Exploring Digital Twins in Transport and Energy Fields

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Logistics and transport are major sources of energy consumption that still rely heavily on fossil fuels. Especially in the freight sector, finding means to optimise fuel consumption and energy efficiency are increasingly important. Digital twins' adaptation in logistics and transport is not as frequent as in production, but their implementation potential is immense. This technology can replicate real environments, allowing verification of various scenarios without real-life application, leading to optimal implementation outcome faster and more efficiently.

Keywords: logistics ; transport ; digital twin ; energy consumption ; optimisation ; literature review ; bibliometrics

1. Introduction

The European Union (EU) has set a goal to become climate-neutral by 2050 [1], meaning the EU's net greenhouse gas emissions will be reduced to zero. This target was first announced in 2018 as a part of the EU's long-term strategy [2] to combat climate change and achieve the goals of the Paris Agreement [3].

The transportation industry significantly contributes to greenhouse gas emissions in the EU, accounting for approximately 25% of total emissions [4]. As such, the EU's climate-neutral strategy includes a range of measures aimed at decarbonising the transportation sector and promoting sustainable mobility. This goal could only be reached by low-emission vehicles powered by electric and/or hydrogen [5].

Today, the primary purpose of digital twins is to simulate and optimise the performance of products [6], services [7], processes [8] or systems [9]. In the case of transport, cyber-physical systems are created with digital twins and are connecting an object's physical counterpart [10][11] with its virtual one [12]. They usually obtain a continuous real-time data stream from the physical environment (e.g., through sensors [10]), consequently allowing to test various scenarios without real-life implementation. Therefore, they find optimal implementation scenarios faster and more efficiently through the digital replica.

Digital Twins are being adapted into all pores of various industries [13], from the beginning in manufacturing [17], after in supply chains [18][19][20], logistics [14], the process industry [21][22], and transport [23][24] with a focal point on energy efficiency [25][26][27]. Specifically in the transport industry, digital twins are anticipated to drastically change the transport systems' technology, as they enable monitoring of the whole transport system life cycle [24]. Digital twins can help manage traffic and avoid traffic jams with real-time traffic information, optimise public transport (e.g., to the number of people using it by leading busses to event locations) and enhance mobility infrastructure using smart sensors [28]. Effective planning (including optimisation) is crucial to success in decarbonisation [29]. For example, digital twin technology can solve the issue of what type of busses and what kind of electric infrastructure (including batteries and chargers) is crucial for sustainable public transportation systems. The technology can also mirror the vehicle on the road, predict and optimise its performance and improve its safety [30]. Simulation of electric vehicle participation in the electricity market is also possible—because of their battery, electricity could be sold to the market after completing the route or journey, reducing the cost of electro peak.

This entry aims to research digital twin use in logistics and transport, focusing on the effects of technology's use towards optimisation of energy consumption by performing a quantitative and qualitative literature review. Previous research on digital twins in the logistics and transport field is identified, followed by a quantitative and qualitative literature review, focusing on codifying the selected publications by the selected criteria. Transport and logistics fields are major sources of energy consumption that also still heavily rely on fossil fuels. Especially in the freight sector, this is not realistically set to change in the following years. The potential for using digital twin technology to optimise fuel consumption and increase transport energy efficiency is considered substantial. Thus, the entry's main contribution is in a systematic overview of contemporary technology, e.g., digital twins, from the viewpoint of energy optimisation and reduction in one of the most energy-dependent sectors-transportation.

2. Results

2.1. Authorship and Source Analysis

There were 234 unique authors in the literature pool overall. Of those, only one author (Wu) has authored three publications, and eleven have authored two. The most cited authors were Zhang Y. (109 citations); Opoku D., Oser-Kyei R., Perera S., and Rashidi M. with 84 citations each; and Bhatti G., Mohan H., and Raja Singh R. with 82 each.

The publications were published in 46 different sources. Five sources have published more than one publication on the researched topic, which were IEEE transactions on intelligent transportation systems (5 publications), Energies (4 publications), IEEE Access (3) and Journal of Cleaner Production and Sustainability with two publications each. Both the author and source analysis showed a considerable lack of connectedness among the active participants in the field since no clusters of citations were evident from the analysis.

Overall, the authors of publications from the literature pool come from 33 countries. To analyse international cooperation in the field, a citation and clustering analysis of co-authorship by countries of author origin was performed. Country dispersion was high since only fifteen countries were the origin of more than two publications, and only five countries of at least five publications (China, the United States, the United Kingdom, Italy and Germany). It is worth noting that a single publication can have more than one country of origin if the co-authors come from different countries.

China was at the forefront of digital twin research on transport and energy since it was the predominant producing country in the absolute number of publications (15) and by citation count (158 citations). This was followed by the United States (9 publications with 136 citations). entrys originating from Hong Kong and India also had a large citation count (85 and 84, respectively), while Germany had larger publication outputs with eight publications but only twelve citations. In terms of connections among publications and, consequently, the international scope of research, three clusters form if clustering is performed on all countries that have produced at least three publications.

Three clusters of co-authorship were evident—China, Hong Kong and Italy (green cluster); Germany, India and South Korea (red cluster); and United States and United Kingdom (blue cluster). It is worth noting, however, that these interconnections were not strong, meaning that there was not much cooperation among researchers from different countries in the current research sphere. The two strongest links shown in the literature pool were between China and Hong Kong (link strength four publications) and China and the United States (link strength three publications).

2.2. Citation Analysis

There were twenty publications in the literature pool cited at least five times, and four were cited over fifty times overall. The top cited publications were Opoku (2021) [32] with 84 citations, Bhatti (2021) [33] with 82 citations, Wang W. (2020) [34] with 64 citations, Defraeye (2019) [35] with 62 citations and Liu Y. (2020) [36] with 45 citations.

A citational analysis was performed to see how often publications in the literature pool cited each other. This showed clear seclusion of publications in the literature pool since only six such links were found. The clustering analysis did not identify any relevant clusters of publications. This clearly points to a need for more connection among the included publications.

To further explain the interconnectedness of publications, co-citation analysis was used for the literature pool analysis. There were 2618 cited references in the literature pool overall. The results again showed a large dispersion of used and cited sources since only three references met the inclusion threshold if the minimum number of cited references was set at four, and no references appeared five times, which is a relatively small number. Therefore, the minimum number of cited references was set to two, which consequently included twenty-seven cited references. The top cited references in the literature pool are shown in **Table 1**. In other words, these are the publications from the literature pool cited most often. All publications that are not shown were cited less than three times.

Table 1. Most cited references by publications in the literature pool.

Publication	Number of Citations in the Literature Pool
Tao [37]	**4**
Rasheed [38]	**4**
Schellenberger [39]	**4**
Rosen [40]	**3**

Publication	Number of Citations in the Literature Pool
Kritzinger [41]	3
Fuller [42]	3

In terms of co-citations, seven clusters formed when further analysis was conducted on the twenty-seven publications that were cited by the publications in the literature pool at least two times. Four clusters formed and three publications were not connected to any of them. The circle size indicates the relative number of times a publication was cited in the literature pool. The size of the connecting lines indicates the number of co-citations that two publications share (meaning that they were cited together in a publication).

The evident clusters show that only two are connected and two clusters are individual. Even with publications that formed clusters, the link strength was small, which means there is not much connection between the presented publications. The latter is also evident from the relatively large number of cited publications overall and the relatively low number of found interconnectedness.

2.3. Keyword Analysis

A co-occurrence analysis of both author and index keywords was performed. If the number of occurrences of a keyword in the literature pool as a base for inclusion into the analysis was set to at least five, then only twenty keywords met the inclusion criteria. The top ones are shown in **Table 2**.

Table 2. Keyword occurrences among all and only author keywords for the top nine keywords.

Keyword	Occurrences among All Keywords	Occurrence among Author Keywords
Digital twin	38	35
Internet of things	13	8
Smart city	12	9
Energy utilisation	10	/
Decision support	9	3
Simulation and modelling	8	3
Urban transport	7	2
Real-time systems	7	2
Energy efficient	7	/

Clustering and co-occurrence are shown graphically below. Each keyword is represented by a circle (node), and the size of the circle points to the relative number of appearances of that keyword in the literature pool. The keywords are connected with lines (links), meaning two connected keywords appear together in a publication (co-occur). The thickness of the connective line points to the relative number of shared repetitions.

If co-occurrence and clustering are performed on only the author keywords from the literature pool, since it can be concluded that these point to the actual publication contents as intended by the authors, only three met the threshold for inclusion if the minimal number of occurrences is set to five. These are “digital twin”, “smart city” and “internet of things”. To obtain a good base for analysis, the minimum occurrence number was set to two so that the niche keywords could have been ruled out. Thirty-four keywords met the inclusion criteria in this case.

There were six clusters of keywords detected in this analysis. Two clusters comprised seven items (red and green), one out of five items (blue), three out of four items (yellow, turquoise and purple) and there are three keywords which could not be connected to any clusters (shown with grey nodes). The clusters, therefore, pointed to the prevalent topics connected to digital twin research: the connection to supply chain management and digitalisation (red cluster), transport and manufacturing applications (green cluster), Internet of Things and Industrial Internet of Things with adjacent technologies (blue cluster), decision support and learning (yellow cluster), sensors and transport (turquoise cluster) and simulation and modelling in connection to anomaly detection and cold chains (purple cluster).

2.4. The Use of Digital Twins' Technology in Logistics and Transport

A table that shows authors and publication year with source, transport type, modality and usage environment, energy distribution or consumption inclusion, classification in constant multitudes of supply chain systems, digital twin objective of the research and other used tools in the research and implementation level of digital twins can be found in Appendix A. All table elements are presented with codes for transparency purposes and will be described in this section.

Of 163 publications, 57 were included in the previous bibliometric analysis based on the required criteria. Unfortunately, it was impossible to obtain the entire content for two publications; thus, they were not included in the detailed content analysis (marked as / in Appendix A). Therefore, the detailed quantitative literature review included 55 publications. In further analysis, the number of publications corresponding to a given category is indicated in parentheses.

Table 3 presents the frequency of identified fields from the research. Some publications had overlapping fields, such as a combination of supply chains and logistics (2) or supply chains, logistics and transport (7), meaning the publications' content can be implemented in either. Most of the publications (24) focused on the field of logistics, where the implementation of digital twins is relatively well integrated since it often includes manufacturing processes where digital twins originate and are still most often used. This also focused on digital twin use in the transport field, where the second largest number of publications was placed (21). The following field was supply chain (19), which is closely correlated to logistics and transport fields. Supply chain management (2) is an essential factor of supply chains' success and sustainability [43], but there was scarcely any research conducted, and the same is true for transport infrastructure (2). Based on this, it can be concluded that the number of research in the transport field is increasing, but still lacking in some essential aspects of operational management and energy use reduction. Lastly, for one of the publications, the field was not identified.

Table 3. Frequency of reviewed fields.

Classification in Appendix A	Reviewed Field	Frequency
LOG	Logistics	24
TRANS	Transport	21
SC	Supply chain	19
SCM	Supply chain management	2
TRANS INF	Transport infrastructure	2
N/I	Not identified	1

When reviewing the transport type, as shown in **Table 4**, only one (review) entry was found with overlapping internal and external transport types. Along with the latter, 39 other publications were related to external transport. Most of the publications researched transport optimisation outside of the company, while manufacturing was the most researched process inside the company. A considerably smaller number of publications focused on internal transport (7). Optimisation of the latter can lead to a well-operating material flow inside a company [44], and modernisation of internal transport can reduce or even eliminate manual labour [45]. The least number of publications focused on whole logistics systems or industrial networks (2), followed by whole supply chain systems and transport in general (1). In three of the reviewed publications, the transport type was not identified.

Table 4. Frequency of reviewed transport type.

Classification in Appendix A	Reviewed Transport Type	Frequency
EXT	External transport	40
INT	Internal transport	7
NET	Network	2
WLS	Whole logistics system	2
GEN	General transport	1
WSCS	Whole supply chain system	1
N/I	Not identified	3

The classification of transport modalities is shown in **Table 5**. Few of the reviewed publications (6) had overlapping transport modalities, meaning the publications' content is connected to more than one modality:

Table 5. Frequency of reviewed modality.

Classification in Appendix A	Reviewed Modality	Frequency
Ro	**Road transport**	**15**
Ur	**Urban transport**	**8**
Mar	**Maritime transport**	**8**
Air	**Air transport**	**6**
ITS	**Intelligent Transport System**	**6**
Ra	**Rail transport**	**5**
OTH	**Other**	**5**
Pip	**Pipeline transport**	**3**
GEN	**General transport**	**2**
N/I	**Not identified**	**10**

- Air, road, rail, pipeline and urban (1);
- Air and urban (1);
- Maritime, air and road (1);
- Maritime, road and rail (1);
- Road and intelligent transport systems (2).

The majority of daily journeys, both personal and business, take place on roads. Furthermore, integrating technology into cities, making them smart cities, is crucial for increased efficiency of physical infrastructures' operations, such as roads, buildings and communication networks [46]. In accordance with the importance of road transport optimisation, the highest number of reviewed publications focused on this modality (15). Just over half as many publications researched urban or maritime transport (8), followed by air transport and intelligent transport systems with smart trolleys (6), rail transport and other modalities (5), such as container, crane, elevator and energy transport, e-mobility and product trolleys. The least number of publications were focused on pipelines (3) and general transport (2). For ten publications, however, it was not possible to identify the modality.

In addition to the modality, the usage environment was examined (**Table 6**), where a high degree of fragmentation was recognised. As a result, individual elements were not included in the classification, and the codes were not assigned. Only publications that appeared at least three times are presented in classification.

Table 6. Frequency of reviewed usage environment.

Reviewed Usage Environment	Frequency
Smart city	**20**
Manufacturing	**9**
Functionalities	**4**
City	**3**
International	**3**
Not identified	**3**

Some of the reviewed publications (6) had overlapping usage environments, such as:

- City and air mobility (1);
- City and e-mobility (1);
- City and streetlights (1);
- Manufacturing and smart city (2);
- Smart city and air mobility (1).

Even though digital twin implementation has spread due to the Industrial Internet of Things, their integration in smart cities has been less popular [47]. This can be attributed to the complexity of a city [48], which is not an automated system but a living one that evolves through variations and developments of its architecture, economic, political, social and cultural activities, with ecological systems [49]. Smart cities present open challenges as they should be treated as "cyber-physical systems of systems" due to their composition—numerous systems of different sizes, complexity and requirements [47]. most publications (20) dealt with the digital twin technology implementation in smart cities. As previously mentioned, internal transport, in this instance, has not been researched as much, corresponding to the number of publications about usage in manufacturing (9). Some publications were classified into the functionalities group (4), where research focused on the functionalities of a vehicle, locomotive or pipeline system. A few publications dealt with research regarding cities and international usage environment (3). The usage environment was not possible to identify for three publications.

here also focuses on digital twins' potential and effects to optimise energy consumption (**Table 7**). Some of the publications (6) had overlapping criteria regarding energy consumption, such as a combination of energy distribution and consumption (3), and energy and fuel consumption (3), meaning the publications' content integrated both. Most publications focused on energy consumption (37), pertaining to autonomous regulations of energy-consuming equipment [50], energy consumption by autonomous unmanned aerial vehicles (drones) [26] or even cranes [51]. A fifth of as many publications dealt with energy distribution (7), and fewer with fuel consumption (4). Even though energy consumption is important, fuel optimisation enables optimisation of operational costs, direct or indirect factors (such as waste and fraud), eco-driving (such as fuel-efficient vehicle operation) [52] and even reduction in CO_2 emissions [51]. One entry researched the energy sector, and no connection to energy could be discerned from twelve publications. The non-mentioned publications dealt with airport hubs, boats, buildings, the construction industry, diverse transport, freight transport, general transport, industrial networks, port, smart grid, UAVs, warehouses, streetlights, air mobility and e-mobility.

Table 7. Frequency of reviewed energy distribution/consumption.

Classification in Appendix A	Reviewed Energy Distribution/Consumption	Frequency
E-CON	**Energy consumption**	**37**
E-DIS	**Energy distribution**	**7**
F-CON	**Fuel consumption**	**4**
E-SEC	**Energy sector**	**1**
N/I	**Not identified**	**12**

Products, services, processes and systems are a regular part of supply chain and logistics systems whilst formulating a multitude of other (semi-)products, services, processes or systems correlated amongst each other. Therefore, the authors [13] named the latter 'constant multitudes of supply chain systems', which served as one of the criteria. Based on the digital twins' use (for a product, service, etc.), the literature pool was divided into one or more (**Table 8**).

Table 8. Frequency of reviewed constant multitude of supply chain systems.

Classification in Appendix A	Reviewed Constant Multitude of SC System	Frequency
SYS	**System**	**52**
PROC	**Process**	**39**
SER	**Service**	**31**
PROD	**Product**	**21**

Practically every reviewed entry had overlapping divisions into constant multitudes of supply chain systems (40). A single division could be attributed to services (1) and systems (13). Otherwise, most publications delved into transport systems multitude (52), corresponding with the fact that transport is a complex composition of infrastructure, networks, nodes, products, services and even people. Process multitude followed (39), where digital twins can be implemented for transport process evaluation and optimisation [53]. In third place was service multitude (31), intended for predictive maintenance and performance (e.g., prediction of estimated travelling distance [54]), fault detection and diagnosis, state monitoring, optimisation [33] and virtual tests [55]. Lastly, the constant multitude of products (21) followed, where the use of digital twins was reflected in manufacturing resources, such as machines and trolleys [34], vehicles [15], products lifecycle management [56] or even development [33].

As with previous criteria, practically every reviewed entry had overlapping divisions of digital twins' objective (46). A single division could be attributed to systems management (2), systems optimisation (2), process management (1), process optimisation (1) and lastly, product management (3). According to the results from the previous table, it was not surprising that most of the research focused on system management (39) and optimisation (26) with the help of digital twins. This was followed by a digital twin objective to manage (23) and optimise (19) a process. Accurate assessment of possible security risks and quality of data and information [53] are essential in every company, even in transport [57], where ensuring timely data integrity, stability, remote control and maintenance [52] can mean the difference between a smooth flow of transport or a possible system collapse. Consequently, risk management as a digital twin objective was in fifth place alongside product management (15). Although systems planning (11) and design (7) are irreproachably the foundation of a company's success or production of a good product, they are not yet at the forefront of digital twin use. Last was product design (2); the digital twin objective could not be identified in one entry. **Table 9** presents the frequency of identified digital twins' objectives.

Table 9. Frequency of reviewed digital twin objective.

Classification in Appendix A	Reviewed Digital Twin Objective	Frequency
SYS-MNG	**System management**	**39**
SYS-OPT	**System optimisation**	**26**
PROC-MNG	**Process management**	**23**
PROC-OPT	**Process optimisation**	**19**
RSK-MNG	**Risk management**	**15**
PROD-MNG	**Product management**	**15**
SYS-PLAN	**System planning**	**11**
SYS-DSG	**System design**	**7**
PROD-DSG	**Product design**	**2**
N/I	**Not identified**	**1**

The penultimate criterion established which other technology tools, besides digital twins, were used in the reviewed publications. A high degree of fragmentation was again recognised, as a result of which only technology tools that were repeated at least three times are presented in **Table 10**. Other individual elements were not included in the classification. Some of the reviewed publications (9) had overlapping used technology tools:

Table 10. Frequency of reviewed other used tools.

Classification in Appendix A	Reviewed Other Used Tools	Frequency
IoT	**Internet of Things**	**11**
AI	**Artificial intelligence**	**5**
ML	**Machine learning**	**4**
Ed-Comp	**Edge computing**	**3**
N/I	**Not identified**	**33**

- Artificial intelligence, augmented and virtual reality, 3D engineering and printing, Internet of Things, machine learning, cloud, blockchain and data analytics (1);
- Artificial intelligence, edge computing and machine learning (1);
- Artificial intelligence and big data (1);
- Artificial intelligence and Internet of Things (1);
- Artificial intelligence and big data (1);
- Machine learning and data analytics (1);
- Internet of Things and machine learning (2);
- Edge computing and cloud (1).

Digital twins are based on the Internet of Things (11) and artificial intelligence (5), corresponding to the number of other used technology in this literature review. Artificial intelligence and machine learning can be used for input processing automation of texts and images [58]. Based on different versions of machine learning (deep learning, federated learning) (4), a digital twin can estimate, forecast, analyse and optimise different variations in challenges [59]. These technologies can bring new capabilities with immense business value [58]. With edge computing (3), digital twins can manage big data and machine learning activities with automatic control and cross-discipline knowledge [59], such as cloud-edge collaborative computation [60] or mobile-edge computing [61].

Other publications had a high degree of fragmentation and were classified as:

- cloud, blockchain, big data, data analytics and virtual reality (2);
- 3D engineering and printing, augmented reality cyber-physical systems (1).

In many publications (33), digital twins were the only technology tool identified.

Lastly, implementation levels of reviewed publications are presented. A little more than half of the reviewed publications (28) had overlapping implementation levels:

- Framework and case study (1);
- Framework and theoretical implementation (1);
- Framework, theoretical implementation and analysis (1);
- Methodology, implementation and analysis (1);
- Model, implementation and analysis (8);
- Model, implementation, analysis and case study (1);
- Model, simulation and analysis (11);
- Model, simulation, analysis and case study (1);
- Model, theoretical implementation and analysis (2);
- Review and theoretical implementation (1).

As for the other publications (27), each had one implementation level type: review (11), theoretical implementation (8), conceptual model (4), case study (2), framework (1) and prototype (1). Only implementation levels repeated at least five times are presented. Most publications encompassed analysis (25) and model presentation (23). There were less than 20 publications that described digital twins' implementation as theoretical implementation (13), review or simulation (12) and practical implementation (10). The least number of publications had implementation level case studies (5). Based on these results, it can be argued that analysing models and theoretical implementations of digital twins in transport are most common, most likely due to not requiring practical tests.

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