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A THREE-ECHELON SYSTEM DYNAMICS MODEL ON SUPPLY CHAIN RISK MITIGATION THROUGH INFORMATION SHARING

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ABSTRACT

Supply chains in the globally interconnected society have more complex structures and are more susceptible to disruptions such as natural disasters and diseases. The impact of the risks and disruptions that occur to one business entity can propagate to the entire supply chain. However, it has been proposed that cooperation amongst business entities can mitigate the impact of the risks. This paper aims to investigate the value of information sharing in a generalized three-echelon supply chain with dual suppliers. The supply chain model is built in a system dynamics software, and three decision making rules based on different levels of information sharing are developed. Performance metrics to measure the resilience of the supply chain under different shock scenarios are defined, and performances of the three ordering policies with shock applied are compared. The results of the experiments illustrates the value of information sharing in the supply chain when shock exists.

1 INTRODUCTION

Supply chains in today's highly globalized society are complex and interconnected networks. Natural disasters, diseases, unexpected events, demand fluctuations and so on are sources of supply chain risks which can lead to the imbalance between supply and demand or even the paralysis of a supply chain. The tendency for companies to adopt lean practices, increase the outsourcing of manufacturing and reduce the supplier base gives rise to supply chains that are more vulnerable to uncertainties and disruptions (Christopher and Lee 2004).

For example, a fire on 18 March 2000 in a sub-supplier's production cell in Albuquerque shut the plan down for six weeks. As this plant is the only source of radio-frequency chips for Ericsson, the largest supplier of mobile telecom systems in the world, Ericsson were not able to deliver one of its key product to customers. Ericsson announced in its annual report a loss of at least $400 million in potential revenue, and the accident partially resulted in Ericssons withdrawal from the mobile phone terminal business (Norrman and Jansson 2004). In this case, dependence on a single supplier is one of the factors that amplified the influence on the supply chain.

Another common practice in supply chains is that entities in a supply chain, especially the upstream suppliers, might be reluctant to disclose private information about their production or inventory situation in order to maintain their competency. This, however, might not be a wise practice. Without cooperation between entities of a supply chain, any the influence of events or disruptions to any entity of the supply chain can propagate and grow along the entire supply chain.

As supply chains have become more vulnerable to disruptions, business entities in supply chains are expected to cooperate and selectively share information with each other so that the robustness of supply chains can be enhanced and the negative consequences of supply chain risk can be mitigated. This study aims

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to study a generalized three-echelon supply chain with dual suppliers and study the impact of information sharing amongst business entities while encountering supply chain risks.

In order to fulfill this aim, the following steps need to be taken. A supply chain model with sub-suppliers, suppliers and a retailer is built and tested. Three ordering policies are developed inside the model with respect to three levels of information sharing: no information sharing, partial information sharing and full information sharing. Shock is then included in the model and is applied to one or more of the sub-suppliers who have certain production capacities. Before looking at the results, a measurement system with different parameters that quantify the robustness of the supply chain under risk is developed. Finally, the performances of the supply chain with the three ordering policies are compared in order to find out whether information sharing is indeed important to a supply chain.

A supply chain is a dynamic system with "internal feedback structure". For example, the fluctuation of supplier's and retailer's inventory level is generated by the interaction of customer demand, ordering and production policies (Barlas 2007). System dynamics, which runs on a continuous time basis, is suitable for studying a supply chain model. Thus, this study applies system dynamics modeling, using the software iThink, to simulate the supply chain itself, different ordering policies, as well as various shocks that are applied to the supply chain.

The remainder of this paper is organized as follows. Section 3 describes the problem and develops respectively the detailed system dynamic models for the three-echelon supply chains. In Section 4, we propose three ordering policies with different information sharing levels. The numerical results are discussed in Section 5, and Section 6 concludes the paper and proposes possible research area for future studies.

2 LITERATURE REVIEW

Since supply chains are treated as complex networks in this project, system dynamics approach is the best way to study the impact of risks on supply chain performances. Wilson (2007) used system dynamics approach to address the impact of transportation disruptions on the performance of two kinds of supply chains. Apart from Wilson (2007), there were other researches that used system dynamics to solve similar problems, such as Fiala (2005) and Barlas and Gunduz (2011). These papers, however, mainly focused on demand side fluctuations. Fiala (2005) described the different components of the STELLA software and how systems dynamics can be used to simulate information sharing in supply chains and how insight can be derived from it. Barlas and Gunduz (2011) showed the different ordering and decision strategies that different echelons make, the order-up-to policy, the anchor and adjust policy and the (s, S) policy, and how each different strategy performs under different demand distributions and the bull-whip effect on these different strategies.

Certain literature pertaining to the use of information sharing has also been explored. Banerjee et al. (2003) explored the effect of lateral information sharing policies within the tier of the supply chain and their effect on supply chain performance. Sahin and Robinson Jr (2005) studied the impact of information sharing on make-to-order systems using a simulation study. Prior to these papers, much literature has also focused on the study on the bull-whip effect on the supply chain.

3 SYSTEM DYNAMICS MODELS

We study a three-echelon supply chain with one retailer, two suppliers and four sub-suppliers. Sub-suppliers 1 and 2 take orders from supplier 1, sub-suppliers 3 and 4 take orders from supplier 2, and the two suppliers take orders from the retailer who aims to satisfy demand from end-users.

The structure of the supply chain as in iThink model can be perceived intuitively. There are four main sectors: the supply chain entity sector, the decision making sector, the shock generator sector and the measurement sector. The entities of the supply chain (as shown in Figure 1) are structured according to the flow of the products, and the flows connect all the entities together as a complete supply chain. Thus, when the model is running, it can be seen clearly how products flow from the top tier to the bottom tier.

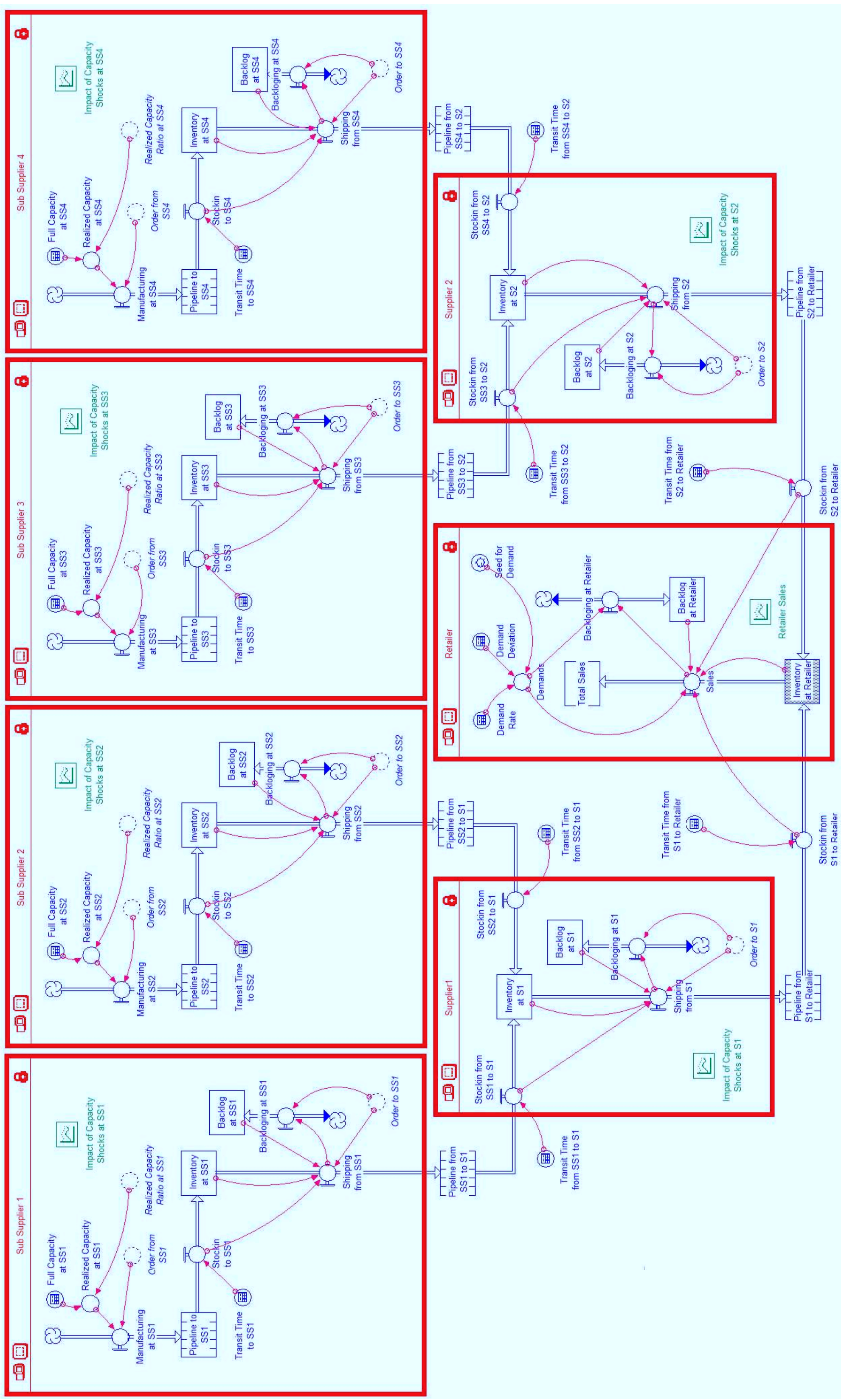


Figure 1: The Supply Chain Entity Sector of the Three-Echelon Supply Chain.

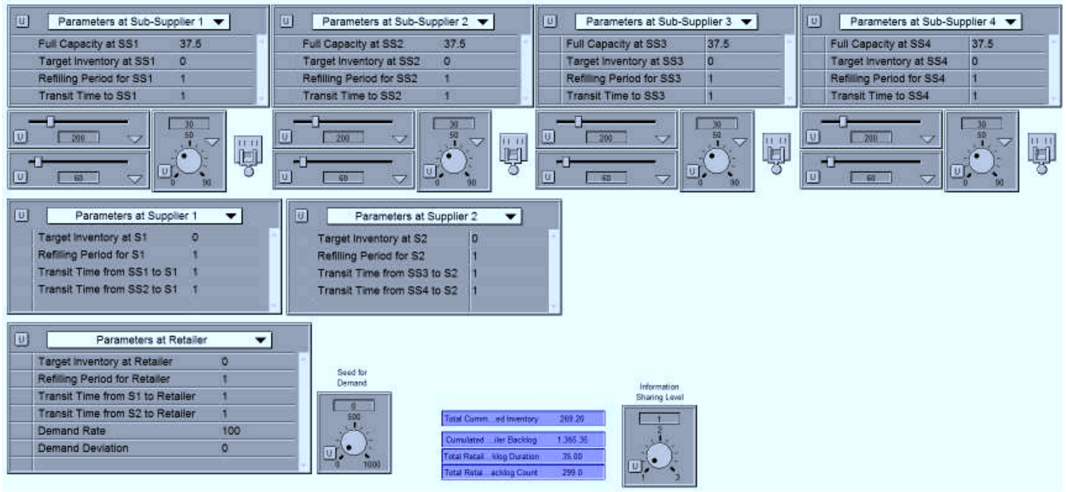


Figure 2: The Interface of the System Dynamics Model.

The decision making sector contains the decision to be made at each entity. It is designed to determine how the retailer and suppliers should place orders as well as how many products sub-suppliers should produce. We have built in the three ordering policies in the decision sector (to be discussed in Section 4) so that only one model is needed to realize the change of ordering policies.

In addition, an interface is built to facilitate the change of parameters, shock scenarios and ordering policies, making the model suitable for training in the classroom (or board room). The interface is shown in Figure 2. Values of the parameters in the model can be changed on the interface; shocks can be controlled by the corresponding buttons so that difference shock scenarios can be created; ordering policies can also be altered by turning the knob to 1, 2 or 3. Apart from these, the measurements of interest are also displayed on the interface.

4 INFORMATION SHARING STRATEGIES

To develop the rules for the information sharing, we firstly study a simple two-echelon case where one retailer has two suppliers. It is established that the retailer will order according to the needs of demand and to fulfill his own policy of maintaining inventory. However, these orders have to be allocated to the two suppliers. The decision sector of the model thus models different ways of decision making, which encompass the three levels of information sharing as discussed in Section 4.1, 4.2 and 4.3.

Then, the three sets of rules are applied on the three-echelon supply chain as modeled in the Section 3. The application is straight forward between each supplier and its two sub-suppliers as it has the same structure as a two-echelon system. However, for the ordering from retailer to the two suppliers, the induced capacity of each supplier takes the sum of the capacities of its two upstream sub-suppliers.

4.1 No information sharing

It is assumed that without information sharing between echelons, the retailer has knowledge of the backorders accumulated at each supplier denoted by B_1 and B_2, since the unfulfilled order is placed by the retailer. Therefor, a good strategy for the retailer is to allocate the orders to each supplier based on the backorder accumulation. Here, we define the ratios,

$$r_1 = \frac{B_2}{B_1 + B_2} \text{ and } r_2 = \frac{B_1}{B_1 + B_2}, \tag{1}$$

as the proportion of ordering quantity place to each supplier if there are any backorders. For special cases, when only one of the two suppliers has backorders, the full order quantity will be placed to the supplier without backorder; and when $B_1 = B_2 = 0$, where r_1 and r_2 are undefined, the order quantity will be split evenly between the two suppliers. The detailed rule can be concluded as following

- $B_1 > 0, B_2 > 0 \implies$ (1);
- $B_1 > 0, B_2 = 0 \implies r_1 = 1$ and $r_2 = 0$;
- $B_1 = 0, B_2 > 0 \implies r_1 = 0$ and $r_2 = 1$;
- otherwise $\implies r_1 = r_2 = 0.5$.

In the event of no information sharing, this ordering policy is chosen because it makes use of the available information, which in this case is the backlog at each supplier B_1 and B_2, in order to make a decision. Intuitively, when orders to a particular supplier are unfulfilled for some time, retailers may postulate that these suppliers are not capable of fulfilling the orders and will change their ordering quantity to divert more orders to the more reliable one.

4.2 Partial information sharing

On basis of Section 4.1, if we assume that the information of inventory levels I_1 and I_2 can be shared across echelons, smarter decisions can be made when no backorder occurs in order to increase the supply chain resilience. As such, the retailer may have a simple ratio calculation based on the inventory levels when either of them is positive, i.e.,

$$r_1 = \frac{I_1}{I_1 + I_2} \text{ and } r_2 = \frac{I_2}{I_1 + I_2}. \tag{2}$$

Following shows the detailed rules:

- $B_1 > 0, B_2 > 0 \implies$ (1);
- $I_1 > 0, I_2 > 0 \implies$ (2);
- $B_1 > 0, B_2 = 0 \implies r_1 = 1$ and $r_2 = 0$;
- $B_1 = 0, B_2 > 0 \implies r_1 = 0$ and $r_2 = 1$;
- otherwise $\implies r_1 = r_2 = 0.5$.

Note that in the case when $B_1 > 0 \bigcap I_2 > 0$ or $I_1 > 0 \bigcap B_2 > 0$, both (1) and (2) provide the same ratios that allocate only to the supplier with no backorder.

With limited information sharing, this is a rather intuitive decision to make on the retailer's part. Essentially, the retailer orders less from the supplier with lower inventory levels, and more from the supplier with higher inventory levels.

4.3 Full information sharing

In an ideal scenario, we assume that besides inventory information the production capacity of both suppliers, i.e., C_1 and C_2, are also known across echelons. Then we are able to further improve the ordering strategy.

Firstly we maintain the previous ordering strategy in trivial cases, i.e., only one of the two suppliers has backorders, or both supplies have neither backorders or inventories. Therefore, we only modify the rules when both suppliers have outstanding backorders or positive inventories.

Then consider the simpler case where both suppliers have positive inventories and the order quantity can be fulfilled by the total production capacity. In such a case, in order to maintain inventory levels at both suppliers, we can allocate to them any quantity which is below their capacity. However, a fairer decision is to split the order quantity based on their capacity ratios, i.e.,

$$r_1 = \frac{C_1}{C_1 + C_2} \text{ and } r_2 = \frac{C_2}{C_1 + C_2}. \tag{3}$$

The same strategy can be applied in the opposite case where both suppliers have outstanding backorders and the ordering quantity is not smaller than the total capacity. It means that the outstanding backorders are not expected to be cleared if the situation remains. Therefore, to distribute the impact of over-demand fairly between the two suppliers, we apply the ratios as in (3).

Special consideration should be taken when both suppliers have positive inventories, but the ordering quantity exceeds the total capacity. It implies that at least one supplies will expect the inventory to drop down towards 0. For a supply chain with higher resilience, we would like to prevent or postpone the situation where either supply exhaust its inventory. Therefore, the best strategy is to allocate the ordering quantity O in the way that

$$\frac{I_1}{r_1 O - C_1} = \frac{I_2}{r_2 O - C_2}. \tag{4}$$

With $r_1 + r_2 = 1$, the equation above can be solved as:

$$r_1 = \frac{(O - C_2)I_1 + C_1 I_2}{I_1 + I_2} \text{ and } r_2 = \frac{(O - C_1)I_2 + C_2 I_1}{I_1 + I_2}. \tag{5}$$

The strategy is similar when both suppliers have outstanding backorders but the ordering quantity is less than the total capacity. It means that both suppliers have a chance to clear their backorders, and we are aiming to reach both clearance soon as possible. Thus the following equation holds,

$$\frac{B_1}{C_1 - r_1 O} = \frac{B_2}{C_2 - r_2 O}. \tag{6}$$

Solving it, we have:

$$r_1 = \frac{(O - C_2)B_1 + C_1 B_2}{B_1 + B_2} \text{ and } r_2 = \frac{(O - C_1)B_2 + C_2 B_1}{B_1 + B_2}. \tag{7}$$

To summarize, when both inventory capacity information are shared among echelons, the rules are as following.

- $B_1 > 0, B_2 > 0 \implies$ if $O \geq C$, (3); else (7);
- $I_1 > 0, I_2 > 0 \implies$ if $O \leq C$, (3); else (5);
- $B_1 > 0, B_2 = 0 \implies r_1 = 1$ and $r_2 = 0$;
- $B_1 = 0, B_2 > 0 \implies r_1 = 0$ and $r_2 = 1$;
- otherwise $\implies r_1 = r_2 = 0.5$.

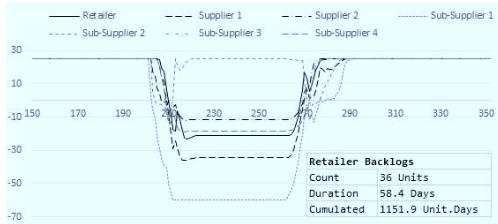
5 NUMERICAL RESULTS

In numerical studies, we consider three scenarios. In the first two scenarios, the supply chain has a symmetric configuration, i.e., all sub-suppliers have the same capacity of 37.5, and the target inventories at all entities are set to 25. However, in Scenario 1 we consider a constant daily demand of 100 at the retailer level; and in Scenario 2, we consider its stochastic counterpart with standard deviation of 10. For the last scenario, we experiment on an asymmetric supply chain with sub-supplier capacity of 20, 30, 40 and 60, with the target inventory levels varied accordingly for all entities to provide sufficient buffer.

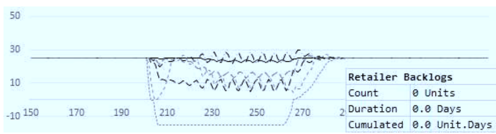
Two types of shocks are tested on each scenario of supply chain. For a single shock, we let the capacity of one sub-supplier (i.e., sub-supplier 1) drop to 0 at Day 200, and last for 60 days and recovers gradually in 30 days. For consecutive shocks, we let the same shock applies to one sub-supplier at Day 200 and a second sub-supplier at Day 240. Obviously, consecutive shocks will have larger impact on the supply chain.. We would like to observe the performance of the three strategies with a different magnitudes of disruption.

5.1 Scenario 1: Symmetric Configuration with Deterministic Demand

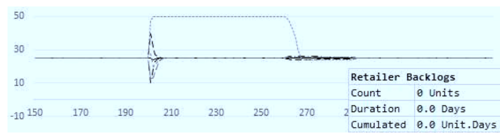
Impacted by the single and consecutive capacity shocks, the resulted inventories (or backlogs for negative values) at all entities with different information sharing levels are displayed in Figure 3 and 4.



(a) No information sharing

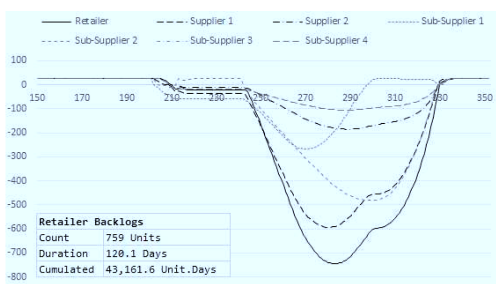


(b) Partial information sharing

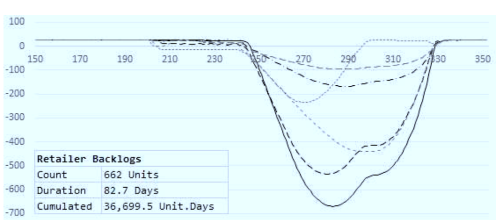


(c) Full information sharing

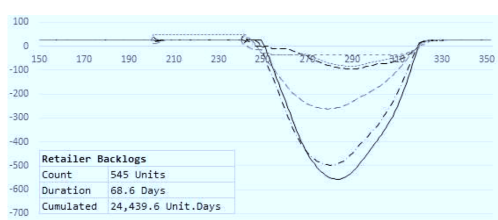
Figure 3: Inventories impacted by the single capacity shock (deterministic demand).



(a) No information sharing

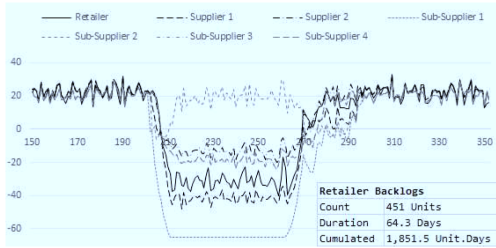


(b) Partial information sharing

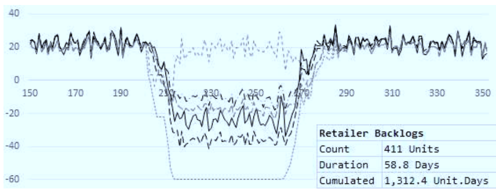


(c) Full information sharing

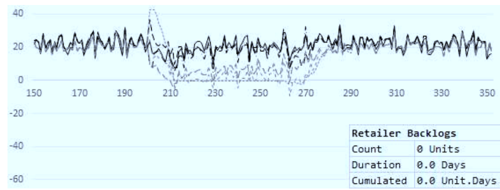
Figure 4: Inventories impacted by the consecutive capacity shocks (deterministic demand).



(a) No information sharing



(b) Partial information sharing



(c) Full information sharing

Figure 5: Inventories impacted by the single capacity shock (stochastic demand).

From the graphs, we notice that in all cases, the capacity shocks cause disturbances of inventory levels at all entities, and the impact can be recovered after the shock terminates. However, with partial and full information sharing, we could mitigate the risks incurred at the retailer level (refer to the solid lines) by eliminating or reducing its backlogs.

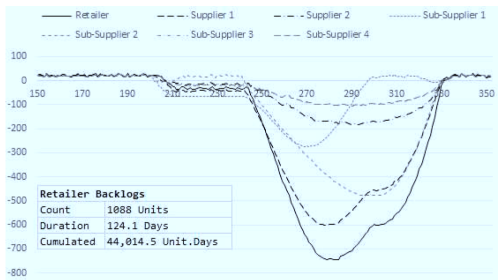
By comparing the Figure 3(a) and 3(b), we can see that when the impact of capacity shock is relatively small, partial information sharing could stop the transmission of the backlog effect to the retailer by enabling it to wisely choose a supplier with higher inventory level. However, it may cause an oscillation between the inventory levels of two suppliers when lead time is positive, which may require a larger buffer inventory to mitigate the effect. Comparatively, in Figure 3(c), full information sharing allows an immediate cut-off of the order made to the sub-supplier with shocked capacity; therefore, none of the entities incurs a backlog throughout the experiment.

When, consecutive shocks happen, although none of the entities survives (i.e., free of backlogs), the discussed advantages of partial and full information sharing slows down the effect to be transmitted to the retailer; and even more, for full information sharing, when the shocked capacity starts to recover, it enables an immediate reaction at both supplier and retailer levels, so that the backlog at the retailer can be fulfilled in a shorter time.

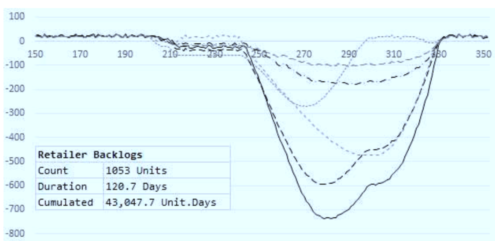
5.2 Scenario 2: Symmetric Configuration with Stochastic Demand

By adding the variation of the demand, the trend remains similar for comparisons among different levels of the information sharing (Figure 5 & 6), except for partial information sharing (i.e., Figure 3(b) & 5(b)) the oscillation effect is not obvious due to the existence of demand variation. Also because of the variation, it is more likely that a retailer in Figure 5(b) drops to an backlog, i.e., the advantage is weakened, although the partial information sharing is able to slow down the process.

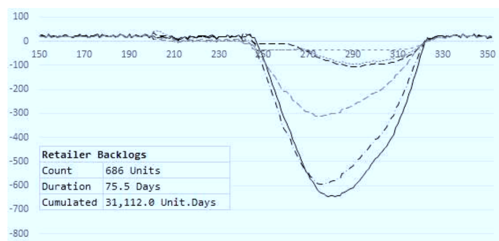
We replicate the experiment for 20 random seeds. The boxplots in Figure 7 shows the comparison of all three backlog measurements. Partial information sharing is slightly better than no information sharing, while the advantage of full information sharing is more obvious.



(a) No information sharing



(b) Partial information sharing



(c) Full information sharing

Figure 6: Inventories impacted by the consecutive capacity shocks (stochastic demand).

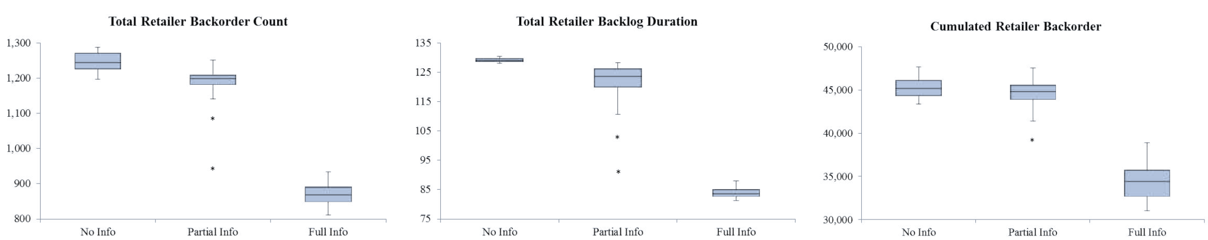
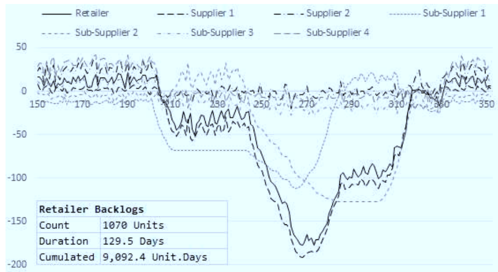
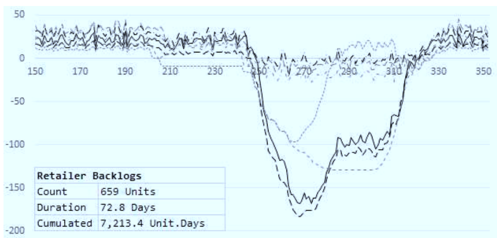


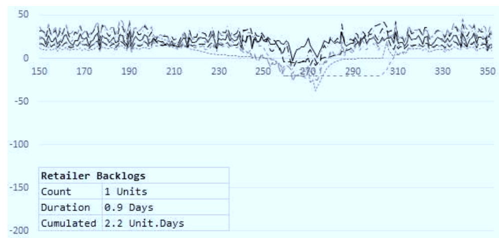
Figure 7: Retailer backorder statuses for three information-sharing levels (symmetric capacities).



(a) No information sharing

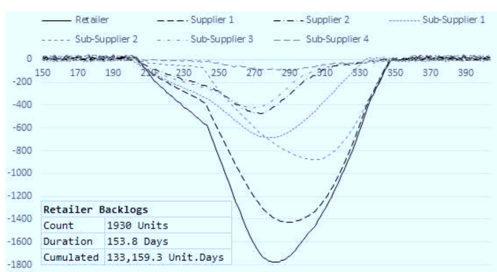


(b) Partial information sharing

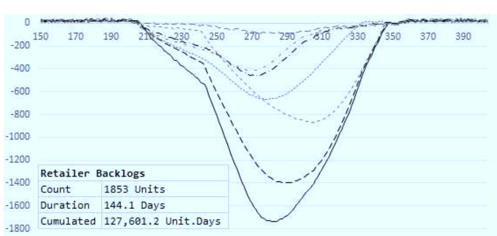


(c) Full information sharing

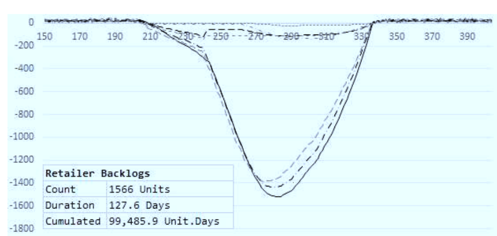
Figure 8: Inventories impacted by weak consecutive capacity shocks.



(a) No information sharing



(b) Partial information sharing



(c) Full information sharing

Figure 9: Inventories impacted by strong consecutive capacity shocks.

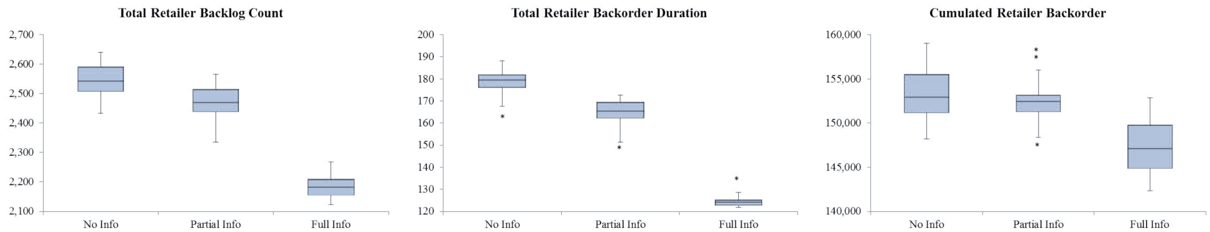


Figure 10: Retailer backorder statuses for three information-sharing levels (asymmetric capacities).

5.3 Scenario 3: Asymmetric Configuration

This scenario is designed to test the three ordering policies in a more general setting, where the downstream business entities do not order the same quantity from both suppliers due to the fact that the suppliers rarely have equal capacities.

When consecutive capacity shocks are applied to sub-supplier 1 & 2, the results as in Figure 8 is very similar to the result in Figure 5 where a single shock is applied to sub-supplier 1. This is because in the asymmetric case, the total capacity of sub-supplier 1 & 2 is only 50, and even if both capacities drop to zero, the remaining capacities are still enough to fulfill customer demand. The shock barely incurs any backlog at the supplier and retailer levels of the supply chain with full information sharing. But because the inventory difference could be large on both supplier and sub-supplier levels, sharing the inventory information becomes more importance. Therefore, the improvement from Figure 8(a) to 8(b) in the early phase is obvious.

In the case where consecutive shocks are applied to sub-suppliers 3 & 4, we expect a substantial impact on the supply chain (Figure 9) because the total capacity of the two are twice as large as that of sub-suppliers 1 & 2. After running for 20 replications, boxplots for backorder measurements are generated to compare the three levels of information sharing (Figure 10), where the same ranking of the three information sharing strategies can be derived.

6 CONCLUSION

In this study, a three-echelon supply chain model has been built using system dynamics software, implemented with three levels of information sharing rules for making ordering decisions. The model is used to investigate the robustness of the supply chain with different information sharing rules when capacity shock occurs to the sub-suppliers. It is shown that, under all the experiment scenarios, a higher information sharing level could make the supply chain more sustainable in a capacity shock.

More topics can be addressed for a future study. For example, currently we fix the target inventory level at each entity and look at how information sharing affect the observed backlogs; and in future, a more realistic study could evaluate the minimum required inventory buffer for achieving a specified service standard, i.e., maximum number of backlogs as a constraint. In addition, we could model the scenario where knowledge of stocking policy is shared across echelons.

We could also study the benefit of information sharing brought to each entity in the supply chain, and subsequently find out a strategy that could encourage each of them to share the information for achieving the overall benefit of the entire supply chain.

At last, the structure of the supply chain in the study can be further expanded to a more complex structure, and more than one product component can be considered, which is more realistic for a practical industrial problem.

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