UNIVERSITY OF THE AEGEAN – DEPARTMENT OF BUSINESS ADMINISTRATION

ΠΑΝΕΠΙΣΤΗΜΙΟ ΑΙΓΑΙΟΥ – ΤΜΗΜΑ ΔΙΟΙΚΗΣΗΣ ΕΠΙΧΕΙΡΗΣΕΩΝ

MSc in Business Administration for Executives – Executive MBA

Πρόγραμμα Μεταπτυχιακών Σπουδών στη Διοίκηση Επιχειρήσεων για Στελέχη – Executive MBA

Thesis Title: Τίτλος Διατριβής:	**Logistics in the Age of Volatility: Inventory Management under Uncertainty of Supply and Demand** Η Εφοδιαστική στην Εποχή της Αστάθειας: Διαχείριση Αποθεμάτων υπό Συνθήκες Αβεβαιότητας της Προσφοράς και της Ζήτησης
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February 2022 / Φεβρουάριος 2022

Εργασία υποβληθείσα στο Μεταπτυχιακό Πρόγραμμα Σπουδών του Πανεπιστημίου Αιγαίου για την απόκτηση του Μεταπτυχιακού Διπλώματος Ειδίκευσης στη Διοίκηση Επιχειρήσεων για Στελέχη – Executive MBA

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Acknowledgements

First of all, I would like to express my gratitude to the professors at the University of Aegean for introducing me to the wonderful world of Business Administration. Their help and guidance throughout my studies has been invaluable.

Finally, I could never have completed this thesis without the kind support of parents and my husband, Jason. Their gentle encouragement during difficult times was essential and will always be greatly appreciated. My heartfelt thanks.

Abstract

This thesis aims to present a simulation model of a supply chain system with three nodes and a continuous review policy facing uncertain demand and constant lead times. We introduce a broad overview of supply chains, supply chain management, strategies, responsiveness, and efficiency; we describe key processes and performance drivers in supply chains; and we showcase their study through qualitative and quantitative models in general and through simulation in particular. Finally, we create a simulation model using the ARENA simulation software package and perform tests to determine the effect of controlled variables – such as the replenishment order quantities and reorder points for the retailer and the warehouse of the system under review – on performance drivers such order fill rate, service level, inventory levels, satisfied and backordered customers. Finally, we pinpoint the current study's limitations and suggest avenues for further research.

Περίληψη

Στόχος της παρούσας εργασίας είναι να παρουσιάσει ένα μοντέλο προσομοίωσης μιας εφοδιαστικής αλυσίδας που αποτελείται από τρεις κόμβους, αντιμετωπίζει αβέβαιη ζήτηση και σταθερούς χρόνους αναπλήρωσης, και η οποία έχει υιοθετήσει πολιτική συνεχούς αναθεώρησης των αποθεμάτων της. Παρουσιάζεται μια ευρεία επισκόπηση της θεωρίας της διοίκησης εφοδιαστικών αλυσίδων, εξερευνώνται πιθανές στρατηγικές και πολιτικές ταχύτητας ανταπόκρισης ή χαμηλού κόστους και παρατίθενται σημαντικές μετρικές απόδοσης. Παράλληλα, αναδεικνύεται η χρήση ποιοτικών και ποσοτικών μοντέλων γενικότερα και ειδικά της προσομοίωσης για τη μελέτη συστημάτων εφοδιαστικών αλυσίδων. Τέλος, διαμορφώνεται προσομοιωτικό μοντέλο του υπό μελέτη συστήματος στο πακέτο λογισμικού προσομοίωσης ARENA, πάνω στο οποίο πραγματοποιείται πείραμα με στόχο την εξερεύνηση των ελεγχόμενων μεταβλητών – όπως το μέγεθος των παραγγελιών αναπλήρωσης ή το σημείο αναπαραγγελίας – και των επιδράσεών τους στα μέτρα απόδοσης, όπως το ποσοστό κάλυψης παραγγελίας, το επίπεδο εξυπηρέτησης, τα επίπεδα αποθεμάτων και ο αριθμός ικανοποιημένων και μη ικανοποιημένων πελατών.

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1. Introduction

Supply chains comprise all necessary operations to receive and fulfill customer requests[1] and thus form an integral part of any business. These complex networks of products, information and funds require effective management to maximize profitability and stave off prohibitive costs; inappropriate decisions may – and indeed have in the past – doom companies to fail.[2]

Globalization has increased the interconnectivity of world economies and, along with the explosive rate of technological advances, has unleashed volatility and unpredictability in unprecedented terms.[3] Supply chains have become increasingly complex and unstable: according to McKinsey Global Institute's *Risk, resilience and rebalancing in global value chains* 2020 report, "companies can now expect supply chain disruptions lasting a month or longer to occur every 3.7 years".

Consequently, supply chain management is becoming ever more relevant and critical to the success of businesses in the modern world. Business will have to face and successfully handle uncertainty in a continuous basis or be extinguished: therefore, we must develop tools to help managers deal with the tumultuousness of today's economic landscape.

[1] Chopra and Meindl 2016.
[2] Ibid.
[3] Βλάδος 2006.

2. Objective

This thesis aims to contribute by researching inventory management policies under uncertain conditions. Specifically, it simulates a three-node supply chain network – consisting of a supplier, a warehouse, and a retailer – and studies its efficiency according to common metrics, such as service level, average inventory levels, etc.

To model the supply chain system, we used the ARENA simulation package. Uncertainty was inserted in the network by modeling demand as a random variable.

3. Structure

Section 1 introduces the subject, whereas Sections 2 and 3 provide the thesis' objective and structure. Section 4 presents the theoretical background on supply chains and supply networks, supply chain management and inventory management under uncertainty. Section 5 describes qualitative and quantitative models in general, focuses on the simulation approach and presents its advantages and disadvantages, as well as a short literature review. Section 6 illustrates the system under consideration, whereas Section 7 describes its simulation model in detail. Section 8 presents the results of the experiment. Section 9 is devoted to the conclusion, whereas Section 10 discusses the limitations of the present study and proposes avenues of further research. Finally, Section 11 lists all literature references.

4. Theoretical Background

4.1 Supply Chains

According to Campuzano and Mula (2011), a supply chain consists of interconnected facilities that source raw materials, process them into intermediate and finished products and deliver them to customers. Lambert et al. (2000) describes it as a structure containing the central, or control, company, as well as its links of suppliers and customers. This high-level view should be complemented by adding the essential nodes of manufacturers, warehouses, and transporters, without which the supply chain would not be able to function (Chopra and Meindl, 2016).

Any supply chain aims to maximize value and create profit by fulfilling the customer needs effectively and efficiently. If, by delivering the final product to a customer, a supply chain produces value which exceeds the costs, it has created *supply chain surplus*. Not all surplus translates into business profits, as some of the value created by the supply chain is captured by the customer in exchange for funds.

$$Supply\ Chain\ Surplus = Customer\ Value - Supply\ Chain\ Cost$$

Supply chain profitability, on the other hand, is defined as total revenue for the business minus overall costs:[4]

$$Supply\ Chain\ Profitability = Revenue - Overall\ Cost$$

As Chopra and Meindl (2016) state, the only source of revenue is the customer; all other operations and flows within the supply chain incur costs. Therefore, in order to gain

[4] Chopra and Meindl 2016.

and retain a competitive advantage, it is critical to manage supply chains in ways that maximize surplus and minimize costs.

4.2 Supply Chain Structure

Lambert et al. (2000) indicate that each supply chain is characterized by three structural aspects: 1) the supply chain members, 2) its structural dimensions, and 3) the links connecting its nodes.

4.2.1 Supply chain members

Although, as we have seen, supply chains include all nodes between the point of origin and the point of sale, Davenport (1993) distinguishes them into primary and support members. Primary members consist of all companies within the chain where value production takes place; support members provide secondary resources and operations such as transportation, renting warehouses etc. In practice, a node may function as both a primary and support member for different activities, and the two categories may not be easily distinguished.[5]

4.2.2 Supply chain structural dimensions

A supply chain's horizontal structure depends on how many levels it consists of; its vertical structure refers to the number of suppliers or customers present at each level. Finally, the position of a company within the supply chain – how close or how far away it is relative to the supplier or end customer – defines its third structural dimension[6].

[5] Campuzano and Mula 2011.
[6] Ibid.

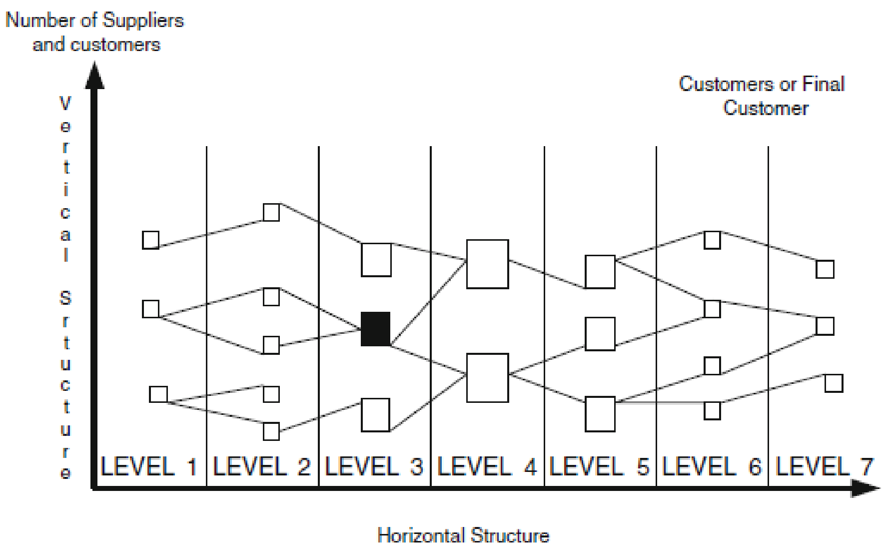

Figure 1 – Network structural dimensions (Source: Lambert et al., 2000)

In most cases, supply chains do not constitute a single, linear, monodirectional flow of goods, information, and funds (Figure 2); on the contrary, supply chain nodes form networks, with nodes interacting dynamically with each other (Figure 3).

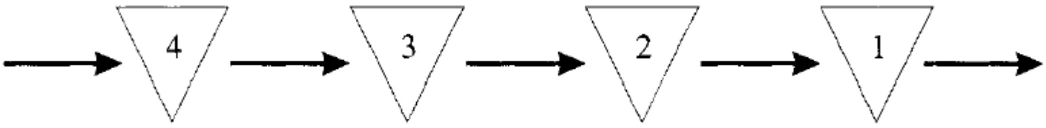

Figure 2 – Linear supply chain (Source: Brandimarte and Zotteri, 2007)

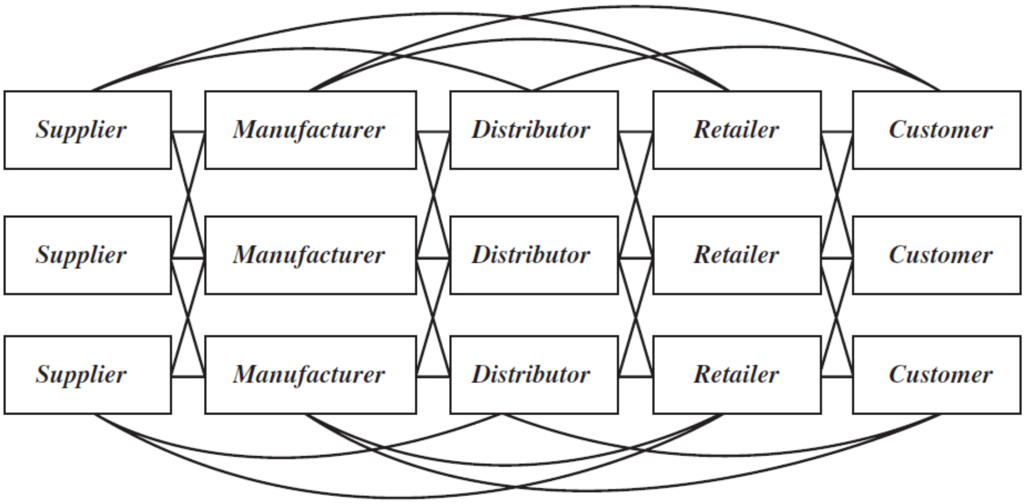

Figure 3 – Supply Chain Stages (Source: Chopra and Meindl, 2016)

Often, semi-finished products from different sources are assembled at a particular node, forming so-called assemblies (Figure 4).[7]

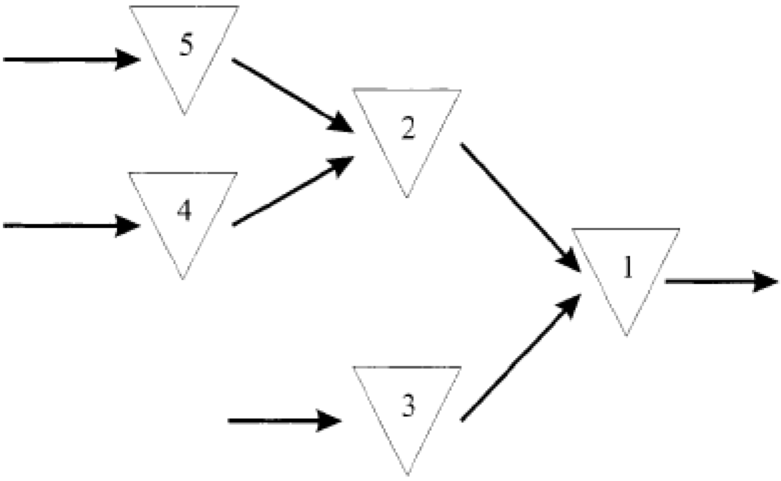

Figure 4 – Supply Chain Assemblies (Source: Brandimarte and Zotteri, 2007)

[7] Brandimarte and Zotteri 2007.

Cooper et al. (1997) suggests that supply chains commonly resemble tree structures (Figure 5); Brandimarte and Zotteri (2007) agree, stating that these *arborescent* or *divergent* forms are typical in distribution networks:

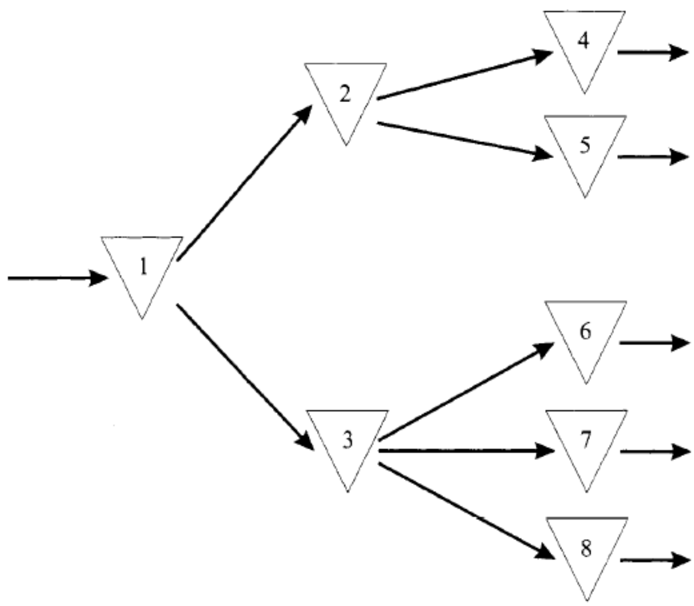

Figure 5 – Arborescent network (Source: Brandimarte and Zotteri, 2007)

However, they note that usually supply chains are hybrids of linear, arborescent and assembly structures.

4.2.3 Supply chain links

According to Campuzano and Mula (2011), links connecting nodes in the supply chain can be categorized into 1) management links, responsible for integration and management by the central company; 2) monitored links, important – but not critical connections; 3) non-management links: non-crucial connections; 4) non-member links: connections that are not part of the supply chain but may affect its effectiveness and efficiency.

4.3 Supply Chain Business Processes

Campuzano and Mula (2011) define business processes as any "activities that generate a specific output of value to the customer". Business processes include:

- Customer relationships management: customer identification, service level identification, performance, and profitability assessments
- Customer service management: provision of information and customer orientation
- Demand management: balancing high service levels with low inventory costs by forecasting demand
- Order fulfillment: balancing distribution costs with customer needs
- Manufacturing flow management: coordinating the manufacturing process via production schedules or a process-oriented approach
- Supplies or purchases: strategic supplier relationships and plans
- Product development and commercialization: customer needs identification, supplier selection, material selection
- Returns or reverse logistics: product return management

Chopra and Meindl (2016) describe three macro-processes, or supergroups of supply chain processes:

- Customer Relationship Management (CRM): includes all processes between the business and the customer
- Internal Supply Chain Management (ISCM): includes all internal processes
- Supplier Relationship Management (SRM): includes all processes between the business and the suppliers

According to the authors, these macro-processes must be aligned with each other; if not correctly integrated, the supply chain will not function properly.

Figure 6 – Supply Chain Macro-processes (Chopra and Meindl, 2016)

4.3.1 Process Views

Traditionally, supply chain processes are described in two ways: a cycle view or a push/pull view.

4.3.1.1 Cycle View

In a cycle view, supply chain processes belong to one of four process cycles: the customer order, replenishment, manufacturing, and procurement cycles.

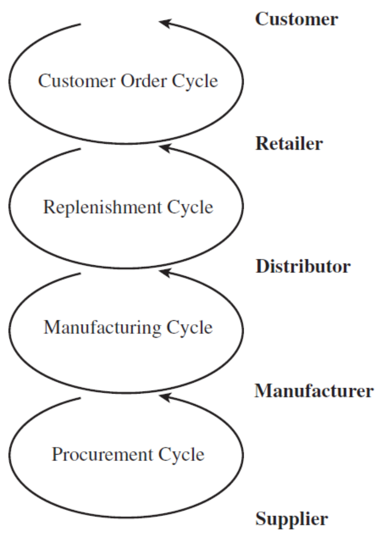

Figure 7 – Supply Chain Process Cycles (Source: Chopra and Meindl, 2016)

These process cycles take place between different supply chain nodes, and may or may not overlap, depending on the business and the design of its supply chain. A cycle view clearly depicts each node's role(s) and operations and is thus useful for managers making operational decisions (Chopra and Meindl, 2016).

4.3.2 Push/Pull View

In a push/pull view, processes are categorized depending on whether they react to customer demand or depend on forecasting. Pull processes are *reactive*, as they respond to customer demand, whereas push processes are *speculative*, relying on predictions of customer demand in an uncertain environment.

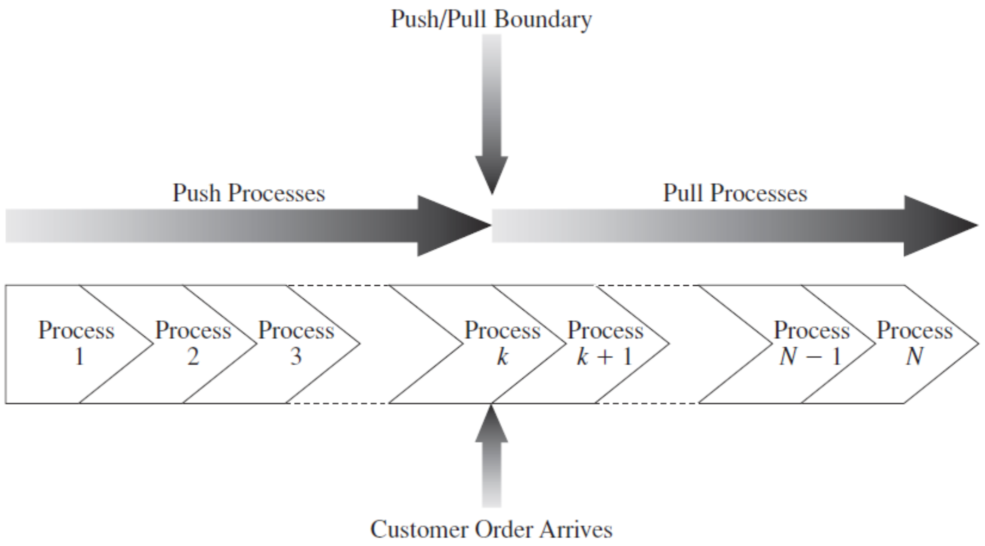

Figure 8 – Push/Pull View of the Supply Chain (Source: Chopra and Meindl, 2016)

Deciding where to place the push/pull boundary, the point that separates push and pull processes, is not an easy decision and involves strategic considerations of uncertainty, inventory costs, customer satisfaction, etc. (Chopra and Meindl, 2016).

4.4 Supply Chain Management

Supply chain management is a subdivision of business administration that aims to maximize supply chain surplus by use of logistical and cross-functional drivers, which we will examine later.

With military origins, supply chain management – initially termed *logistics* – was conceptualized as the efficient management of army supplies during war. Expanded to include the administration of flows within a supply chain at the dawn of quantitative management in the late 19th and early 20th centuries[8], supply chain management is inextricable from today's business administration practices. As Chopra and Meindl (2016) state, "supply chain design, planning and operation decisions play a significant role in the success or failure of a firm".

These decisions of supply chain managers are categorized into strategic, planning, and operational, depending on the time frame they cover. Specifically:

- Strategic decisions are long-term designs, which will affect a supply chain for multiple years. For example, they may relate to the chain's overall structure, its location, the number of its nodes, outsourcing, transportation, etc.
- Planning decisions refer to management choices which will be in effect for a few months or up to a year. They complement and are constrained by strategic decisions, and usually aim to maximize surplus within this mid-term time horizon. Examples include inventory policies, pricing, and marketing decisions.
- Operation decisions apply to daily (or weekly) functions of the supply chain. Evidently, they are confined within the strategic and planning constraints of

[8] Brandimarte and Zotteri 2007.

overarching decisions. They include replenishment orders, delivery dates, delivery schedules, shipping management, etc.

4.5 Supply Chain Strategies

Supply chain strategies, as all functional strategies within a business, must complement and integrate with its overarching competitive strategy[9]. Any mismatch between the company's goals and the goals of individual departments will prove at best inefficient, and at worst catastrophic; decisions may directly antagonize and refute each other. Conversely, complementing strategies may create synergies that allow a company to gain significant competitive advantage.[10]

According to Chopra and Meindl (2016), supply chains must be able to support the company's ability to satisfy customer needs, and thus must be designed with the targeted customer segment in mind. Specifically, the company should be able to grasp core customer traits, understand the level of (implied) demand uncertainty[11], review the supply chain's strengths and weaknesses and decide how to best approach strategic fit: unless the chosen strategy and the supply chain are aligned, either the strategy or the supply chain itself must be restructured.

4.6 Supply Chain Responsiveness and Efficiency

Depending on the customer segment a company targets, its supply chain may emphasize responsiveness, efficiency, or a combination.

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[9] Chopra and Meindl 2016.
[10] Βλάδος 2016.
[11] Demand uncertainty is defined as the uncertainty of customer demand for a specific product. Implied demand uncertainty, on the other hand, is defined as the segment of demand the supply chain targets, according to the customer needs it aims to satisfy.

Responsiveness refers to a supply chain's service levels: a supply chain is responsive when it satisfies a wide range of needs, handles a large variety of – often innovative – products and delivers them in a short amount of time. Efficiency, on the other hand, denotes a supply chain's ability to incur low costs.

Responsiveness and efficiency are inversely proportional; it is impossible for a company to maximize both at the same time, as responsiveness increases costs and efficiency reduces responsiveness.

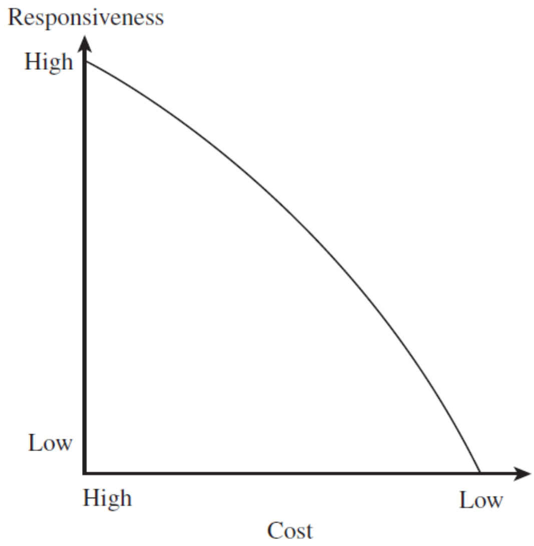

Figure 9 – Cost-Responsiveness Frontier (Source: Chopra and Meindl, 2016)

Therefore, a company must decide where to place its supply chain in the cost-responsiveness front, according to its competitive strategy.[12] In general, as Chopra and Meindl (2016) underline, "the goal is to target high responsiveness for a supply chain facing high implied uncertainty, and efficiency for a supply chain facing low implied uncertainty".

[12] Brandimarte and Zotteri 2011; Chopra and Meindl 2016.

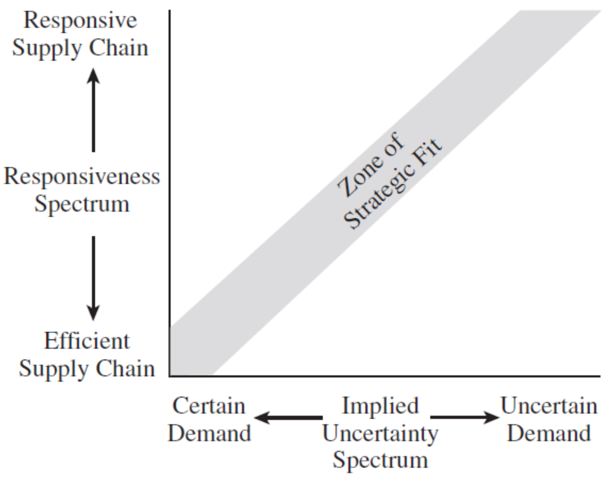

Figure 10 – Zone of Strategic Fit (Source: Chopra and Meindl, 2016)

4.7 Supply Chain Performance Drivers

The supply chain's position on the cost-responsiveness front depends on specific *drivers*. Drivers are parameters with a significant effect on supply chain operations and include the following:

- Facilities: the physical locations, such as production, manufacturing, or assembly sites
- Inventory: all materials, intermediate products, and finished products
- Transportation: the movement of materials and products around the supply chain
- Information: data, as well as insights based on the data
- Sourcing: selecting who will perform supply chain operations such as transportation or assembly
- Pricing: setting the cost of goods to the customer

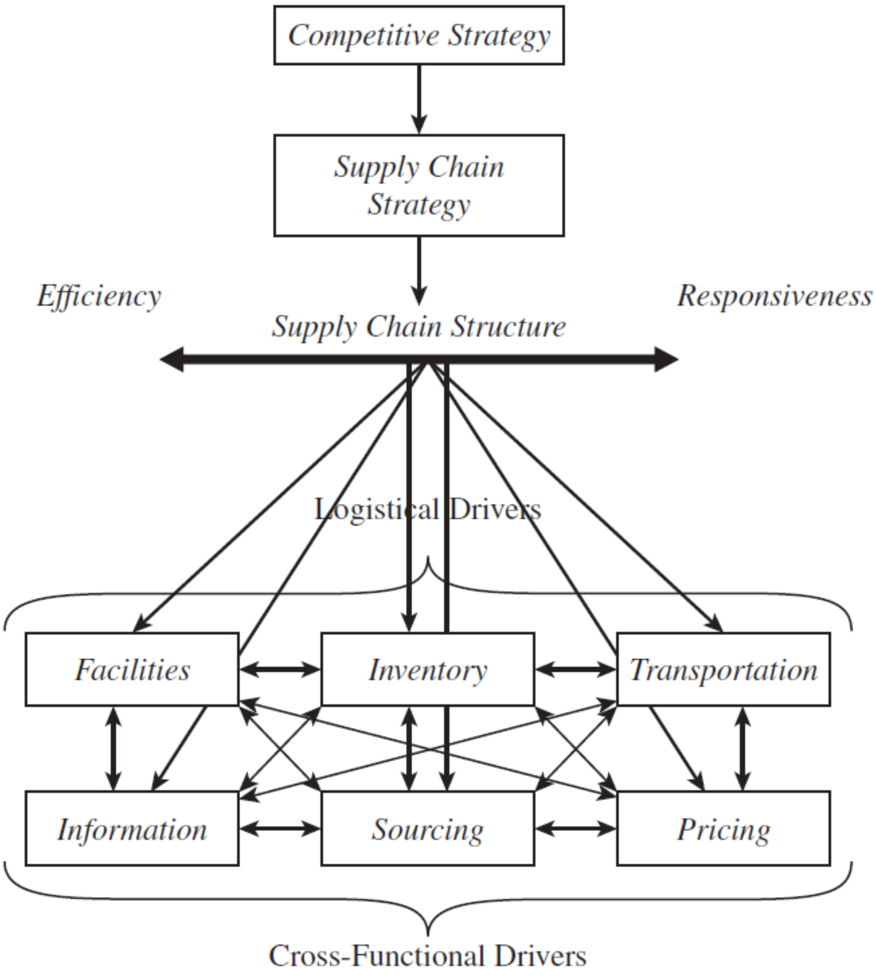

Figure 11 – Supply Chain Drivers (Source: Chopra and Meindl, 2016)

Below, we will focus on each of the drivers in turn and illustrate how they affect the supply chain's position on the cost-responsiveness front.

4.7.1 Facilities

A company makes multiple decisions about its facilities, regarding their role, location, and capacity. First, a facility may be flexible, used for a variety of products, or dedicated, focusing only on a subgroup. The facility may be centralized, increasing cost-effectiveness, or decentralized, increasing responsiveness. Likewise, a facility may have increased capacity and responsiveness, or decreased capacity and lower costs.

4.7.2 Inventory

Inventory policies greater affect a supply chain's cost-efficiency, responsiveness, and strategic fit. High inventory levels improve responsiveness and lower production and transportation costs; at the same time, they can incur prohibitive inventory hold costs and limit cash flow. On the other hand, low inventory levels may result in lost sales and low customer satisfaction, if demand exceeds supply.

4.7.3 Transportation

A company must choose the network of nodes and routes that form the supply chain, as well as the transportation mode between nodes. In general, direct, faster transportation may increase responsiveness, but will probably be less cost-effective.

4.7.4 Information

Information is a cross-functional driver directly affecting all aspects of the supply chain. In some cases, it may allow for the simultaneous increase of responsiveness and cost-effectiveness – for example, by reducing uncertainty and aligning supply and demand. However, large volumes of information may increase the cost of handling it; management must carefully consider the trade-offs between reducing uncertainty and increasing complexity.

Decisions regarding information include the choice of push pull approaches, coordination, sales, and operations planning, as well as selecting supporting technology, such as ERPs.

4.7.5 Sourcing

Sourcing decisions include choices about outsourcing or in-house production, supplier selection and procurement.

4.7.6 Pricing

Pricing is a versatile tool allowing companies to ply demand, as well as a driver affecting customer expectations. Decisions must be made regarding how accurately pricing reflects economies of scale, whether everyday low pricing or high-low pricing occurs, or whether fixed price vs menu pricing will be offered. Of course, the choice depends on the company's competitive strategy and the implied customer demand it serves.[13]

4.8 Inventory Management and Uncertainty

As we mentioned in the introduction, the new globalized economy has ushered in an age of increased competition, as well as high levels of uncertainty.[14] Since 2000, uncertainty has affected, among others, currency valuations and exchange rates, customer demand, energy prices, the cost of raw materials and even international trade rules.[15] Clearly, in this era of unprecedented volatility, supply chains must be prepared to react nimbly to changes in the environment and build flexibility to overcome uncertain conditions.

Inventory managers, in particular, face unpredictable fluctuations in customer demand, and must plan accordingly. Traditional models of excess demand assume that if demand

[13] Chopra and Meindl 2016.
[14] Βλάδος 2006.
[15] Chopra and Meindl 2016.

is greater than inventory levels, customers will wait until the inventory is replenished instead of purchasing a different product, turning to another supplier, or not buying at all[16]. However, Verhoef and Sloot (2006) estimate that most worldwide out-of-stock orders results in lost sales.[17] Therefore, unless the system under examination operates in an industrial, it is best to assume that any demand not covered by inventory will be lost.[18]

Safety inventory – that is, inventory carried to satisfy demand that exceeds predictions – may safeguard against lost sales; however, it increases inventory holding costs that may result in complete losses, especially if the products are volatile or feature short life cycles.[19]

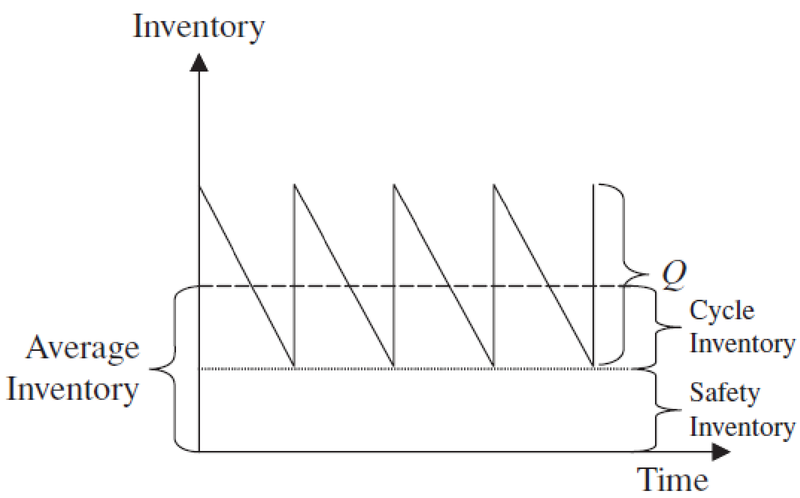

Figure 12 – Inventory Profile with Safety Inventory (Source: Chopra and Meindl, 2016)

Therefore, managers must consider both lost sales and inventory holding costs before deciding on safety inventory levels. Demand and supply uncertainty must be taken into

[16] Bijvank and Vis 2011.
[17] Verhoef and Sloot 2006.
[18] Bijvank and Vis 2011.
[19] Chopra and Meindl 2016.

account: the higher the uncertainty, the higher the level of safety inventories required. Secondly, if the company targets high availability for its products, higher levels of safety inventory are critical.[20] To accurately predict supply and demand, we must first be able to measure demand, lead time and product availability using historical data, as well as select an inventory replenishment policy.

4.8.1 Demand uncertainty, lead time and product availability

Demand is calculated based on past data, the average demand over a time period, as well as a random component, its standard deviation, which represents uncertainty. Of course, over time we may notice alterations in average demand itself, as a product reaches different phases of its lifecycle.[21]

Lead time is the average time between ordering a product and its delivery. The longer and more unpredictable supply lead times are, the higher the safety inventory required to prevent lost sales.[22] It may be affected by shortages or variable transportation time.[23]

Product fill rate (fr) equals the probability, or the fraction of demand served from products in the inventory. *Order fill rate*, on the other hand, is the fraction of orders filled from the inventory. *Cycle service level (CSL)* reflects the portion of replenishment cycles where customer demand is fully met.

4.8.2 Replenishment policies

Replenishment policies are divided into *continuous review* or *periodic review* policies, according to when reorders are placed and what quantities are reordered.

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[20] Chopra and Meindl 2016.
[21] Brandimarte and Zotteri 2007.
[22] Chopra and Meindl 2016.
[23] Brandimarte and Zotteri 2007.

- A continuous review policy tracks inventory continuously. When the inventory reaches the reorder point (ROP), a replacement order of size Q is placed.
- A periodic review policy checks inventory levels at regular intervals and places orders to replenish it up to a particular level.

5. Modeling and Simulation

So far, we have introduced and briefly described the main variables that must be taken into consideration when predicting supply and demand. We have not, however, seen how to utilize them in order to gain insight into the system under consideration.

Below, we will explore the methods of modeling and simulation, their advantages and disadvantages, and how we might use them to accurately infer a supply chain's performance under certain constraints.

5.1 Why do we use models?

"All models are wrong, but some are useful", state Brandimarte and Zotteri (2007). Models are abstractions of a target system that bear some degree of isomorphism, or similarity, with it; they are used when direct analysis is not possible, either due to high costs, complexity, accessibility, or ethical reasons, and as such, underpin most scientific enquiry.[24]

Despite their necessary approximations and simplifications, models can and do produce valuable insights (Batterman 2009) and that is precisely why they are so often employed in science (Nersessian 2006).

[24] Varlas 2020.

5.2 Model methodology in Management Science

According to Frigg and Hartman (2012), the modeling process includes specific steps. In management and operational research, specifically, the steps are as follows:[25]

1. Define the problem: describe the problem, define the relevant variables and constraints, set objectives, and gather data.[26]
2. Construct the model: translate the problem into mathematical functions.[27]
3. Solve the model via a mathematical or algorithmic process and perform sensitivity analysis to determine robustness.[28]
4. Validate the model: confirm model validity via *verification* and *validation*. Verification, or internal validity, confirms that the model is logically coherent and that the relationships between variables have been correctly mapped to the mathematical relationships and the algorithm. Validation, or external validity, ensures that the model appropriately represents the real-world target system; this is achieved by comparing the results to historical data or exploring model behavior by altering inputs.[29]
5. Implement the solution: Produce and evaluate alternative solutions, then select and implement the most beneficial in the target system. Monitoring, performance evaluation and feedback are necessary to detect internal and external circumstances that might hinder this implementation or render it obsolete.[30]

[25] Varlas 2020.
[26] Daellenbach 2005; Hillier 2014.
[27] Taha 2017.
[28] Ibid.
[29] Ibid; Daellenbach 2005; Truran 2013.
[30] Varlas 2020.

5.3 Quantitative vs Qualitative Models

Models may be broadly classified as qualitative and quantitative. Qualitative models rely on subjective observations and are thus error prone. Their use is thus limited and should be restricted in cases when data is scarce and quantitative models consequently unusable.[31]

Quantitative models, on the other hand, are more objective, as they rely on carefully mapped mathematical relationships and solutions. However, as we have seen, models – even quantitative ones – always entail a degree of arbitrariness and should be validated and verified before their solutions are applied in the real world.[32] Quantitative models cover a broad super-category, comprising a wide range of prescriptive and descriptive models.

We will focus specifically on *performance evaluation models*, a descriptive model subtype which aims to predict a system's performance, given specific *decision* and *random variables*. Decision variables are parameters within the manager's control, such as the reorder point (ROP) of a continuous review policy; random variables are not controllable or easily predictable, such as lead time or demand uncertainty.[33]

Performance evaluation models may be categorized, in turn, into *analytical* and *simulation* models. Analytical models rely solely on mathematical methods to infer system behavior; as such, they are accurate, but require extensive simplifications that may not be representative of the real world. We have already seen that most excessive

[31] Chopra and Meindl 2016.
[32] Brandimarte and Zotteri 2007.
[33] Ibid; Varlas 2020.

demand models, for example, assume backorders instead of lost sales, to reduce complexity.[34]

Simulations, on the other hand, are computer models of real-word systems. They allow for increasing complexity in research[35] and, for this reason, are frequently used in modern operations research.[36] Of course, due to computational constraints, even simulation models are limited; they do constitute, however, a highly sophisticated and flexible method of operational research.[37] Disadvantages include the requirement for a large amount of appropriate data and familiarity with simulation packages or programming. Furthermore, simulation models do not, by themselves, provide one optimal solution, but rather a range of feasible solutions. Therefore, they must be combined with optimization algorithms to produce decision-making advice.[38]

5.4 Literature review

Research in supply chain management has been extensive and employs a variety of methodological choices. For example, authors have utilized linear programming, dynamic programming, and Markov chains as well as differential equations, discrete even simulation[39] or even machine learning algorithms[40].

Due to space limitations, we will only present a cursory review of systems closely related to the supply chain under consideration: systems with fixed order policies facing uncertain demand, which results in backorders or lost sales:

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[34] Brandimarte and Zotteri 2007.
[35] Chopra and Meindl 2016.
[36] Anderson et al. 2019.
[37] Varlas 2020.
[38] Brandimarte and Zotteri 2007.
[39] Varlas 2021.
[40] Boute et al. 2022.

Karlin and Scharf (1958) and Scharf (1960) used backorder systems to optimize order-up-to policies. Similarly, Zabel (1962), Veinott Jr. (1966), Johnson (1968), Federgruen and Zipkin (1984) and Zheng and Federgruen (1991) expanded and modified their models, attempting to pinpoint optimal reorder and order-up-to levels in analogous systems.

Huh et al. (2009), however, illustrated that backorder models are not appropriate for most real-word systems and provide poor approximations. Zipkin (2008a), after all, claimed this may result in cost deviations of up to 30%.

Therefore, lost sales models are essential to properly describe systems and optimize their parameters. Early scholars include Hadley and Whitin (1963), who studied lost sales systems with fixed order size replenishment policies. Ravichandran (1984), Buchanan and Love (1985), Beckmann and Srinivasan (1987) further developed the systems with stochastic lead times. Johansen and Thorstenson (1993, 1996) studied supply chains with continuous review policies and lost sales and calculated optimal order quantities based on a semi-Markov decision model.

Later, Kalpakam and Arivarignan (1988, 1989a, b) and Mohebbi and Posner (1998a) abandoned Poisson demand, which reigned in previous models, and instead assumed an exponential distribution. Hill (1992, 1994, 1999, 2007) described inventory models with a maximum of two outstanding orders and deterministic or Erlang lead times, whereas Mohebbi and Posner (2002) returned with a compound Poisson demand and exponential lead times. Mohebbi and Hao (2006, 2008) explored systems with an unreliable supplier, resulting in compound Poisson and Erlang lead times.

Aardal et al. (1989) introduced a unique continuous review policy model that is characterized by a fill rate constraint.

Finally, Tamjidzad and Mirmohammadi (2015) studied systems with supply deficits, stochastic demand and more than one outstanding order. In their model, deficits may be covered, incurring additional cost.

	Demand	Lead time	Assumption	Objective
Hadley and Whitin (1963)	P	D	$s < Q$	C/S
Ravichandran (1984)	P	PH	$s < Q$	–
Beckmann and Srinivasan (1987)	P	Ex	$s < Q$	C
Buchanan and Love (1985)	P	Er	$s < Q$	C
Johansen and Thorstenson (1993, 1996)	P	Er	$s < Q$	C
Kalpakam and Arivarignan (1988, 1989b)	uR	Ex	$s < Q$	C
Kalpakam and Arivarignan (1989a)	M	M	$s < Q$	C
Mohebbi and Posner (1998a)	CP	Er/HEx	$s < Q$	C/S
Rosling (1998)	P/Cont	G	$s < Q$	C
Hill (1992)	P	D	$Q \leqslant s < 2Q$	S
Hill (1994)	P	Er	$Q \leqslant s < 2Q$	S
Morse (1958)	P	Ex	–	C
Kalpakam and Arivarignan (1991)	uR	Ex	–	C
Mohebbi and Posner (2002)	CP	Ex	–	C
Johansen and Thorstenson (2004)	P	Er	–	C
Aardal et al. (1989)	G	G	–	S

Figure 13 – An overview of lost-sales inventory models with an (s, Q) replenishment policy (Source: Bijvank and Vis, 2011)

6. The System

6.1 System overview

The system under review is a serial supply chain consisting of a retailer (A), warehouse (B) and a supplier (C), which has adopted a continuous review policy. The retailer, based in the US, sells electronic products. Apart from inventory kept at hand, it stores products in a leased facility in Mexico, the warehouse. All electronics are produced by and transported from the supplier, based in Vietnam. Customer demand triggers supply flows based on a kanban system[41]: therefore, all processes in the supply chain are pull processes.

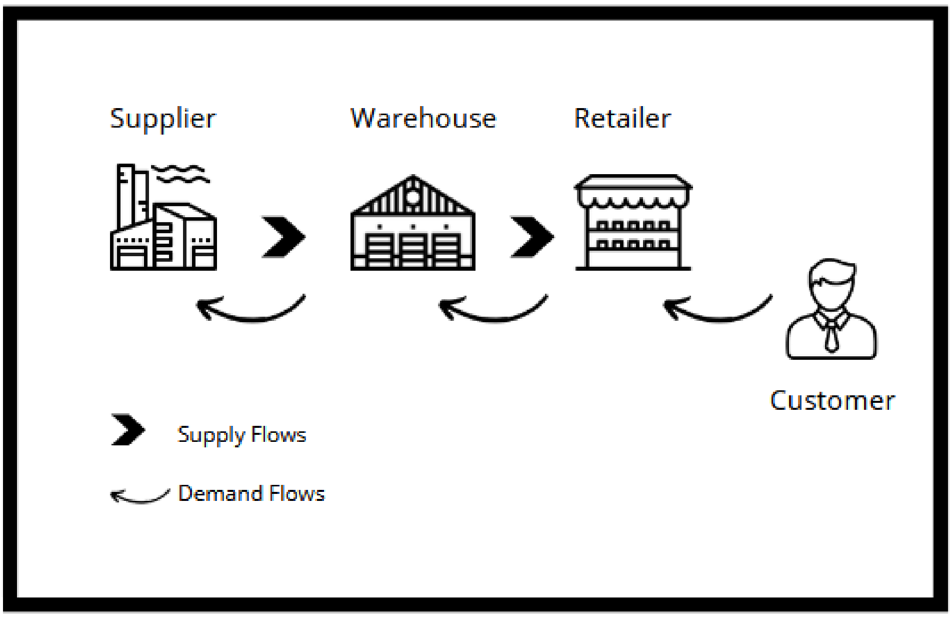


Figure 14 – The system: a linear supply chain with three nodes

[41] Kanban is a pull system developed in Japan to deliver assembly parts "just in time". In essence, supply is only triggered by a request (or card or kanban); no products may me made or transported without it. Kanban systems are useful in situations where demand is uncertain and small inventories are preferred (see Vitasek 2013; Ohno 1988).

6.2 Processes

- The retailer interfaces with the final customer. It retains products in store, along with a safety inventory s_A. Once inventory falls below a certain reorder point r_A, the retailer places an order of size Q_A to the warehouse.
- The warehouse connects the supplier and retailer and retains safety stock s_B. When inventory levels fall below its reorder point r_B, the warehouse releases a kanban card to the supplier for a batch of size Q_B.
- The supplier remains idle until an order is placed by the warehouse. As it operates on a kanban system, it only produces batches of size Q_B once it receives a supply order. The supplier is saturated, which means it carries unlimited inventory and is able to satisfy unlimited orders from the warehouse.

6.3 Demand and lead times

In the absence of historical on demand, we will assume uncertain demand following an uniform distribution. Lead times from the supplier and the warehouse are considered constant but may be easily modeled to follow random distributions. This is an arbitrary decision and should be altered according to the system in focus.

7. Simulation

We used the simulation software package ARENA to study the system described above. Below, we will examine the simulation in detail.

7.1 Modules

We constructed three nodes representing the real system's three stages or echelons: the retailer (A), the warehouse (B) and the supplier (C).

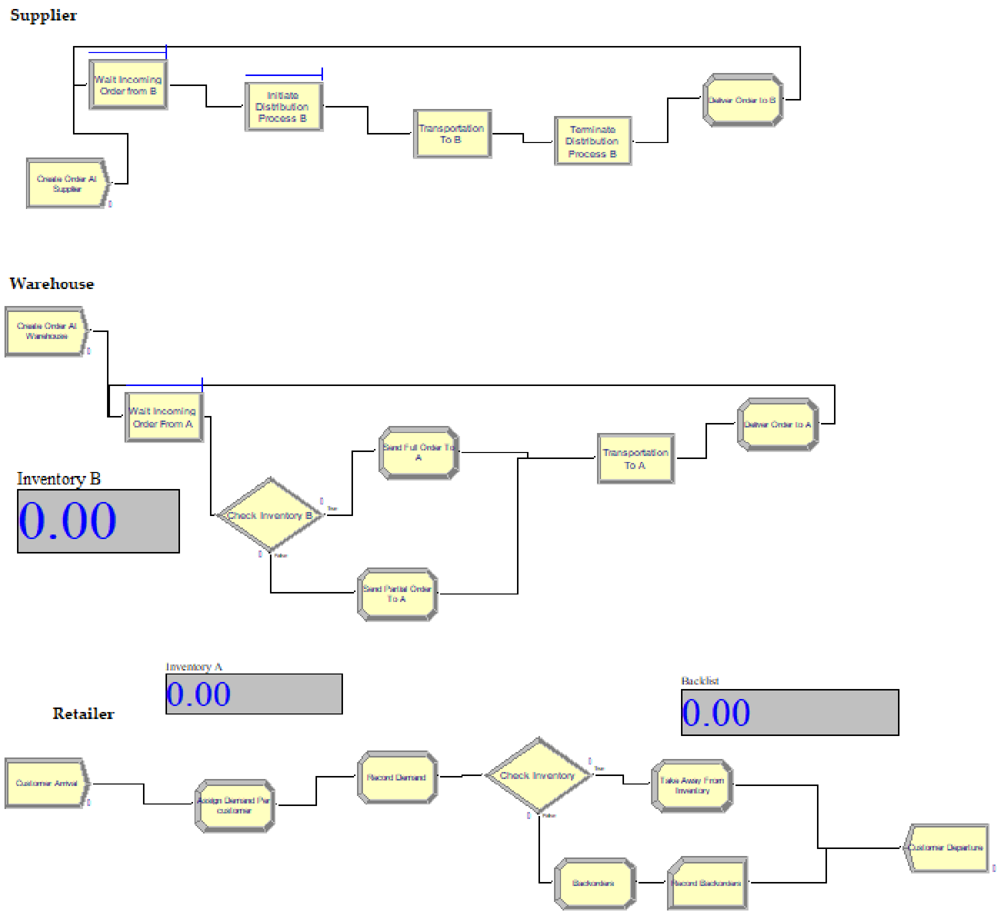


Figure 15 – Simulation Model Flowchart

7.1.1 Node A: Retailer

The flow diagram below describes the retailer and its processes as triggered by customer demand:

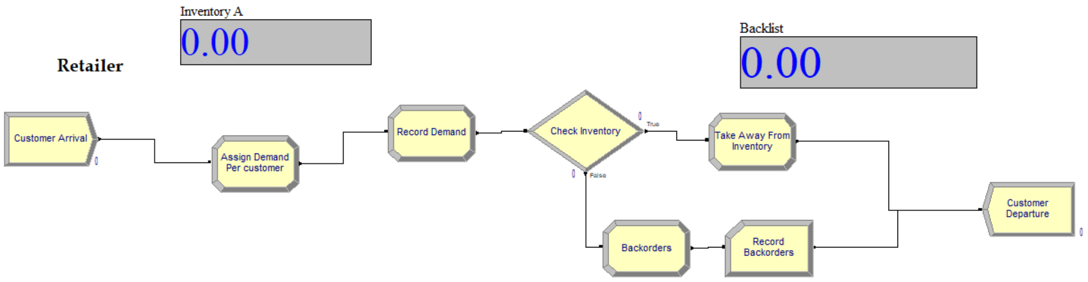


Figure 16 – Retailer Flow Diagram

First, the generator *Customer Arrival* creates customers based on an exponential distribution with a mean of two customers per hour:

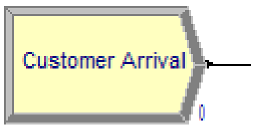


Figure 17 – Customer Arrival Module

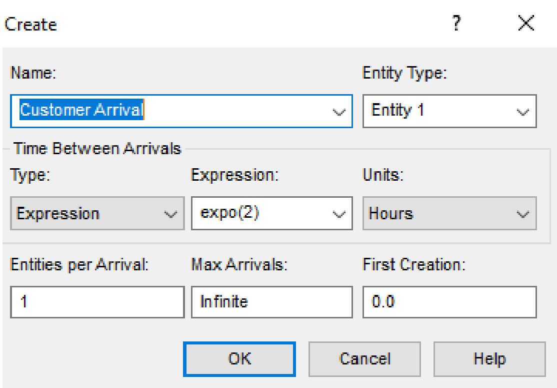


Figure 18 – Customer Arrival Settings

Next, we assign demand per customer, which follows a uniform distribution in the range (3, 9).

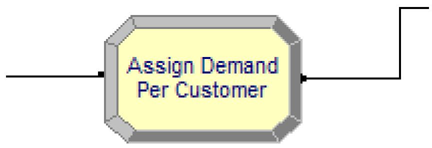


Figure 19 – Assign Demand Per Customer Module

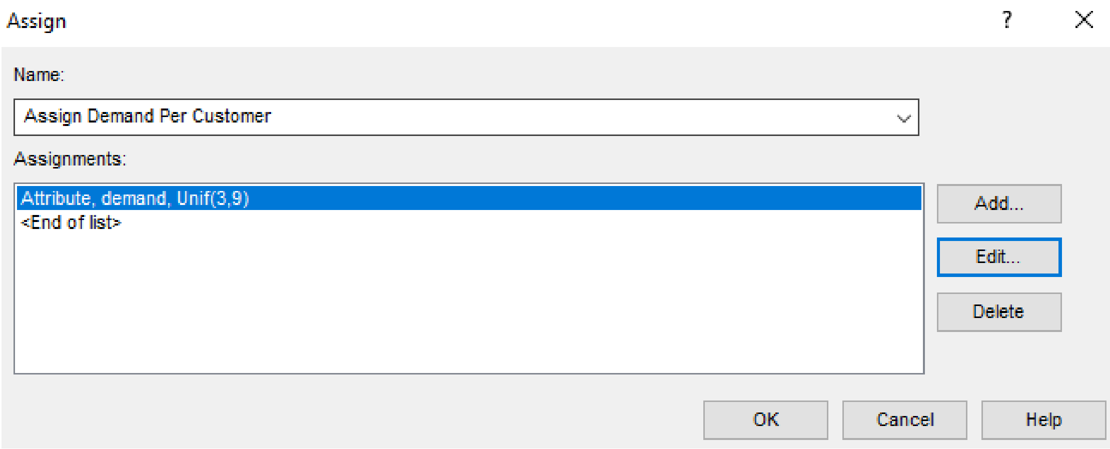


Figure 20 – Assign Demand Per Customer Settings

The next module is a counter, which calculates total demand in each iteration of the loop, i.e., every time a customer arrives:

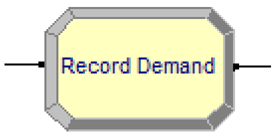


Figure 21 – Record Demand Module

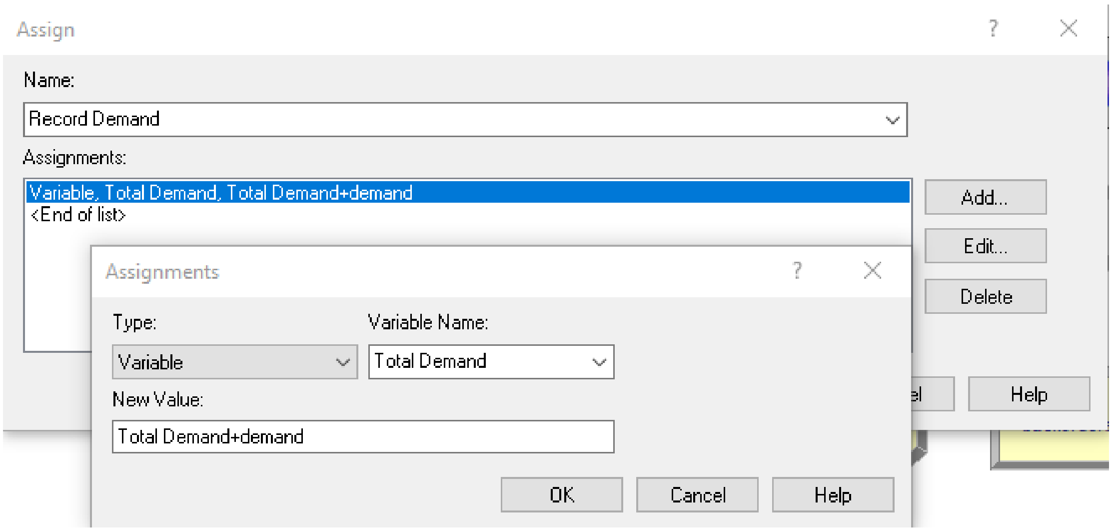


Figure 22 – Record Demand: Update Total Demand Counter

Next, a Boolean operator checks if the retailer's inventory is able to cover the demand:

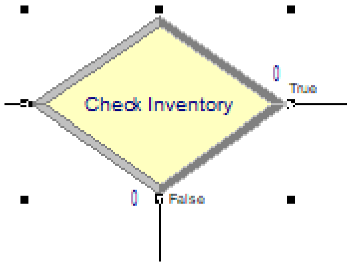


Figure 23 – Check Inventory Module

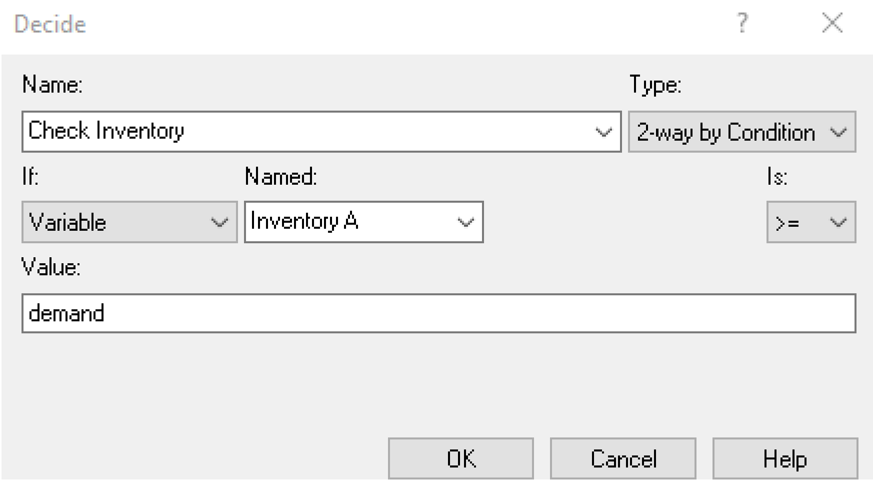


Figure 24 – Check Inventory: Is inventory greater or equal to demand?

If True, that is if the inventory exceeds demand, product is removed to satisfy the customers' needs. The module *Take Away From Inventory* a) saves order total supplied or total satisfied demand in the variable OTS, which is raised by the amount delivered to customers in each iteration:

Figure 25 – Take Away From Inventory Module

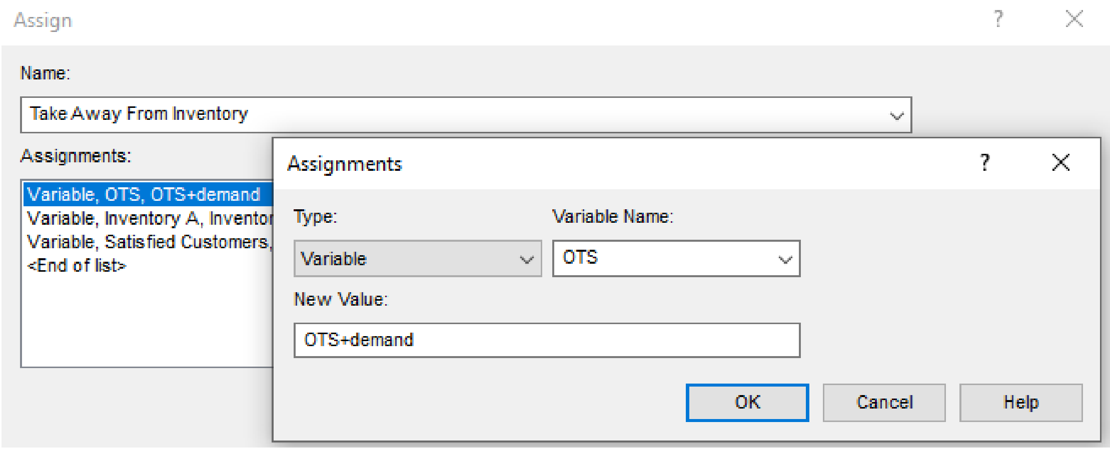


Figure 26 – Take Away From Inventory: Update Order Total Supplied (OTS)

b) updates the variable Inventory A by subtracting demand:

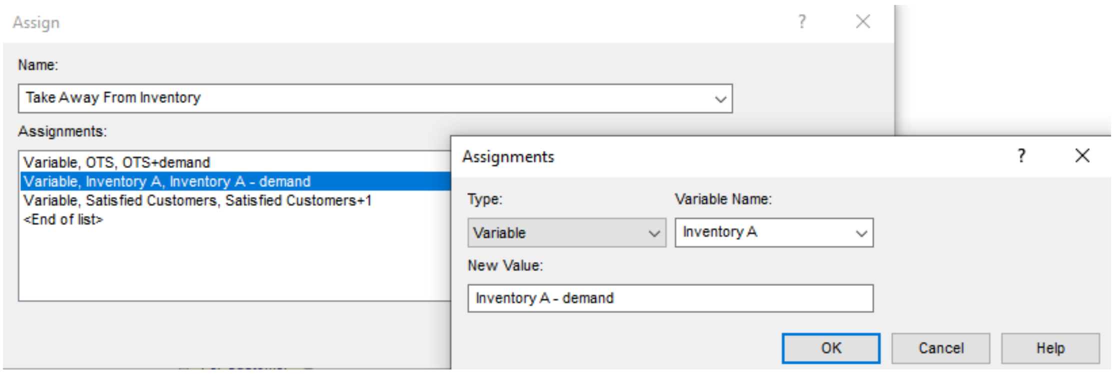


Figure 27 – Take Away From Inventory: Update Inventory A

c) tracks Satisfied Customers using a simple counter, updated each time an order is fulfilled:

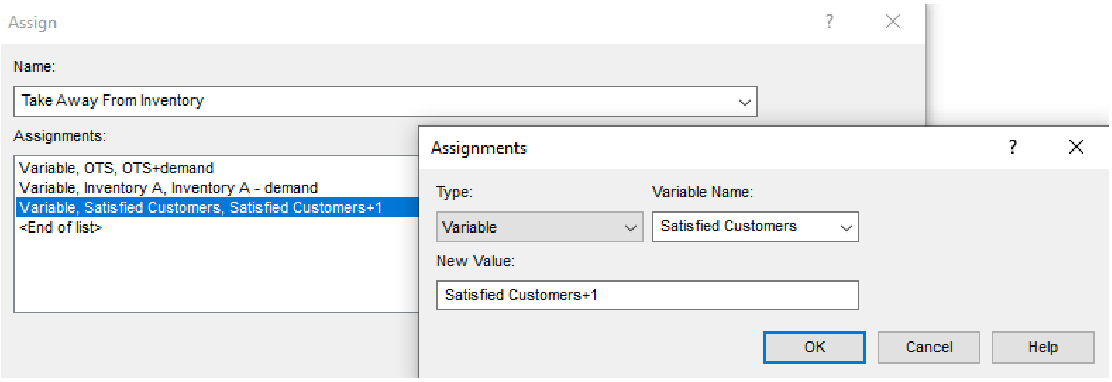


Figure 28 – Take Away From Inventory: Update Satisfied Customers Counter

If, however, inventory is not sufficient to cover demand and the Boolean operation returns False, excess demand is placed on backorder:

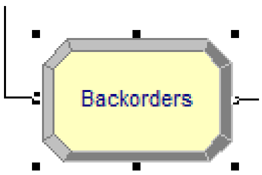


Figure 29 – Backorders Module

a) The portion of demand that was satisfied is added to Order Total Supplied (OTS):

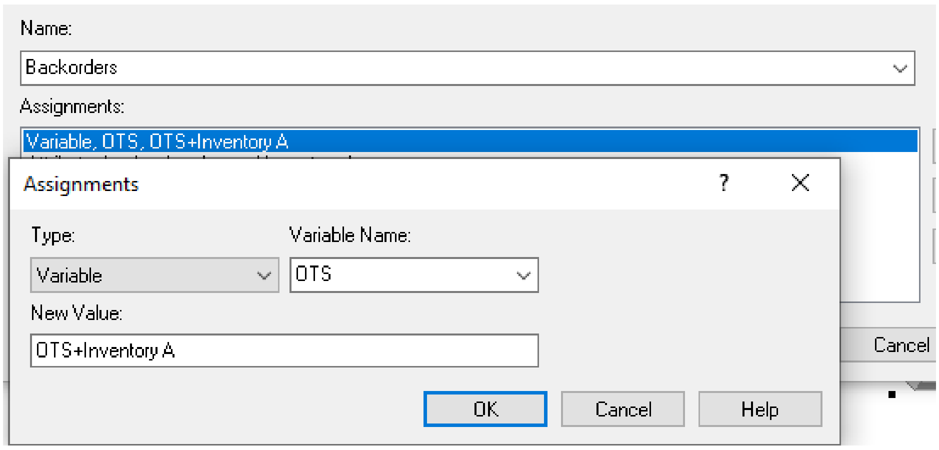


Figure 30 – Backorders: Update Order Total Supplied (OTS)

b) Any unsatisfied demand is tracked by the variable Backorders:

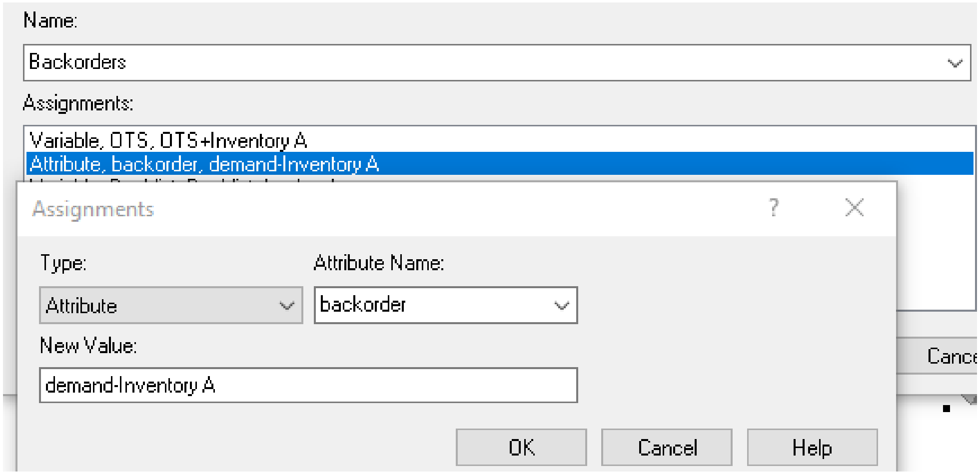


Figure 31 – Backorders: Update Backorder Variable

c) Backorders are also added to the variable Backlist, which tracks total unsatisfied demand during the entire system runtime.

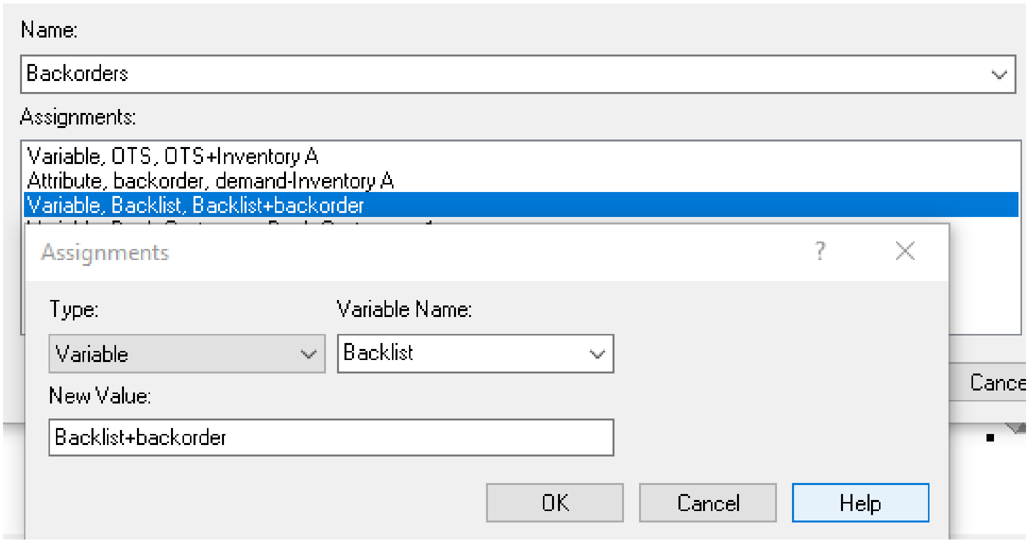


Figure 32 – Backorders: Update Backlist Variable

d) Furthermore, the variable Back Customers tracks the number of unsatisfied customers. Every time demand exceeds inventory levels, this counter rises by one.

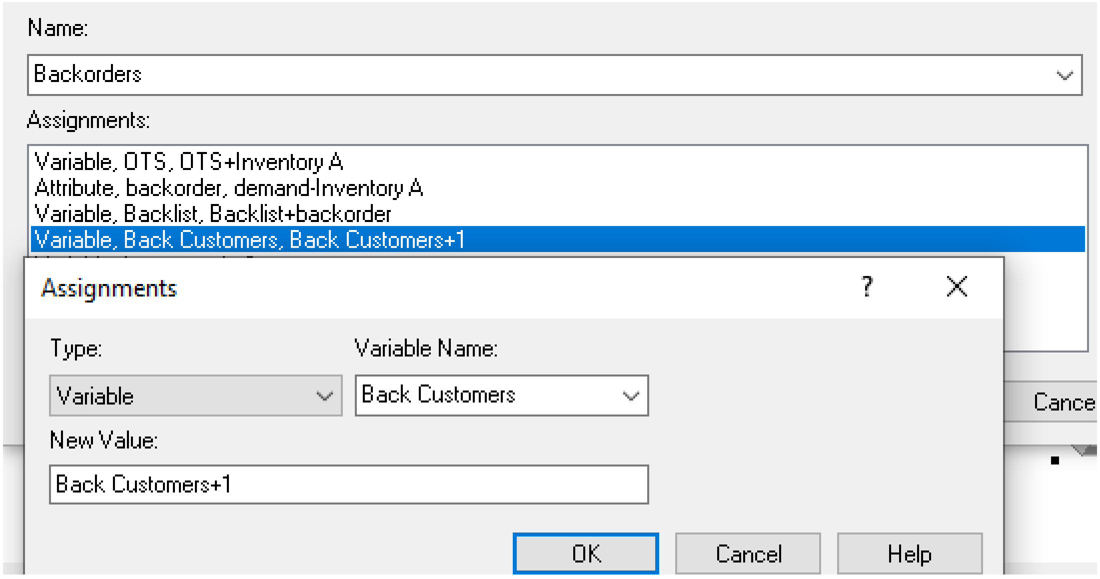


Figure 33 – Backorders: Update Back Customer Counter

e) Finally, Inventory A is set to 0, since all products were used to satisfy demand.

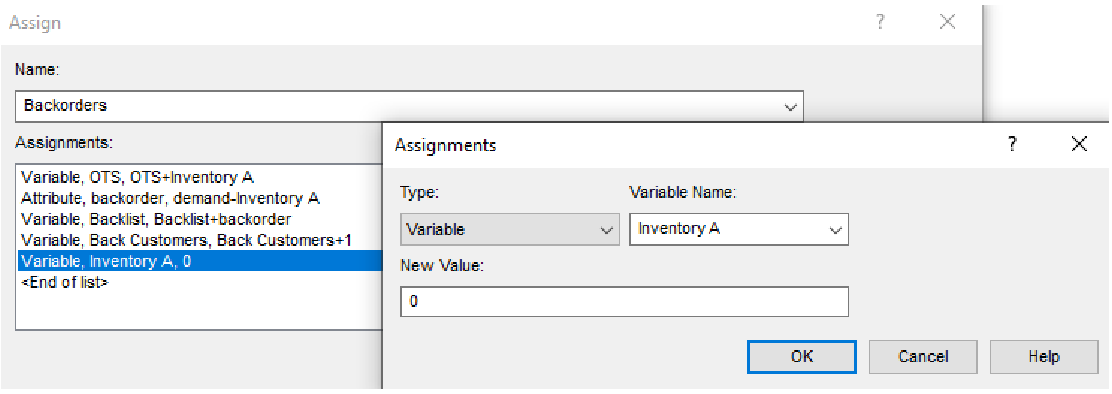


Figure 34 – Backorders: Update Inventory A

The next module, *Record Backorders*, tracks backorders per customer. Backorders are tracked in each iteration and divided after the system's runtime by the number of total customers:

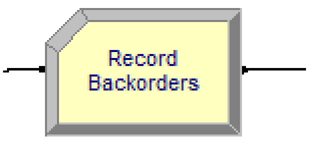


Figure 35 – Record Backorders Module

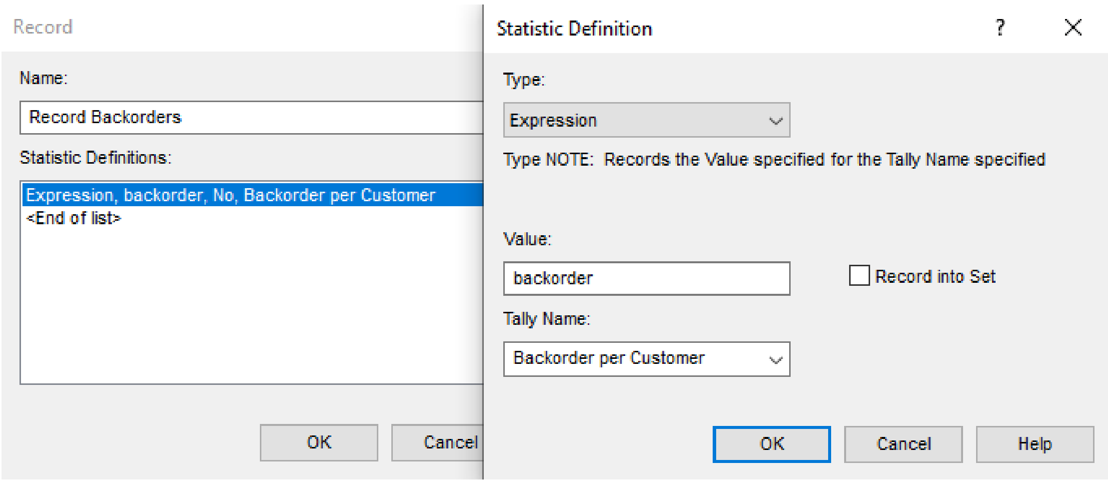


Figure 36 – Record Backorders: Update Backorder Value

Finally, the module *Customer Departure* removes the customer, who has finished their transaction, from the system:

Figure 37 – Customer Departure Module

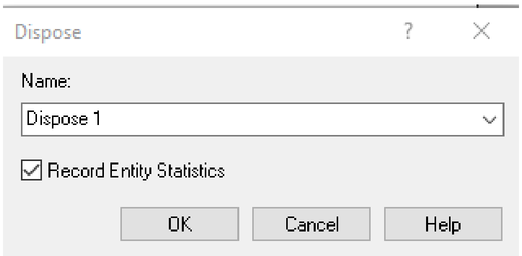


Figure 38 – Customer Departure Module: Details

7.1.2 Node B: Warehouse

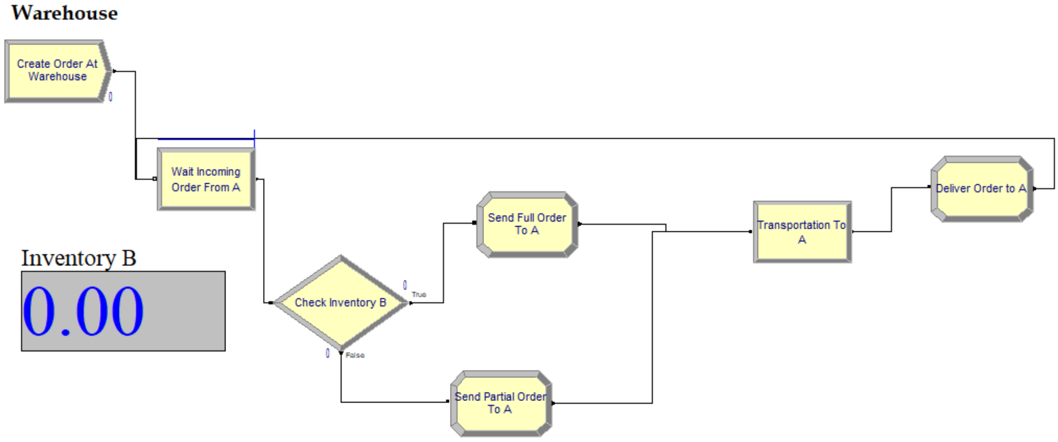


Figure 39 – Node B: Warehouse

The module *Create Order At Warehouse* generates orders to the supplier:

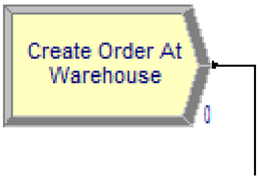


Figure 40 – Create Order At Warehouse

Orders remain inactive until Inventory A falls below the reorder point rA:

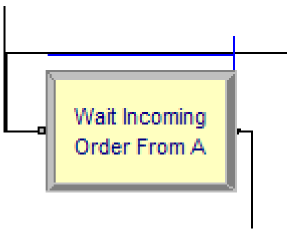


Figure 41 – Wait Incoming Order From A Module

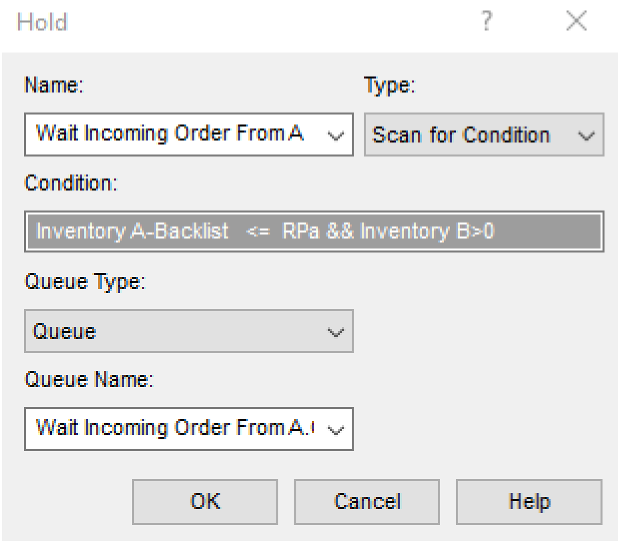


Figure 42 – Orders remain inactive until the retailer's inventory falls below the reorder point

Next, a Boolean operator checks if the warehouse has sufficient inventory levels to fulfill the order:

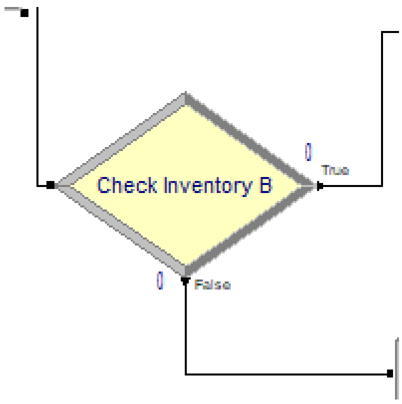


Figure 43 – Check Inventory B Module

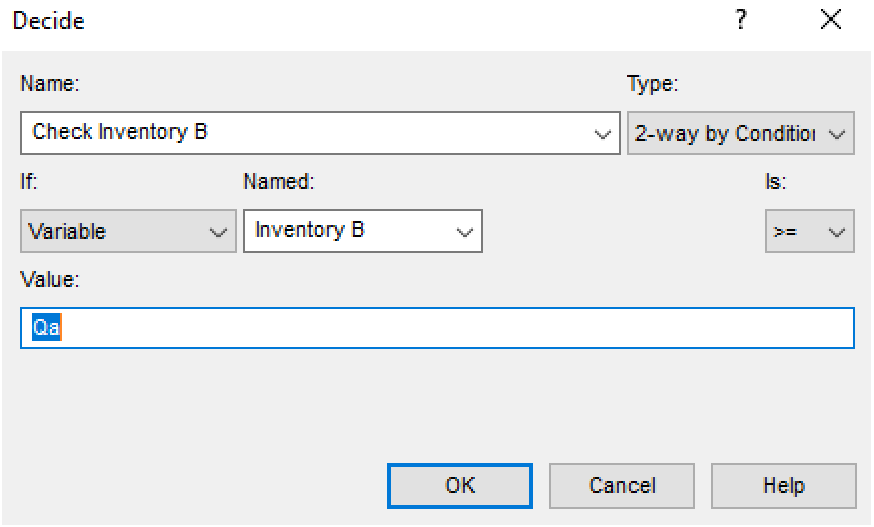


Figure 44 – Check Inventory B: Is Inventory B sufficient to fulfill the order?

If True, the next module, *Send Full Order to A*:

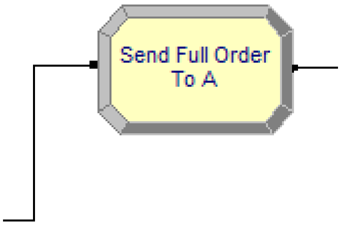


Figure 45 – Send Full Order To A Module

a) Updates the variable Inventory B:

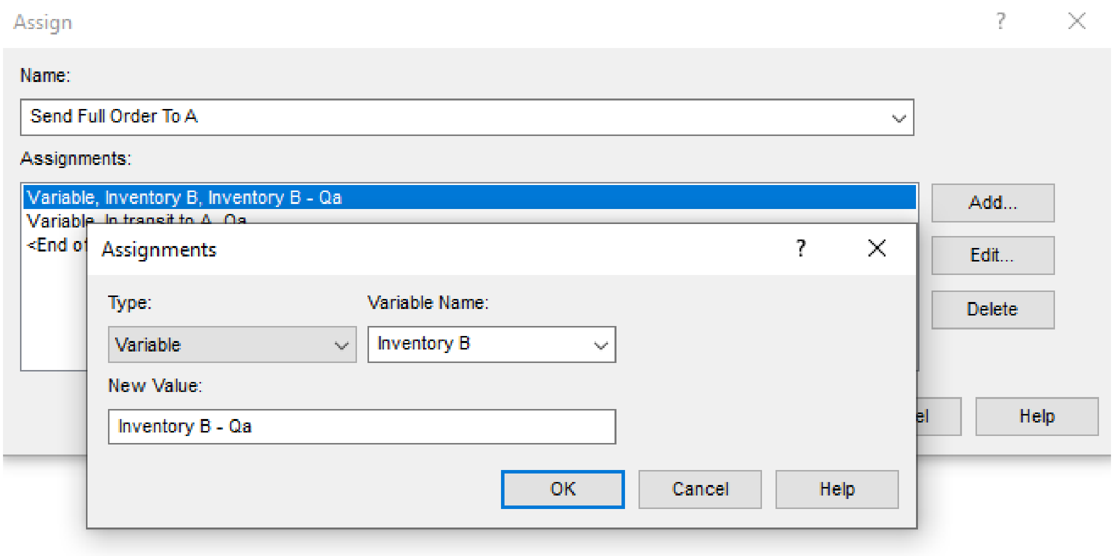


Figure 46 – Send Full Order To A: Update Variable Inventory B

b) Sets the variable In Transit to A to value Q_A:

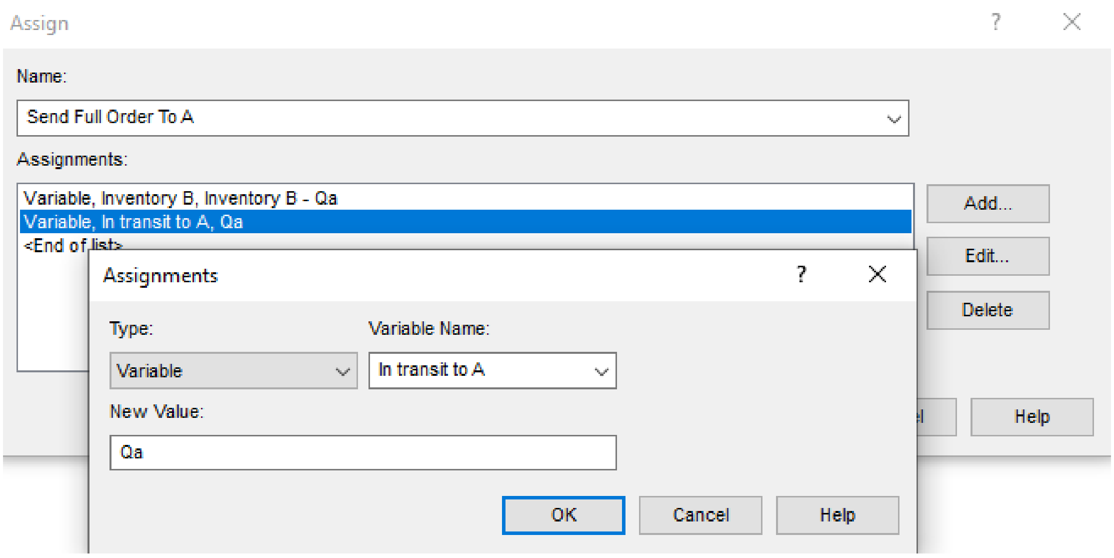


Figure 47 – Send Full Order To A: Set Variable In Transit to A to Value Q_A

However, if False (B <= Q_A), only a partial order is sent to the retailer via the module Send partial order to A:

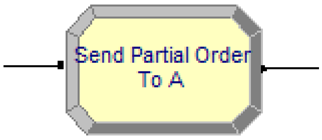


Figure 48 – Send Partial Order To A Module

a) In Transit to A is set to a value equal to Inventory B:

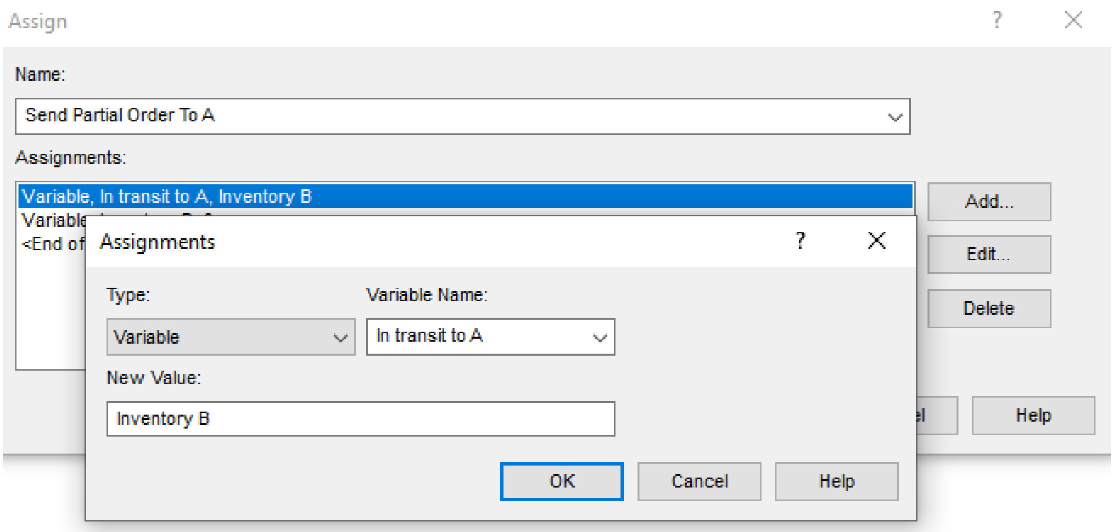


Figure 49 – Send Partial Order To A: Set Variable In Transit to A equal to Inventory B

b) Inventory B is set to 0:

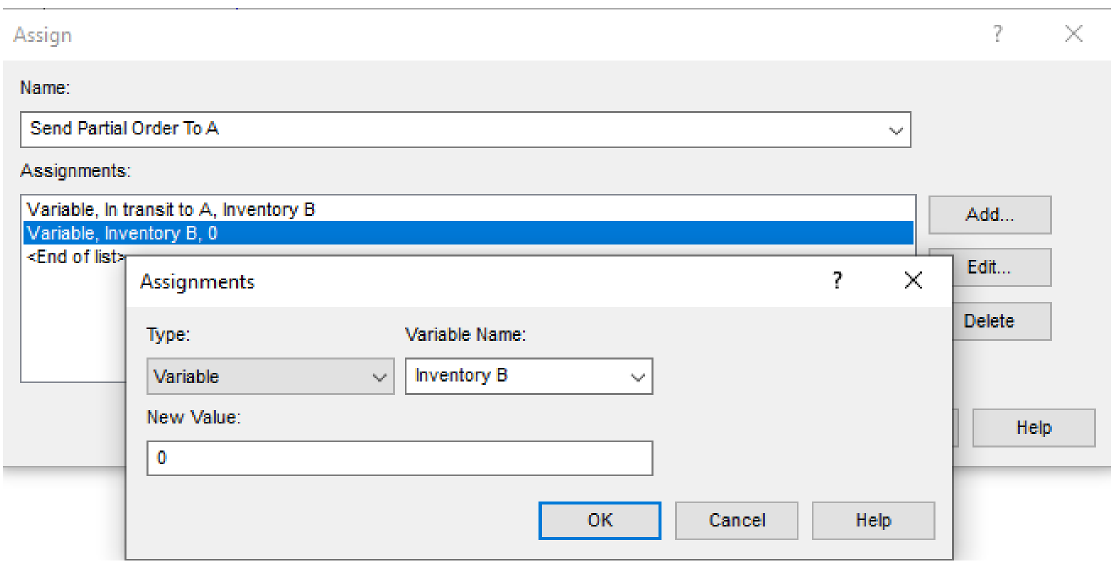


Figure 50 – Send Partial Order To A: Set Inventory B to 0

The module *Transportation to A* tracks the lead time between the warehouse and the retailer (Lead Time A), which remains constant, at two days:

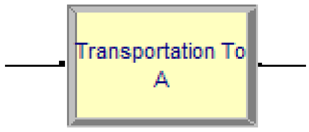


Figure 51 – Transportation To A Module

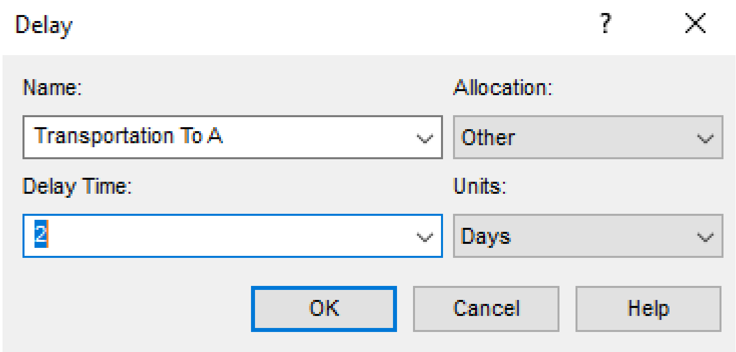


Figure 52 – Lead Time A = 2 days

Finally, the *Deliver Order To A* module describes the replenishment of Inventory A:

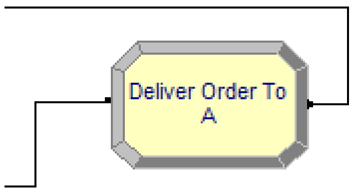


Figure 53 – Deliver Order To A Module

a) It updates the variable Units Delivered by adding the product just transported to the retailer:

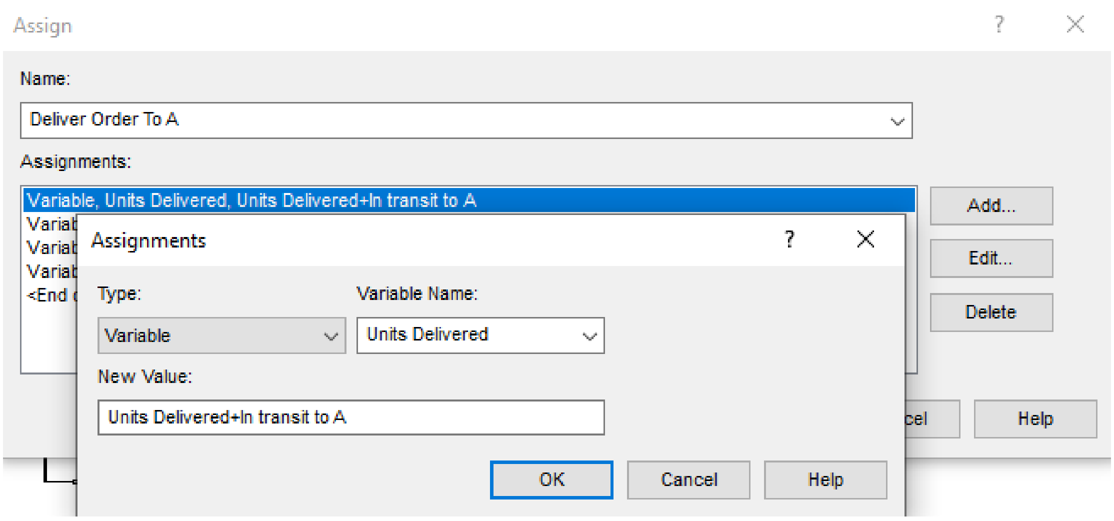


Figure 54 – Deliver Order To A: Update Variable Units Delivered

b) It updates the retailer’s inventory, by adding the products delivered minus any backordered demand. Of course, if backordered demand is greater or equal to the delivered order, Inventory A is set to 0:

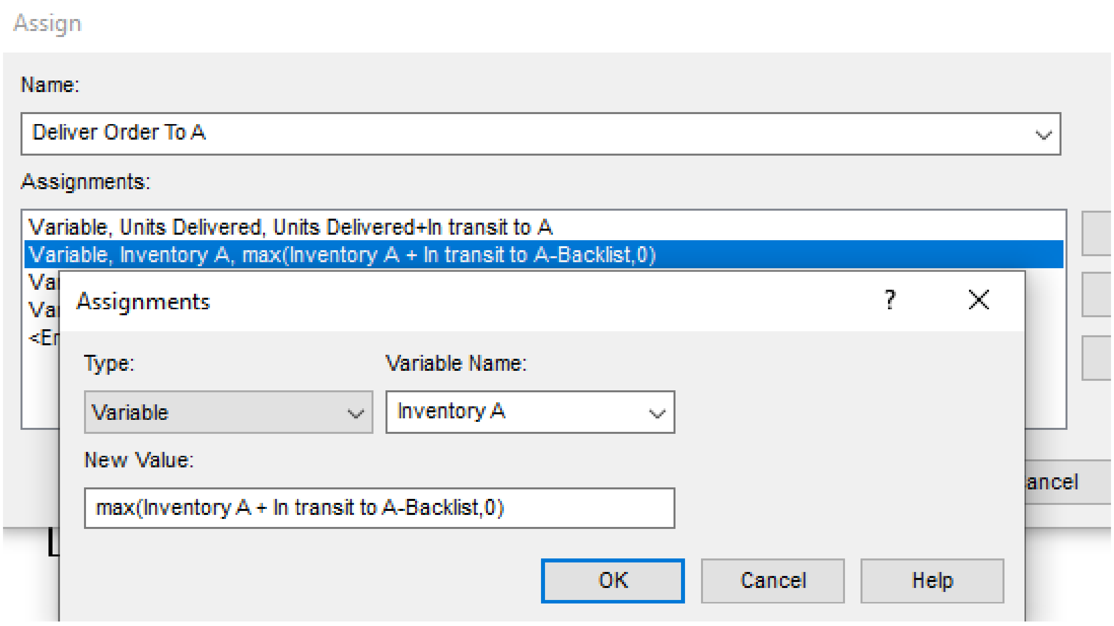


Figure 55 – Deliver Order To A: Update Variable Inventory A

c) It updates the variable Backlist accordingly, by subtracting the delivered product. If the delivered product exceeds backorders, Backlist is set to 0 (a negative value would be meaningless):

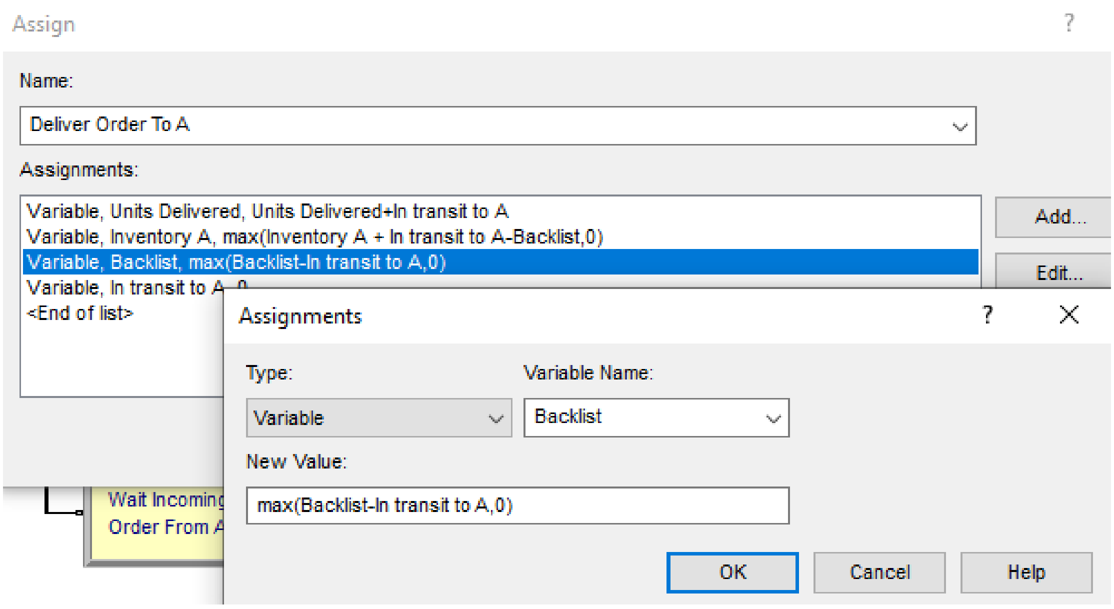


Figure 56 – Deliver Order To A: Update Variable Backlist

d) Finally, the variable In Transit to A is set to 0:

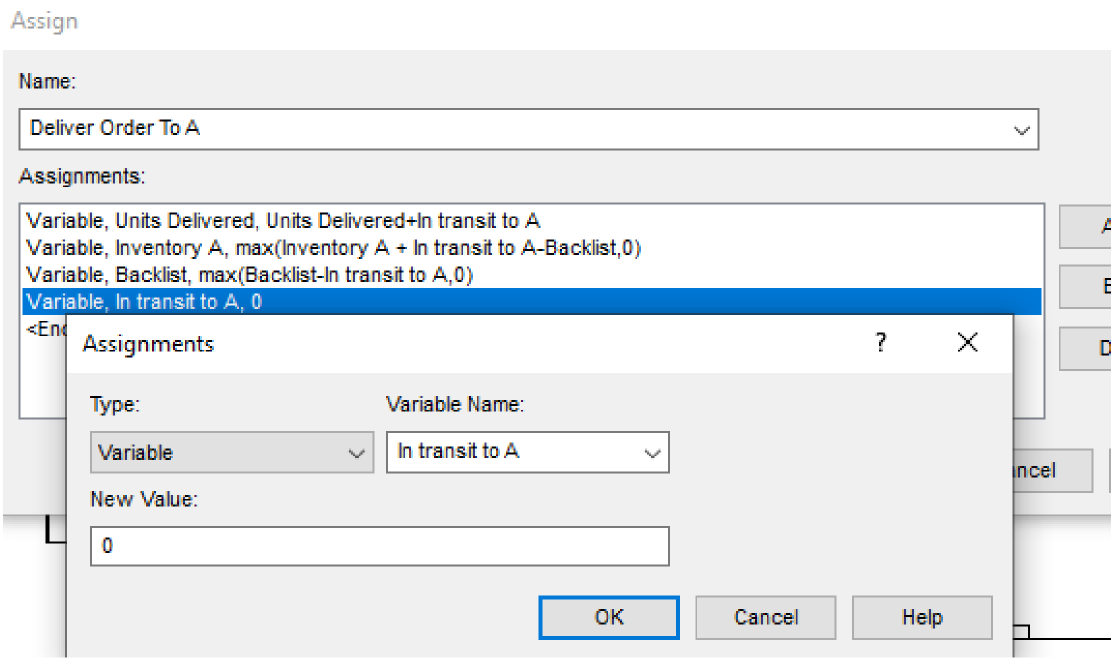


Figure 57 – Deliver Order To A: Set In Transit to A to 0

The process loops back to the module *Wait for Demand* to service the next order when it arises.

7.1.3 Node 3: Supplier

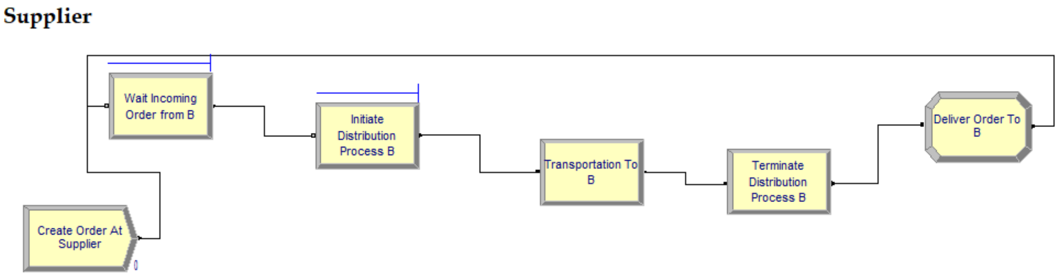


Figure 58 – Node 3: Supplier

The module *Create Order At Supplier* generates orders to the warehouse:

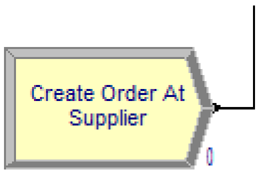


Figure 59 – Create Order At Supplier Module

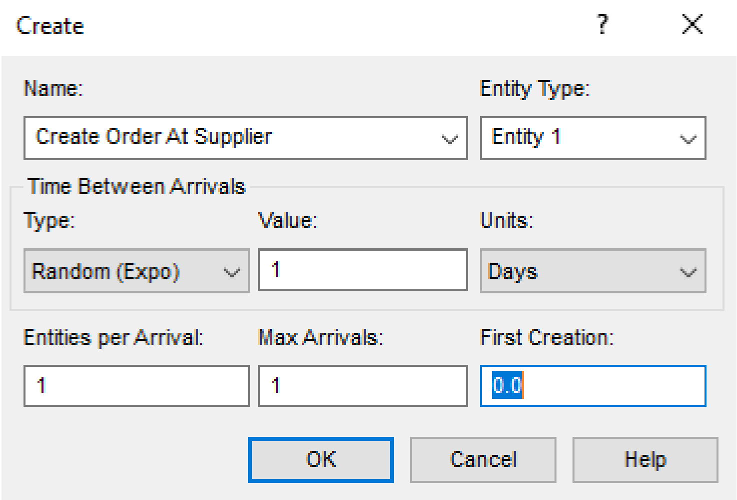


Figure 60 – Create Order At Supplier: Detailed Settings

Orders remain inactive until the inventory on hand of the retailer plus the warehouse falls below the reorder point r_B:

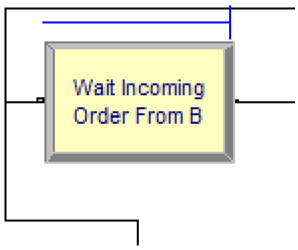


Figure 61 – Wait Incoming Order From B Module

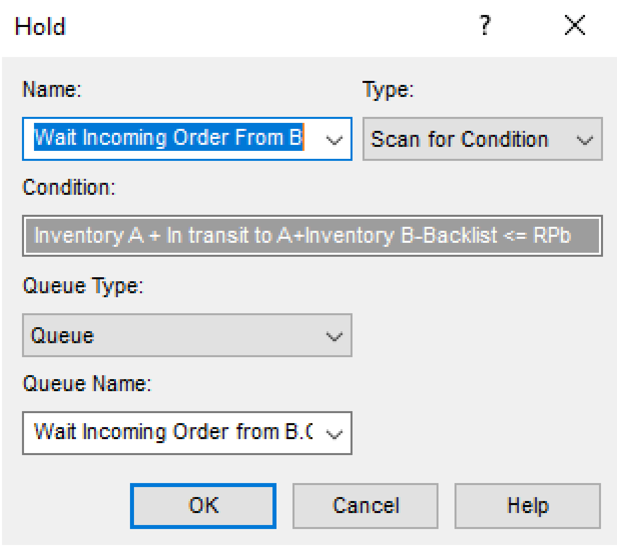


Figure 62 – Wait Incoming Order From B: Orders remain inactive until the warehouse & retailer's inventory on hand falls below the reorder point r_B

Once an order is activated, module *Initiate Distribution Process B* releases a kanban card for a unit of size Q_B:

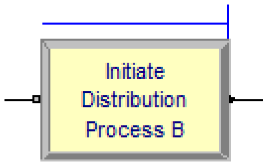


Figure 63 – Initiate Distribution Process B Module

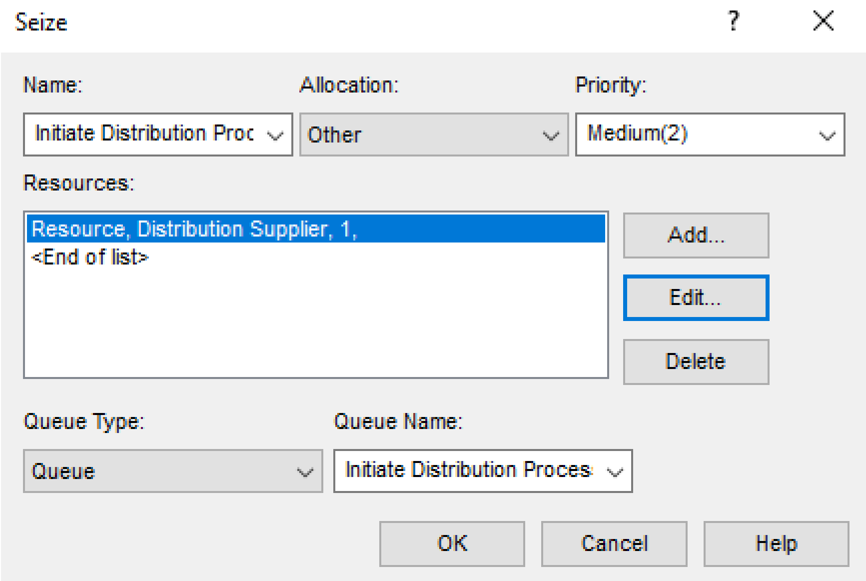


Figure 64 – Initiate Distribution Process B Module: Release one kanban card

The module *Transportation To B* represents the lead time from the supplier to the warehouse, which equals 120 days:

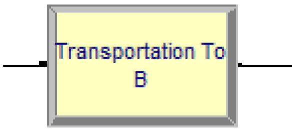


Figure 65 – Transportation To B Module

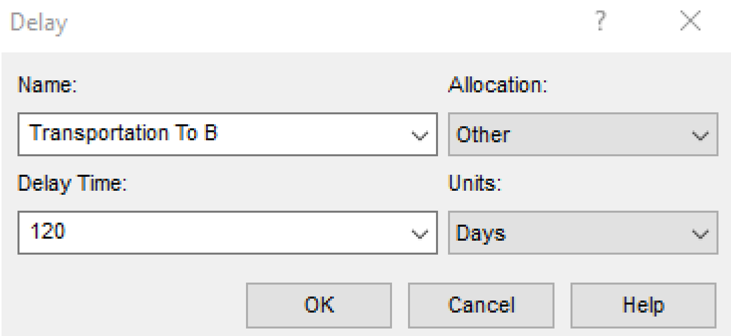


Figure 66 – Lead Time B = 120 days

Next, the module *Terminate Distribution Process B* deactivates the kanban card, so that the supplier is ready for the next order:

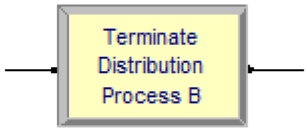


Figure 67 – Terminate Distribution Process B Module

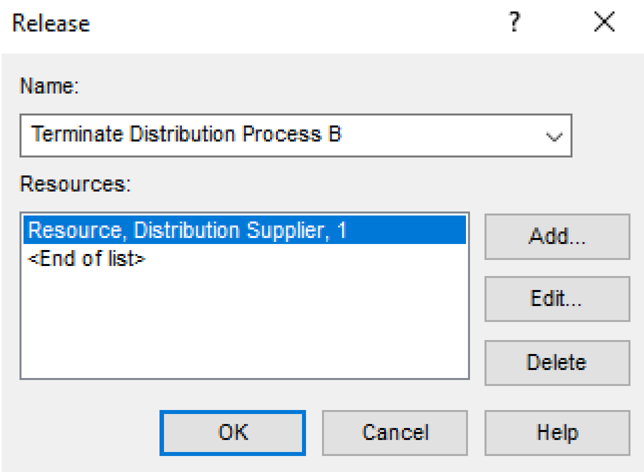


Figure 68 – Terminate Distribution Process B Module: The kanban card is disengaged

Finally, the module *Deliver Order To B* represents delivery and updates the relevant variables:

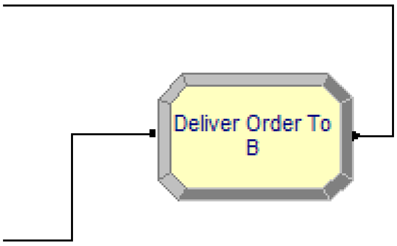


Figure 69 – Deliver Order To B Module

a) The variable Units Delivered to B is updated, by adding the delivery quantity Q_B:

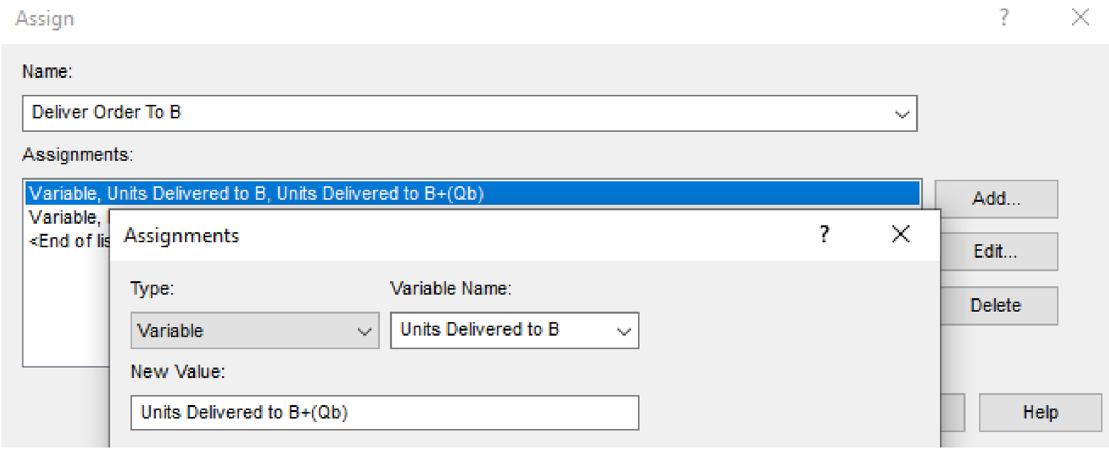


Figure 70 – Deliver Order To B Module: Update Units Delivered To B

b) The variable Inventory B is updated, by adding the delivery quantity Q_B:

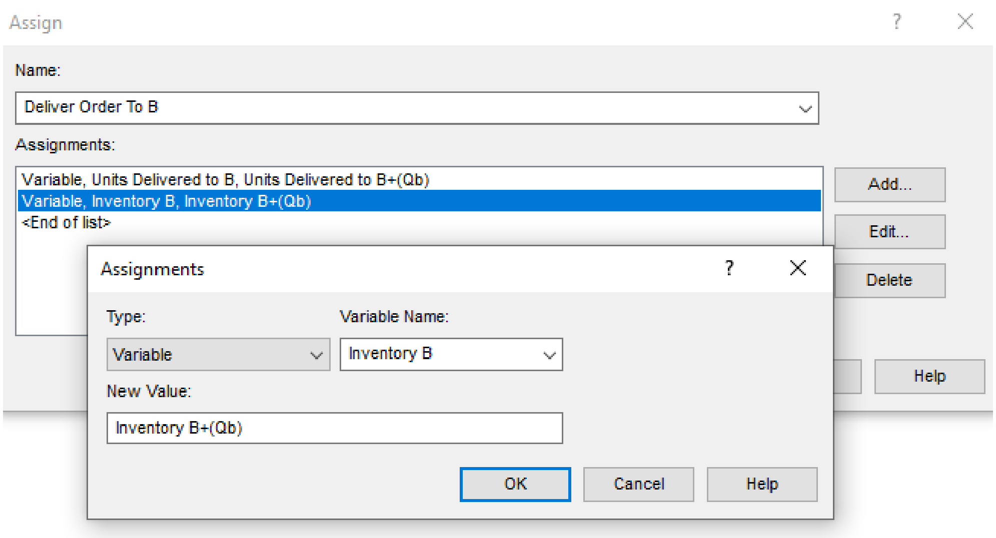


Figure 71 – Deliver Order To B Module: Update Inventory B

Finally, the process loops back to the module *Wait for Demand* to service the next order when it arises.

7.1.4 Backend Variables

In addition, we calculate some variables – mostly performance drivers – at the backend. These will enable us to assess the system's performance under different settings:

	Name	Type	Expression	Collection Period	Report Label	Output File
1	Inventory on hand A	Time-Persistent	Inventory A	Entire Replication	Inventory on hand A	
2	WIP in transit to B	Time-Persistent	ResUtil(Distribution Manufacturer)*(Qb)	Entire Replication	WIP in transit to B	
3	Inventory on hand B	Time-Persistent	Inventory B	Entire Replication	Inventory on hand B	
4	WIP in Transit to A	Time-Persistent	In transit to A	Entire Replication	WIP in Transit to A	
5	Average Backlist	Time-Persistent	Backlist	Entire Replication	Average Backlist	
6	Order Fill Rate	Output	(Satisfied Customers)/(Back Customers + Satisfied Customers)	Entire Replication	Order Fill Rate	
7	Service Level	Output	OTS / Total Demand	Entire Replication	Service Level	

Figure 72 – Backend Variables

7.2 Model parametrization

Having described the system and its simulation model, we now move to setting the simulation's parameters.

7.2.1 Controllable variables

Controllable variables consist of attributes that are open to manipulation; the system's manager is able to set specific values at will. In our case, control variables include:

- The order quantities Q_A and Q_B
- The reorder points r_A and r_B

7.2.2 Uncontrollable variables

Uncontrollable variables consist of attributes that are outside a manager's control. In this case, they include:

- Customer arrival, which follows an exponential distribution with a mean of two customers per day.

- Customer demand, which is uncertain and follows a uniform distribution in the range (3, 9).
- Lead time A, between the warehouse and the retailer, which is set at two days.
- Lead time B, between the supplier and the warehouse, which is set at 120 days.

7.2.3 Performance Drivers

Performance drivers are metrics that capture how a system performs under constraints. In our model, we will focus on the following:

- Inventory on hand A: the inventory the retailer carries throughout the entire replication.
- Inventory on hand B: the inventory the warehouse carries throughout the entire replication.
- Satisfied Customers: the number of customers whose demand was fulfilled.
- Back Customers: the number of customers whose demand was backordered.
- Order Fill Rate: the fraction of individual orders fulfilled through inventory supplies and not backordered. Here, it is calculated by dividing the number of satisfied customers by the total number of customers:

$$Order\ Fill\ Rate = \frac{Satisfied\ Customers}{Back\ Customers + Satisfied\ Customers}$$

- Service Fill Rate: the fraction of demand fulfilled over total demand:

$$Service\ Level = \frac{Order\ Total\ Supplied}{Total\ Demand}$$

8. Experiment

8.1 Methodology

The experiment aims to monitor key performance drivers for different values of controlled variables.

Using the ARENA tool Process Analyzer, we run the simulation four times, one for every controlled variable (Q_A, Q_B, r_A, r_B). Each time, the system underwent five different scenarios for different values of the selected controlled variable. The values of variables as well as performance drivers was recorded and reported in tables (see Results).

8.2 Results

8.2.1 Iteration 1: Effects of Order Quantity Q_A

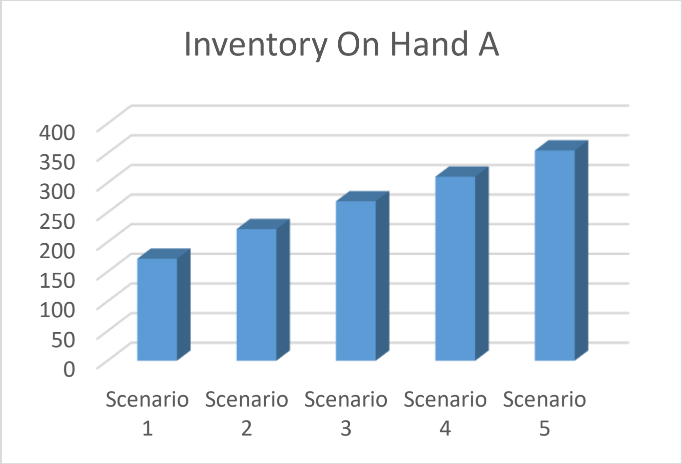
Table 1 reports Q_A values as well as performance drivers during each scenario:

Table 1 – Iteration 1: Effects of Order Quantity Q_A

	Scenario Properties				Controls				Responses					
	S	Name	Program File	Reps	Qa	RPa	Qb	RPb	Inventory on hand A	Inventory on hand B	Order Fill Rate	Service Level	Back Customers	Satisfied Customers
1		Scenario 1	4 : Supply_Ch	1	300.0000	200.0000	10000.0000	8000.0000	172.090	4082.986	0.852	0.853	177219.000	1023820.000
2		Scenario2	4 : Supply_Ch	1	400.0000	200.0000	10000.0000	8000.0000	222.068	4019.369	0.880	0.881	144298.000	1056741.000
3		Scenario 3	4 : Supply_Ch	1	500.0000	200.0000	10000.0000	8000.0000	268.898	3966.342	0.892	0.892	129964.000	1071075.000
4		Scenario 4	4 : Supply_Ch	1	600.0000	200.0000	10000.0000	8000.0000	310.306	3921.420	0.899	0.899	121904.000	1079135.000
5		Scenario 5	2 : Supply_Ch	1	700.0000	200.0000	10000.0000	8000.0000	354.688	3874.786	0.903	0.904	116316.000	1084723.000

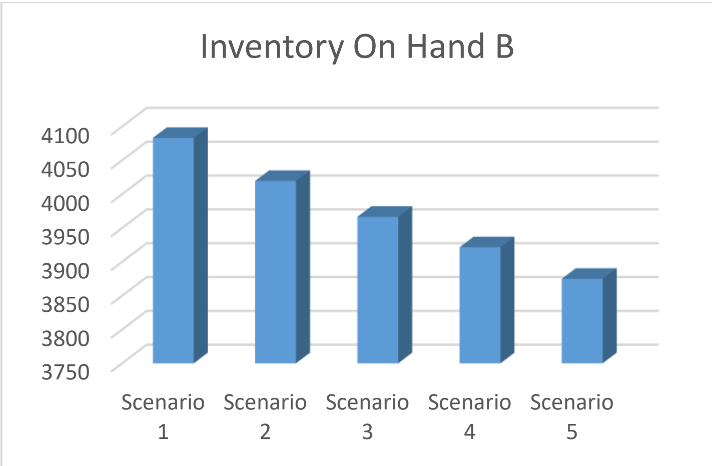
We may note the following:

- The value of Q_A was raised by 100 units in each scenario.
- The retailer's inventory on hand increased by approximately 106% between the first and last scenarios.



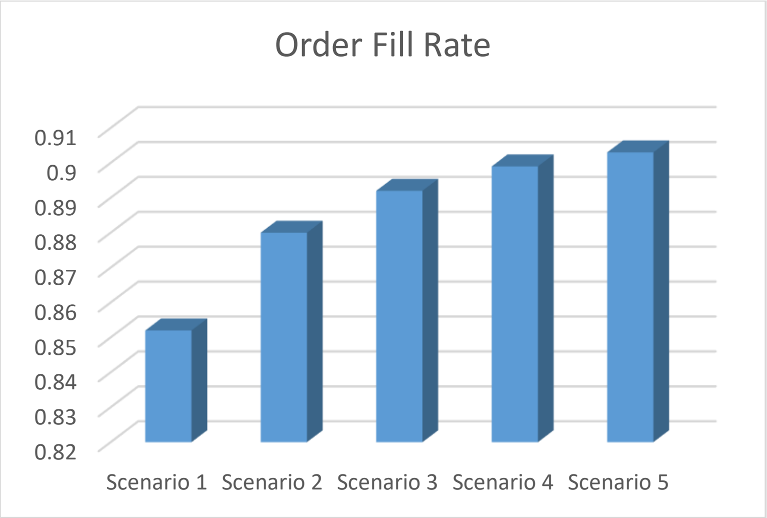
Graph 1 – Effects of Q_A: Inventory On Hand A

- The warehouse’s inventory on hand decreased by approximately 5% between the first and last scenarios.



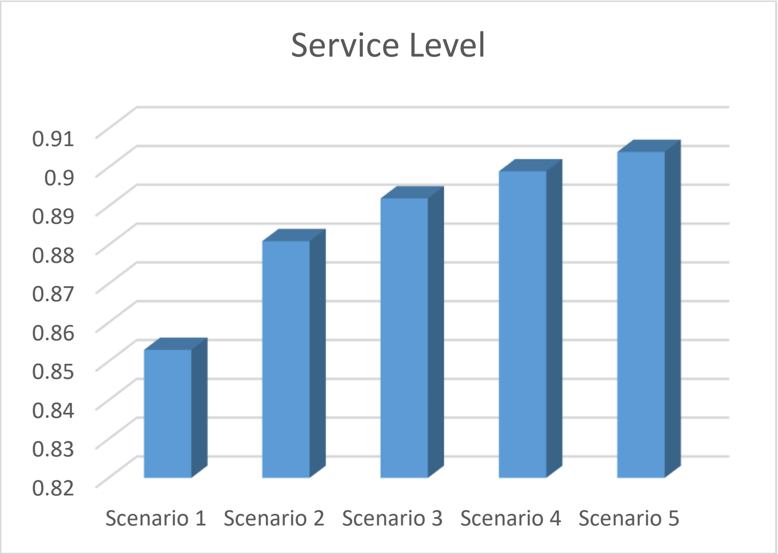
Graph 2 – Effects of Q_A: Inventory On Hand B

- Order fill rate increased by approximately 5.1%.



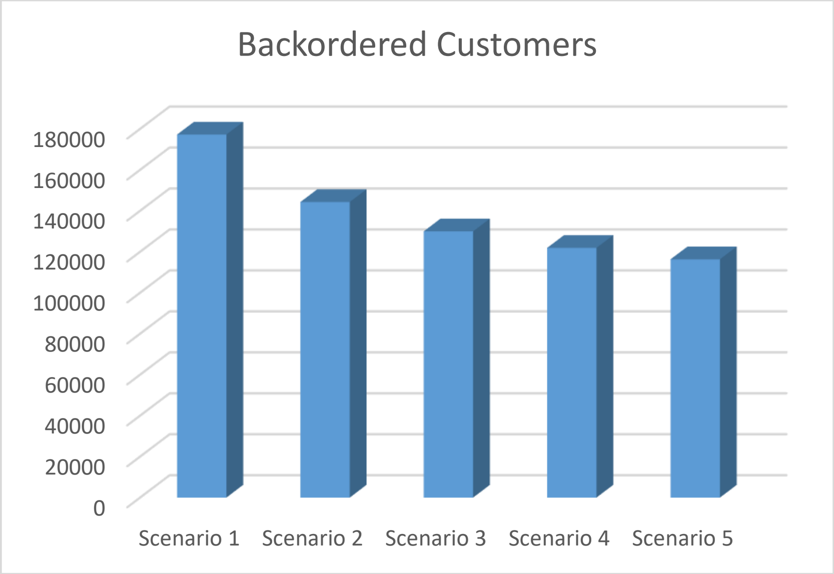
Graph 3 – Effects of Q_A: Order Fill Rate

- Service level increased by approximately 5.1%.



Graph 4 – Effects of Q_A: Service Level

- The number of backordered customers fell significantly by approximately 34.4% between the first and last scenarios.



Graph 5 – Effects of Q_A: Backordered Customers

- The number of satisfied customers rose by approximately 5.9% between the first and last scenarios.

Graph 6 – Effects of Q_A: Satisfied Customers

8.2.2 Iteration 2: Effects of Order Quantity Q_B

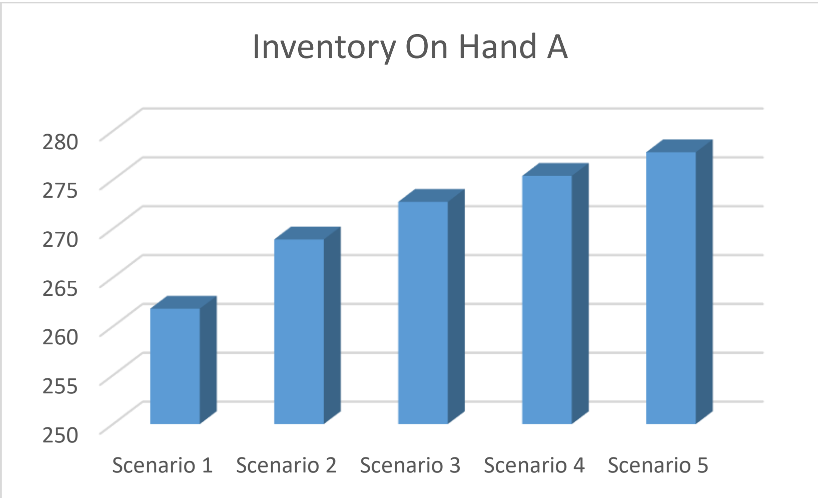
Table 2 reports Q_B values as well as performance drivers during each scenario:

Table 2 – Iteration 2: Effects of Order Quantity Q_B

	Scenario Properties				Controls				Responses					
	S	Name	Program File	Reps	Qa	RPa	Qb	RPb	Back Customers	Inventory on hand A	Inventory on hand B	Order Fill Rate	Service Level	Satisfied Customers
1		Scenario 1	4 : Supply_Ch	1	500.0000	200.0000	9000.0000	8000.0000	154222.000	261.810	3437.987	0.872	0.872	1046817.000
2		Scenario 2	4 : Supply_Ch	1	500.0000	200.0000	10000.0000	8000.0000	129964.000	268.898	3966.342	0.892	0.892	1071075.000
3		Scenario 3	4 : Supply_Ch	1	500.0000	200.0000	11000.0000	8000.0000	116850.000	272.741	4463.958	0.903	0.903	1084189.000
4		Scenario 4	4 : Supply_Ch	1	500.0000	200.0000	12000.0000	8000.0000	106621.000	275.400	4961.419	0.911	0.912	1094418.000
5		Scenario 5	4 : Supply_Ch	1	500.0000	200.0000	13000.0000	8000.0000	99343.000	277.822	5451.872	0.917	0.918	1101696.000

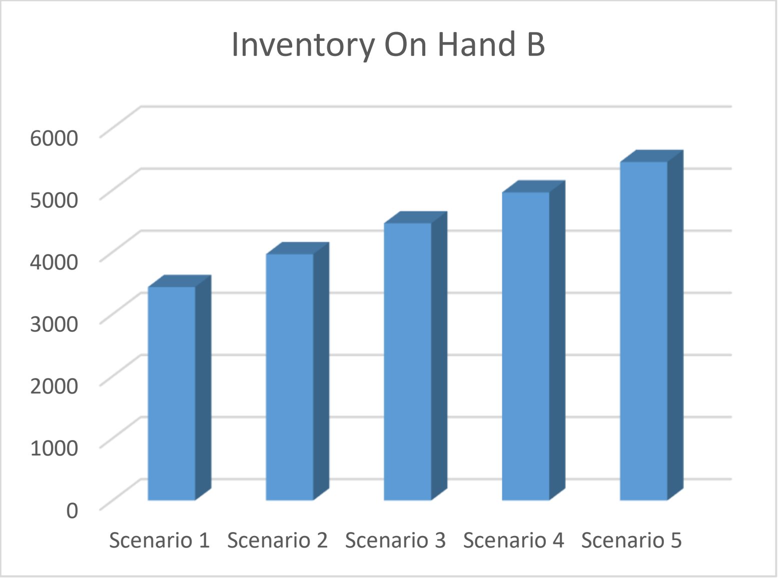
We may note the following:

- The value of Q_B was raised by 1000 units in each scenario.
- The retailer's inventory increased, albeit slightly, by about 6.1% between the first and last scenarios.



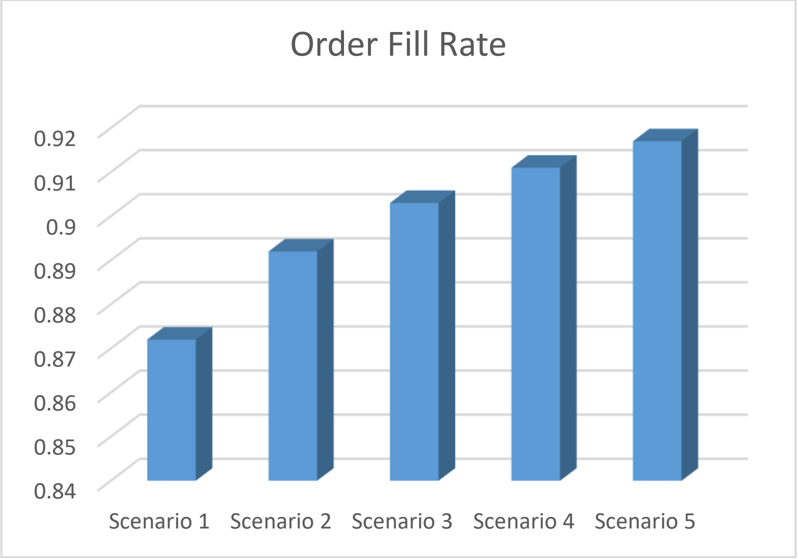
Graph 7 – Effects of Q_B: Inventory On Hand A

- The warehouse’s inventory increased significantly, by approximately 58.6% between the first and last scenarios.



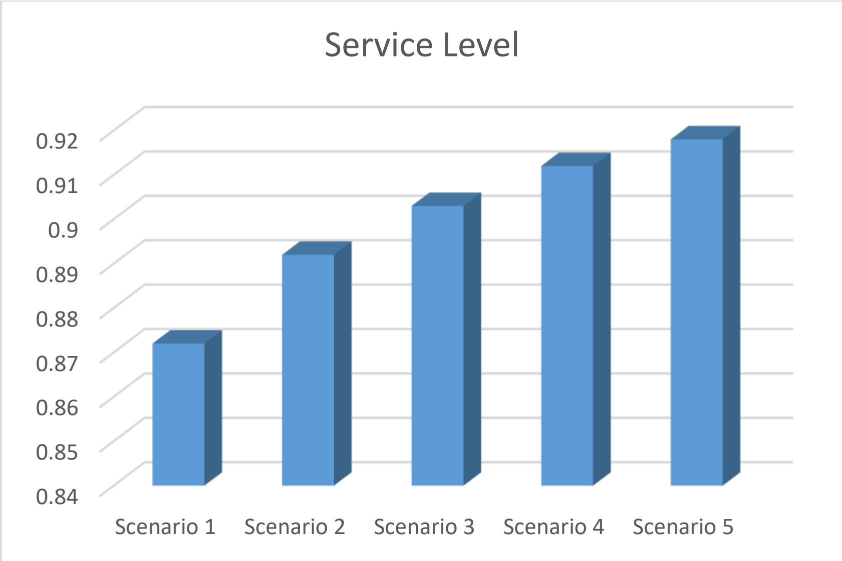
Graph 8 – Effects of Q_B: Inventory On Hand B

- Order fill rate increased by approximately 4.5%.



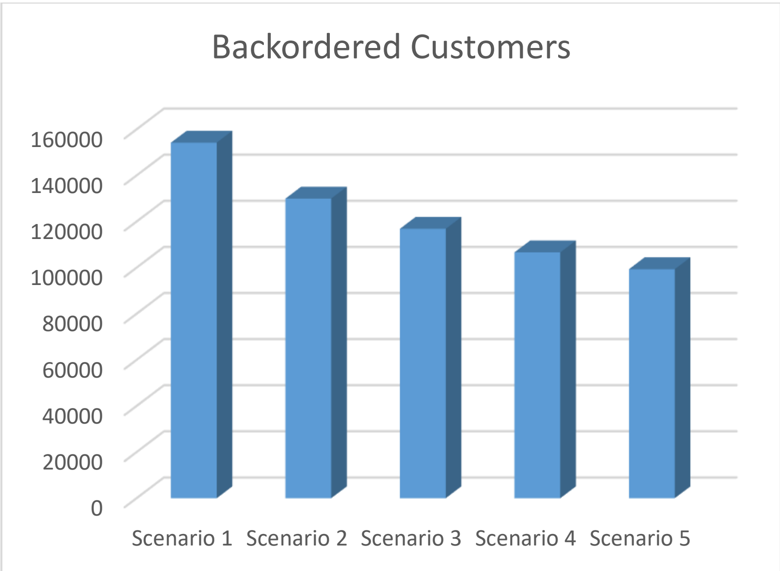
Graph 9 – Effects of Q_B: Order Fill Rate

- Service level increased by approximately 4.6%.



Graph 10 – Effects of Q_B: Service Level

- The number of backordered customers fell significantly by approximately 35.6% between the first and last scenarios.



Graph 11 – Effects of Q_B: Backordered Customers

- The number of satisfied customers rose by approximately 5.2% between the first and last scenarios.

Graph 12 – Effects of Q_B: Satisfied Customers

8.2.3 Iteration 3: Effects of Reorder Point r_A

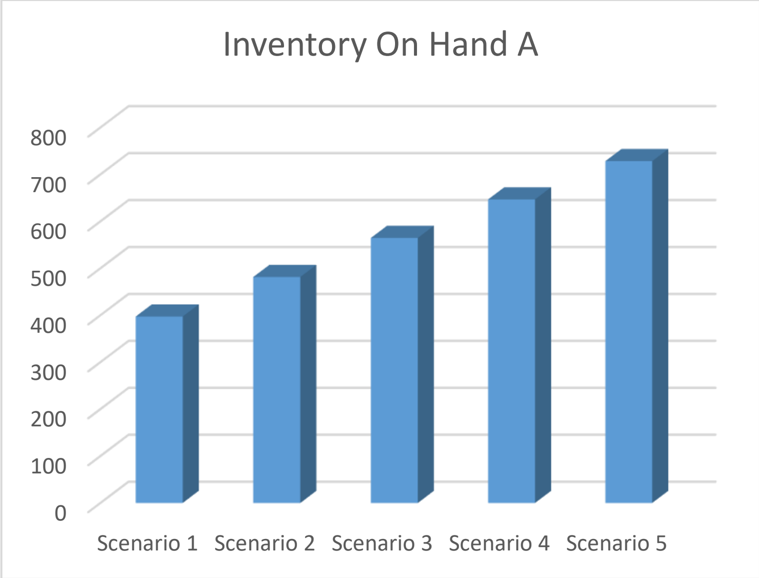
Table 3 reports r_A values as well as performance drivers during each scenario:

Table 3 – Iteration 3: Effects of Reorder Point r_A

	Scenario Properties					Controls				Responses					
	S	Name	Program File	Reps	Qa	RPa	Qb	RPb	Back Customers	Inventory on hand A	Inventory on hand B	Order Fill Rate	Service Level	Satisfied Customers
1		Scenario 1	4 : Supply_Ch	1	800.0000	200.0000	10000.0000	8000.0000	112685.000	397.082	3830.845	0.906	0.907	1088354.000
2		Scenario 2	4 : Supply_Ch	1	800.0000	300.0000	10000.0000	8000.0000	111503.000	481.439	3746.480	0.907	0.907	1089536.000
3		Scenario3	4 : Supply_Ch	1	800.0000	400.0000	10000.0000	8000.0000	111503.000	564.621	3663.298	0.907	0.907	1089536.000
4		Scenario 4	4 : Supply_Ch	1	800.0000	500.0000	10000.0000	8000.0000	111503.000	646.724	3581.195	0.907	0.907	1089536.000
5		Scenario 5	4 : Supply_Ch	1	800.0000	600.0000	10000.0000	8000.0000	111503.000	728.281	3499.627	0.907	0.907	1089536.000

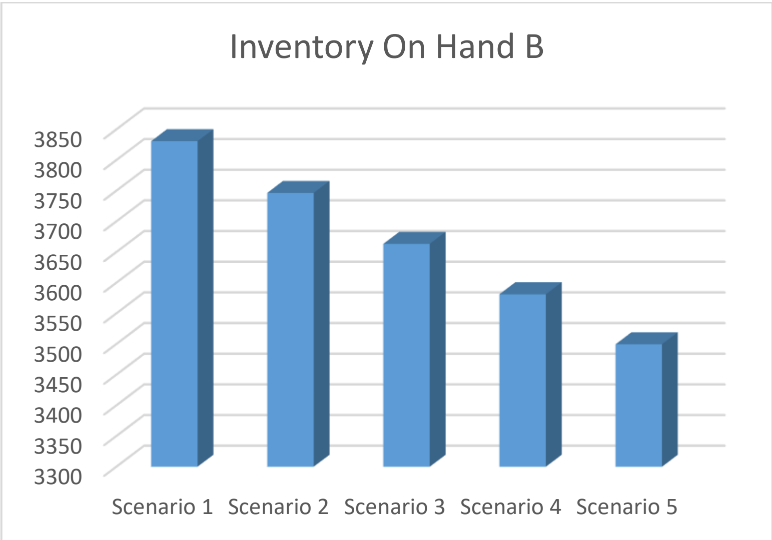
We may note the following:

- The value of r_A was raised by 100 units in each scenario.
- The retailer's inventory increased by about 83.4% between the first and last scenarios.



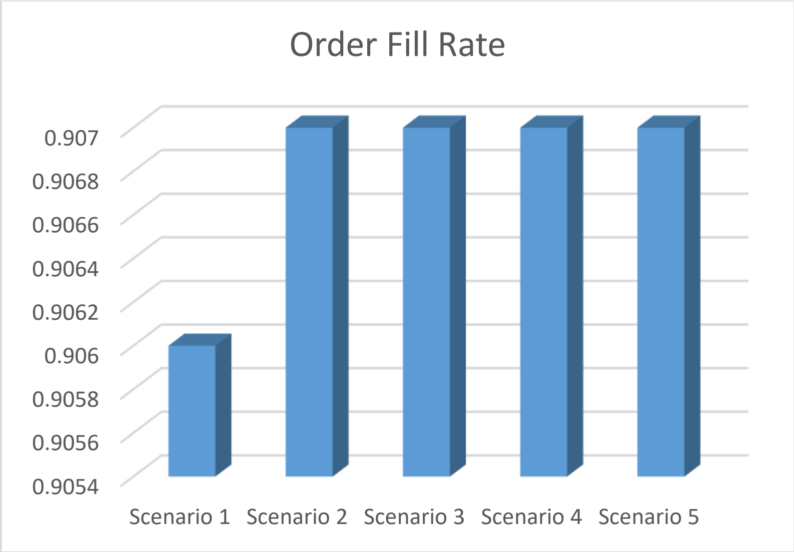
Graph 13 – Effects of r_A: Inventory On Hand A

- The warehouse's inventory decreased by approximately 8.6% between the first and last scenarios.



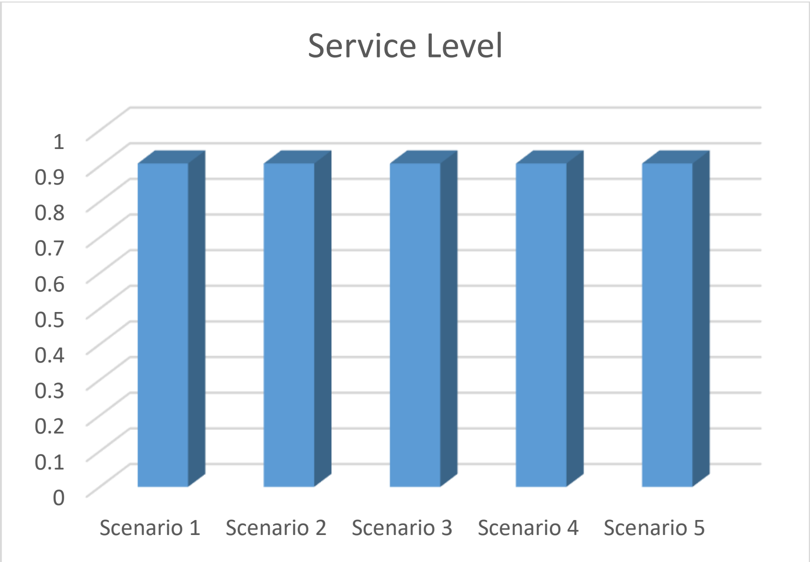
Graph 14 – Effects of r_A: Inventory On Hand B

- Order fill rate remained constant.



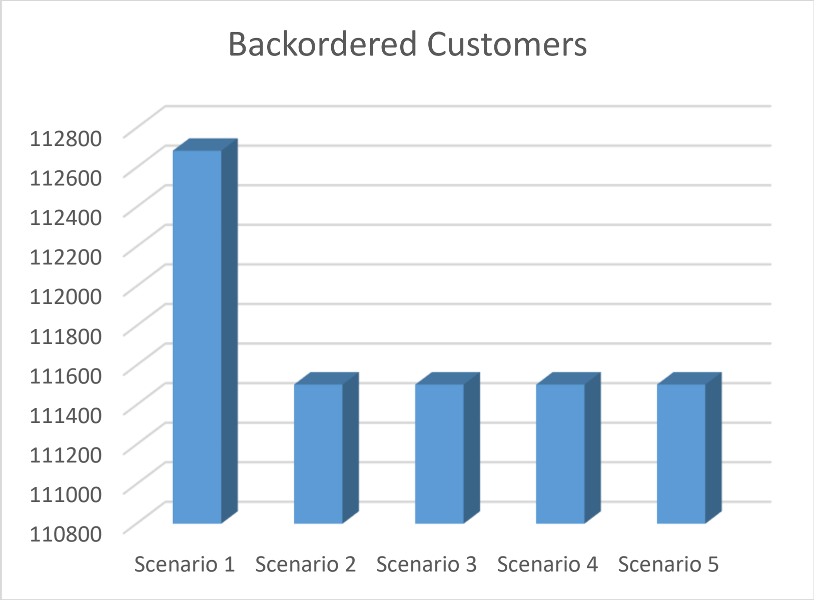
Graph 15 – Effects of r_A: Order Fill Rate

- Service level remained constant.



Graph 16 – Effects of r_A: Service Level

- The number of backordered customers fell slightly by approximately 1% between the first and last scenarios.



Graph 17 – Effects of r_A: Backordered Customers

- The number of satisfied customers rose by approximately 0.1% between the first and last scenarios.

Graph 18 – Effects of r_A: Satisfied Customers

8.2.4 Iteration 4: Effects of Reorder Point r_B

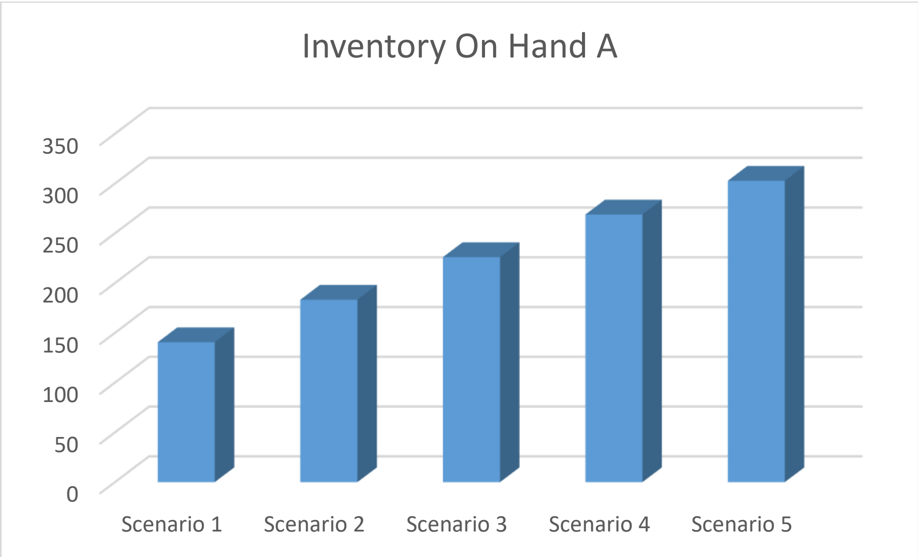
Table 4 reports r_B values as well as performance drivers during each scenario:

Table 4 – Iteration 4: Effects of Reorder Point r_B

	Scenario Properties				Controls				Responses				
	S	Name	Program File	Reps	Qa	RPa	Qb	RPb	Back Customers	Inventory on hand A	Inventory on hand B	Order Fill Rate	Service Level II
1		Scenario 1	4 : Supply Ch	1	500.0000	200.0000	10000.0000	5000.0000	632244.000	140.628	2042.060	0.474	0.474
2		Scenario 2	4 : Supply Ch	1	500.0000	200.0000	10000.0000	6000.0000	464959.000	183.317	2542.612	0.613	0.613
3		Scenario 3	4 : Supply Ch	1	500.0000	200.0000	10000.0000	7000.0000	297500.000	226.071	3185.732	0.752	0.753
4		Scenario 4	4 : Supply Ch	1	500.0000	200.0000	10000.0000	8000.0000	129964.000	268.898	3966.342	0.892	0.892
5		Scenario 5	4 : Supply Ch	1	500.0000	200.0000	10000.0000	9000.0000	12181.000	302.815	4881.292	0.990	0.990

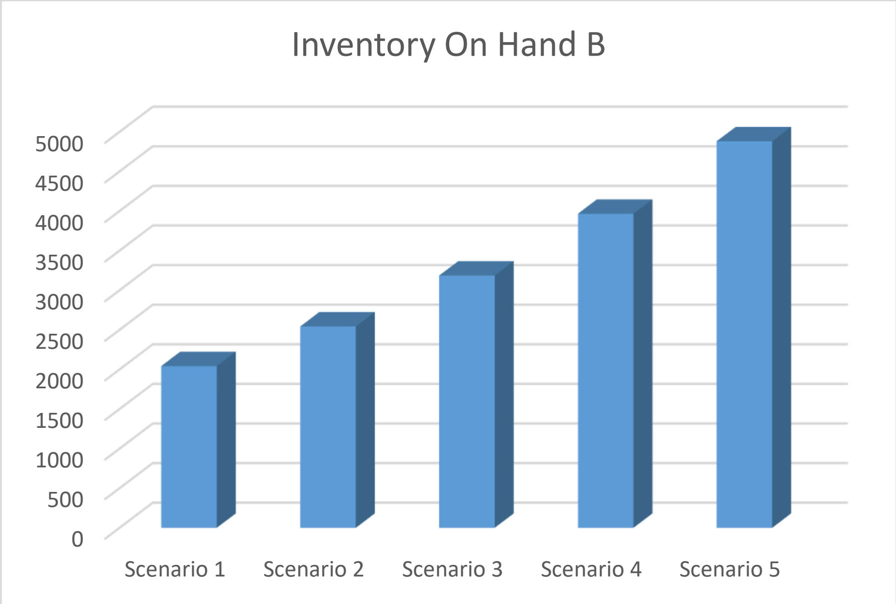
We may note the following:

- The value of r_B was raised by 1000 units in each scenario.
- The retailer's inventory increased significantly, by about 115% between the first and last scenarios.



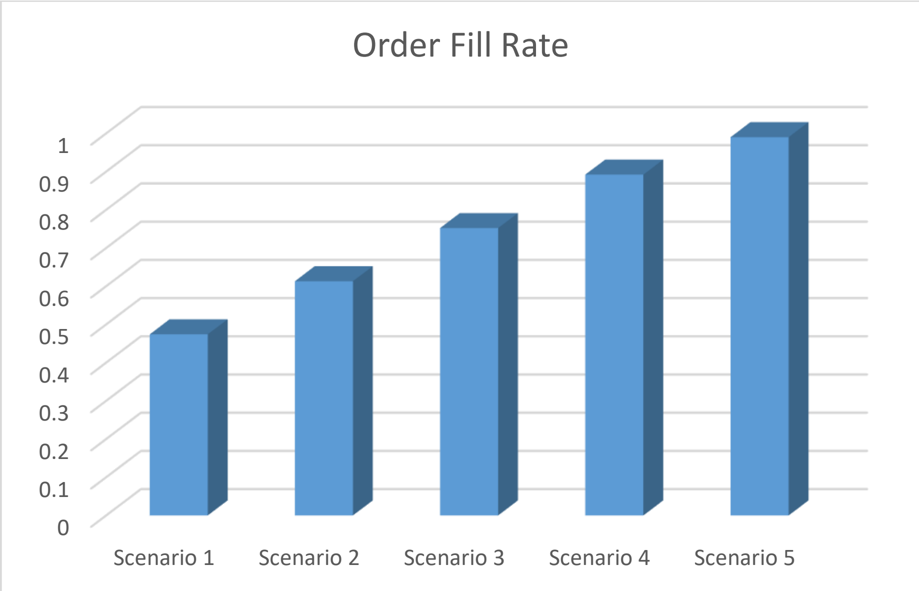
Graph 19 – Effects of r_B: Inventory On Hand A

- The warehouse's inventory increased significantly, by approximately 139% between the first and last scenarios.



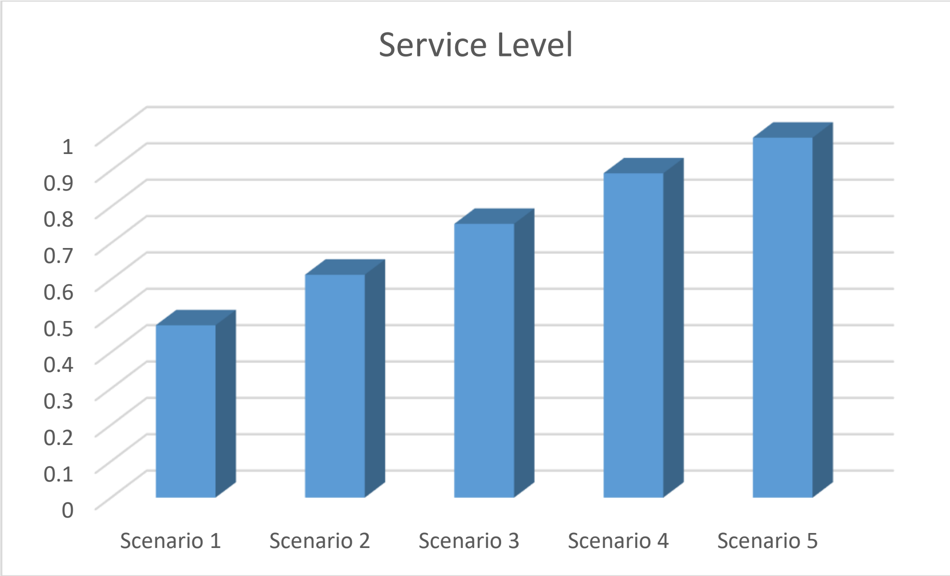
Graph 20 – Effects of r_B: Inventory On Hand B

- Order fill rate increased significantly, by approximately 51.6%.



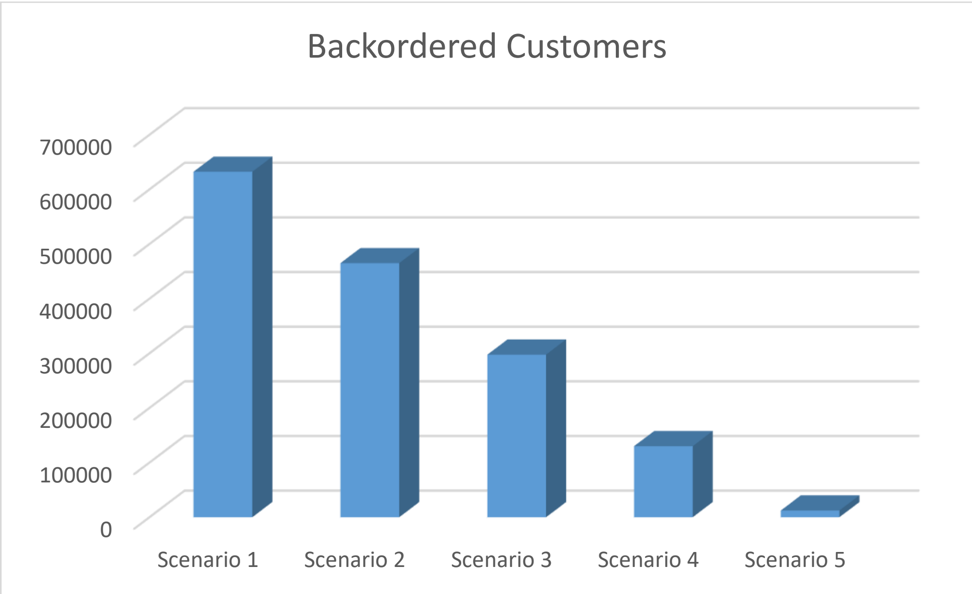
Graph 21 – Effects of r_B: Order Fill Rate

- Service level increased significantly, by approximately 51.6%.



Graph 22 – Effects of r_B: Service Level

- The number of backordered customers fell dramatically by approximately 98% between the first and last scenarios.



Graph 23 – Effects of r_B: Backordered Customers

- The number of satisfied customers rose significantly by approximately 109%.

Graph 24 – Effects of r_B: Satisfied Customers

8.3 Discussion

Based on the above, we may observe the following:

- Increasing the retailer's order quantity Q_A does not significantly affect order fill rate or service level, even though it leads to a mild decrease of backordered customers. On the other hand, it raises the retailer's inventory levels considerably. This may incur significant inventory costs to the retailer without great benefits.
- Similarly, increasing the warehouse's order quantity Q_B does not seem beneficial overall. The order fill rate and service level increase only slightly, but inventory levels at both the retailer and the warehouse pile up, potentially incurring high costs. The significant decrease in backordered customers does not seem to affect performance greatly.

- Increasing the retailer's reorder point r_A performs significantly worse: despite raising the retailer's inventory levels, the order fill rate and service level remain constant. Its effect on backordered and satisfied customers is also negligent.
- Increasing the warehouse's reorder point r_B, on the other hand, produces significant results. As above, inventory levels at both the retailer and the warehouse increase; however, the order fill rate and service level rise by a dramatic 51.6%. At the same time, the number of backordered clients drops steeply, and satisfied customers multiply. It seems likely that the wholesaler's high reorder point functions as safety inventory for downstream demand until stocks are replenished by the supplier.

9. Conclusion

This thesis aimed to introduce a simulation model of a supply chain system with three nodes and a continuous review policy facing uncertain demand and constant lead times.

We explored the theoretical background of supply chains, supply chain management, strategies, responsiveness, and efficiency. Furthermore, we described key processes and performance drivers in supply chains.

Moreover, this thesis introduced qualitative and quantitative models for the study of supply chains and focused in on simulation, a quantitative, descriptive performance model technique that uses computer algorithms.

Finally, we constructed a simulation model for the system under review and performed tests to pinpoint which controlled variable (Q_A, Q_B, r_A, r_B) lead to an increase in performance, as measured by order fill rate, service level, inventory levels, satisfied and backordered customers.

10. Limitations and further research

The goal of this thesis was to provide an overview of supply chain systems and their study through simulation. As such, this is a limited presentation of the vast field of supply chain management, modeling, and simulation.

While our model delivered valuable conclusions, it faced critical constraints that limited its scope and interpretative powers. First, in absence of historical data, we resorted to arbitrary selection of demand distributions, as well as lead times. For the same reason, it was impossible to validate the model internally or externally; it was merely an abstract representation not anchored in a real-world, tangible system.

Secondly, due to limitations of time and space, we assumed excessive demand was backordered and not lost. As we have seen, this assumption does not represent real-world data, except for industrial supply chains.

Therefore, future research would benefit from being based on real systems and checked against real data. Furthermore, percentage estimates of lost sales by scholars such as Verhoef and Sloot (2006) should be incorporated into the model.

Moreover, our simulation was not pared with an optimization algorithm. While one could be tempted to underline the increase of r_B as the best possible solution in our model, they might be misled: cost, though hinted at through high inventory levels, has not been calculated. To maximize future models' usefulness, considerations of cost and responsiveness and how they factor in a supply chain's strategy should be included. After all, cost efficiency and responsiveness are almost always mutually exclusive; a supply chain must set priorities according to its strategic fit and act accordingly.

Our rudimentary, linear supply chain may also be expanded to include more nodes and complex structures, with potential push-pull processes at different stages of the chain. Finally, it would be worthwhile to explore a similar or more complex system under a periodic review policy.

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