

Intelligent Supply Chains Through Implementation of Digital Twins

Oray Kulaç¹[0000-0003-3734-5785] Banu Y. Ekren^{2,3}[0000-0001-6491-1389] and A. Özgür Toy²[0000-0003-1603-6860]

¹ Yasar University Graduate School, Izmir, Turkey

² Yasar University Industrial Engineering Department, Izmir, Turkey

³ Cranfield University, Cranfield, UK

oray.kulac@gmail.com

Abstract. Data-driven decision-making process can be defined to be the sequential activities of real-time data collection, data analytics, optimization and decision making. Developments in Industry 4.0 technologies have made it possible to realize that new quality decision-making process. When that decision-making process is performed under the simulation model of a system developed on real-time data-based and end-to-end connection manner, to prevent the disruption risks and to improve resilience in a system, then it constitutes a digital twin (DT). A DT is a virtual representation of an object or system that can help organizations monitor operations, perform predictive analytics, and improve processes. For instance, a DT could provide a digital replica of the operations of a factory, communications network, or the flow of goods through a supply chain system. In this work, we focus on DT implementations in supply chain networks. We present state of the art implementation of DTs in supply chains and their prospective utilizations towards creating intelligent supply chains.

Keywords: Digital Twin, Supply Chain Management, Data-driven Decision Making.

1 Introduction

Data-driven decision-making process is the sequential activities of data collection, data analysis, data interpretation and decision making. Customarily, this process is run over the models detached from the actual system. Likewise, simulation is one of the modelling approaches that is used to understand and predict the behavior of the system under interest. Developments in information, computation, and communication technologies as well as Industry 4.0 technologies like IoT, real-time data collecting, and embedded sensors in physical systems etc. have created opportunities for restructuring and reengineering the simulation modelling paradigm emerging with the Digital Twin (DT). DT is a virtual replica of an object or system helping organizations monitor operations, perform predictive analytics, and improve processes. While it could be a digital replica of operations in a factory, communications network, or the flow of goods

through a supply chain system, it could also be a replica of a physical object such as an airplane, a space craft, or a wind turbine, etc.

A DT consists of three main components. These are: an actual system, a detailed simulation model of that system (virtual system) and a data link in between [1]. High quality data is the backbone of a DT. Specifically, a data link flow exists between the actual system and its digital replica where continuous correspondence and inference information flow take place in both directions.

Different debates on definition of DTs exist in literature. In this work, we carry out a survey study to identify those definitions by also presenting how the technological developments affect those definitions in time. To contribute to the dissemination of DT applications, the intelligibility of the concept, as well as the implementation of DTs specifically on supply chain (SC) problems, we conduct an extensive literature survey work. Here, we focus on SC problems. Recent COVID-19 pandemic has shown the clear shortcomings of traditional manufacturing's over-reliance on complex and often very extended supply chains, and the growing necessity for sustainable, resilient, and innovative designs in product supplies. By the help of DT implementations, it might be possible to alter disruption risks by predictive analytics and improve resilience in SCs.

The main research question of the work can be given as:

RQ: How does SCs benefit from DT for resilience and efficiency?

The rest of this work is organized as follows. In Section 2 we outline the evolution of DT along with its enabling technologies. We discuss implementation areas of DTs in Section 3. We focus on implementation of DTs in SCs in Section 4. Finally, we conclude in Section 5.

2 Evolution of DT

DT has been first applied by the NASA Apollo program, where simulators and physical models of space crafts are developed to mimic the effects of space conditions on the actual vehicle. Apollo-13 rescue mission may be considered a successful implementation of a basic DT concept. In that case, the data from the crippled space vehicle is utilized to modify the simulators on ground, and then their outputs are used to produce new policies to rescue the crew [2].

The DT concept emerges in academia with the studies of Grieves. He explores the opportunity of utilization of DT in product life-cycle management [3]. Later on, Grieves and Vickers propose following definition for DT “A set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin” [4].

By the technological developments, the definition of DT has changed by involving the utilization of advantages of those technologies. For instance, a definition involving Internet of Things (IoT) is given by Lee and Kim [5] as follows: “A near real-time digital image of a physical object or process that helps optimize business performance.

Two concepts of IoT (Internet of things) and IoS (Internet of Service) are combined to realize the smart factory based on a digital twin”.

Another definition is given by Asimov et al. [6] including the Artificial Intelligence (AI) concept as: *“a virtual replica of real physical installation, which can check the consistency for monitoring data, perform data mining to detect existing and forecast upcoming problems, and which uses an AI knowledge engine to support effective business decisions”.*

In their systematic literature review, Semeraro et al. [7] summarize different definitions as: *“A set of adaptive models that emulate the behavior of a physical system in a virtual system getting real-time data to update itself along its lifecycle. The digital twin replicates the physical system to predict failures and opportunities for changing, to prescribe real-time actions for optimizing and/or mitigating unexpected events observing and evaluating the operating profile system”*

While the definition of DT evolves over time, meanwhile several characteristics of DT have also been identified. From findings of Moshood et al. [8] and Gerlach et al. [9] following list of characteristics is formed:

- **Physical and virtual:** As discussed earlier a DT is composed of both a physical system and a detailed simulation model of that system (the virtual system).
- **Bidirectional data:** There is a data link between physical and virtual systems. On this link data exchange is bidirectional. Data flow from physical system to virtual system allows managers and decision makers to receive early warnings, to conduct risk analysis and identify bottlenecks for various physical and operational conditions. Data flow from virtual system carries inferences and advised policies to the physical system.
- **Timely updates:** Bidirectional data exchange is conducted on regular intervals. A continuous data flow is preferred when possible.
- **Maintain state:** A DT holds the last state of the physical system in memory in the case of disconnection of data link. Keeping the different states of different case scenarios is also a desirable characteristic.
- **Modelling and analytics:** A DT provides modelling and analytics capabilities. By using these capabilities, various scenarios on different states of physical system can be experimented, for the purpose of optimization or prediction. Moreover, integration of machine learning (ML) methodology may increase the power of analytical capabilities.
- **Reporting:** A DT generates reports and visualizations of analyses results for the user (human or machine) in certain formats.

In the following section, we give information on the enabling technologies of DTs.

2.1 Enabling Technologies

The latest developments in hardware, software, and communication technologies have paved the way of improved capabilities of simulation modelling. In addition to those,

Industry 4.0 technologies, and the ML applications are embodied in DT. In this section, we investigate the enabling technologies of DT.

- **Machine Learning:** ML is a part of Artificial Intelligence (AI) field which relies on the fact that machines can process larger data and information compared to human. In this process, machines can recognize the patterns and complex relationships which can be used as basis for policy analysis and decision making in DTs.[7]
- **Internet of Things:** IoT describes the objects connected via an internet network. These objects can collect, process and exchange data with each other or with other devices connected to this internet network. As discussed above, Lee and Kim describe implementation of IoT in DT. [10], [11]
- **5G:** 5G is the new technology standard for mobile networks. 5G transmits data at faster speeds than its predecessors with lower latency rates. This technology enhances data collection and communication capacity in a DT structure through establishing a broadband link between virtual and real system. [11]
- **Cloud Computing:** Cloud computing delivers easy access to computing services from a network. There are three different services offered by cloud computing. These are infrastructure as a service (IaaS), platform as a service (PaaS) and software as a service (SaaS). The advantage of using a cloud platform is that there is no investment cost for hardware, computing space or software. This technology helps DT to become more accessible by any user at a lower cost. [10], [11]
- **Augmented and Virtual Reality:** Virtual reality is a technology that emulates the real world by simulating different senses to create a virtual world. Augmented reality embeds virtual world to real world. For DT, both augmented and virtual reality may become useful tools for visualization and monitoring purposes. [10]
- **Application Programming Interface (API) and Open Standards:** APIs are the interface programs between softwares/computers. APIs and open standards enable sharing of data among different software and computers. Moreover, reusability of software pieces has been improved by the help of APIs and Open Standards. These interfaces and standards enhance DTs capability of sharing and exchanging data easier and more reliable than ever. [10]
- **Cyber Security:** Cyber security is the combination of all efforts to protect digital systems, software, and data from malicious cyber-attacks. Due to their nature, DTs are attractive targets for cyber criminals. Since any distrust in security of DT may diminish the desire for such a system, cyber security becomes an important enabler technology for DTs. [10]

Next, we discuss implementation areas of DTs based on aforementioned technological developments.

3 Implementation Areas of DT

DTs tend to be implemented by several different sectors. To investigate the implementation areas, a literature search is conducted in the peer reviewed journals and conference proceedings indexed in Scopus and WOS by using the keywords of “Digital

Twin” and the business areas listed in Table 1. Number of publications for each business area in between 1994-2022 depicted in Table 1.

Table 1. The number of publications about DT based on business areas.

Business Areas	Number of Publications
Manufacturing/Production	3,248
Maintenance	851
Service Systems	265
Supply Chain /Supply Chain	262
Management	
Marketing	73
Retail	6
Management/Leadership	6

Our findings in Table 1 verify findings of [1], [12] where DT is mostly implemented in the “manufacturing and production” area. “Maintenance” and “service industry” follow the manufacturing sector in order. DT is implemented on “SC management” relatively less than the “manufacturing and maintenance” areas. Scarcity of DT research on the SC area has motivated us to focus on this field.

When we repeat the literature search with the sectoral keywords, we obtain Table 2.

Table 2. The number of publications published in DT based-on sectors.

Sectors	Number of Publications
Energy /Energy Management	1776
City/City Management	730
Aerospace	576
Education	380
Automotive	254
Healthcare	192
Construction Industry	150
Maritime/Shipbuilding	87

From Table 2 it is observed that “Energy/Energy Management” area is the widely applied sector in DT implementations. City/City management, aerospace, education, and automotive follow that sector in order.

4 DT in Supply Chain Management

Supply Chain Management (SCM) is the management of the flow of goods and services including all processes to transform raw materials into final products. It is a complex management issue that involves all stages in the chain to complete an efficient operation. Recent COVID-19 pandemic has shown the clear shortcomings of traditional manufacturing's over-reliance on complex and often very large supply chains. The

experience during the pandemics made it well understood that there is a growing necessity for sustainability and innovation by renewal of manufacturing and product design which is also shown in Barclays' survey where 25% of professional participants declare that they had to change their supply chains in response to the pandemic [13]. DT may provide advantage for SCM by creating value in the following dimensions:

- **Descriptive Value:** End-to-end visibility of a SC is a significant issue in intelligent SC designs. DT may provide immediate and real-time visualization of those systems. By the embedded sensors and information technologies like ERP, real time data can be tracked and processed in SCs. Thus, real-time state of any asset in SC system can be traced, and necessary precautions can be taken. DT can provide SCM transparency by providing visibility in all stages such as, warehouses, transportations (cargo and fleet), and production. [8] [11]
- **Analytical and Predictive Value:** By the help of DT of a system, it would be possible to conduct an enhanced what-if analysis on the simulation model, which might not be reasonable to apply directly on the real system. This capability can be utilized efficiently in complex problem solving and optimization purposes. By the help of end-to-end visibility, high quality data gathered from the real system can be utilized in real-time decision making in SCM. For instance, predictive analytics, and necessary precautions can be proposed in advance. [8]
- **Diagnostic Value:** DT can provide huge amount of data about assets of a SCM system. By using big data analytics and machine learning algorithms embedded in DT, hidden patterns, complex relationships, and abnormalities can be identified. This knowledge helps us to understand the causes of the assets' behaviors, and again necessary precautions can be taken in advance. [8]

A SC may be investigated in four levels: Asset Level, Site Level, Network Level 1-2. DT has the potential of implementation and contribution at all levels [8],[14].

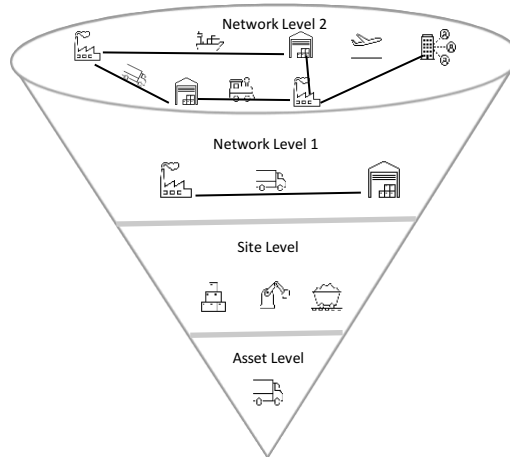


Figure 1. DT levels for SCM.

Followings are some other examples of DT implementations in different levels of SC systems [10]: Packaging and container DTs, DTs for shipments, DTs of warehouses and distribution centers, DTs of logistics infrastructure, DTs of global/local logistics networks.

DTs increase visibility, resilience and flexibility in SCs as well as reduction in lead times and reaction times and increase efficiency in processes. DTs may provide basis for construction of enhanced SCs such as agile SC, adaptive SC, etc.

Besides those benefits, there are challenges in successful implementation of DTs in SCs. Detailed modelling requirement and investment on technologies may come with high cost. Moreover, data and communication infrastructure in DTs may bring up high cost Cyber security precautions. Another challenge would be the collection of precise and timely data collection from SC systems. DT set up for SC yields excessive data and information which need to be analyzed and processed for any decision making. Due to the closed structure of legacy systems interoperability issues, that may create challenges in implementation of DTs in SCM [10].

5 Conclusion

In this study we survey the Digital Twin technology implementations in industry focusing on supply chain systems. We provide a statistical summary of publications on DT which display a growing interest in all business areas and sectors. Our aim is to shed a light on how SCs can benefit from DT applications. DT has the capability to cope with the recent resiliency and sustainability design requirements of SCs which emerged by the recent COVID-19 pandemic. By the recent technological and IT developments, it is possible to realize the digital replica of such complex systems to make intelligent decisions towards their efficient management. The literature indicates that 80% of executives expect increase in spending on digital business initiatives in the near future. Hence, although there might be several challenges in their implementations, SCs may benefit from DTs in variety of ways. We foresee that along with the digitalization efforts DT employment will be widespread for decision making in SCs as well as in other fields.

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