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RESEARCH ARTICLE

Digital Twins for Railway Sector: Current State and Future Directions

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ABSTRACT Today, digitalization is a ‘‘must’’ for all industries and sectors. One of the most promising and popular concepts of digitalization in the last decade is certainly the technology of the digital twin (DT). As rail transport ranks very high among transport modes in terms of sustainability, resilience and reliability, its digitalization is of great importance. Since any disruption or interruption of normal rail operations with the aim of improving conditions could have many negative consequences, the technology of DT is perfect in this sense, as it allows testing changes on a virtual copy of the real system without directly affecting its operation. Combined with machine learning and other artificial intelligence algorithms, it can also be used to predict and forecast operational characteristics, events and failures that can trigger rapid management and action and prevent disruptions and cost increases. This article, therefore, aims firstly to provide a comprehensive and overarching overview of the application of DT technology in the rail sector using a newly proposed multi-layered classification, and secondly to highlight the research gaps that need to be addressed in the near future to enable the transition to Rail 4.0. The result of this research, which examined 58 research articles published in scientific journals, shows that the application of DT in the railway sector has increased in recent years, that investigations in infrastructure for maintenance purposes receive the most attention in the scientific community, and that there is still much room for research and development of DT in the railway sector.

INDEX TERMS Digital twin, DT, rail, railway, rail system, rail industry, DT application, rail DT classification, rail DT domains.

I. INTRODUCTION

This section explains the background and motivation for this literature review, describes the concept of the digital twin, introduces related previous review studies and provides a summary description of the research aims of this review and the structure of the article.

A. THE BACKGROUND AND MOTIVATION

According to ERRAC, The European Rail Research Advisory Council [1], rail is seen as the backbone of mobility by 2030. As rail is the cleanest mode of transport, a shift to rail is recognized as a measure leading to a more sustainable European transport system. Based on Commission data [2], rail is the least used mode of passenger transport in the EU-27 countries in 2020. In terms of passenger kilometers, rail accounts for 5.5%, cars, buses and coaches for 93.3% and trams and metros for 1.3%. However, this status was largely impacted by COVID-19 and in 2022 the EU rail passenger transport performance significantly recovered from the sharp fall in 2020[1]. The same conclusion can be drawn for freight transport. 74.4 ton-kilometers in % of freight transport is by road, and only 16.1% by rail. In addition, in 2022 EU rail freight transport performance slightly decreased in compared

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[1] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Railway_passenger_transport_statistics_-_quarterly_and_annual_data#In_2022.2C_the_EU_rail_passenger_transport_performance_significantly_recovered_from_the_sharp_fall_in_2020

with the 2021 year.[2] Therefore, in order to achieve the goal of promoting a modal shift to rail and to improve the role of rail in the transport market, more investment should be made in technical innovation in rail transport. It can also be concluded from OECD data [3] that investment in road infrastructure still dominates compared to rail. This is the main reason for the stagnation of rail's share of the transport market. Therefore, the only opportunity and the most important effort that should be made in rail transport is to continue investing in the digitalization and automation of the rail system so that "the digital railway drives the integration of the overall mobility-digital ecosystem" [1], [4], [5]. To further improve the position in the transport market, technologies such as advanced interoperable train control systems, real-time operations management, virtual coupling and platooning, autonomous trains, smart communication between trains and other concepts and elements also pointed out by UNIFE [1] and [4] will increase capacity and resilience, user satisfaction through higher punctuality and comfort, and safety of rail transport without major infrastructure investments.

To achieve these milestones in the predicted time frame, radical and rapid changes need to be made in the rail industry. According to the findings from the railway symposia, conferences, debates in the railway community, participation in Shift2Rail and EUrail projects and the literature, the most important challenges on the way to the railway system are the following:

- The rail system is very complex [6], comprising a large number of assets and subsystems of different types with varying maintenance needs. These assets are interconnected and interdependent and must work together to ensure that goods and people reach their destinations safely and on time.
- The rail system is dynamic and its behavior in terms of real-time organization and management is complex,
- As the population grows and the need for efficient and effective transport of goods and people increases, so does the importance of reliable and sustainable rail transport. Furthermore, rail transport should be cost and environmentally efficient and effective, while the satisfaction of rail users (passengers or shippers/receivers of transport goods) should be high.
- The rail network is territorially dispersed, the infrastructure and equipment in each area or locality vary in age, quality and functionality, so there is a different need for modernization and maintenance. This makes the management of maintenance very complex.
- Any change in the rail network, infrastructure or other systems means high investment and disruption to normal operations.
- There is an urgent need for the digital transformation of railway systems, which means "synchronization" with the requirements of Industry 4.0. According to [7], digitalization is "an ongoing process of convergence of the physical and virtual worlds" that is responsible for innovation and change in the economy. The concept of Industry 4.0 means the implementation of new information and communication technologies in the industry with the aim of enabling data collection through sensors installed on physical equipment, the storage of this data (usually in clouds) and its analysis, the exchange of information between physical assets and, above all, the possibility of real-time decision-making based on real data from the physical world, thus creating the cyber-physical system. To achieve this, many technologies are available today: artificial intelligence (AI), machine learning (ML), the Internet of Things (IoT), Big Data Analytics (BDA), Blockchain (BC) technology, cloud computing (CC), sixth generation networks (6G), augmented reality (AR), digital twin technology (DT) [8] and others. When combined, they can meet very demanding and high-level stakeholder requirements. In the context of railways, there is a wide range of data on the condition of railway assets (e.g., temperatures, light, vibration, humidity, GPS) [6] and their operational status, which, if collected and processed with the right technology or set of technologies, could bring great benefits to the railway industry. In this way, the concept of Railway 4.0 or Digital Railway, which is a digital transformation or digital technological evolution of railways, can be realized. According to [7], the key areas of railway digitalization are "mobile applications, e-ticketing, digital train control, signaling and traffic management, and digital platforms for predictive maintenance".

Most of the above challenges could be overcome if the railway system was always in good condition. To be in good condition, all railway components and equipment should be properly maintained. Otherwise, various problems may occur that may affect the safety, reliability and stability of railway operations.

To this end, constant monitoring of the condition of infrastructure and operations, detection and prediction of faults and possible failures, testing of new or modified equipment or modification of operating conditions should be carried out with the least possible negative impact on timetables and train safety. All this has a significant impact on rapid maintenance, reliable operation and high performance. Expenditure on railway infrastructure maintenance is made on a regular basis. Figure 1a and [3] and [9] show that some countries (e.g., France, Hungary, Poland) actually spend more on rail infrastructure maintenance than on road infrastructure, while Figure 1b shows that in the majority of countries, the cost of rail infrastructure maintenance is higher or even significantly higher than the investment in rail infrastructure. However,

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[2] https://ec.europa.eu/eurostat/statistics-explained/index.php?title= Railway_freight_transport_statistics#EU_rail_freight_transport_performance _slightly_decreased_in_2022_compared_with_the_previous_year

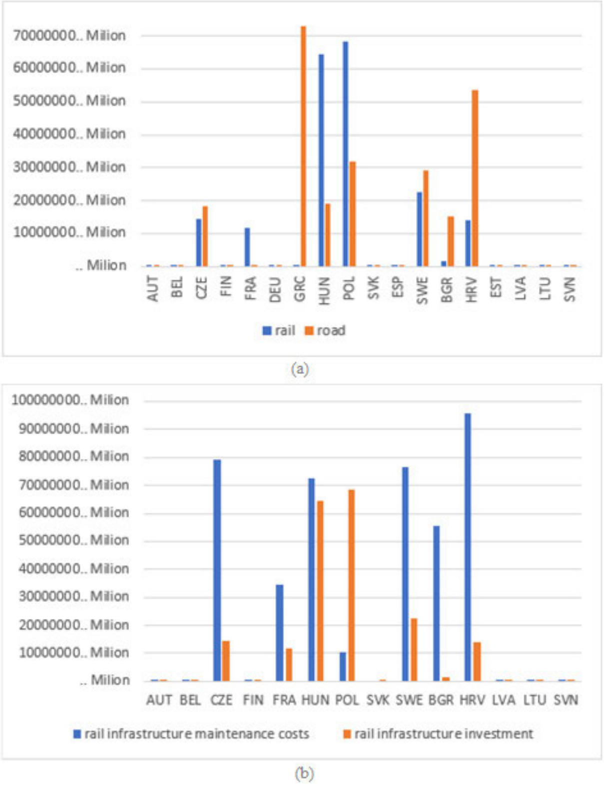


FIGURE 1. **(a) Comparison of investments in road and rail infrastructure (2021). (b) Comparison of rail infrastructure investments and maintenance cost for European countries (2021).**

the fact is that maintenance and fault detection, which are still mostly performed manually today, are among the most critical points in railway systems [8]. This is why they have received and continue to receive so much attention in the scientific literature [10], [11], [12], to name but a few.

In recent years, digital twins (DTs) technology has been highlighted as "the one" promising technology that can significantly improve many rail sector operations and contribute significantly to achieving the goal of Rail 4.0 [13]. The use of DT technology in combination with other disruptive information and communication technologies, in particular artificial intelligence (AI), blockchain technology (BC) and 5G communications [5], could also digitalized asset management and enable the planning of infrastructure and rolling stock use and maintenance activities at the right time [1]. As DTs provide a highly accurate digital copy of the physical asset, process or system [5] that can be observed and tested in the real environment under different conditions, independently of its physical (real) twin and without interrupting ongoing processes, DT can also be of great help in planning, designing, building and manufacturing railway assets, monitoring, detecting and predicting infrastructure faults and failures, as well as proper train operation, real-time scheduling and rescheduling. Another major advantage of DT, highlighted by ERRAC [1] and UNIFE [5], is that DTs technology covers the whole life cycle of assets and enables the tracking of railway assets from design to recycling phase.

TABLE 1. **Cumulative numbers of articles regarding DT, DT in transport and DT in rail transport.**

Database	DT	DT in transport	DT in railway transport
SCOPUS	13659	695	219
TRID	232	146	10
ScienceDirect	2379	100	24
WoS	7615	658	121

Although DT technology is very popular in many industries, it has only recently been applied in the railway sector [14], [15]. From the conclusions of some previous studies [16], [17], DT in the railway sector is mainly focused on infrastructure and traffic management. According to [6] and [18], the larger number of DTs as proprietary solutions and prototypes are mainly realized in the manufacturing and production industry and thus at an early stage.

The popularity of DT technology in the scientific community is evident: to show the increase in publications related to the use of DTs in recent years, regardless of the industry or field of application, we first performed a simple search (without restrictions) in several representative databases using the string ("*digital twin*" OR "*DT*"). The number of publications shows that the interest of the scientific community in the DT technology is very high. We also wanted to show that only a small proportion of these articles deal with the application of DT in transport, and even fewer with rail transport. Therefore, we repeated the search in the same databases with the additional keywords "transport or transportation" and "rail or railway" and included these results in Table 1.

To see the distribution of these publications over the years, Figure 2 was created. Since the number of publications before 2017 was quite small, the time frame shown is limited to 2017 to 2023. It is clear that DT is not a new concept, but its popularity and researchers' interest in this technology have steadily increased after 2017. From Table 1 and Figure 2, it can be seen that the research of DT in rail transport is very recent and has increased by at least 30% in the last 2-3 years.

B. THE DEFINITION OF DIGITAL TWIN

The concept of DT has been extensively studied and described in a large number of articles. Many discussions of various names that appear in the vicinity of DT technology, e.g. digital model, digital shadow, digital mirror, virtual mirror, BIM (building information model), virtual copy, etc., have been presented in [11], [15], [16], [17], [19], [20], and [21], among others. Some detailed descriptions of the architecture and the different types of DT can be found in [22]. A review of definitions of DT can be found in many articles, including [11], [15], [17], [23], [24], [25], and [26] where no less than 46 definitions were systematically reviewed. In [27], the difference between a standard train DT and an augmented one is also given. Different types

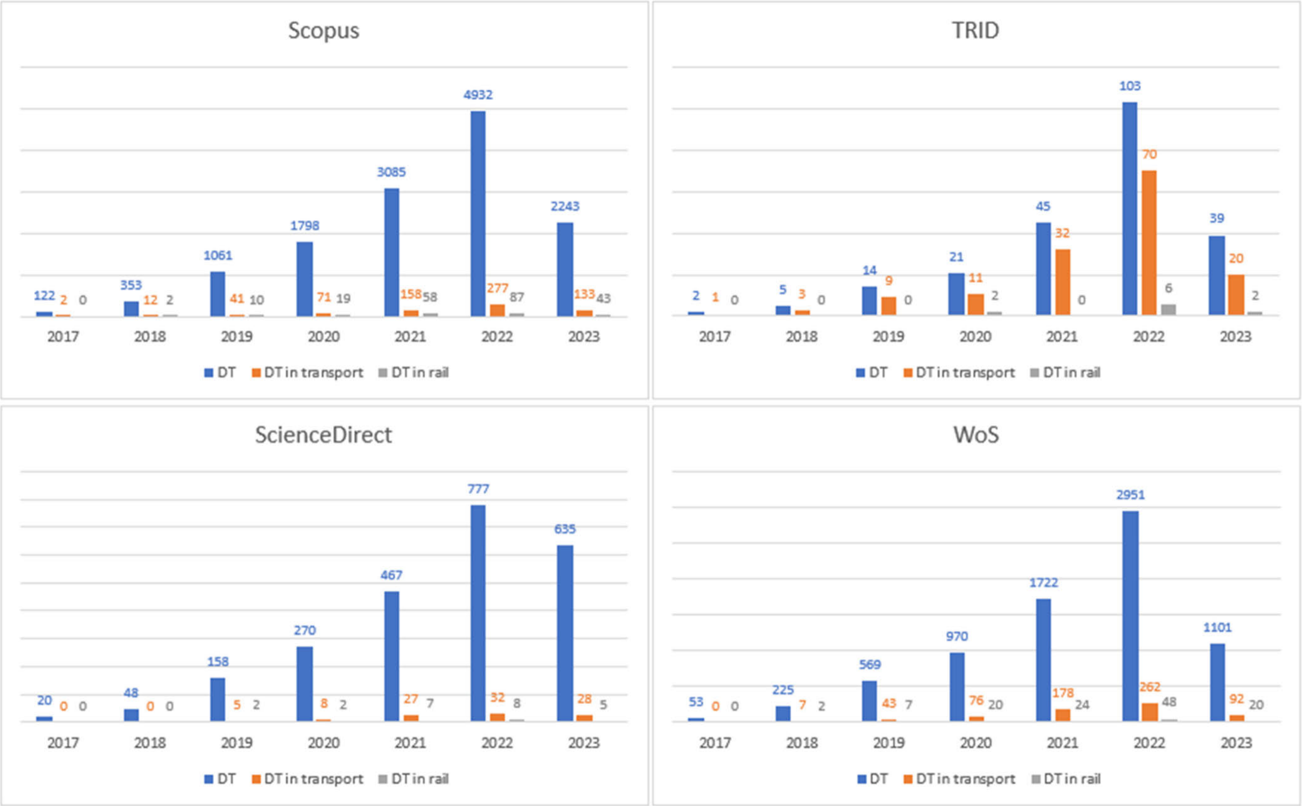


FIGURE 2. **Distribution of publications regarding DT, DT in transport and DT in rail transport.**

of DTs, the structure of DT, the development of DTs, the models used and the milestones of development have also been described in detail by [10], [18], [25], and [28], to name a few.

To understand the classification framework, we have defined for the purposes of this literature review and how the classification and subsequent analysis have been carried out in this review, we present the definition of DT, which we have used as a reference:

A digital twin is a dynamic virtual model or representation of a physical entity (this can be a specific object or system element, a whole system, a network of components or systems, a process, or even a human or group of humans) together with its context that automatically collects raw data from the real environment in real time and processes this data for the purpose for which it was created (i.e., online visualization/simulation of an object or process in real time, making predictions or forecasts, detecting anomalies, assisting in decision making) to improve the performance of or increase knowledge about the physical entity.

C. RELATED REVIEW STUDIES

At the time of writing, our literature search found no previous systematic literature review on the use of DT in rail transport that had been published as a journal article. The article that came closest to this topic is a review article [29], in which the authors aimed to present the current extent of DT deployment in rail and road networks, but focusing only on rail and road infrastructure (i.e., immovable assets on road and rail) and the resilience and sustainability of road and rail infrastructure. This systematic literature review was conducted using 20 journal articles found in the Scopus database and published up to November 2021. They concluded that 46% of the studies reviewed were in the field of engineering and information technology and that only 32% of all studies were related to rail transport. Finally, they found that most studies focus on the use of DT in the operation and maintenance phase and that due to the growing trend of DT, more studies can be expected in the rail and road transport sector as well. The scope of other review articles is much narrower. McDonald et al. [30] gave an overview of developments in 3D visualization of underground inspection of railway tunnels for maintenance purposes, mentioning only the potential of Digital Twin Tunnel (DTT) BIMs as a means for two-way information exchange available at any time, where changes in the physical tunnel led to changes in the digital tunnel providing information for future maintenance. Spiryagin et al. [17] review the application of vehicle system dynamics theories that could serve as a basis for the development of DT. They concluded that most work examines the developments of DT "at the top of the pyramid" and therefore more comprehensive and in-depth research is needed in the application of vehicle system dynamics in the processes of design and construction of DT. Feng et al. [31] investigated the application of DT in intelligent transport systems (ITS) with the aim of exploring the role of DT resilience in the applicability of ITS. They found that current research on DT technology has varying degrees of success in different aspects of ITS and that the system performance of DT should be optimized. They also concluded that the data exchange between vehicles and infrastructure in the transport network can be solved well if blockchain technology is integrated with DT. They confirm the assumption that the improved resilience of DT has an impact on the adaptability of the transport system. Errandonea et al. [32] conducted a literature review on DT for maintenance in general, which is one of the most researched applications of DT. Of the 167 studies found (articles, conference papers and other publications), only 68 were relevant as they investigated the use of DT in maintenance. The railway sector was only studied in two cases, while the leading sector was manufacturing with 29 cases.

In our backward snowballing process, we came across the project [33] in which a systematic literature review of all publications published in English between 2000 and 2022 was conducted with the aim of producing a "guideline to support the design of a DT for predictive maintenance in the railway sector". This review examined and classified 60 publications mentioning challenges, open issues or future opportunities and dealing with predictive maintenance in the railway sector, including the railway manufacturing process. First, they were classified into 8 subsectors of the railway sector based on the classification of [34] and it was found that of all the subsectors, maintenance and inspection were covered in the most publications. The second classification was made according to which of the DT enabling technologies were discussed, and it was found that in most publications more than one technology was discussed and that artificial intelligence (AI) was most often discussed (in 25 out of 60 publications) in combination with other technologies. The third classification made by [33] was to sort these 25 "AI" publications into 8 subcategories, of which machine learning algorithms and techniques were most frequently used in the development of DTs, mainly for fault detection, failure prediction, automated decision making and health monitoring. Dirnfeld [33] also concluded that only half of the publications studied discussed challenges, open questions and future opportunities. In the end, the guideline to support the design of a DT for predictive maintenance was created in the form of a flowchart.

While our article was under review, the survey by Ghaboura et al. [35] was published, which focused on clarifying "how DT can serve the railway twin system designers and developers" by presenting a taxonomy for them and giving a rough and detailed overview of the emerging technologies and techniques used for the application in the rail sector. This survey was conducted on 80 articles (45% of these were conference papers, book chapters and books, and 55% journal articles, of which only two were published in 2023) found in the Scopus and WoS databases and published between 2018 and January 2023 (including 31 that are also included in our systematic review). The survey can be seen as complementary to our literature review (or vice versa) and both are a good basis for future upgrade.

D. RESEARCH AIMS AND CONTRIBUTIONS

The aim of this study is not to provide an overview of the general concept of DT, descriptions of the development process, models and key technologies used for the development of DT and an overview of the industrial applications of DT, but to provide a comprehensive and overarching overview of the popularity of the development of DT for the railway sector in the research community in terms of the number of publications, the railway domains and the DT purposes that have attracted the most attention so far. The novelty of this paper lies in the completely new and unique scheme of an overview of the perspective of DT development in the railway sector. Moreover, the novelty of the paper reflects the finding that DTs have been developed mainly for railway infrastructure so far. Furthermore, the novelty in the research brings additional knowledge to the research community. DTs have so far mainly been developed using simulations and prediction tools. The aims and main contributions of this systematic literature review are therefore to

- assess the extent to which the technology of DT has influenced scientific publications in the field of rail transport so far;
- provide a comprehensive classification framework that allows a deep insight into the role of DT in rail transport;
- collect information on already realized implementations of DT in rail transport;
- identify current research gaps (i.e., aspects of rail transport that have not yet been studied from the perspective of DT and concepts related to the development of DT that could be (re)used in another area of rail transport or beyond);
- find the most promising trends and opportunities for future research.

The results and conclusions in the form of an overview of realized implementations of DTs and existing gaps as well as possible future research directions gained from this review can be used by both the research communities and practitioners involved in rail transport to take advantage of the promising technology of DT when it comes to improving the rail system and promoting the digital transformation of railways.

E. ARTICLE STRUCTURE

The article is structured as follows: Section II is devoted to the presentation of the research questions, the search process and the newly defined classification scheme and classification criteria for the classification of the reviewed studies. Section III contains the analyses of the articles reviewed in relation to the classification used and the presentation of the correlations between each classifier or aspect, highlighting the most important ones. Section IV is devoted to concluding reflections and a summary of possible future research areas and directions.

II. RESEARCH METHODOLOGY

The entire research process described in this article comprises four main steps. In the first step, the research questions and the scope of the literature review were defined. In the second step, the search was conducted, while in the third step the classification criteria were established and the articles were classified according to these criteria. Finally, the analysis of the search results was conducted and research gaps were identified.

A. RESEARCH QUESTIONS

The research questions that have guided all the research in this work are in line with the main objectives of this review (see 1.4) and are as follows:

RQ1: What is the state of the art of DT technology in the rail industry?

RQ2: In which domains of railway systems have DTs been developed most frequently and which domains offer the greatest scope for future developments of DT?

RQ3: What are the most common uses of the developed DT?

B. LITERATURE REVIEW APPROACH

In order to conduct a general (i.e., overarching) and comprehensive literature review, we systematically searched the literature using the PRISMA approach [36]. The main reason why we chose this approach is that the PRISMA model can help researchers to write a literature review. In practice, this model can help to find numerous answers to the research questions. Moreover, it can be used to find new aspects in the respective research topics, and it can be further expanded depending on how many more references are added to each criterion, or the criteria can be divided into some sub-criteria. The entire search process is illustrated in Figure 3.

In the identification phase, we first **established the inclusion or eligibility criteria** in relation to the research objectives and questions. We decided on four general inclusion criteria and one specific inclusion criterion. The general inclusion criteria are the requirements that the article (1) is about a development of DT in railways; (2) has already been published or accepted for publication in a scientific journal (i.e., has already been peer-reviewed); (2) is freely in full text (i.e., open access); and (4) is written in English. A specific inclusion criterion was the requirement that both keywords "digital twin" and "rail" appear at least once in the text of the article and not only in the abstract, title or keyword. There were no restrictions on the year of publication, the source of the publication, the number of citations or other criteria. Then we made the **selection of databases**. Four of the most reliable databases with sufficient coverage were selected, which were then searched in the following order: Scopus (the "broader" one), TRID (the specific database for transport), ScienceDirect and WoS (the last two were included to check if any relevant article was missed in the first two searches). We started by **formulating the search queries**. Since the selected databases use different search engines, two different search strings were formulated. For the search in Scopus and TRID we used (("*digital twin**" OR *DT*) AND *rail**), and for ScienceDirect and WoS the string (("*digital twin*" or *DT*) and (*rail* or *railroad* or *railway*)) was used. With these strings, the **database searches were carried out** in 4 iterations (first Scopus was searched, then TRID and ScienceDirect, finally WoS). At the end of the 4 iterations, 125 articles were selected for screening (see Table 2).

TABLE 2. Search results in the identification stage.

Database	Without limitations	With limitations
SCOPUS	405	73
TRID	265	39
ScienceDirect	34	9
WoS	167	4
Total	871	125

In the screening phase of each iteration, we **first read titles, abstracts and keywords**. Since we used the EndNote library for a collection of selected articles, we removed duplicates after each iteration. At the end of the screening phase, we had 78 articles. In the eligibility phase, we first **checked** whether **the specific inclusion criterion** was met and then **read** the remaining 68 **articles in full text**. During the reading, data were extracted for each article (year of publication, scope/aim of the article, purpose of a DT, scope of DT, railway aspect studied, rail assets considered and other details). **Backward snowballing** was applied to the remaining 52 articles.

Ten new articles were found and steps 2 to 5 were repeated for these articles (see Figure 3).

After the snowballing, 5 of these articles were included in the final group of articles for **classification**. Based on the data collected, the classification categories and criteria or categories were first established (see 2.3) and then the articles were classified. Data collection began on 2 May 2023 and classification ended on 28 June 2023, on which day an **additional search cycle** was conducted to take into account articles that had been published in the meantime before the analyses began. From two articles found, one more was added, so that the final number of articles for the analysis was 58.

The identification phase was carried out jointly by both authors, while the other steps were first carried out by one author and then repeated by another. Any disagreements or differences were discussed immediately and consensus was reached before proceeding.

C. CLASSIFICATION CRITERIA

The articles studied are classified according to a new classification that we have created for the purposes of this literature review. We have selected five different representative criteria or classifiers that allow us to roughly assess the state of DT

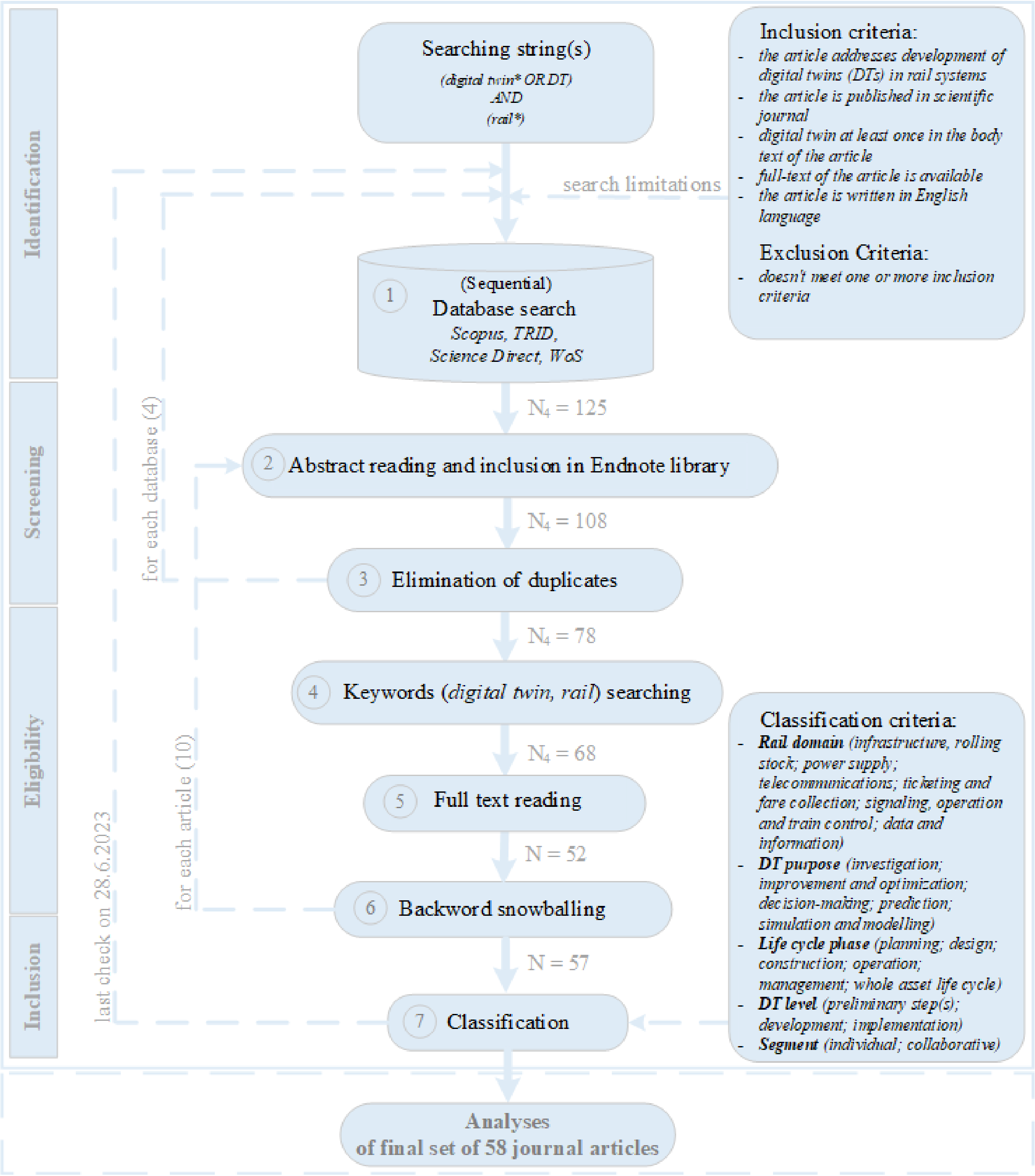


FIGURE 3. PRISMA diagram for searching process.

development in rail transport up to June 2023 that has been published in scientific journals and to provide an insight into research gaps that could or should be filled by future research. The selected classifiers - rail domain, DT purpose, asset life cycle phase, DT development phase and DT segment - are described in detail in the following subsections.

In the "DT railway literature" some classifications and categorizations have already been used for the purpose of the literature review. For example, in [34] a division of the railway system into seven main areas is used (i.e., maintenance and inspection, safety, planning, management and policy, passenger services, optimization and monitoring). This division was also used by [33] who provided an overview of DT in the railway system with a focus on predictive maintenance. In [11], DT was investigated in the field of maintenance and for this purpose the authors divided the applications of DT into five groups, namely maintenance, PHM (Prognostic Health Management), life cycle optimization, process/logistics/production and design. Broo and Schooling [10] stated that the full life cycle of assets includes all activities from identifying the need, planning and designing to construction, operation, integration and maintenance.

In [29], where the focus of the study was on immovable assets in road and rail transport, sectors such as buildings, transport, general, energy and telecommunications were used for classification. In all cases, the categories were defined based on the literature review, while our classification is based on the composition and characteristics of the railway system on the one hand, and on the characteristics of DTs and their development on the other.

1) RAIL DOMAIN

In creating the new classification, we have assumed that the railway domain or subdomain or area or subsystem is a set of related ‘‘elements’’ or ‘‘components’’ of the railway system to which the ‘‘twinned’’ component belongs, while the description of the scope of DT for this component falls into the category DT purpose, and the phase of the life cycle of the component for which DT is used falls into the category Life cycle phase.

We therefore assume that the main railway areas or domains are as follows: **infrastructure**, including track infrastructure (track, rail sleepers and ties, ballast, rail joints, level crossings) and infrastructure facilities (including bridges, viaducts, tunnels, stations, maintenance and repair facilities); **rolling stock** (locomotives, passenger and freight wagons and special vehicles); **power supply** (power distribution system, overhead lines, third rails and transformers that supplying power to trains); **telecommunications** (communication devices and media for data and information transmission); **ticketing and fare collection** (vending machines, ticket offices and systems for collecting fares from passengers); **signaling, operation and train control** (signaling systems, signals, track circuits and other equipment providing information to train operators and controlling train movements, control or dispatch centers); **data and information** (databases and data management applications); system as a whole.

All these components make up the railway system. They work together to create a functioning railway base that supports the safe and efficient operation of trains.

2) DT PURPOSE

DT purpose describes the reason for which a particular DT is used, or the scope of a particular DT, or even what activities a particular DT supports. In order to cover the widest possible range of possible uses in rail transport, we have divided the purposes into five groups as follows: **investigation** (real-time monitoring, inspection, diagnosis, measurement, detection, evaluation); **improvement and optimization** (optimizing safety, operations, efficiency, asset management, resilience, sustainability, maintenance, life cycle or a combination of these aspects); **decision-making** (analytical processes); **prediction** (analytical processes involving machine learning and artificial intelligence algorithms); **simulation and modelling**.

3) LIFE CYCLE PHASE

Each specific DT also has a scope covering the life cycle phase (LC) or stage of the railway asset under consideration. The phases introduced describe for which stage of the rail asset a DT has been developed or in which stage it has the greatest impact or its benefits are greatest. DTs can support all the initial phases of asset development, i.e., planning, design and construction, their main phase, i.e., operation, assist in decision-making regarding upgrades, replacements and capacity expansions, and their decline at the end of their life cycle. To this end, we address the following seven possible phases: **planning** (development of goals and tasks); **design** (conception and definition of the asset, identification of requirements); **construction** (manufacturing or fabrication, building, construction, testing of the asset and its connections with the environment); **operation** (function or use of the asset); maintenance (repair and remove of faults or damages, reconstruction or replacement of components and upgrading of systems); **management** (asset, operations management or maintenance management and all supporting activities); **whole asset LC**.

4) DT LEVEL

To assess the maturity of the development of DT, we introduced a four-point scale with the following categories: exploratory (only an idea or a study of the realization possibilities with the concept of DT); **preliminary step(s)** (some modelling and simulation activities that can be further developed into DT have already been carried out, usually also tested in a real use case); **development** (DT is fully developed and validated against a test data set); **implementation** (developed DT is validated by use in a real use case).

5) SEGMENT

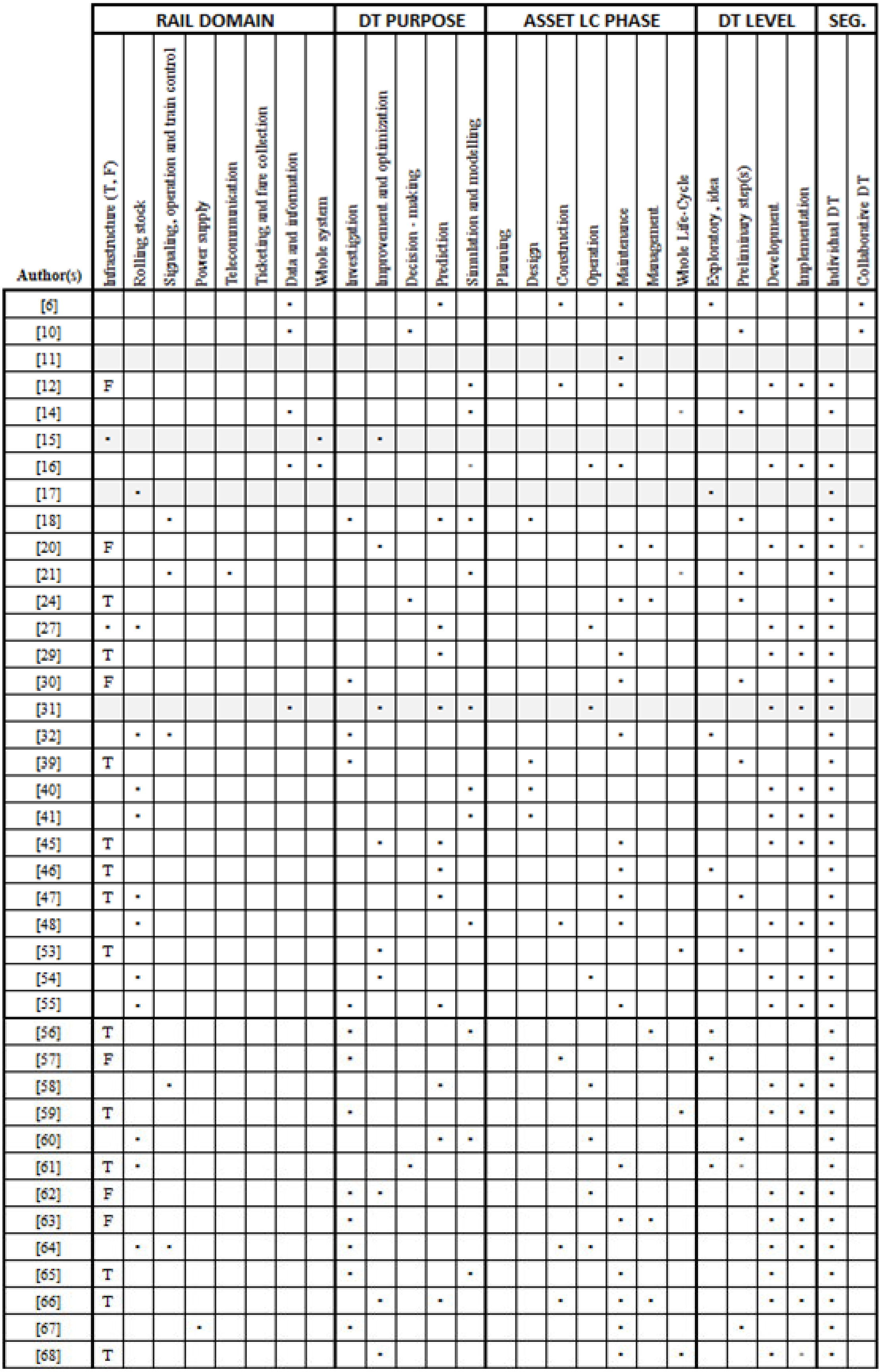
As a final classifier, we have used the description of the segment or part of the rail system covered by DT. Thus, DT can either be **individual**, meaning that only one aspect or component is ‘‘twinned’’, or **collaborative**, meaning that the integration of two or more individual DT is set up or discussed.

III. CURRENT RESEARCH ON DIGITAL TWIN IN RAILWAY TRANSPORT - ANALYSIS OF LITERATURE

In the spirit of a comprehensive and overarching literature review (the summary of reviewed studies is presented in Figure 4), we first conducted some basic analyses, followed by the critical analysis of the classification results and concluded with the presentation of the most important correlations between classifiers from different categories.

A. BASIC ANALYSES

Figure 5 shows that most articles examine the infrastructure aspect of the railway system. Investigation is the fundamental



	RAIL DOMAIN								DT PURPOSE					ASSET LC PHASE							DT LEVEL				SEG.	
Author(s)	Infrastructure (T, F)	Rolling stock	Signaling, operation and train control	Power supply	Telecommunication	Ticketing and fare collection	Data and information	Whole system	Investigation	Improvement and optimization	Decision - making	Prediction	Simulation and modelling	Planning	Design	Construction	Operation	Maintenance	Management	Whole Life-Cycle	Exploratory, idea	Preliminary step(s)	Development	Implementation	Individual DT	Collaborative DT
[6]							•					•				•		•			•					•
[10]							•				•											•				•
[11]																		•								
[12]	F												•			•		•					•	•	•	
[14]							•						•							•		•			•	
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[16]							•	•					•				•	•					•	•	•	
[17]		•																			•				•	
[18]			•						•			•	•		•							•			•	
[20]	F									•								•	•				•	•	•	•
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[24]	T										•							•	•			•			•	
[27]	•	•										•					•						•	•	•	
[29]	T											•						•					•	•	•	
[30]	F								•									•				•			•	
[31]							•			•		•	•				•						•	•	•	
[32]		•	•						•									•			•				•	
[39]	T								•						•							•			•	
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[45]	T									•		•						•					•	•	•	
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[53]	T									•										•		•			•	
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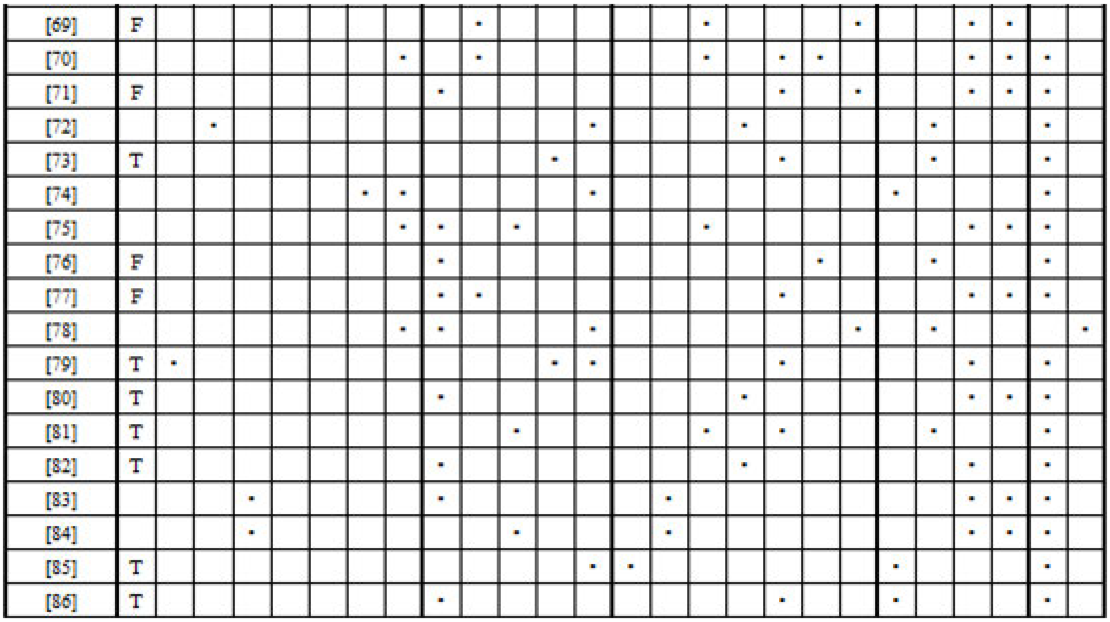
[68]	T									•								•		•			•	•	•	

FIGURE 4. Classification of articles studied.



[69]	F									•						•				•			•	•		
[70]								•		•						•		•	•				•	•	•	
[71]	F								•									•		•			•	•	•	
[72]			•										•				•					•			•	
[73]	T											•						•				•			•	
[74]							•	•					•								•				•	
[75]								•	•		•					•							•	•	•	
[76]	F								•										•			•			•	
[77]	F								•	•								•					•	•	•	
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[85]	T												•	•							•				•	
[86]	T								•									•			•				•	

Legend: T – track infrastructure; F – infrastructure facilities; • - totally fall in the observed element; • - only partially fall in the observed element; grey fill – review article

FIGURE 4. ***(Continued.)*** **Classification of articles studied.**

activity in maintenance, which of course was most often highlighted as the phase that will benefit most from a DT. Half of all DT presented were actually developed and most of them were validated in a real railway use case. Almost all articles presented the development of an individual DT.

Figure 6 shows the number of publications per year for the rail domain and the categories with the highest number of studies. Figure 6a shows the large difference between 2020 and 2021, indicating that DT in rail transport has only recently become a popular research topic. As this overview only includes articles published in the first half of 2023, it can be assumed that the number will be highest at the end of 2023 compared to the other years. DT publications from DT in the field of rail infrastructure follow the increasing trend of all publications, while publications from in the field of rolling stock are constant over the last two and a half years (see Figure 6b).

B. ANALYSES OF CLASSIFICATION RESULTS

In the last year and a half, the number of studies in the areas of investigation, simulation and modelling has decreased, with a slight decrease in the number of studies in the area of investigation. As for maintenance and development, Figures 6d and 6e show an increase over the years. Finally, Figure 6f shows the number of studies dealing with the integration of different DTs into collaborative DTs, which has only recently become of interest to the research community.

1) RAIL DOMAIN

Railway **infrastructure** consists mainly of static physical components and includes all components from the overhead line to the track bed [37]. However, there are also components that can change their position, such as turnouts, switching points and level crossings. Therefore, the behavior of such infrastructure components can be considered as static or dynamic components [38]. Based on the definition of DT, it can be developed to mimic a physical component or system. However, even though there are static and movable infrastructure components, the results of the review show that the developed DTs mainly refer to static components such as tracks and rails and infrastructure facilities (see Figure 7). Furthermore, the developed DTs mainly refer to the third part, which is generally used for the purpose of their condition assessment. For the same purposes, DTs have also been developed for turnouts, the only studied case of dynamic components [39]. Nevertheless, it should be noted that DT has not been developed to plan and schedule maintenance and monitor real-time operation of movable infrastructure components such as switching points, level crossings and yard braking systems (i.e., retarders). Furthermore, our review did not find DT capable of monitoring, for example, the transmission of electrical power and the stability of the catenary network.

Figure 8b again shows that DTs for the **rolling stock** domain were developed mainly to monitoring states, conditions and damage to vehicles and locomotives and some of their parts. As for behavior, Sun et al. [40] developed DT to evaluate the stability of the vehicle. However, the behavior of other movable components of vehicles such as bogies, axles and couplers and their impact on the environment and society were not found. The important aspect of rolling stock is fleet planning to minimize vehicle usage and empty kilometers for which DTs are missing as well. A locomotive can be further divided into different components. However, DT does not exist for individual components of the locomotive from the pantograph to the power axles [41]. Furthermore, there are no DT models to monitor and improve of energy consumption or emission production of diesel locomotives as well as noise.

Some studies were found in the domain of **railway signaling** (see Figure 8c). However, these studies dealt with the DT for European Traffic Management Systems (ERTMS). A signaling system with all connected components operating in a synchronized manner [42] presents a unique opportunity for the development of individual or cooperative DT. Such DTs can improve and optimize train operations and real-time decisions on train movement authority especially for advanced signaling concepts such as moving block, virtual coupling and driverless trains. Only a small amount of work was found that relates to the **control of train operations**. DTs for these purposes are useful as they can facilitate the decision-making of traffic management systems. In addition, DTs in this domain can help predict failures based on past experience and provide appropriate solutions in a timely manner. Moreover, DTs can simultaneously improve real-time capacity and reduce delays without compromising service safety and stability [43].

Figure 8d shows some studies that have been conducted in the context of **power supply**. The studies have developed models for the design and maintenance of the power system. It can be concluded that there is a lack of DTs to simulate and optimize the power distribution in the network and the use by the locomotive using DT models.

Only the article by Kochan [21], which develops a DT for ETCS, classified and described under the signaling, operation and train control, falls under **telecommunications**, while no article deals with the domain of **ticketing and fare collection**.

The **exchange of data and information** has been an essential part of railway operations since the early days of the railway and is the most important component of railway operations today. Some of the studies shown in Figure 8e were concerned with the development of DTs for the exchange, storage and management of data. This is particularly important for railways, a well-known transport system with the worst data assets. Collecting and sorting data is crucial for all components to ensure smooth railway operations. Nevertheless, the representation of data sharing through DT would be useful for the purposes, especially between physical and movable rail components and within the physical and movable components themselves [44].

In addition to the studies that looked at DT for specific components or purposes, there are also studies that provide DT initiative for the **entire railway system** (Figure 8f). From the perspective of the whole system, DT is more useful than a separate system as it incorporates data from different sources and also historical data to reflect the real-time state and behavior of the railway assets. In addition, DT provides synchronization of the many properties and behaviors of each real object for the whole system.

2) DT PURPOSE

Looking at the results of the review, the purpose of the **investigation** in DT studies can be divided into two groups. In the first group of papers, the use of the DT model was investigated, while in the second group, different models or approaches to investigation make up the part of the DT system. In both cases, the investigation is mainly related to the maintenance of tracks, rails and/or wheels. This DT purpose is related to maintenance, as good maintenance and fault analysis are prerequisites for safe and proper railway operation.

For **improvement and optimization**, only one DT was developed, which focuses on movable components such as turnouts.

The aim of railway digitalization and automation is to reduce the workload and improve the working environment. For example, digital automatic coupling (DAC) is being introduced in rail freight to reduce the number of work accidents. Therefore, DT has been proposed for improving the working environment, the environment for passengers in a railway coach, for the construction, maintenance and structural health monitoring and condition assessment of infrastructure assets. However, almost all studies focused on the perspectives of maintenance and construction. Few or no studies dealt with railway components to improve or optimize the real-time operation of trains. With the introduction of new signaling concepts, optimizing the location and arrangement of balises is the crucial issue to be addressed.

Only one study was found on this, while communication between vehicles, trains and infrastructure facilities has not yet been researched.

Preliminary steps to develop DT or to fully develop DT have been presented for the purpose of **decision-making**. Decision-making is an important aspect for all railway phases from construction to operation, i.e., for the whole life cycle. Among the results of this study are asset management, decisions related to manufacturing and design, and necessary investigations and maintenance. Apart from the DTs for the above decisions, no real-time decision support was found for train rescheduling, rolling stock management on the network, train movement authority or other decisions related to real-time operation.

With the aim of creating appropriate strategies in planning and management, **predictions** are the basis. Therefore, DTs have also been developed for forecasting purposes in the railway sector. Similar to the previous purposes, DTs for prediction were mainly concerned with maintenance issues, more specifically prediction of surface damage to rails, maintenance of switching points, derailment risks and prediction of wheel and rail life. In addition, DT was developed for predicting the thermal performance of electric motors. Although maintenance is one of the most common topics, the development of DTs to predict damage that can cause high expenditure and loss of life has been omitted. These damages can be related not only to the damage of rails, but

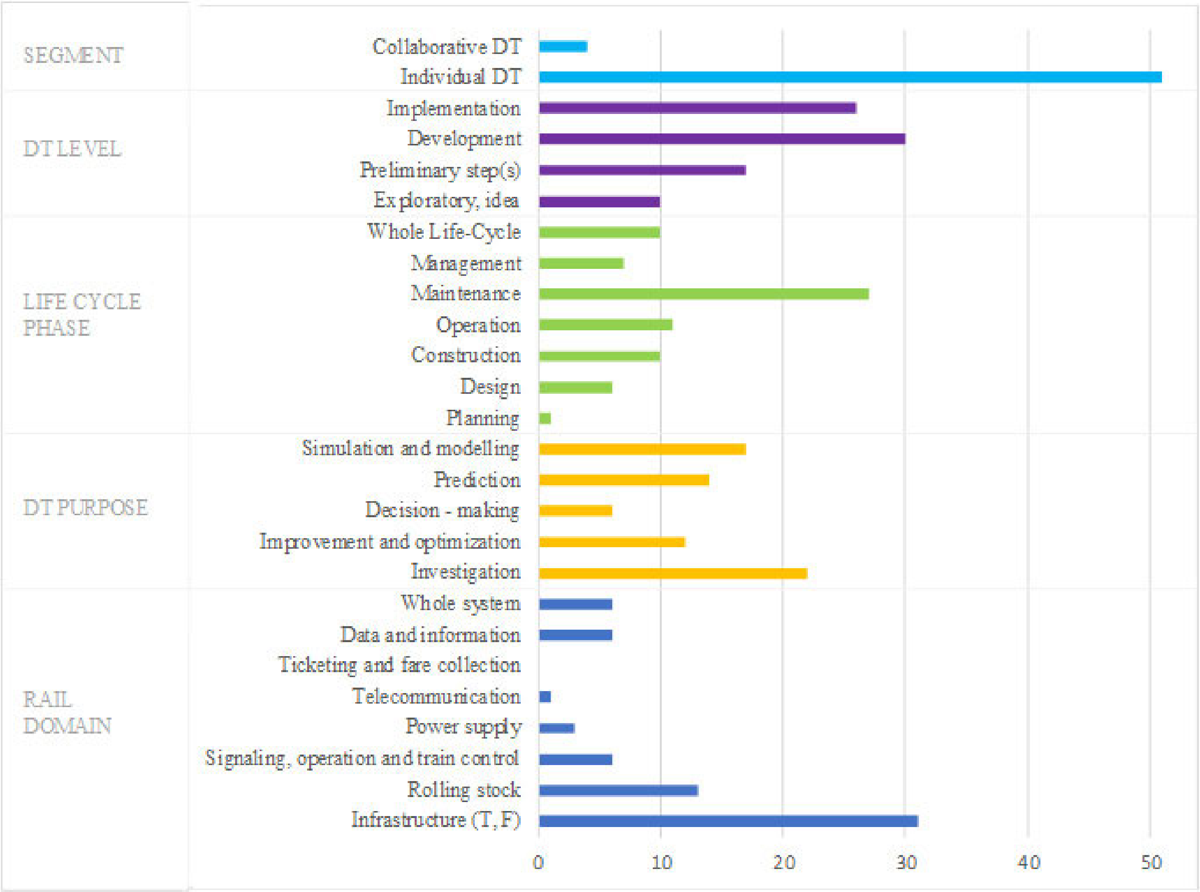

FIGURE 5. Coverage of classifiers and categories.

FIGURE 6. Distribution of publications by years (a) of DT in rail; (b) of DT in rail infrastructure and rolling stock; (c) of DT for the investigation and simulation and modeling in rail; (d) of DT for rail maintenance; (e) of developed rail DT; (f) of collaborative DT for rail.

also to the damage of axles, the heart of switching points or other rail elements, passing the red signal, etc. In addition, no train delay prediction models were found at DT, which may affect service quality and are related to decision making.

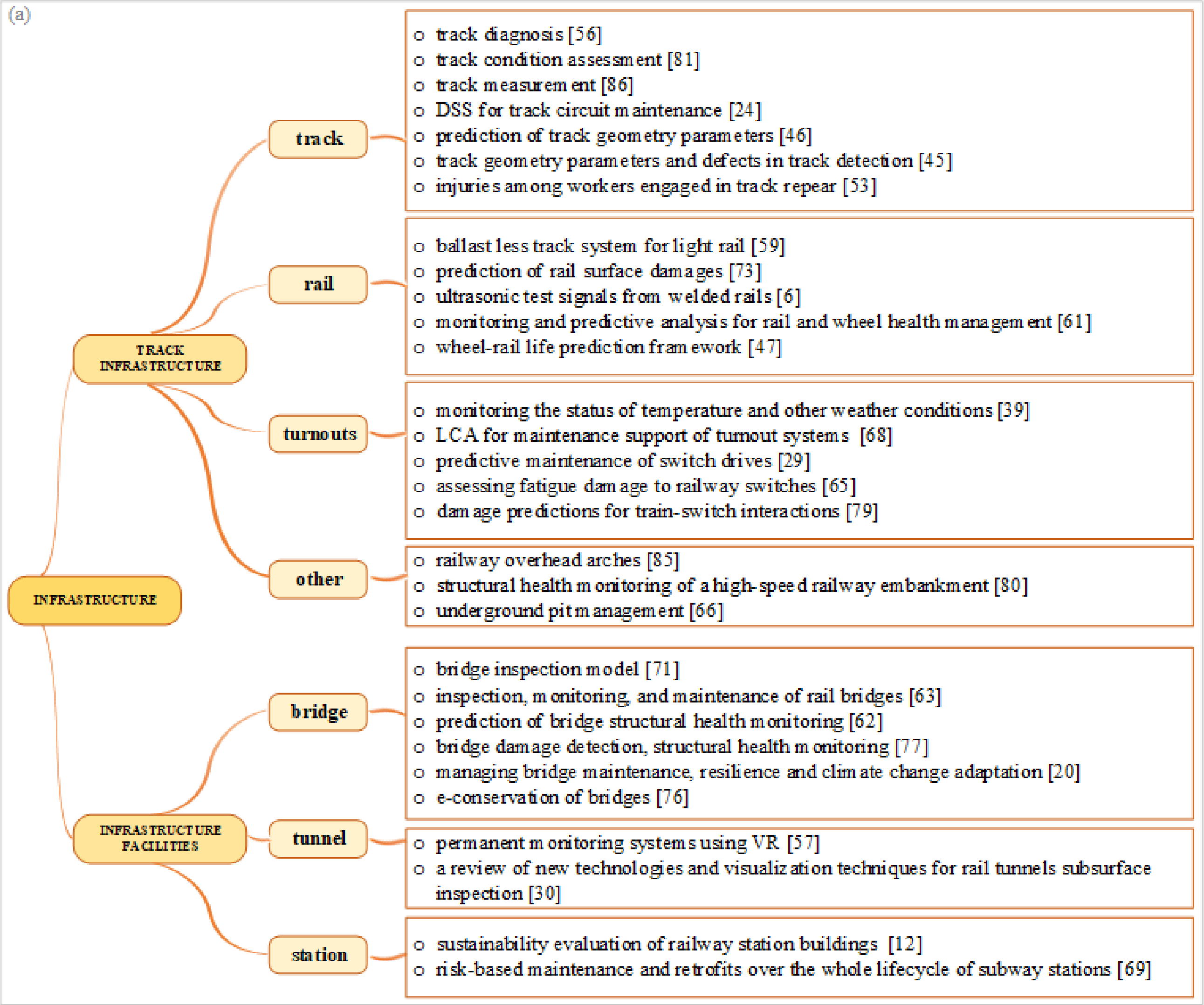

FIGURE 7. Detailed classification of overviewed studies – Part I (Infrastructure).

DTs for predictive purposes can be useful to detect incidents, human and technical failures and errors that can lead to earlier damage in railway systems.

Simulation and modelling are used as a central part of the development of DT or to investigate the feasibility of DT. In the railway sector, simulation is a common approach to explore new concepts or possibilities.

Nevertheless, simulation and modelling are used to explore DT application and validation. Mainly simulation and modelling in DTs were developed for earlier purposes. For example, simulation in DTs has been used to investigate fatigue damage, semantic segmentation tasks, track diagnosis, optimization of the electrical side of medium voltage lines DC and to decide on control equipment in ERTMS. However, simulations are also used in the railway sector when there is a lack of data. Therefore, the question arises why the development of DT for this purpose is limited, although the automation and digitalization of rail transport is a hot topic in the last decade. Modelling in DTs has been used to improve the relationship between rail traffic characteristics, to support the design model for locomotives and to improve the safety and stability of wagons.

3) DT LEVEL

The results of the review have shown that different levels of DT development have been achieved. Some studies only discussed the possibility of DT for certain rail sections and/or components, while there are also studies that initiated pilot studies of DTs. In most of these cases, DTs were not built due to the lack of data and information. From the results, it appears that most DTs were also developed and implemented in a real case.

4) ASSET LIFECYCLE

Maintenance, “a complex and complicated task in the rail industry” [45] and beyond, is a life cycle phase that can incur huge costs, take up a lot of time, disrupt normal operations and, as mentioned in [46], affect safety and passenger

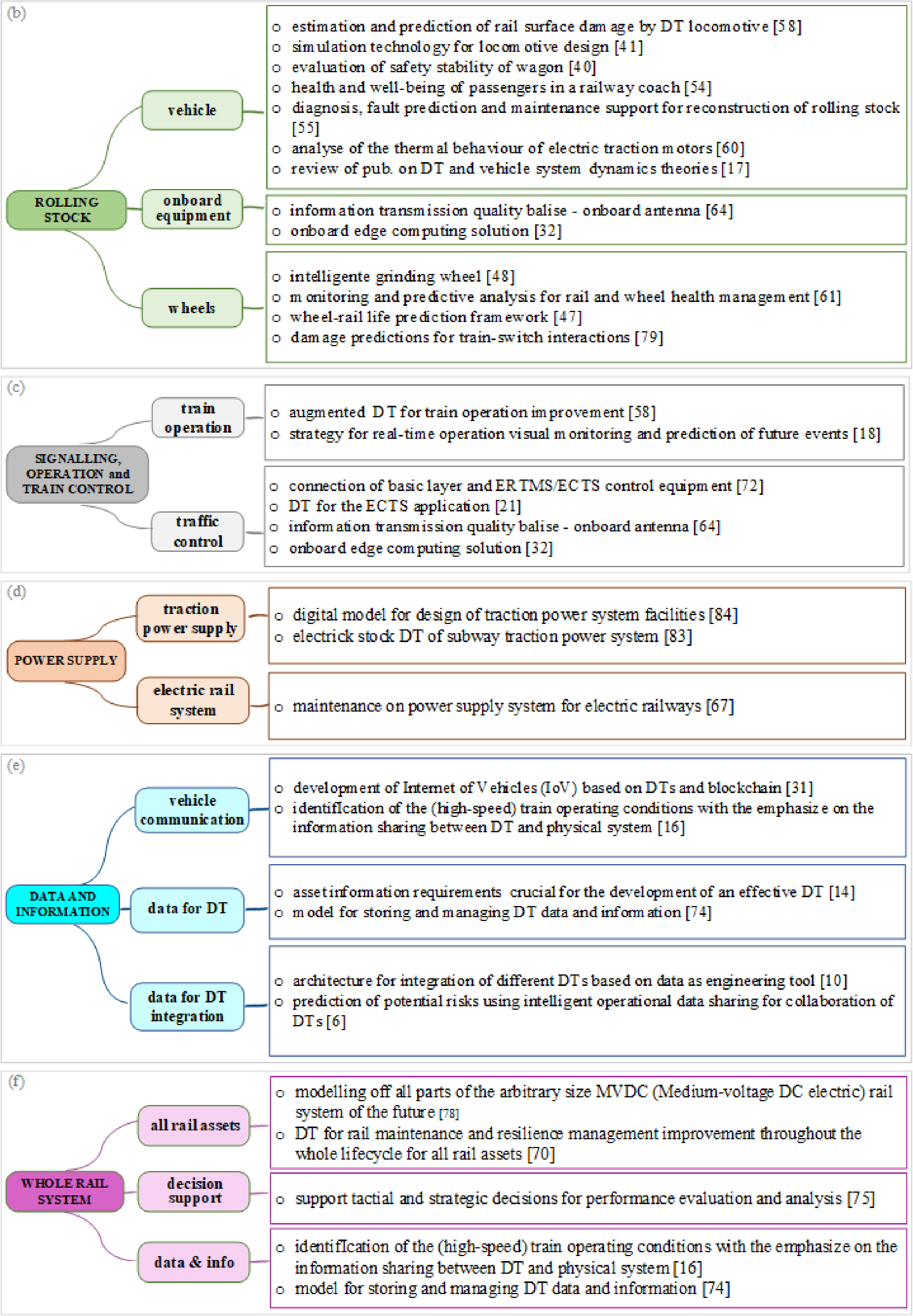

FIGURE 8. Detailed classification of overviewed studies – Part II (other domains).

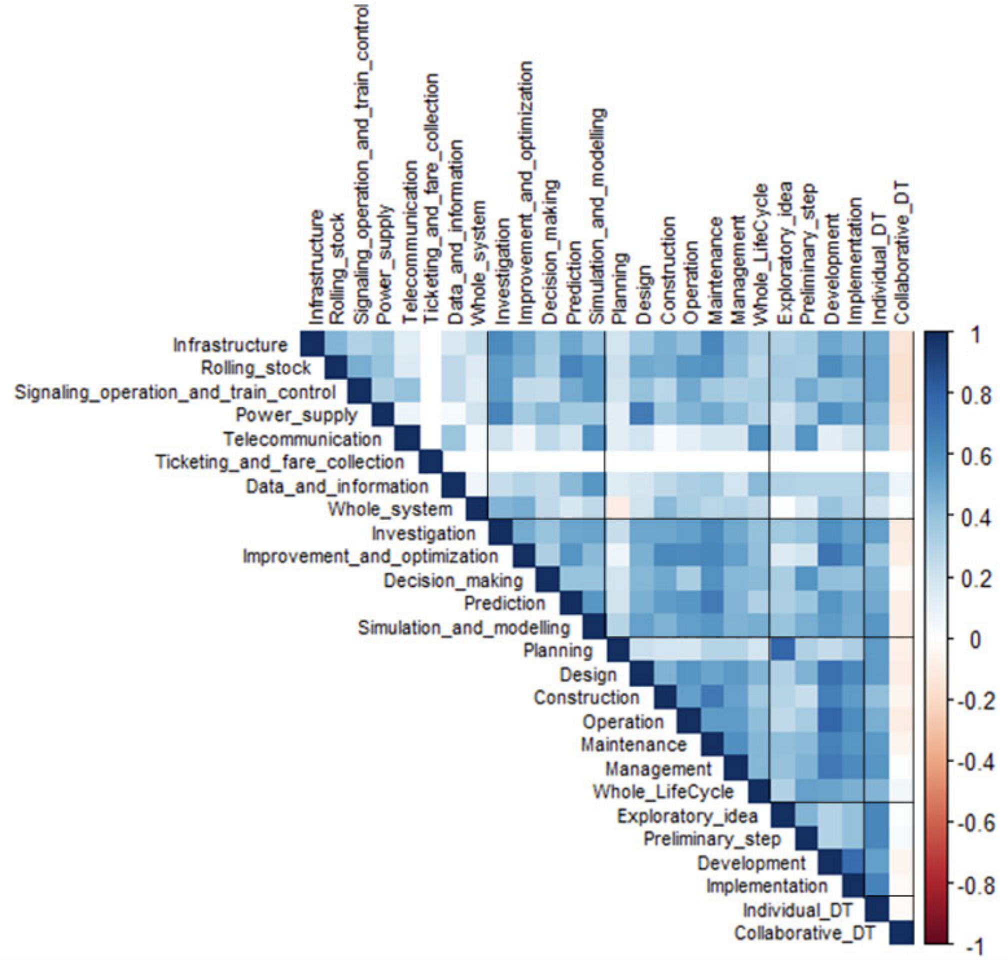

FIGURE 9. Correlations between categories and classifiers.

comfort. The negative impact can be even greater if maintenance is not supported by timely management of spare parts or the tools and machinery required for maintenance. As outlined in [11], [47], and [48], among others, it is important to take advantage of digital technology that enables the transition from traditional, mostly manual maintenance that occurs after a failure, to condition-based maintenance that is demand-driven depending on the condition or state of the asset, and to predictive and preventive maintenance. The latter two are based on predictions and anticipation of future conditions based on continuous monitoring and diagnosis. If until today DTs have mainly focused on supporting the design or manufacture of railway assets and condition-based maintenance by monitoring and inspecting the current state [10], [11], [12], today we are moving to a higher level of maintenance and operations by combining data analytics with machine learning and artificial intelligence to support the whole life cycle of railway assets, which is also confirmed by the above analyses of the reviewed publications.

5) SEGMENT

A digital twin of a system such as a railway system is only possible if individual, specific DTs are first developed that ‘‘simulate’’ the basic units or assets of the railway system and connect them with data and information flows in such a way that they form a ‘‘whole’’. For such a system, [18] have used the term ‘‘supra-system’’ and emphasized that its realization requires an ‘‘open and comprehensive networked platform’’, which in turn means that it enables the avoidance of data silos and the integration of additional services from which all stakeholders can benefit. The importance of such collaborative DTs is also highlighted by [49], who states that by 2027, more than 40% of large organizations worldwide will use a combination of Web3, spatial computing and digital twins in metaverse-based projects to increase revenue, where metaverse means a combination of multiple technologies that corresponds to DT technology and the concept of Industry 4.0, especially that of tomorrow.

C. CORRELATION BETWEEN CLASSIFIERS

Figure 9 shows the correlations between the categories of the classifiers used for this report. The graph was created using the *corrrplot* function, which plots a matrix of Pearson correlation coefficients calculated using the *cor* function, both in R. The strength of the correlation between the variables (i.e., the categories) is shown with the intensity of blue (i.e., for positive values) and orange (i.e., for negative values), while the white *colour* is used to visualize the value 0 (i.e., in our case for the variable *Ticketing_and_fare_collection* all values are 0, as we did not find any article for this category).

The key finding from these correlations is that half of all infrastructure DTs were dedicated to the investigation, mostly in support of the maintenance lifecycle phase. Furthermore, infrastructure DTs focused on only one asset or aspect and were mainly developed and implemented for a real use case. The same is true for DTs for rolling stock, with a slightly higher proportion of DTs for the purposes of prediction and simulation and modelling. Investigation and prediction are strongly related to maintenance, yet DTs are developed for this area. The focus is on individual DTs, regardless of the domain, DT purpose or supporting life cycle phase. The number of DTs developed and implemented is also high. Except for signaling, operations and train control domain and data and information, at least half of all DTs have been developed (and most of them also implemented).

IV. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

This study provides a comprehensive overview of DTs in the rail sector, focusing on the domain of DTs development, the level of development, the life cycle phase in which DT is used, and the purposes of DTs application in the rail sector. The results show that for the purposes of the study, DTs have been mainly limited to infrastructure. The main reason for this is that railways are complex and consist of various components that need regular maintenance to ensure proper operation of trains. Therefore, the most DTs have been provided for monitoring and maintenance of assets. The study has also highlighted promising applications of DTs, as well as potential challenges and future opportunities.

The results of this research have several particular implications. First of all, the study covers the knowledge gap in terms of where DT development in railways has gone so far and where the potential lies. In addition, the study presented DTs for specific railway components that can be used as good practice in the future. The study is useful for the research community to investigate the state of the art of DTs in rail sector. Given that DTs are promising technologies for the future, the study provides a basis for encouraging and raising awareness of the potential of DTs in the rail sector among stakeholders and policy makers in the rail sector.

Rail services are being deducted to passengers and freight customers and the potential of DT in passenger rail transport is recognized as the option to improve the overall passenger experience and ensure a switch to rail. Nevertheless, it can be concluded from the results that a small number of DT studies can be found on the quality of service for passengers. By monitoring and collecting data from various sources such as ticketing systems, traffic flow sensors and train timetables, operators can predict overcrowding, inform passengers in real time about delays or disruptions and work on better utilization of their fleet.

Although the infrastructure components and facilities for passenger and freight transport are the same, the results of the study show no difference between passenger and freight rail transport. Rail freight can benefit from DT as it is characterized by challenges such as heterogeneous traffic, ongoing innovations and multimodal opportunities. In creating a European multimodal transport system with rail as its backbone [1], the connectivity and interoperability of digital technologies to support each mode will be of great importance. Again, the concept and interconnectivity of DTs could be the challenge that the research community should focus on. Therefore, the use of DTs could enable the railways to further meet the requirements of the circular economy under the European Green Deal [5].

As the development of collaborative DTs increases, we can expect DTs to also support asset and system planning as the need for assets from other DTs from the "Rail DT" or DToC, Digital Twin of the Customer, "a dynamic virtual representation of a customer that simulates and learns to emulate and anticipate behavior" [49], which is slowly gaining traction in the economy and will be part of our business in 5 to 10 years, according to Gartner [50] and DHL [51]. DHL [51] also emphasizes in its forecasts for DT that the main application areas for DT will be single assets and closed systems for the time being, and that broad adoption in the next 5 to 10 years will focus on DT for whole systems and networks as an integration of thousands of assets across different actors.

Over the last two decades, there has been much discussion about the full automation of railway operations and the upgrading of railway infrastructure and rolling stock with intelligent software and hardware. Therefore, the railway sector is expected to witness high demand for the development of DT and its application to monitor proper operations, control risks, reduce costs and improve predictions. However, along with the growth in the development and application of DTs, railways also face many challenges. The biggest challenge is the timing of the application of DTs, as there is still no general consensus on the concept of a DTs, while there are different understandings and definitions of DTs in different industries. This is also related to the fact that models are often created separately by operators, infrastructure managers and manufacturers, who rarely collaborate on sharing concepts or models.

Therefore, the rail industry should follow the ideas of the core theory and the concepts of DTs. Another challenge for the rail industry is to identify the scope and scale of DTs, develop use cases and drive large-scale adoption of DTs. The challenge is also to demonstrate the DT concepts developed and the ability of DTs to operate in real time. Therefore, the concept of DTs in the rail industry can be developed and applied on a larger scale in terms of capacity, operational efficiency and reliability, structural and component issues, and safety issues. DTs in the rail sector can be produced at component level or based on the whole rail system with different levels of detail for all phases of the life cycle. However, the creation of trustworthy, validated and less costly concepts and models is the main requirement as the improvement of all mentioned rail services is key for a shift to rail.

It should also be noted that the research community has only just begun to develop and explore DT collaboration in/for the rail sector, which is in line with other sectors, so this is certainly one of the biggest research gaps and a fairly certain future research direction.

From the results of the literature review, DTs are useful concepts that combine real-time modelling, simulation, agent-based modelling, machine learning, prototyping, optimization and Big Data. Consequently, research directions for DTs in the rail industry should focus on developing models based on different techniques for the virtual component of DTs. These models should be created and tested using various unique use cases that meet the needs and requirements of the rail industry, as well as real-world scenarios. In addition, the benefits of improving railway functions should be quantified by exploring the end products and solutions. Consequently, the first phase of DT development should be the definition of quantitative indices. These are also important to understand the accuracy and effectiveness of a DT. Such metrics can help to identify potential errors to assess the stability of the DT, and they can provide a quantification of uncertainty to assess the confidence level of DT results and recommendations. However, from a research perspective, there are many challenges in the railway industry for DT that require attention, especially related to DT setup, grouping and integration of layers or DTs if required, experimentation, calibration and management, which is very difficult, including how to collect, transmit, process and use the DT data.

Data for the rail sector at the macro level are mainly protected for use as commercial or trade secrets, while there are databases with some basic rail performance data and data collection initiatives. Nevertheless, there is no micro-level data related to the condition and operation of a single system [52]. The main constraint to the development of DTs in the rail sector is the availability of data.

In summary, to further assist researchers and practitioners, this study provides an initial overview of the creation of DTs in the rail sector and serves as a basic framework for the further development of DTs, with the aim of filling the research gap. This study also found that the design of DTs in previous literature mainly focuses on the physical infrastructure components. Since the movable component of railway infrastructure is not only switches, DTs for other movable devices can be part of future work. Movable devices in railway infrastructure are mainly automated due to their limited functions and positions. However, future work can focus on developing models and techniques for DTs that can calculate and optimize the operation of movable devices in real time. Besides the main role of DTs to simulate, monitor and testing physical systems, they can also be developed in the future as a basis for managing devices in real time and as a data collector for providing policies and monitoring physical systems. In addition, DTs can be developed as a tool for testing the implementation of new technologies.

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