Modelling and Analysis of Supply Chain Disruptions through Simulations

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Abstract

A supply chain is a network between a company and its suppliers to produce and distribute a specific product/service to consumers. This network constitutes people, entities, information, activities, and resources. A supply chain disruption occurs when demand or supply spikes or falls unexpectedly, resulting in a massive imbalance between the two. As supply chains become more global, the risk of such interruptions has aggravated considerably. In fact, catastrophic occurrences have highlighted the importance of analyzing disruption risk and developing mitigation plans to deal with it. In this research, we use the simulation software Arena to model a supply chain and analyze the consequences of network disturbances. The present research seeks to assist an organization in determining its level of risk in terms of disruptions that compromise product availability. A discrete-event simulation model of a multi-echelon supply chain consisting of a retailer, a manufacturing plant maintaining an input and output buffer, and a supplier is developed. Disruptions are introduced at different echelons of the system, and the dependence of customer fill rate and the demand fill rate on disruption durations are investigated in detail. The research offers a detailed understanding of the consequences of disruptions by capturing both risk profiles and material flow. Mitigation strategies, namely, safety inventory (inventory control) and contingency strategies for backing up specific suppliers or links in the supply chain (sourcing), are examined in the present paper. Furthermore, the effect of these mitigation strategies on the customer service level is also analyzed.

Keywords
Supply chain, Risks, Disruptions, Mitigation strategies, Discrete-event simulation and Arena.

1. Introduction

A supply chain is a network between organizations to produce and distribute a specific product/service to consumers. The global supply chains are now dipping into a vortex of disruptions primarily driven by socio-political, environmental and technological factors. For instance, supply chains across the globe faced a meltdown during the COVID-19 outbreak that is still looming large (Dohale et al., 2021). The ongoing conflict between Russia and Ukraine and the advent of disruptive technologies like the blockchain technology and artificial intelligence also pose significant operational challenges to the business process. In this milieu, it is essential to explore some of the less dissected issues plaguing supply chain performance in the industry.

A supply chain disruption is an unusual spike or steep fall in demand or supply, leading to a massive imbalance between the two. These disruptions may occur mainly due to: inefficient response to technology trends, natural or environmental calamities and inaccurate planning and forecasting. When products do not reach customers on time, it will result in a loss of revenue for the business and is generally accounted for as the cost of supply chain disruption. In the manufacturing industry, a delivery delay on the supply side results in production suspension and compromises workforce utilization, which further manifests as revenue loss (Ivanov and Dolgui, 2021). At the same time, finding and onboarding other suppliers is time-consuming. Further consequences of supply chain interruption include a tarnished reputation, which encourages clients to seek alternatives. The COVID-19 epidemic immobilised the world and, maybe more than any other catastrophe in recent history, demonstrated the fundamental need of supply chain risk management. There is a requirement for a resilient supply chain system that can survive any disruptions while minimising the impact on customer experience (Katsaliakiet al., 2021). To realize such a risk resistant supply chain, proactive risk mitigation strategies have to be tested and deployed. To facilitate this activity, it is absolutely essential to identify the vulnerabilities in the system towards disruptions of varied nature and types (Chopra and Meindl, 2011; Vishnu et al. 2019). The objectives of the present research are framed in this direction.

Initially, a hypothetical multi-echelon supply chain model consisting of a supplier, manufacturer, distribution centre and retailer is developed in Arena simulation software. The model is employed to assess the vulnerability to disruption risk and quantify its impact on customer service using performance indices such as customer fill rate and demand fill rate. Additionally, the current level of supply chain disruption risk is analysed in a hypothetical supply chain configuration. Disruptions of different frequencies and durations are introduced using the different modules in Arena to make the disruptions as realistic as possible. Disruptions are also introduced at different levels of the supply chain using disruption initiators and disruption duration modules. Modelling various mitigation strategies like setting up a backup production plant and adding safety inventory at the retailer side is done to minimize the risk impact and maintain product availability to the customer. The effect of the mitigation strategies on the performance of the disrupted supply chain model is evaluated by analysing the changes in the customer and demand fill rates. Experiments with the model also offer exciting insights. In fact, multiple graphs are plotted to understand the different disruption scenarios in a supply chain and how to tackle them. This simulation model can act as a tool to validate recovery steps before executing them in case of a disruption.

In short, the objectives of the present research are as follows:

- Develop a discrete-event simulation model of a multi-echelon supply chain consisting of a supplier, manufacturer, distribution centre and retailer to assess the vulnerability to disruption risk and quantify its impact on customer service.
- Analyse the system's performance with respect to customer and demand fill rates in response to various types of disruptions occurring at different levels of the supply chain.
- Investigate the characteristics of multiple mitigation strategies like introducing a backup production facility and introducing safety inventory to maintain product availability to the customer.

2. Literature Review

According to a recent study, disruption events and recovery procedures play a critical role in the supply chain. Despite the abundance of literature on supply chain design with disruption concerns, there is only a few research reporting surveys on supply chain disruption and recovery factors. Many studies demonstrated the importance of supply chain disruption and its importance of early recovery. Schmitt and Singh (2009) proposed a model to assess the vulnerability to disruption risk and quantify its impact on customer service, and model various mitigation strategies for coping with the risk in the system in order to maintain product availability to the customer.

Hishamuddin et al. (2012) analysed a model of an efficient heuristic approach that determines the optimal recovery plan for a production-inventory system with scheduled disruptions. The authors conclude that the optimal recovery schedule is highly dependent on the relationship between the backorder and the lost sales cost, as well as the extent of the disruption. In another study, Hishamuddin et al. (2013) developed a recovery model for a two-tier supply chain system with the possibility of transportation disruption by employing a particular heuristic. In addition, Paul et al. (2017) propose a reactive and predictive mitigation plan in a three-stage supply chain system to manage known and predicted changes in data and demand.

Supply chain resilience no longer refers solely to risk management. It is now assumed that being able to manage risk means being better positioned than competitors to deal with disruptions and even profit from them. Supplier selection and order allocation are also crucial in a supply chain. Esmaeili-Najatabi et al. (2018) developed a mixed-integer nonlinear programming model to optimize supplier selection and order allocation simultaneously in centralized supply chains considering disruption risks. Sabouhi et al. (2018) proposed a model to develop an integrated hybrid approach based on data envelopment analysis and mathematical programming methods to design a resilient supply chain. Mikhail et al. (2019) presented a tool for designing resilient supply chain networks. Different structures are proposed considering the design determinants of supply chain density and node criticality.

Vishnu et al. (2019) provide a systematic review of empirical and analytical models for analysing supply chain risk management adopted in the literature. A bibliometric analysis of the literature is presented, followed by a detailed discussion of the salient aspects of the literature on supply chain risk management. Marmolejo (2020) has established the methodological bases for designing and developing a digital twin technology, which consists of creating virtual replicas of objects or processes that simulate the behaviour of their natural counterparts in the supply chain. Ivanov and Dolgui (2021) report on developing an integrated decision-support system (DSS) for data analytics-driven, proactive resilient SC design and reactive real-time disruption risk management. Katsaliaki et al. (2021) have reviewed the literature on supply chain disruptions that have been published in prestigious journals. Important research studies are identified and analysed in this review paper. The researchers observe that it is difficult to totally avoid disruption and that attention should also be focused on recovery policies. To adjust supply chain plans, inventory rules, and schedules to attain the desired performance, human-driven adaptation is required first, followed by computer-driven adaptation.

The authors have conducted a detailed review in the domain; however, all the research outcomes reported in the literature is not discussed in detail due to space limitation. Instead, the significant inferences drawn from the exercise are as follows. The studies reported in the literature show that the recovery plan for the transportation disruption is highly dependent on the relationship between the backorder cost, lost sales cost along with service level commitments. Furthermore, the domain warrants methodologies to assess the impact of different types of disruptions occurring at different stages of a supply chain on service levels. It was also found that the investigations will be meaningful and complete only if it can identify the appropriate mitigation strategies to ensure customer satisfaction. The present research is motivated from these research opportunities identified from the literature review. Accordingly, the methods adopted to fill these research gaps are explained in the subsequent section.

3. Methods

The Arena model implementation is done in two parts. In the first part, disruptions are introduced as constant delays in each supply chain segment except the retailer. In the second part, disruptions which were earlier modelled as constant delays are modified to represent a disruption duration model in which disruption occurs according to a random exponential function with uniformly distributed disruption durations. The supply chain simulation model developed in Arena consists of a supplier, a manufacturer and a retailer. The Arena model developed consists of five segments, each associated with an inventory holding buffer in a system echelon. Each such buffer is subjected to the following events: order arrival, inventory updating, replenishment order triggering, and order shipment, along with disruptions. Additional supply chain activities are modeled at the endpoints of the supply chain, namely, demand arrival on the downstream end and product manufacturing on the upstream end.

3.1 Problem Statement

A multi-echelon supply chain with a single product is analysed, which includes a retailer (R), distribution centre (DC), manufacturing facility (P), and supplier (S). Being experimental research, variable values and parameters of the simulation model are carefully set based on an extant literature review to resemble a real supply chain. Two buffers interact with the manufacturing plant: an input buffer (IB) that stores entering raw material and an output buffer (OB) that stores outgoing finished product. The retailer faces a steady stream of client demand, and to manage inventory, it employs a continuous-review (Q_R, R_R) control strategy based solely on data from the store. When the inventory position (inventory on hand plus outstanding orders minus backorders) falls below level R_R, a replenishment of quantity Q_R is ordered from the distribution centre. If the distribution centre has enough inventory on hand, the order lead time is merely the time it takes to get it to the customer. Otherwise, additional delays occur as a result of additional transportation delays and possibly stock-outs upstream of the distribution centre.

Any extra demand at the retailer that cannot be met quickly with on-hand goods is squandered. Orders from retailers make up the demand stream at the distribution centre. The unmet demand has been backordered. Based on a (Q_DC, R_DC) continuous-review inventory strategy, the distribution centre replaces its stocks from the upstream plant's output buffer (OB). Backorders are placed for the unsatisfied sections of orders placed with the plant.

The plant's manufacturing policy is a continuous-review (R_OB, r_OB) policy. After consuming one unit of raw material from the input buffer, the plant makes one product unit at a time. The input buffer, in turn, orders from an external supplier who is expected to always have limitless stockpiles, limiting the raw-material lead time to transportation delays and ensuring that the plant's demands are always fully satisfied. A continuous-review (Q IB, R IB) policy corresponds to the inventory control policy. To the above mentioned supply chain model, disruptions are introduced as constant delays at each of the segments except the retailer to understand the impact of these disruptions on the demand fill rate at the retailer (Figure 1).

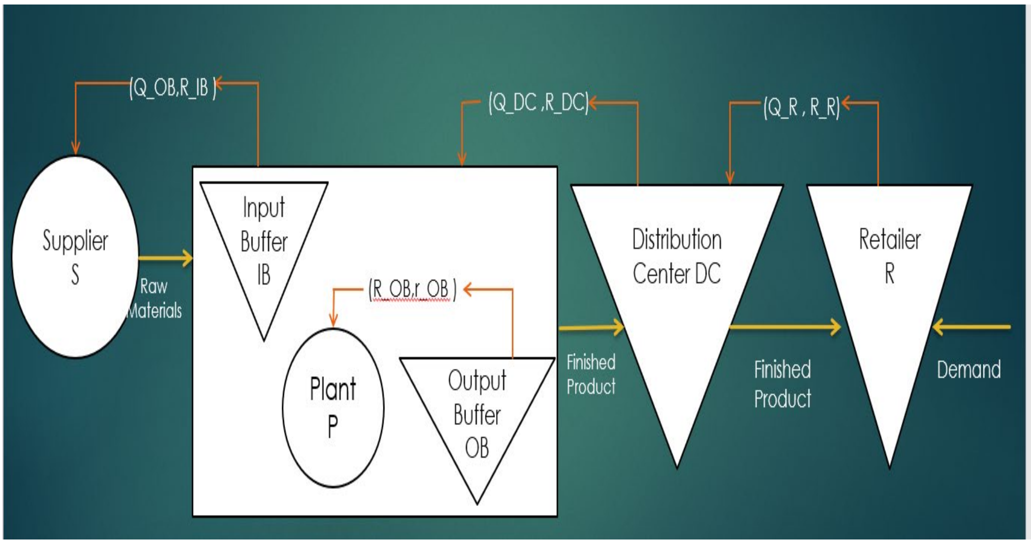

Figure 1. Multi-echelon supply chain system

3.1.1 Assumptions in the Model
The retailer faces customer demand that arrives according to a Poisson process. The demand quantity of each arrival is one product unit, and all unsatisfied demands are lost. For modeling generality and versatility, we assume that the manufacturing time distribution of a product unit and all transportation time distributions are of the Normal distribution type. At all echelons, orders are received in the order they were placed. In fact, an order shipment is launched only after the previous one is received at its destination. When a stock-out occurs in the DC or plant and the unsatisfied portion of the order is backordered, order fulfillment (shipment) is deferred until the full order becomes available. In brief, there is no shipping of partial orders.

3.2 Base Simulation Model in Arena
3.2.1 Inventory Management Segment for Retailer
Figure 2 depicts the retailer inventory management segment of the Arena model. This section generates demand, performs demand fulfilment, and sends replenishment orders to the distribution centre. The customer proceeds to test if the retailer has adequate inventory on hand by generating a Poisson stream of customer arrivals with single-unit demand quantities. If the condition holds, the on-hand inventory is decremented. The existing demand will be lost if the condition does not hold. To maintain track of inventory information, the two Assign modules require two variables: The first is used to fulfil a customer's request, while the second is used to initiate a refill order. An order is placed upstream whenever the reorder point is crossed.

3.2.2 Inventory Management Segment for Distribution Centre
This model segment creates incoming retailer orders, updates distribution centre inventory levels, triggers replenishment orders from the manufacturing plant's output buffer, ships orders to the retailer, and updates the retailer's inventory level. Due to space limitations, the diagram for the Arena model is not included. The order enters the system when a replenishment order is made from the retailer side. The DC inventory is decremented, if necessary inventory is available to satisfy the replenishment order from the retailer else a replenishment order is sent to the output buffer of the production plant. It is checked whether any backorders in present in the system, if such a backorder occurs first it has to be taken care of before satisfying the retailer demand. We assume that product units are processed sequentially in the transportation system (involving transportation delays), so as to preclude overtaking.

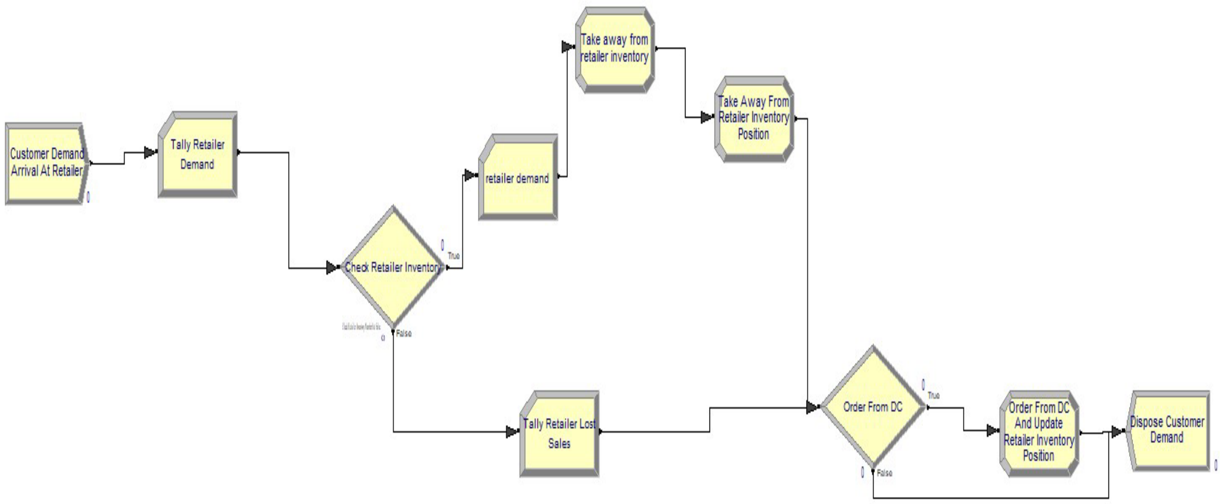

Figure 2. Retailer inventory management segment of the Arena model

3.2.3 Inventory Management Segment for Output Buffer

The output-buffer inventory management component of the Arena model is depicted in Figure 3. This model segment creates distribution centre orders, updates the output buffer inventory level, restarts halted manufacturing as needed, sends shipments to the distribution centre, and updates the distribution centre inventory level. The logic for producing distribution centre orders stored in the output buffer is nearly identical to that of the previous segment's generation logic. Further, if output buffer inventory, has sufficient inventory on hand to satisfy its demand. it decrements the on-hand inventory by order quantity. else, the demand is not fully satisfied and is backordered from the output buffer, and the Backorder is increased. The checking of Inventory at Output buffer is done and if the inventory has down-crossed the reorder level the production process is started at the Production Plant where the raw material is converted into finished goods and is placed at the output buffer.

3.2.4 Inventory Management Segment for Input Buffer

By keeping track of a circulating control entity that adjusts the suspension and resumption of production, this model segment manages raw-material consumption and finished-goods production. Due to space limitations, the diagram for the Arena model is not included. To make a product unit, the plant takes one raw material unit from the input buffer, processes it, and then adds the final product to the output buffer inventory, updating its level. If the target level is attained, production is halted until the reorder point is crossed; production is resumed when the reorder point is crossed. Production may also be halted due to a lack of raw material in the input buffer, which will have to be replaced by the supplier.

3.2.5 Inventory Management Segment for Supplier

This model segment creates input buffer orders, transfers shipments from the supplier to the input buffer, and updates the inventory level of the input buffer. Due to space limitations, the diagram for the Arena model is not included. The logic of generating input buffer orders to the supplier is virtually identical to the generation logic used in the previous segments however, this model segment is a bit simpler than its counterparts; because the supplier always has sufficient inventory on hand, replenishment delays reduce to transportation delays.

3. 3 Modified Simulation Model in Arena

The changes or modifications made to the base model to obtain a revised model are listed below: Disruptions which were earlier modelled as constant delays are now modified to represent a disruption duration model in which disruption arrive according to random exponential function with uniformly distributed disruption durations. The supply chain system which was modelled in Arena with demand arrivals was modified to have customer arrivals at the retailer. A backup facility for production was implemented as a part of mitigation strategy. Production lot size was varied to find the variation in customer and demand fill rates.

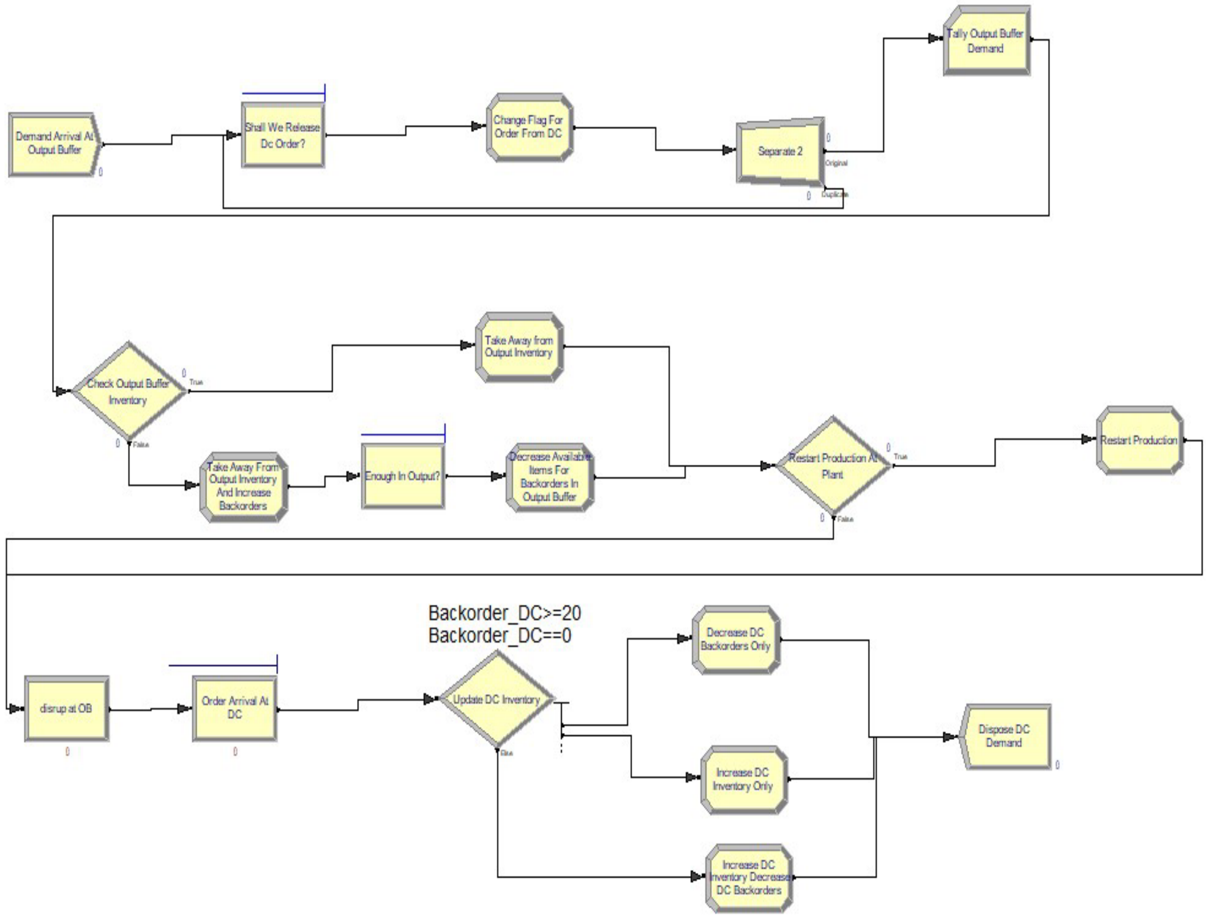

Figure 3. Output Buffer inventory management segment of the Arena model

3.3.1 Disruption duration module

The disruption duration model in each echelon consists of a decide, delay and assign module as shown in Figure 4.

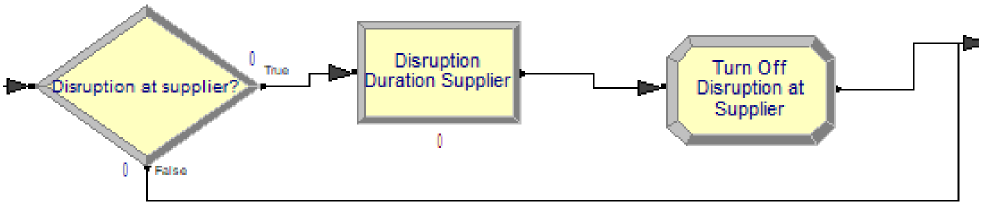

Figure 4. Disruption duration module introduced at each echelon

The Decide module checks if the global variable for disruption is set to 1(which means there is disruption). If the condition becomes true, then the control moves to the delay module which puts a stochastic delay on the system. After this delay the control moves to the assign block where the disruption is turned off. In an attempt to model different types of disruptions that can happen in a supply chain, different types of distributions are considered for the disruption duration. They are Uniform distribution, Normal distribution and Triangular distribution. In order to compare the Demand, Customer fill rate with the disruption duration for the three distributions, the parameters for the distributions are given below. For Uniform distribution, the maximum parameter is set as D_MAX and the minimum parameter is set as D_MIN. For Triangular distribution, the required parameters while simulating the model are D_MAX, D_MIN and the most likely value which is taken as $\frac{D\_MAX+D\_MIN}{2}$. For normal distribution the required parameters while simulating the model are mean which is taken as $\frac{D\_MAX+D\_MIN}{2}$ and the standard deviation which is taken to be $\sqrt{\frac{\mathrm{D\_MAX}^2-\mathrm{D\_MIN}^2}{12}}$.

3.3.2 Disruption Initiators

The disruption initiators module consists of a create, assign and dispose modules as shown in Figure 5. Similar disruption initiation modules are created for output buffer, supplier and input buffer as well. Disruptions occur randomly in the simulation using a "Create" block that schedules disruption-entities with an exponential inter-arrival time. The rate parameter is given the value 30 days. In the assign module the variable indicating the presence of disruption at each stage is set as 1. Two types of disruptions are considered in this model.

Figure 5. Disruption initiation module for the DC segment of the arena model

- *High frequency low duration*: High frequency less duration types of disruptions are disruptions that occurs in most of the supply chain networks and most of the time they don't affect the performance of a supply chain in very high levels, as the supply chain network returns to its original performance before the next disruption. If the frequency of the disruptions increases beyond a limit, the working of the supply chain will be affected as the next disruption comes at a time when the supply chain hasn't recovered from the previous disruption. This can lead to compounding of disruptions and can drastically affect the performance of the supply chain.

- *Low frequency high duration*: These types of disruptions which are unpredictable in nature can be a result of a natural calamity or global events (like pandemics). Disruptions of this type often remains in the supply chain for a long amount of time and proper risk management is necessary to avoid these kinds of disruptions from affecting the performance of the supply chain.

3.4 Mitigation Strategy

3.4.1 Setting up a backup production plant

When there is a disruption at the main production plant the disruption variable associated with the plant, IB_DV is set as 1. The Create module create a single disruption entity that flows throughout the system to check if there is disruption at the main plant. The Initialize variable assign block is used to identify the first time that disruption occurs. The ramp up period represents the time for the backup plant to be able to produce material in main plant's place. After the ramp up completes, the backup plant continues to produce material for as long as the disruption lasts. When the disruption entity at the production plant reaches the end of its stochastic delay, it changes the variable IB_DV to 0 to indicate that the main plant is no longer disrupted, waits for backup plant to finish any back-up processing it is conducting, resets the system so that a ramp-up would again be required for the next disruption, and is disposed. The Production for the backup manufacturing facility is taken to be almost 80 percent of the main plant.

3.4.2 Safety Inventory

The demand fill rate was recorded to be 82 % while simulating the arena model. The disruption scenario considered was based on two parameters. The parameters are disruption duration which followed uniform distribution with a minimum of 1 and a maximum of 7 days and inter-arrival time which followed exponential distribution and the rate parameter as 80 days. We desire to achieve a service level of 95% and for that the required safety inventory is to be calculated at the retailer. Mean demand μ_d= 5 and Standard deviation σ_d=2 Demand inter-arrival time is 75 minutes.
For one day $\mu_d = \frac{24*60*5}{75}$ = 96 units/day
Standard deviation σ_d=$\sqrt{\frac{2^2*24*60}{75}}$ = 8.763 / day
Here the lead time which is the transportation time from Distribution centre to the retailer follows a normal distribution with mean 7 days and standard deviation 2 days. Hence, L = 7 days and S_L = 2 days

Safety Inventory (SI) = Z *σ_L

$\sigma_L = \sqrt{\sigma_d * L^2 + \mu_d{}^2 * S_L{}^2} = \sqrt{8.763 * 7^2 + 96^2 * 2^2} = 193$ units

Accordingly, SI = Z *σ_L = 1.645 *193 = 317 units.

4. Results and Discussion

Disruptions modelled as constant time delays in the Arena software were introduced at each segment in the supply chain system. The durations of disruptions are varied at individual segments in the model to understand the variation of demand fill rate. The results obtained are plotted in Figure 6, showing the variation of fill rate with disruption duration when the disruptions are introduced at each echelon. It is inferred that as the disruption duration increases (constant delays increases), the demand fill rate decreases. It is also observed that the production plant is the most affected stage in the supply chain while introducing the disruptions and it must be the major point of concern in the supply chain model.

4.2.1 Changing Inter-arrival time and Disruption Duration

Disruptions are modelled to represent a disruption duration model in which disruption arrive according to random exponential function with uniformly distributed disruption durations. Variation of Customer fill rate and demand fill rate is plotted against production lot size for cases with and without a backup production facility. Graphs for variation of customer and demand fill rate with disruption inter-arrival time and disruption duration are also plotted. As the disruption inter-arrival time increases, the demand as well as the customer fill rate increases. In the case of disruption duration, as the disruption duration increases, the demand as well as the customer fill rate decreases.

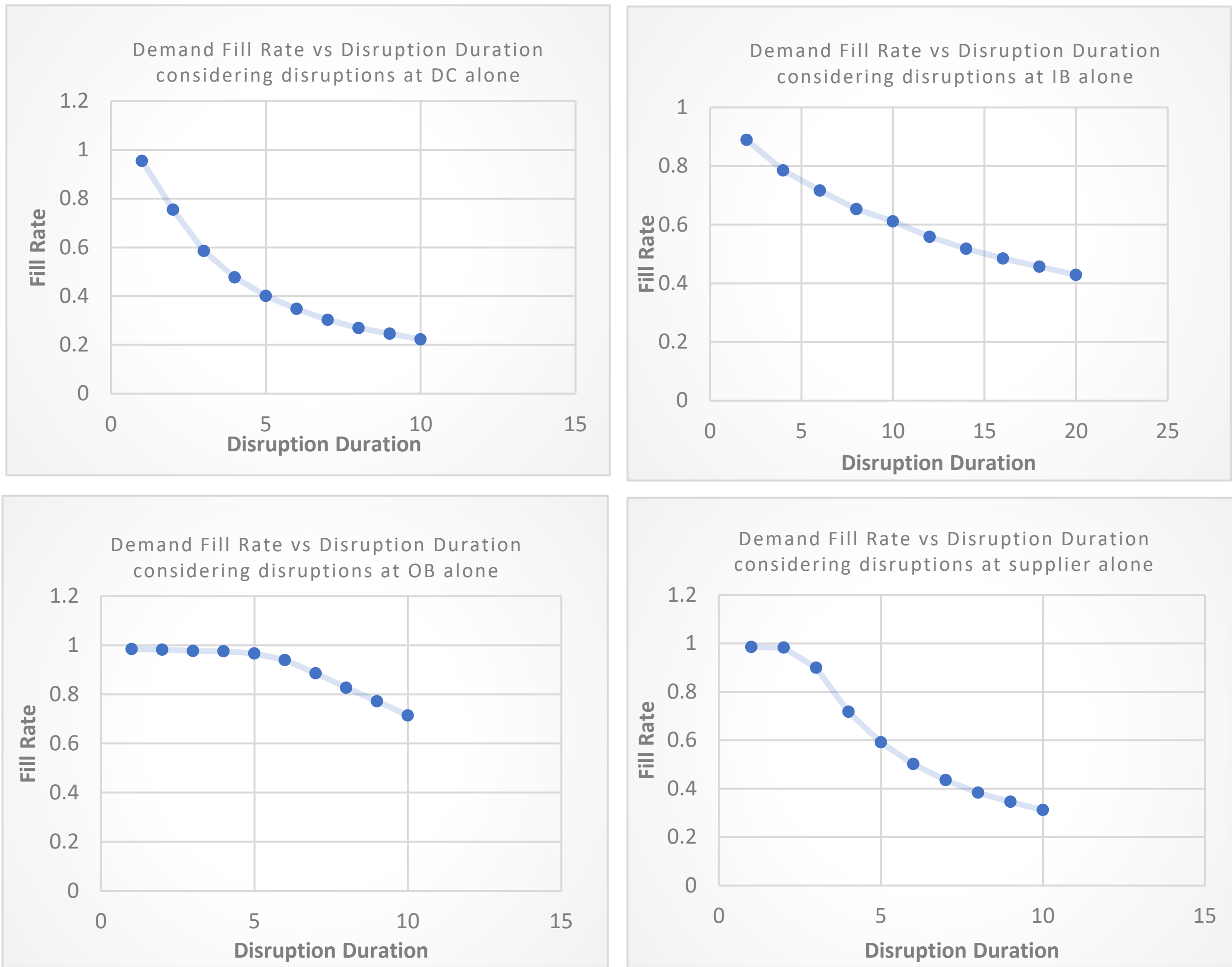

Figure 6. Demand fill rate vs Disruption Duration considering disruptions at different echelons

4.2.2 Different types of distributions for disruption duration

The modified Arena model mainly consists of two parameters which are inter-arrival time and the disruption duration. The resulting plot for Demand Fill Rate Vs Disruption Duration is shown in Figure 7.

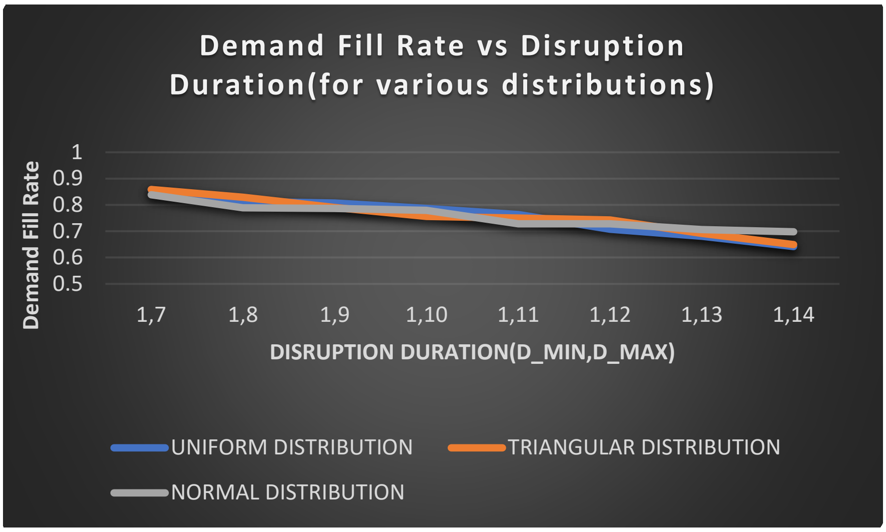

Figure 7. Demand fill rate vs Disruption duration for Uniform, Triangular and Normal Distributions

Here, the distribution for the disruption duration is taken as Uniform, Normal and Triangular distributions. From the graph, it is observed that as the maximum parameter (D_MAX) and the minimum parameter (D_MIN) increases the demand/ customer fill rate decreases since the disruption duration increases for all the considered disruption distributions. It is seen that the least fill rate occurs in case of uniform distribution since each of the disruption durations has the same chance of occurring and this includes the maximum disruption duration considered. But in case of Both triangular and normal distributions the chances of having the extreme disruption durations are least likely to occur and the most likely duration is somewhere close to the mean of the distribution.

4.3 Mitigation strategy 1- Backup production plant

4.3.1 Disruptions with different frequencies and durations

Here we consider two types of disruptions. The first one is the high frequency low duration type of disruptions and the second one is low frequency high duration kind of disruptions. Figures 8 depicts the variation in demand and customer fill rate for the two types of disruptions with and without the presence of a backup production plant. When comparing the first and the second type of disruption we can see that the second type of disruption (which is the low frequency high duration kind of disruption) is the disruption that drastically affect the customer as well as demand fill rate. The presence of a backup production plant is able to increase the fill rate when both kinds of disruptions are present in the system. The presence of a backup production plant is able to tackle the second type of disruptions more effectively.

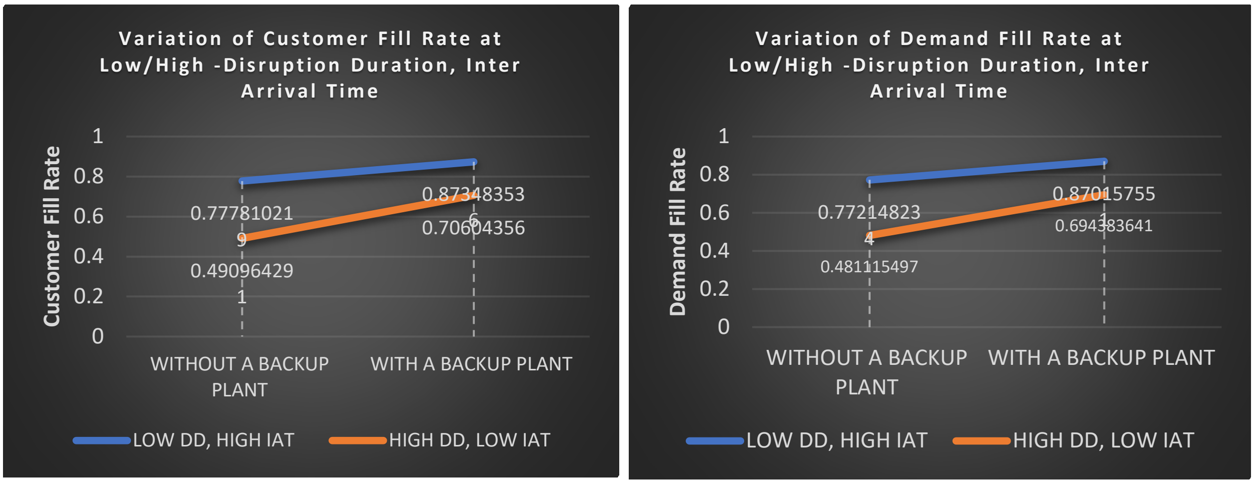

Figure 8. Fill rates for the two types of disruptions with and without backup facility

4.3.2 Varying lot sizes and measuring the fill rates

The variation of demand as well as customer fill rate with production lot sizes are plotted in Figure 9. The increase of the fill rates with increase in lot size is more in case of the scenario with backup facility. This is because when the produced items at the backup facility is directly supplied to the distribution centre whereas when the lot size is increased at the main plant the maximum limit is always constrained by the maximum limit of the output buffer. Furthermore, it is found from the plotted graphs that the production plant is the most vulnerable segment against disruptions, and a backup facility will help to improve the fill rate. In the case of no backup facility, it is found from the results that even when the production lot size was increased, there was no significant increase in the customer fill rate. This can be because of the maximum inventory level constraint on the output buffer. In the case where there is a backup facility for production, a rapid increase in fill rate is observed. These characteristics can be attributed to the fact that the backup production facility increases the inventory level of the distribution centre instead of the inventory-constrained output buffer.

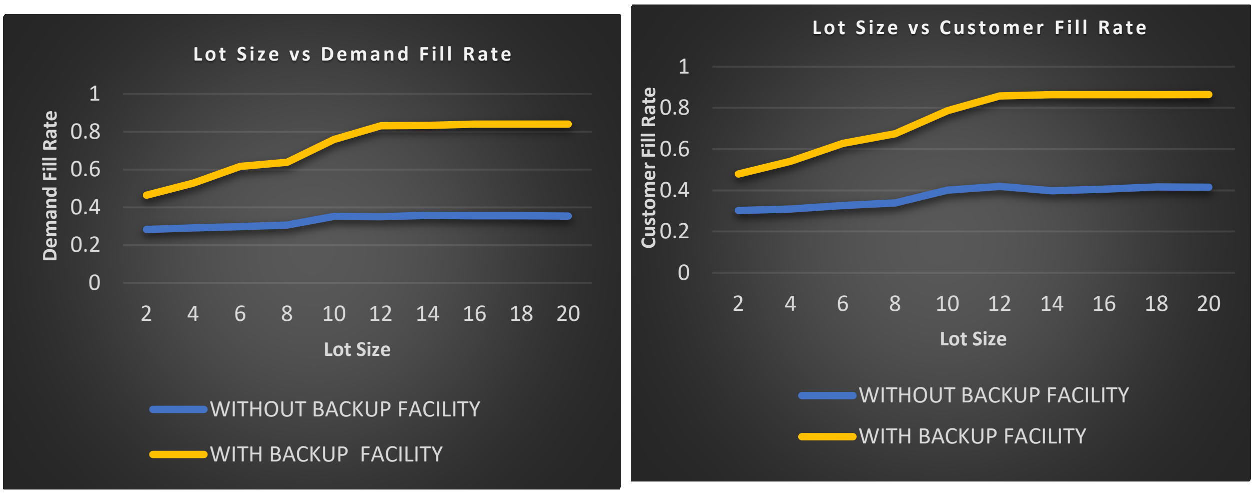

Figure 9. Lot size vs Fill Rates with and without backup facility

4.4 Mitigation strategy 2 – Safety Inventory

Safety Inventory (SI) is introduced at the retailer side so as to minimise the stock out situations as much as possible. It is calculated using demand and lead time variability and also to attain a service level of 95%. Figure 10 illustrates the variation of the fill rate with change in disruption inter-arrival time with and without introducing safety inventory at the retailer side.

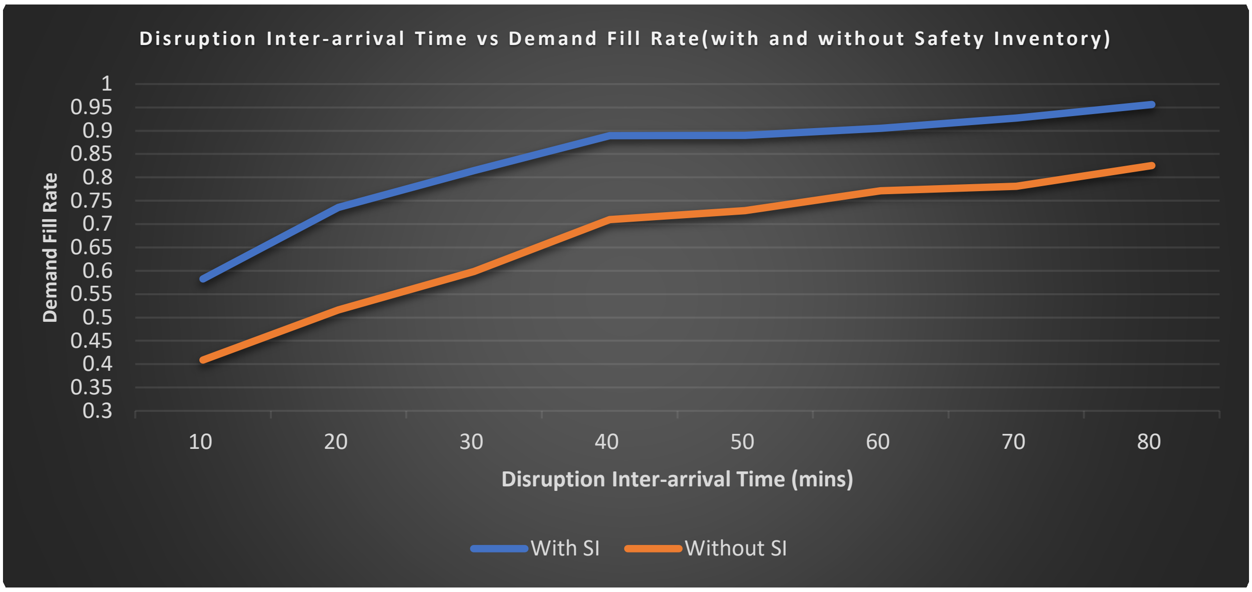

Figure 10. Demand fill rate vs Disruption inter-arrival time with and without Safety inventory

It is found that an increase in the safety inventory at the retailer side also helps in increasing the customer service level. Ultimately, these analysis offers valuable insights for supply chain practitioners to understand the sensitivity of both customer and demand fill rates with respect to multiple parameters including disruption duration, lot size and the availability of backup facilities.

5. Conclusion

It is observed that disruptions even at one segment of the supply chain system significantly impact the performance of the entire supply chain system. A disruption in the upstream can significantly affect all the downstream segments. Therefore, it is essential to focus on each supply chain segment while developing mitigation strategies. Investing in backup facilities throughout the supply chain network should be done to minimise disruption risks in the system. It is observed from the results that when the mean inter-arrival time of the disruptions increases, the demand fill rate also increases. As disruptions occur less frequently and the system has sufficient time to recover from the earlier disruption, the disruptions do not get cumulated. An increase in disruption durations decreases the demand fill rate since the longer disruption durations make the system more prone to disruptions getting cumulated which can lead to a high level of retailer lost sales. While considering different types of distributions for the disruption durations, it is observed that as the maximum parameter (D_MAX) and the minimum parameter (D_MIN) increase, the demand/ customer fill rate decreases since the disruption duration increases for all the considered disruption distributions. It is noted that the least fill rate occurs in the case of uniform distribution since each disruption duration has the same chance of occurring, including the maximum disruption duration considered. But in the case of both triangular and normal distributions, the chances of having the extreme disruption durations are least likely to occur. As a result, the most likely duration is close to the distribution's mean. This feature implies that a triangularly or normally distributed disruption is easier to handle than a uniformly distributed disruption duration. Furthermore, the presence of a backup production plant can tackle the type of disruptions having high disruption duration and low disruption frequency (disruptions with high inter-arrival time) more effectively. Therefore, this type of disruption can be tackled by introducing backup facilities at each supply chain echelon. However, this option may not always be financially feasible.

Quantification of the risk associated while introducing disruptions can be studied in a more realistic manner in the simulation model. Extending the current simulation model to include multiple entities at each stage/segment of the supply chain is an area for further work. More mitigation strategies can be developed and tested. Future work can also focus on optimising various parameters by considering cost aspects in the modelled supply chain to maximise the performance of the supply chain using the OptQuest extension in Arena simulation software.

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