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*Review*

# Towards Resilient and Sustainable Rail and Road Networks: A Systematic Literature Review on Digital Twins

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**Citation:** Vieira, J.; Poças Martins, J.; Marques de Almeida, N.; Patrício, H.; Gomes Morgado, J. Towards Resilient and Sustainable Rail and Road Networks: A Systematic Literature Review on Digital Twins. *Sustainability* **2022**, *14*, 7060. https://doi.org/10.3390/su14127060

Academic Editor: Marilisa Botte

Received: 11 April 2022
Accepted: 7 June 2022
Published: 9 June 2022



**Abstract:** The digital transformation of engineering assets has been receiving increased attention from the scientific community in the last few years. In this regard, Digital Twins (DTs) have been widely applied in the industry and are now reaching the civil infrastructures domain. At the same time, infrastructure managers face an increasing need to improve the sustainability and resilience of their assets. This paper aims firstly to map and present the current extent of DT application in rail and road networks, and secondly to perceive how these applications can contribute to increase their sustainability and resilience. To achieve this, the authors propose a systematic review on the DT literature related to rail and road infrastructure networks. The results show that the DT research in this domain is still scarce and that only a few use cases have attracted the attention of the scientific community. The results also indicate that most applications in rail and road networks focus on their operation and maintenance, and that there is a considerable unexplored potential for DT applications in this sector. More DT-related studies within this scope are expected to emerge in the coming years, and further research regarding its contribution to sustainability and resilience is needed.

**Keywords:** digital twin; rail; road; critical infrastructure; asset management; systematic review

## 1. Introduction

This introduction section includes the study's background, its significance and motivation, a clarification of terms and definitions used in the paper and a summary description of the research objectives and paper organization.

### *1.1. Background*

#### 1.1.1. Sustainability and Resilience of Rail and Road Networks

Transport infrastructures can be seen as a subset of civil infrastructures, which are the backbone of any nation [1]. They play a unique role in connecting people, delivering goods, and providing services and economic opportunities [2]. When these critical infrastructures fail to deliver their expected function (e.g., service interrupted due to physical failure), considerable economic losses are incurred [3].

Transport infrastructures are also key to progress in achieving the Sustainable Development Goals, especially those concerning resilient infrastructures, innovation (Goal 9), sustainable cities, and communities (Goal 11). Target 11.2 aims to provide access to safe, affordable, accessible, and sustainable transport systems for all by 2030. Target 9.1 aims at quality, reliable, sustainable, and resilient infrastructure, to support economic development and human well-being [2]. Sustainability and resilience, both trending topics among the asset management research community [4], can be challenging concepts to understand and aim for objectively, namely in the rail and road transportation sectors.

Sustainability was defined in 1987 in the "Brundtland Report" as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [5]. According to Bruneau et al. [6], resilience can be defined as the ability of assets to reduce the chances of a disruption, to absorb and adapt to the disruption, and to quickly recover its functional performance after a disruption. As stated by Bruneau and Reinhorn [7], asset resilience can be characterised by the following properties:

- Robustness: the ability of assets or asset systems to withstand a given level of stress/demand without suffering degradation or loss of function;
- Redundancy: the extent to which assets or asset systems are substitutable, capable of meeting functional needs in case of disruption, degradation, or loss of function;
- Resourcefulness: the ability to identify problems, establish priorities, and mobilise material (i.e., monetary, physical, technological, and informational) and human resources during asset recovery, to meet established priorities and achieve goals;
- Rapidity: the capacity to meet priorities and achieve goals in a timely manner to contain losses, maximise functionality recovery, and avoid future disruptions.

Both sustainability and resilience are topics intimately related to asset management practice. ISO 55000 [8] states that asset management systems ensure that organisation objectives can be achieved consistently and sustainably over time. On the other hand, asset resilience management is closely associated with managing asset-related risks [9], i.e., the effect of uncertainty on the objectives of asset-intensive organisations [10]. These two topics are key to the management of critical infrastructures, such as transportation, as they guarantee, in tangible and intangible forms, the economic, social, and environmental needs of modern society, and so they need to be preserved and adapted to satisfy future needs.

By 2030, annual passenger traffic is expected to increase by 50%, and global freight volumes by 70% [2]. Transport infrastructures will then have a crucial role in meeting this additional demand while ensuring adequate levels of quality, reliability, safety, and sustainability [2]. With increasingly challenging environmental targets to achieve, countries are expected to invest in innovative, integrated, energy-efficient, and low-emission transport modes (e.g., bus and rail services [11]), which contributes to increase transportation sustainability.

However, the future needs mentioned above may encompass more than the direct needs of future generations. Due to climate change, extreme weather events are expected to occur more frequently and with higher intensity, which raises concerns regarding the resilience of current and future infrastructures. Moreover, unpredictable events with major impacts, also known as "black swans" [12], such as earthquakes, tsunamis, terrorism, or volcanic eruptions are also a threat to transport infrastructures and to the services they provide. Increasing infrastructure resilience is essential to minimise the impacts on transportation services, even if the magnitude and timing of these events are unpredictable.

The rail and road networks, as two important subsectors of the transport network [13], cover a wide range of assets—many are shared with other sectors (such as power or buildings)—and require multiple and interrelated areas of expertise in their daily asset management activities.

These networks account for more than 63% of goods transport and almost 90% of passenger transport within the European Union (EU) [14]. These can be considered as critical infrastructure. The definition for "critical infrastructure "adopted in this study follows the 2008 Directive on European Critical Infrastructures [15], which defines it as "an asset, system or part thereof ( ... ) which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in a Member State as a result of the failure to maintain those functions". This Directive also recognizes, in Annex I, road and rail transport infrastructures as two critical infrastructure subsectors.

Investment in their expansion and maintenance is vital due to the increasing demand (in quantity, performance requirements, and resilience) and the large maintenance backlogs accumulated by many countries [13]. Deficiencies and infrastructure ageing are some of the problems asset managers are currently facing [16]. These issues cover a wide variety of key infrastructures, such as bridges [17–21], buildings [16], roads, and tunnels [20].

Managing such critical and ageing infrastructures requires tools to accurately assess and balance their cost (e.g., operational expenditure, capital expenditure), risk (e.g., likelihood and consequences of potential events) and performance (e.g., levels of service) [8,10,22], based on objective data that can support asset management decision making [1,18,23]. In this regard, the transportation sector has been adopting innovative technologies, many already used and proven in other sectors, such as buildings [1]. The digitalisation of road and rail networks is also part of the EU Digital Agenda and is one of the current global megatrends [16].

#### 1.1.2. Digital Twin Concept

For decades, civil infrastructures have operated with limited computing capabilities [24]. Over the last decade, there have been significant advances in both software and hardware, which have increased accessibility and decreased the costs of technologies. In this context, Industry 4.0 has emerged as a new industrial revolution [25], bringing new tools and approaches (such as the Internet of Things and cloud computing) to increase the efficiency of industrial processes. The subject of Industry 4.0 is relevant and broad, but not the focus of this study.

Infrastructure asset management involves various data-intensive processes and a constant need for data collection and analysis to support decision making. Together with accessible Industry 4.0 tools, this need is driving the digitalisation of critical infrastructure systems and the transition into “smart infrastructures”. Smaller, more powerful, and cheaper sensors, and more advanced computing technologies coupled with data transfer, storage, and management technologies (including Big Data analytics and Artificial Intelligence) may provide new capabilities for decision making and opportunities for efficiency gains in infrastructure networks [24,26–28].

Among Industry 4.0 tools, one of the trending approaches is Digital Twin (DT). Although DT has become popular in recent years, with high interest from the industry and scientific community [26,29–32], it is not a new idea [32]. The notion of DT dates back to 2002, when Prof. Michael Grieves presented it as a conceptual model for Product Lifecycle Management [33]. This model had all the three elements that form a DT: real space, virtual space, and the data flows between the real and virtual spaces.

In 2010, the term “digital twin” was first introduced by the National Aeronautics and Space Administration (NASA) in a roadmap regarding the strategic use of technologies. This roadmap presents the first formal definition for a DT [34] (p. 11):

> *“A DT is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin. ( . . . ). In addition to the backbone of high-fidelity physical models, the DT integrates sensor data from the vehicle's on-board integrated vehicle health management (IVHM) system, maintenance history and all available historical/fleet data obtained using data mining and text mining. ( . . . ) the digital twin continuously forecasts the health of the vehicle/system, the remaining useful life and the probability of mission success. The systems on board the DT are also capable of mitigating damage or degradation by recommending changes in mission profile to increase both the life span and the probability of mission success.”*

This definition validated all three elements proposed by Prof. Grieves in his conceptual model. However, it was highly related to the aerospace context and to NASA's specific purposes.

The most relevant experience of DT application comes mainly from specific industries such as aerospace and manufacturing [35–41], with very few examples for the built environment, especially for infrastructure [37,39]. Lamb [37] even states that fully realised examples of DTs in individual built assets are rare.

Although the origins of DT concept are well documented and have a general consensus among the literature, the same does not seem to happen with its definition [26,42–44]. As many authors already discussed, DTs have been interpreted in many ways, depending on each author and even on the sector in which is explored [37,45–47]. While some authors defend that a digital representation of a physical asset or asset system is sufficient to form a DT [18,48–51], others state that a DT is much more than a digital representation [28,32,34,52–55]. While some say that a DT is a technology [17,28,36,55–58], others say that it is rather an approach or a process, instead of a product or a technology [26,59]. While some authors [57,60] use the terms "BIM"(Building Information Modelling) and "DT" interchangeably, to others [26,61–63] these are two distinct concepts. Kaewunruen et al. [57] state that "a DT ( . . . ) or so-called BIM ( . . . ) is a digitization technology ( . . . )" (p. 2) and Heaton et al. [60] present the creation of a "DT BIM model" (p. 180) in Revit, which are some examples of the vocabulary misuse previously discussed.

Kritzinger et al. [45] proposed a classification of DTs in three types: "digital model", "digital shadow", and "digital twin"—depending on the automation level of data transfer between the physical and the virtual assets. This classification has become popular in the literature, but it is still quite debatable. It not only considers "digital models" and "digital shadows" as types of a DT, but "digital twin" is also classified as a type of DT, which raises misunderstandings and increases the risk of vocabulary dispersion. The terms "digital model" and "digital shadow", for example, are already used simultaneously for types [45] and components of a DT [25]. In a DT literature review, Liu et al. [41] reported that over half of the reviewed papers described "digital models" or "digital shadows", although their authors claimed to have studied DTs ("claimed twins"). Some authors have also reported that "true digital twin" applications are rare [26], and so DT systematic research is difficult [41].

Additional misunderstandings also emerge from software vendors and suppliers, who are renaming products and selling DTs as products and technologies [53], like a "black box of magic" [26].

With respect to all these different interpretations and approaches, some authors [26,32] conclude that DT is currently a buzzword.

### *1.2. Significance of the Study and Motivation*

DT research is currently being promoted in the road and rail sector, either through innovation recommendations [64] or ongoing research projects (e.g., In2Smart2, In2Track3). The challenges arising for DT application in this particular joint context [65] and the need for clear conceptual constructs are similar to those described above. However, due to the great impacts that road and rail networks have on society, there are significant challenges and opportunities still to explore from DT application. The authors believe that understanding the current state of DT application in the rail and road networks should be the first step to be taken by an organization of such sector that pretends to explore the potential value derived from the use of DTs.

Although DT has already been intensely discussed and studied in literature reviews—in more generic scopes [29,41] or more specific ones, such as buildings [63,66], logistics [67], and manufacturing [40,45,68,69]—there is a gap in knowledge focusing on the transportation sector, namely on rail and road networks. This gap was previously identified in an exploratory study about this subject [70] and, for that reason, motivates the research that is presented in this article.

### *1.3. Terms and Definitions*

In this section, the authors propose a definition for DT for rail and road networks.

Because of the novelty and multiplicity of DT literature, filtering out the relevant studies about DT in rail and road networks represents the first challenge to be addressed.

The authors consider that, as a starting point, a proposal for the DT definition is beneficial. This allows the development of an eligibility criterion, which is essential to conduct the literature review and to separate the relevant articles from those out of scope.

In that regard, the authors consider previous research and relevant articles on DT and suggest conceptual boundaries for interpreting the concept of DT as adopted in this paper:

- Each DT serves a specific purpose in a given context, thus allowing the definition of the resources required to support it and to assess the benefits and value derived from it;
- A DT includes a digital representation of the physical asset or asset system and its context (the complexity and accuracy of the digital representation should suit the available resources and the DT purpose);
- Following other researchers [28,34,71–74], a DT needs to integrate automated data transfer, through sensor monitoring, allowing synchronisation in time between the physical and the virtual spaces;
- Because real-time data alone do not add value to the decision-making process, the DT should have some form of data analytics (Artificial Intelligence, Big Data, etc.) to generate insights for the user (or the twin itself) and to support the asset management decision-making process. As stated by Shafto et al. [34], other information sources such as physical models and available records can be integrated into the DT. The DT might incorporate predictive or simulation capabilities, depending on the purpose of the DT;
- DTs might have different integration scales, from single asset or component level to asset system or network level [37]. Higher levels of asset aggregation in the DT imply higher potential benefits but also higher complexity (data security, interoperability, etc.);
- DTs might have different levels of development and complexity, but always include some sort of automated data transfer—i.e., take the form of "digital shadows" or "digital twins" according to the classification proposed by Kritzinger et al. [45]—at least from the physical asset to the digital asset. The data refresh rate needs to be adequate for the purpose.

Following the propositions above, a DT for rail and road networks is considered to be a digital representation of a physical asset or asset system and its operational environment, integrating a real-time data connection with the physical asset or asset system and other support tools and sources (such as physical models, data analytics, simulation, and prediction capabilities), used to generate insights aligned within a pre-defined purpose and, ultimately, to overcome barriers and promote sound physical asset management decision-making processes [22].

### *1.4. Research Objectives and Paper Organization*

This study aims to address the knowledge gap mentioned in 1.2 and shed light on the current extent of DT application in rail and road networks. This paper does not aim to review general DT concepts, key technologies, or industrial applications, but instead focuses on rail and road infrastructure applications and their potential contributions for enhancing the sustainability and resilience of these infrastructures.

This research goal supports secondary objectives and future research plans, such as establishing a roadmap that can be used by both practitioners and the research communities, namely those dealing with rail and road networks. A roadmap could allow rail and road asset management organizations to better identify innovation opportunities and to promote digital transformations using DTs.

The main research question is complemented by the following research objectives:

- Identify knowledge gaps and research opportunities;
- Perceive how DT can impact the resilience and sustainability of rail and road infrastructures.

This paper is organised as illustrated in Figure 1. Section 2 presents the method used in this study (PRISMA) to complete a systematic literature review of DT in rail and road networks. Section 3 focuses on the bibliometric analysis of the literature review outputs. Section 4 presents the contributions of the selected papers to the discussion on the resilience and sustainability of road and rail infrastructures. The paper concludes with Chapter 5, dedicated to the main research outcomes and possible future research developments.

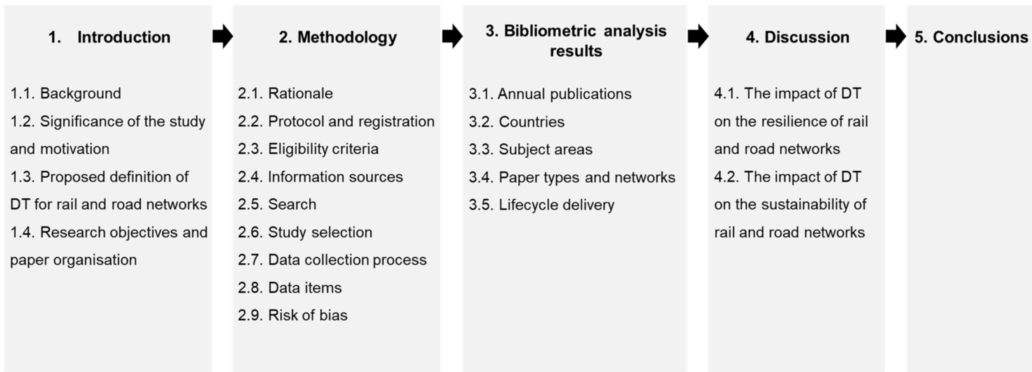


**Figure 1.** Paper organization.

## 2. Methodology

### *2.1. Rationale*

This article explores the current extent of DT application in rail and road networks. To achieve this, the authors conduct a systematic literature review to guarantee that the research results follow a pre-defined and reproducible approach, and that the research quality is not influenced by either a priori assumptions or the researcher's experience (typical features of narrative literature reviews).

### *2.2. Protocol and Registration*

The authors developed a systematic literature review following the structure of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). PRISMA consists of a widely used literature review protocol, developed by a group of authors from the medical field [75] to increase the transparency, reliability, and accuracy of systematic literature reviews. These authors proposed a 27-item checklist and a corresponding flow diagram for transparent reporting in a systematic review [75]. The authors chose PRISMA to conduct the systematic literature review of DTs in rail and road networks due to its transparency, consistency, and comprehensiveness.

The systematic research begins with an identification phase, followed by a paper screening, eligibility, and the final selection of the records to be included in the content analysis. These steps are illustrated in Figure 2. The review process begins with setting up the eligibility criteria (Section 2.3), the information sources (Section 2.4) and the search query (Section 2.5). The first set of results is then filtered according to the eligibility criteria, the remaining articles are joined into a single set, and the duplicates are removed. Next, the papers are analysed according to their title, abstract and keywords, and the papers out of scope are excluded (Section 2.6.1). Finally, the texts of the remaining papers are fully read (Section 2.6.2) and some additional and relevant references are included in this step (Section 2.6.3). Again, the articles out of scope are removed and the final list of papers is obtained.

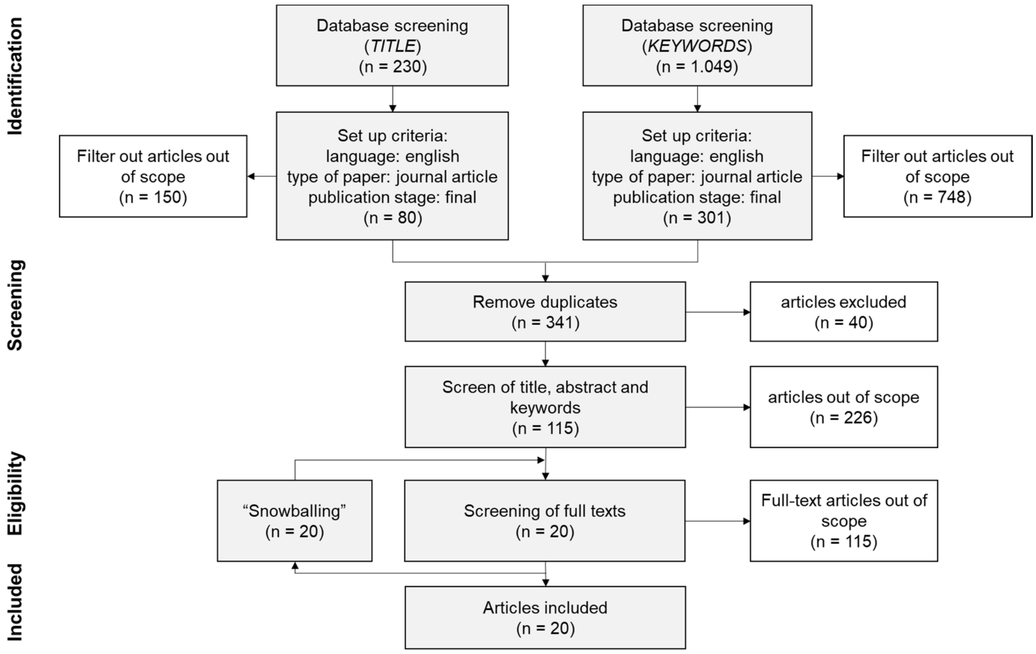


**Figure 2.** The PRISMA flow diagram (adapted from [75]).

## 2.3. Eligibility Criteria

All articles included in this study meet three pre-defined eligibility criteria.

First, the publication language was restricted to English. Although English is not the native language of the single reviewer (J.V.), this decision allowed the most candidate records to be reviewed.

The second and third criteria were that only journal articles in the final publication stage were admitted to the review. This was imposed to ensure that all the candidate records had been peer-reviewed and to provide an additional level of quality assurance.

No restrictions were made to the year of publication, journal title, number of citations, or others.

## 2.4. Information Sources

The information sources used in the search, including the data for the bibliometric search, were acquired from the Scopus database. This database is recognised by the academic field for having rigorous quality criteria [26], wide article coverage, significant citation, and abstract sources [76]. The Scopus search engine also uses a Boolean syntax, which allows the introduction of specific restrictions and obtainment of more refined results. Moreover, this search engine provides an instant bibliometric analysis of the results obtained (distribution of publications per author, country, year, etc.), which adds value to the search and supports the iterative process of choosing an adequate search string. The last search was run on 5 November 2021.

## 2.5. Search

The query structure and the keywords used for this literature review are presented in Table 1. For details about this syntax, the authors refer to the Scopus Search Guide [77]. Choosing the right structure and keywords for the search process was part of an iterative process, which began with a preliminary keyword search and was followed by a refinement process, according to the results obtained. The search string is composed of three main parts: (i) the DT domain; (ii) the rail and road networks domain; and, (iii) the exclusions and limitations of the search scope.

**Table 1.** Structure of the search string used in the Scopus Search API.

| Domain | Operators and Keywords Used |
|---|---|
| Article elements | TITLE/KEY |
| Digital Twin [1] | (“digital twin*” OR “as-is BIM” OR “virtual twin” OR “cyber*physical system*” OR “digital representation” OR “virtual representation” OR “digital counterpart” OR “digital replica”) |
| Operator | AND |
| Rail and road networks | (“rail*” OR “road*” OR “transport*” OR “asset management” OR “infrastructure” OR “track” OR “drainage” OR “culvert” OR “platform” OR “bridge” OR “tunnel” OR “overpass” OR “underpass” OR “retaining wall” OR “level crossing” OR “superstructure” OR “switches and crossings” OR “turnout” OR “access way” OR “signalling” OR “telecommunication” OR “electrical plant” OR “electric power” OR “*station” OR “catenary” OR “pavement” OR “highway” OR “traffic sign” OR “lighting” OR “toll” OR “building” OR “embankment” OR “escape ramp” OR “runaway*ramp” OR “automatic train protection”) |
| Operator | AND NOT |
| Exclusions | (“manufactur*”) |
| Operator | AND |
| Limitations of scope | (LIMIT-TO (SRCTYPE, “j”)) AND (LIMIT-TO (PUBSTAGE, “final”)) AND (LIMIT-TO (DOCTYPE, “ar”)) AND (LIMIT-TO (LANGUAGE, “English”)) |

[1] A basic search (without limitations) for TITLE-ABS-KEY (“digital twin”) resulted in 4.187 hits (1 August 2021).

First, because DT is a relatively recent keyword [29], some papers may be in scope with DT but not feature its keyword. In that regard, a preliminary keywork search was performed to identify the existing “synonyms”. Some authors identified current synonyms of DT, such as “virtual twin” [31,37,78], “cyber-physical system” [36], “digital replica” [78,79], or “digital representation” [31,80]. Hence, these are included in the query, within the DT domain.

Then, in the second part, the road and railway networks are decomposed according to their keywords and the main asset classes they cover (e.g., “track”, “pavement”, “overpass”, etc.). This step was executed with the support of the Commission Regulation No. 851/2006 [81] guidelines, which identifies the many items that are part of rail and road infrastructures. It is worth mentioning that this step is also quite challenging, not only in choosing the most adequate level of asset decomposition, but also because rail and road assets are very diverse and they often overlap with other sectors of activity (power, telecommunications, buildings, etc.). Following the asset taxonomy proposed by Dieter [82], the asset scope is defined by focusing on the constructed, durable, and immovable physical asset classes (see the Asset Taxonomy proposed by [82]) of rail and road networks (see Figure 3).

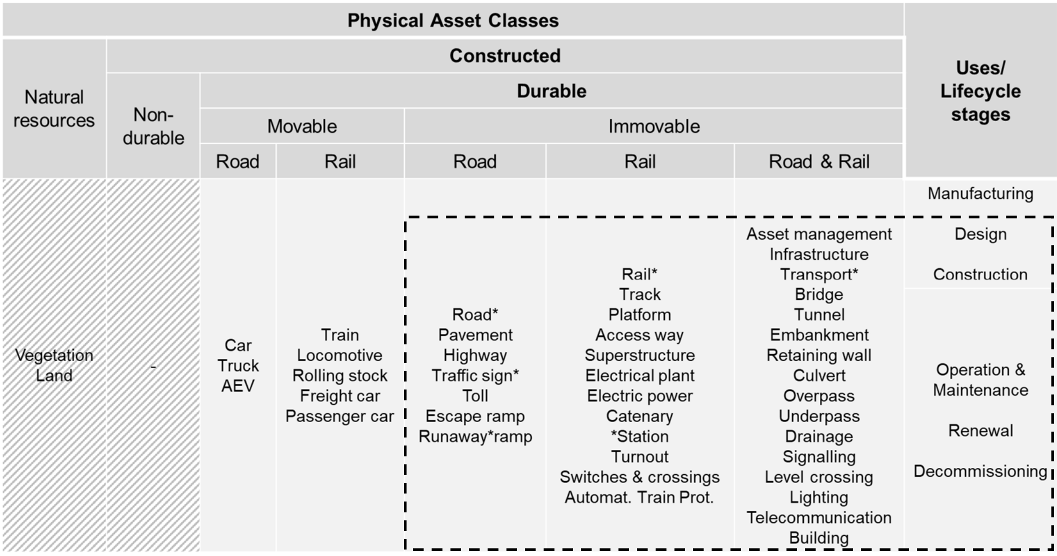


**Figure 3.** Asset scope of search.

Some exclusions and limitations are included in the last part of the query. Because DTs have been studied intensively in the manufacturing field [30,32,35,36,39,41,83] as verified by the existing literature and search attempts with Scopus, the authors decided to exclude this subject from the literature review and, consequently, to exclude the keyword "manufactur*" from the title and keywords of results. This allowed the removal of many manufacturing-related publications and, thus, reduced the list of records for further review.

Regarding the search scope, some limitations were included (see "LIMIT-TO" in Table 1) to transfer the eligibility criteria presented in Section 2.3 into the query, namely the language, type, and status of publications. Only final-stage journal articles published in English were included.

It is also worth mentioning that the authors chose to apply this search string to the title and keywords of papers, leaving aside the possibility of also applying it to their abstract. Initial tests allowed us to verify that, given the diversity of keywords used in the search query (Table 1), the number of papers grew significantly with the addition of the abstract (TITLE-ABS-KEY). Within this large number of records, only a very small portion had the potential for further analysis. For that reason, the authors considered that the title and the keywords were more reliable and more efficient search sources than the abstract. Because the Scopus search API does not have the option to perform a simultaneous search in the title and in the keywords of the records, the authors decided to divide it into two separate searches, one only for the title and another for the keywords. After these two searches, the records were merged, and the duplicate records were removed.

The title and keywords searches resulted in 80 and 301 papers, respectively. After merging these two groups and removing the duplicates, a list of 341 papers was obtained (see Figure 2).

### *2.6. Study Selection*

Eligibility assessment was performed by one reviewer. The screening process was structured in three phases: screening, eligibility, and "snowballing". The workflow is summarised in Figure 2.

#### 2.6.1. First Phase ("Screening")

In the screening phase, the reviewer read the title, the abstract, and the keywords of each of the 341 articles and assigned a classification of 0 (out of scope), 1 (in scope) or 2 (not yet sure if in or out of scope). The following articles were rejected from the study and classified as out of scope:

- articles without developments or contributions within the rail and road network scope (see the asset scope presented in Section 2.5);
- all manufacturing-focused papers, due to the reasons discussed in Section 2.5;
- all articles without available abstracts.

This first phase rejected 226 of the 341 papers assigned for review, mainly articles outside the scope of rail and road, and manufacturing-focused papers.

Each article in scope was classified according to the sector and infrastructure it covers (Table 2).

**Table 2.** Papers in scope after screening phase, by sector and infrastructure.

| Sector | Infrastructure | No. of Papers | % |
|---|---|---|---|
| Buildings | Building | 48 | 44 |
| Transportation | Railway | 16 | 15 |
| | Bridge | 15 | 14 |
| | Roadway | 10 | 9 |
| | Tunnel | 9 | 8 |
| General | General | 6 | 6 |
| Energy | Electricity | 3 | 3 |
| Telecommunication | Telecommunication | 1 | 1 |
| | **Total** | **108** | **100** |

The results indicate that nearly half of the 108 papers classified as "in scope" are building-related. This revealed that the building sector (residences, schools, offices, commercial facilities, etc.) dominates the DT research within this asset scope. This conclusion is validated by other publications, which suggest that the building sector has received increased attention about DT studies when compared to other infrastructures [1,42,55], namely the civil infrastructures [73]. Moreover, the majority of these papers focused on specific applications in the building sector, such as Nearly-Zero Energy Buildings (NZEB), user comfort, BIM and Building Energy Modelling (BEM). Indeed, the current availability of sensing systems for Indoor Air Quality (IAQ) and thermal comfort [84], as well as accurate surveying technologies and Natural User Interfaces (NUI), enable the development of digital models and cyber-physical systems at reduced costs [85]. Even though buildings are part of the infrastructure portfolio of rail and road sector (office buildings, operational and control buildings, etc.), the authors decided to not include articles in the second review stage after assessing titles, abstracts and keywords, unless they focus on the remaining infrastructures, which are closer to the core of a rail and road network and to which less attention has been given by scientific literature.

#### 2.6.2. Second Phase ("Eligibility")

After the screening process, the articles classified as 1 or 2 (115 in total) were cleared to the second review stage, where the full papers were downloaded and fully read. At the end of this stage, each article was classified as being in (1) or out (0) of scope. The following articles were rejected from the study and classified as being out of scope:

Papers without full texts available;

Papers focused on non-DT approaches, even if their authors described them as such. This was a recurrent situation during the literature review, and it validates the findings of other DT research [26,37,41]. Many papers focusing on BIM, point-cloud extraction, finite element models, or virtual environments claim to be within DT research, which is not aligned with the most consensual concept of DT, and somehow increases undesirable noise around this concept.

#### 2.6.3. Third Phase ("Snowballing")

The third and last review phase was dedicated to "snowballing", where the most relevant references from the second stage papers were also included in the full-text review. Only journal articles were accepted for the "snowballing" stage (for the same reasons mentioned in Section 2.3).

The final list is formed by the 20 papers within scope, according to the results of the second and third review stages.

### *2.7. Data Collection Process*

The records collected from the Scopus search engine were exported to a spreadsheet and were processed according to the PRISMA flow diagram.

For the full paper review stage, the author downloaded each available paper and reviewed them using "Mendeley". This software allowed the storage and taking of notes about each paper. The author also took notes about each paper in the spreadsheet (e.g., justification for exclusion, paper objectives, achievements, relevance, etc.).

### *2.8. Data Items*

During record export, the reviewer chose the most relevant attributes to be exported. In the end, each paper had the following data: Title, Year, Source title, Volume, Issue, Art. No., Page start, Page end, Page count, Number of citations, DOI, Link, Abstract, Author Keywords, Index Keywords, Document Type, and Publication Stage.

During the review process, a few columns were added for relevance classification, as described in Section 2.6.

### *2.9. Risk of Bias*

This literature review presents a few sources of bias risk.

First, the reviewing process was conducted by a single person, which entails the risk of affecting the general quality of the study, since there is no redundancy for conflict resolution. Another possible risk factor is the number of articles to be reviewed. During the screening process, the reviewer faced significant reading effort due to the high number of articles to be screened. This could lead to reading fatigue and possible bias in the classification of paper relevance. To mitigate this circumstance, the reviewer self-imposed a maximum number of articles to screen every day.

Article restrictions are another possible source of bias. Choosing only journal papers in the final publication stage for increased quality assurance was a trade-off that might have left relevant and good quality conference papers aside, for example. Moreover, there are other sources of information, such as web articles, books, or reports, that could provide useful insights on the current state of the art of DTs in rail and road networks. However, since this literature review focused on a scientific and academic approach, using adequate search engines, those sources were left aside.

The exclusion of the word "manufactur*" from the title and keywords of the articles could also have led to the rejection of papers that, for some reason, included that word in the title or the keywords but were not specifically related to that lifecycle stage. Although this can increase the risk of bias, the authors consider that this decision significantly increased the efficiency of the reviewing process, leaving aside many manufacturing-related papers that were out of the scope of this literature review (as observed in Section 2.6.1).

One last example of a possible risk of bias is present in the publication language. Even though the English language is the most common in the academic field, some articles were left aside due to this constraint. Some of those articles could provide useful information about the research topic, namely those from countries where DT applications already have a relevant level of deployment (e.g., Germany and China).

## 3. Bibliometric Analysis Results

Compared to other reviews on DT (e.g., [29,41,67,83]), this article presents a relatively short bibliometric analysis. However, this situation is a direct result of the adoption of a Systematic Literature Review (using PRISMA) prior to the bibliometric analysis, which allowed to remove articles out of scope and to work only with those inside the pre-defined scope (see Sections 2.3 and 2.4). Moreover, the lack of studies regarding the application of DT in rail and road networks significantly reduced the number of articles during the filtering process (see flowchart in Figure 2), resulting in a bibliometric analysis with only 20 journal papers. For this reason, some bibliometric analysis methods (such as keyword co-occurrence, clustering, etc.) produced, in this case, inconsequential results, and the authors chose to present only those with meaningful results.

### *3.1. Annual Publications*

The bibliometric analysis shows that 95% of the total number (20) of selected papers were published in the last four years, from 2018 to 2021, and the number of annual publications has increased continuously by, at least, 100% per year (Figure 4).

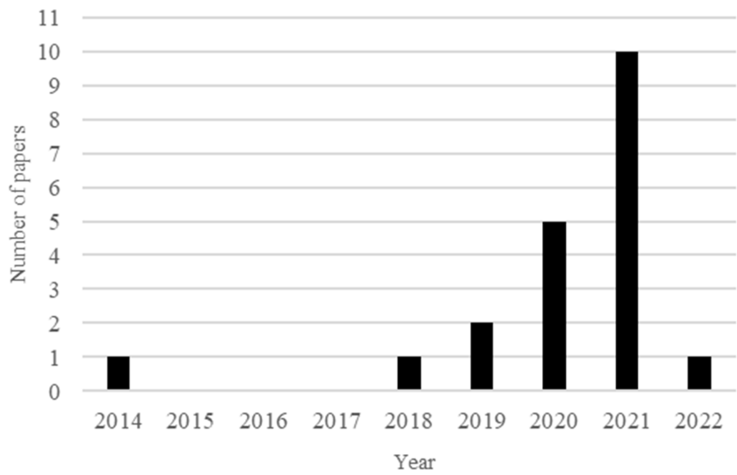


**Figure 4.** Number of papers published per year.

This growth pattern matches the results of other DT-related reviews [31,41,58,69], which corroborates the idea of DT as a trending topic, with growing interest from academia. The results also showed no predominant journals in terms of DT research in rail and road networks.

### *3.2. Countries*

The papers were produced by authors of 17 different nationalities, as shown in Figure 5. The total number of papers per country is 27, as some papers were produced in collaboration between researchers from different countries. These results show that, although the United States appear as the most productive country (with 4 of the 27 results), there is no significantly predominant country in terms of DT-related journal paper publications in the rail and road infrastructure sector.

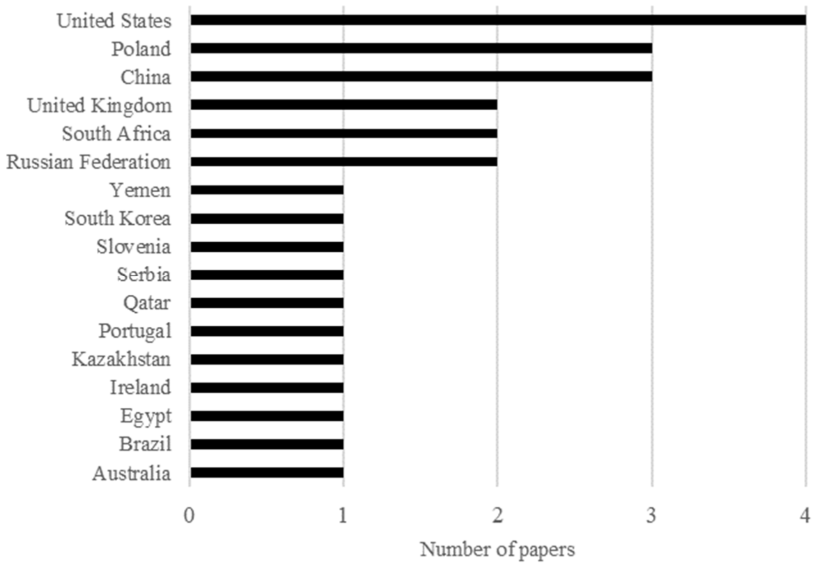


**Figure 5.** Number of papers by country/territory.

### 3.3. Subject Areas

Figure 6 presents the distribution of papers per subject area, provided by Scopus search engine. Again, each paper can cover more than one subject area, which justifies the total number of results (45) being higher than the total number of papers (20). The graph shows that 46% of the results are related to Engineering and Computer Science fields, with 54% being scattered among the remaining 12 subjects.

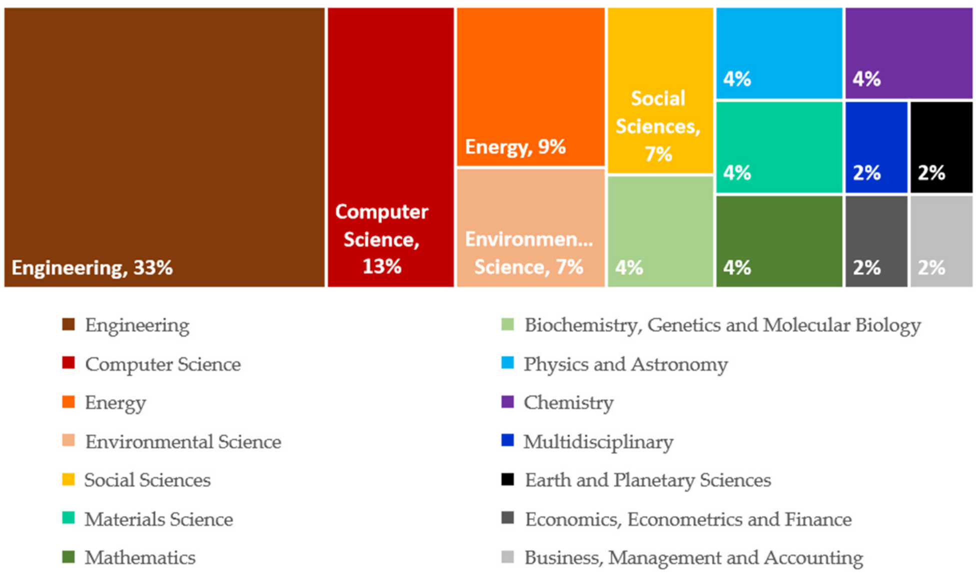


**Figure 6.** Results by subject area.

### 3.4. Paper Types and Networks

Figure 7 presents the type of paper and networks covered by the 20 papers. Of the papers, 55% (11) have a practical application of DT and 25% of papers are exploratory (4) or literature reviews (1). As expected, the majority of results (68%) focus specifically on rail and road networks. The rail and road networks are represented by almost the same number of records (7 and 8, respectively), which excludes the presence of a dominant network in this research scope. There is also a share of 28% of the results (4) related to the energy and telecommunication sectors, which is explained by the wide range of disciplines and sectors of activity involved in managing rail and road infrastructures, as introduced in Section 1. It is also worth mentioning that 14% of results (3) do not have a specific sector or network attributed. These records usually have a generic and exploratory focus on DT, or only briefly mention the rail and road networks.

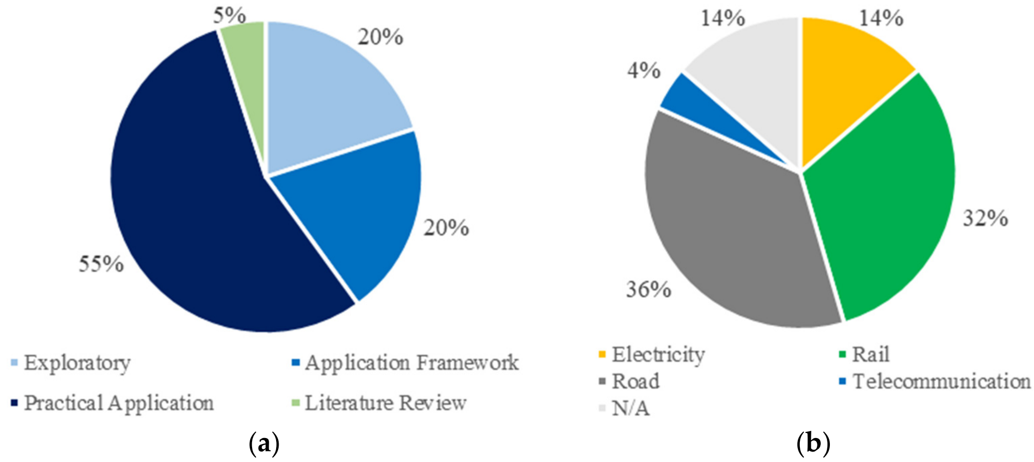


**Figure 7.** Results by paper type (**a**) and network (**b**).

### 3.5. Lifecycle Delivery

According to GFMAM [86], there are 39 subjects that constitute the Asset Management Landscape. This landscape contains 11 subjects that constitute the lifecycle delivery activities in asset management. This bibliometric analysis maps the papers according to the lifecycle delivery subjects in rail and road networks. Figure 8 presents the number of results, from the 15 papers classified as "Application Framework" or "Practical Application", by each of the 11 lifecycle delivery subjects.

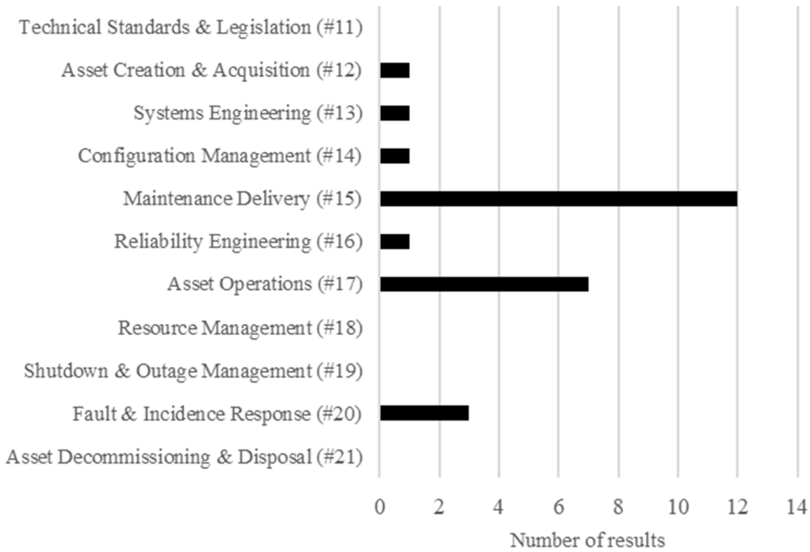


**Figure 8.** Results by lifecycle delivery subjects.

The results show that there is a clear predominance of maintenance and operations activities covered by the articles included. From the 15 eligible papers, there are 19 references impacting on either maintenance or operation activities (73% of total). There are also three papers that discuss impacts on fault and incident response (12%). The first and last asset lifecycle stages (acquisition and disposal) have very few references, which massively contrasts with the operation and maintenance phases.

This conclusion corroborates the results presented by other authors. The study of Callcut et al. [26] shows that every use case covered by the study attempts to improve operational performance, and it even states that DTs will be more beneficial and provide much greater value when used in an operations context. The literature review of Jones et al. [29] also points out that most research papers focus on the realization and support/use phases of the life cycle, with few articles focusing on the remaining stages (imagine, design and retire/dispose). Lamb [37] cites a study from Negri et al. [47] to inform that the motivations regarding the use of DTs are different according to each sector. While manufacturing has mostly production-related motivations, the oil and gas sector, for example, focuses on safety, security, operation and maintenance needs. It also informs that many papers appear to focus on maintenance and production efficiency, ignoring the significant value that DTs could generate to the services provided. The study provided by Macchi et al. [46] concludes that the use of DTs is consistent with the benefits discussed by the literature, namely performance and long-term behaviour prediction and improved maintenance decision making. These results are also confirmed by an exploratory study conducted by Vieira et al. [70], whose application examples for the rail and road infrastructures show that most of the opportunities relate to the operation and maintenance phases. Kim and Kim [87] describe that DTs are mostly used during the operational stage, with benefits such as real-time condition analysis and lifespan prediction. With a study focusing on buildings, Lu et al. [88] state that the operation and maintenance stages—that take the longest timespan in the asset lifecycle—may experiment relevant improvements, namely through environment monitoring, maintenance optimization and prioritization, and anomaly detection. Sayyad et al. [89] also refer that DT is widely used for operational and maintenance activities, such as predictive maintenance, fault diagnosis, anomaly detection and system real-time monitoring.

Finally, the authors used a software tool for constructing and visualizing bibliometric networks. However, due to the small sample of collected papers and the lack of common authors or keywords (except for "digital twin" and "digital twins"), the visualisation networks did not add significant value to the bibliometric analysis. For that reason, the authors decided not to include them in the paper.

## 4. Discussion

### *4.1. The Impact of DT on the Resilience of Rail and Road Networks*

Although the 20 papers selected from the literature review are very diverse, with very few common connections, it is possible to identify relevant contributions concerning the subject of asset resilience (see Table 3). The authors reviewed each paper and, according to the respective applications and findings, identified the existence of impacts on resilience according to the four resilience aspects mentioned in Section 1.1.1 and further detailed in [7].

Table 3 shows that almost all paper contributions relate to the robustness and resourcefulness of physical assets. Most papers include the use of sensor monitoring to improve operation and maintenance decision making, so, understandably, the maximisation of condition levels prior to extreme events (through constant operational and condition monitoring) can contribute to increase asset robustness. However, since DT requires the use of automated data transfer, from the physical asset to the virtual asset, or vice-versa, the risk of cyber-attacks and data leaks also emerge [26,56]. These vulnerabilities, together with an increasing number of sensors and actuators used in infrastructure management [59], might compromise, in limit cases, the robustness of the physical asset or physical asset system itself. Therefore, cybersecurity should always be a concern when developing DT applications, mainly in DT interconnected environments [26].

**Table 3.** DT contribution to resilience of rail and road infrastructure networks.

| Ref. | Resilience Properties | | | | Network | Observations |
|---|---|---|---|---|---|---|
| | Robus. | Redun. | Resou. | Rapid. | | |
| [17] | X | | | | Road | Continuous monitoring of road infrastructure conditions provides for early warning and indication of potential distress, enabling early remedial action. |
| [26] | X | X | X | X | General | Data collection through DTs helps to increase the efficiency, sustainability, and resilience of CISs, under normal conditions or following extreme events. Cybersecurity is an important and complex issue, especially in interconnected DTs. |
| [38] | X | | X | | Rail/Road | DT timely returns maintenance information, provides inputs for mitigation plans, analyses the impact of extreme loads on bridge performance, and issues early warnings. |
| [39] | X | | X | | - | DT can share information and focus on condition monitoring, asset performance management, or predictive maintenance. |
| [43] | X | | X | | Rail | The DT-EA allows monitoring the system state, running application diagnostics, and simulating and predicting various operational and failure scenarios. |
| [52] | X | | X | | Rail | The solution provides cyclic data for analysis and verification of the turnout's condition. The solution might capture emergency conditions. |
| [55] | X | | | | Road | The visual information service of the DT provides reliable data for preventive maintenance, which improves the efficiency of prediction and decision-making. |
| [56] | X | | X | | Rail | The sensor data and the DT simulations and predictions can capture the early fault, support track maintenance and deliver safe, reliable, and resilient service. DTs collaboration suffers from single failure due to attack and connection in a centralised manner, data interoperability, authentication, and scalability. |
| [61] | X | | X | X | Road | The decision analysis method can help O&M managers to quickly analyse the fault cause and identify maintenance measures for the tunnel jet fans. |
| [73] | X | | X | | Road | The DT continuously monitors the assets to support proactive maintenance and ensure mechanical stability, safety, economy, and environmental requirements. |
| [87] | X | | X | | Road | Real-time condition analysis and life prediction of NBTs enables timely asset replacement and resource procurement, increasing maintenance sustainability. |
| [90] | | | X | | Electricity | Remote inspection of substation power switches avoids unnecessary operator travel and allows for quicker and cheaper reestablishment. |
| [91] | X | | | | Electricity | An autonomous system performs diagnostic on power lines. The timely elimination of defects reduces failures and improves the reliability of the power supply. |
| [92] | X | | X | | Rail | The constant infrastructure monitoring improves the control of the HVAC system and the energy efficiency, while guaranteeing the comfort requirements. |
| [93] | X | | X | | Electricity | The online measured data are used in the analysis of power cable displacement and may be applied for maximising power cable capacity. |
| [94] | X | | X | | Rail | Condition is simulated with a bridge DT, which identifies structural damage before it becomes critical, enabling preventive actions and cost minimisation. |

**Table 3.** *Cont.*

| Ref. | Resilience Properties | | | | Network | Observations |
|---|---|---|---|---|---|---|
| | Robus. | Redun. | Resou. | Rapid. | | |
| [95] | X | | X | | Road | The hyper-connected pavement environment allows for a continuous understanding of infrastructure conditions, leading to timely decision making. |
| [96] | X | | X | | - | IoT and a common data environment can reduce costs, improve maintenance productivity, and enhance the accuracy and quality of information. |
| [97] | X | X | X | | Telecomm. | A network of DT avoids negative consequences when sharp increases occur in traffic, especially in emergency and destructive events. |
| [98] | | | X | | Rail/Road | The VT/IM environment provides interactive accessibility to information, which can help them identify and diagnose unusual bridge behaviours. |

Maintaining adequate levels of condition and investing in limiting initial losses might contribute to maximising the asset/asset system capacity to withstand an unusual level of stress or demand and, consequently, reduce the recovery time. In other words, if the initial loss is more significant, it may take longer to restore an asset/system to its initial capacity. Thus, asset robustness can indirectly increase asset rapidity [7]. Furthermore, DT capacity of integrating multiple sources of data (e.g., sensor data, asset properties, localisation; plans, etc.) can also enhance the ability of a given asset system to restore its functionality, by providing response teams with a pre-disruption point of truth of each asset/asset system. Concerning the list of papers, only one includes a practical and direct contribution of DT to increase system rapidity after an unexpected event. In this paper [61], the DT has the capacity to suggest actions and resources to allocate following a failure situation, increasing the rapidity and accuracy of the response. Even though this capability can add a lot of value to asset management decision making, it can be challenging to achieve, mainly in DTs with lower levels of development.

Along with robustness, the resourcefulness dimension of resilience is also highly enhanced using a DT and its sensor monitoring capabilities. The real-time collection of asset data allows asset managers and emergency teams to identify service disruptions in real-time and react more quickly to a given event. When discussing the impact of extreme events on critical infrastructure networks, this issue becomes even more relevant. Indeed, the timely identification and localisation of disruptions and failures are key to minimising their impacts (economic, social, and environmental) and recovering their functionality in a faster and prioritised way.

Simulation capabilities, here less frequently mentioned, are typical in DTs and can contribute to the robustness and redundancy of asset systems [43,56,94]. These can be used in design, configuration, and commissioning phases, to assess the capacity of an asset/asset system to withstand an extreme event and the consequences generated to the whole network or system (e.g., electrical grids, road and rail tracks, telecommunications).

Within the DT and resilience subjects, a wide range of topics are yet to be addressed in relation to its overall impact on asset management development programs in infrastructure organizations, such as those developments leading to real-time risk assessment of assets/asset systems and optimum maintenance/renewal strategies in the asset lifecycle management.

### *4.2. The Impact of DT on the Sustainability of Rail and Road Networks*

The sustainability concept implies assessing needs across two time frames: present and future. To take these two horizons into the real-time decision-making process, decision makers need adequate tools and approaches. DT has capabilities that might help in tackling those challenges. DT not only focuses on the present and future but also looks at the past (through data analytics) to help understand the present and predict or assess the impacts on future scenarios. Moreover, DT can integrate multiple data sources during the asset lifecycle, from simple condition or performance data to environmental or economic inputs. The simulation and predictive capabilities, together with this wide range of data, has the potential to generate more sustainable, comprehensive, and accurate asset decision-making. Regarding this subject, there a just a few references within the collected papers that approach the contributions of DT to sustainability and the UN Sustainable Development Goals.

Broo and Schooling [39] state that the proposed DT architecture aims to identify common goals from stakeholder contributions and develop a continuous assessment of sustainability indicators.

Meža et al. [73] propose a DT for roads constructed using secondary raw materials. The subject of sustainability is not only inherent to their scope of study, but also present in asset sensing (e.g., monitoring of environmental impacts in the form of leaching potential toxic elements, particle and gas emissions), which is crucial to monitor mechanical stability, safety, economy, and environmental impacts, and to identify improvement opportunities. The authors concluded that sensing road assets and their environmental impact is key to guaranteeing safety and operability throughout the lifecycle, all the way to decommissioning, recycling, and potential reuse.

Callcut et al. [26] report that DTs have the potential to increase the efficiency and sustainability of critical infrastructure systems. The collection of infrastructure data will enable stakeholders to reduce emissions, make sustainable decisions regarding infrastructure services, and proactively manage climate resilience.

In another paper, Kim and Kim [87] discuss that the use of DT in noise barrier tunnels can support decision making regarding the lifespan of assets, thereby enhancing sustainability. The study points out that the use of DTs for condition assessment of NBTs can help determine lifespans and predict resource procurement, production, and replacement times, which increases sustainability.

In essence, there are not many studies regarding the DT and sustainability issues within this set of papers, which is aligned with the findings of other authors regarding the sustainability impacts of DT-based systems [99]. However, the improvement of asset data quality through real-time asset monitoring across the lifecycle can contribute to improve the decision-making process in asset management (e.g., through better planning, resource usage, and monitoring of asset environmental impacts) and, ultimately, to increase asset sustainability. More sustainable asset designs [99] are another example of a direct contribution of DT to increase asset lifecycle sustainability. There is also the opportunity for future DT studies in rail and road infrastructures to focus on real-time monitoring of specific environmental metrics (such as lifecycle carbon emissions, water consumption, energy consumption, etc.) and to incorporate them into the decision-making process [73,87,92].

## 5. Conclusions

This study confirms that DT studies on rail and road infrastructure networks are still scarce, even if the application potential in this sector is evident. Since the rail and road infrastructure networks provide a critical service to society and face constant challenges (increasing demand, investment backlogs, territorial dispersion, wide range of asset types, etc.), the application of DT could help in addressing some of these issues, by increasing the quality and efficiency of asset information and, ultimately, the quality of the asset management decisions.

The bibliometric analysis shows that the DT research in rail and road infrastructures is very recent and has increased at a minimum rate of 100% over the past four years—a similar growth pattern compared to other DT studies. It has also shown that 46% of DT studies are in the engineering and computer science fields, with no predominant country in terms of scientific output. The list of collected papers covers diverse sectors of activity, such as rail

(32%), road (36%), electricity (14%), and telecommunications (4%). The results also show that the DT contributions are more evident during the operation and maintenance phases (73%), when the physical assets are already constructed and capable of being monitored in real time, corroborating the conclusions of previous studies.

The authors verified that, although the DT subject indirectly addresses the resilience and sustainability of rail and road infrastructure assets, there is vast exploratory potential concerning the impacts of DT on these topics. There are prospects for future research on DT with expected impacts on the monitoring capabilities of the condition and performance of rail and road assets in real time, thus contributing to enhancing their resilience. This is due to the constant assessment of their ability to withstand unexpected events, as well as the quality of long-term decision making regarding the lifecycle of these assets, which also contributes to a more sustainable rail and road infrastructure asset management.

Since the literature review showed a scarcity of DT applications in rail and road networks, the increasing need to accelerate and facilitate timely decisions to enhance the sustainability and resilience of these critical assets suggests that more studies are expected to emerge within this scope in the coming years, in alignment with the recent growth trends of DT applications. Additional DT applications—with various asset types, lifecycle stages, levels of DT integration, etc.—that follow the concept proposed by this paper contribute positively to the state-of-the-art of DT in the rail and road sector. Moreover, since resilience and sustainability are two major drivers in rail and road asset management, the authors also recommend future works to study the added value in these subjects.

As the DT concept is yet to be consolidated, the authors believe that the discussion and proposal of an official definition (e.g., by ISO technical standardization committees) could help in stabilising the DT concept and provide a clear reference for future studies and applications. This is a particularly important issue because interest in DT is growing, which rises the "snowball effect" about interchangeable DT interpretations. Organisations and innovation projects would benefit from a clear understanding of the DT concept, allowing the alignment of contributions, and ultimately, the optimisation of the value realised from infrastructure assets to organisations/projects, to end-users, and to society as a whole.

**Author Contributions:** Conceptualisation and methodology, J.V., J.P.M., N.M.d.A., H.P. and J.G.M.; data collection and curation, J.V.; writing—original draft preparation, J.V.; writing—review and editing, J.V., J.P.M., N.M.d.A., H.P. and J.G.M.; supervision, J.P.M., N.M.d.A., H.P. and J.G.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was supported by Infraestruturas de Portugal, S.A. and the Shift2Rail Joint Undertaking funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101012456 (IN2TRACK-3). The authors are also grateful for the Foundation for Science and Technology's support through funding UIDB/04625/2020 from the research unit CERIS. Additionally, this work was financially supported by: Base Funding—UIDB/04708/2020 of the CONSTRUCT—Instituto de I&D em Estruturas e Construções—funded by national funds through the FCT/MCTES (PIDDAC).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data that support the findings of this study are available on request from the corresponding author.

**Acknowledgments:** J.V. would like to thank Infraestruturas de Portugal, S.A. and the Shift2Rail Joint Undertaking for supporting this research. This manuscript is part of J.V. PhD dissertation.

**Conflicts of Interest:** The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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