33 | 15 | 51.74 | 40.51 | 7.75 |
| 0.200 | -2.23% | 24 | 25 | 50.35 | 39.96 | 9.70 |
| 0.300 | -4.96% | 12 | 37 | 51.94 | 41.28 | 6.78 |
| 0.400 | -5.83% | 5 | 44 | 53.81 | 42.55 | 3.65 |

*Table 10: Impact of Holding Cost % on Profit and MTS/MTO Assignments*

Figure 8 illustrates how changes in *h* affect the optimal profit obtained from the hybrid MTS/MTO model, highlighting the sensitivity of profitability to inventory carrying costs.
Figure 9 also shows how increasing *h* influences the allocation between MTS and MTO assignments, illustrating a pronounced shift toward MTO as safety stock costs become more costly.

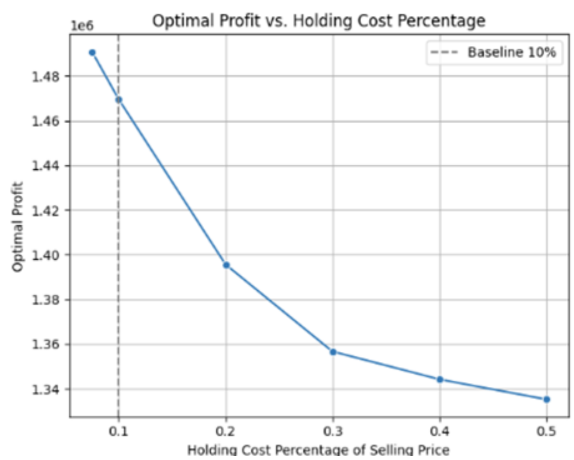


*Figure 8: Impact of Holding Cost % on Optimal Profit*

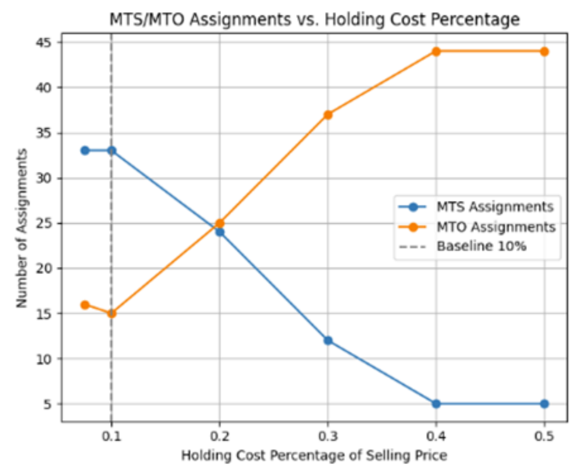


*Figure 9: Impact of Holding Cost % on MTS/MTO Assignments*

Key Insights:

A. As *h* increased, safety stock becomes increasingly expensive, driving a strong shift from MTS toward MTO fulfillment.
B. High *h* environments led to sharp profit declines, as MTS assignments incurred disproportionately large inventory carrying costs.
C. MTO revenue increased as more products transition to order-based production in response to rising holding costs.
D. When *h* exceeded approximately 40% of selling price, the system behavior converged toward a predominantly MTO network.

Overall, these results confirmed that $h$ is a dominant driver of fulfillment strategy selection, with higher inventory carrying costs strongly favoring MTO and reducing the economic viability of MTS within hybrid production systems.

### 4.2.4 Sensitivity to Lead Time:

This subsection analyzes the effects of variations in lead time on fulfillment decisions and profitability within the hybrid MTS/MTO model. Lead time influenced the model through two competing mechanisms: demand decay under MTO fulfillment and safety stock requirements under MTS fulfillment. To evaluate these effects, the baseline is defined by a lead time factor of 1.0, and lead times were scaled around this baseline to take values from 0.20 to 1.50, while all other model parameters were held constant. Table 11 summarizes the impact of these variations on optimal profit, MTS/MTO assignment decisions, and the relative shares of production, transportation, and safety stock costs within total cost.

| Lead Time factor | Profit | MTS assignments | MTO assignments | Production Cost % | Transportation Cost % | Safety Stock Cost % |
|---|---|---|---|---|---|---|
| 0.20 | +5.07% | 5 | 44 | 55.36 | 43.99 | 0.65 |
| 0.46 | +2.70% | 24 | 25 | 52.86 | 42.17 | 4.97 |
| 0.72 | +1.13% | 25 | 24 | 52.08 | 41.39 | 6.53 |
| 0.98 | +0.07% | 31 | 18 | 50.02 | 39.44 | 10.54 |
| 1.24 | -0.73% | 32 | 17 | 49.30 | 38.40 | 12.31 |

*Table 11: Impact of Lead Time on Profit and MTS/MTO Assignments*

Figure 10 illustrates how changes in lead time affect the optimal profit obtained from the hybrid MTS/MTO model, highlighting the combined impact of revenue decay and inventory-related costs. Figure 11 shows how increasing lead time influences the allocation between MTS and MTO assignments, revealing shifts in fulfillment strategy driven by the opposing effects of demand decay and safety stock growth.

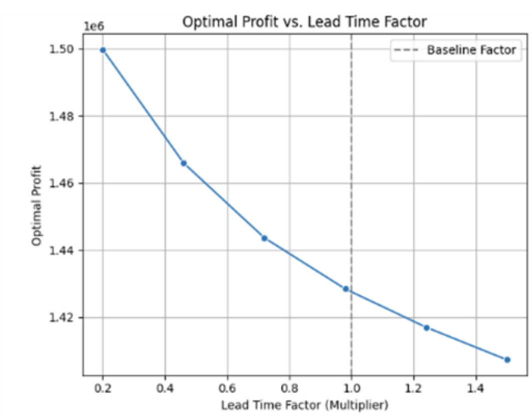


*Figure 10: Impact of Lead Time on Optimal Profit*

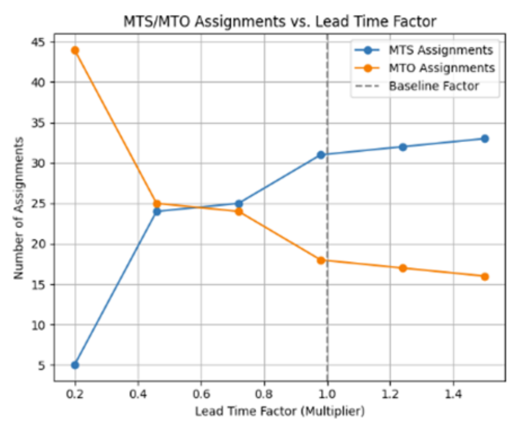


*Figure 11: Impact of Lead Time on MTS/MTO Assignments*

Key Insights:

A. As lead time increased, MTO revenue declined due to stronger demand decay, while MTS safety stock costs rose, jointly exerting downward pressure on profitability.

B. The model progressively shifted toward MTS at longer lead times, since MTO becomes less profitable under severe revenue decay.

C. Shorter lead times strongly favored MTO fulfillment, as both demand decay and safety stock burdens remained limited.

Overall, these results demonstrate that lead time introduces a complex trade-off between responsiveness and inventory risk, making it a critical driver of both fulfillment structure and economic performance in hybrid MTS/MTO systems.

### 4.3 Limitations

The proposed model has several limitations that should be noted. Demand variability was synthetically generated due to the absence of historical forecast error data, which may affect the accuracy of safety stock estimates. The demand-decay parameter was not empirically calibrated and would require estimation using observed customer lead-time tolerance or order-loss data in real applications. Factory capacities were intentionally scaled to ensure feasibility, as a result, the model does not capture congestion effects or binding capacity tradeoffs. The production process is also simplified, assuming a single stage and excluding bill-of-materials relationships, multi-stage routing, and sequence-dependent setup times. Finally, transportation costs are modeled at a high level and do not reflect factors such as mode choice, consolidation constraints, or dynamic routing decisions.

## 5. Recommendations

This section presents high-level recommendations derived from the optimization model and its baseline and sensitivity results, highlighting the key trade-offs that drive optimal MTS/MTO decisions.

### 5.1 Management Recommendations

Based on the baseline results and the full set of sensitivity analyses, the following recommendations translate the model's insights into actionable guidance for production-planning decisions.

A. Items with long lead times and relatively stable demand tend to be better suited for MTS production, as pre-positioning inventory mitigates demand decay and supports higher realized revenue.

B. In contrast, products with high demand variability tend to be better allocated to MTO, since the safety-stock requirements needed to support MTS increase rapidly under uncertainty for these items and can erode profitability.

C. Production volumes should be rebalanced toward factories with shorter lead times, lower holding costs, and proximity to major demand centers, as these locations consistently emerge as cost-efficient hubs for MTS fulfillment.

D. Demand decay effects should be actively managed as part of commercial strategy, because higher decay substantially reduces the economic viability of MTO, making demand-shaping and delivery-flexibility mechanisms critical.

Overall, a hybrid MTS/MTO strategy delivers the strongest performance by dynamically aligning fulfillment modes with product-level cost, risk, and market characteristics. The results underscore the integrated nature of the decision problem, where interacting cost, demand, and operational factors jointly determine the optimal fulfillment structure.

## 5.2 Future Work

Future work should focus on making the model more realistic and improving data quality. Adding multi-stage production steps, BOM relationships, and real forecast error data would lead to better estimates of demand variability. Calibrating the decay factor using real customer lead-time behavior would also improve accuracy. Expanding the model to include transportation options, environmental measures, and pricing decisions could further increase its usefulness in practice.

Overall, this study shows that a hybrid MTS/MTO approach can improve profit and service performance in complex supply networks. The results are relevant not only to the sponsoring company but also to any firm managing multiple factories under uncertain demand and lead-time pressures.

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