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Revealing interfaces of supply chain resilience and sustainability: a simulation study

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Dynamics of structures and processes is one of the underlying challenges in supply chain management, where multiple dimensions of economic efficiency, risk management and sustainability are interconnected. One of the substantiated issues in supply chain dynamics is resilience. Resilience has a number of intersections with supply chain sustainability. This paper aims at analysing disruption propagation in the supply chain with consideration of sustainability factors in order to design resilient supply chain structure in regard to ripple effect mitigation and sustainability increase. Ripple effect in the supply chain occurs if a disruption at a supplier cannot be localised and cascades downstream impacting supply chain performance. This simulation-based study helps to identify what sustainability factors mitigate the ripple effect in the supply chain and what sustainability factors enhance this effect. The results indicate that (i) sustainable single sourcing enhances the ripple effect; (ii) facility fortification at major employers in regions mitigates the ripple effect and enhances sustainability; and (iii) a reduction in storage facilities in the supply chain downstream of a disruption-risky facility increases sustainability but causes the ripple effect.

Keywords: supply chain dynamics; supply chain resilience; supply chain design; simulation; supply chain risk management

1. Introduction

Dynamics of structures and processes is one of the underlying challenges in supply chain management, whereas multiple dimensions of economic efficiency, risk management and sustainability are interconnected in this research field (Dolgui and Proth 2010; Fahimnia, Sarkis, and Eshragh 2014; Aqlan and Lam 2015; Chan et al. 2017; Ivanov, Tsipoulanis, and Schönberger 2017; Ivanov et al. 2017; Yu, Li, and Yang 2017). One of the substantiated issues in supply chain dynamics is resilience, which refers to development of the ability to remain robust and change (adapt) system behaviour in dynamic environments in the case of severe disruptions with the achievement of acceptable performance (Craighead et al. 2007; Ivanov and Sokolov 2013; Benyoucef, Xie, and Tanonkou 2013; Ho et al. 2015; Gunasekaran, Subramanian, and Rahman 2015; Tukamuhabwa et al. 2015; Khalili, Jolai, and Torabi 2017).

Resilience in supply chains has been extensively studied in the literature from strategic, tactical and operative perspectives in light of numerous severe disruptions such as tsunamis, fires and floods. At the same time, resilience issues in supply chains go far beyond risk management only. The methodical elaborations on the evaluation and understanding of low-frequency/high-impact disruptions are vital for understanding and further development of network-based supply concepts in a broader sense and from a cross-disciplinary perspective. One of the important interfaces is design and management of resilient and sustainable supply chains (Linton, Klassen, and Jayaraman 2007; Carter and Rogers 2008; Fahimnia and Jabbarzadeh 2016).

Organisations extensively incorporate sustainability metrics into their supply chain management practices and supplier selection concepts (Das, Narasimhan, and Talluri 2006; Bai et al. 2012; Choi 2013; Ahi and Searcy 2015; Nair, Jayaram, and Das 2015). In this setting, the development of models and decision support tools can improve decision-making on resilient and sustainable supply chains (Brandenburg and Rebs 2015; Giannakis and Papadopoulos 2016). Studies on supply chain sustainability differ across methodologies but they commonly argue that the adoption of sustainable supply chains is maintaining business continuity in order to reduce long-term business risks. Business continuity is at the same time one of the fundamental characteristics of supply chain resilience.

Resilience has a number of intersections with supply chain sustainability (Derissen, Quaas, and Baumgärtner 2011; Seuring 2013; Fahimnia, Sarkis, and Eshragh 2014; Chan et al. 2017). Since supply chains became more and more global, these network structures build a backbone of modern economy and directly influence such sustainability issues as

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employment rates, natural resource consumption, etc. Important issues of supply chain sustainability are an assessment of supply chain design resilience and efficient supply chain structure reconfiguration in the case of disruptions from the perspectives of environmental, political and society impacts.

In practice, there are tangible intersections in which sustainability and resilience can influence each other. One of these situations is ripple effect in the supply chain (Ivanov, Sokolov, and Dolgui 2014). The scope of the rippling and its impact on economic performance depends on robustness reserves (e.g. redundancies like inventory or capacity buffers), flexibility in products and processes and speed and scale of recovery measures.

Ripple effect describes the impact of a disruption on supply chain performance, disruption propagation and disruption-based scope of changes in supply chain structures and parameters. Examples include but are not limited to fires at the distribution centres, tsunami and floods leading to production facility disruptions, legal conflicts between suppliers and strikes at airlines and railway companies (Craighead et al. 2007; Chopra and Sodhi 2014; Simchi-Levi, Schmidt, and Wei 2014; Ho et al. 2015; Hasani and Khosrojerdi 2016; Sawik 2016).

The ripple effect in the supply chain occurs if a disruption cannot be localised and cascades downstream impacting supply chain performance (Ivanov, Sokolov, and Dolgui 2014). Ripple effect analysis includes consideration of supply chain structural changes (i.e. structural dynamics) as consequences of disruption and recovery actions and the impact of the disruptions and recovery actions on the operations execution and supply chain performance indicators such as sales, service level and total costs. The ripple effect has been extensively investigated in literature (Tomlin 2006; Liberatore, Scaparra, and Daskin 2012; Ivanov, Sokolov, and Dolgui 2014; Ivanov et al. 2016; Mizgier, forthcoming), however, without consideration of sustainability factors.

Contribution of this article aims at analysing the performance impact of disruption propagation in the supply chain with consideration of sustainability factors in order to design a resilient supply chain structure in regard to ripple effect mitigation and sustainability increase. We apply discrete event simulation in order to identify what sustainability factors mitigate the ripple effect in the supply chain and what sustainability factors enhance this effect. In particular, three sustainability factors are considered: (i) single sourcing and its impact on the ripple effect; (ii) facility fortification of major employers in regions and its impact on the ripple effect and sustainability; (iii) inventory placement in the supply chain and the impact on the ripple effect and sustainability.

2. State-of-the-art analysis

Academic research on sustainable supply chain design and management has been substantially developed over the past two decades (Seuring 2013; Fahimnia, Sarkis, and Eshragh 2014; Chan et al. 2017). Achievement of supply chain sustainability has been predominantly focused on reducing environmental impacts of the supply chain, commonly measured in terms of greenhouse gas emissions and resource consumption (Gaussin et al. 2013; Seuring 2013; Yu, Li, and Yang 2017). One of the key determinates in literature has been a relation between efficiency, lean practices and sustainability. For example, Seuring (2013) and Ahi and Searcy (2015) identify that sustainable supply chains aim at reduction of stock points and safety inventory in the supply chain and single sourcing practices with sustainable suppliers.

Another important interface of sustainability has been considered in regard to supply chain resilience (Fahimnia et al. 2015; Tukamuhabwa et al. 2015; Fahimnia and Jabbarzadeh 2016). Simchi-Levi et al. (2015) consider the customer satisfaction aspect of supply chain sustainability and develop a risk exposure index for the case of an automotive supply chain. The index computation is based on two models – time-to-recovery and time-to-survive – in order to assess the performance impact of a disruption on the supply chain in terms of service level. The model allows identifying risk exposure at different suppliers and recommends proactive strategies for different suppliers in regard to performance impact and purchasing volume. Ivanov et al. (2016) consider return flow minimisation in the supply chain driven by severe disruptions. The authors address the sustainability issue of waste reduction in the supply chain and develop a model to generate resilience for supply chain design and recovery actions.

Nevertheless, research on a combined supply chain sustainability and resilience analysis is still at the beginning of its development (Fahimnia, Sarkis, and Eshragh 2014). Among others, the literature considers risks of severe accidents and recoverability along with customer satisfaction as important sustainability aspects (Ahi and Searcy 2015). Giannakis and Papadopoulos (2016) underline the crucial role of risk management in supply chain sustainability. Brandenburg and Rebs (2015) analyse the quantitative methods for supply chain sustainability. At the same time, the investigation of supply chain sustainability and resilience together with the help of model-based decision support techniques has yet to be explored in a focused and structured way.

Because of the time aspects and dynamics in structures and flows, it is natural to use simulation for ripple effect analysis in the supply chain (Ivanov 2017). Discrete event simulation has been extensively used in the area of supply chain severe disruptions and resilience analysis. Carvalho et al. (2012) analyse a four-stage supply chain based on the

real case study of a Portuguese automotive supply chain. Focusing on the research question of how different recovery strategies influence supply chain performance in case of disruptions, the authors analyse two recovery strategies and six disruption scenarios. The scenarios differ in terms of the presence or absence of a disturbance and presence or absence of a mitigation strategy. The performance impact has been analysed in regard to lead-time ratio and total supply chain costs using an ARENA-based simulation model.

Schmitt and Singh (2012) present a quantitative estimation of the disruption risk in a multi-echelon supply chain using discrete event simulation. The disruption risk is measured by 'weeks of recovery' as the amplification of the disruption. The modelled proactive and recovery strategies include satisfying demand from an alternate location in the network, procuring material or transportation from an alternative source or route, and holding strategic inventory reserves throughout the supply chain. In regard to ripple effect, this study provides two interesting results. First, increases in inventory levels of raw material and finished goods in anticipation of disruptions significantly exceed those required when only stochastic demand is considered. Second, 'upstream disruptions in the supply chain may not be felt as quickly as downstream disruptions, but their impact can be amplified, outlasting the disruptions themselves'.

Lim et al. (2010) analyse fortification of supplier factories as an advantage to increase supply chain resilience. Lewis et al. (2013) analyse the disruption risks at ports of entry with the help of closure likelihood and duration, which are modelled using a completely observed, exogenous Markov chain. They developed a periodic review inventory control model that for studied scenarios indicates that operating margins may decrease 10% for reasonably long port-of-entry closures or be eliminated without contingency plans, and that expected holding and penalty costs may increase 20% for anticipated increases in port-of-entry utilisation.

Hishamuddin, Sarker, and Essam (2015) simulate a three-echelon inventory system in the supply chain with multiple sourcing, and consider both supply and transportation disruptions. They include in the model disruption duration, recovery costs and a random disruption generator. The most important finding of this study is that back-order quantity and recovery duration have strong positive correlations with total supply chain costs as compared to the importance of lost sales. This study contributes to the body of knowledge on the ripple effect in the supply chain by revealing the fact that disruptions between the supplier and manufacturer imply higher average supply chain costs as compared to disruptions between the producer and distributor. At the same time, the authors reveal that both performance impacts of recovery duration and disruption location are quite similar for both supply and transportation disruptions.

Ivanov (2017) analysed recent literature on simulation modelling and developed a multi-stage supply chain design simulation model with consideration of capacity disruptions and experimental results. This study depicts major areas of simulation application to the ripple effect modelling. anyLogistix simulation and optimisation software has been used. The author also identified a framework of simulation modelling concerning supply chain disruption management and delineated commonalities and differences of optimisation and simulation methods within this framework.

In regard to research gap identification, it can be observed that the literature typically analyses four levers of supply chain resilience increase, i.e. using backup facilities, using inventory buffers, elimination of single source suppliers with high risk exposure and facility fortification. From sustainability point of view, single sourcing, inventory reductions, and labour market stability in regions are important sustainability factors. As a new contribution to the research field, we aim at observing in this study how the resilience levers interact with corresponding sustainability factors in a multi-stage supply chain.

3. Problem statement and methodology

3.1 Problem statement

We use an example of the supply chain in electronics described in literature (Ivanov, Tsipoulaidis and Schönberger 2017). Without loss of generality, we consider only a part of the supply chain that contains the most representative features of the overall supply chain, i.e. multi-stage supply chain with suppliers, factory, distributions centres and customers in order to make the result analysis depictive (Figure 1).

Smartphone assembly is performed in the factory in China. For assembly, one display and two chips are needed. The Chinese supplier delivers displays by truck and the supplier from Taiwan delivers the chips by ferry to the assembly plant. From the factory, goods are delivered by air to the distribution centres in the USA. From there, goods are shipped by air to customers. We assume that distribution centres and factory are running s, S inventory control policy. The following demand data is used for computational analysis (Table 1).

Demand is normally distributed within the fixed re-order period which is 10 days for all markets. The re-order period of 10 ten days means that every 10 days the orders are placed to the DC, the sizes of which correspond to the mean demand and the standard deviation of demand. Other parameters in the model are as follows.

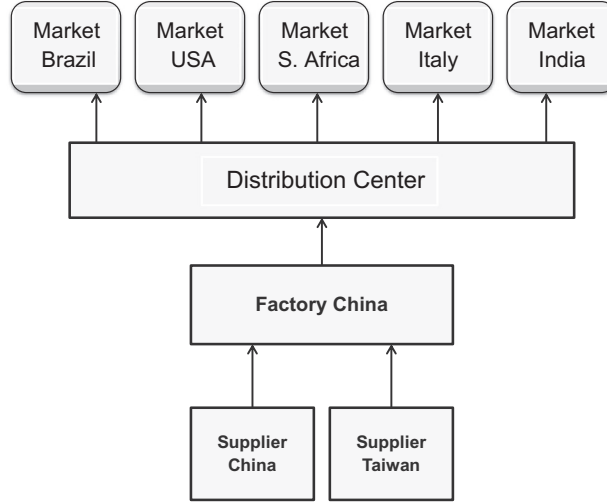


Figure 1. Supply chain fragment for smartphone production.

Table 1. Demand data.

Market	Mean demand during re-order period, in conditional units	Standard deviation of demand	Re-order period, days
USA	75	15	10
Italy	10	2	10
India	30	6	10
Brazil	10	6	10
South Africa	50	10	10

- Expected lead time at customer is 10 days.
- Service level is measured as ELT (expected lead-time) service level subject to customer demand satisfaction during the expected lead time.
- Lead time between distribution centre and customers is normally distributed with a mean of three days and a standard deviation of one day.
- Lead time between factory and distribution centre is normally distributed with a mean of three days and a standard deviation of one day.
- Lead time between suppliers and factory is normally distributed with a mean of two days and a standard deviation of one day.
- Transportation policy is LTL (less than truckload) without order aggregation.
- Inventory control policy at distribution centre: $s = 780$; $S = 1560$ (subject to 90% customer service level and demand/lead-time data).
- Inventory control policy at the factory: $s = 390$; $S = 780$ (subject to 90% customer service level and demand/lead-time data).
- There are no capacity limits on transportation, warehouse storage area, or production quantities.
- Production batch at factory is 50 units with an increase step 5 units.
- Sales batch at distribution centre is 5 units with an increase step 1 unit.
- Backordering is not allowed.

3.2 Supply chain operation

In this section, we describe the supply chain operation concerning material and information flows as well as to production, ordering, and sales rules. In Figure 2, the supply chain operation model is presented.

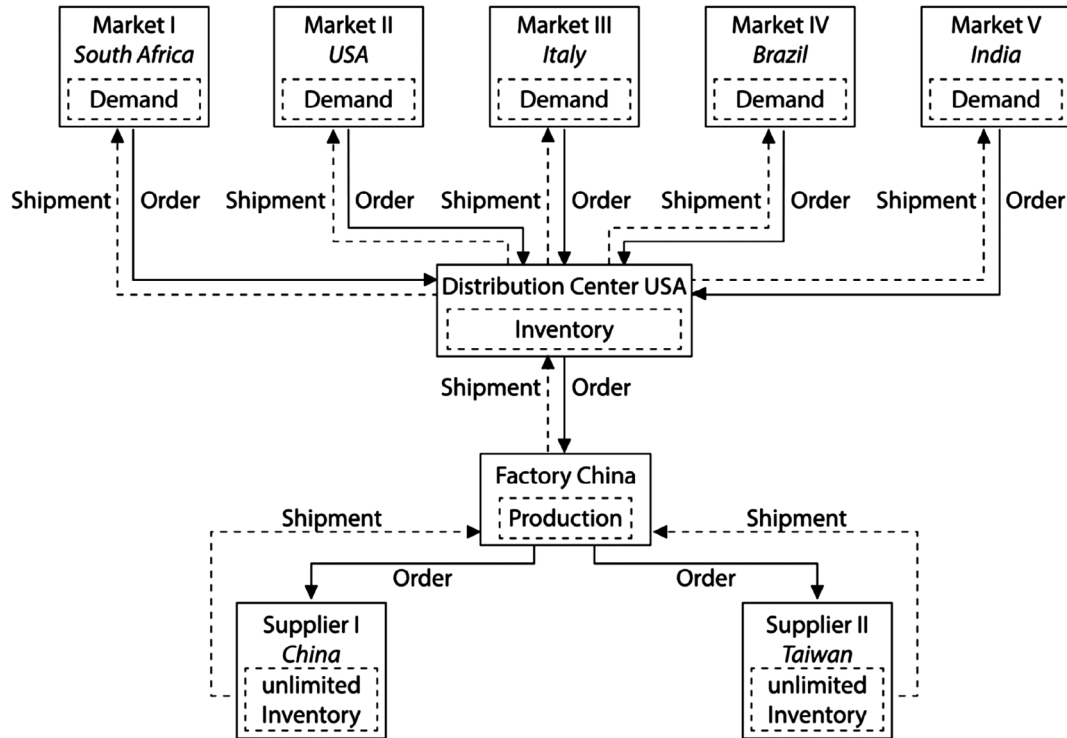


Figure 2. Supply chain operations model.

The supply chain is characterised by partial visibility, i.e. the demand of an upstream echelon is visible for the downstream echelon that immediately communicates with the upstream echelon. The markets generate orders to the distribution centre according to their demand which is normally distributed. The orders are placed according to a fixed re-order period (cf. Table 1). The distribution centre exhibits the s, S inventory control policy and places the orders at the factory. Production is controlled by the parameters of inventory control policy. Production batch function works using the following rules:

- s -parameter in the inventory control policy determines the reorder point and S -parameter in the inventory control policy determines the order quantity.
- If a production batch is higher than order quantity, then nothing is produced.
- If a production batch is lower than order quantity, then the factory produces the maximum possible quantity subject to the batching rules but not more than order quantity.

For example, if the batch size is 100 and order quantity is 90, then nothing is produced. If batch size is 100, size step of a batch is 100, and order quantity is 290, then the factory will produce 200 units and the rest 90 units will be added to the next order.

Ordering rules and sales batches are defined as follows. An ordering or sales batch rule allows either to increase the order size or a sales batch on up to 'Limit' number of units or to decrease the order size or the sales batch by 'Limit' number of units. Under a 'Limit' we understand the number of units within the order size or the sales batch can be adjusted. For example, if the Brazil customer orders 4 units, the ordering rule sets up the increase limit of 6 units, and sales batch is set up at 10 units, an order of $4 + 6 = 10$ units will be created.

3.3 Methodology

This study's research programme addresses two interfaces of social sustainability and resilience in the supply chain. First, employment issues will be included in the ripple effect and resilience analysis. Second, sourcing strategy, inventory control policy and facility fortification will be analysed about sustainability, resilience and supply chain ripple effect.

Three hypotheses will be tested:

H1: Sustainable single sourcing enhances the ripple effect.

Sustainable sourcing practices imply the selection of a single source supplier. However, the most sustainable supplier might be not the most efficient or robust supplier. Long-term trust-based relations with suppliers and securing steady employment relations in supply regions may collide with supply base flexibility to mitigate the ripple effect by dual/multiple sourcing and backup facilities.

H2: Lower inventory enhances sustainability but causes the ripple effect.

Cost efficiency and waste minimisation practices imply less inventory along the supply chain. While such strategies may be environmentally sound and economically grounded, they may negatively impact the supply chain resilience subject to limited availability of risk mitigation inventory to cope with disruptions.

H3: Reinforcing major employers' facilities in regions mitigates the ripple effect and enhances sustainability.

Supply chain design structures and networking have a long-term nature; largely they shape the labour market and employment developments in the regions. In many cases, the facilities represent major employers in a region. That is why it is mandatory to consider resilience and sustainability issues having such facilities in the supply chain design.

Two sustainability perspectives are addressed in the experiment design. On the one hand, the risk and resilience perspective is modelled with the help of disruptions and observations of the supply chain performance and structure dynamics for different supply chain designs. On the other hand, the customer satisfaction perspective is considered for different disruptions and supply chain designs with the help of customer service level analysis in supply chain performance. For this purpose, we suggest a concept of performance impact index (PI). We suggest introducing an index of performance impact that represents a relation between the planned key performance indicators in a disruption-free mode and the actual key performance indicators in the disruption case (Equation (1)):

$$PI = \frac{KPI_{plan}}{KPI_{disruption}} \quad (1)$$

In particular, sales at customers will be measured as performance impact of the ripple effect in the supply chain. PI index > 1 will mean that there is a ripple effect in the supply chain. PI index $= 1$ means that there is no ripple effect. PI index < 1 indicates low quality of initial supply chain planning. In this study, we use customer service level as KPI to compute the PI index.

3.4 Modelling approach

The developed discrete event simulation model exhibits the following characteristics. It is created and solved in anyLogistix simulation and optimisation toolkit. We created a large-scale simulation model for a similar problem of higher complexity in order to test the scalability. Simulation was run for a period of one year with a disruption early in July. In the case of disruption and scarce supply, deliveries are directed randomly with equal distribution probability to the destinations downstream of the supply chain. For testing the hypothesis, event-driven disruptions and backup facilities were modelled. Backup facilities were switched on one day after the disruption happened, and were switched off one day after the disruptions were recovered. 100 replications have been created for reducing output randomness.

For testing Hypothesis 1, a backup second source is included in the model and is switched on if a disruption takes place at the primary source. For testing Hypothesis 2, parameters of inventory control policies are increased to different extents subject to differing durations of disruption. In addition, a regional distribution centre at the market in South Africa with a higher safety stock will be added to analyse the impact of distribution system decentralisation on the ripple effect in the supply chain. For testing Hypothesis 3, we compare supply chain performance for different periods of disruption for the case of additional investment into facility fortification. We test the impact of three levels of factory building protection on disruption duration and supply chain performance.

Organisation of the experiments is as follows. First, we compute supply chain performance subject to such key performance indicators as service levels, sales, lead time, inventory dynamics and profit for a disruption-free scenario and the initial supply chain design (cf. Figure 2). Subsequently, supply chain dynamics in different disruption scenarios and the respective key performance indicators are computed in order to analyse the estimated annual magnitude of the

disruptions and the ripple effect. Such analysis will be performed for different proactive supply chain designs with different combinations of resilience and sustainability elements. Finally, we compare the PI index for different supply chain designs and draw conclusions on the ripple effect with sustainability considerations in these supply chain designs along with recommendations on the supply chain structural design. For verification, tracking of the simulation runs, analysis of output log files and testing at deterministic parameters were used. For testing, we use replications in comparison and variation experiments.

4. Experimental results and insights

4.1 Disruption-free scenario simulation

First, we run simulation subject to a disruption-free scenario. The following key performance indicators have been computed (Figure 3).

The customer service level at distribution centre (i.e. ELT service level) of 100% (i.e. order fulfilment from distribution centre to customers within expected lead time) with no delayed orders can be observed in Figure 2. In the inventory dynamics diagram, the blue line is the distribution centre inventory and the red line is the factory inventory. Subsequently, we tested the three hypotheses for disruption cases.

4.2 Disruption scenario simulation

In this section, we analyse supply chain behaviour subject to different disruption durations and proactive policies.

H1: Sustainable single sourcing enhances the ripple effect.

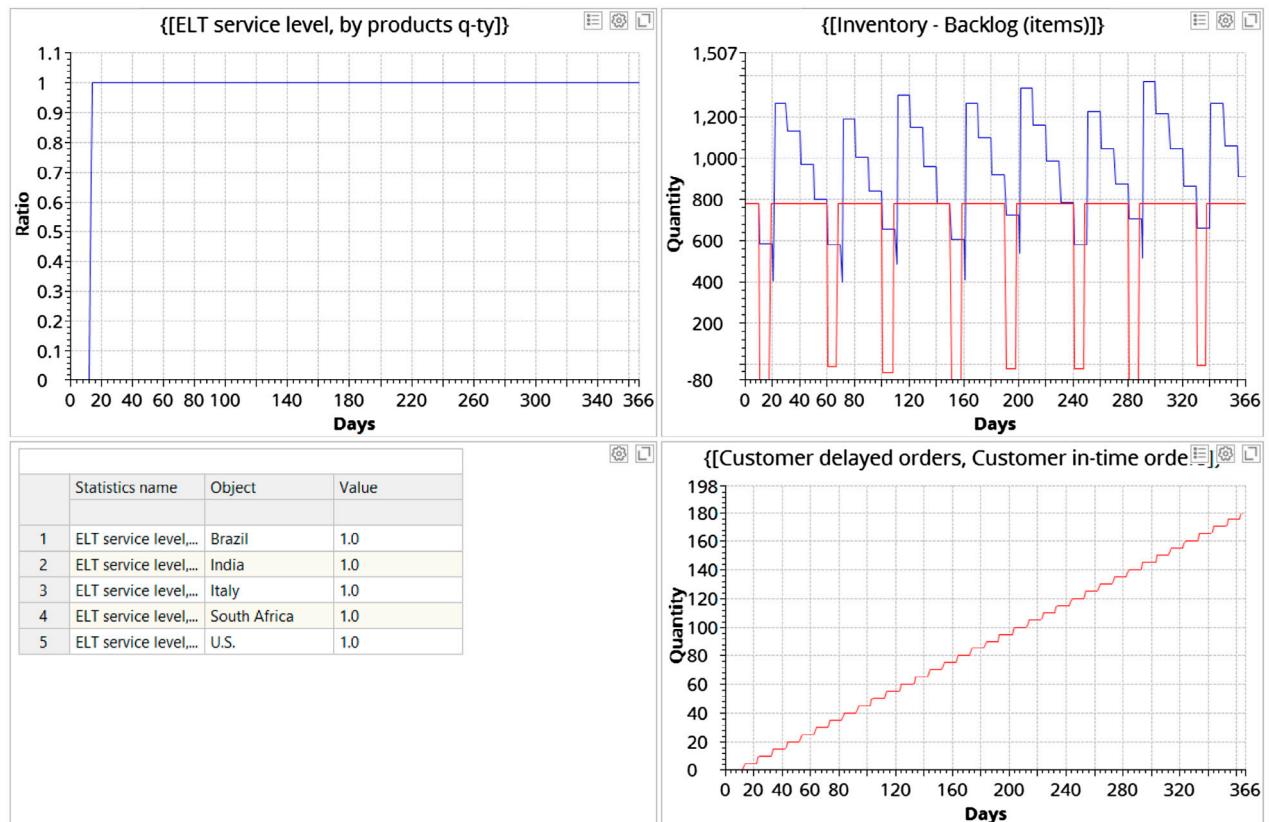


Figure 3. Supply chain performance in disruption-free mode.
Note: blue line – distribution centre statistics; red line – factory statistics.

In the experiments from this group, we assume a disruption at the distribution centre for two weeks, one month, and two months, respectively. We compare supply chain performance with the disruption-free mode. Subsequently, we introduce a backup distribution centre that is switched on for the period of disruption at the primary distribution centre. The simulation results are depicted in Figures 4–9 and Table 2.

4.2.1 Insight 1

It can be observed in Figures 4, 6 and 8 that in the case of a backup distribution centre (green line in the inventory control diagram), disruption duration does not affect the service level gap (i.e. 100% – actual ELT service level). At the same time, in the case without a backup distribution centre, the gap between the disruption-free service level and service level in the presence of disruptions becomes greater with increasing disruption duration (cf. Figures 3, 5 and 7). It can be observed that ripple effect increases with disruption duration following the performance impact values in Table 2. It can, therefore, be concluded that backup facilities are to be recommended for cases of severe and lengthy disruptions. In the short-term perspective (i.e. 14 days), the backup distribution centre can only slightly improve the service level

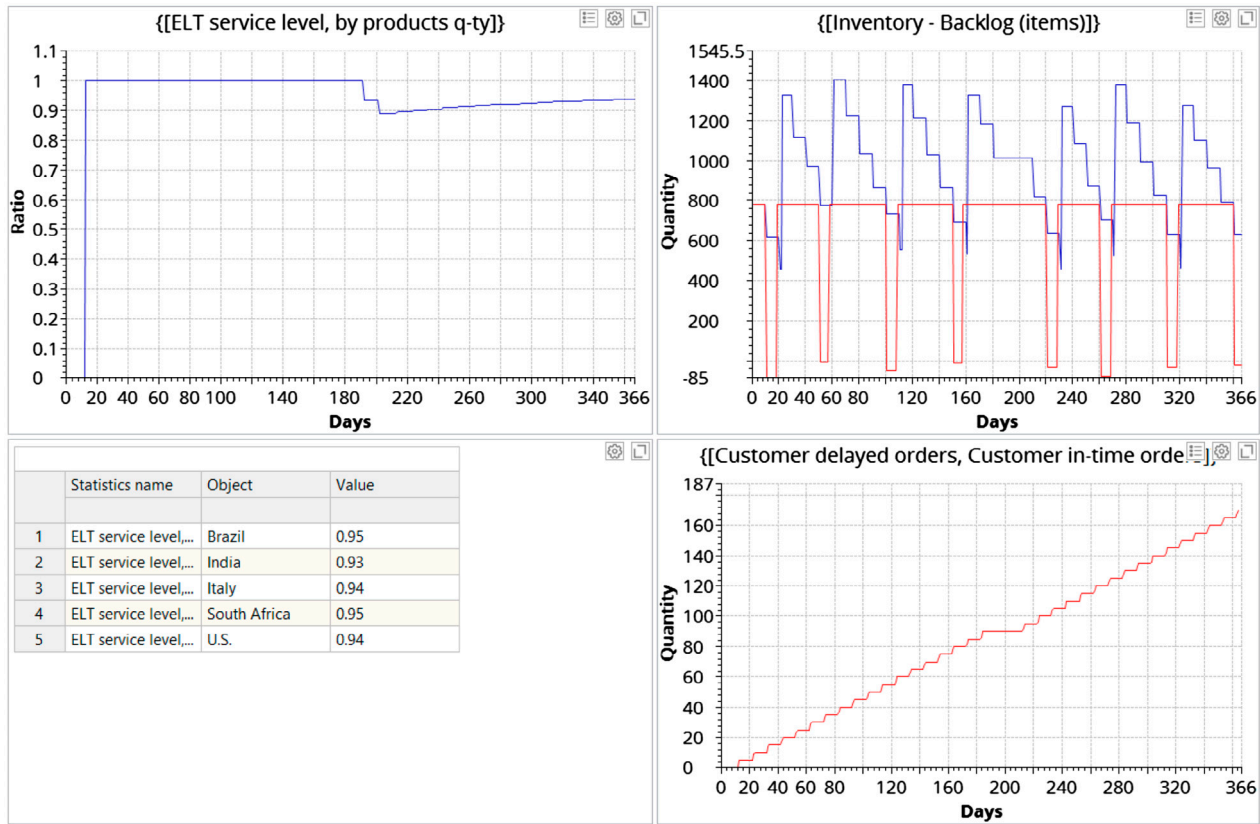


Figure 4. Experimental results for testing the hypothesis 1: no back-up distribution centre, disruption duration 14 days. Note: blue line – distribution centre statistics; red line – factory statistics.

Table 2. Performance impact computation results.

Disruption duration	Performance impact with no backup distribution centre	Performance impact with backup distribution centre
Disruption-free mode	1	1
14 days	1.05	1.03
30 days	1.08	1.03
60 days	1.18	1.03

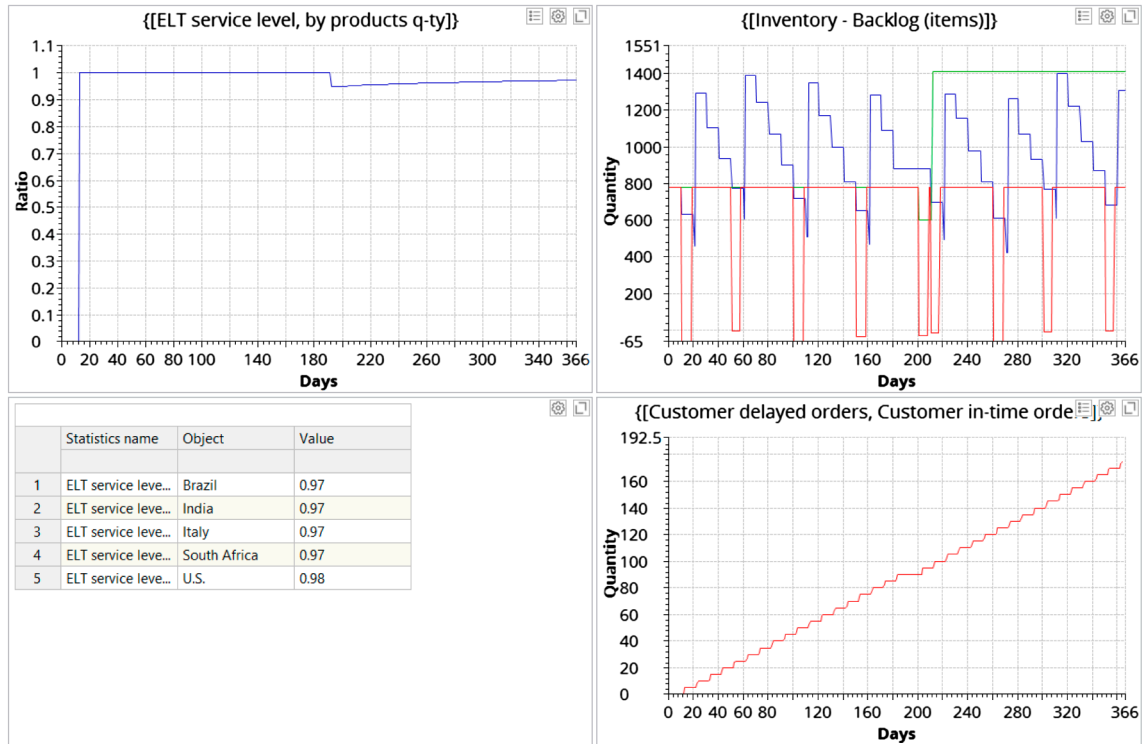


Figure 5. Experimental results for testing the hypothesis 1: back-up distribution centre, disruption duration 14 days.
Note: blue line – distribution centre statistics; red line – factory statistics; green line – back-up distribution centre statistics.

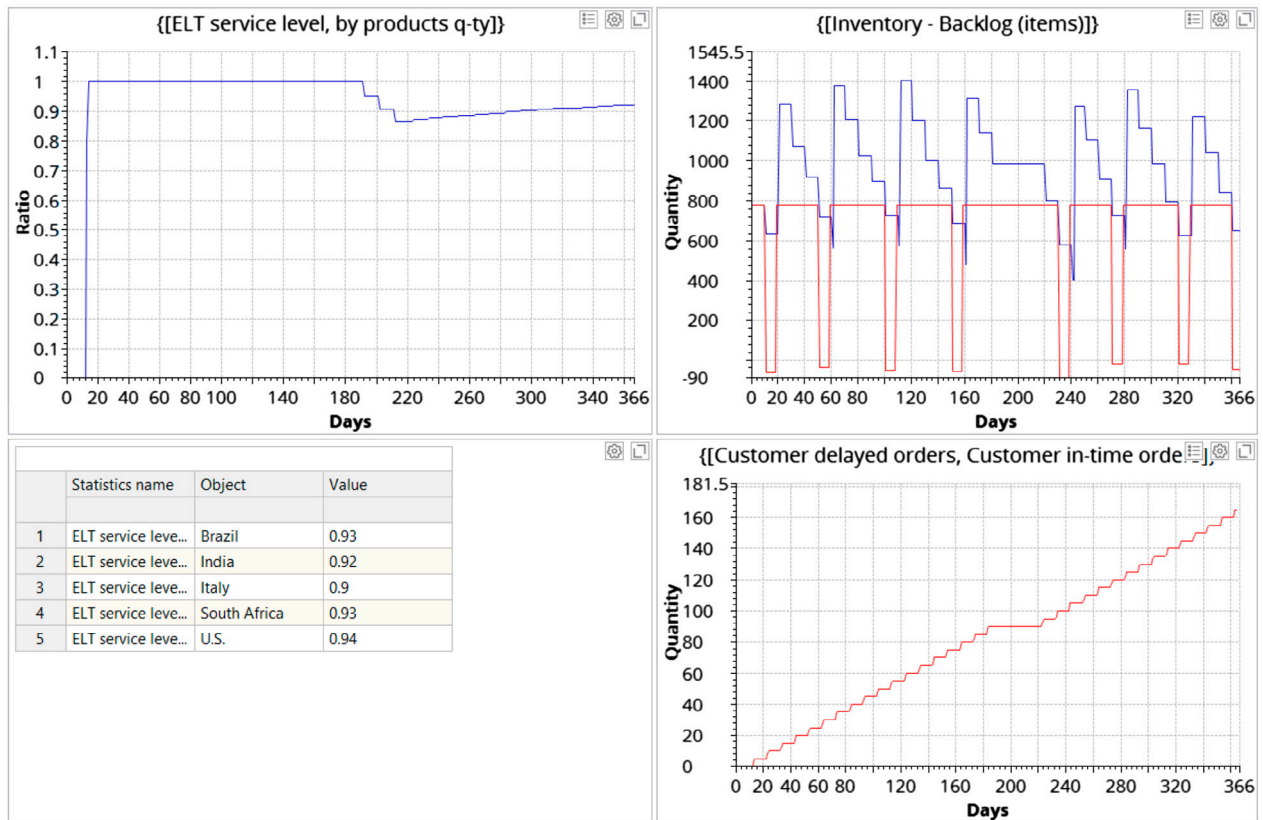


Figure 6. Experimental results for testing the hypothesis 1: no back-up distribution centre, disruption duration 30 days.
Note: blue line – distribution centre statistics; red line – factory statistics.

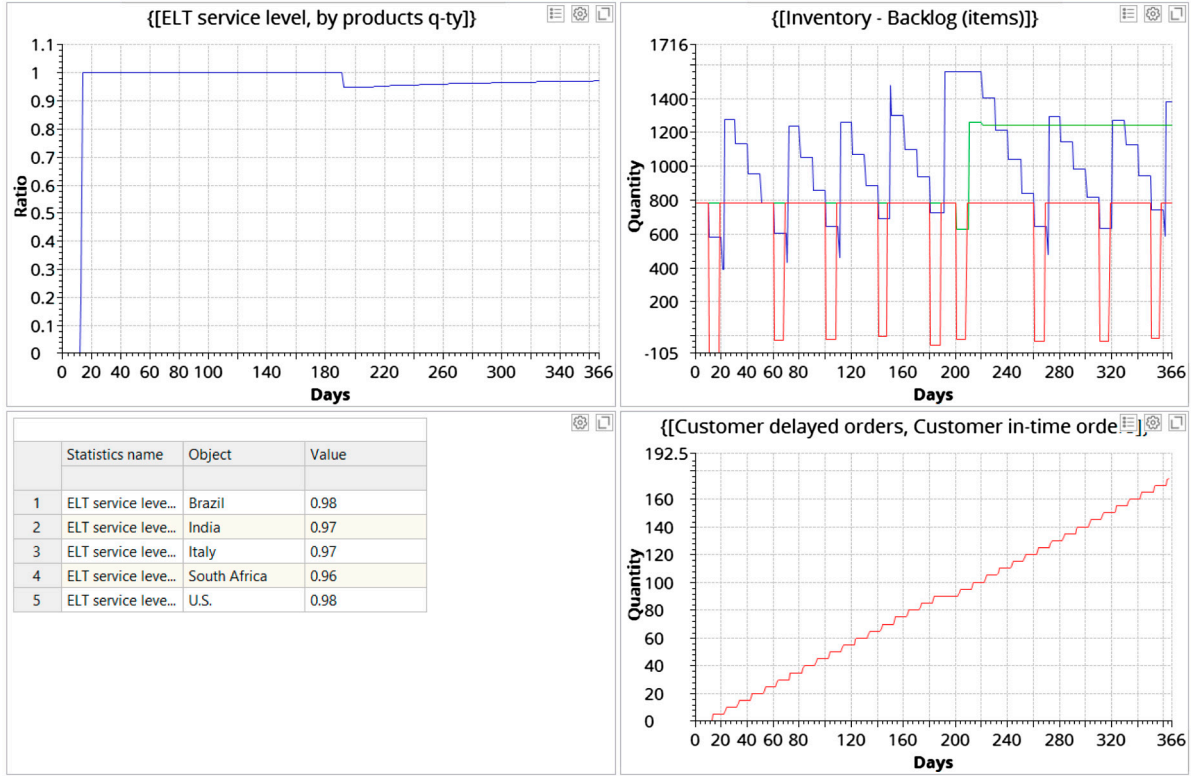


Figure 7. Experimental results for testing the hypothesis 1: back-up distribution centre, disruption duration 30 days.
Note: blue line – distribution centre statistics; red line – factory statistics; green line – back-up distribution centre statistics.

that nevertheless falls below 100% (cf. Figures 3 and 4). The reason is that, unlike in technical systems where 100% robustness is ensured by an immediate switch to the backup resource, any change in the supply chain as a socio-organisational system occurs with a certain time lag and requires coordinated efforts and the adaptation of supply chain behaviour to the disruption (Figure 10).

Figure 10 depicts a time lag between the recovery launch and recovery impact on service level gap reduction that has been observed in Figures 4–9. This allows a conclusion that proactive policies in the supply chain need to be designed in regard to the disruption durations. In the considered example, it is questionable if a backup distribution centre is to be recommended for short-term disruption expectations. Another reason for the reaction time delays in service level reduction below 100% is batching in production, transportation, and sales. In addition, backorder rules and capacity flexibility issues need to be included in analysis. Moreover, human aspects need to be involved with this analysis (Figure 11).

Figure 11 depicts the perception (partially derived from the experiments and literature) that for short-term disruption durations, adaptability is low and recovery actions are at the beginning of their implementation causing high coordination efforts. The intersection point of the two opposite behaviours can be read as a kind of a break-even point concerning recovery investments. Prior to this point, the recovered performance is lower as the efforts for the recovery. Passing this point, the system performance recovery can be seen as a surplus in regard to the recovery efforts. This trade-off represents a promising future research avenue.

H2: Lower inventory enhances sustainability but causes the ripple effect.

In the experiments for this group, we compare supply chain performance for different disruption durations for the case of three s , S policies at DCs. We perform a variation analysis for $s = [400; 1500]$ and $S = [1000; 3000]$ with step 50 and 100 replications in order to observe the resulting service level. The results indicate that there is no change in service level. This is quite intuitively understandable since if the distribution centre is disrupted it does not matter how much inventory it carries; the outgoing operation is broken and customers will not receive the order products.

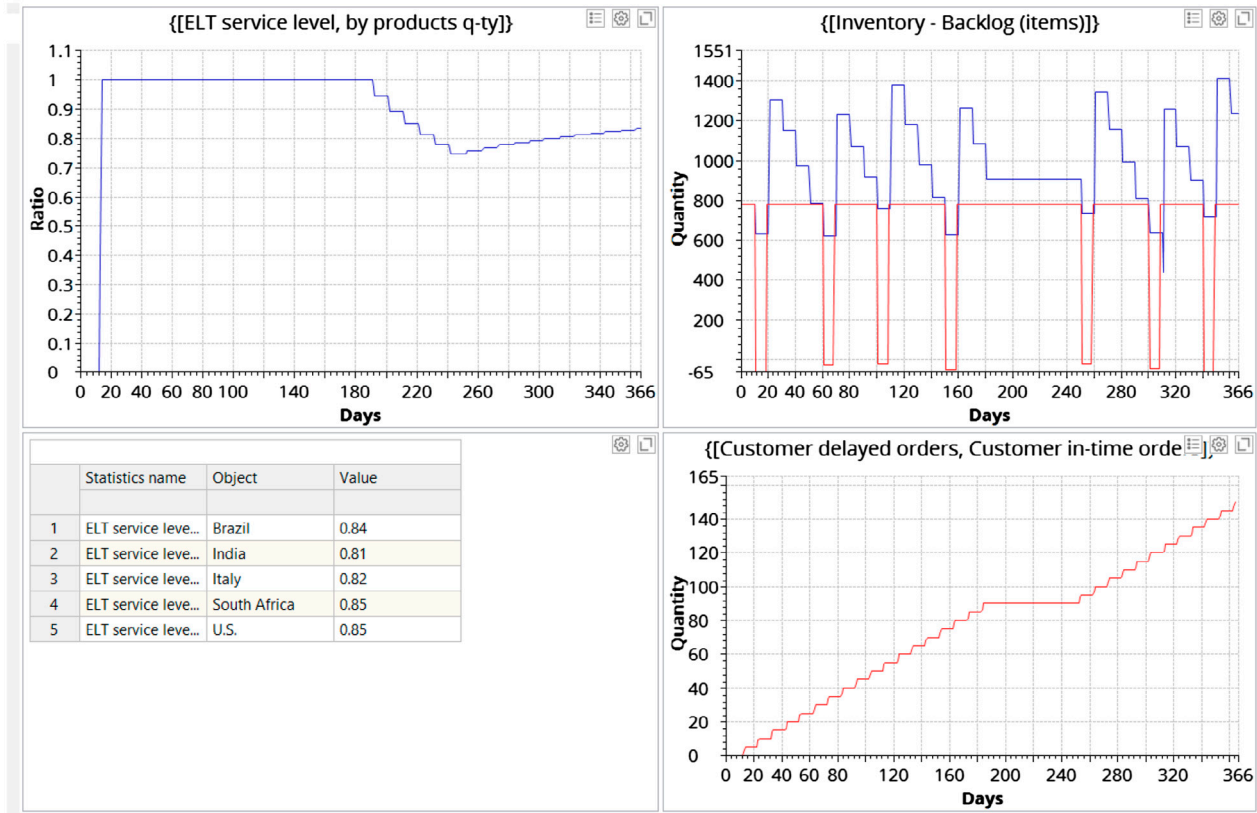


Figure 8. Experimental results for testing the hypothesis 1: no back-up distribution centre, disruption duration 60 days. Note: blue line – distribution centre statistics; red line – factory statistics.

Second, we introduce an additional regional warehouse in South Africa with $s = 70$ and $S = 140$ subject to a risk mitigation stock for two months in regard to regional demand (Figure 12).

The simulation results are shown in Figure 13, which depicts the performance impact for the case of a 60-day disruption.

It can be observed from Figure 13 that a regional distribution centre (i.e. green line in the inventory-backlog diagram) with sufficient risk mitigation stock allows avoidance of the ripple effect in regard to the market in South Africa where 100% service level has been achieved, unlike in all other markets where a ripple effect can be observed through service level reduction.

We do not perform experiments with inventory level and warehouse number upstream of the distribution centre because recent literature identified the necessity of placing safety stock and additional warehouses downstream of facilities at risk of disruption (Schmitt and Singh 2012; Ivanov 2017).

4.2.2 Insight 2

The experiments agree the conclusion that the inventory level at the facility at risk of disruption does not influence the service level and the ripple effect. Therefore, sustainable practices to reduce inventory can be applied at those facilities without restrictions in regard to resilience and ripple effect. On the other hand, an increase in the number of storage facilities in the supply chain downstream of the at-risk facility allows the ripple effect to be reduced.

H3: Reinforcing major employers' facilities in regions mitigates the ripple effect and enhances sustainability.

In the experiments in this group, we compared supply chain performance for different disruption durations in the case of additional investment for reinforcing facilities. We tested the impact of three levels of factory building protection on disruption duration and supply chain performance. Here, graphics and diagrams are avoided, since they are quite similar to the results of the disruption-free case and scenarios in H2. In general, higher investment in facility protection leads to shorter disruption time or even to an avoidance of disruptions.

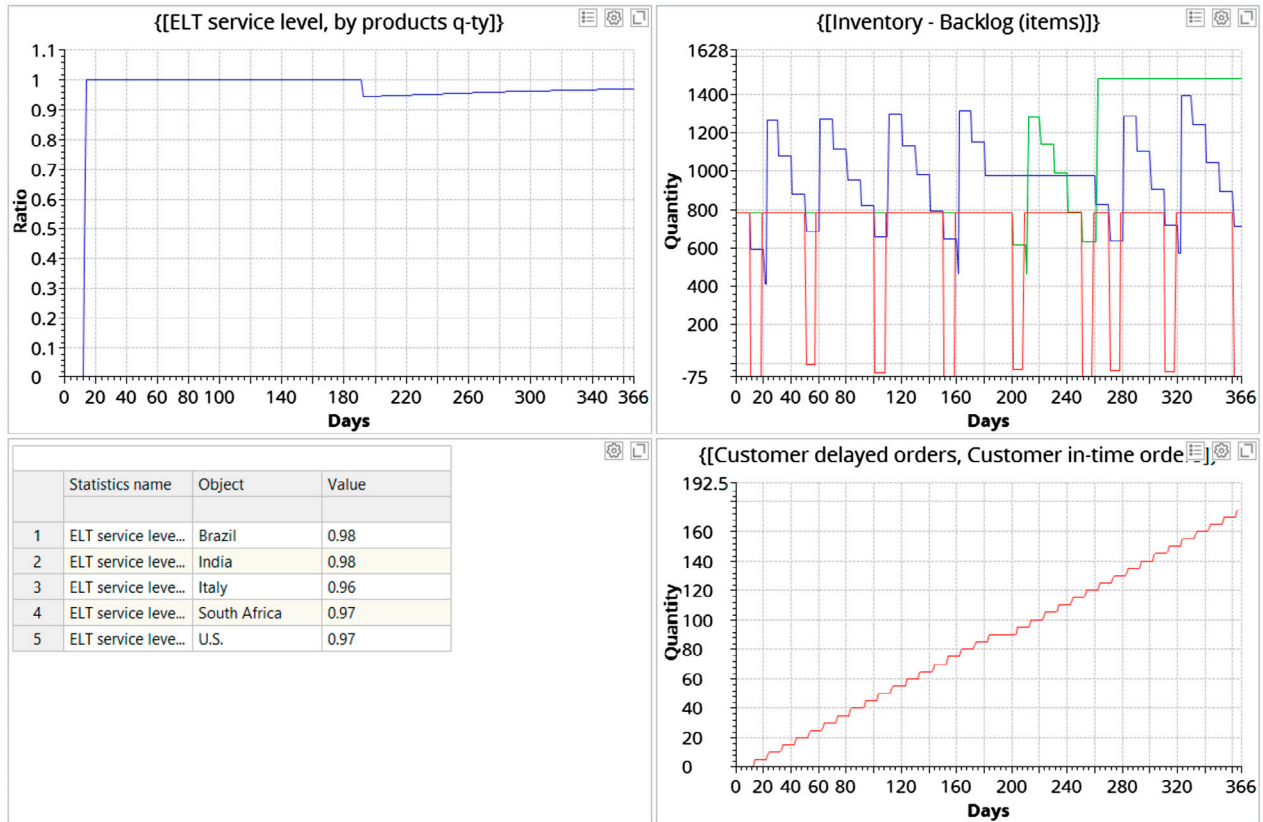


Figure 9. Experimental results for testing the hypothesis 1: back-up distribution centre, disruption duration 60 days.
Note: blue line – distribution centre statistics; red line – factory statistics; green line – back-up distribution centre statistics.

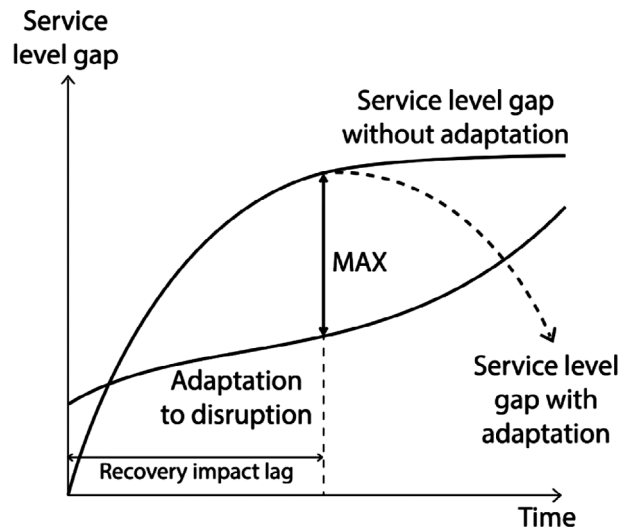


Figure 10. Impact of time on service level gap and adaptability.

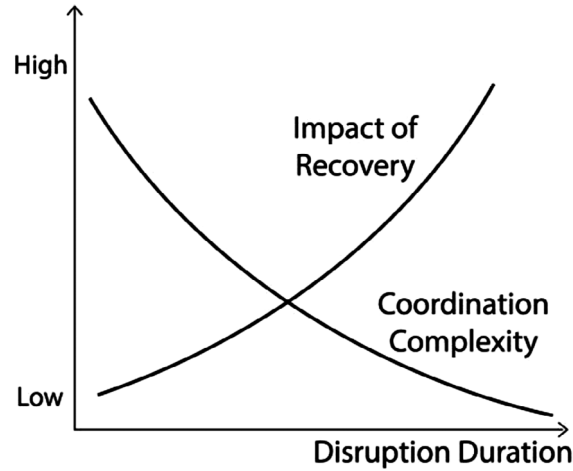


Figure 11. Dependence of coordination complexity and recovery impact on disruption duration.

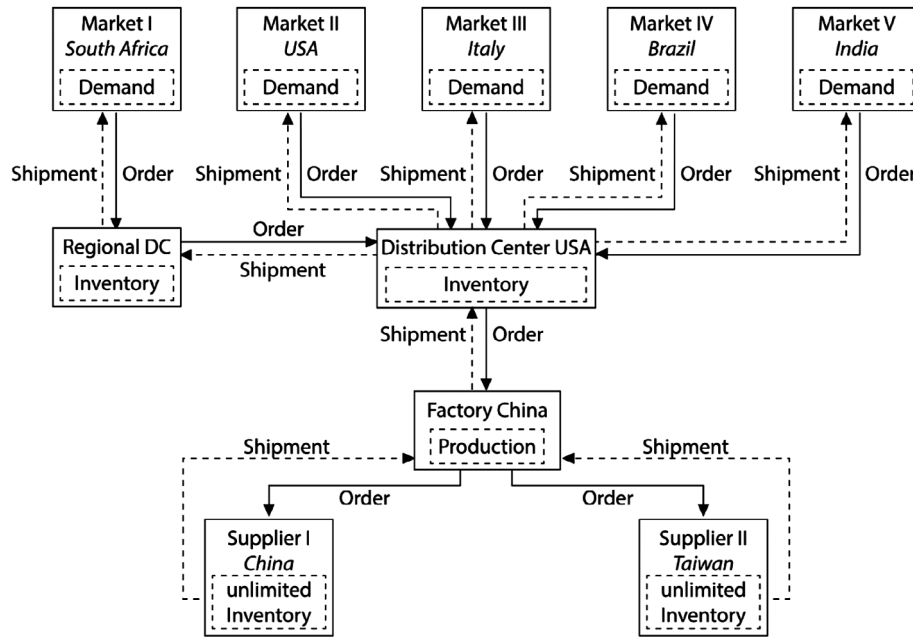


Figure 12. Re-designed supply chain with a regional distribution centre.

4.2.3 Insight 3

This simulation experiment showed that facility protection mitigates the ripple effect and positively affects customer service level. At the same time, investment in facility reinforcement can be considered an important sustainability driver, since many suppliers play the role of major employers in their regions and their ability to survive is crucial for regional and societal development. In addition, this may have positive effects on environmental protection. Therefore, facility protection both increases supply chain resilience and enhances sustainability.

4.3 Result analysis

Let us summarise the analysed relations of supply chain resilience and sustainability concerning three hypothesis:

H1: Sustainable single sourcing enhances the ripple effect.

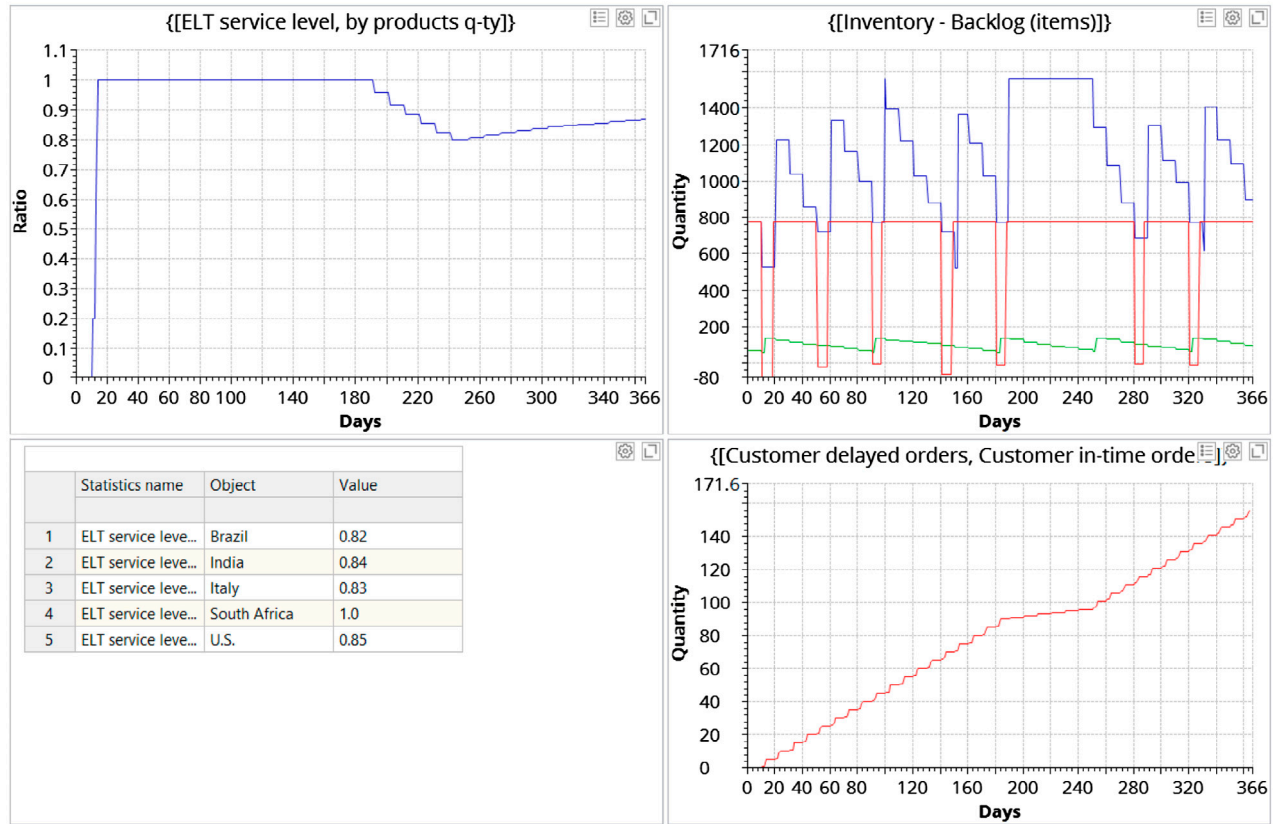


Figure 13. Experimental results for testing Hypothesis 2.

Note: blue line – distribution centre statistics; red line – factory statistics; green line – regional distribution centre statistics.

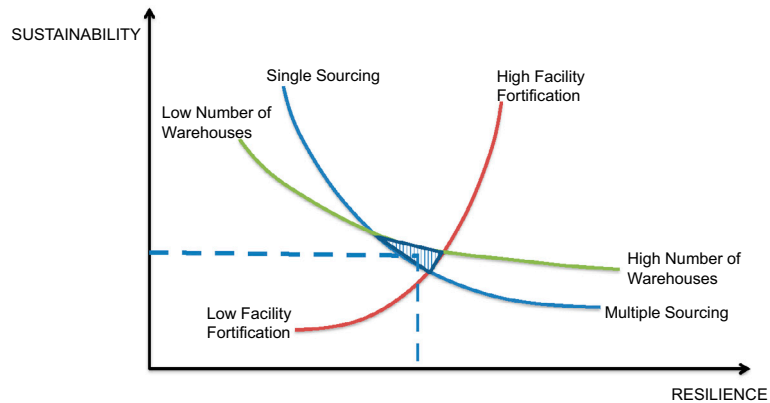


Figure 14. Sustainability and resilience drivers in the supply chains.

H2: Lower inventory enhances sustainability but causes the ripple effect.

H3: Reinforcing major employers' facilities in regions mitigates the ripple effect and enhances sustainability.

The investigation results are summarised in Figure 14.

Sustainable sourcing practices imply the selection of a single source supplier. However, the most sustainable supplier might be not the most efficient or robust supplier. Long-term trust-based relations with suppliers and securing steady

employment relations in supply regions may collide with supply base flexibility to mitigate the ripple effect by dual/multiple sourcing and backup facilities.

Cost efficiency and waste minimisation practices imply less inventory along the supply chain. While such strategies may be environmentally sound and economically grounded, they may negatively affect the supply chain resilience subject to limited availability of risk mitigation inventory to cope with disruptions.

Supply chain design structures and networking have a long-term nature; largely they shape the labour market and employment developments in the regions. In many cases, the facilities represent major employers in a region. That is why it is mandatory to consider resilience and sustainability issues having such facilities in the supply chain design.

The gained simulation results can also be generalised beyond the tested hypotheses. All three insights clearly depict the fact that sustainability issues are encountered in resilient supply chain design. At the same time, a general correlation between efficiency, sustainability and resilience is difficult to state and it requires a further detailed investigation. Lean management practices mostly imply a trade-off between efficiency and resilience whereas sustainability drivers imply both contradictory and complementary goal relations. This trade-off requires a more detailed analysis in future using real data on costs and revenues of the companies. In this study, we avoided an explicit costs consideration and focused on service level and lead time issues. The efficiency considerations in this paper are based on commonly known assumptions (i.e. single warehouse system has lower fixed and operating costs as a dual-sourcing system).

5. Conclusions

The empirical, experimental and quantitative modelling efforts in the two areas – supply chain resilience and sustainability – have previously been conducted in isolation with a few studies on their correlations. This paper aimed at analysing disruption propagation in the supply chain with consideration of sustainability factors in order to design resilient supply chain structures concerning ripple effect mitigation and sustainability increase.

Ripple effect in the supply chain occurs if a disruption at a supplier cannot be localised and cascades downstream, impacting supply chain performance. In this research, a simulation-based study was designed to identify what sustainability factors mitigate the ripple effect in the supply chain and what sustainability factors enhance this effect. Three hypotheses have been tested concerning the impact of sourcing, inventory and facility protection policies.

The results indicate that (i) sustainable single sourcing enhances the ripple effect; (ii) facility protection for major employers in regions mitigates the ripple effect and enhances sustainability; (iii) reduction of storage facilities in the supply chain downstream of a facility at risk of disruption increases sustainability but causes the ripple effect.

An interesting effect has been observed in testing the hypotheses on the impact of single vs. dual sourcing. In the case of a backup distribution centre, disruption duration did not influence service level gap. At the same time, in the case without the backup distribution centre, the gap between disruption-free service level and service level in the presence of disruptions became greater with increasing duration of disruption. However, in the short-term, the backup distribution centre could only slightly improve the service level as compared to the supply chain design with single sourcing. In short-term disruption durations, adaptability is low and recovery actions are at the beginning of their implementation requiring high coordination efforts. That is why it is questionable if a backup distribution centre is to be recommended for short-term disruption expectations. Another reason for the reaction time causing delays in service level reduction to below 100% is batching in production, transportation, and sales. This aspect can be highlighted as a future research topic.

The limitations of the gained results belong to data-dependent analysis whereas the managerial insights are based on multiple simulation runs with replications. Nevertheless, more detailed sensitivity analysis and using different data-sets would allow precisising the gained findings and, probably, revealing additional managerial insights. This is a topic of future research. Similarly, another supply chain structures need to be considered to generalise the gained results to different industry sectors.

In future research, recommendations need to be developed that include specific management practices such as dual sourcing policies, risk sharing contracts or continuous capacity tracking at the interface of resilience and sustainability. Since supply chain design structures and networking are of a long-term nature, they shape the labour market and employment development in the regions largely. That is why it is mandatory to consider these issues while developing contingency and recovery plans for cases of disruption. In addition, both backup suppliers and alternative transportation channels require sustainability assessment as both single entities and in the light of new supply chain design structure formations because of dynamic reconfigurations in the case of disruptions.

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