Replenishment Policy in a Two-Echelon Supply Chain: An Analysis Using Discrete-Event Simulation

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Abstract

The present study identifies optimal inventory policies for two-echelon systems under the effects of supply disruptions and stochastic demand. Previous research has incorporated and addressed stochastic demand quite extensively but the study of supply disruptions is relatively new. Presently, supply disruptions are studied heuristically and through theoretical analysis to identify optimum inventory levels. The current study uses discrete event simulation to arrive at optimal policies under varied levels of supply disruptions and stochastic demand. It uses a designed experiment to vary disruption length and disruption frequency. We find that under conditions of supply disruption, a decentralised policy is more likely to yield lower costs than a centralised policy when disruption levels are high but a centralised policy is better otherwise.

Keywords: Supply Disruptions, Discrete-Event Simulation, Two-Echelon System, Experimental Design

Introduction

Much research on supply chain and inventory models has focused on demand uncertainty. However, there has been a growing interest in supply uncertainty amongst academics and practitioners, particularly over the last decade (Snyder, Atan, Peng, Rong, Schmitt, & Sinsoysal, 2016). Supply uncertainty occurs when either a company or its suppliers, or both, are not able to deliver the required quantity at the right time (Al-Rifai & Rossetti, 2007. It is broadly classified into three categories, the first of which is supply disruption, that is, when the organisation or the suppliers cannot deliver or operate until the disruption is over. The second is yield uncertainty, where the quantity supplied by the supplier or organisation is subject to variation and uncertainty, while the third is stochastic lead-times wherein the amount of time to supply the goods is subject to variation (Arreola-Risa & DeCroix, 1998).

In this study, we considered the first kind, that is, supply disruptions. Disruptions in a supply chain can occur due to a variety of causes such as natural disasters, political or social unrests, strikes, and accidents. Even small disruptions in a supply chain can have a debilitating impact on the production and supply of goods and services of more than one firm. Thus, though a given type of disruption may be rare in the sense that it may occur less than once a year, it is important to be aware of the harm it can cause when it does occur, and to take appropriate preventive measures. Though some disruptions might be preventable, some are not under control and hence effective planning to mitigate or minimise the damage becomes crucial for an organisation. The effects of disruptions may last a very long time and even minor disruptions can have significant effects.

We modelled a two-echelon system, or more specifically, a one-warehouse multiple-retailer system (OWMR). An earlier work on OWMR systems is that of Atan and Snyder (2012). Two-echelon system can experience

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more severe effects because of disruptions than single echelon systems. We explore whether a centralised or de-centralised system will be better for an organisation in the longer run by comparing costs and cost-variances for centralised and de-centralised system with optimal costs and variance under given simulation conditions for both scenarios, that is, with and without supply disruptions. In doing all this, we developed a discrete event simulation model and used it to conduct a series of experiments. Essentially, we quantified disruption risk using discrete event simulation and a few simplifying assumptions. The results from our analyses can help identify effective strategies under disruptions and the parts of supply chains to be focused on for minimising their effects.

The rest of this paper is as follows. In the following section, we present a review of the literature on supply chain disruptions and present the specific model addressed by this study. Then we discuss the simulation models built and the experiments conducted with the same. Subsequently, we present the results of the analyses and implications drawn from the same. The paper concludes by highlighting the key findings and suggests some directions for the future.

Literature Background

A detailed literature review of OR/MS models of supply chain disruptions is offered by Snyder *et al*. (2016). This work reviews supply disruptions against the broad backdrop of supply uncertainty and discusses common modeling approaches. Some early authors in this area focused on risk in a JIT system, highlighting the importance of sharing the risk throughout the supply chain (e.g. Simchi-Levi, Snyder, & Watson, 2002) and keeping reserves of inventory to protect against disruptions (e.g. Sheffi, 2001).

Tang (2006) identifies two types of supply chain risk strategies: those that increase a supply chain's efficiency and those that increase its resilience. Efficiency is about a firm's operational ability to handle a disruption, while resilience is the ability of a firm to sustain operation and recover quickly, in the face of a disruption. Sheffi (2005) focuses on the latter and suggests that using local suppliers may be safer due to decreased transportation times and lengths, even though they may not quote the lowest unit costs. According to Tang and Tomlin (2008) a small amount of flexibility in a supply chain can have large payoffs if disruptions occur.

There have been both analytical as well as simulation-based approaches to model supply chain disruptions. Atan and Snyder (2012) study a two-echelon, one-warehouse, multiple retailer (OWMR) distribution system subject to supply disruptions. They build analytical models of the supply chain system and propose algorithms to find the optimal stocking levels of all locations in the system. They assume periodic review base-stock policies and deterministic demands at the retailers. Qi, Shen, and Snyder (2010) model an integrated supply chain design problem that determines the locations of retailers and the assignments of customers to retailers. Their aim is to minimise the expected costs of location, transportation, and inventory. The system is subject to random supply disruptions that may occur at either the supplier or the retailers and these authors demonstrate numerically that the cost savings from considering supply disruptions at the supply chain design phase, rather than at the tactical or operational phase, are usually significant.

Rong, Atan, and Snyder (2015) study continuous-review distribution systems with Poisson customer demands under a first-come, first-served allocation policy and develop heuristics to approximate the base-stock levels of all the locations in the system and discuss the strengths and limitations of these heuristics. Schmitt, Sun, Snyder, and Shen (2015) study a multi-location supply chain system in which supply is subject to disruptions and examine expected costs and cost variances in centralised and decentralised systems. They demonstrate that when demand is deterministic and supply may be disrupted, using a decentralised inventory design reduces cost variance through the risk diversification effect, and therefore a decentralised inventory system is optimal. When demand is stochastic and supply may be disrupted, they suggest that a risk-averse firm should typically choose a decentralised inventory system design.Some two-echelon models allow for disruptions only at the most upstream locations, that is the suppliers (e.g. Bollapragada *et al*., 2004, Boute *et al*., 2009), while some allow for disruptions at both echelons of a one-warehouse multiple-retailer (OWMR) system (e.g. Bulut and Snyder, 2009, Atan and Snyder, 2012).

Snyder *et al*. (2016) assess the effect of supply disruptions on inventory decisions by considering deterministic demand in a two-echelon system. Through theoretical analysis and numerical study, they obtain and propose the solution to find optimum stocking level under different disruption conditions. They also assess the effect of disruptions if they occur close to the customer. This work considers three cases for disruptions, disruptions occurring at warehouse only, disruptions occurring at retailers only and disruptions occurring at both warehouse and retailers. Schmitt *et al*. (2014) study the cost and cost variances for the two inventory policies of centralisation and decentralisation under supply disruptions, in particular, the classical effects of risk pooling and risk diversification using an analytical approach and numerical study. Under some simplifying assumptions, the paper proposes decentralisation as the optimal policy under supply disruptions as the risk diversification effect prevails but notes that under stochastic demand and deterministic supply centralisation may be a better policy due to risk pooling effect.

For models considering more than two echelons, Hopp and Liu (2006) model an assembly system where disruptions may occur at any location in the network. Schmitt (2011) also considers a multi-echelon system where any stage may be disrupted, focusing on a combined serial-distribution system.

In contrast to these analytical approaches, a study that uses simulation is Deleris and Erhun (2005) who build a Monte Carlo model, while Snyder and Shen (2006) use discrete-event simulation to contrast supply chain uncertainty and demand uncertainty in optimal system design. Schmitt and Singh (2009) use a combination of Monte Carlo and discrete-event simulation to model downtime due to disruptions. In a later study, Schmitt and Singh (2012) use a discrete-event simulation based approach to demonstrate how system resilience can be improved by focusing on a supply chain network as a whole. They analyse inventory placement and back-up methodologies in a three echelon network and view their effect on reducing supply chain risk. They focus on risk from both supply disruptions and demand uncertainty and compare their impacts and mitigating strategies. A simulation model developed to capture an actual network for a consumer packaged goods company is used for the analysis. They present analysis and insights for multi-echelon networks and show how network utilisation and proactive planning enable reductions in supply chain disruption impact.

The current study considers an OWMR system with both supply-side disruptions as well as stochastic demand. Further, we also consider lead time to be uncertain or stochastic in nature. As analytical modeling with these conditions can be quite complex, the current study uses discrete-event simulation.

Summarising the discussion so far, the specific questions that this study aims to address are:

1. How does centralisation compare with decentralisation on cost of backordering and inventory holding?
2. Under stochastic demand and supply disruption which inventory management strategy is better, centralisation or decentralisation?
3. How does the inventory management strategy change with respect to varying levels of disruption length and frequency?

Discrete-Event Simulation Model

A discrete-event simulation model was developed using Arena for Windows version 14 (Fig. 1). Inventory replenishment is considered to follow the base-stock approach and the simulation is run for multiple identical retailers. The model has ten identical retailers with individual demand of 30 per day and standard deviation of 5. Since the retailers are identical, correlation is assumed to be 1, hence the pooled demand comes out to be 300 and pooled standard deviation comes out to be 50. The model can be broken down into three modules, one each for the retailers, the warehouse and the plant. The retailers and the warehouse are assumed to incur backordering and inventory holding cost whereas the plant is assumed to have infinite capacity and can thus fulfill the demands of warehouse without any backordering or holding inventory. All the retailers are assumed to be identical and a cumulative analysis for all the retailers is done (Atilok *et al*., 2010). The base time unit is taken as one day and the model has been replicated for 500 days with 30 replications for each day.

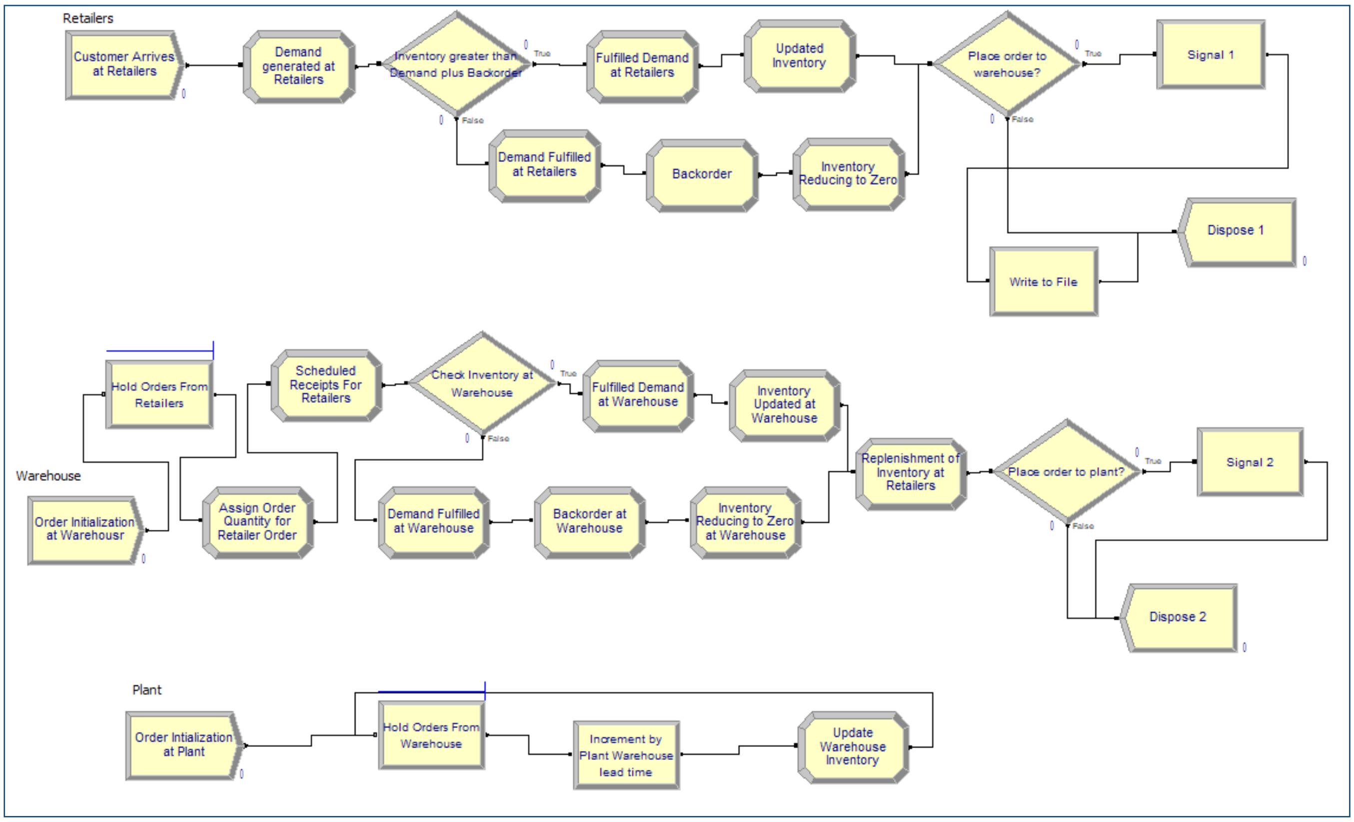

Fig. 1: Arena Simulation Model Developed in the Study

Retailers

Customer demand is generated at the retailers, which is distributed normally with a mean of 300 units per day and a standard deviation of 50 units. The model then computes the inventory level of retailers at a cumulative level and proceeds to calculate demand fulfilled and total backorders. Updated inventory level and inventory position is calculated to compare with the target stock and finally the requisite order is placed to the warehouse. The formula used to calculate inventory position and order quantity is:

$$Q_{ir} = T_{ir} - (OH_{ir} + SR_{ir} - BO_{ir}) \qquad \ldots(1)$$

where,

Q_{ir}: Quantity ordered by the retailers

T_{ir}: Target Stock at the retailers

OH_{ir}: On-hand Inventory at the retailers

SR_{ir}: Scheduled receipts at the retailers

BO_{ir}: Backorders at the retailers

Warehouse Modeling

The orders received from the retailers act as the input demand for the warehouse. Similar to the retailers' model, the inventory level at warehouse is compared with demand to calculate orders that can be fulfilled and backorders if any. The updated inventory position is compared with the target stock to calculate orders to be placed at the plant as per this formula:

$$Q_{iw} = T_{iw} - (OH_{iw} + SR_{iw} - BO_{iw}) \qquad \ldots 1$$

where,

Q_{iw}: Quantity ordered by the warehouse

T_{iw}: Target Stock at the warehouse

OH_{iw}: On-hand Inventory at the warehouse

SR_{iw}: Scheduled receipts at the warehouse

BO_{iw}: Backorders at the warehouse

Further, the orders processed by the warehouse for the retailers are dispatched and delayed as per the lead time which is assumed to be 1 day. Also, the supply disruptions are modelled in the delivery to retailers by disrupting the delivery with additional lead time as done by Schmitt *et al* (2012).

Plant Modelling

The orders from the warehouse are processed in this module. Since the plant is assumed to infinite capacity, each order received from warehouse is directly processed and delivered with a lead time on 1 day. There is no backordering and inventory holding at plant and no disruptions are introduced in this module for delivery to the warehouse.

Parameters for Simulation

The model explained in the previous section is varied for parameters to simulate the two inventory policies of centralisation and decentralisation.

Centralisation

The inventory policy of centralisation entails that the inventory is primarily stocked at the warehouse and retailers maintain only a reasonable level of stock. In this study, we have assumed target stock of 300 units for retailers, which is same as the mean demand per day, the retailers. The warehouse is maintained at target stock of 1000 units that is more than three times the mean demand at retailers.

Decentralisation

In decentralisation, the inventory is stocked primarily at the retailers as opposed to centralisation. For this model, we have assumed target stock of 1000 units for the retailers and 300 units for the warehouse. Thus, this stocking approach is the reverse of that followed in centralisation. The list of parameters for the complete model and the inventory policies of centralisation and decentralisation are given in Table 1.

Table 1: List of Parameters Used in Simulation Model

Parameters		*Centralisation*	*Decentralisation*
Demand at Retailers (units per day)		300	300
Standard Deviation (units per day)		50	50
Target Stock	Retailers (units)	300	1000
	Warehouse (units)	1000	300
Delivery Lead Time	Warehouse to Retailers (days)	1	1
	Plant to Warehouse (days)	1	1
Backordering Cost (per unit)		1	1
Inventory Holding Cost (per unit)		1	1

Experimental Design

The type of disruption considered for this model is the stochastic lead-time for delivery to the retailers. Since the model considered is a two-echelon system with one warehouse and multiple retailers, disruptions have been introduced at warehouse with respect to factors:

1. Frequency of disruptions
2. Length of Disruption

As explained in the model, the disruptions are introduced in the warehouse model for the delivery of orders to the retailers. The frequency of disruption is varied from 10% till 90% intervals of 10%. The length of the disruption is varied from 1 day to 10 days. The base model considers the lead time as 1 day for delivery from warehouse to retailers, so with disruptions the lead times are effectively varied from 2 days to 11 days. Since the disruption frequency is governed by module based on chance, it is possible that disruptions length are duplicated, that is, if another disruption occurs during an already occurring disruption the total disruption length might be distorted. However, since the iterations are run for 500 days such variations tend to even or average out, where the disruption length is only varied from 1 day to 10 days.

Cost Analysis of Centralised and Decentralised System

The model records inventory and the backorder levels at the retailers as well as the warehouse. These are the two major areas of cost which an operations manager has to deal with. It is quite obvious that if inventory holding cost is given preference the backorder increases and vice versa. The idea of this study is to give an operations manager optimal strategy that needs to be followed in case of supply disruptions which will minimise the overall cost (inventory holding + backordering cost). Parameters chosen to identify a suitable policy under stochastic demand and supply disruptions are cost under different levels of disruption length and frequency. The two cost components considered for comparing centralised and decentralised systems are:

1. Backordering cost
2. Inventory holding cost

Backordering cost is calculated by multiplying average backorder quantity with a constant assumed to be 1 unit of cost in this case. Similarly, inventory holding cost is calculated by multiplying average inventory with a constant, again assumed to 1 unit. Moreover, this study compares the total cost for the two systems to identify a suitable policy in addition to individual cost components of backordering and inventory holding costs. Further, this study tries to identify the main cost component for the total cost and the individual characteristics of cost components. The final output that the model will produce will help an operations manager to come up with an optimal inventory management policy in case of supply disruptions (Mak & Shen, 2012).

Cost Analysis for the Centralised System

In this section, we examine the results obtained from simulations of the centralised system. Figs. 2 and 3 respectively present the backordering and inventory holding costs for a centralised system under varied disruption length and frequency. As it is evident from this, both costs are lower with lower levels of disruptions. For disruption frequencies less than 20%-30% and disruption length less than about 2-4 days the costs are lower than those with higher orders of disruption.

Fig. 2: **Plot of Backordering Costs for Centralised System Under Varied Disruption Length and Frequency**

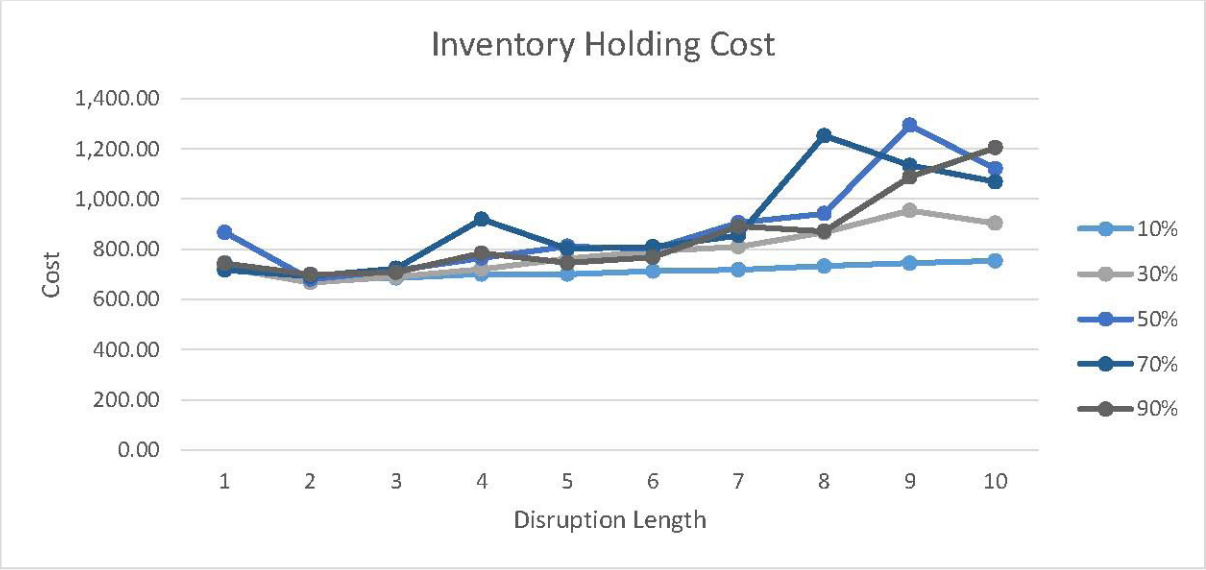

Fig. 3: Plot of Inventory Holding Costs for a Centralised System Under Varied Disruption Length and Frequency

Cost Analysis for the Decentralised System

This section presents the results obtained from simulations of the decentralised system. Figs. 4 and 5 respectively present the backordering and inventory holding costs for a decentralised system under varied disruption length and frequency. Backordering costs follow the same pattern as in centralised system. Costs are lower for low levels of disruption with disruption frequency lesser than 10%-20% and disruption length lesser than 2-3 days. However, the inventory holding costs follow an opposite pattern to that of the centralised system, since they are observed to be lower for higher levels of disruption. Inventory holding costs are decreasing as the level of disruption increases and within disruption frequency of 80%-90% the costs are lowest.

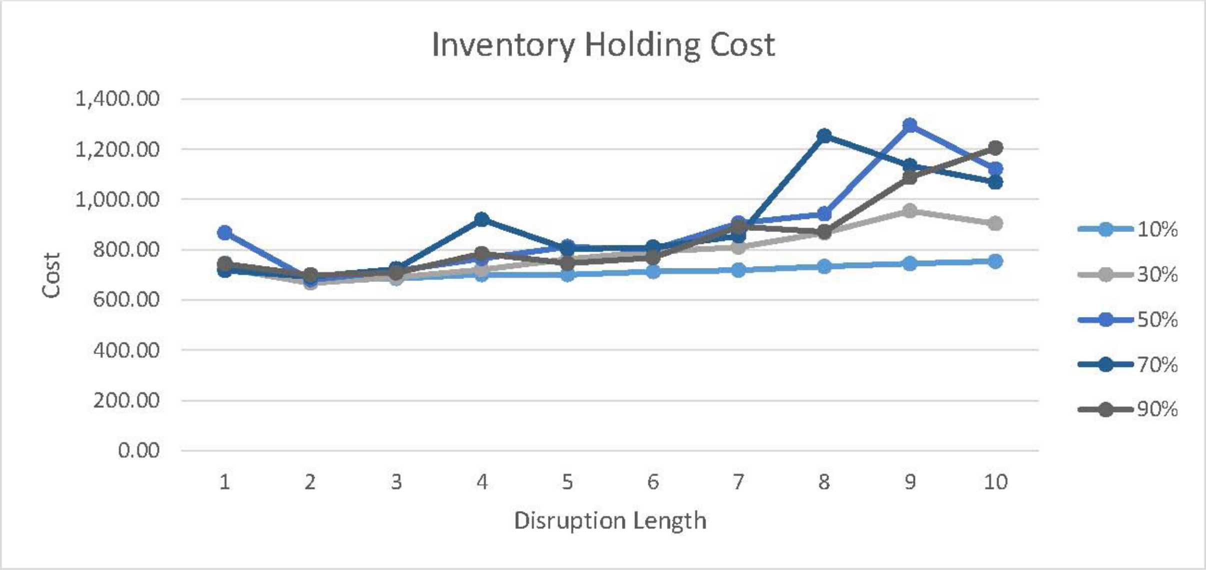

Fig. 4: Plot of Backordering Costs for De-Centralised System Under Varied Disruption Length and Frequency (percentages are for disruption frequencies and disruption length is lead time delay)

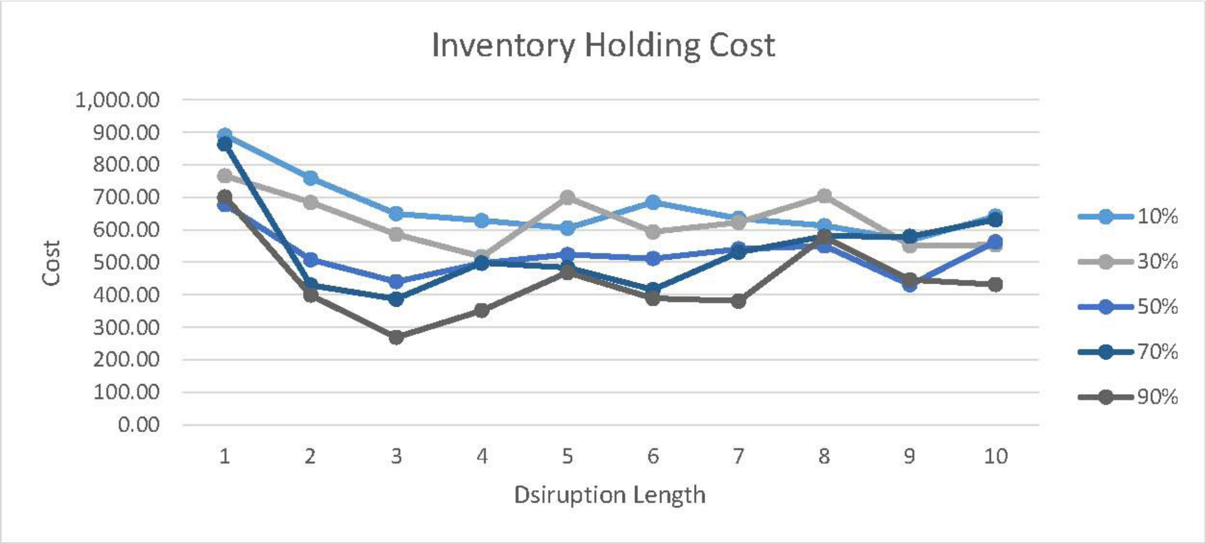

Fig. 5: Plot of Inventory Holding Costs for De-Centralised System Under Varied Disruption Length and Frequency (percentages are for disruption frequencies and disruption length is lead time delay)

Cost Comparisons Between Centralised and Decentralised Systems

In this section, we compare the backordering, inventory holding and total costs between centralised and decentralised systems. We do the comparison by plotting the ratios of each cost under centralisation to that under decentralisation (see Figs. 6-8 respectively for backorder, holding and total cost ratios).

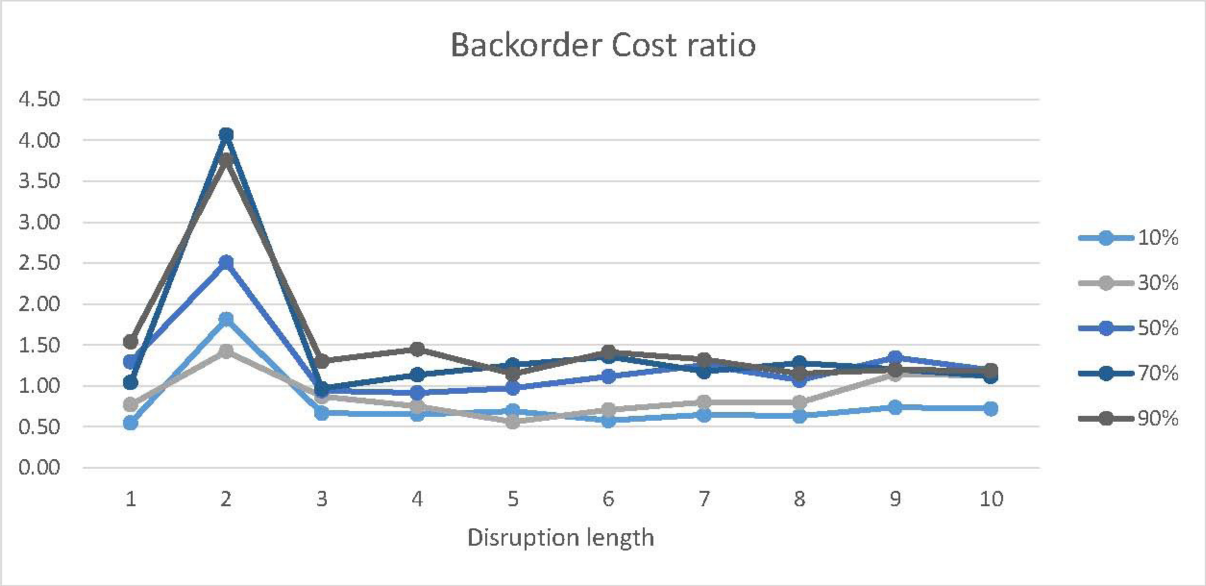

Fig. 6: Plot of Backorder Cost Ratio Between Centralisation and De-Centralisation Under Varied Disruption Length and Frequency

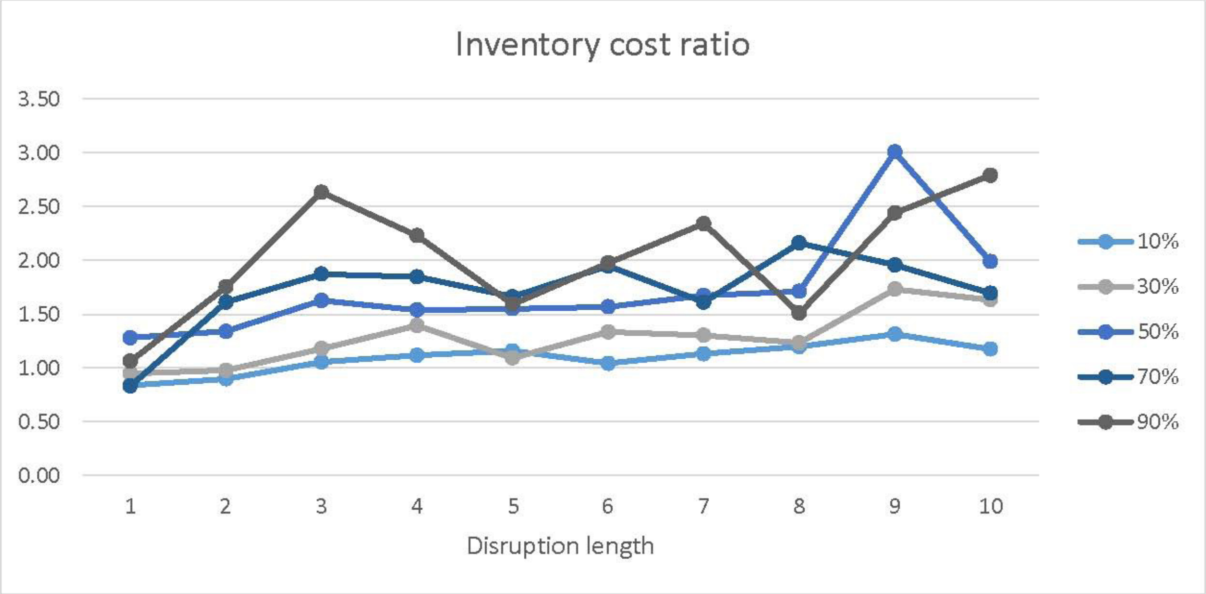

Fig. 7: Plot of Holding Cost Ratio Between Centralisation and De-Centralisation Under Varied Disruption Length and Frequency

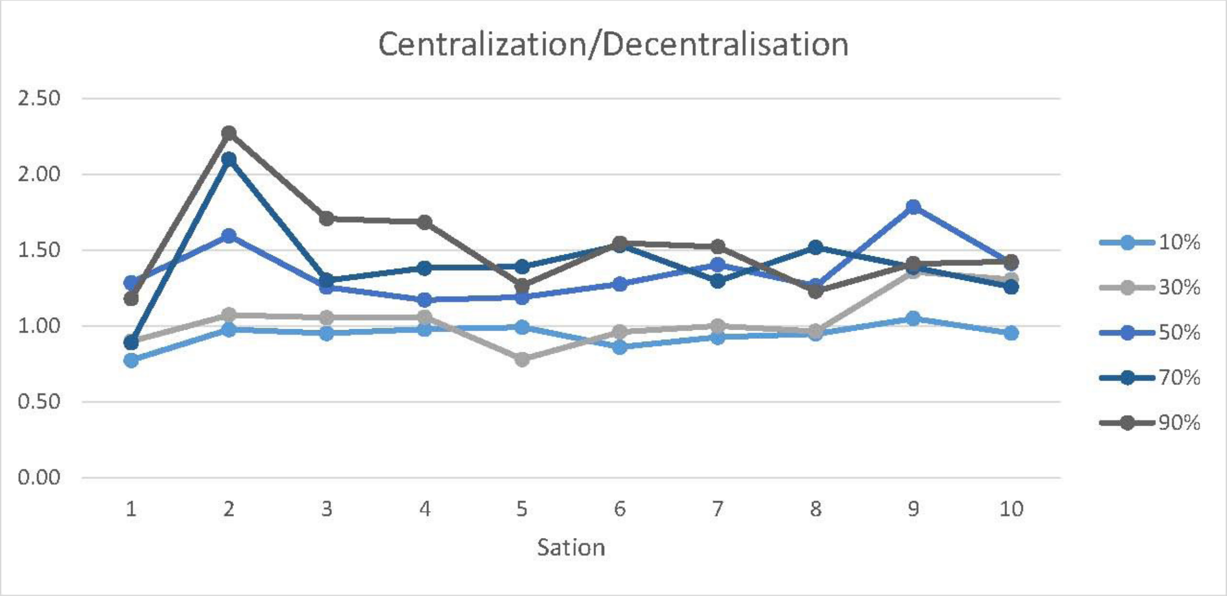

Fig. 8: Plot of Total Cost Ratio Between Centralisation and De-Centralisation Under Varied Disruption Length and Frequency (percentages are for disruption frequencies and disruption length is lead time delay)

It is noted that the backordering costs for the centralised system are lower for almost half of the cases. Lower costs for centralisation go up to 50% of disruption frequency. Therefore, decentralised system has lower backorder costs for only higher levels of disruption. Unlike backorder costs, holding costs for centralised system are lower only for 10% of cases. This is concentrated for lower levels of disruption length (1-2 days) and lower levels of disruption frequency (40%). If we consider only holding costs under disruption, then decentralised system will be a better policy for minimising costs. Finally, when compared the total costs, the centralised system has lower values than the decentralised system for almost one-third of cases. Mostly, the centralised system fares well under lower levels of disruption, that is, when either or both the disruption frequency is low (10%-20%) or disruption length is low (1-2 days). Thus, a decentralised system is more likely to yield lower costs under higher disruption levels and if we are not expecting disruptions or lower level of disruption, centralisation may be a better policy.

Results

Summarising the analyses presented above, it is noted that:

- For total of holding and backordering costs, the centralisation approach is a better strategy when disruption levels and disruption are lower, while decentralisation is better as disruption increases.
- From the perspective of backordering costs alone, centralisation is better strategy for lower levels of disruption length and frequency, but the pattern was slightly different than total cost because in relatively more number of cases centralisation gave minimum cost.
- Holding costs also moved in the same pattern as the combined cost and it is noted that the overall combined cost is majorly governed by holding cost. In this case too, centralisation was a better strategy for lower levels of disruption frequency and length.

Holding cost is the governing factor for the combined costs for both the systems. While, backorder cost has almost equal instances where the centralised and decentralised systems have lower costs, inventory costs are highly skewed towards decentralised system. Overall, holding costs are the reason for bringing down the number of instances where centralised system has a lower cost. Clearly, under low or no disruptions centralised inventory policy would fare better. However, if the disruptions are frequent and large, decentralisation must be adopted to bring down the cost and ensure delivery.

Conclusion and Future Research Directions

Firm survival in the modern business environment is no longer an issue of one firm competing against another but has, instead, become an issue of one supply chain competing against another supply chain. In most of the top global firms supply chain disruptions and their associated operational and financial risks are the most pressing concerns (Green, 2004).

Indeed, research on issues ranging from business continuity planning (e.g., Zsidisin, Melnyk, & Ragatz, 2005) to supply chain vulnerability (e.g., Svensson, 2000) to supply chain resilience (e.g., Sheffi and Rice, 2005) to supply chain risks (e.g., Chopra & Sodhi, 2004) has not only confirmed the costliness of supply chain disruptions but has also contributed insights to this very concern. Our study research has provided additional value to the rich and growing body of knowledge on supply disruptions, particularly on the issue of choosing between centralisation and decentralisation. Some research has also discussed supply chain cost under production disruption when retailers compete with price and service levels (Giri & Sarker, 2016). This study mostly focuses on decentralised system of inventory management. To add to this, our study further focuses on both centralised and decentralised inventory management policies under supply disruptions.

In our study we have analysed holding and backorder costs under stochastic demand and supply disruptions for the two-inventory policies, centralisation and decentralisation. In the course of this, we have made certain assumptions. The unit cost for both inventory holding and backorder are assumed to be one unit. For the sake of simplicity, all the retailers are assumed to be similar. However, this might not be possible in real scenario and a differentiation of retailers may lead to different results. Costs for holding unit inventory and backorder are assumed to be one unit, which might have an impact on the level of costs, observed for the two policies. If the costs for holding inventory are different for warehouse and retailers, then this might yield different results. Disruptions are introduced in supply link to the retailers. Disruptions could also be introduced at plant to warehouse supply.

In this study, we have also assumed 10 identical retailers. However, it is possible that the results may vary if the number of retailers is varies. The same could be analysed further in future course of study. Future studies can also explore relaxing one or more of our assumptions and take the discussion forward.

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