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ORIGINAL PAPER

THE EFFECTS OF SUPPLY CHAIN COMPLEXITY ON RESILIENCE – A SIMULATION-BASED STUDY

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ABSTRACT. Background: The aim of the paper is to analyse the effects of disruptions on supply chain performance and overall resilience. In recent years, global supply chains have been under great pressure and faced many challenges, like demand fluctuation, lack of raw materials or supply, disruption of transportation corridors and lockdowns. As a response to this, global companies started to reorganize their supply chains, trying to save and maintain their core operations by reshoring, multiple sourcing or increasing their inventory levels, and thereby reaching a higher level of long-term supply-chain sustainability.

Methods: The disruptive changes in transportation resources and their overall impact on supply chains and their complexity were explored. By using the simulation tool Simul8, hypotheses on how disruptive events influence supply chain performance were tested. The model tested key performance indicators (KPIs) of 3- and 4-tier supply chains, primarily average lead time in the system, average idle time in process, and resource utilization level.

Results: In this study, a standard 3-tier supply chain model was compared with a 4-tier supply chain model to determine how KPIs change when there is disruption to transport and storage capabilities. The results indicate that in case of disruption, the 3-tier supply chain performs better than the 4-tier supply chain, even if the 4th tier is a cross-docking center inserted into the system to be able to react to demand fluctuations quickly. Based on this outcome, complexity does not serve resilience.

Conclusions: Based on the simulations performed, recommendations are formulated for practitioners on how to develop the structure of supply chains, taking into account their level of resilience.

Keywords: supply chain structure, resilience, simulation, Simul8

INTRODUCTION

In practitioner papers and supply chain portals, companies report on various methods they have used to try to handle the disruptive events of recent years. There are only a limited number of studies and academic papers pointing out how supply chain complexity reduction or inventories can help increase resilience. At the same time, there is only a limited amount of research involving large samples, statistical analysis or simulation. For this reason, the developed simulation models of 3-tier and 4-tier supply chains, based on real geographical data, represent a contribution to a better understanding of potential and real ties and their behaviour when some disruptive constraint appears.

The aim of this paper is to contribute to the assessment of disruptions on supply chain performance and overall resilience. In recent years, global supply chains have come under significant strain, grappling with various challenges, such as demand fluctuations, shortages of raw materials or supplies, disruptions in transportation routes, and lockdowns [Guann et al. 2020]. As a response, global companies started to reorganize their supply chains, trying to save and maintain their core operations by reshoring, multiple sourcing or increasing inventory levels [Medyakova et al. 2020] to increase the long-term sustainability of their supply chains [Nagy et al. 2022].

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In this study research results are presented about how the complexity of a supply chain affects its resilience to a specific disruption [Helou and Caddy 2006; Rangel et al. 2015]. A standard single 3-tier supply chain model was developed, and its complexity was enhanced by additional tiers. Since the role of transportation in effective customer satisfaction is widely discussed [Jałowiec and Dębicka 2017], the main focus of the study was disruptions threatening the transportation process. By using the simulation tool Simul8, the influence of disruptive events on supply chain performance was tested [Rehak et al. 2023; Nagy and Foltin 2022]. The authors hypothesise that the level of complexity and the number of stock-keeping points in the supply chain increase the level of resilience. Simul8 and a standard sample dataset were used to test supply chain structures with different complexity and inventory levels.

The paper is structured as follows. In the literature review, supply chain resilience is defined, and measures are described. The methodological applications of the modelling and simulation help in understanding complex supply chains and their disruptions. In the modelling and simulation, a What-If analysis is applied to identify possible connections within the complex systems and possible sources of increased resilience. In the results section, the findings are presented. In the discussion and conclusion the main message of the research is summarized, together with the limitations and future research directions.

SUPPLY CHAIN RESILIENCE AND THE ROLE OF SIMULATION

Supply chain security refers to the measures that are taken to protect the integrity and reliability of a supply chain. This includes protecting against physical threats such as theft, tampering, and natural disasters, as well as cyber threats such as data breaches and cyberattacks [Dey et al. 2022; Tonn et al. 2019]. Supply chain resilience, on the other hand, refers to the ability of the supply chain to withstand disruptions and continue to function effectively [Ponomarov and Holcomb, 2009]. This includes the ability to adapt to changing conditions, recover from disruptions and maintain the delivery of goods and services to customers, together with minimization of the impact of disruptions and the maintenance of operational efficiency [Jámbor and Nagy 2022; Stone et al. 2020; Yao and Meurier 2012].

One of the most critical processes in supply chains is transportation. During recent years, there have been many disruptions in the transportation networks of global supply chains, e.g. border and port lockdowns during the Covid-19 pandemic or the Suez Canal incident. Within transportation networks, vulnerability refers to susceptibility to external disruptions that could diminish service performance. In contrast to the concepts of network robustness and reliability, vulnerability analysis places greater emphasis on understanding how external interference can affect a network [Sun et al. 2022]. Traffic congestion, as per the definition provided by Weisbrod et al. [2003], arises from traffic delays resulting from the volume of vehicles on the road surpassing the transportation network's capacity. This phenomenon is a common occurrence in everyday life, particularly during peak rush hour periods, but can be extreme in case of a natural disaster [Chang et al. 2022; Cárdenas et al. 2018].

There are several ways to increase the resilience of a supply chain [Rennane et al, 2022]. One method is to assess the vulnerabilities and risks within the supply chain, and then implement measures to mitigate or eliminate those risks. This can include measures such as diversifying the supply chain, building redundancy into the system, and implementing robust contingency plans. The performance of transportation networks is vulnerable to variations stemming from a combination of factors, including traffic incidents, construction zones, weather conditions, special events, control mechanisms, and shifts in demand [Filipovska et al. 2021].

Another method is to conduct regular simulations or exercises to test the resilience of the supply chain. These can include simulations of various types of disruptions, such as natural disasters, cyberattacks or supply chain breakdowns, to see how the supply chain responds and to identify any weaknesses that need to be addressed.

Simulation is a method that can be used to realistically model the operation of processes and systems so that their state changes can be evaluated [Tamás, 2017]. There are several advantages of simulation modelling: it is cheaper and safer than testing the real system and the model can be tested in parallel with the real system [Gubán, 2017]. Simulation software analyses the complex system by mimicking its real behaviour, but because it only considers the important elements, it is much simpler than the real model [Gubán, 2017]. So, the model is actually a simplified version of the real system that works in reality. It is an attempt to describe how the system works so that it can be analysed. These models are created with a specific objective in mind, such as reducing operational risks or costs, but also to increase customer satisfaction.

Byritis [2014] used Simul8 in his dissertation to simulate the time needed to cross the port of Dover, and the dimensions he evaluated were time and performance. By modelling port transit processes, the simulation helped him find the bottlenecks. Filipovska et al. [2021] dealt with the problem of travel times in a transportation network and found Monte Carlo Simulation (MCS) an appropriate tool for the estimation of path travel time distributions. Suryawanshi et al. [2021] used MCS in sensitivity analysis when analysing the impact of operational risk, demand uncertainty and perishability on the expected costs in e-commerce supply chains. Sopha et al. [2020] applied Agent-based Modelling methodology and Netlogo software to simulate the long-term performance of regional distribution centres in archipelagic logistics systems in Indonesia. They found that a hub and spoke distribution system can be more cost effective. Wang et al. [2022] used the SUMO simulation package to design the optimal routing strategy for shuttle buses at Dallas Airport (DFW). Chang et al. [2022] used a simulation optimization technique, sample average approximation methodology, to solve the split delivery multiple destination inventory routing problem in the case of an earthquake in Thailand, and they were able to obtain the best vehicle and inventory routing decision under varying disaster scenarios. As can be seen, researchers have used various simulation methodologies and software packages to study a variety of problems while analysing the transport process, but no research could be identified that examines the impact of supply chain complexity on resilience in case of a disruption in transport.

Based on this literature review, the following hypothesis was formulated:

H1: A supply chain with higher complexity has greater resilience towards disruptive events that limit the availability of transportation capabilities.

In the next section, the plan for the simulation is introduced, and the exact methodology is described in detail.

THE SIMULATION MODEL

Simulation plan

The study analyses how supply chains with different structures react to disruptive events in the transportation process given the same initial supply, inventory and demand data.

The disruptive events in the model affect transportation capabilities. The network's configuration, the existence of travel patterns, and the interdependence of traffic flow between its segments further introduce spatio-temporal interconnections among travel times within the network [Filipovska et al. 2021]. The assessment of travel times is of paramount importance when examining the operational effectiveness of the network [Stajniak and Koliński, 2016].

The inserted distribution centres and cross-docking facilities serve as hubs responsible for aggregating and merging the complete supply of goods, subsequently dispersing these items to various national regions. Optimization and simulation represent the predominant modelling methodologies applied extensively in the realm of supply chains, especially concerning the identification of the most advantageous node placements within a network [Sopha et al. 2020].

A significant challenge in simulating transportation systems lies in the validation of simulation models as accurately mirroring real-world conditions. This challenge arises from the stochastic characteristics of both the micro-level behaviour of drivers and the macro-level properties of road links, necessitating a close correspondence between the statistical outcomes of a substantial volume of simulations and real-world observations [Wang et al. 2022].

The scenarios are theoretical and were tested in Simul8 software. The applied supply chain models are based on the supply chain structures operated by a fictional global company. The sample company is a large company, having subsidiaries throughout Europe and the world. The supply chains it operates represent different levels of complexity both in terms of horizontal and vertical structure as well as in global-local extension; however, we focused on European final product distribution. It was supposed that each supply chain handled the same standard product based on a pallet unit, and the simulations used the same initial supply and demand data. Similar disruption occurred through reduction of the transportation capacity available as a result of a disruptive process. For this reason, four scenarios were tested:

- Model #1: 3-tier supply chain model operating under standard conditions;
- Model #2: 3-tier supply chain model with disruption;
- Model #3: 4-tier supply chain operating under standard conditions;
- Model #4: 4-tier supply chain with disruption.

The results would thus allow the hypothesis to be verified or rejected and answer questions regarding the relevance of supply chain complexity and inventory level in the context of disruptive events.

Design of simulation

The overall research is based on theoretical modelling of the realistic variants of supply chains in the simulation environment Simul8. The initial modelling assumptions are the following:

- the distribution scenarios start from the port of Trieste (Italy) and pass through a cross-docking centre in Maribor (Slovenia) to cover customer needs in and around Budapest (Hungary) and Brno (Czechia);
- distribution models cover distribution from the port of Trieste through the port storage facility, the distribution of palletised unit loads on trucks to a cross-docking centre in Maribor, which is an important crossroads on the highways to the targeted regional distributional areas, which are the surroundings of Budapest and Brno;
- for further testing of supply chain resilience, based on the availability of drivers/trucks, road availability and storage constraints (time and capacity), both 3-tier and 4-tier models were tested, with further consideration of an additional cross-docking in Bratislava (Slovakia);
- on the basis of the developed model, a suitable simulation timeframe was identified by the What-If testing method, where the distribution of the considered material within the selected time constraints given by the working hours did not exceed 6 working days, i.e. the timeframe for the simulations was chosen to be 6 working days, from 9 a.m. to 4 p.m.;
- the distribution roads are highlighted in Figure 1.

The overall approach in the modelling application was implemented in steps: (1) creation of the basic model structure, (2) initial model setup, (3) setting of ideal conditions and overall model optimization, (4) What-If analysis to test the resilience of the prepared models at three levels of efficiency of the resources used (trucks and drivers) and the supply chain elements (cross-docking centres and regional depot).

Fig. 1. Regional dimension of the developed models. Source: own work.

Two optimized models were tested, and both were examined in the context of possible disruptions to transportation resources and capabilities. The developed models were:

- Model #1: 3-tier supply chain model operating under standard optimised conditions, with the structure depicted in Figure 2. This model represents the case of a supply chain originating at the Port of Trieste, continuing through port storage and distribution capabilities to a cross-docking centre located in Maribor, and then splitting into two directions to regional centres in the Budapest and Brno regions, with three local depots each.
- Model #2: 3-tier supply chain model with disruption, with the same structure as Model #1, as depicted in Figure 2;

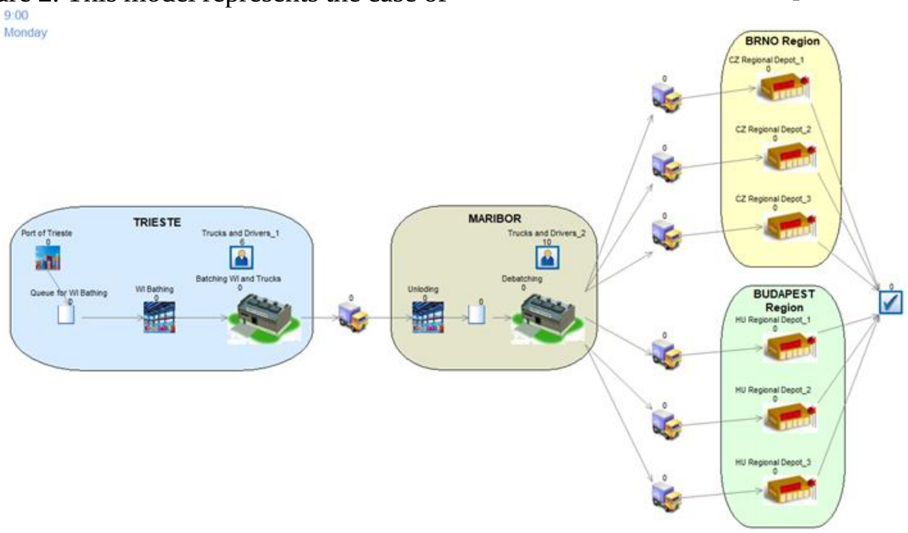

Fig. 2. The 3-tier supply chain model. Source: own work.

- Model #3: 4-tier supply chain, operating under standard optimised conditions, with the structure depicted in Figure 3. This 4-tier supply chain contains an additional regional cross-docking centre located in Bratislava, with the main purpose of satisfying uncovered demand in Budapest and Brno regional depots.
- Model #4: 4-tier supply chain with disruption, with the same structure as Model #3, as depicted in Figure 3.

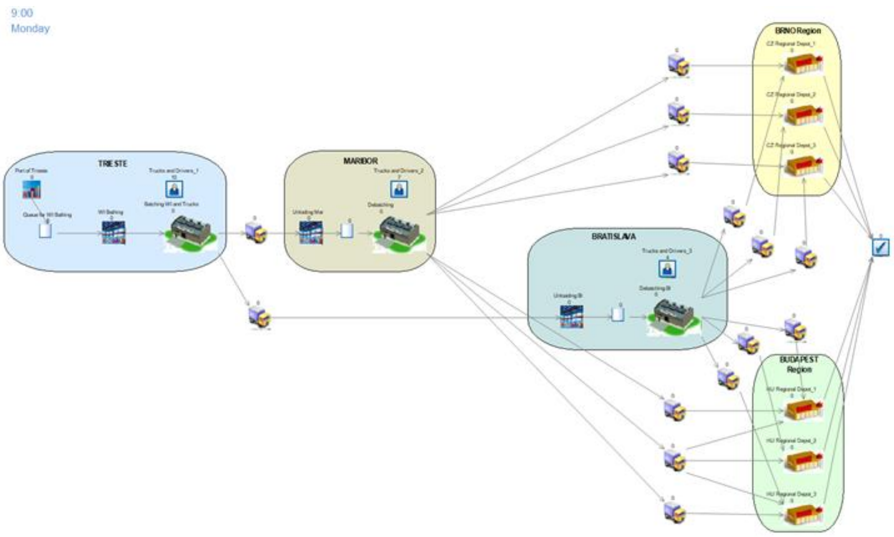

Fig. 3. The 4-tier supply chain model. Source: own work.

Models #2 and #4 were tested according to the key features of real conditions [Kolinski et al, 2017]. Key performance indicators (KPIs) of the two supply chains were tested, primarily lead times and the rate of utilisation of transport capacities while minimising overall distribution times [Sun et al. 2022; Sliwczynski & Kolinski, 2016; Dujak et al, 2017]. At the same time, changes in the overall efficiency of transport and storage capacity utilization, the percentage of drivers working and waiting times were examined.

Model assumptions and limitations

Certain assumptions and constraints had to be made to develop the models and their subsequent testing. However, individual constraints were chosen to ensure that the basic criteria and model functionality were consistent with reality. The model parameters were as follows:

- 1000 pallet units were distributed from the port facility to the port storage facility every 2 minutes;
- trucks/drivers only left the port storage facility fully loaded (FTL), and the maximum capacity of a vehicle was 20 pallets;
- the average speed of the trucks was 80 km/h, with working hours for drivers from 9 till 16 hrs every working day, from Monday to Friday;
- a rounded uniform distribution with a lower bound of 10 and an upper bound of 20 was adopted, meaning that trucks left the cross-docking centre with at least 10 pallets, up to a maximum capacity of 20 pallets;
- all storage capabilities were unified;
- distances and speed within both models were as follows:
    - Trieste-Maribor was 240 km, with 180 mins as a minimum time for a truck to cover the distance;
    - Maribor-Budapest was 350 km, rounded to 260 mins as a minimum time for a truck to cover the distance;
    - Maribor-Brno was 390 km, rounded to 290 mins as a minimum time for a truck to cover the distance;
    - Trieste-Bratislava was 550 km, rounded to 410 mins as a minimum time for a truck to cover the distance;
    - Bratislava-Budapest was 200 km, rounded to 150 mins as a minimum time for a truck to cover this distance, and 100 mins as a minimum time to cover the distance of 130 km between Bratislava and Brno;
    - the average time for drivers and trucks to return to their original destinations was 180 mins for Maribor-Trieste, 290 mins for Budapest-Maribor and Brno-Maribor, 410 mins for Trieste-Bratislava and 150 mins for Bratislava-Budapest/Brno;

- the optimised models were set up for ideal conditions, without any significant sources of disruption exceeding standard normal distribution values.

SIMULATION RESULTS

The actual construction of Models #1 and #3 was intended to reveal the relationships within 3-tier and 4-tier supply chains. Within the basic setup of Models #1 and #3, the models created were primarily optimised for the most efficient use of resources, i.e. the available capacity of trucks and drivers.

Results of Optimal Model Conditions

The optimised #1 3-tier supply chain model was tested by applying a possible disruption in the available resources in transportation and the availability of cross-docking centres and depots. The disruption affected all 3 tiers of supply chain model #1. Then 3 scenarios were tested representing different extents of disruption, as Preston et al. recommend [2018]: thanks to the indicated disruption only 99%, 95% and 90% of the functionality of the optimal model was available. Similarly, the Model #3 4-tier supply chain with disruption was tested, having 99%, 95% and 90% of functionality and capabilities available.

Table 1. The results from the developed models and their tests

Model	resource utilisation [% level of availability]		average time in system [min]	average waiting time in process [min]
(1) 3-tier chain	#1 trucks/drivers: #2 trucks/drivers:	66.3% 61.4%	545.17	11.56
(2) 3-tier chain under disruption	#1 trucks/drivers [99%]: #2 trucks/drivers [99%]:	32.0% 34.1%	546.07	12.94
	#1 trucks/drivers [95%]: #2 trucks/drivers [95%]:	36.5% 38.7%	548.98	12.38
	#1 trucks/drivers [90%]: #2 trucks/drivers [90%]:	40.7% 42.6%	561.41	15.59
(3) 4-tier chain	#1 trucks/drivers: #2 trucks/drivers: #3 trucks/drivers:	34.4% 35.0% 56.6%	604.22	13.39
(4) 4-tier chain under disruption	#1 trucks/drivers [99%]: #2 trucks/drivers [99%]: #3 trucks/drivers [99%]:	35.3% 36.0% 57.7%	604.16	13.27
	#1 trucks/drivers [95%]: #2 trucks/drivers [95%]: #3 trucks/drivers [95%]:	39.5% 39.3% 61.6%	612.85	15.39
	#1 trucks/drivers [90%]: #2 trucks/drivers [90%]: #3 trucks/drivers [90%]:	43.2% 45.0% 67.0%	641.02	25.80

Source: own work.

The simulations showed that strengthening the 3-tier supply chain structure with an additional cross-docking centre does not have clear benefits for the resilience of the chain as a whole. The interconnection of the individual parts of chains was considered. For example, in the 3-tier model, when we used 6 trucks/drivers between tiers 1 and 2 and 10 trucks/drivers in tier 3, the efficiency of the trucks/drivers between tiers 1 and 2 was 61.4% and the efficiency of the tier 3 trucks/drivers was 66.3%. Increasing the number of tier 3 trucks/drivers from 10 to 11 caused a decrease in the efficiency of the tier 1 and 2 truck/drivers (from 61.4% to 55.8%), while the efficiency of the tier 3 trucks/drivers remained the same, 66.3%.

The reduction in the availability of resources (trucks/drivers) and the efficiency of cross-docks and depots in the 3-tier supply chains resulted in a difference between the optimal variant and the capability constraint (90% availability) – an average difference of 16.24 mins. In the case of the 4-tier supply chain, despite the additional cross-docking centre and the increase in transportation capacity (trucks/drivers resources), the difference in average times between the optimal and the 90%-capacity variants was 36.8 mins. In absolute terms, for the 3-tier and 4-tier supply chains, this is a difference of 545.17 mins compared to 641.02 mins, which is 14.2% more time to cover the average distances in the model.

The same is true of the average waiting times in the system, since the difference in the average waiting time between the optimal case and the case of limited availability of resources in 3-tier supply chains is relatively small. In the case of a decrease in the performance of the entire chain by 1% or 5%, the difference in the delays when passing through the system is negligible (less than 1 min). When only 95% of capacity is available in the 3-tier chain, the reduction of waiting times – compared to the 99% variant – becomes interesting. This fact points to a certain paradox, since despite the temporary lack of availability of resources and a higher rate of waiting in the system, the overall efficiency can be even higher.

In the case of 90% availability of supply chain capacity, the increase in waiting time to pass through the system was 4.03 mins, which is a 34.9% increase. In the case of 4-tier supply chains, a 1% drop in performance results in a slight reduction in the average waiting time. On the contrary, a higher level of disruption in the 4-tier supply chain causes an increase in delays of 14.9% when the capacity is limited to 95%. When the capacity of the chain is significantly disrupted and only 90% of capacity is available the increase in delays is 92.7%.

Utilization of cross-docking capabilities during the whole simulation

The application of the concept of cross-docking centres aims to handle and balance fluctuating demand and optimize distribution channels. If capacities are sized appropriately, they allow the absorption of possible disruptions in the flow of materials, both up- and downstream. This was also the case in the 3-tier and 4-tier models, where the object of the investigation was to identify the absorption capacity of each type of supply chain. The effort was focused on determining, for the chosen case study, which of the supply chain types exhibits a greater ability to absorb potential disruptions.

In the proposed 3-tier and 4-tier supply chains, the cross-docking centre in Maribor plays a decisive role. For a 3-tier supply chain, in optimal conditions, 25.62% of the warehouse operations are picking/stocking and the remaining average time required for the distribution of all pallets (545.17 min. in ideal conditions) represents 74.37% of the time, when the warehouse performs the role of storage and is waiting for the next order or dispensing material. In this case, there are no other conditions such as waiting due to unavailability of resources, system overload, or system blockage (Figure 4).

In the case of a 10% limitation of distribution and resource capacity, the average distribution time increases to 561.41 mins, and warehouse utilization during loading/unloading operations increases to 30.75%. The potential expected increase in cross-docking centre capacity utilization is reduced by 6.56% due to the need to wait for available transportation resources (i.e., trucks/drivers) and by 7.17% due to overcrowding of the centre hindering it in performing its function. The changes in centre efficiency are shown in Figure 4, on the left for optimal conditions and on the right for the situation where capacity is constrained to 90% of the optimal conditions. If the total capacity of the cross-docking centre drops to 90%, the available capacity drops to 13.73%.

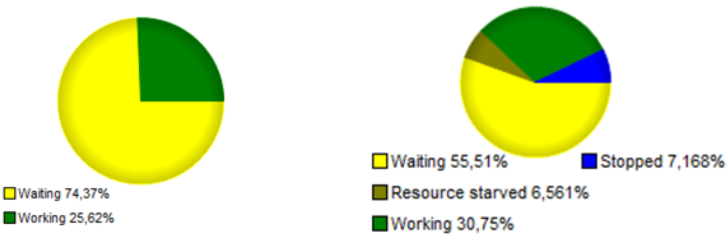

Fig. 4. Utilization of cross-docking centre in Maribor, under optimal conditions (left) and under 90% system efficiency (right). Utilization of cross-docking centre in Maribor in the 3-tier supply chain, under optimal conditions (left) and under 90% system efficiency (right). Source: own work.

The 4-tier supply chain already exhibits longer average transit times in the optimized state, given the same distances and distribution conditions (Figure 5). Under optimal conditions, the 4-tier supply chain time requirement in the cross-docking centre in Maribor for loading/unloading operations is 12.18%, and in the cross-docking centre in Bratislava represents 8.44% of the total time. In the case of capacity constraints due to disruption in functionality resulting in only 90% available capacity in the 4-tier supply chain, the utilization of the cross-docking centre in Maribor remains at the same level; however, resource needs increase to 5.94% and the time requirement increases from 8.44% to 9.91%.

In case of the Bratislava cross-docking centre, the active use of resources also remains at the same level, but their availability is limited; distribution takes place only 6.54% of the time, and the warehouse is unavailable for 10.61% of the simulated time. A combined representation of the simulated availability of cross-docking centre capacity in Maribor and Bratislava within a 4-tier supply chain is shown in Figure 6.

The simulated real usage of the Maribor centre drops by a total of 15.85% when the system capacity availability drops by 10%. In the case of the cross-docking centre in Bratislava, when the system availability drops by 10%, its efficiency drops by 17.15%. Moreover, the reduction in capacity availability is 34.9%, which is more than in the 3-tier supply chain.

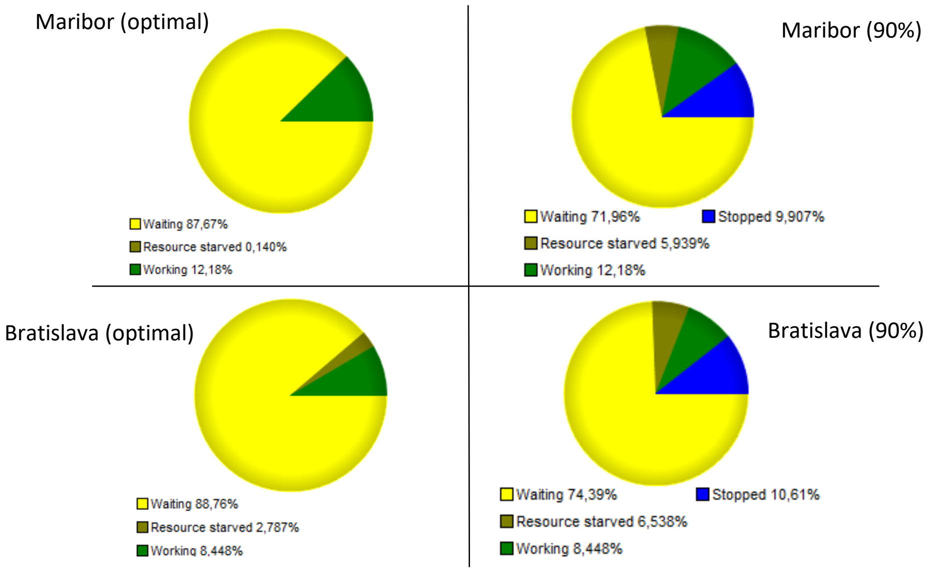

Fig. 5. Utilization of the cross-docking centres in the 4-tier supply chain, under optimal conditions (Maribor left top, Bratislava left bottom) and under 90% system efficiency (Maribor right top, Bratislava right bottom). Source: own work.

A limitation of the simulations and the results is that the efficiency of cross-docking centres in the whole simulation was calculated assuming that they worked for six working days between 9 am and 4 pm. The time distribution in Figure 4 and 5 are based on these working hours.

To better understand the impact of potential supply chain disruptions and capacity constraints, it is useful to observe the utilization patterns throughout the simulation study. A time analysis of the availability and capacity utilization of the cross-docking centre in Maribor for 3-tier and 4-tier supply chains is shown in Figure 6.

The time courses (Figure 6) show a difference in absorption capacity between the 3 and 4-tier chains. Within the 3-tier chain, there is less frequent congestion of individual system elements (upper part of the image, blue colour), unlike in the 4-tier supply chain (lower part of the image, blue colour). Also, within the 4-tier supply chain, more frequent blocking of entries to cross-docking centres can be observed (lower part of the image, red colour). In the same way, there is a more significant reduction in the suspension of distribution processes due to the limitation of transport and distribution capacities, such as trucks and drivers (lower part of the image, dark-green colour).

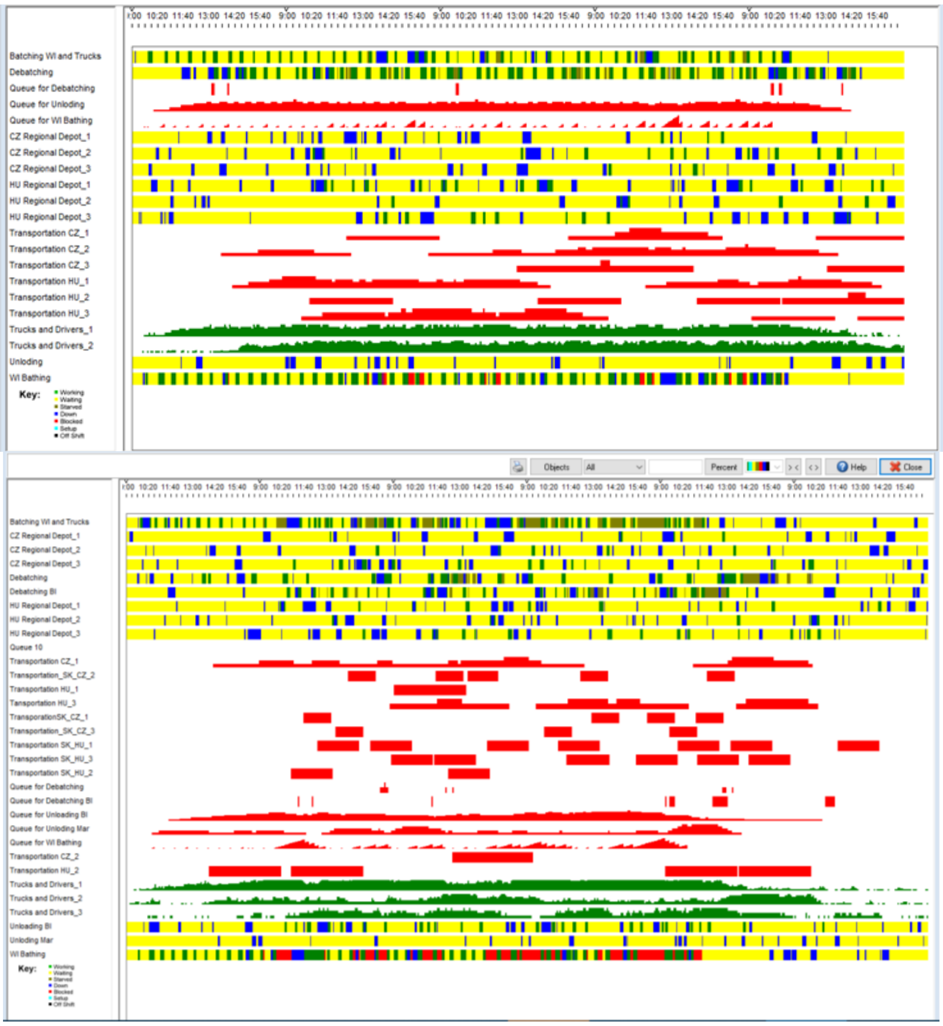

Fig. 6. Comparison of the time course of 3-tier (top) and 4-tier (bottom) supply chain model functionality when capacity and resource availability drop to 90%. Source: own work.

DISCUSSION AND CONCLUSION

The aim of the conducted research was to contribute to a better understanding of the relationships and ties within supply chains and their ability to face possible disruptions. Although a number of studies have used simulations to investigate elements of the transport process, even at the supply chain level, no studies were found that correlated the complexity of a supply chain with its resilience to a disruptive event. In this respect, this study is unique, and its findings do not confirm preliminary expectations.

In the simulation, Preston's [2018] approach was applied, and pessimistic, normal and optimistic scenarios were tested for disruption in the transport process. The problem was approached from the micro point of view [Wang et al. 2022], and the operative transport capabilities were analysed. The travel time (transit time) of goods proved to be crucial in the current model [Filipovska et al. 2021] and was sensitive to exogenous operational conditions. The study confirmed the statements of Sopha et al. [2021] about point-to-point networks having lower performance than a hub-and-spoke system, and this is a good further improvement possibility for the research. Suryawanshi et al.

[2021] proposed prepositioning inventory, and Yang et al. [2021] argue for surplus inventory as disruption management techniques. The study does not support these ideas, as additional stock-keeping points in the 4-tier supply chain did not increase resilience.

Within the identified research gap, models of 3-tier and 4-tier supply chains were created and their ability and effectiveness to absorb potential disruptions of supply chains and efficiency were tested. The created models were optimized through a What-If analysis and set to a stable level showing optimal use of resources (primarily trucks/drivers). Subsequently, disruption of their functionality was investigated at 99%, 95% and 90% of the original optimized level. In order to realize the examined links of 3-tier and 4-tier supply chains, a theoretical geographically localized model was chosen to analyse the possibilities of distributing 1000 pallets from the port of Trieste through an imaginary cross-docking centre in Maribor, with subsequent distribution to the regions around Budapest and Brno. For the 4-tier supply chain, a compensating cross-docking centre was added to the 3 tiers to better absorb potential disruptions.

From the experiments carried out for the given region, the given distances and the throughput of the road network, it was found that:

- the 3-tier supply chain had a higher time efficiency in an optimized state without disruption, on average by 9.8% compared to the 4-tier supply chain, while at the same transportation resource requirements were 31.3% lower compared to the 4-tier supply chain;
- when the available capacities and resources were limited to 90% of the optimized state, the 3-tier supply chain was 14.2% more time-efficient than the 4-tier supply chain, with the same resource needs as in the optimized state, i.e. 31.3% lower demands on distribution-transportation capabilities;
- following a reduction of the available distribution capacity within the 4-tier supply chain by 10%, the degree of non-functionality of the main cross-docking centres was approximately 10%, but in the case of 3-tier supply chains, part of the disruption could be absorbed, and their blocked capacity was approximately 7.17%, which shows their ability to absorb 2.8% of malfunctions only due to their appropriate structure and location;
- at the same time, when the availability of transport and storage capacities of the supply chain was reduced to the level of 90% of the optimized chain, the 3-tier supply chain was able to absorb possible disruptions and spread them over smaller periods of time, thereby increasing the absorption capacity of the system and thus its overall resilience.

The research confirms hypothesis H1, that shorter distances could lead to higher efficiency for supply chain with fewer elements, both under optimal conditions and also if potential disruptions decrease the available capacity to 90% of the optimized level. It was proved that creating an additional cross-docking centre did not improve resilience in the case of the malfunction of supply chains, even though one may imagine that a depot close to the market or additional inventory would increase resilience. Based on these results, it would be appropriate to verify the given findings concerning 3-tier and 4-tier chains, completely or at least partially, on real data. At the same time, it would be appropriate to try to link the given findings to other important attributes of logistics analysis, such as, for example, cost and profitability analysis and ecological footprints.

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