Digital Supply Chain Twins for Sustainable Planning of a Logistics System

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Abstract. Digital Supply Chain Twins (DSCT) are gaining more and more attention both in science and in practices. They are considered to be one of the most disruptive technologies in logistics and supply chain management. In the literature, there are a variety of DSCT benefits in the case of planning and control a logistics system. Some of these potentials could also be highly suitable for the use case of sustainable and resource-efficient logistics, which, however, have been insufficiently explored in research so far. This paper will investigate to what extent the DSCT can be used to enable sustainable network planning and which potentials the DSCT implies for the predictive planning within logistics systems. Building on a literature review and interviews with industry experts a case study was conducted at a business partner in the automotive industry.

Keywords: Digital supply chain twin · logistics · supply chain · sustainability · planning

1 Introduction

Logistics is an interdisciplinary, cross-sectional function that not only enables companies to meet market demand and ensure their long-term success, but also to master future challenges along increasingly complex logistics chains in the long term [1]. In this context, logistics plays a key role, particularly in meeting future climate targets.

Within the context of globalization, there is an increasing spread of manufacturing sites, warehouses and corporate locations, which can on the one hand guarantee cost advantages with lower labor levels or geographical proximity to customers and the respective target market. However, recent crises have been an unprecedented stress test for many international logistics chains [2]. Latest crises have been an unprecedented stress test for many international logistics chains. Above all, the Covid-19 pandemic had a huge impact on future design and the management of logistic networks. Many global value chains have been disrupted by closed factories, ports or airports, leading to longer transport times and lack of resources [3, 4]. The war in the Ukraine and the resulting economic sanctions are another challenge for international value chains. Uncertainty about future energy supplies, the operations of companies in Ukraine and Russia, and shortages of agricultural products are just a few examples [5].

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The economic success of a company no longer depends only on the product and the associated processes, but also on the degree of service orientation of the company. Customers will prioritize the company whose offer corresponds to their individual prioritization of the critical success factors of time, cost, quality and flexibility [2].

One of the greatest overall societal, economic and political challenge of recent times has not yet been named: The climate change. Logistics has a crucial function in meeting this challenge by planning and operating sustainable value chains [6].

Besides the ecological aspect, the concept of sustainability is complemented by the economic and social dimensions that need to be addressed in achieving a future-oriented balance in society and the environment. These dimensions considerably increase the complexity of globally grown supply chains [7]:

For more than a century, the critical success factors of quality, cost, time and flexibility dominated global value chains. Through technological advances and digital transformation in companies across all sectors of the economy, logistics systems worldwide have grown so efficient that we are today in an unprecedented state of global prosperity. However, the planet's natural boundaries and limited natural resources are putting a definite end to the constant growth and endless demand for resources. Consequently, the optimization of our systems must take place with equal consideration of sustainability. It is mandatory that the critical success factors be fully complemented by the aspect of ecological sustainability [7].

The growing complexity caused by disruptions and integration of sustainability as an equal success factor can only be implemented with the support of digitalization. On the path to digital transformation in companies, a wide variety of technologies are being discussed, some of them in a concerted manner [8]. The Digital Supply Chain Twin (DSCT) is considered a promising opportunity due to its simulation-based recommendations for action, forward-looking planning and control of global logistics systems. The topic of sustainability cannot only be implemented as a selective optimization of the network, but also requires a collaborative and cooperative approach between different stakeholders within the value network. The DSCT was included in Gartner's Hype Cycle in 2017 and is considered one of the most disruptive technologies in logistics and supply chain management [9].

Scientists have criticized the predominant theoretical research in the field of the digital supply chain twin [10], which is why this paper has examined a case study of a real material flow in the automotive industry. Here, on the basis of historical data, it is conceptually worked out when the DSCT could have predicted a proactive demolition of the delivery capability on the basis of its characteristics (RO1) and which transport routes, which were non-transparent up to this point, can be shown by the created visibility of the network by the DSCT for sustainability assessment (RO2).

2 Theoretical Background

2.1 Conceptual Clarification of Digital Supply Chain Twins

The primary idea of the concept goes back to NASA's Apollo mission and was further developed by Professor Grieves in the early 2000s [11]. The focus was to predict the behavior of physical objects through simulations and to enable foresighted planning.

Initially, the concept was applied to the product life cycle application domain [12]. In the course of further technical development, the asset-centric approach could be further developed and transferred to entire value creation systems. The paper follows the following definition: *"A digital logistics twin or digital supply chain twin (DSCT) is a digital dynamic simulation model of a real-world logistics system, which features a long-term, bidirectional and timely data-link to that system. The logistics system in question may take the form of a whole value network or a subsystem thereof."* [10].

The DSCT is therefore a dynamic simulation model, which has 3 unique characteristics that distinguish it from other technologies. The DSCT operates in the long term and can therefore learn from historical data. Additionally, there is a bidirectional data exchange between the real and the digital system. The DSCT's recommendations for action are based on various simulations, which can be given timely.

2.2 Scopes of Digital Twins and Digital Supply Chain Twins

The DSCT has evolved from an asset-centric approach to a systemic scope. To describe the different scopes of the DSCT, the differentiation between DSCT and DT is as follows (Fig. 1):

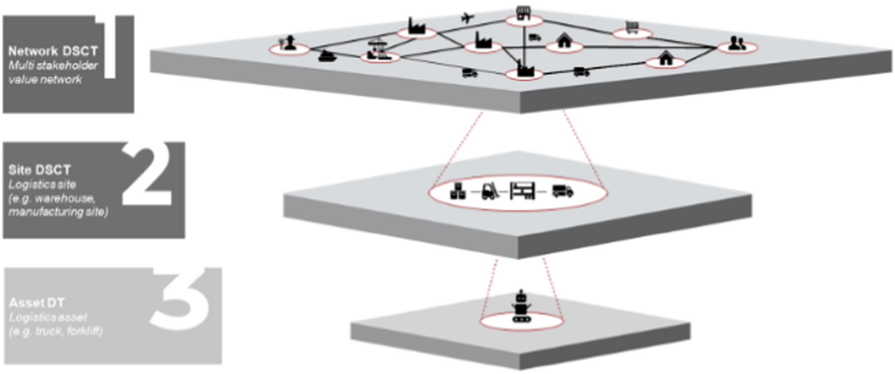

Fig. 1. Scopes of digital twins [13]

The categorization differentiates in particular between Digital Twins and Digital Supply Chain Twins. The Digital Twin refers to the digital representation of assets. In this context, machines or robots can be mentioned, for instance. The Digital Supply Chain Twin is at least a dynamic simulation model of a physical location. This location can be a warehouse, a production site or an infrastructural hub. The most complex DSCT is a dynamic simulation model of an entire network. This includes a wide range of stakeholders.

2.3 Planning

This work focuses on the planning of a logistics system. The planning in the sense of this work has the primary goal to fulfill future performance requirements of the system at any time. For this purpose, the internal processes have to be optimized and the resources should be used accordingly, in order to achieve this at any time. This optimization takes place through the selection, structuring and dimensioning of internal processes. In planning, a distinction is made between medium-term and long-term planning. The long-term planning usually includes the strategic planning, which covers a period of several months up to one year. Due to the lower information density of these periods, the information is uncertain. The accuracy of medium-term planning is correspondingly higher due to a higher information density [14].

3 Research Design

The authors first conducted expert interviews in the automotive industry in order to visualize a real supply chain. Furthermore, an explorative case study is conducted with the aim of gaining pre-theoretical insights [15]. Here, an attempt is made to evaluate to what extent the transparency created by the construction of a DSCT helps to assess the system in terms of forward planning and to evaluate when the DSCT could have predicted bottlenecks based on historical data. Consequently, an exploratory-descriptive case study has been conducted. Based on Yin's approach, the case study was planned, executed and evaluated from planning to interpretation [16].

First of all, according to Yin, the *case study* was sufficiently *planned*. The DSCT creates transparency across all flows of goods in the supply chain. Besides the customers and the corresponding sales markets within the network, various stakeholders such as suppliers can be included. The aim of this study is to examine the extent to which the DSCT can be used for the (predictive) planning of logistics systems. This leads to the following research question: What are the potentials of DSCT to predictive and sustainable planning of logistics systems?

In the next step, the case study was *designed.* In order to validate to what extent, the DSCT would have enabled predictive planning, historical data from the year 2020 is used for the case study. The aim is to anticipate possible bottlenecks at an early stage. For this purpose, data sets from suppliers in Africa and South America as well as from the production site and customer orders were requested. Data was collected on inventories, customer orders, forecasted customer orders, supplier backlogs and customer backorders. The aim is to prevent customer backlogs and the associated inability to deliver. As part of this, the *data collection* could be started. In addition to an extensive literature review and expert interviews to visualize the supply chain of the specific case, the datasets outlined above could be pulled from the MySQL database. Each data set was summed up per calendar week to show the interactions. Starting with week 1/2020 until week 52/2020. In order to *analyze* the case study, the data sets were visualized and their interactions in a demonstrative way, these data sets were transferred to a Gantt chart. Bottlenecks could be visualized with different color codes. In this case, the stocks were brought into relation with the reserve stocks and if those were below the safety stock, they were colored red. Additionally, the actual orders from customers were compared with the forecasts to visualize volatile order behavior. In the next step, the network of suppliers, production and customers was visualized on a global map. The goal of this was to make the transport routes completely transparent.

4 Discussion of Results

The last steps of the case study according to Yin are the analysis and interpretation of the results. However, caution should always be exercised when generalizing specific results [16].

As a first benefit, the production paths of the product were visualized and transparently presented in consultation with industry experts. A major benefit of the DSCT is that an entire value network from suppliers to customers is visualized and complete transparency is created. This transparency did not previously exist within the practice partner and was developed during the case study at the outset. In this example, the creation of the map was done manually, but should illustrate the benefit of a DSCT which can visualize this map automatically. Thus, irrelevant transport routes could be visualized rather rapidly, which would be restructured in terms of environmental sustainability. A full DSCT with all its characteristics is able to identify the optimal locations in terms of environmental sustainability.

Here, there are not only the movement flows with the facility locations illustrated, but also other data sets about customer demand or inventory policy. The model can thus show vulnerabilities due to long transport routes, for example, at first view. Since the DSCT is continuously supplied with data, disruptions can be identified in this model as soon as they occur. Companies and users are thus able to recognize disruptions at a very early stage and to react to them as efficiently as possible [17–20].

The following product consists of three different components. Two of these components are coming from the African continent, the other one is delivered from South America to Europe. The assembly of the product is a very simple form of manufacturing and requires no special know-how. The customers of the product are mainly in South and Central America. A critical evaluation must be made of the extent to which the network planning can be considered optimal purely for sustainability reasons. A relocation can be done by the simulation capability of the DSCT.

It can be assumed that production site will be relocated by the DSCT to the customer and main sales market. Thus, this could reduce thousands of tons of CO2 consumed for transport. The network should be critically examined to see whether production could not take place in South America, and the deliveries from South Africa go directly to South America. The company already operates very successful production facilities in South America and the complexity of assembling the final product is not considered complex (Fig. 2).

All in all, this example showed how much value the creation of transparency through a DSCT can create and demonstrates the ecological implementation potential of this technology. Especially for the evaluation of ecological sustainability, the visualization of value chains can quickly make unnecessary transport routes visible. Through simulation-based optimization, the DSCT could simultaneously provide recommendations for further action. (RO2).

The following elaboration is intended to demonstrate the extent to which the DSCT would have enabled predictive planning through its high level of data density. (RO1) During the Corona crisis, bottlenecks occurred several times so that large customer backlogs accumulated because customers could not be supplied. With the help of a Gantt

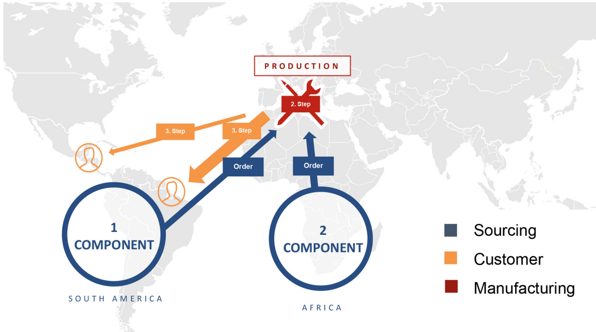

Fig. 2. Transparency (Compiled by author)

chart, it will be shown how a DSCT could have acted as a forward-looking planning tool at an early stage (Fig. 3).

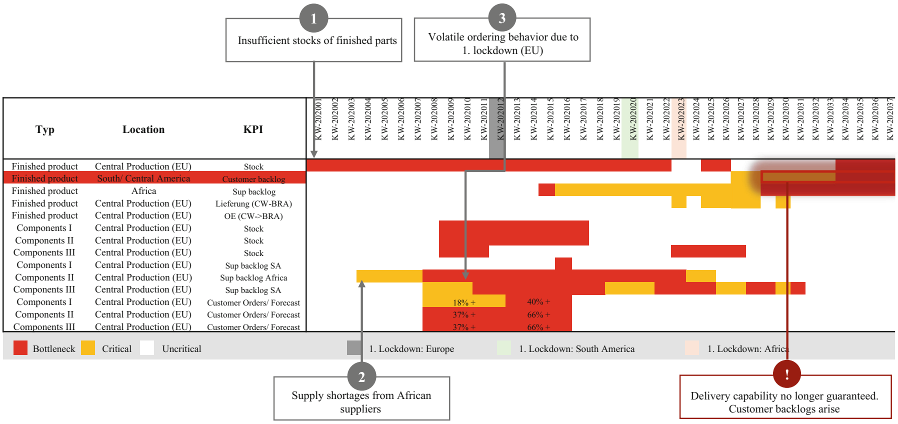

Fig. 3. Gantt chart source: compiled by authors

In the following, a wide variety of data sets were visualized in the form of a Gantt chart to explain the delivery problems starting in calendar week 27 and delivery breakdowns starting in calendar week 34. The goal is to proactively react to such failures through the transparency created by the DSCT. In the following example, three key indicators were shown to what extent the failures could have been detected at an early stage.

1) **Insufficient stocks of finished parts:** The European producer already had insufficient parts in stock at the beginning of the year. In this case, the minimum stock level was used as an indicator. Until calendar week 22 there were not sufficient parts in stock.
2) **Supply shortages from African suppliers:** Already in the fourth calendar week there were difficulties and pending shortages on 1/3 components, which are necessary for the final product. Such an early allocation of shortages could have been avoided

by an efficient back-up arrangement. From week 8, the supplier from Africa could not deliver the part at all.

3) **Volatile ordering behavior due to 1st lockdown:** Due to the corona pandemic already occurring in China at the beginning of the year and the rapid spread in the European region, the 1st lockdown was announced in Europe in calendar week 12. It could be observed that already in the weeks before the lockdown the number of orders increased by about 18–37%. From calendar week 13 (1 week after the 1st lockdown in Europe) the number of orders increased sharply by 40–66%. Based on other previous global crises, it could have been anticipated that a volatile, rapidly increasing demand for parts has occurred regularly in the past.

As the transport takes at least 8–10 weeks from Europe to the customer in Central and South America, it was impossible to have enough parts in stock again from calendar week 23. Due to the long transport distances, the network is not flexible and agile enough to react quickly to the requirements and fulfill the customer order. All in all, a shortage, meaning that the customer order can no longer be fulfilled, was already announced in the 1st quarter of the year, which subsequently began in the 3rd quarter.

The example demonstrates to what extent the DSCT could have predicted a bottleneck occurring in the third quarter. Through data availability, access to different data sources and continuous simulations of various scenarios, the DSCT would have made the insufficient stock of the finished part visible already at the beginning of the year (transparency creation) and simulated possible scenarios to solve the problem (optimization). For instance, by the failure of a necessary component from the 8th calendar week, a DSCT would have found back up suppliers for that part. Finally, the volatile ordering behavior of customers during international crises could have been anticipated, as this phenomenon has been observed in the past in various crises. (RO1).

5 Conclusion and Final Remarks

The paper provides an overview of how DSCT can be used for predictive planning to optimizing the ecological sustainability of logistics networks. First of all, the transparency created across the entire value network from suppliers to customers can be used to identify planning errors. In this case, the example can be used to show the extent to which unnecessary transport routes can be identified in this very simple model. Assuming that the network is continuously updated with data from the system (such as data about the ordering behavior of customers, the inventories of suppliers and manufacturing companies, or the demand of customers), conclusions can be drawn about the system at a very early stage.

The DSCT creates a very accurate representation of the current state of the network and simulates possible scenarios through this high data concentration and information from different stakeholders at the network level. Thereby, the network can be optimized and evaluated on the parameter of sustainability. The DSCT offers a space for experiments in which, for example, the network planning can be adapted, transportation modes changed or production techniques modified in order to evaluate the effectiveness of the change in terms of sustainability.

Clear limitations of the work are that no DSCT has been implemented so far. However, it should be understood as a proof-of-concept that DSCT is very suitable for predictive planning and sustainability assessments in production and logistics systems. Additionally, other application fields and possible potentials of DSCTs should be scientifically tested and evaluated. Furthermore, there is a need for research on the technological, process and organizational requirements to implement a DSCT on network level.

References

1. Busse, A., Gerlach, B., Lengeling, J.C., Poschmann, P., Werner, J., Zarnitz, S.: Towards digital twins of multimodal supply chains. Logistics. **5**, 25 (2021). https://doi.org/10.3390/logistics5020025
2. Straube, F.: e-Logistik: Ganzheitliches Logistikmanagement. Springer, Berlin, Heidelberg (2004)
3. Belhadi, A., Kamble, S., Jabbour, C.J.C., Gunasekaran, A., Ndubisi, N.O., Venkatesh, M.: Manufacturing and service supply chain resilience to the COVID-19 outbreak: Lessons learned from the automobile and airline industries. Technol Forecast Soc Change. **163**, 120447 (2021). https://doi.org/10.1016/j.techfore.2020.120447
4. Nitsche, B., Straube, F.: Defining the "New Normal in International Logistics Networks: Lessons Learned and Implications of the COVID-19 Pandemic. WIST. **50**, 16–25 (2021). https://doi.org/10.15358/0340-1650-2021-11-16
5. Liadze, I., Macchiarelli, C., Mortimer-Lee, P., Juanino, P.S.: The economic costs of the Russia-Ukraine conflict, 32nd ed. National Institute of Economic and Social Research, London (2022)
6. Abdalla, S.S.A., Nakagawa, K.: Entrepreneurial Leadership, Supply Chain Innovation, and Adaptability: A Cross-national Investigation. Operations Research Forum **3**(1), 1–21 (2022). https://doi.org/10.1007/s43069-022-00135-x
7. Bergs, T., et al.: (eds.) Nachhaltige Produktion mit dem Digitalen Zwilling. Apprimus Verlag, Wissenschaftsverlag des Instituts für Industriekommunikation und Fachmedien, Aachen (2021)
8. Tao, F., Zhang, H., Liu, A., Nee, A.: Digital Twin in Industry: State-of-the-Art. IEEE Transactions on Industrial Informatics 2405–15 (2019)
9. Gartner: Gartner Top 8 Supply Chain Technology Trends for 2020 (2020). https://www.gartner.com/smarterwithgartner/gartner-top-8-supply-chain-technology-trends-for-2020/. Accessed 4 Jan 2021
10. Gerlach, B., Zarnitz, S., Nitsche, B., Straube, F.: Digital Supply Chain Twins: Conceptual Clarification. Use Cases and Benefits (2021)
11. Grieves, M.: Conceptual ideal for PLM.: Presentation for the Product Lifecycle Management (PLM) center (2002)
12. Grieves, M., Vickers, J.: Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems (Excerpt). In: Kahlen, F.J., Flumerfelt, S., Alves, A.: (eds) Transdisciplinary Perspectives on Complex Systems, 85–113 (2017). https://doi.org/10.13140/RG.2.2.26367.61609
13. Gerlach, B., Zarnitz, S.: Typologien und Anwendungsnutzen digitaler Zwillinge in Logistiksystemen: Definition: Der Digitale Logistik Zwilling (2021). https://www.logistik.tu-berlin.de/fileadmin/fg2/JPGs/Paxisseminar_2021/Typologien-und-Anwendungsnutzen_VortragFS.pdf. Accessed 26 Apr 2021
14. Gudehus, T.: Logistik 1. Springer Berlin Heidelberg, Berlin, Heidelberg (2012)
15. Meyer, J.-A.: Die Fallstudie in der betriebswirtschaftlichen Forschung und Lehre: WiSt (2003)

16. Yin, R.K.: Case Study Research: Designs and methods. Sage Publications, California (2003)
17. Ivanov, D., Dolgui, A., Sokolov, B.: Handbook of ripple effects in the supply chain. Springer (International series in operations research & management science), Switzerland (2019)
18. Semenov, Y., Semenova, O., Kuvataev, I.: Solutions for Digitalization of the Coal Industry Implemented in UC Kuzbassrazrezugol. E3S Web Conf. **174**, 1042 (2020). https://doi.org/10.1051/e3sconf/202017401042
19. Barykin, S.Y., Bochkarev, A.A., Kalinina, O.V., Yadykin, V.K.: Concept for a Supply Chain Digital Twin. Int J Math, Eng, Manag Sci. **5**, 1498–1515 (2020). https://doi.org/10.33889/IJMEMS.2020.5.6.111
20. Marmolejo-Saucedo, J.A.: Design and Development of Digital Twins: a Case Study in Supply Chains. Mobile Networks and Applications, 2141–60 (2020). https://doi.org/10.1007/s11036-020-01557-9