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APPLIED RESEARCH

Network Digital Twins: A Systematic Review

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ABSTRACT Network management is becoming more complex due to various factors. The growth of IoT increases the number of nodes to control. The combination of Edge and Fog Computing with distributed algorithms makes network synchronization challenging. Softwarized technologies simplify network management but create integration issues with legacy networks. Even in industrial settings where drones and mobile robots are used, proper network management is crucial yet challenging. In this context, digital twins can be used to replicate the structure and behavior of the physical network and at the same time can be used to successfully manage the complexity and heterogeneity of current networks. Despite the rapid growth of interest in the topic, a comprehensive overview of Network Digital Twin research is currently missing. To address this gap, in this paper, we present a systematic review of the Network Digital Twin literature. From the analysis of 138 primary studies, various insights emerge. Networking Digital Twin is a particularly recent concept that has been explored in the literature since 2017 and is experiencing a steady increase to this day. The vast majority of the studies propose solutions to optimize network performance, but there are also many oriented towards other goals such as security and functional suitability. The three most recurrent application domains, as self-reported in the primary studies, are those of smart industry, edge computing, and vehicular. The main research topics aim at network optimization, support for offloading, resource allocation, and floor monitoring, but also support in the implementation of machine learning algorithms such as federated learning. As a conclusion, Networking Digital Twin proves to be a promising emerging field both for academics and practitioners.

INDEX TERMS Digital twins, computer networks, systematic literature review.

I. INTRODUCTION

New generation networks are expected to support ever-increasing demand for novel applications, heterogeneous in quality of service (QoS) constraints, needing to be supported anywhere and anytime, with availability, continuity, and scalability, especially in shared, diversified, and resource-constrained network settings [1], [2], [3].

Self-configuration, proactive learning, and support for high-rate, high-reliability, and time-critical applications, e.g., haptics, brain-computer interaction, flying vehicles, and extended reality (XR), to name a few, play a pivotal role in context-aware new-era services [4]. As a consequence, new challenges in terms of both runtime monitoring and execution are recently emerged [5], providing the motivation to mint novel wave simulation paradigms to model and predict the behavior and performance of wireless systems. In this picture, the digital twin (DT) paradigm has gained momentum as enabling technology to promote the seamless integration between the physical and the cyber realities, providing virtual models for physical objects in the digital way, and simulating their behaviors [6]. Accordingly, the connection between physical and cyber spaces permits ongoing monitoring, extensive data collection [7], and processing to enhance and facilitate the optimization of goal-conditioned problems. In this scenario, energy-efficient wireless sensor networks, e.g., low-power wide-area networks [8] may represent valuable support for real-world monitoring and data gathering. Then, DTs mirror physical objects in dedicated servers, forming virtual multi-dimensional models that empower applications

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to catch their behavior, aided by models, algorithms, and advanced data analytics. On the one hand, these analytics are valuable for discovery or prediction, optimization and measurement of system performance, and enhancing its efficiency. On the other hand, in order to realize a DT within a wireless system, significant computing resources and the transmission of large volumes of data are required. Moreover, gathering DT data on one or more servers can be highly inefficient in terms of resource utilization, resulting in high latency, elevated power consumption, and diminished spectrum efficiency [4]. In this perspective, different network infrastructures and technologies may imply different performance. With the advent of edge computing paradigm, computation and data collection are moved to the edges of the network, close to the data source, reducing network congestion and latency compared to previous network architectures like cloud computing, facilitating real-time data gathering and interactions between DTs and the physical world. However, edge nodes have typically limited resources and this may affect performance.

For all these reasons, the realization of a DT within a wireless system (e.g., at a base station or mobile edge computing server), here referred to as network DT (NDT), potentially composed of sub-DTs mutually inter-connected, is a multi-faceted issue, where different criteria need to be considered. While the literature on NDT is rapidly expanding gaining ever-increasing attention from both industry and academia, it remains scattered and disjointed. This is evidenced by the wide range of infrastructures, methodologies, and technologies employed in existing literature. A rich variety of studies have been proposed to concretely realize an NDT and theoretically analyze its potentiality within wireless networks. Therefore, there is a need to integrate these diverse perspectives to pinpoint gaps where alternative studies can enhance and progress in this domain, and to guide future researchers over time to develop techniques and methods for producing robust research outcomes [9].

Due to the utmost significance of realizing NDT in practice, and the fragmented nature of literature in the field, there exists a notable opportunity for academics and practitioners to benefit from a systematic synthesis of the current literature. A systematic literature review (SLR) is here employed to systematically synthesize the literature and the knowledge collected so far in this domain. The ambition of this paper is to conduct an SLR on NDT, considering all the applications of the DT within the network area, i.e., DTs facing networked systems. Specifically, the objective of the proposed SLR can be summarized in the following contributions.

- Synthesis of the existing studies about NDT to analyze the evolution of the DT-enabling technology over time within the network area. This SLR will focus on different aspects such as the characterization of the DT within the network, the context of its application, and the properties involved in the NDT object of the study.
- Comprehensive understanding of the NDT based on insights that emerged from the literature synthesis.
- Identification of areas for future research in NDT by highlighting gaps in the existing literature. This SLR represents a pioneering effort to provide comprehensive insights into NDT research. It evaluates NDT literature from diverse perspectives and suggests directions for future research.

The rest of the paper is organized as follows. In Section II an in-depth review of the literature is provided, while in Section III the methodology applied is detailed. In Section IV results are presented, and in Section V the data obtained are critically discussed. Section VI describes the threats and the validity of the study conducted, while conclusions are drawn in Section VII.

A companion package containing all intermediate and final data considered in this study is made available online for replicability and scrutiny purposes at:

`github.com/STLab-UniFI/slr-ndt-rep-pkg`

II. RELATED WORK

There exists a rich variety of studies focusing on DT and its integration within networks.

A. SLRs FOCUSING ON DT

An SLR is conducted in [10], where a detailed DT description and analysis are provided, posing particular emphasis on the smart manufacturing landscape. Specifically, the authors highlight the emerging challenges of variable market demand and characterize the main DT components, their features, and corresponding interaction problems. Overall, a systematic literature review of scientific research, tools, and technicalities is presented. A common understanding of the definition of the DT technology is proposed in [11]. In particular, a thematic analysis of 92 publications involving the DT from the last ten years is conducted to characterize the DT, the gaps in both topic knowledge and its practical realization, and areas of future research development. In so doing, the following knowledge gaps are identified: Perceived Benefits; Digital Twin across the Product Life-Cycle; Use-Cases; Technical Implementations; Levels of Fidelity; Data Ownership; and Integration between Virtual Entities. In the field of cyber-physical-system testing, paper [12] proposes an SLR investigating the role of the DT in safety-critical and collaborative environments. The systematic study has the ambition to answer to the following questions: *How digital twins are currently used to test cyber-physical systems? How corresponding test oracles can be defined? What are the modeling techniques used for digital twins devoted to cyber-physical system testing? How are test cases defined?* Results show promising adoption of digital twins in industrial contexts and the potentialities of DT in providing predictive and active testing. Similarly, authors in [13] propose an SLR to analyze the link between the capabilities of DT in simulation for industrial environments. Today's limitations and reasons behind some misconceptions of DT are also highlighted, in terms of discrepancy between the DT concepts and its actual applications, which are typically simulation models. The combination of DT, artificial intelligence (AI), and data mining is studied in [14], where authors denote the future role of AI in the development of DT, in order to guide the efforts of both academia and industry in making the DT empowered by AI a concrete reality. In addition to a detailed SLR, the work also designs a big data-driven and AI-empowered reference architecture to realize a DT-enabled system.

B. DTs FOR NETWORKS

Paper [15] investigates the challenges related to a networking perspective to properly support the real-time synchronization between the physical and the digital plane. Proposals of large-scale frameworks to offer networking support to enable future DT applications are designed. In particular, the authors present a feature-based method with networking constraints to discuss the properties desired by embracing a networking perspective. The survey [16] provides a literature review for the performance evaluation of DT networks. Specifically, a comparison of data-driven methods is critically discussed, considering the fidelity, efficiency, and flexibility requirements of the DT network. The survey presented in [17] discusses the key features and definitions of emerging DT networks, highlighting the technical challenges involved in mapping the physical world in the digital plane. In this context, DT modeling, communication, computing, and data processing technologies are analyzed in reference of several application scenarios, such as sixth-generation networks, manufacturing, healthcare, and so on. A networking perspective is also considered in [18], where authors survey the state-of-the-art of DT technology for natural environments. In this picture, digital models are developed to understand, manage, and protect environmental ecosystems. The SLR provided emphasizes the importance of high-reliable network communications arranged to support synchronization between the physical and the virtual worlds. Furthermore, geographical variations and the outdoor environment induce complex propagation conditions.

III. METHODOLOGY

In this section, we document the *a priori* defined research methodology that was rigorously followed throughout the study. The protocol is based on well-established guidelines for executing SLRs presented by Kitchenham [19].

A. RESEARCH GOAL

By utilizing the research goal formulation proposed by Basili et al. [20], the goal of this study is formulated as follows:

Analyze *digital twin literature*
For the purpose of *systematic knowledge gathering, categorization, and analysis*
With respect to *publication trends, application context, and properties*
From the viewpoint of *researchers and practitioners*
In the context of *networking.*

The research goal aims to address several crucial open research issues regarding NTDs, namely the lack in current NDT research of (i) a comprehensive overview the current state of the art and trajectory of NTD research endeavors, (ii) a categorization of the most frequently considered NDT application domains, and (iii) a systematic understanding of the properties of NDTs present in the literature.

Based on this research goal, we designed the SLR to provide a comprehensive overview of the current state of the art regarding the application of digital twins in the context of networking. More specifically, through a systematic data collection, classification, and analysis, we aim to collect knowledge on three main facets of NTDs, namely (i) characterize the research activities on the topic, (ii) understand the application context of NDTs, *e.g.,* a specific domain or communication paradigm, and (iii) study NDT properties, *e.g.,* the deployment strategy and technologies used.

B. RESEARCH QUESTIONS

From the goal of the research (see Section III-A), we can determine three main research questions (RQs) guiding this investigation, which are documented in the remainder of this section.

RQ_1: *How are the research activities on networking digital twins characterized?*

With this RQ, we aim to understand the current state of the art of NDT research activities. Answering this RQ allows us to understand the evolution of NDT academic interest, the research goals addressed by NDT research, the topic considered, and the frequency of research strategies utilized. More information on the specific data extracted to answer each RQ is reported in Section III-C4.

RQ_2: *What is the application context of networking digital twins?*

With this RQ, we aim to understand the context considered by NDT research. More specifically, by answering this RQ, we can determine the NDT application domains considered in the literature, the communication technologies used, and the assets modeled *via* NDTs. As for the first RQ, we refer to Section III-C4 for the definition of data extraction attributes used to answer RQ_2.

RQ_3: *What are the properties of networking digital twins?* With this last RQ, we shift our focus on studying NDT themselves, by gaining further knowledge on the properties of NDTs presented in the literature. Answering this RQ allows us to understand at a finer level of granularity how NDTs are defined and designed, *e.g.,* by considering, among others, the communication paradigm NDTs adopt, their deployment strategy, and the algorithms they consider.

C. RESEARCH PROCESS

An overview of the research process followed in this study, which rigorously adhered to the SLR guidelines

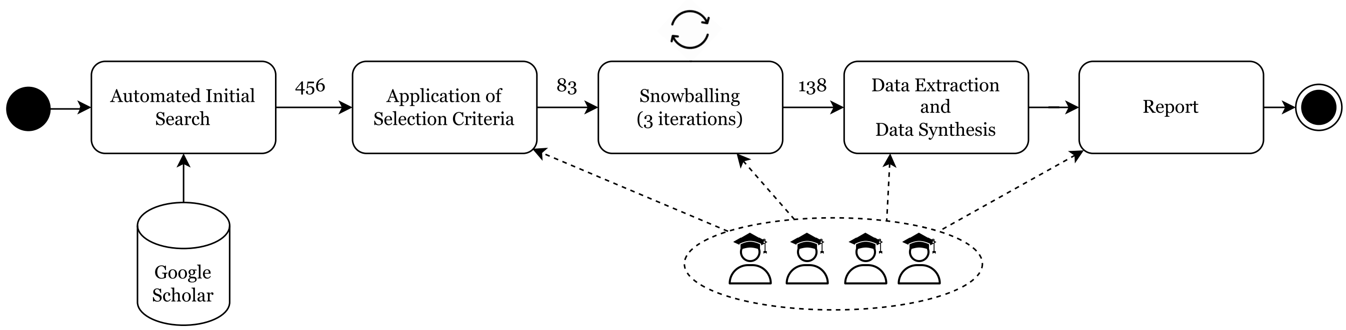

FIGURE 1. **Research process overview.**

outlined by Kitchenham [19], is depicted in Figure 1. The research process is composed of five main steps, namely (i) automated initial search, (ii) application of selection criteria, (iii) snowballing, data extraction and synthesis, and (iv) final report writing. In the remainder of this section, each of the research process steps is carefully documented in detail.

1) AUTOMATED SEARCH

As the first step of the SLR, in order to identify an initial set of potentially relevant literature, we execute an automated query on the digital literature indexer Google Scholar. Considering such an indexer allows us to execute an encompassing automated literature search, which includes the superset of literature indexed by other popular digital libraries considering topics related to networking and DTs (*e.g.,* Scopus and Web of Science [21]). Adopting Google Scholar for the automated search allows us also to identify a sound initial literature set on which snowballing can be conducted, as demonstrated in a dedicated tertiary study [22].

In order to query the digital literature indexer, the query documented in Listing 1 is adopted.

```
1 INTITLE "digital␣twin" AND
2 INTITLE("newtork" OR "edge" OR
3 "cloud" OR "iot" OR "wireless")
```

LISTING 1. **Automated search query.**

The query is designed to retrieve an encompassing set of literature related to NDTs, which is then manually scrutinized to identify the papers suited to answer our RQs, *i.e.,* the primary studies of our SLR.

With the first keyword of the query (Line 1 of Listing 1), we collect potentially primary studies focusing on digital twins by including researches containing "digital twin" in their title. As identified *via* an exploratory scrutiny, the "DT" acronym appears to be seldom used in the title of the manuscript to refer to digital twins, and was therefore not included in the automated query.

The second set of keywords instead (Line 2-3 of Listing 1) are used to identify literature focusing on the networking context. To this end, the keyword "network" and related terms, namely "edge", " cloud", "iot", and "wireless" are considered.

We note that the aim of the automated initial search is not to identify the final set of primary studies from which the data is extracted, but rather to establish a sound initial set of primary studies from which a snowballing process can be initiated.

In order to avoid potential threats to external validity, the publication year is left unbounded during the automated search execution.

The query is executed on the 14th of February 2024, and leads to the identification of 456 potentially primary studies.

2) APPLICATION OF SELECTION CRITERIA

To select the initial set of literature relevant to our research, we manually scrutinize the potentially primary studies identified with the automated query *via* a set of *a priori* defined selection criteria. A paper is identified as a primary study if it adheres to all the inclusion criteria (I) and none of the exclusion criteria (E). The selection criteria are as follows:

- I1- The paper focuses on digital twins
- I2- The paper focuses on networks
- E1- The study is not written in English
- E2- The study is not available
- E3- The study is a duplicate or extensions of an already included study
- E4- The study is a secondary or tertiary study
- E5- The study is in the form of editorials, tutorials, books, extended abstracts, etc.
- E6- The study is a non-scientific publication or grey literature

With the inclusion criteria (I1-I2), we ensure that the primary studies focus on the topic investigated with this SLR, namely digital twins (I1) in the networking context (I2).

With the exclusion criteria instead, we ensure that the data of the paper is accessible to the researchers (E1-E2), is a unique and original research (E3-E4), and is a peer-reviewed scientific paper (E5-E6).

All paper are assessed through the lens of the selection criteria by utilizing adaptive reading depth [23], to efficiently and effectively identify the initial set of primary studies.

Rather than basing the literature review process on personal expertise, as done in the survey on mobility-aware computational offloading in mobile edge networks by Zaman et al. [24], we follow a systematic literature review research approach. In a similar fashion to the study of Ahmad et al. [25], which presents an SLR on scientific workflows management and scheduling in cloud computing, we adopt as research process automated query followed by a selection process based on pre-defined criteria, complemented in this work *via* a snowballing process.

The paper selection process is conducted by four researchers, with weekly meetings held to align the selection process, present examples, and discuss doubts. To evaluate the quality of inter-rater agreement, Fleiss' kappa is calculated among a statistically relevant sample of 57 cases comprising 228 decisions. The test returns a substantial agreement among raters, with a κ equal to 0.75 and an observed agreement of 0.883.

The process of applying the selection criteria on the automated query results terminates with the identification of 83 primary studies, which are considered for the subsequent literature snowballing process.

3) SNOWBALLING

In order to complement the set of primary studies identified with the initial automated search, we conduct an exhaustive bidirectional snowballing process [22]. During this research process, the paper either citing or cited by the already included primary studies are evaluated against the selection criteria (see Section III-C2) for inclusion. The same researchers involved in the application of selection criteria conduct the snowballing. During each snowballing iteration, weekly meetings are held to jointly discuss divergences, examples, doubts and discuss the identified studies for inclusion. A total of three forward and backward snowballing rounds are conducted before theoretical saturation is reached, *i.e.,* no new papers are identified for inclusion, and the snowballing process ends. 55 new primary studies are identified for inclusion *via snowballing*, leading to a total of 138 primary studies to be considered for the data extraction process.

4) DATA EXTRACTION AND SYNTHESIS

In order to systematically define *a priori* a data extraction framework through which the primary studies are analyzed, we conduct a preliminary exploratory phase. During this phase, the primary studies are skimmed through to identify common data available in the papers that is useful to answer our RQs. By considering both the RQs and the primary study content, we then define the data extraction framework, composed of three main segments mapped to the RQs. Each segment is composed of multiple attributes, that can assume two or more values according to different coding strategies (*e.g.,* open coding, axial coding, or provisional coding [26]).

While extracting the information from the primary studies, the data is harmonized by relying on a process of constant comparison [27]. Constantly comparing the extracted data ensures that (i) codes are uniformly used across all researchers, (ii) all attribute values present the same level of abstraction, and (iii) similar codes are revised to avoid redundancy.

In the following, the attributes used to answer each RQ are presented, supported by the coding strategy (CS) used to determine the attribute values.

RQ_1: Data Attributes (NDT Research Activities): To answer RQ_1 (see also Section III-B) we consider the following attributes:

- *Publication year:* Year in which the primary studies was published. CS: provisional coding,
- *Venue type:* Venue in which the publication appeared, namely a workshop (W), a conference (C), or a journal (J). CS: Provisional coding.
- *Research strategy:* Research method adopted, as defined by Stol and Fitzgerald [28]. CS: Provisional coding.
- *Research Goal:* Main quality concern(s) addressed in the primary study, as defined in the ISO/IEC 25010 [29]. CS: Provisional coding.
- *Topic:* Topic addressed in the paper, *e.g.,* resource allocation or connectivity. CS: Open and axial coding.

RQ_2: Data Attributes (NDT Application Context) To answer RQ_2 (see also Section III-B) we consider the following attributes:

- *Application domain:* Application domain considered, *e.g.,* healthcare, vehicular, or general. CS: open and axial coding.
- *Communication technology:* communication technology considered to model the NDTs, *e.g.,* 5g, 6g, or wifi. CS: Provisional coding.
- *NDT asset:* Asset modeled with the NDT, that can be either of *physical* or *logical* nature. CS: Provisional coding.

RQ_3: Data Attributes (NDT properties) To answer RQ_3 (see also Section III-B) we consider the following attributes:

- *Deployment paradigm:* Strategy used to deploy the NDTs, *e.g.,* centralized or distributed. CS: Provisional coding.
- *Deployment location:* Location where the NDT is deployed, *e.g.,edge* or *cloud*. CS: Open and axial coding.
- *Communication paradigm:* If an *infrastructured* or *not-infrastructured* communication paradigm is considered.
- *Architectural description:* If an architectural description of the NDTs is reported or not. CS: Provisional coding.
- *Hierarchies:* If a hierarchical structure of NDTs (*e.g.,* a DT composed of different NDTs) is described. CS: Provisional coding.
- *AI-enabled:* If NDTs make use of AI-based technologies and/or algorithms. CS: Provisional coding.
- *Methods, technologies, and approaches:* Specific procedures, algorithms, and technologies used, *e.g.,* blockchain, neural networks, and microservices. CS: Open, axial, and selective coding.

IV. RESULTS

In this section, we provide an objective description of the data collected for this study, by strictly following the SLR approach presented presented in Section III.

The results are presented by following the three RQs guiding our study and their related attributes, as further documented in Section III-B and Section III-C4.

A. RESULTS RQ_1: RESEARCH ACTIVITIES ON NETWORK DIGITAL TWINS

In this section, we present the results collected to gain an overview of the research activities carried out on NDTs throughout the years.

1) PUBLICATION YEARS

As first data considered, we study the research intensity on the NDT topic. An overview of number of publications focusing on the topic is depicted in Figure 2.

As we can observe from the figure, publications on the topic span from 2017 to the present year (*i.e.,* 2024), and showcase an overall increasing frequency. The first study considers NDT results to be the investigation of Alam et al. [110], which presents a reference architecture for cloud-based cyber-physical systems based on DTs.

While presenting a negligible growth in the first few years (2017-2019) the NDT publication trend results to be overall increasing throughout the years, reaching a peak in 2022 with 41 publications in that year.

While the figures for 2024 need to be considered as partial, as the automated initial search is executed at the beginning of such year (see also Section III-C1), we observe a forecasted maximum of yearly publications on NDT in 2024.

2) PUBLICATION VENUES

By considering the venue types targeted by NDT researches, we note that journals are by far the most considered venue, with 121 out of 138 primary studies being published in international journals focusing on related topics, *e.g.,* wireless communications [108] or mobile computing [93]. Studies published in conference proceedings result instead far less popular (13 out of 138), and target conferences focusing on more heterogeneous topics, such as knowledge science [112], industrial informatics [86], and transportation and smart technologies [45]. Finally, a single NDT research results appear in a workshop, namely the International Symposium on Quality of Service [94]. However, by considering the long-lasting establishment of such workshop within the quality of service community, we note that such a venue can be considered *on par* to a conference in terms of the number of attendees.

3) RESEARCH STRATEGY

By considering the categorization of research strategies presented by Stol and Fitzgerald [28], we note that NDT studies adopt a total of 9 different approaches.

An overview of the distribution of research strategies across the primary studies is depicted in Figure 3.

From the figure we can observe that the vast majority of studies utilizes computing simulations to gain insight into the NDT they consider. For example, in the study of Hui et al. [67], a completely *in silico* vehicle traffic simulation is used to evaluate the performance of a collaborative and distributed autonomous driving service.

Experimental simulations, *i.e.,in virtuo* approaches considering NDT in a controlled setting that resembles a real-world setting, result to be the second most popular research method (36 out of 138 studies). Under this category mostly fall studies that consider concrete NDTs and the data they use and/or produce in a controlled environment. For example, in study of Malik et al. [78] real data generated from edge, fog, and cloud layers of systems are used to evaluate a novel framework for data-driven applications systems.

Less frequently, more concrete research strategies closer to *in vivo* studies, such as laboratory experiments (15 out of 138) field studies (10 out of 138), and field experiments (5 out of 138) are used. In this cases, studies either evaluate dependent and independent NDT variables in a controlled setting, *e.g.,* Ozdogan et al. [84] experiment with a 6G Edge Network based on blockchain, or evaluate NDT in a real-life setting, as done in a case study used to evaluate the feasibility and effectiveness of an DNT-enabled smart tracking system [115].

Finally, in some cases researchers leverage formal abstractions of NDTs in order to study, from a theoretical point of view, potential NDT properties, that then may be ported to concrete implementations (7 out of 138 studies). The identification and subsequent mathematical representation of a specific NDT property seems to lay the groundwork for all primary studies leveraging formal theories. For example, Feng et al. [122] use a mathematical abstraction based on game theory to study secure communication between NDTs.

4) QUALITY REQUIREMENTS

In order to understand the overarching goal of the NDTs presented in the literature, we study the core software product quality considered in the primary studies, by following the categorization of the ISO/IEC standard 25010 [30].

An overview of the quality attribute considered in the papers is depicted in Figure 4.

As can be observed in the figure, performance efficiency, *i.e.,* the degree to which NDT perform their functions within specified time and resource use, is by far the most considered quality aspect (78 out of 138 papers). By scrutinizing with more care the primary studies falling in this category, we observe that most often studies focus on optimizing network processes through the use of NDTs. As exemplary article, Ferriol-Galmés et al. [49] use graph neural networks to design NDTs to optimize the network throughput.

The second most considered topic, which results however to be considered far less than performance efficiency, results to be network security (23 out of 138 studies). In this case, studies result to mostly focusing on the security

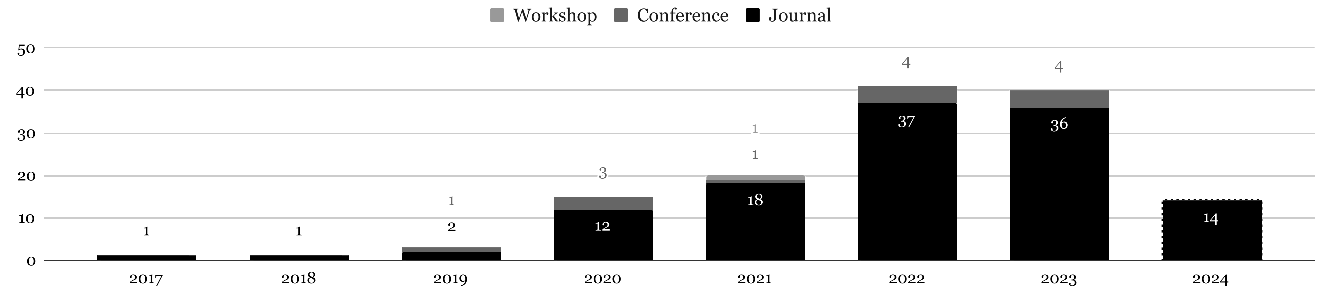

FIGURE 2. Publication frequency per year.

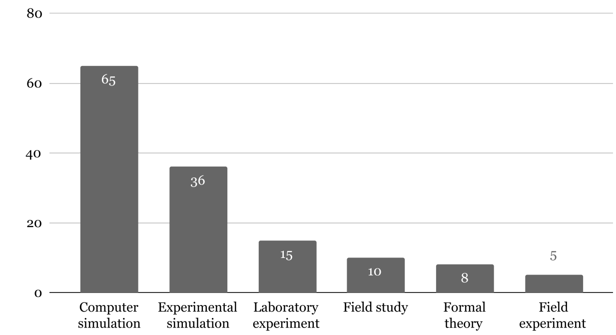

FIGURE 3. Research strategy.

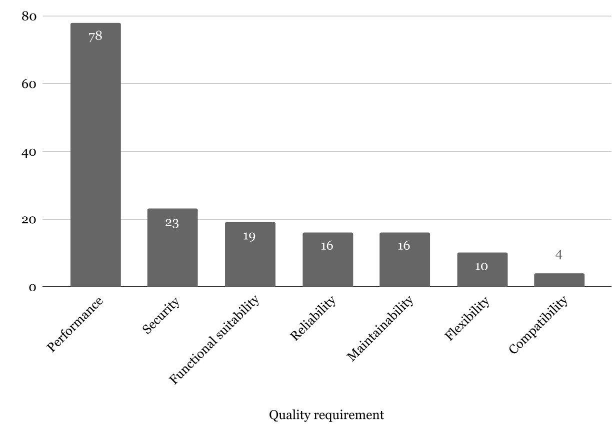

FIGURE 4. Considered quality requirements.

of networks adopting NDT, rather than achieving security *through* NDTs.

Functional suitability, *i.e.,* the extent to which NDTs can satisfy their functional requirements, is the third most considered quality attribute in the NDT literature. Studies in this category primarily focus on assessing the viability of adopting NDT to various contexts, such as driver congestion avoidance [125], intelligent communication in industrial environments [135], and collaborative content delivery [113].

Other NDT quality aspects considered less often in the literature regard reliability (16 out of 138 studies), maintainability of NDTs (16 out of 138), flexibility of NDT to either adapt to different contexts or their ability to scale (10 out of 138), or the ability of NDTs to interact between each other (4 out of 138).

5) RESEARCH TOPIC

Regarding the main research topic covered in the primary studies, an overview of their recurrence is documented in Figure 5.

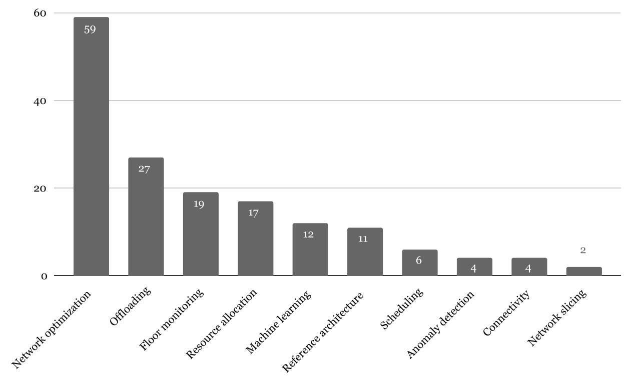

FIGURE 5. Research topic considered.

As can be observed in the figure, almost half of the primary studies focus on optimizing network properties *via* DTs (42.75%), *e.g.,* to achieve security-aware resource management [129], higher quality of service [135], or connectivity optimized for industrial scenarios [136].

The second most recurrent topic, covered by 19.56% of the primary studies, results to be offloading, followed by various studies related to the use of NDTs for floor monitoring (13.77%), *e.g.,* in the context of intelligent manufacturing industrial systems [50] or collaborative autonomous vehicle [67].

Efficient resource allocation by utilizing NDT, often relying on machine learning algorithms [88], [101], [123] is the fourth most considered topic in the NDT literature (12.32%). Machine learning also result to be a topic central in approximately 8.69% of the total primary studies considered in this SLR.

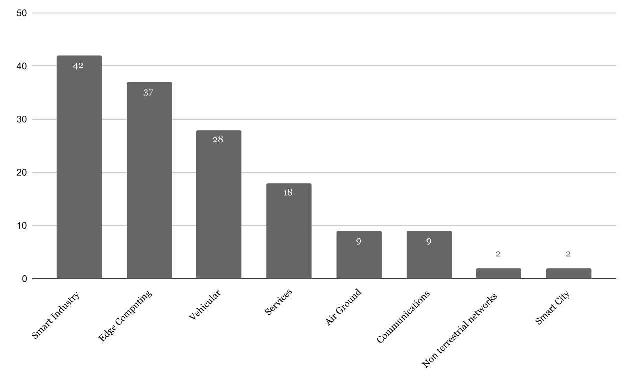

FIGURE 6. Application domains of DTN.

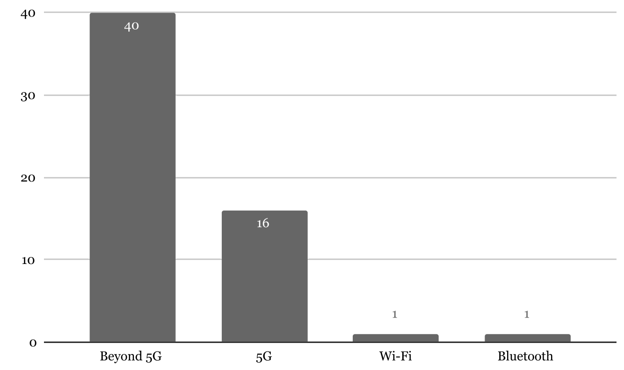

FIGURE 7. Communication technology involved in the DTN.

A similar portion of studies focuses instead on presenting NDT reference architectures predicting how systems based on NDT should be modeled and templated (7.97%).

Less recurrent topics considered in the NDTs literature are scheduling algorithms (4.34%), anomaly detection (2.89%), NDT connectivity (2.89%), and network slicing (1.45%).

B. RESULTS RQ_2: DOMAINS, TECHNOLOGIES AND ASSET TYPES IN RESEARCH ON NETWORK DIGITAL TWINS

In this section, we present the application domain, the communication technology, and which type of digital assets are investigated in the research activities focused on NDTs.

1) APPLICATION DOMAIN

We have analyzed the typology of the application domain addressed by NDT studies. An overview of the domain and their distribution in literature is depicted in Figure 6.

From our results, eight main functional domains are considered in the literature. In a small fraction of primary studies (8,9%), more than a single functional domain is considered, presenting a cross-domain or inter-domain research context.

The predominant domain is the smart industry, with 42 out of 138 papers focused on it (31%). For example, authors in [31] consider an IoT industrial environment, where a simulator is integrated to collect real-time data and to support decision-making strategies. The subsequent domain is edge computing. In this case, there is a substantial number of papers focusing on this application domain, 37 publications, which constitute 27.4% of the total number of primary studies.

The third domain, in terms of occurrences, pertains to vehicular topics. Twenty-eight papers (20.7%) are dedicated to this application domain. It is important to note that the term "vehicular" consistently refers to connected cars and other road vehicles. Connected flying objects, such as drones, fall instead under the less recurrent air-ground networks application domain. In this reference, the paper [32] proposes an integrated IoT-UAV network, where the DT is exploited to optimize the energy consumption of the system.

Services is the following application domain, with 18 papers that are focused on it (13,3%).

The following application domains consist in the long tail of the distribution reported in Figure 6, as the sum of all the papers focusing on them are 20, which represent less than the 1% of the overall distribution, namely 14,81%.

In particular, we have air-ground networks and communications with 9 entries (6,7%) each.

The last two functional domains, in terms of occurrences, are non-terrestrial networks and smart cities, with two entries each.

2) COMMUNICATION TECHNOLOGY

To gain insights into the communication technologies NDTs use, we consider the communication topology of NDT reported in the literature. Figure 7 provides an overview on the communication technology distribution. We can see that four main topologies are considered in the literature, namely 5G, Beyond 5G, and, with two single entries, Wi-Fi and Bluetooth. In this context, an example can be represented by the paper [33], where the DT technology is exploited to enable 6G vehicle-to-everything (V2X) communications.

It has to be outlined that the majority of papers do not address a specific technology, 79, which constitutes the 58,2% on the overall number of studies.

For those papers which address specifically a communication technology, the most relevant one, in term of occurrences, is beyond 5G, with 40 entries (29,6%). Here, we precise the term beyond 5g encompasses all the technologies that have or will evolve after 5G, comprising extension to 5G, 6G, and others.

There is just a single entry for Bluetooth and Wi-Fi communication technologies, respectively Wieme et al. [154] and Bilen et al. [34].

3) DT ASSET

As last attribute considered to answer RQ_2, we have analyzed the typology of DT asset present in the NDT literature. Figure 8 provides an overall view on the type of asset the studies address.

DT can model to two main families of assets: physical and logical. Historically, digital twins were born as a digital representation of physical assets, while the capability to represent logical ones was introduced in later years [35].

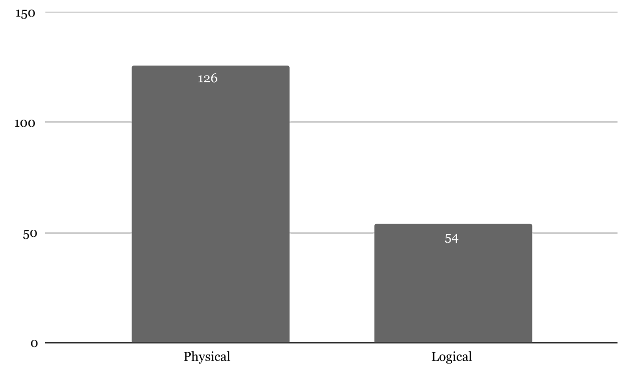

FIGURE 8. DT Asset Type involved in the DTN.

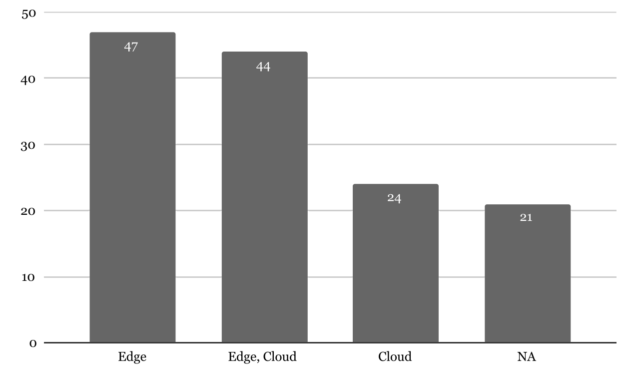

FIGURE 9. Type of NDT deployments.

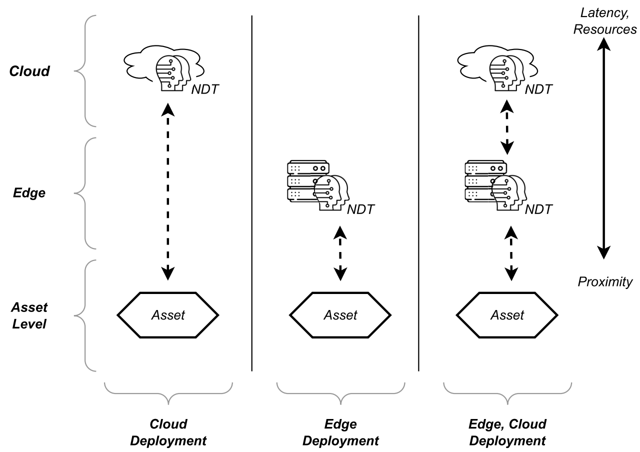

FIGURE 10. NDT deployment and computing paradigms relation.

Our analysis performed on the NDT literature shows that 126 out of 138 studies focus on physical assets, representing the 93% of the total primary studies considered. A minor portion, namely 54 out of 138 studies (39,8%) relates instead to logical assets. For example, in the [36] the DT maps virtual network function and scheduling models.

We note the sum is more than 100% since 44 papers (the 32,5%) are based on the hybrid logical and physical assets. This configuration can be associated both in scenarios where both physical and logical elements are present or where there is a presence of physical entities, that have both physical and logical properties.

C. RESULTS RQ_3: PROPERTIES OF NETWORKING DIGITAL TWINS

To provide a comprehensive response to RQ_3, in this section we present the NDTs properties collected in the NDT literature.

1) USE OF ARTIFICIAL INTELLIGENCE

The initial attribute we seek to verify is whether the solutions presented in the papers demonstrate integration with artificial intelligence algorithms. From our analysis, 57.4% of the articles on NDTs, 78 papers, make use of artificial intelligence. This result is not surprising and allows us to affirm that artificial intelligence plays a fundamental role also in the field of NTDs.

2) HIERARCHICAL NETWORKING DIGITAL TWINS

We also investigate whether and to what extent the use of hierarchical networking digital twins is widespread in the NDT literature. We consider a hierarchical digital twin when the solution proposed by the paper involves the use of digital representations of physical assets at various levels of granularity. From the results obtained, only 7.4% of the articles on NDTs (10 out of 138 papers) propose solutions based on hierarchical digital twins.

3) NETWORKING DIGITAL TWIN DEPLOYMENT

Figure 9 represents the type of deployment proposed in the NDT papers. In particular, we classify the type of deployment based on where the DT is deployed. The type of deployment also identifies the computing paradigm that the NDT follows. As shown in Figure 10, an NDT deployed on the cloud will inherit all the typical feature of cloud computing, such as centralized computations and large availability of resources. Conversely, an NDT deployed at the edge will be characterized by typical features from the edge computing paradigm, such as locality, low latency, and scarcity of resources. If the NDT can be deployed both in the cloud and at the edge, we consider the deployment as mixed (reported in Figure 9 as ''Edge,Cloud''). This type of NDTs can leverage the benefits of both the cloud and edge paradigms, while also needing to face the challenges inherent to each.

As can be observed from Figure 9, the majority of papers consider DT deployed at the edge. This is particularly due to papers proposing solutions based on edge networks and specifically the mobile edge computing paradigm, such as the paper of Zhang et al. [152]. However, there are also solutions based on IoT, such as the works of Zhao et al. [115] and Qi et al. [63]. As can be observed, also hybrid solutions involving both edge and cloud are common in NDT literature. Typically, in this kind of work, a NDT architecture is proposed where NDTs are deployed on edge nodes. These NDTs provide functionalities that require low computational and storage resources, while resource-intensive functionalities are reserved for cloud deployment. An example of this strategy is seen in the work of Gu et al. [155], where the cloud layer serves as a support for tasks that are demanding both computationally and in terms of storage. Cloud solutions are still common in NDTs and have the advantage of managing a specific problem in a centralized manner and with high resource demand. This is the case with Zhang et al. [128] for instance, where a resource allocation problem is addressed using Deep Reinforcement Learning strategies, and the digital twin is used to obtain data both from the real world and through simulation. Finally, there are also works that do not specify exactly where to execute the deployment (21 out of 138 studies). In this case, the solution is assumed to be deployment-independent.

4) NDTs ARCHITECTURAL DESCRIPTIONS

A significant proportion of papers, approximately 49.3%, provide an architectural description of the NDTs solution proposed. By architectural description, we mean a depiction of the proposed architecture that defines the possible physical entities, their corresponding DT, their characteristics, and the functionalities the architectural elements expose. It also explores whether these DT have the ability to collaborate with each other.

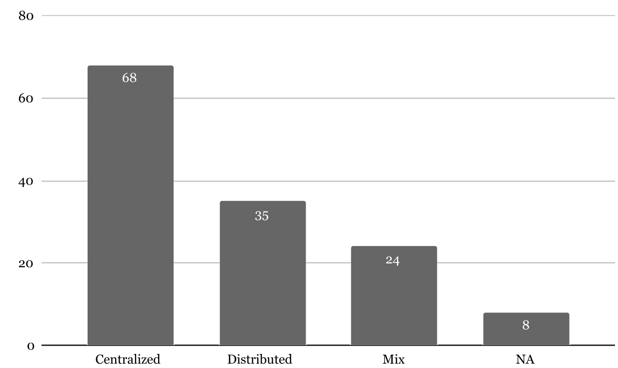

FIGURE 11. Paradigm of NDT deployments.

5) NDTs DEPLOYMENT PARADIGMS

Figure 11 documents the type of deployment paradigm implemented by the NDT primary studies. We considered 3 possible options: centralized, decentralized, and mixed. A centralized deployment usually involves a single NDT which is updated with data from the entire network. An example of this type of paradigm is represented by the work of Ferriol-Galmés et al. [49], where a centralized solution aimed at optimizing the network based on graph neural networks is provided. Conversely, distributed approaches involve multiple DTs of different physical elements coexisting and cooperating with each other to achieve a specific goal. An example of this type of paradigm is reported in the work of Yao et al. [151], where each Mobile Edge Computing server maintains a digital twin of the physical network. A digital twin edge network (DITEN) is formed where each digital twin collaborates with the other digital twins through twin-to-twin communication in order to identify the best network optimization strategy i.e., service caching and task offloading. A mixed architecture consists of a hybrid solution where for some tasks the digital twins work in a distributed manner while for others they work in a centralized manner. A remarkable example is the solution of Yuan et al. [70], where the digital twins deployed in small base stations operate as workers and the digital twins deployed on MEC servers operate as global agents in an Asynchronous Advantage Actor-Critic (A3C)-based scheme.

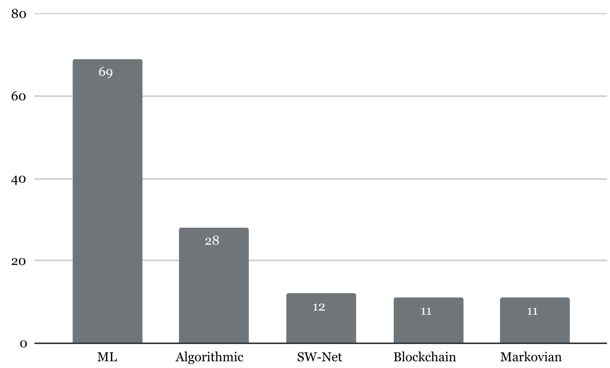

FIGURE 12. Technologies implied in NDTs.

6) NDTs AUXILIARY APPROACHES AND TECHNOLOGIES

Figure 12 illustrates the frequency of utilization of specific approaches and technologies that we identified as being particularly integrated and employed in the NDT literature. In particular, as already discussed in Section IV-C1, machine learning is frequently leveraged in NDT research. More in detail, solutions based on deep reinforcement learning for network optimization are often proposed, such as the works of Li et al. [83] and Yang et al. [103]. However, solutions aiming to support federated learning algorithms are also common, such as Sun et al. [68] for example. Algorithmic solutions are often employed in NDT architectures. By algorithmic solutions, we consider all those strategies that require an algorithm that does not fall within the machine learning paradigm. Among these, we often find solutions based on game theory [108], optimization algorithms [104], and evolutionary algorithms [99]. A paradigm that is gaining more and more ground is that of virtual networks, in particular Network Function Virtualization (NFV) [37] and Software Defined Networking (SDN) [38]. The graph reported in Figure 12 also shows how frequently these types of technologies are used within the selected articles. Blockchain-based technologies are also frequently used in NDTs, mostly to ensure a higher degree of security, as in the work of Lu et al. [82]. In the realm of NDTs, we have identified a particular type of model that is frequently used beyond neural networks, namely Markovian models [39]. In particular, in the class of Markovian models, we have frequently encountered the class of Markov Decision Processes (MDP), such as the works of Jeremiah et al. [141] and Ozdogan et al. [84].

7) NDTs COMMUNICATION PARADIGMS

From the results of our analysis, the majority of the papers, 89.7% with a total of 122 papers, provide solutions using infrastructured communication paradigms. The remaining 14 papers, accounting for 10.3% of the primary studies, propose non-infrastructured solutions, most of which are based on the vehicle-to-vehicle (V2V) paradigm, such as the work by Jeremiah et al. [141].

V. DISCUSSION

In this section we will provide a commentary on the result of the study, with the aim of providing perspectives for interpreting the collected data.

From the collected data it is possible to notice a more than linear increase in the number of publications from 2017 to 2022: this trend can be coupled with the introduction of digital twin as an approach to model networks, as an evolution of the software defined network (SDN) and virtual network function (VNF) [40].

We can see a plateau in the number of publication reached in the year 2024, after the maximum of 2023: this can be explained by digital twin becoming a well-established approach to model network.

Analyzing the publishing venues, we can see that journals represent the most considered venues. This can be explained as the concept of Network Digital Twin borrows many of the concepts and theory, mathematics, and architecture, from the use of digital twins in the industrial domain. Hence the concept of Digital Twin Network can be considered more an evolution of existing concepts than a completely novel construct [41]. This allowed us to introduce advanced concepts at the very early stage of the study of Network Digital Twin.

From the analysis of quality requirements, we can observe that performance represents the leading requirement, with more than 75 paper addressing it. This can be explained as Digital Twin Network represents an evolution of Software Defined Network (SDN) and Virtualized Network Functions (VNF). One of the key challenges of such an evolution is to address the evolutionary requirements of the network, especially in its developing direction which encompass all beyond 5G standards, particularly regarding optimizing edge-to-cloud deployment with ultra-low latency requirements. Coupled with this aspect, there is the demand for high reliability, which pertains to the domain of Ultra Reliable Low Latency Communications (URLLC) networks, and the need for secure networks, which are related to the cybersecurity domain.

Analyzing Research Topic addressed in the studied venues, we can see that Network Optimization is the most considered topic among the papers analyzed, with more than 55 papers addressing it.

This is related to the considerations addressed regarding the quality requirements: we can see a remarkable symmetry between the two domains, as it could be expected reflecting on their logical relationship. Hence we can parallel the majority of paper addressing performance requirements with a similar amount that are focused on Network Optimization, as the latter is a tool to guarantee the first. Similarly, URLLC themes, and more in general deployment across the cloud-to-edge continuum, are strictly connected with offloading topics and resource allocation.

We can observe that Smart Industry and Edge computing are the most represented application domains in the papers that have been analyzed.

This can be related, for the Smart Industry, to the very historical nature of Digital Twin, which are born in an industrial context and have evolve into the communication domain only in a latter stage.

Regarding the Edge Computing domain, this is strictly related to the themes of low latency requirements and optimal cloud-to-edge deployment, discussed above.

It is relevant to notice the interest of the vehicular domain, which is related to the themes of autonomous driving, which has been a key pillar of AI research in the field of computer vision, further propelled by the artificial intelligence rapid acceleration in the years considered in this paper.

In terms of communication technology, it is possible to notice that, due to their innovative nature, digital twins and DTN are mostly related to future protocols, namely all technologies beyond 5G. There is also a relevant quota of studies focused on 5G, due to the high cost related to switch towards new technologies, as there is an ongoing trend of leveraging the current 5G technology, which has not yet been fully deployed and leveraged.

Digital Twin as a concept was born in the industrial domain, therefore most of the studies are focused on physical assets. However, as the concept of digital twin evolved, there is a progressive trend of applying DT to logical asset or to ecosystem that have both physical and logical components, labeled as phygital domains.

AI rising application in the telecommunication domain is visible also in DT studies, where a majority of the paper analyzed utilize some technology related to artificial intelligence.

Most studies highlight an edge deployment, reflecting the industrial roots of digital twins. However, an increasing trend towards edge-to-cloud continuum deployments is noted, emphasizing the importance of deployment strategies in the overall architectural layout of digital twin implementations. More than half of the reviewed papers discuss specific architectural considerations, underscoring the significant impact of telecommunication principles on digital twin deployments. Centralized versus decentralized architectures form a key part of this discussion, with centralized approaches providing tighter control over communications.

VI. THREATS TO VALIDITY

Despite our best efforts, the reported research results have to be interpreted in light of a set of threats to validity that might have influenced the study. By following the categorization of Wohlin et al. [42], and by considering the common pitfalls of threats discussed by Verdecchia et al. [43], we discuss four threats categories, as documented in the reminder of this section.

A. EXTERNAL VALIDITY

A threat that might have undermined the resented results is represented by the set of primary studies utilized to answer our RQs. As mitigation strategies, the initial set of primary studies is identified by adopting an encompassing digital literature indexer (namely Google Scholar), that encompasses publications provided by various digital libraries (*e.g.,* Scopus and Web of Science [21]). To further mitigate this threat, the initial set of primary studies is complemented with a recursive bidirectional snowballing process, that is terminated only upon theoretical saturation is reached. An additional threat to external validity is constituted by the nature of the primary studies, namely academic peer-reviewed literature. The scope of the study is designed prior to its execution and purposely avoids the inclusion of white and grey literature. For this reason, we remind that the research goal is to provide an overview of the state of the art of NDTs, and by no means should be interpreted as representing the state of practice as a byproduct.

B. INTERNAL VALIDITY

An internal threat to validity inherent to the research method adopted, namely an SLR, lies in the soundness of the research steps and the rigor used for their execution. Regarding the research method, we mitigated potential threats by strictly adhering to widely adopted guidelines for conducting SLRs and snowballing processes [19], [22]. In order instead to mitigate potential threats related to subjective literature interpretation, different strategies are adopted. First, a set of well-defined selection criteria and data extraction attributes are established prior to the research execution. Such research framework is strictly followed throughout the study execution, with potential doubts and possible interpretations thoroughly discussed among all researchers. Second, throughout the entire research execution, weekly alignment meetings are held to align the literature selection and data extraction processes. Third, the alignment among researchers is quantitatively measured in terms of inter-rater agreement by adopting Fleiss' Kappa, which yields to a considerable observed agreement among raters (see also Section III-C2).

C. CONSTRUCT VALIDITY

Potential threats to validity of the study may lay in the interpretation of the main concepts the SLR focuses on, namely "digital twins" and "networking". Given the widespread and unequivocal use of the term "digital twin", during the primary study identification, the active effort is put in selecting literature explicitly containing such keyword (see also I1, Section III-C2). Regarding the second term instead, conscious attention is put into considering various potential interpretations and presentation formulations of the concept, in order to select in a more semantic manner papers focusing on such multifaceted topic.

Further potential biases regarding the validity of the observed construct are mitigated by discussing among researchers a common understanding of the terms during the research protocol formulation, and strictly adhering to the protocol during the study execution, while constantly discussing potential doubts, alignment opportunities, and exemplary papers.

D. CONCLUSION VALIDITY

To avoid potential threats to conclusion validity, the goal and RQs guiding the study are formulated during the early stages of the study, and the research design is tailored around them. To further mitigate potential threats to conclusion validity, the results collected in this study are provided in a "raw" format in Section IV, limiting potential subjective biases in the interpretation of the results. As further mitigation strategy, the entirety of the intermediate and final artifacts produced with this research, including paper selection processes, extracted data, and source code utilized, is publicly made available for the sake of scrutiny, reproducibility, and replicability (see Section I). Finally, a rigorous documentation of all research practices, which are derived from existing and widely utilized guidelines [19], [22], is provided as part of this inquiry to transparently document potentially unrecognized conclusion threats.

VII. CONCLUSION AND FUTURE WORK

With the evergrowing popularization of networking digital twins, the research landscape on the topic experienced a rapid and diversified development in recent years. Albeit the growing industrial and academic interest in the topic, an in-depth analysis of the related literature still seems to be missing.

In order to fill this gap, with this research, we present a systematic review of the networking digital twins body of knowledge. Specifically, we thoroughly select *via* an automated query complemented by a directional snowballing process, 138 primary studies. The studies are then analyzed according to a *pre-defined* set of selection criteria, and data is extracted according to 15 distinct attributes.

From the conducted research, it is possible to identify a trajectory in the research related to digital twin networks. Firstly, there is noticeable interest within the scientific community, which has led to the number of publications increasing from single digits to dozens in five years. Besides the interest, this progress has been made possible by the preceding literature on digital twins related to industrial assets, which has provided a solid foundation for the creation of concepts underlying digital twin networks

From the analysis of the collected data, a clear picture regarding the state of the art of network digital twins emerges. Performance is the most considered quality requirement, while smart industry and edge computing are the most represented application domains. Most digital twins focus on future communication protocols, i.e., technologies beyond 5G. With the evolution of the digital twin concept, there is a progressive trend of applying DT to logical assets or to ecosystems which have both physical and logical components, i.e., phygital domains. AI algorithms, combined with edge or an increasing number of edge-to-cloud continuum deployments are frequently considered in the literature.

The analysis also allows for the identification of several areas for future development in the field of digital twin networks. In particular, there is a noticeable evolution from the traditional industrial domain approach toward a vision characterized by hierarchical structures. These structures enable progressive levels of abstraction and a high-level perspective, along with stylized facts of the network as a whole. This can be appreciated from the increasing role of digital or phygital assets.

Another significant area in the evolution of digital twin networks is the management of what is referred to as the cloud-to-edge continuum. This involves networks designed for differentiated management of nodes near end-users, known as edge nodes, and nodes located remotely, in the so-called cloud. This approach allows for the development of paradigms focused on performance, efficiency, and reliability, which are prominent themes in the literature on digital twin networks. Additionally, these approaches are characteristic of beyond 5G paradigms, which constitute a major focus of the analyzed literature.

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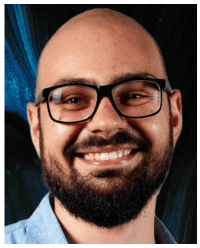

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