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Discrete Event Simulation and Digital Twins: Review and Challenges for Logistics

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Abstract

In the Logistics 4.0 era, the demand for anticipating asset behaviour and make decisions in an almost real time fashion has led to the evolution of DES into an integral part of what is currently known as the Digital Twins (DTs). A Discrete Event Simulation software is assuming the role of the cyber twin, executing simulation software queries on real time data produced by IoT devices embedded on the physical twin, i.e. the automation, which are then processed, updating the simulation to the next system state. In that way, DTs facilitate the convergence of the physical and virtual warehouse, thus supporting efficient and responsive warehouse planning, management and decision making. This paper explores the current literature on the integration of DES and DTs and identifies trends and challenges for contemporary Logistics.

Keywords: Warehouse Logistics, Discrete Event Simulation, Internet of Things, Logistics 4.0, Warehouse Automations, Digital Twins

1. Introduction

During the last decades, remarkable leaps in the fields of information technologies and digitalization have led to the creation of autonomous, web-based, self-regulating systems, widely described as Industry 4.0 [1]. Their effect on the competitive markets in the contemporary digital era is anticipated to be transformative [2]. In particular, the Industry 4.0 paradigm is expected to enhance efficiency, flexibility, productivity, visibility, cybersecurity, the quality of products and services as well as facilitate decentralized decision-making processes [3], thus, revolutionizing companies' competitive landscape. Its ultimate objective is to result in versatile "intelligent" enterprises [4], with a view to ameliorating their overall performance.

Internet of Things (IoT) emerges as an essential driving force behind Industry 4.0, whose actualization into the real world is translated into the integration of a multitude of internet-linked technologies [5], enabling the aforementioned "smartification". These technologies include "smart" embedded sensors, promoting the continuous exchange of real-time data, with the aim of allowing connectivity with existing networks as well as device-to-device and human-to-device communication [6].

Cloud computing plays an instrumental role in this endeavor by storing, processing and transferring the enormous amounts of data generated by various types of said sensors, in the cloud instead of the connected devices [7]. On the other hand, the emerging paradigm of edge computing, asserts that the data is processed at the network edge instead of the centralized cloud infrastructure addressing potential bandwidth, latency and

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energy expenditure concerns [8]. Therefore, edge and cloud computing are complementing each other to achieve useful real-time automated, sense-and-respond feedback mechanisms.

Cloud-based real-time data analysis provides information regarding the status and location of inherently mobile objects [9] as well as their surroundings [10], hence, improving parameter surveillance, monitoring and evaluation. Furthermore, intelligent robotic automations are capable of data processing and command execution, rendering them able to actuate, namely influence their environment [11]. In light of the above, the interoperability in the unified framework of IoT is inclined to drastically change industrial processes, predominantly contributing to optimizing warehouse operations.

Warehouse operations, especially material handling (e.g. storage, picking etc.), are constructively strengthened through the adoption of IoT solutions. On a more detailed level, Industry 4.0 will trigger changes that affect material handling and in-house Logistics, through improvements in materials and information, robotics and cloud technologies, RFID, Autonomous Guided Vehicles (AGVs) and autonomous decisions and configuration of material handling systems [12]. For example, "smart" sensors will be able to support constant inventory monitoring, generating replenishment alerts [13], with a view to subsequently minimizing operating expenses deriving from unmet customer needs or increasing unwanted items. Additionally, autonomous picking and packaging robots as well as collaborative robots working alongside humans, also known as "cobots", seem to help reduce mistakes and increase efficiency [14]. Overall, it appears that IoT is disrupting Warehouse Logistics (WL) in a multifaceted manner, necessitating its adaptation to the new concept of Logistics 4.0.

Nevertheless, notwithstanding obvious merits, IoT implementations tend to be intrinsically complex, therefore dictating the need for experimentation with several parameter settings, so as for any specified objectives to be accomplished. This need is conventionally accommodated with the support of Discrete Event Simulation (DES) software applications. Nonetheless, the growing demands for almost real-time decision making has resulted in the evolution of DES into a fundamental component of what is presently termed as the Digital Twins (DTs).

In this paper, the current literature on the integration of DES and DTs in the warehouse is investigated, in order to recognize trends, limitations, future prospects and challenges for modern Logistics.

2. The Role of Traditional Discrete Event Simulation Systems

The use of simulation in its traditional design role is able to present a "smart" company with a major competitive advantage during development, deployment and execution of its plans and strategies. Simulations are achieved through the virtualization of processes with the use of tools, testing virtual models *prior* to real-world application and proven to assist with: i) predicting performance, such as latency, utilization and bottlenecks, ii) divulging how the diverse components of a system interact, iii) experimenting with and evaluating the merits of alternative scenarios, iv) providing a knowledgebase of system configuration, v) serving as a valuable means of demonstration and as a result of the above vi) supporting decision-making [15].

Discrete event simulation (DES) is a form of computer-based modeling of a system as a discrete sequence of events. A major advantage of simulation over other operational research (OR) techniques is that it allows for experimentation with any element of a business system [16]. The term "discrete" refers to the simulation moving forward in time at mutually exclusive intervals. On account of the dynamic nature of the systems to be modeled, a mechanism for tracking the evolution of time is required. This is achieved by a tool called "simulation clock", which varies with the occurrence of events. DES models employ two eminent approaches, as described above [17]:

a) *Next Event Time Advances (NETA)*: NETA is a mechanism determining the time of occurrence of futuristic events based on a list. Under this typical approach, the "simulation clock" is initialized to zero and between successive events, under no circumstances is a change in the system supposed to occur.

b) *Fixed Increment Time Advances (FITA)*: This alternative approach advances the "simulation clock" by a specified unit of time *delta-t* irrespective of the events. The system state is updated after examining the event list, so as to detect the possible occurrence of any event in past period of time *delta-t*.

In general, NETA is more commonly used in simulation than FITA due to being less intricate [18].

All in all, the efficiency of DES [19] and its flexibility stemming from its stochastic nature [20] render it suitable for being used in a broad spectrum of applications [21], including warehouse operations, as a means to validate the performance of various indicators, e.g. concerning material handling systems [22] or order-picking and product location strategies [23]. Still, the increase of computing processing power, the emergence of artificial intelligence and the expansion of IoT sensing in the modern warehouse has created the need and subsequently gave birth to a new kind of 'simulation' paradigm, called the 'Digital Twin' enabling the real-time control and digitization of a physical system.

3. The Era of the Digital Twin Simulation Paradigm

"A digital twin (DT) is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin" [24]. Thus, the concept of a DT, which is comprised of a physical entity in the physical world, a virtual entity in the virtual world and connected data tying the two worlds, is able to realize the convergence between physical and virtual space [25]. In the process of this interaction, the virtual entities are capable of interpreting data transmitted by the physical ones, therefore, grasping their state. In this way, dynamic changes are predicted, approximated and examined, allowing the physical entities to dynamically adjust, based on the optimized scheme from simulation, ultimately, creating a cyber-physical closed loop [26]. DT technology plays a crucial part in deploying the Industry 4.0 concepts by presenting companies with the following benefits [27]: a) highly synchronized reflection of the physical space, b) juxtaposition between historical and real-time data, c) interactions among physical objects, d) convergence between physical and virtual space [28] and e) continuous improvement of the virtual model [29], since it can be overlapped with a physical object feeding real-time data, being processed in an inconspicuous manner [30].

The abovementioned advantages are proven to be exceptionally useful, in the field of warehouse logistics, in which the flow of products is contingent on the orchestration of a plethora of elements in a multi-stakeholder environment. DTs' added value lies in the optimization of the infrastructure, eliminating errors and delays [31]. In the next section, a short review on the integration of traditional DES approaches with the new DT paradigm is presented, followed by a discussion on the findings, highlighting current research challenges and identifying future research opportunities and implementation priorities.

4. Review

A literature review was carried out, in order to identify and critically evaluate the findings of peer-reviewed studies, pertaining to the integration of DES and DTs in the warehouse. The data collection process was conducted on January 19, 2020, based on papers from the Scopus database, using a query of the key word terms "(Discrete Event Logistics OR DES) OR (Digital Twin* OR DT*) AND (Warehouse Logistics)". Please note that the asterisk (*) at the end of a key word ensures the inclusion of the term in both singular and plural forms as well as its derivatives. Further research results added on a later date to the Scopus database, are, therefore, not included in this study. This query was entered into Scopus's default tab (Document Search form), followed by the selection of the search field "Article Title, Abstract, Keywords".

This initial search yielded 49 results. This number decreased after limiting "Year" to exclusively include papers after 2015, when it was made clear that the exploration of potential use cases for digital twins across the logistics space became worthwhile, thus, amounting to 29 results. After meticulously examining their content, namely their abstract, keywords, table of contents and main body, several papers were deemed inadmissible, on account of lacking relevance. Furthermore, we were not able to retrieve the full text of a number of papers, thereby reducing the final sample size to 14 papers.

Grey literature was, additionally, examined through the websites of logistics and consulting companies, with the aim of unraveling significant information unavailable in commercially published literature. Finally, manual searching was complementarily pursued to fill the remaining knowledge gaps.

The final sample size resulting from the data collection process, namely fourteen (14) papers, explores the application of DES in WL almost in its entirety.

Starting with the works of Korth et al. [32], one can see the use of DES and DT in tandem for a critical real-time use case in logistics, i.e. creating the digital twin of a warehouse used for shift planning of blue-collar workers and time window planning. The authors argue about the need of an efficient integration of DES into a DT architecture in real-time logistics use cases by separating the static and dynamic parts of the model making past, present and future of the logistics system efficiently available for decision support in the same semantic and syntactic data model. In particular, unstable non-linear business conditions have demonstrated a requirement for more transparency in daily planning which can be met by DES. However, a tool transferring the decisions to the DES, while at the same time mirroring the current warehouse situation is also of paramount importance. In this study, these needs were accommodated through a DT with DES capability. When a decision scenario is complete, it is assessed by DES, which plays through the scenario and creates measurements. Then, the decisions are modified until satisfactory results are achieved.

In a similar vein, Ashrafian et al. [33] used the analysis software Flexsim to perform a DES model of a fully automated modular conveyor system, so as to alleviate impaired material flow, caused by bottlenecks. The data used to carry out DES was gathered from the system over one week of operation and amounted to roughly 500,000 totes. During this process, the authors identified some requirements for rendering DES modeling an instrumental tool for DTs. The authors elucidated the importance of accomplishing connectivity to the operational resource planning database. A high level of detail in all aspects of the modelled system was also deemed an essential factor. Moreover, manual modifications of a DES model can be time consuming, especially if a plethora of scenarios need to be tested. Hence, with a view to enhancing decision-making and achieving optimization without manual interventions, the development of various model versions should be automated to the highest degree possible.

Rabe and Dross [34] presented the architecture and working principles of a simulation-based Decision Support System (DSS) predicting the repercussions of possible changes, for logistics networks, with the support of a data-driven DES model. The system was tested with data from over 100 warehouses in different countries through the collaboration with a large, international trading company. The data were collected from the Data Warehouse (DWH) in predefined periods and the simulation tool used for the implementation was SimChain. Cooper et al. [35] proposed a cost-to-serve model, which they implemented as a DES, in order to cost-effectively assess the delivery frequency, as a result of the potential addition of a cross-dock node between Distribution Centers (DCs) and stores to a supply chain network. The DES was fed input data concerning product characteristics, store locations, and demand, truck routes for store delivery from the DC or the cross dock and delivery schedules from suppliers to the DC.

van Lier et al. [36] performed a DES to analyze the potential internal horizontal collaboration among three neighboring DCs. In particular, they evaluated a scenario in which outbound product flows are gathered in a hypothetical cross-dock situated next to the three DCs. In order to carry out the DES, a data set of load orders from the three DCs was collected over 10 weeks of operation. In [37], Rosi et al. presented an evaluation of the performance of an automated single-tray Vertical Lift Module (VLM) warehouse system by using DES technique. The aim of this paper was to investigate VLM's benefits in regards to decreasing transactions' mean cycle time.

Sun et al. [38] designed an automated warehouse sorting system, whose feasibility was verified by experiments in a small scale bag manufacturing enterprise through the application of a DES model, using the popular simulation tool "AutoMod" (http://www.automod.se/eng/home.html). Burinskiene et al. [39] presented a DES analysis of various inner-warehouse transportation processes, in an attempt to reduce waste. The results indicated that 67% of waste in warehouses could be avoided. Merschformann et al. [40] simulated pick and replenishment processes, order assignment as well as pod selection and storage assignment problems in a robotized, parts-to-picker material handling system, using DES, by evaluating multiple decision rules per problem. Zhang et al. [41] proposed a new service mode for final vehicle assembly and logistics, which was simulated based on data from AnJi Automobile Logistics Company by a DES software called "Flexsim" (https://www.flexsim.com/). Viet et al. [42] used a DES and a simulation-based scheduling algorithm, as decision support tools to evaluate the information flows, planning daily warehouse operations, through a case study of the distribution process in a Dutch floricultural supply chain.

Smith and Srinivas [43] proposed and compared various truck check-in policies to be applied to warehouse receiving processes, using DES models. Their objective was to minimize detention fees paid to the carrier as well as reduce CO_2 emissions. At the same time, Timperio et al. [44] provided a hands-on decision support framework integrating Multi-Criteria Decision Making (MCDM), network optimization and DES to address distribution network design and transport optimization. The results demonstrated 18%-22% cost saving in transportation and warehousing along with 30% reduction in CO_2 emissions.

Finally, one has to note the excellent efforts of Brenner and Hummel [45] at the University of Reutlingen in building an innovative digital shop floor management system. The program aims to implement the intralogistics concept in the lab of the ESB Logistics Learning Factory with sensor mounted autonomous navigating transport vehicles and dynamic logistics and production processes.

As it can be inferred, based on the coding criteria imposed, during the last five (5) years the concept of DES was utilized in a variety of applications, whose common objective was the validation or refutation of a hypothesis to be implemented in the context of warehouse logistics. Conversely, DTs are a relatively new powerful tool justifying the lack of scientific research on their application to warehouse logistics thus far. The authors of this paper mostly turned to grey literature, which provided considerable insights, so as to overcome the deficiency of scientific studies pertinent to the subject.

The sole relevant study retrieved in Scopus was an article by Petković et al. [46] who proposed a human intention estimation algorithm which realistically simulates worker behaviour in robotized warehouse settings. With the aim of exhibiting the scalability of their approach to larger warehouses, the authors not having the use of a full-scale commercial warehouse for testing, carried out intention estimation experiments in a large warehouse virtual reality (VR) DT. The experiments proved that the proposed framework estimates warehouse employee intentions with great accuracy.

On the other hand, grey literature pointed to the works of Dohrmann et al. [31], who through expressing DHL's perspective, shed light on the effect of warehouse DTs on the optimization of a logistics facility. In particular, using a 3D model of the infrastructure itself fed by IoT data harvested from a plethora of automation technologies, DTs enable companies to create vivid simulation scenarios, predicting the movement of products, personnel, and material handling equipment, thus, contributing to space utilization optimization, reduced energy expenditure as well as improved employee productivity. The IoT data mostly refer to inventory levels, demanded quantities, item location and characteristics etc. DHL implemented this technology for an international packaging group's warehouse (Tetra Pak), where the cyber twin was fed IoT data from warehouse's forklift trucks [47]. In this context, a retail company employed DT technology, in order to simulate its current operations, with the aim of ameliorating the overall flow of products in one of its fresh food warehouses. Two different layouts were tested for manifold scenarios, so as to assess the change in performance measures, hence, amplifying decision-making [48].

Rosemann [49] discussed the trust and transparency in partner and consumer relationships, as a result of network visibility provided by DTs, concluding that the implementation of DTs leads to improved collaboration and increased consumer confidence respectively.

Last but not least, in their handbook, Ivanov et al. [1] referred to how DTs are able to provide end-to-end supply chain (SC) visibility, while interacting with other SC management tools. In the event of a disturbance in a warehouse process, the urgent state can be reflected by a risk data monitoring tool and passed on to the virtual model of the DT, which helps forecast possible disruption propagation, assess its ramifications, experiment with potential recovery policies and verify the adherence to contingency plans.

Taking into consideration all of the above, it can be deduced that the implementation of DTs –or rather the integration of DES approaches with DTs- in the field of warehouse logistics is still at a primitive stage, yet, it presents promising potential for future applications.

5. Conclusion

Discrete Event Simulation and digital twins share a lot of characteristics, which sometimes lead researchers and mostly practitioners to misconceptions. It is true, that sometimes a digital twin can be used as an initial structure for building a DES model and at the same time an initial simulation effort could later be expanded so that physical simulation (twinning) is possible. It is only when these two discrete worlds merge, when an actual digital twin is created duplicating the physical model and providing monitoring and controlling capabilities based on real-time data from various sensors, while at the same time producing forecasts and future state estimations with the support of machine learning and AI techniques embedded in the system. Currently, most of the available DES software solutions are still process-based scheduling applications. Still, there is an increasing trend for enhancing DES functionalities offering real-time simulation scheduling.

In this paper, the authors attempt to clarify these two terms and showcase their differences, but most importantly highlight interesting research efforts as retrieved by reviewing the available literature at the intersection of these two system modelling approaches, with an emphasis on logistics. As it is evident by the number and the level of maturity of reviewed documents, the research efforts are currently at an embryonic stage of development. More research is needed and fortunately is welcomed and expected by both the industry and academia, as a result of Industry 4.0 growth driving adoption of closely interrelated technologies, such as Additive Manufacturing, IoT Sensors and IoT devices. The need for DES and DT models will be further enhanced by the increasing trend of real-time scheduling and decision making supporting intelligent enterprises in handling business process exceptions such as machine failures and rescheduling based on the updated system conditions. DES software is traditionally used for addressing these kinds of business issues. In the near future, when 'sensing' shop floor data will become vastly available, DES and DT applications will be able to execute real time simulations and provide almost real time solutions enhancing performance of both manufacturing and logistics processes. To that end, future research should focus on addressing the limitations and complying with the requirements for integrating DES into DTs, followed by applying uses cases of DES and DT in tandem, so as to enrich current knowledge and progress the discipline forward.

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