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Review

Exploring Digital Twins in the Transport and Energy Fields: A Bibliometrics and Literature Review Approach

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Abstract: 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. This paper aims to research digital twins' use in logistics and transport, focusing on digital twins' potential and effects to optimise energy consumption. Firstly, previous research on digital twins in specified fields was identified, followed by a quantitative literature review. The latter focused on codifying the selected publications based on criteria such as modality, specific environment, energy consumption, etc. Furthermore, a qualitative overview of 57 relevant publications on digital twins' use in logistics and transport was made. The main contribution of this paper is the systematic overview of digital twins from the viewpoint of energy optimisation in one of the most energy-dependent sectors. This gives researchers a good starting point for further research and digital twins' practical implementation cases.

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

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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. This is made possible by several different technologies, working synchronously in a symbiotic mutualism:

- Internet of Things represents the backbone that allows the physical twin to provide a continuous real-time data stream to the digital twin [13,14];

- Artificial Intelligence (AI) represents the components of digital twins that analyse, interpret, orchestrate and optimise the operation of the physical twin [15];
- Machine Learning (ML) allows analysis of large amounts of data from the physical twin so the digital twin can learn and expand its ability to orchestrate and optimise the physical twin [13,16];
- Data analytics enables analysis of data to describe, diagnose, predict and prescribe actions to optimise the operation of the physical twin [15];
- Cloud computing platforms are fundamental components of virtual replicas (digital twins) of observed real-world objects [15].

Digital Twins are being adapted into all pores of various industries [13], from the beginning in manufacturing [17], after in supply chains [18–20], logistics [14], the process industry [21,22], and transport [23,24] with a focal point on energy efficiency [25–27]. 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 paper 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. A particular emphasis on the research publications that include elements of energy consumption (e.g., do the publications estimate fuel or energy usage reductions or optimisation measures) is made. In addition, a bibliometrics-based analysis, a quantitative and qualitative overview of the contents of the 55 most relevant publications using digital twins in the logistics and transport field, is made. 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 paper'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.

The paper's main research questions are as follows:

RQ1: What are the main topics included in the research so far in the fields connecting digital twins, logistics and/or transport and energy consumption?
RQ2: What areas and environments are digital twins most used concerning these topics, and how do they take energy consumption in regard?
RQ3: What objectives does the introduction of a digital twin have?

RQ1 will be evaluated via a bibliometric keyword analysis, while RQ2 and RQ3 will be answered with an in-depth quantitative content analysis of the relevant publications.

2. Methodology

The literature pool selection and inclusion process followed the PRISMA guidelines [31]. A search with the string ((“digital twin *”) AND (logistic * OR transport * OR mobility *) AND (energy * OR fuel *)) was performed in January 2023 in Scopus in the title, abstract and keywords fields. The search returned 153 results overall. The exact search in Web of Science (WoS) returned 104 results. After combining the results and removing irrelevant documents (patents, datasets without analysis, whole conference proceedings, software), 163 documents remained in the literature pool, which included journal papers, conference papers, book chapters, review papers and editorials. The process of selecting the included publications is shown on Figure 1.

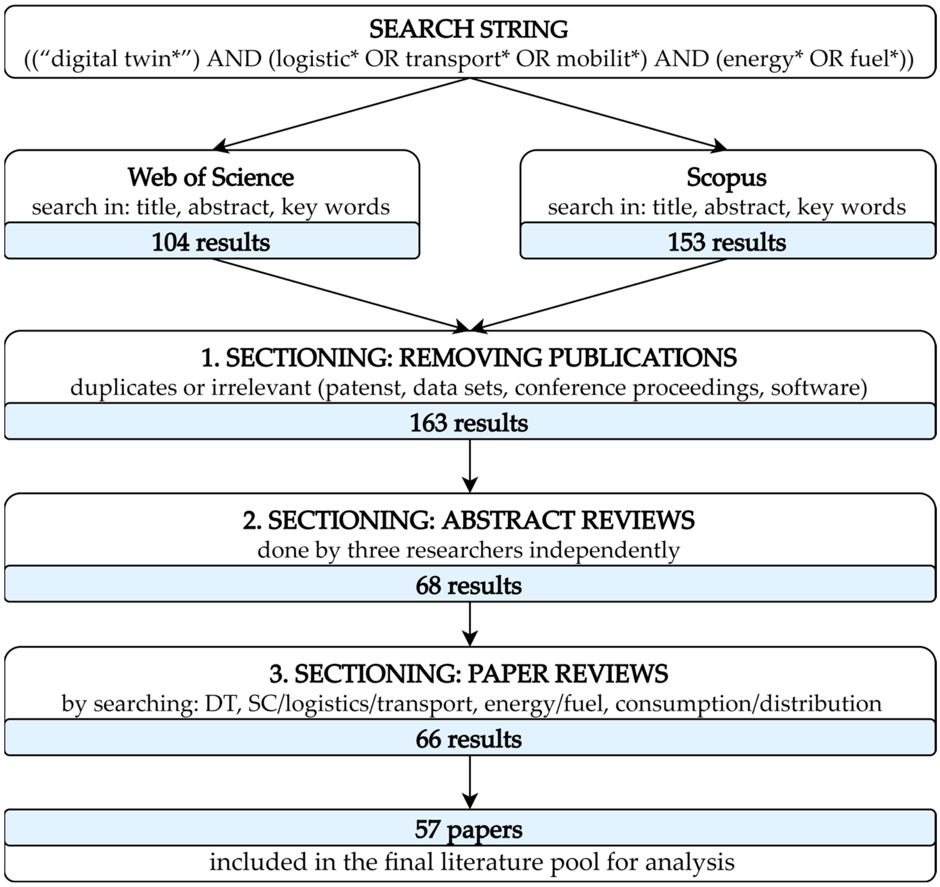

Figure 1. Publication selection and literature pool process.

To build the first version of the literature pool, all authors independently assessed the title and abstract of the documents, and, where needed, also the document itself, and prepared a list of documents to be included in the final literature pool per the inclusion criteria below. Where there were disagreements, the majority opinion prevailed. This brought a set of 57 publications included in the final literature pool.

The inclusion criteria for the documents to be included in the bibliometrics analysis, and quantitative and qualitative review of the literature pool, were as follows:

- Publications containing logistics and transport operations in at least some part of the research, regardless of the primary industry of research;
- Publications focusing on the design of transport means, vehicle modelling, testing, etc., were discarded;
- Publications with enough information in English (title, abstract, keywords) were included in the bibliometrics analysis even if the full publications were not in English (they were excluded from the qualitative review);
- Publications had to contain content on energy or fuel distribution or consumption; the energy sector was also included.

The literature pool was analysed in two steps. The first was a general bibliometrics analysis of the whole literature pool, which aims to present an overview of the status quo of the field of research. This step included the 57 publications as described above.

Bibliometrics (co-citation, co-authorship, keyword co-occurrence) were analysed using the VOSviewer tool [32], version 1.6.19 (Leiden, The Netherlands). The tool was used for basic analysis, clustering and the preparation of figures, as presented below. The reason for selecting this tool lies in its wide application in the (systematic) literature review field for displaying clustering results.

Co-authorship analyses the links and connections between authors, publications or origin countries. A co-authorship denotes those two different authors co-authored a particular publication. In this paper, co-authorship in terms of the origin countries was analysed to identify which countries are at the forefront of current research and to assess the international scope of research by analysing co-authorship from more than one country. Additionally, a clustering analysis was performed on the most productive countries to identify which countries have the most evolved scientific cooperation in the researched field of digital twins in transport and energy efficiency.

Regarding interconnected publications, co-citation analysis was used for the literature pool analysis. Two publications are co-cited when a publication cites both as sources, which points to the publications' relatedness regarding their research topic and potential for further research.

Keyword co-occurrence was analysed using a joined pool of author and index keywords. There were 895 keywords in the first step (729 index and 277 author keywords). There was a large dispersion of the used terms since only forty-two keywords met the inclusion threshold if the minimum number of occurrences threshold was set to at least three. Consequently, a detailed data clean-up was performed to join keywords with the same meaning into one keyword. For example, the keywords "digital twin", "DT", "digital-twin" and "digital twins" were all joined into a single keyword of "digital twin". A conservative approach was applied since the objective was to analyse the literature pool on a detailed scale and not on the level of topics. This means that, e.g., the keywords "electric car" and "electric train" were not joined into a shared keywords topic of "electric vehicles", but rather all three keywords were kept separately in the keyword pool. The process resulted in a total of 618 keywords remaining altogether: 244 author keywords and 552 index keywords. The keywords were analysed regarding their number of repetitions in the literature pool, their co-occurrence and clustering, which pointed to the interconnectedness of the used keywords. If two keywords were used together in a publication, there was a link between them, and the larger the number of those appearances, the larger the connection between them. If more keywords were interconnected, VOSviewer recognised this pattern and formed a cluster of those that often occurred together. A cluster's minimal number of keywords was set to three to avoid small clusters.

To further analyse the publications, a qualitative overview was undertaken through a codification process, which enabled the categorisation of publications. The latter were individually analysed by a set number of criteria:

- Publications had to contain either supply chain, logistics or transport field;
- Publications were classified into different transport types regarding their scope, i.e., external, internal and general transport, whole supply chain or logistics system and networks;
- Publications were further divided into different modalities: road, rail, urban, air, maritime, pipeline and general transport, intelligent transport systems and other modality;
- Criteria about usage environment divided publications into fragmented groups of potential use, such as manufacturing, smart city or city, air mobility, functionalities of a product or system etc.;
- Publications were reviewed by energy criteria regarding energy or fuel distribution or consumption;

- Content of each publication included at least one constant multitude of supply chain systems, which are product, service, process or a system [13];
- Publications' inclusion was also reflected through the digital twin objective, classified as system management, system optimisation, system design, system planning, risk management, process management, process optimisation, product management and product design;
- The last criteria encompassed other technological tools used or researched in the reviewed publications.

The set number of nine criteria enabled a quantitative analysis of publications' contents to conclude what topics are of most interest for digital twin research on transport and logistics in terms of energy distribution or consumption. Each criterion was assigned a code, as seen in Appendix A, together with the literature pool. The codes are explained in Section 3.4, alongside the frequency of occurrence of the criteria in question.

Each publication was read by two researchers independently and evaluated by the set nine criteria. Where there were discrepancies in the final codification, a third researcher evaluated the publication to determine the final codification. A publication could contain more than one element of a single criterion, e.g., it could research both system management and system optimisation according to the criteria of digital twin objective, in which case, both elements would be coded for the publication in question.

3. Results

This section provides results regarding the quantitative and qualitative literature review. Sections encompass a detailed review of authors, their correlations and source analysis, followed by citations and keywords analysis. Lastly, digital twins' use in logistics and transport is presented.

3.1. 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). Papers 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. The clustering results are shown on Figure 2. The circle size points to the relative number of publications from a country, and the line thickness to the relative number of commonly published publications.

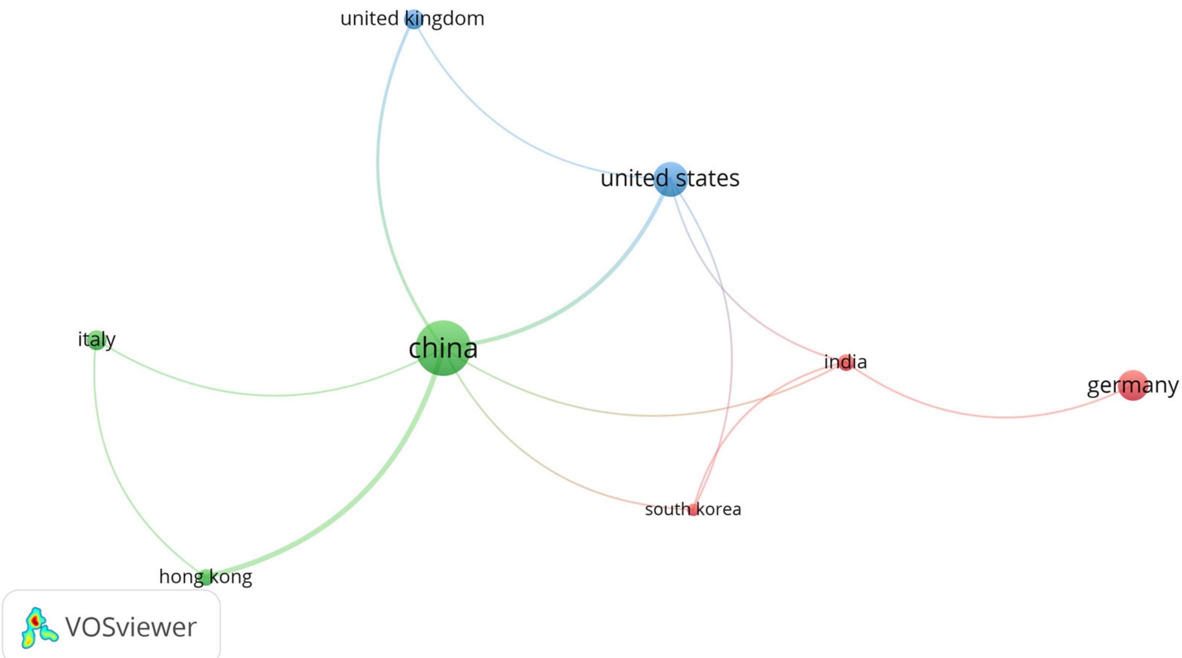

Figure 2. Co-authorship and clustering of origin countries of countries with at least three publications.

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).

3.2. 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) [33] with 84 citations, Bhatti (2021) [34] with 82 citations, Wang W. (2020) [35] with 64 citations, Defraeye (2019) [36] with 62 citations and Liu Y. (2020) [37] 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 [38]	4
Rasheed [39]	4
Schellenberger [40]	4
Rosen [41]	3
Kritzinger [42]	3
Fuller [43]	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 clustering and interconnectedness of publications are shown on Figure 3 below. 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). Authors who researched the topic of digital twins that was paramount for this research, are cited throughout this paper (such as: [12,38–43]), but the rest are not, as the reference publications in question did not research digital twins or the content was not relevant.

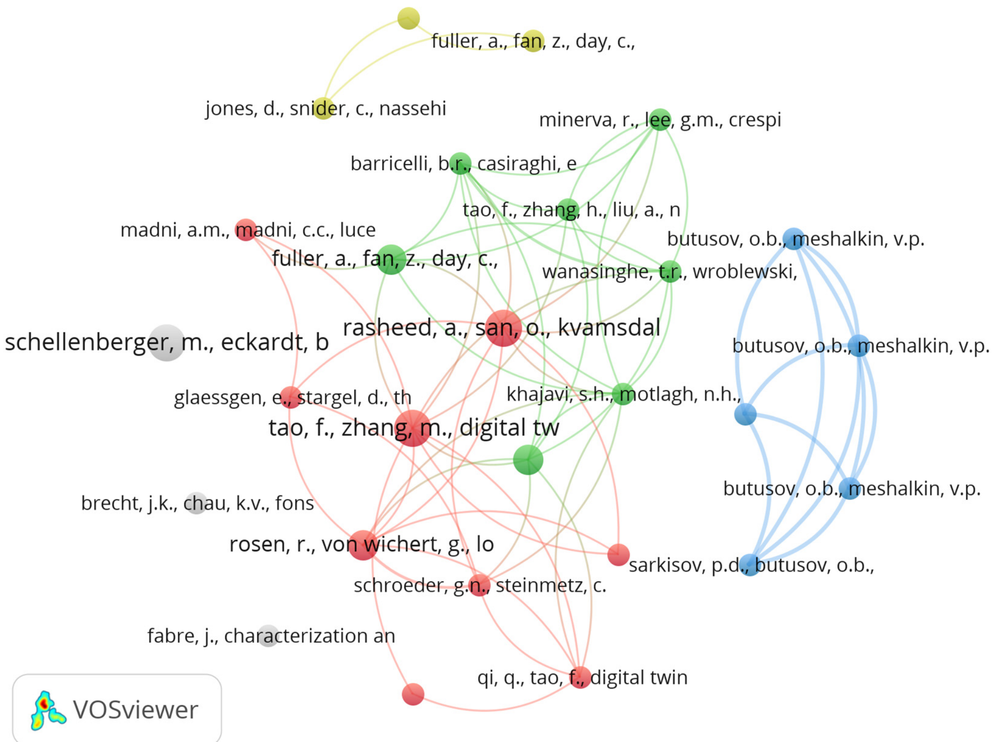

Figure 3. Co-citation of sources from publications in the literature pool [12,38–43].

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.

3.3. 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.

Figure 4 shows the 20 keywords that were seen as most prominent in the literature pool. Based on the number of times the keywords occurred together in publications, clustering revealed three clusters. The green cluster revolves around connecting the physical to the cyber since the included keywords point to both spheres. The red cluster focuses on energy efficiency and carbon emissions in transport and supply chain management. The blue cluster seems most connected with intelligent systems in a real-time use setting.

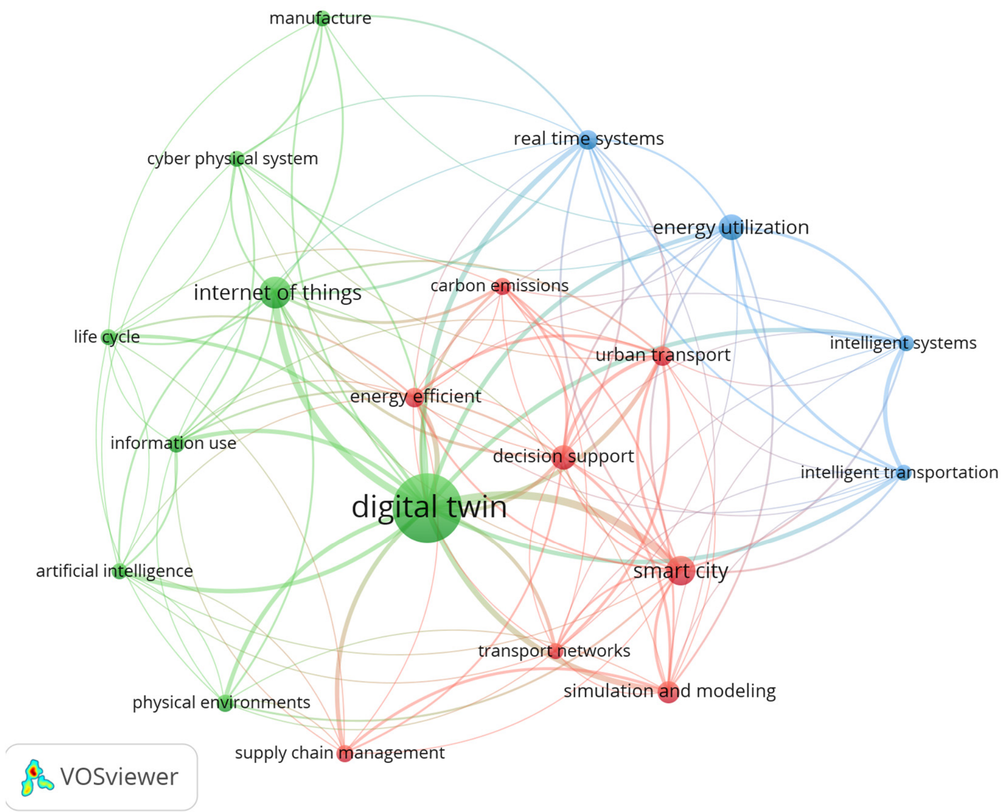

Figure 4. Co-occurrence and clustering of all keywords with at least five repetitions.

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. The co-occurrence and clustering space are shown on Figure 5.

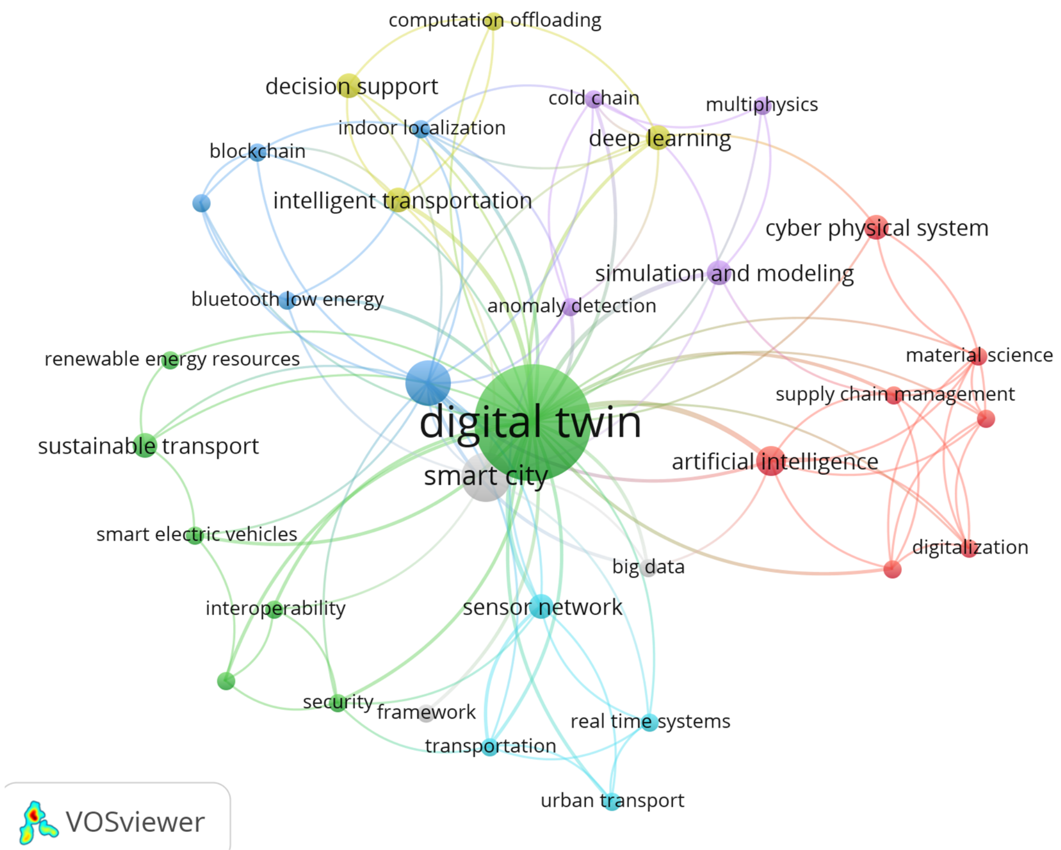

Figure 5. Co-occurrence and clustering of author keywords with at least two repetitions.

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).

3.4. 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 research 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 [44], 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) paper 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 [45], and modernisation of internal transport can reduce or even eliminate manual labour [46]. 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:

- 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 [47]. 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.

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

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 [48]. This can be attributed to the complexity of a city [49], 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 [50]. 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 [48]. In this research, 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.

This paper 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 [51], energy consumption by autonomous unmanned aerial vehicles (drones) [26] or even cranes [52]. 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) [53] and even reduction in CO_2 emissions [52]. One paper 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 for this paper. 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 paper 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 [54]. In third place was service multitude (31), intended for predictive maintenance and performance (e.g., prediction of estimated travelling distance [55]), fault detection and diagnosis, state monitoring, optimisation [34] and virtual tests [56]. Lastly, the constant multitude of products (21) followed, where the use of digital twins was reflected in manufacturing resources, such as machines and trolleys [35], vehicles [15], products lifecycle management [57] or even development [34].

As with previous criteria, practically every reviewed paper 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 [54] are essential in every company, even in transport [58], where ensuring timely data integrity, stability, remote control and maintenance [53] 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 paper. 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:

- 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).

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

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 [59]. 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 [60]. These technologies can bring new capabilities with immense business value [59]. With edge computing (3), digital twins can manage big data and machine learning activities with automatic control and cross-discipline knowledge [60], such as cloud-edge collaborative computation [61] or mobile-edge computing [62].

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 (Table 11). 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.

Table 11. Frequency of reviewed implementation level.

Classification in Appendix A	Reviewed Implementation Level	Frequency
ANA	Analysis	25
MOD	Model	23
THEO IMPL	Theoretical implementation	13
REV	Review	12
SIM	Simulation	12
IMPL	Implementation	10
CaStu	Case study	5

4. Discussion

The clustering, as revealed by keyword analysis, shows the three prevalent topics in the research of digital twins in connection to transport and energy efficiency: how they can be used in connecting or using the potentials of artificial intelligence, the Internet of Things and alike in the physical world, how they bring the aspect of intelligence to real-time systems, and how they connect to transport and supply chain management.

In the second part of the review, a qualitative overview of the 55 most relevant publications for using digital twins in logistics and transport was made. Based on the results, the main findings can be pointed out as follows:

- The most common field of digital twins use for transport purposes is undoubtedly logistics, and the least common are supply chain management and transport infrastructure;
- External transport is researched much more often, as it can lead to more significant challenges and, at the same time, greater advantages;
- Road transport is leading in the frequency of research since it is used daily;
- When speaking about the usage environment of digital twins in transport, most publications focus on smart cities;
- Energy consumption prevails in the publications, whereby fuel consumption is not necessarily the focal point;
- In the constant multitudes of supply chain systems section, publications focus the most on systems;
- Most common digital twins' objective are system management and optimisation;
- Internet of Things prevails in the literature review as most often appearing other technology tools used;
- Most publications are model presentations and analyses.

Roughly, it is possible to understand that among these publications, only five are practical (presented model, implementation and analysis). Others are reviews (7), conceptual models (3), frameworks (2), case studies (2), theoretical implementations (2), simulation (1) and a prototype (1). The results identify a lack of publications on practical implementations of digital twins in the logistics and transport sector. Furthermore, this literature review concluded that there is an almost negligible number of publications with detailed descriptions of digital twins as industrial solutions (or their implementation) in real environments (e.g., in organisations and sectors). The field of digital twins is relatively young (despite its actual 'age'), consequently leading to the unrecognisable potential of contemporary technology as an industrial solution; meaning digital twins are presently not significantly recognised as the subject of scientific publications in the field of logistics and transport.

Based on the results, out of fifty-five publications, twenty-three are identified, strictly focusing on four essential criteria: field, transport type, energy distribution or consumption and digital twin objective. Each publication that did not cover these criteria was eliminated from the 'future literature pool'. The collection of 23 publications exemplifies the potential for further examination to determine the extent of digital twins' implementation in the transport field.

4.1. Limitations

The first existing limitation of this paper is the use of two established databases (Web of Science and Scopus) to obtain suitable literature. Both databases provide peer-reviewed publications required for the literature pool and further review. The number of databases could be expanded, as these two do not contain descriptions of industrial solutions since the latter are usually not published in databases. In addition, the type of publication was also a limitation, excluding patents, datasets without analysis, whole conference proceedings and software.

Another limitation is that this paper did not include a review of digital twins' use in logistics and transport as an industrial solution by recognised international organisations, such as Gartner and DHL.

This paper also did not include mathematical models and statistical studies—its purpose was to review the criteria and determine the range and frequency in which they appeared in individual publications. The paper itself includes publications that mostly do not contain quantitative outcomes, i.e., they mostly did not measure, for example, the energy use decrease in percentages or alike. That would allow us to perform a quantitative meta-analysis of the included publications. Since the literature pool is very diverse in scope (which is evident from the results since the included publications vary from purely theoretical work to practical implementations), it is nearly impossible to introduce a statistical measure that could be extracted from all of the publications in the literature pool to perform a meta-analysis.

The following limitation is the exposure of objectively verifiable criteria, avoiding the subjective treatment of individual publication. The preference for objectivity was important, as the purpose of this paper was not a subjective review of the literature—in this case, another, a separate paper could be written.

Furthermore, this paper did not include an in-depth content analysis but rather an overview of the digital twins' usage in researching energy use in transport and logistics. If the paper focused on an in-depth analysis, different input parameters focusing more on one, e.g., field or type of digital twin application, would have to be chosen. Since the statistical analysis of publications' content, included in the research, shows a great diversification of the usage environments and application types, an overall in-depth content analysis of all included publications was unsuitable in this case.

The last limitation is the paper's length—if only one of the aforementioned limitations was included, the paper would have been considerably longer. Each limitation can be viewed as potential future research, forming an individual research subject and, consequently, an independent paper.

4.2. Future Directions

Extensive research is needed in supply chain management and transport infrastructure to provide fundamental integration conditions for digital twin use in transport. With sensors, digital twins can send data to the objects' virtual version in real-time. The information and data can then be analysed and used to optimise transport, not forgetting that the latter is crucial for supply chain management. In-depth research is also needed in internal transport, which substantially impacts the operations of the individual organisation as well as the ones of supply chains in which the organization is included.

The main challenge in transport is undoubtedly fuel consumption, a topic on which, unfortunately, there has not been as much research as on energy consumption. Although transport is part of a system, it is a process in itself. Therefore, research on managing and optimising processes as a whole would be preferable rather than as part of a more extensive system. Furthermore, transport also includes risks, which can cause many challenges if they are not properly managed and mitigated promptly.

Building on the previous proposal, future research should also focus on the sustainable aspect, which includes three components: environmental, economic and social. Transport has an enormous impact on the sustainability of supply chains, which is emphasised through the close correlation between environmental and economic aspects. The latter are related to fuel consumption, which is also the subject of many regulations. Meanwhile, both previous aspects impact the social aspect.

Out of fifty-five publications, twenty-three were focused on four essential criteria (field, transport type, energy distribution or consumption and digital twin objective). This narrowly oriented literature pool contains the potential for further examination to determine to what extent the digital twin implementation was performed in the transportation field. In such research, individual publications could be examined in detail, where subjective criteria can be included in addition to objective ones.

Overall, the main future direction is that the academic world needs more research on digital twins in logistics and transport, with case studies and practical directions intended for the market implementation, which immeasurably supports the operation of companies and the wider community. Perhaps the reason for such a small number of practical research is the lack of market demand or financial investments in the technology, which are only speculations.

5. Conclusions

Although an abundance of digital twin studies have been conducted with intelligent manufacturing [63–65] and Industry 4.0 [66,67], only a few are very recent from the transportation domain [23]. There is little systematic research with a holistic framework connecting various mobility entities [68]. Both transport and logistics are dominant sources of energy distribution and consumption. Thus, the potential of digital twins' implementation and integration into logistics and transport is considerable, especially for optimising fuel consumption and increasing transport energy efficiency.

This paper aimed to research digital twin use in logistics and transport, focusing on the effects of digital twins' use towards energy consumption optimisation to reduce greenhouse gas emissions by performing a quantitative and qualitative literature review. This paper's main contribution is in a systematic overview of a contemporary technology, named digital twins, energy optimisation aspect in the most energy-dependent sectors: transportation. Moreover, the paper presents an overview of the field and current research directions in a way that is accessible to researchers and practitioners. The conducted research presents a very good starting point since researchers preparing to further research the under-explored potential practical applications of digital twins in the reviewed fields can easily use this paper to identify the most important publications, see what types of applications there are, on what level they exist and also what the content of each publication focuses on. Furthermore, researchers can choose a niche to dive further into by preparing an in-depth content analysis of chosen publications.

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Appendix A

Authors, Publication Year	Field	Transport Type	Modality	Usage Environment	Energy Distribution/ Consumption	Constant Multitude of SC Systems	Digital Twin Objective	Other Used Tools	Implementation Level
Vechart and Kawecki, 2015 [69]	SCM	EXT	Air	City; Air mobility	N/I	PROD; SER; PROC; SYS	SYS-MNG	N/I	THEO IMPL
Sládek and Maryška, 2018 [59]	LOG	EXT	N/I	City; E-mobility	E-CON	PROC; SYS	SYS-DSG; RSK-MNG	AI; AR; VR; 3D; IoT; ML; CLO; BLOC; D-ANA	REV
Defraeye, Tagliavini, Wu, Prawiranto, Schudel, Assefa Kerisima, Verboven and Bühlmann, 2019 [36]	SCM	EXT	Mar; Air	International	N/I	PROD; PROC; SYS	PROC-OPT	N/I	THEO IMPL
Nikander, Autiosalo and Paavolainen, 2019 [70]	LOG	EXT	OTH	N/I	N/I	PROC; SYS	SYS-OPT	N/I	THEO IMPL
Jetter, 2019 [71]	LOG	INT	OTH	Buildings	E-CON	SER	SYS-MNG; SYS-DSG; SYS-PLAN; RSK-MNG	N/I	THEO IMPL
O'Dwyer, Pan, Acha, Gibbons and Shah, 2019 [72]	SC	EXT	Ur	Smart city	E-CON	SYS	SYS-MNG; RSK-MNG	N/I	MOD; IMPL; ANA

Authors, Publication Year	Field	Transport Type	Modality	Usage Environment	Energy Distribution/ Consumption	Constant Multitude of SC Systems	Digital Twin Objective	Other Used Tools	Implementation Level
Wang, Zhang and Zhong, 2020 [35]	LOG	INT	ITS	Manufacturing	E-CON	PROD; SER; PROC; SYS	SYS-MNG; RSK-MNG; PROD-DSG; PROC-OPT	CPS	MOD; IMPL; ANA
Diaz, Ghita, Copot, Birs, Muresan and Ionescu, 2020 [73]	SC; LOG	GEN	GEN	General	E-CON	SER; PROC; SYS	SYS-MNG; PROC-MNG; PROC-OPT	N/I	REV
Al-Ali, Gupta, Batool, Landolsi, Aloul and Nabulsi, 2020 [15]	LOG	EXT	Ro; ITS	Manufacturing	E-CON	PROD; PROC; SYS	SYS-MNG; PROC-MNG; PROD-MNG	ML	C-MOD
Shrivastava, Berry, Cronje and Defraeye, 2020 [74]	/	/	/	/	/	/	/	/	/
Guo, Wu, Liang, Hu and Liu, 2020 [75]	TRANS	EXT	Ra	Smart city	E-DIS	SER; PROC; SYS	SYS-MNG; SYS-DSG; SYS-PLAN	N/I	C-MOD
Liu, Zhang, Ren, Yang, Wang and Huisingh, 2020 [37]	LOG	INT	GEN	Manufacturing	E-CON	PROD; SER	PROD-MNG	N/I	REV
deMeer, 2020 [76]	LOG	INT	OTH	Manufacturing	E-DIS	SYS	PROC-MNG	N/I	CaStu
Moghadam, Foroozan, Gheisarnejad and Khooban, 2021 [77]	SC	EXT	Mar	Boats	E-CON	PROC; SYS	SYS-MNG; SYS-OPT; RSK-MNG	N/I	THEO IMPL
Lu, Jiang, Chen, Gu, Gao and Zhang, 2021 [60]	TRANS	EXT	Ur	Smart city	E-DIS	PROC; SYS	SYS-DSG; SYS-PLAN; PROC-MNG	AI; Ed-Comp; ML	MOD; IMPL; ANA
Meshalkin, 2021 [57]	SC	WLS	N/I	Manufacturing	E-CON	PROD; SER; PROC; SYS	RSK-MNG; PROC-OPT; PROD-DSG	N/I	REV
Saroj, Roy, Guin and Hunter, 2021 [78]	LOG	EXT	Ro	Smart city	E-CON	SER; PROC; SYS	SYS-DSG; SYS-PLAN	N/I	MOD; IMPL; ANA
Opoku, Perera, Osei-Kyei and Rashidi, 2021 [33]	LOG	INT	N/I	Construction industry	E-CON	PROC; SYS	SYS-MNG	N/I	REV
Kuo, Pilati, Qu and Huang, 2021 [79]	LOG	INT; EXT	Ur	Manufacturing; Smart city	E-CON	SER; PROC; SYS	SYS-MNG; PROC-MNG; PROD-MNG	N/I	REV
Callcut, Cerceau Agliozzo, Varga and McMillan, 2021 [80]	SC	EXT	Air; Ro; Ra; Pip; Ur	N/I	E-CON	PROD; SER; PROC; SYS	SYS-OPT	ML; D-ANA	REV
Liu, Li, Bai, Luo, Lv and Lv, 2021 [58]	TRANS	EXT	Mar	International	E-CON	SYS	SYS-OPT; SYS-DSG; RSK-MNG	IoT	MOD; THEO IMPL; ANA
Malé and Lagier, 2021 [81]	/	/	/	/	/	/	/	/	/
Portapas, Zaidi, Bakunowicz, Paddeu, Valera-Medina, Didey, 2021 [82]	SC; LOG; TRANS	EXT	Mar; Air; Ro	Smart city; Air mobility	E-CON; E-DIS	SYS	SYS-MNG; SYS-DSG; RSK-MNG	N/I	C-MOD
Wanner, Bahr, Full, Weeber, Birke and Sauer, 2021 [83]	SC; LOG	N/I	N/I	Manufacturing	E-CON	PROD; PROC; SYS	PROD-MNG	N/I	THEO IMPL
Bhatti, Mohan and Raja Singh, 2021 [34]	TRANS	EXT	Ro; ITS	Smart city	E-CON	PROD; SER; PROC; SYS	SYS-MNG; PROD-MNG	IoT; ML	REV
Paprocki, 2021 [56]	TRANS	EXT	Air	Airport hub	E-CON	SER; PROC; SYS	SYS-MNG; SYS-OPT; PROC-MNG; PROC-OPT	AI; BD	MOD; SIM; ANA
Ivanov, 2022 [84]	SC	WSCS	N/I	N/I	E-CON	PROD; SER; PROC; SYS	SYS-MNG; SYS-OPT; RSK-MNG	N/I	MOD; SIM; ANA; CaStu
Sleiti, Al-Ammari, Vesely and Kapat, 2022 [54]	TRANS	EXT	Pip	Functionalities	E-CON	SER; PROC; SYS	SYS-MNG; RSK-MNG; PROC-MNG; PROD-MNG	N/I	FRAM; THEO IMPL; ANA
Yang, Park and Kim, 2022 [85]	TRANS	EXT	Ro	Smart city	E-CON	SER; PROC; SYS	SYS-MNG; PROC-MNG; PROD-MNG	N/I	MOD; SIM; ANA
Xu, Liu, Bilal, Vimal and Song, 2022 [62]	TRANS	EXT	Ro; ITS	Smart city	N/I	PROD; SER; PROC; SYS	SYS-MNG; PROC-MNG	Ed-Comp	MOD; SIM; ANA
Chen, Chen, Miao, Wang and Zhao, 2022 [61]	N/I	NET	N/I	Industrial networks	E-CON	SER; PROC; SYS	SYS-MNG; SYS-OPT	Ed-Comp; CLO	MOD; SIM; ANA
Akkad, Haidar and Bányai, 2022 [86]	SC; LOG; TRANS	EXT	Ro	Smart city	E-CON	SER; PROC; SYS	N/I	IoT	MOD; IMPL; ANA
Liao, Wu, Bashir, Yang, Li and Tariq, 2022 [87]	SC	EXT	ITS	Smart city	N/I	SER; PROC; SYS	PROC-MNG; PROC-OPT	BLOC	MOD; SIM; ANA
Traoré and Ducq, 2022 [88]	SC; LOG; TRANS	EXT	Ur	Smart city	E-CON	SER; PROC; SYS	SYS-MNG; SYS-OPT; PROC-MNG	N/I	THEO IMPL
Jeong, Baek, Lim, Kim, Kim, Lee, Jung and Lee, 2022 [89]	LOG	EXT	Ro	Manufacturing; Smart city	N/I	PROD; SER; PROC; SYS	SYS-MNG; SYS-OPT; PROC-MNG; PROC-OPT	N/I	REV

Authors, Publication Year	Field	Transport Type	Modality	Usage Environment	Energy Distribution/ Consumption	Constant Multitude of SC Systems	Digital Twin Objective	Other Used Tools	Implementation Level
Steinmetz, Schroeder, Binotto, Panikkar, Papenfuβ, Schmidt, Rettberg, Pereira, 2022 [90]	SC	EXT	Ro	Smart city	N/I	PROD; SER; PROC; SYS	SYS-MNG; SYS-OPT	IoT	MOD; SIM; ANA
Tu, Qiao, Nowak, Lv and Lv, 2022 [91]	TRANS INF	EXT	ITS	Smart city	N/I	PROC; SYS	SYS-MNG; PROC-MNG	N/I	MOD; SIM; ANA
Zhao, Fu, Sun, Pu and Luo, 2022 [52]	SC; LOG; TRANS	WLS	OTH	Construction industry	E-CON; F-CON	PROD; SER; PROC; SYS	SYS-MNG; SYS-OPT; PROC-MNG; PROC-OPT; PROD-MNG	N/I	FRAM; CaStu
Hammerschmid, Konrad, Werner, Popov and Müller, 2022 [92]	LOG	NET	N/I	Smart city	E-DIS		PROC-MNG		MOD; SIM; ANA
Casavola, Franzé, Gagliardi and Tedesco, 2022 [93]	SC	N/I	N/I	City; Streetlights	E-CON	PROD; SER; PROC; SYS	SYS-MNG; SYS-OPT; SYS-PLAN; PROD-MNG	N/I	MOD; SIM; ANA
Zhan, Wu, Shen, Liao, Zhao and Xia, 2022 [94]	LOG	N/I	N/I	Warehouse	E-CON	SYS	SYS-MNG; SYS-PLAN; RSK-MNG; PROC-MNG; PROC-OPT	IoT; ML	MOD; THEO IMPL; ANA
Wu, Shen, Zhao, Li and Huang, 2022 [95]	LOG	INT	OTH	Manufacturing	E-CON	PROD; SER; PROC; SYS	SYS-MNG; SYS-PLAN; PROC-OPT; PROD-MNG	IoT	MOD; IMPL; ANA
Stahl and Reiterer, 2022 [96]	SC	EXT	Ur	Smart city	E-CON	SYS	SYS-MNG; SYS-OPT; PROC-MNG; PROC-OPT; PROD-MNG	N/I	C-MOD
Aguiar, Fernandes, Guerreiro, Tomas, Agnelo, Santos, Araujo, Coelho, Fonseca, d'Orey, Luis and Sargento, 2022 [97]	TRANS	EXT	Ro	Smart city	N/I	PROD; SER; PROC; SYS	SYS-MNG; SYS-OPT; PROC-MNG; PROC-OPT	IoT	MOD; SIM; ANA
Priyanka and Thangavel, 2022 [98]	TRANS	EXT	Pip	Functionalities	N/I	PROC; SYS	SYS-MNG; SYS-OPT; RSK-MNG; PROD-MNG; PROD-OPT	IoT	MOD; IMPL; ANA
Saroj, Trant, Guin, Hunter and Sartipi, 2022 [99]	SC	EXT	Ro	Smart city	E-CON; F-CON	SYS	SYS-MNG; SYS-OPT; RSK-MNG; PROC-MNG; PROC-OPT; PROD-MNG	N/I	FRAM; THEO IMPL
Agostinelli, Cumo, Nezhad, Orsini and Piras, 2022 [100]	TRANS	EXT	Mar; Ro; Ra	Diverse	E-CON	SYS	SYS-MNG; SYS-OPT; SYS-PLAN	AI; IoT	MOD; IMPL; ANA; CaStu
Michalik, Kohl and Kummert, 2022 [101]	TRANS	EXT	Ro	Smart city	N/I	SER; PROC; SYS	SYS-MNG; SYS-OPT; SYS-PLAN; PROC-OPT; PROD-MNG	VR	METH; IMPL; ANA
Kaleybar, Brenna, Castelli-Dezza and Zaninelli, 2022 [102]	TRANS	EXT	Ra	Smart grid	E-CON; E-DIS	SYS	SYS-MNG; SYS-OPT	N/I	MOD; IMPL; ANA
Agavanakis, Cassiam Drombry and Elkaim, 2022 [53]	SC; LOG; TRANS	EXT	N/I	International	E-CON; F-CON	SYS	SYS-OPT; RSK-MNG; PROC-OPT	N/I	CaStu
ElSayed and Mohamed, 2022 [26]	LOG	EXT	Ur; Air	UAVs	E-CON	PROD; SER; PROC; SYS	SYS-MNG; SYS-OPT; PROC-OPT; RSK-MNG	N/I	FRAM
Newrzella, Franklin and Haider, 2022 [103]	SC; LOG; TRANS	EXT	Ro	Functionalities	E-SEC	PROD; SER; PROC; SYS	SYS-MNG; SYS-OPT; SYS-PLAN	N/I	REV; THEO IMPL
Yang, Meng, He, Wang and Gao, 2022 [27]	LOG	EXT	Mar	Port	E-CON	PROD; SER; PROC; SYS	SYS-MNG; SYS-OPT; PROC-MNG; PROC-OPT	N/I	MOD; SIM; ANA
Ciampolini, Balduzzi, Romani, Bellucci, Bianchini and Ferrara, 2022 [104]	TRANS	EXT	Mar	Boats	F-CON	PROD; SER; PROC	PROC-MNG; PROD-MNG; PROD-OPT	N/I	PROT
Alva, Biljecki and Stouffs, 2022 [51]	LOG	EXT	Ur	Freight transport	E-CON	SYS	SYS-MNG; SYS-OPT; PROC-MNG; PROC-OPT	N/I	REV
Yu, Zhaoyu, Yifen, Nengling and Jun, 2023 [105]	SC; LOG; TRANS	EXT	Mar	Port	E-CON; E-DIS	SYS	SYS-MNG; SYS-OPT; SYS-PLAN	AI	THEO IMPL
Avdienko and Tretyakov, 2023 [106]	TRANS INF	EXT	Ra	Functionalities	N/I	SYS	SYS-MNG; SYS-OPT; PROC-MNG; PROC-OPT	IoT; BD	REV

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