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Towards Digital Twins of Multimodal Supply Chains

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Abstract: Both modern multi- and intermodal supply chains pose a significant challenge to control and maintain while offering numerous optimization potential. Digital Twins have been proposed to improve supply chains. However, as of today, they are only used for certain parts of the entire supply chain. This paper presents an initial framework for a holistic Digital Supply Chain Twin (DSCT) capable of including an entire multimodal supply chain. Such a DSCT promises to enable several improvements all across the supply chain while also be capable of simulating and evaluate several different scenarios for the supply chain. Therefore, the DSCT will not only be able to optimize multi- and intermodal supply chains but also makes them potentially more robust by identifying possible issues early on. This paper discusses the major requirements that such a DSCT must fulfil to be useful and how several information technologies that matured in recent years or are about the mature are the key enablers to fulfil these requirements. Finally, a suggested high-level architecture for such a DSCT is presented as a first step towards the realization of a DSCT, as presented in this work

Keywords: digital twin; supply chain; multimodal; intermodal; hinterland

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1. Introduction

Globalization, the cross-border economic integration of companies, and changing customer behavior lead to the increasing complexity of supply chains and poses major challenges for companies ([1], p. 5, [2]). Functioning and efficient supply chains are crucial to modern society as it is the central factor to ensure the supply of goods matching the demand. Thus, they need to be repositioned to react flexibly and fast to these challenges to stay competitive in the long-term. As an interdisciplinary cross-sectional function for the planning, implementation, and control of all material and information flows, logistics plays a key role in meeting these challenges ([3], p. 5). For example, modern production and sales nowadays often follow just-in-time principles and try to reduce the necessity to store goods and raw materials. At the same time, companies increased their service orientation, mainly through a shift from a seller's to a buyer's market ([3], p. 5), which leads to an increase in the diversity of goods and customization of individual goods. On the one hand, they are highly complex and, on the other hand, they require the highest degree of flexibility [4] and efficient responsiveness to volatile markets [5] at very low costs.

Technological advances have allowed us to improve and manage such complex supply chains, for example, Transport Management Systems (TMS), Customer Relationship Management Systems (CMS), or Enterprise Resource Planning (ERP) Systems. However, the management and optimizations often happen only locally. In particular, in multimodal transport chains with many actors as crucial parts of supply chains, a considerable optimization potential might exist but cannot be leveraged. That is for two reasons—on the one hand, it is difficult to determine what actions in such a complex system can yield what results, and on the other hand, data is often not shared among different participants. As mentioned, logistics uses different technologies to address these challenges. However, the Digital Supply Chain Twin (DSCT) is discussed as a promising solution to develop a holistic and agile logistics network, at the latest after the DSCT was entered in Gartner's Hype Cycle 2017 as one of the most disruptive technologies in the supply chain. A DSCT is a dynamic simulation model [2,6,7] that aggregates the available data in a structured way and allows simulations on the supply chain, including transport chains that are close to reality. In this context, it is essential to differentiate between asset-focused twins (e.g., digital twins of individual machines) and digital supply chain twins. Asset-focused twins do not sufficiently represent the wide range of applications and the diverse areas of application and possibilities of implementing the whole concept. This allows for an evaluation of different scenarios and their outcome and allows the selection of the most beneficial setup. Because of its digital nature and easy accessibility, the DSCT will also allow the evaluation of unlikely scenarios and allow preparation for them, as was observed during the SARS-CoV-2 pandemic in 2020 and 2021. Furthermore, the DSCT would not only allow considering pure economic and reliability aspects but could also take into account ecological aspects and, therefore, could allow increasing ecological sustainability. Even though not presenting a final design, but only initial steps for a DSCT for multimodal supply chains, it outlines the potential and benefits and discusses its feasibility substantiated through a possible framework.

As a methodology for this paper, Design Science Research (DSR) is used. In DSR, an artifact is created to address an unsolved and vital problem. Thereby, the artifact should offer a solution for the defined problem and be drawn from existing knowledge (cf. [8]). In particular, for this research, we adopt the DSR process of Pfeffers [9]. We applied a Problem-Centered approach due to the reason the shortcomings in current transport networks were the entry point of our research. This is done on the maritime transport chain example, which represents an important element in international supply chains. Based on these shortcomings, the objectives of a solution are presented. Then, a vision for a DSCT made possible by using new technologies is presented and how exactly a DSCT can help overcome the existing shortcomings in transport networks and supply chains is highlighted. The evaluation of the artefact is performed theoretically, based on the outlined shortcomings. Therefore, no further iteration of the DSR process was conducted.

The remainder of the paper is structured as follows—Section 2 describes the current situation with multimodal supply chains and the intended goal. In Section 3, we list and describe the technologies that will enable DSCTs to reach the goals summarized in Section 2. The subsequent Section 4 describes and discusses the envisioned holistic digital supply chain twin. The final section concludes this paper.

2. Current and Target State of Multimodal Supply Chains

The coordination of today's supply chains is becoming an increasing challenge for logistics and industrial companies. On the one hand, the networks are showing increasing complexity due to a rising number of actors as well as global dimensions, while their vulnerability to disruptions is growing as a result of outsourcing, single-sourcing strategies, and the reduction of risk buffers through Just-in-time strategies. On the other hand, logistics and industrial companies are faced with increasing requirements regarding reliability, efficiency, and sustainability (cf. [10], p. 12f) (cf. [11]). Optimal control of such complex systems requires the highest possible transparency across the entire network. Nevertheless, transparency across the entire system is usually not available. At most, a stakeholder may have transparency over the part of the network the stakeholder operates in. But even this local transparency is often not available. The maritime transport chain is well suited to demonstrate the need for transparency.

More than 90% of the world's trade goods and about a quarter of Germany's foreign trade volume are transported by sea ([12], p. 8), multimodal transport chains such as the maritime transport chain are a central component of global logistics networks. The coordination of transport chains requires the synchronization of numerous consecutive transport and transshipment processes (see Figure 1). These are each carried out by a large number of different logistics actors, for example, freight forwarders, CT (Container Terminal) operators, shipping companies, rail companies, seaport terminal operators, to name only a few (cf. [13], pp. 208–211). Despite the significant need for cross-actor coordination, the information transparency between these actors is currently very low, so that no actor can trace the overall progress of transports in detail. One reason for this is that process tracking is only partially implemented so that no continuous status information is available for the whole chain. Another reason is that existing information is not systematically transmitted to other actors as a consequence of a low level of digitization of communication processes, missing compatibility of IT systems, and confidentiality requirements (cf. [14]).

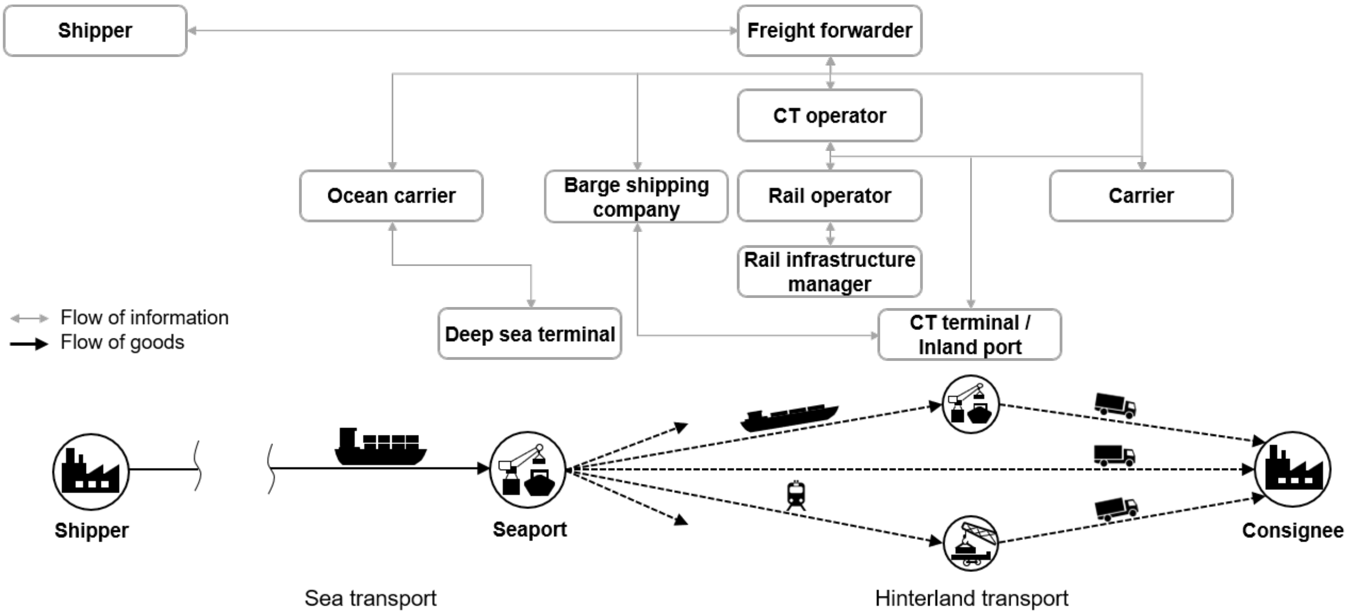

Figure 1. Exemplary flow of goods and information within a maritime transport chain.

Consequently, the planning and control of the transport chain follows a very static and less flexible top-down-process and does not take place in the sense of an overall optimum, but rather each actor carries out an isolated optimization for its area of responsibility. Hence, available capacities of transport modes and resources are not used optimally, and road transport is prioritized over more sustainable rail and water transport modes due to its flexibility. Furthermore, the uncertainty caused by a lack of information causes high-risk buffers within the chain and, as a result, long transport times. Another result of this situation is the less than optimal handling of disruptions, as the low level of transparency makes both early detection and cross-stakeholder coordination of measures more difficult (cf. [14]).

To meet the requirements named above, optimized and synchromodal transport planning and control procedures are required, which provides the following capabilities:

- *Visibility*: Real-time transparency across the entire transport network, including available capacities, disruptions, and process status information
- *Data Analysis*: Predictions on future states of the system, for example, upcoming disruptions and lacks of capacity
- *Extensive Decision Support*: Process optimization by providing decision support for both transport planning as well as handling of disruptions

Those capabilities would allow further management of the previously explored challenges. *Visibility* and *data analysis* improve resilience towards complexity and disruptions. Additionally, *visibility* and *data analysis* provide the opportunity to improve reliability and sustainability, while especially *extensive decision support* provides the opportunity to improve efficiency.

3. Enabler

To reach the goals discussed above, several technologies were identified that have only matured in in recent years or mature in the near future. This will allow the combining and adaptation of these technologies to reach the intended goal. Before going into more detail about how those technologies are used, they will be briefly introduced:

3.1. The Internet of Things

The Internet of Things (IoT) is a concept that allows things or objects to communicate with each other through a unique addressing scheme similar to computers that can communicate with each other over the internet [15]. This communication and addressing allow physical objects to interact with each other without mandatory human intervention. This is limited to communicating information about an object or thing like, for example, location or temperature and actions through actuators. Even though the first concepts were discussed in the 1980s and the term IoT was coined in 1999, real-world applications are only emerging in recent years as devices became substantially smaller and cheaper with more capabilities, especially regarding communication.

3.2. 5G

5G is the fifth generation standard for broadband cellular networks. Compared to its predecessor, 5G offers an increased performance regarding throughput and latency [16]. It also allows the deployment of private campus networks. In summary, this will allow a degree of ubiquitous connectivity that was unknown before. The introduction of 5G from 2016 promises new and innovative applications, particularly in the context of IoT.

3.3. Cloud Computing

Cloud Computing describes IT services such as computing power, storage, or applications, which can be used via the internet. According to NIST, cloud computing characteristics are on-demand self-service, Broad network access, Resource pooling, Rapid elasticity, and Measured service [17]. Thereby, realizable advantages of cloud computing can be financial, operational, or strategic. Possible financial advantages include lower investment, lower operating, and lower maintenance costs in IT. As the most significant operational advantages, elasticity and scalability of IT resources are seen, and a reduction of complexity can result in reduced administration and maintenance efforts. Strategic advantages can include better access to technologies, the development of new business areas, reduced barriers to market entry, or increased data security through better availability of IT systems [18].

3.4. Artificial Intelligence

Artificial Intelligence (AI) refers to the ability of an IT system to show human-like intelligent behaviors [19], which includes independent learning and thereby finding solutions independently [20]. Machine Learning is often used as a method in the field of AI and thus is an elementary component of AI procedures. It describes computer algorithms, which learn from data, such as recognizing patterns or showing desired behaviors. The characteristics for these algorithms are independent learning and improvement, and they can be categorized based on their approach to learning into Supervised Learning, Unsupervised Learning, and Reinforcement-Learning. Different application areas of AI are, for example, Natural Language Processing, Natural Image Processing, Expert systems, and Robotics [20].

3.5. Data Availability

The quantity of data generated is continuously increasing, which also applies to data in companies. An increase of up to 530% of globally generated data is forecast, from 33 ZB (zettabytes) in 2018 to 175 ZB in 2025 [21]. One reason for this increase can be the use of new technologies and concepts, such as sensors, Machine to Machine Communication, IoT, RFID, and so forth, [22]. Additionally, methods for using the data have also improved, for example, by using AI methods for the analysis of the data or cloud computing for the technical infrastructure.

3.6. Blockchain

Blockchain technology was conceptualized in the early 1980s but became available only in the 2000s. First, only as a digital currency, it has since evolved to a technology that allowed the immutable storage of data and ensured process execution. Through its distributed nature and consensus mechanism, it requires no trusted third party to establish trust [23]. The introduction of Smart Contracts [24] allows a very generalized use of blockchain technologies for applications that require a certain degree of trust regarding the integrity both of the data itself and the processing of the data.

3.7. Privacy-Preserving Computation

Combining information from different parties is often necessary to achieve a goal or perform optimization. However, sharing data is often not desired by the stakeholders for privacy or confidentiality reasons. Several technologies were developed that allow the usage of data or computation on data without revealing its content with varying restrictions, for example, Secure Multi-Party Computation, Homomorphic Encryption, Differential Privacy, Zero-Knowledge Proofs, or Trusted Execution Environments [25]. Even though initial research for some of these technologies started in the 1970s, most of them became usable only in recent years or are still in early stages of development.

4. Holistic Digital Supply Chain Twin

The current problems in intermodal transport networks call for a modern and digital solution. Several technological advances that were made in the past act as enablers in that regard, as previously described. This section outlines a possible solution that both tackles the identified problems and benefits greatly from the mentioned enablers: the Digital Supply Chain Twin.

A Digital Supply Chain Twin (DSCT) is a digital simulation model of a real logistics system, which features a long-term, bidirectional and timely data-link to that system. Through observing the digital model it is possible to acquire information about the real logistics system to conclude, make decisions and carry out actions in the real world [26]. The DSCT maps data, state, relations, and behavior of the logistics system in a digital simulation model and stores them permanently in a database (cf. Figure 2). Optimally, any relevant information obtained by observing the logistics system can (also) be obtained by observing the digital model. Three attributes characterize the data exchange between the logistics system and its DSCT:

- *Bidirectional*: Data is exchanged in both directions. Therefore, changes in the state of the logistics system lead to changes in the state of the digital model. Similarly, the knowledge gained from the digital model leads to actions or decision-making in the logistics system. A certain degree of automation of the data exchange is explicitly not a prerequisite for a DSCT.
- *Timely*: Data exchange takes place in a timely manner. The use case determines the specific frequency. Continuous updates in real-time are explicitly not a prerequisite for a DSCT unless the use case requires this.
- *Long-term*: The data exchange and thus the lifetime of the DSCT are designed for continuous, long-term use. Digital simulation models created as part of project activities or for one-time use are explicitly not considered DSCTs.

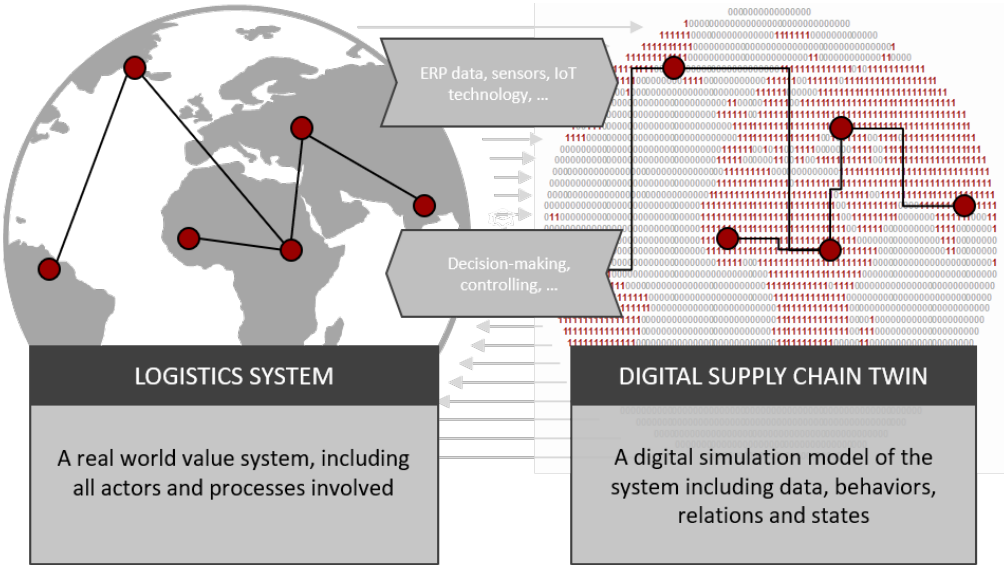

Figure 2. Concept of a Digital Supply Chain Twin (DSCT) (cf. [26]).

Gerlach and Zarnitz [26] propose four levels for the use of Digital Twins in Logistics and Supply Chain Management (LSCM), three of whom are to be considered Digital Supply Chain Twins (cf. Figure 3):

- Macro Level: DSCT of a multi stakeholder value network
- Macro Level: DSCT of an internal supply chain
- Site Level: DSCT of a logistics site (e.g., warehouses, production facilities, etc.)
- Asset Level: DT of a logistics asset (e.g., trucks, forklifts, etc.)

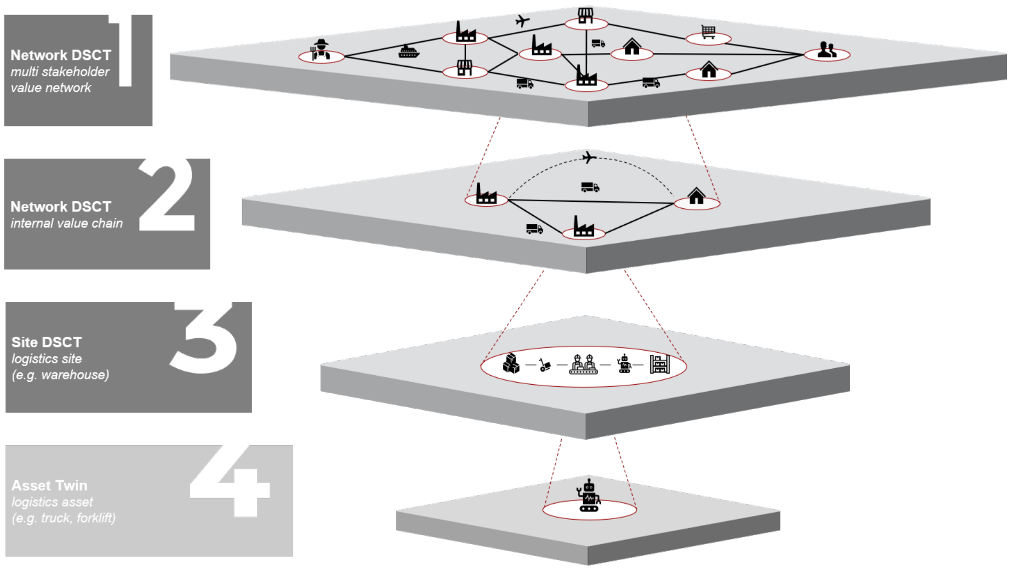

Figure 3. Relation of DSCTs and granularity of the supply chain (cf. [26]).

In the scientific literature, a DSCT is described in many ways. It can function as a means for providing enhanced visibility, traceability, and authentication (cf. [27]), as a decision-support system for disruption risk management (cf. [28]), or as a tool for resilient supply chain controlling (cf. [29]), just to mention a few. However, before going into more detail about the DSCT, a distinction from other similar systems should be made, currently being used in Logistics and Supply Chain Management.

4.1. Distinction from Other Digital Solutions

There are several digital solutions currently being used in LSCM. Firstly, there are Online Freight Exchange Platforms. An online freight exchange, also known as freight exchange, is an online service that connects haulage, logistics, and freight forwarding companies on the web. It allows the companies to go through a database for available freight and market their available vehicle capacity. However, most such platforms lack holistic optimization capabilities. Also, the level of detail regarding freight and order information is not sufficient for sophisticated analyses (cf. [30]).

Other commonly used digital systems for organizing freight orders include Advanced Planning and Scheduling Systems (APS-Systems), Transport Management Systems (TMS), and Supply Chain Management Systems (SCM-Systems). These systems might or might not be integrated with a companies ERP system (cf. Chapter 4.1 [31]). In simplified terms, an SCM system represents an ERP system extended to include the cross-company view. Due to the plurality of existing supply chain management systems, it is not always easy to clearly distinguish them from other software packages, such as ERP/APS systems or TMS. Precisely because modern ERP solutions also integrate the interface to external partners as an architectural concept, functional as well as business process-related overlaps of the system solutions sometimes inevitably arise (cf. Chapter 4.7 [31]). However, regardless of the specific definition, all these solutions show clear disadvantages compared to the DSCT:

1. Update Frequency: Most of the currently used systems do not support real-time data exchange. While this is not a requirement for every single use case, it is crucial for time-sensitive tasks like acute risk management functionalities (cf. [28]).
2. Advanced Analytical Capabilities: The classic ERP system was static and focused on information retrieval only. Modern ERP systems are more user-oriented and offer some functions to analyze data. Still, in most cases, these functions are not sufficient for a holistic optimization approach toward an improved logistics performance (cf. Chapter 4.7 [31]).
3. Simulation Capabilities: Ultimately, there exist virtually no solutions today that feature simulation capabilities regarding the Supply Chain level (cf. Chapter 2.7 [32]). These are, however, indispensable for the assessment of probable future scenarios. Without the ability to run these what-if-scenarios, there are serious limitations to a systems decision-making capabilities (cf. [33]).

The DSCT promises to be an improvement in these regards. This paper, therefore, aims to define a theoretical framework for a DSCT in the context of intermodal transport chains. To achieve this, a set of requirements is first derived from the desired target state as well as the flaws of the currently used systems. Later it will be discussed to what extent the presented solution meets these requirements to ensure its effectiveness.

4.2. Requirements and Framework for a Digital Supply Chain Twin in Intermodal Transport Networks

Table 1 summarizes the chosen requirements necessary for implementing a DSCT in a supply chain. The Digital Supply Chain Twin can first and foremost create visibility and transparency along the entire supply chain, if the partners of the network are able and willing to share their data and thus form a collaborative environment. A digital, simulation-capable model is created based on the required data, which should be continuously updated to reflect the real, cross-system state. Depending on the use case, internal data from the systems of the actors, but also external data sources (e.g., weather, traffic, prices of competitors) can be combined. This forms the foundation for the DSCT to create a realistic model that is as precise as possible to carry out analyses/simulations based on this high data quality. In summary, data quality, quantity, and combination, and smart evaluation are the basic prerequisites for efficient use of the DSCT.

Table 1. Criteria for a solution.

Criteria	Reasoning
visibility and transparency	across the entire network, including...
update frequency	e.g., real time in some use cases
data collection	e.g., + external data + IoT-Data in some cases
data analysis	advanced predictive analytics + holistic optimization
simulation capabiltiies	enabling what-if-scenarios
decision support capabilities	for both transport planning as well as handling of disruptions

Figure 4 depicts an exemplary model of a Digital Supply Chain Twin. The Digital Supply Chain Twin digitally mirrors the physical supply chain by being fed by various information flows to simulate different scenarios. The information flows are bidirectional, generating information from the system's behavior, which can be converted into recommendations for action.

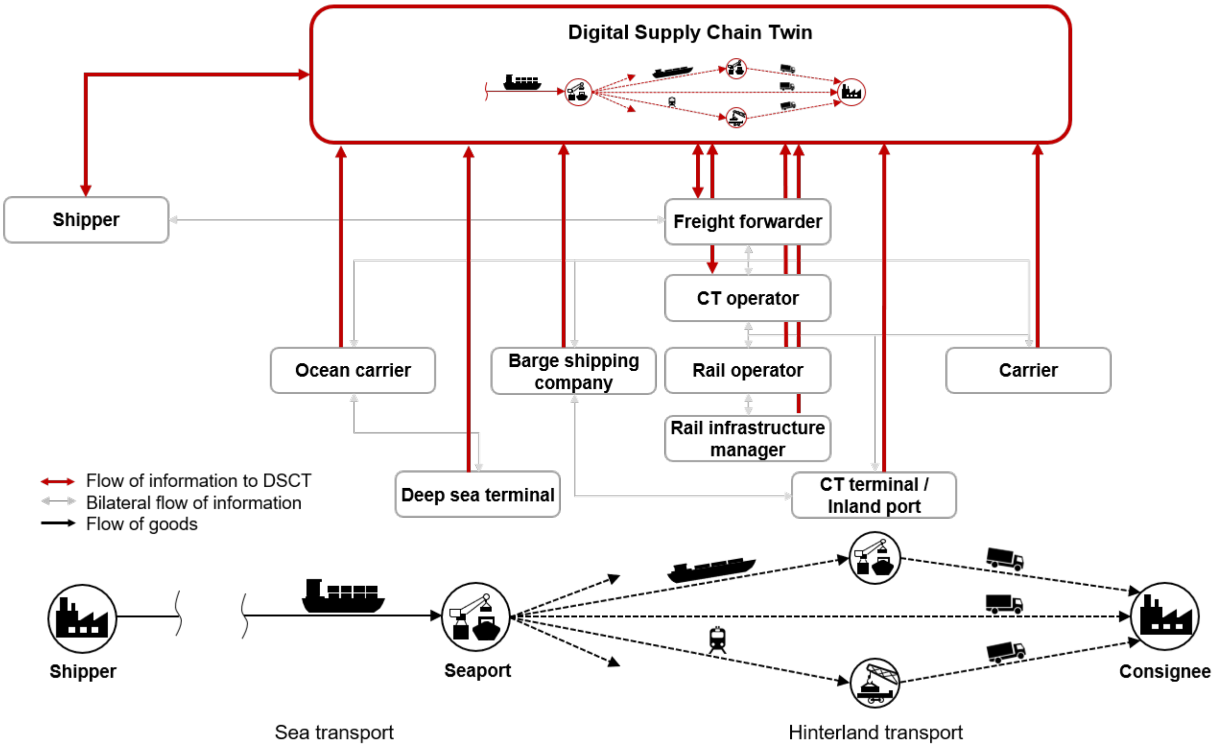

Figure 4. Exemplary flow of goods and information within a maritime transport chain with an additional DSCT.

Based on this, a high level architecture for the DSCT is proposed as depicted in Figure 5 that is discussed below regarding the design decisions as well as regarding the benefits that can potentially be gained from this approach. A more detailed architecture with an in-depth discussion of every component is beyond the scope of this paper. The framework describes a DSCT consisting out of five distinct modules. At the core of this framework is the *Supply Chain Model* module. This module models the physical supply chain and describes all its properties and interdependencies. It can be parametrized through data of the real world to give description states of the real-world supply chain inside the DSCT. The model could be realized through classical algorithms or could use AI technology as described in Section 3.4. To parameterize the Model, an *Interface* module is necessary. The *Interface* module has to fulfill several requirements. Most importantly, this module needs to translate data from multiple different data sources of the physical supply chain into processable data used as input for the Model module. Besides collecting, storing, and preprocessing data that could be enabled through IoT (cf. Section 3.1), 5G (cf. Section 3.2), data availability (cf. Section 3.5), and cloud computing (cf. Section 3.3) respectively, AI technology might be used to process unstructured data towards a structure usable in the Model module. Operations from the privacy-preserving computation domain as briefly discussed in Section 3.7 may be incorporated into this part of the DSCT to fulfill possible privacy and/or confidentiality requirements. If data integrity and trustworthiness is are further requirements for the use of the DSCT, they could be guaranteed through the use of blockchain technology as discussed in Section 3.6. The *Simulation* module that is enabled through the computing capacities provided through Cloud Computing can determine potential future states of the real-world supply chain through applying alternative parameters to the model of the DSCT. This allows to improve decision-making in the supply chain as the results and impact of one or several possible decisions can be determined without actually influencing the real supply chain. Furthermore, stratic planning processes like, for example, scenario planning [34] could use the DSCT to evaluate possible scenarios and outcomes in the longer term. The *Optimization* module utilizes both the *Supply Chain Model* module and the *Simulation* module in order to optimize the supply chain represented through the DSCT. Again, AI techniques are the most promising technology to realize this functionality. This module potentially allows a wide range of improvements in the supply chain like more efficient route planning, the maximization of carrier utilization, additional flexibility in order planning, optimized modal split planning, or the reduction of lead times. The *Reporting* module, finally, prepares the results from the *Optimization* module and the *Supply Chain Model* module individually for each stakeholder and provides them with a structured presentation of all the information and recommendations available through the DSCT.

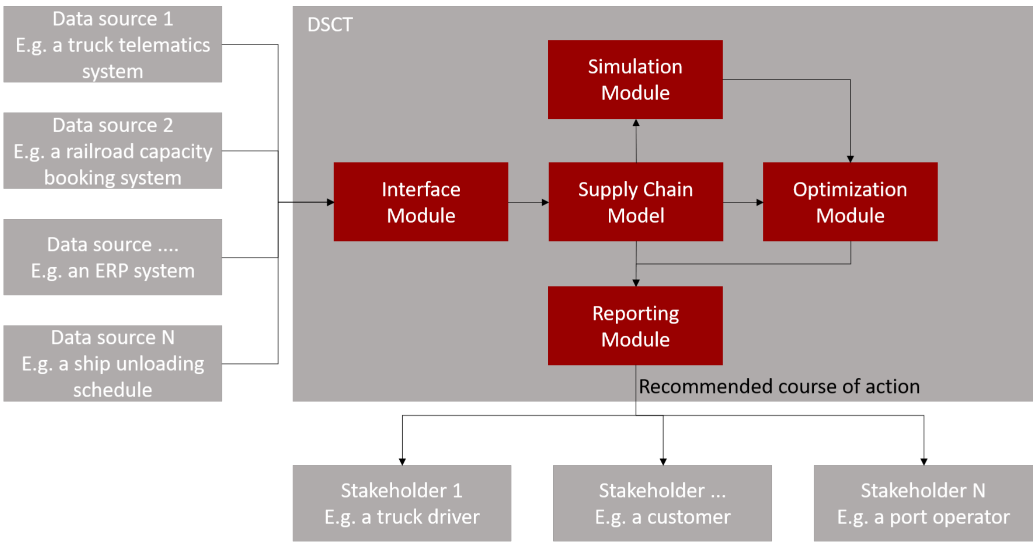

Figure 5. Proposed DSCT Framework.

4.3. Validation of the DSCT Framework

In this section, we validate the DSCT using the criteria mentioned above. For this purpose, we also consider how these criteria were met, for example, by using technologies and concepts that enable fulfillment. An overview of the results is given in Table 2.

For the collection of data, the *Interface* module of the DSCT is used, which allows a wide variety of data sources, for example, external data sources like environmental data for temperature forecasts. The amount of data available for this purpose has increased due to the greater availability of data. Also, actual data can be integrated using IoT-Technology. To consider the specifics of different stakeholders, which can be competitors, concepts of privacy-preserving computation are useful. These data can be stored using the scalability storage capacities of cloud computing. Besides that, the update frequency of the data can be increased using IoT-Technology capabilities (e.g., smaller and cheaper devices) in combination with the communication advantages of 5G. For example, this enables IoT sensors to be used more frequently. The next criterion fulfilled is the capabilities for data analysis based on the *Supply Chain Model* module as the core of the DSCT and can use advantages of cloud computing (e.g., scalability of computation power). Additionally, methods of AI can be used for automation and to generate new insights.

In contrast to this, for the simulation capabilities, no new technologies must be adopted. Since the DSCT, whose model is represented by the *Supply Chain Model* module, provides the foundation for the supply chain's dynamic simulation model. The same applies to decision support capabilities based on other parts of the DSCT, namely on the *Supply Chain Model* and *Simulation* modules. The DSCT itself also fulfills the visibility and transparency requirements as one of the main criteria, and it is provided to the stakeholders by the *Reporting* module. It depends mainly on the dynamic simulations of the optimization and the *Supply Chain Model* Module. For this purpose, technologies can be used, such as cloud computing and advances in connectivity.

Table 2. Validation of DSCT.

Criteria	Enabled by
visibility and transparency	cloud computing connectivity(5G)
update frequency	IoT-technology connectivity (5G)
data collection	IoT-technology cloud computing (storage) privacy-preserving computation
data analysis	cloud computing (computation) artificial intelligence
simulation capabilities	model module (DSCT)
decision support capabilities	reporting module (DSCT)

5. Discussion and Conclusions

In this paper, we have presented the idea of a DSCT for an entire multimodal supply chain. Contrary to the current state where DSCT only covers a small part of the supply chain, we aim for larger parts of the entire supply chain. We have discussed possible benefits resulting from a DSCT and which technologies can enable it. In particular, we have briefly outlined how the latest advances in IT play a major role.

For a complex supply chain like the maritime one discussed in this paper, with a complex hinterland transportation structure, a DSCT can have many benefits. For example, the prediction of delivery times could be improved through the DSCT by taking the various individual factors of the different transportation modes into account. The prediction could be further improved through machine learning of the DSCT to learn from previous transportations of goods through the supply chain. Another central capability of DSCT is a simulation that would allow gaining insides about the existing transport network. For example, it would be easy to determine the limits and bottlenecks of the supply chain that could arise when the number of ships that have to be unloaded increases. The DSCT could also be used to determine the most cost efficient measures to resolve those issues.

However, this work is only the first step towards a DSCT as many questions, especially regarding details, are still open. For example, even though several technologies exist that allow the shared use of data while maintaining the data's confidentiality, how such technologies can be integrated into the DSCT have to be considered in future work. Also, questions about the actual low-level architecture of DSCT have to be researched. For example, centralized, decentralized, or hybrid solutions seem feasible as every single approach has advantages and disadvantages. Whether one of those architectures is strongly superior or not has to be researched. Those decisions might also be influenced by the actual supply chain that is supposed to be modeled. It could differ depending on the goods that are transported or on the composition of the supply chain. For example, in this paper, we chose ocean-going ships as an example, but the situation might differ for entirely continental transport or transport chains, including transportation by air. Another aspect that has to be considered in more detail possible in a testbed are costs of the DSCT and precise benefits that can be generated from its use, and whether the benefits can outweigh the costs. Lastly, the adoption of DSCT will also greatly depend on the acceptance of the different market players and the impact on the market in general. On the one hand, some or many players can benefit greatly from a DSCT, but on the other hand, there might be players who lose the foundation of their business. The different market players' interests have to be researched in detail, and the effects have to be weighted.

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