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Risk Reduction in Transportation Systems: The Role of Digital Twins According to a Bibliometric-Based Literature Review

Vittorio Astarita *, Giuseppe Guido, Sina Shaffiee Haghshenas and Sami Shaffiee Haghshenas

Department of Civil Engineering, University of Calabria, 87036 Rende, Italy; giuseppe.guido@unical.it (G.G.); sina.shaffieehaghshenas@unical.it (S.S.H.); sami.shaffiee@gmail.com (S.S.H.)
* Correspondence: vittorio.astarita@unical.it

Abstract: Urban areas, with their dense populations and complex infrastructures, are increasingly susceptible to various risks, including environmental challenges and infrastructural strain. This paper delves into the transformative potential of digital twins—virtual replicas of physical entities—for mitigating these risks. It specifically explores the role of digital twins in reducing disaster risks, such as those posed by earthquakes and floods, through a comprehensive bibliometric-based literature review. Digital twins could contribute to risk reduction by combining data analytics, simulation, and predictive modeling by creating virtual replicas of physical entities and integrating real-time data streams to better address and manage risks in urban environments. In detail, they can help city planners and decision-makers analyze complex urban systems, simulate potential scenarios, and predict potential outcomes. This proactive approach allows both the identification of vulnerabilities and better implementation of targeted mitigation strategies to enhance urban resilience and sustainability. More informed decisions can be made relying on simulations, and it can also be possible to optimize resource allocation and better respond to emerging challenges. This work reviews the key publications in this domain, with the aim of finding relevant papers that can be useful to urban planners and policy-makers. The paper concludes by discussing the broader implications of these findings and identifying challenges in the widespread adoption of digital twin technology, including data privacy concerns and the need for interdisciplinary collaboration. It also outlines prospective avenues for future research in this emerging field.

Keywords: digital twins; urban risk management; predictive analysis in urban planning; disaster response and mitigation; urban resilience and sustainability

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1. Introduction

This paper focuses on the utilization of digital twins in urban risk management, specifically in addressing disaster risks and enhancing resilience in urban environments.

In the context of growing urban challenges, there exists a pressing need for innovative approaches that can comprehensively address the risks connected with the complexities of urban environments [1–3]. Traditional methods of risk assessment and disaster management may fall short in providing real-time insights and predictive capabilities necessary for proactive risk mitigation [4–6]. This gap underscores the significance of exploring advanced technologies such as digital twins to revolutionize urban risk management practices.

In the 21st century, urban areas are increasingly becoming hotbeds of complex challenges. Characterized by dense populations and intricate infrastructures, these areas are exposed to a spectrum of risks, ranging from environmental pressures to infrastructural strains [7]. The urgency to address these risks is compounded by the phenomena of rapid urbanization and environmental uncertainties. Among the burgeoning technological advancements, digital twins—virtual replicas of physical entities—have emerged as a useful tool for assessing the behavior of complex systems. By creating dynamic, real-time models of urban environments, digital twins enable city planners and decision-makers

to visualize, simulate, and analyze urban dynamics comprehensively. This capability is pivotal in enhancing urban risk reduction strategies, especially in the realms of disaster response, infrastructural management, and risk reduction. For this reason, this study aims to investigate the potential of digital twins as a cutting-edge tool for enhancing urban risk reduction strategies. The objective is to explore how digital twins can be integrated into urban planning and disaster management processes to improve the resilience, response mechanisms, and overall sustainability of urban areas. Digital twins offer a promising avenue in this regard, leveraging the power of data analytics, simulation, and predictive modeling to preemptively address and manage urban risks.

In urban risk management, the concepts of resilience and sustainability are important in shaping the adaptive capacity and long-term viability of urban environments [8,9]. Resilience refers to the ability of cities to withstand and recover from various shocks and stresses, including natural disasters, climate change impacts, and socio-economic challenges [9]. By enhancing resilience, cities can bounce back stronger, ensuring the continuity of essential services and minimizing disruptions in the face of adversity. Sustainability [10], on the other hand, emphasizes the importance of balancing environmental, social, and economic considerations to meet the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable urban development practices aim to create harmonious and livable cities that promote resource efficiency, social equity, and environmental stewardship. By integrating resilience and sustainability principles into urban risk management strategies, cities can build robust, adaptive, and better communities that are better equipped to tackle emerging challenges and uncertainties [11–15].

The following works that had similar objectives [16,17] are discussed in the following section and have also been evaluated by the methodology employed in the proposed literature review.

The novelty of this research lies in applying a specific bibliometric-based literature review procedure that shows how recent scientific literature presents digital twins as a new paradigm in risk reduction strategies that leverages advanced simulation and predictive modeling techniques to enhance decision-making and resource allocation in urban environments.

1.1. How Existing Research Gaps Have Been Addressed in This Paper

A critical aspect of advancing knowledge in the field of urban risk management and digital twin technology is the identification of research gaps that warrant further investigation. By conducting a comprehensive exploration of earlier studies and the existing literature, this study aims to shed light on significant gaps and unaddressed aspects in the current body of research. Previous research has laid a foundation for understanding the potential of digital twins in urban environments, yet there remains a need to delve deeper into specific areas such as the integration of real-time data streams, the scalability of digital twin models for different urban contexts, the development of decision support systems based on digital twin simulations, and data security and privacy issues. By pinpointing these research gaps, this study seeks to contribute to the ongoing discourse on urban risk management and digital twin applications, providing valuable insights for future research directions and practical implementations in urban settings.

1.2. Structure of the Paper

This introduction sets the stage for a comprehensive exploration of the role of digital twins in urban risk management by specifying the research problem, the objective of the research, and the novelty of what has been proposed in the literature.

Moreover, the structure of this paper is designed to facilitate a thorough understanding of the subject. It is based on a comprehensive literature review, illustrating how digital twins facilitate informed decision-making in urban planning and disaster management. The subsequent sections delve into specific applications of digital twins, such as in climate change adaptation and emergency response scenarios. Finally, this paper concludes by

discussing the broader implications of these findings, along with identifying potential challenges and future research directions in the field of digital twin technology and urban risk management

2. Materials and Methods

This section outlines the methodology employed for conducting a systematic literature review, which is based on a Scopus search using specific keywords [18,19]. The flowchart of the methodology is presented in Figure 1.

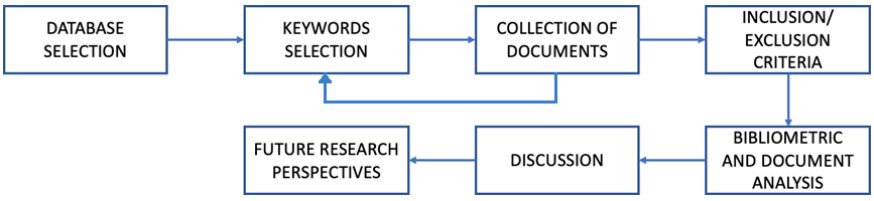

Figure 1. Methodology flowchart.

The methodology implemented follows a structured approach aimed at conducting a systematic and unbiased review of digital twins applied to urban risk reduction. This methodology encompasses a seven-step process, as follows (similar methodologies are often employed in academic research [18]):

1. Selection of databases;
2. Determination of keywords;
3. Compilation of relevant literature;
4. Application of inclusion/exclusion criteria;
5. Bibliometric analysis and examination of documents;
6. Synthesis in discussion;
7. Identification of avenues for future research.

In this research, the Scopus database served as the primary source of data. Selecting the right keywords is a pivotal part of the process, as it directly influences which scientific papers are included or excluded. The goal was to assemble a collection of the most impactful and relevant publications within the field while deliberately omitting unrelated papers. The authors adopted a meticulous, iterative approach to refine the selection, a process depicted by the backward arrow linking the third and second steps in the methodology flowchart (see Figure 1).

The last step in our selection process for identifying relevant documents involved precise criteria: specifically, studies and articles that mentioned "digital twin" along with the terms "disaster" or "emergency" in their titles were considered. This means that only those publications that explicitly included both the concept of "digital twin" and referenced either "disaster" or "emergency" scenarios were considered for inclusion in our review. This approach helped us narrow down the vast amount of available literature to focus exclusively on works that directly relate to the application of digital twin technology in situations of disasters or emergencies, ensuring the relevance and specificity of our research compilation.

It must be noted that for a systematic literature review, the selection of appropriate keywords plays a crucial role in locating the relevant literature accurately. While specific keyword combinations and selection procedures can be useful to increase the quality of search results, it is essential to acknowledge the limitations associated with keyword screening and how sensitive the results could be to variations in the keywords and selection procedure. The choice of keywords can influence the inclusiveness of the search results, potentially introducing biases based on the selected terms. Moreover, the precision of the search results may vary based on the specificity and relevance of the chosen keywords. In this work, careful consideration to keyword selection was given, and a multiple-step

selection procedure with the aim of ensuring a comprehensive and unbiased literature search was introduced.

Our first search yielded an initial collection "A" of 370 documents. This collection was then manually refined to include only those documents relevant to the research objectives, resulting in a condensed list "B" of 98 documents (Table 1 and Figure 2).

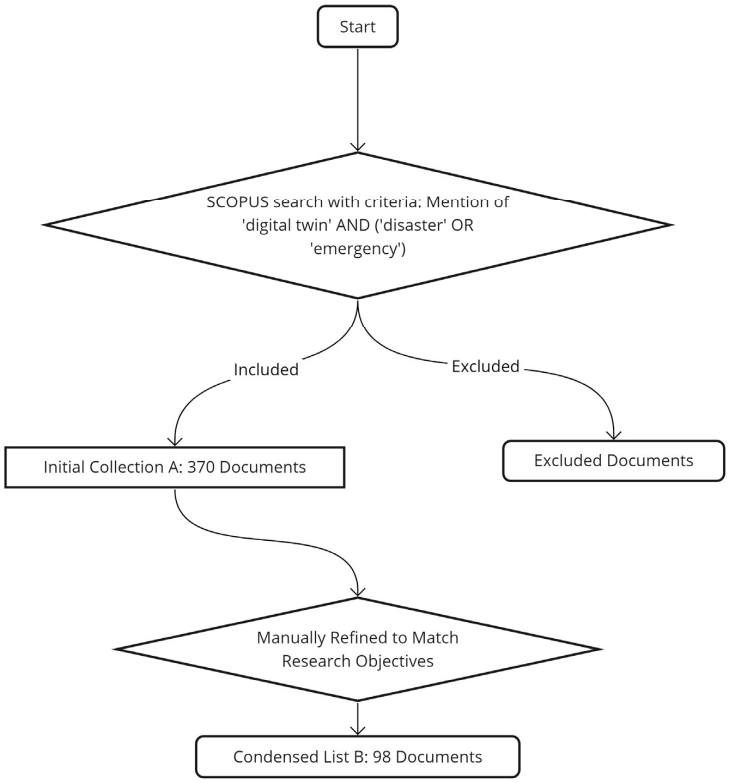

Figure 2. The process to obtain condensed list "B" of 98 documents.

Table 1. Number of documents in list "B" per year (this paper was completed at the beginning of 2024).

Year	Number of Documents
2018	2
2019	1
2020	8
2021	9
2022	26
2023	50
2024	2

It should be noted that previous search attempts employing different keywords and logical operators either retrieved an excessive number of non-pertinent documents or yielded an insufficiently small dataset. Therefore, the selection of keywords is the culmination of preliminary investigations.

With the refined set of 98 documents, the temporal distribution of the publications was analyzed, and the results are presented in Table 1 and Figure 3. This analysis reveals a growing trend in the number of documents published per year. However, it is important to acknowledge that the overall number of documents indexed in Scopus has also been increasing annually. Therefore, a more nuanced analysis would be required to ascertain whether there is an actual increase in scientific interest in this area. Figure 4 presents the distribution of documents by country and the average yearly growth rate (averaged over previous sampled years).

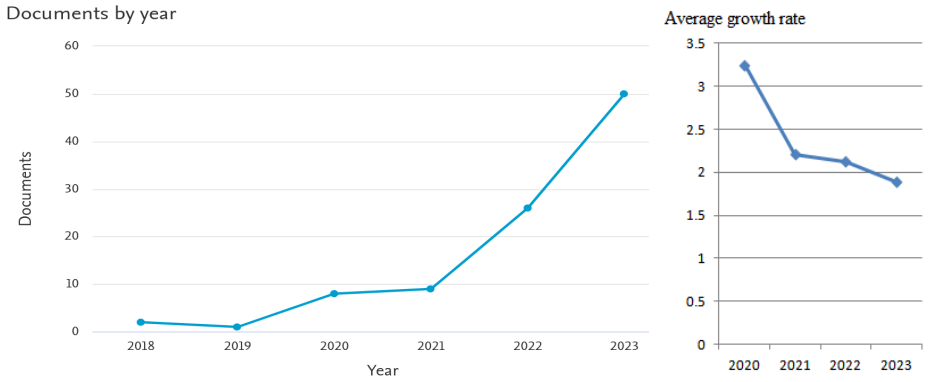

Figure 3. Number of documents per year and average growth rate (source: Scopus database. The year 2024 was excluded in this image).

It can be noted that the overall growth rate has been almost 2 on a yearly base. In other words, in the examined years, the number of papers almost doubled every year.

Of the 98 documents belonging to list "B", the following four analytical scientometric tools were applied, and the results are described in the following subsections:

- Topic visualization carried out by text mining abstracts and titles;
- Co-citation analysis to establish influential journals and references;
- Country analysis based on co-authorship;
- Trending topic analysis carried out by over-lay visualization.

The software that was used to perform the bibliometric analysis was VOSviewer 1.6.20 [20], a dedicated software tool developed for creating maps based on network data and for visualizing and exploring these maps.

The bibliometric analysis was carried out with an objective, and the automatic approach was then complemented with a manual procedure to extract the most influential works that might have been left out from the automatic procedure and that can be useful as a base to investigate this research sector.

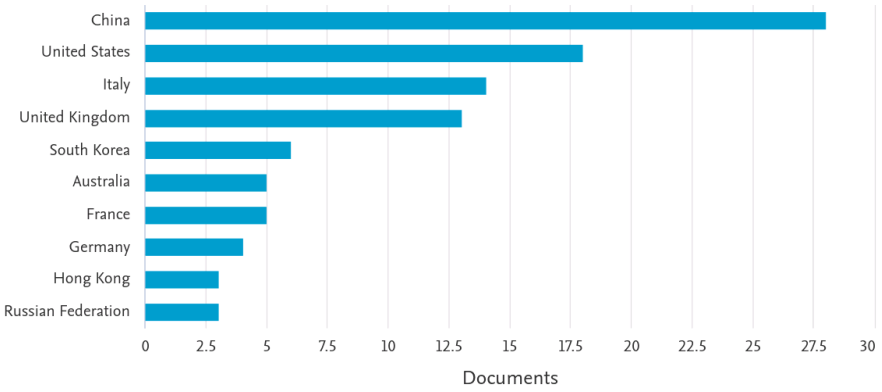

Figure 4. Documents by country (this image contains the documents published in 2024).

2.1. Topic Visualization Analysis

To create a profile of the most important issues arising in the field and to perform a visualization of main topics, text-mining analysis was carried out using the VOSviewer-suggested procedure to text-mine the abstract and title fields of the papers.

VOSviewer applies natural language calculation methods to analyze the abstracts and titles of selected references. Indications and considerations from [21] were followed.

With this procedure, a "co-occurrence network" was generated (Figure 5).

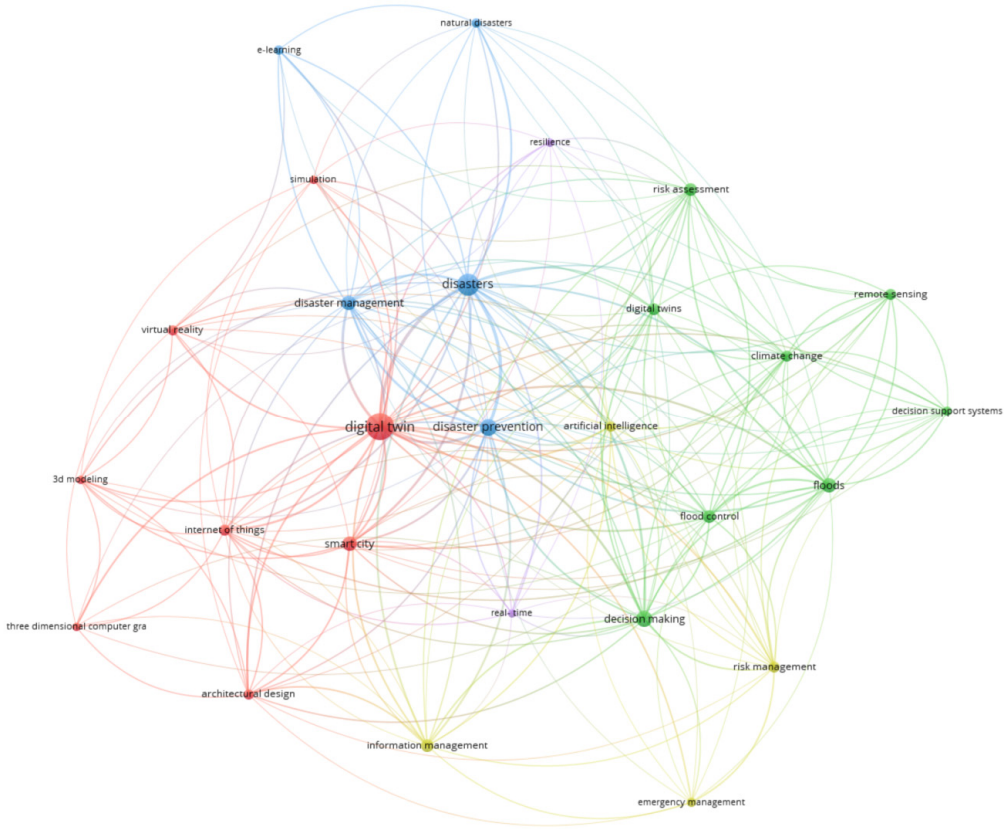

Figure 5. Topic visualization analysis—co-occurrence network (the different clusters are indicated with colors).

In this network, the most relevant terms were highlighted, and a cluster analysis was performed, identifying 5 clusters that theoretically gathered themes which shared some higher connection. In the pursuit of discerning the thematic structure, a cluster analysis was performed on this collection of keywords derived from the Scopus database. The keywords, representing focal topics of scientific works, were classified into distinct clusters. Each cluster signifies a thematic concentration of research interests and is identified by a unique number.

The clustering was guided by the following metrics: the number of links, total link strength, and occurrences within the database. Additionally, average publication year, average citations, and average normalized citations were calculated to provide a temporal and citation-based context for each keyword. The results revealed several thematic clusters (see also Table 2). A title was given to each cluster in agreement with what the leading topic seemed to be:

- Cluster 1 "Digital Technologies and Virtual Modelling in Urban Planning": This primarily encompasses keywords related to technology and modeling, such as "3D modeling", "architectural design", "digital twin", "internet of things", "simulation", "smart city", "three-dimensional computer graphics", and "virtual reality". This cluster is characterized by a significant presence of keywords that have a strong technological orientation, reflecting a current trend towards digital and computational methodologies.
- Cluster 2 "Environmental Management and Risk Assessment Tools": This includes keywords that focus on environmental aspects and management tools, such as "climate change", "decision-making", "decision support systems", "digital twins", "flood control", "floods", "remote sensing", "risk assessment", and "resilience". These terms suggest a research focus on developing strategies and systems for environmental monitoring and risk mitigation.

- Cluster 3 "Disaster Management and Educational Strategies": This is defined by keywords associated with disaster response and management, with terms like "disaster management", "disaster prevention", "disasters", "e-learning" (possibly in the context of disaster education), "natural disasters", and "flood control". This cluster indicates a concerted research effort directed at understanding and managing natural disasters.
- Cluster 4 "Advanced Computational Methods in Emergency and Risk Management": This revolves around advanced computational methods and their application, with keywords such as "artificial intelligence", "emergency management", "information management", and "risk management". The prominence of these keywords demonstrates an increasing reliance on intelligent systems for managing emergencies and risks.
- Cluster 5 "Real-Time Systems and Resilience in Crisis Management": This is less populous but features keywords indicative of real-time processing and systemic resilience, such as "real-time" and "resilience". These keywords reflect an interest in immediate response mechanisms and the ability of systems to withstand and recover from adverse conditions.

Table 2. List of main keywords divided into clusters.

Cluster	Keywords
1	architectural design, 3D modeling, digital twin, internet of things, simulation, smart city, three-dimensional computer graphics, virtual reality
2	climate change, decision-making, decision support systems, digital twins, flood control, floods, remote sensing, risk assessment
3	disaster management, disaster prevention, disasters, e-learning, natural disasters
4	artificial intelligence, emergency management, information management, risk management
5	real-time, resilience

A more detailed analysis of the five clusters identified in this study can shed some light on the diverse thematic dimensions that collectively contribute to general urban risk reduction. The following interconnections between these clusters can be evidenced: Cluster 1, focusing on digital technologies and virtual modeling in urban planning, lays the foundation for advanced technological solutions and simulation techniques; this sets the stage for Cluster 2, which emphasizes environmental management and risk assessment tools, highlighting the importance of monitoring and mitigating environmental risks. Cluster 3, centered on disaster management and educational strategies, is interconnected with all other clusters outlining the importance of human knowledge in all other sectors to enhance preparedness and response mechanisms. Furthermore, Cluster 4, emphasizing advanced computational methods in emergency and risk management, presents the role of cutting-edge technologies such as artificial intelligence that can be also applied in all the other 4 clusters. Lastly, Cluster 5, centered on real-time responses, evidences the importance of adaptive strategies and dynamic responses to emerging risks. Adaptive strategies can be applied by combining Clusters 1, 2, and 4 together in real-time applications.

This cluster analysis clarifies the multi-faceted nature of research in the application of digital twins to disaster management, highlighting the integration of technological advancements, environmental concerns, and disaster management strategies. This keyword-based clustering also provides a contemporary snapshot of research directions and can guide future inquiries into unexplored or under-represented areas within the discipline.

2.2. Co-Citation Analysis: Influential Journals, References, and Authors

Following standard VOSviewer-suggested procedures, a co-citation analysis was performed to establish the more influential journals and references. Reference co-citation can allow observers to automatically recognize the shape, qualities, and scientific progress of a

research field. In the same way, journal co-citation analysis can be a useful instrument for assessing the general layout of a scientific field relative to the current theoretical framework of specific journals. The algorithm considers that two references or two journals are more strongly connected when they are more frequently co-cited. Again, a clustering algorithm is applied to discover clusters of connected references and journals. In this procedure, only references and journal sources with a minimum of 2 co-citations were included.

The results show that, among 4707 cited references, only 58 meet the threshold of 2 citations. For each of the sorted references, the total strength of the co-citation links with other cited references is calculated, and among the 58 works, 30 have been selected according to the strengths and weights of the connections. Two separate clusters surfaced, differentiated by colors. Larger nodes indicate a higher number of citations, and the different clusters evidence the connections among references (see the following Figure 6).

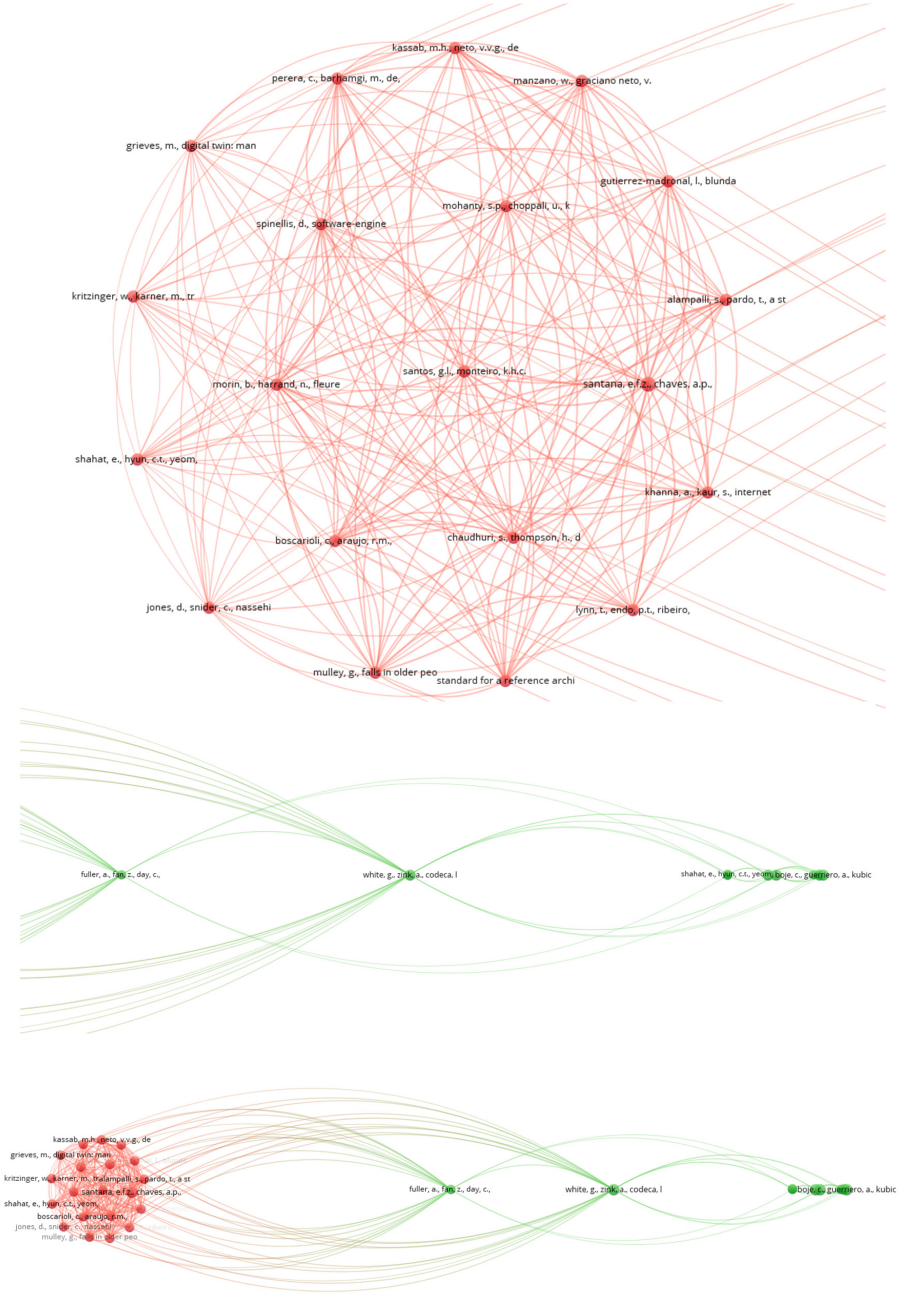

Figure 6. Reference visualization of the 30 most cited works in list "B".

Figure 5 shows that these 30 works can be divided into two clusters, the first indicated in red consisting of 20 papers and very well connected, and the second one consisting of 10 works. Among these 30 papers, 14 have been manually selected as more pertinent to the objectives of this work and are listed in Table 3 in order of total link strength.

Table 3. More pertinent papers (manually selected among works in list B).

Cited Reference (This List of Influential Works Was Obtained from the Papers That Are Cited by the Papers of List "B")	Citations	Total Link Strength
E. F. Z. Santana, A. P. Chaves, M. A. Gerosa, F. Kon, e D. S. Milojicic, «Software Platforms for Smart Cities: Concepts, Requirements, Challenges, and a Unified Reference Architecture», *ACM Comput. Surv.*, vol. 50, 6, pp. 1–37, Nov. 2018, doi: 10.1145/312439 [22]	3	108
S. Alampalli e T. Pardo, «A study of complex systems developed through public private partnerships», in *Proceedings of the 8th International Conference on Theory and Practice of Electronic Governance*, Guimaraes Portugal: ACM, Oct. 2014, pp. 442–445. doi: 10.1145/2691195.2691212. [23]	2	74
C. B. Medeiros, «Grand Research Challenges in Computer Science in Brazil», *Computer*, vol. 41, 6, pp. 59–65, June 2008, doi: 10.1109/MC.2008.188. [24]	2	74
W. Manzano, V. V. Graciano Neto, e E. Y. Nakagawa, «Dynamic-SoS: An Approach for the Simulation of Systems-of-Systems Dynamic Architectures», *Comput. J.*, vol. 63, 5, pp. 709–731, May 2020, doi: 10.1093/comjnl/bxz028. [25]	2	74
S. P. Mohanty, U. Choppali, e E. Kougianos, «Everything you wanted to know about smart cities: The Internet of things is the backbone», *IEEE Consum. Electron. Mag.*, vol. 5, 3, pp. 60–70, lug. 2016, doi: 10.1109/MCE.2016.2556879. [26]	2	74
G. White, A. Zink, L. Codecá, e S. Clarke, «A digital twin smart city for citizen feedback», *Cities*, vol. 110, p. 103064, Mar. 2021, doi: 10.1016/j.cities.2020.103064. [27]	3	49
A. Fuller, Z. Fan, C. Day, e C. Barlow, «Digital Twin: Enabling Technologies, Challenges and Open Research», *IEEE Access*, vol. 8, pp. 108952–108971, 2020, doi: 10.1109/ACCESS.2020.2998358. [16]	2	43
D. Jones, C. Snider, A. Nassehi, J. Yon, e B. Hicks, «Characterising the Digital Twin: A systematic literature review», *CIRP J. Manuf. Sci. Technol.*, vol. 29, pp. 36–52, May 2020, doi: 10.1016/j.cirpj.2020.02.002. [28]	2	38
E. Shahat, C. T. Hyun, e C. Yeom, «City Digital Twin Potentials: A Review and Research Agenda», *Sustainability*, vol. 13, 6, p. 3386, Mar. 2021, doi: 10.3390/su13063386. [29]	2	38
Ford, David N., and Charles M. Wolf. "Smart cities with digital twin systems for disaster management." *Journal of management in engineering* 36.4 (2020): 04020027. [30]	3	13
C. Fan, C. Zhang, A. Yahja, e A. Mostafavi, «Disaster City Digital Twin: A vision for integrating artificial and human intelligence for disaster management», *Int. J. Inf. Manag.*, vol. 56, p. 102049, Feb. 2021, doi: 10.1016/j.ijinfomgt.2019.102049. [31]	3	11
C. Boje, A. Guerriero, S. Kubicki, e Y. Rezgui, «Towards a semantic Construction Digital Twin: Directions for future research», *Autom. Constr.*, vol. 114, p. 103179, June 2020, doi: 10.1016/j.autcon.2020.103179. [32]	3	8
Q. Lu et al., «Developing a Digital Twin at Building and City Levels: Case Study of West Cambridge Campus», J. *Manag. Eng.*, vol. 36, 3, p. 05020004, May 2020, doi: 10.1061/(ASCE)ME.1943-5479.0000763. [33]	2	7
M. Yu, C. Yang, e Y. Li, «Big Data in Natural Disaster Management: A Review», *Geosciences*, vol. 8, 5, p. 165, may 2018, doi: 10.3390/geosciences8050165. [34]	2	7

The main connected cluster of 20 works can be seen expanded in Figure 7.

The largest node is represented by a work from Santana, E.F.Z., Chaves, A.P., Gerosa, M.A., Kon, F., and Milojicic, D.S. (*software platforms for smart cities: concepts, requirements, challenges, and a unified reference architecture, 2018*) [22].

This procedure, in fact, is able to find influential documents that might not be present in the original database (list "B") and that might have received a high number of co-citations in the database.

Among these 30 co-cited documents, it is also possible to see general documents which constitute a scientific basis for the research field under investigation that do not necessarily specifically pertain to the specific field investigated.

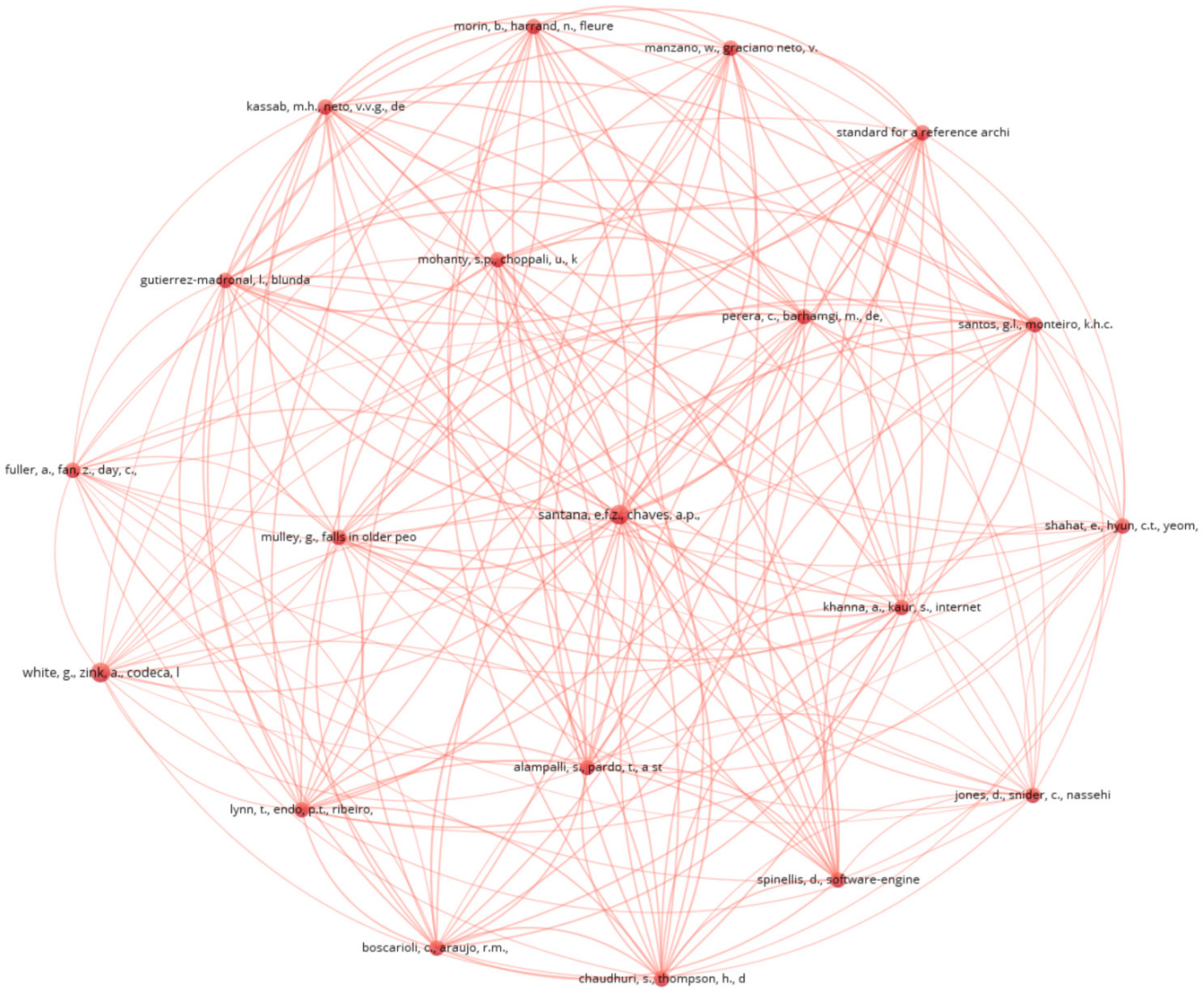

Figure 7. Reference visualization of 20 well-connected works cited in list "B".

2.3. The Most Influential Documents in List "B"

The documents of list "B" have been analyzed to establish the most influential documents according to the number of citations. Using the keywords indicated above, 98 documents were selected manually. By applying a threshold of 20 citations, 10 documents were extracted from the original 98. By performing a network analysis with VOSviewer, only four documents were connected by references and are as follows:

1. Ford, David N., and Charles M. Wolf. "Smart cities with digital twin systems for disaster management." *Journal of management in engineering* 36.4 (2020): 04020027 (130 citations according to Google Scholar) [30];
2. Ham, Youngjib, and Jaeyoon Kim. "twin city: Updating virtual city models for enhanced risk-informed decision-making." *Journal of Management in Engineering* 36.3 (2020): 04020005 (120 citations according to Google Scholar) [35];
3. Park, Sangmin et al. "Design and implementation of a smart IoT based building and town disaster management system in smart city infrastructure." *Applied Sciences* 8.11 (2018): 2239 (93 citations according to Google Scholar) [36];
4. Yu, Dianyou, and Zheng He. "disaster prevention and mitigation for infrastructure: Advances, challenges, and opportunities." *Natural hazards* 112.1 (2022): 1–36 (32 citations according to Google Scholar) [37].

3. Analysis of the Most Relevant Papers

Combining the 4 most influential documents in list "B" and the documents listed in Section 2.2 17 documents that seemed to be more relevant were extracted, and the main contents and main findings are described in this section. All the processes taken from list B are described in Figure 8.

In Santana et al. [22] the main concepts discussed are as follows:

1. Smart Cities: The authors provide various definitions of smart cities, focusing on the integration of social, physical, and IT infrastructure to improve the quality of city services. They also mention the dimensions of a smart city, including smart economy, smart people, smart governance, smart mobility, smart environment, and smart living.
2. Enabling Technologies: The paper identifies four enabling technologies for the development of software platforms for smart cities. These technologies are Cyber–Physical Systems, internet of things, big data, and Cloud Computing. Each technology plays a crucial role in supporting the functionalities and requirements of smart city applications.
3. Software Platforms: The authors define a software platform for smart cities as an integrated middleware environment that supports software developers in designing, implementing, deploying, and managing applications for smart cities. They emphasize the importance of using a software platform rather than ad hoc solutions to ensure robustness and sustainability.
4. Functional and Non-functional Requirements: The paper discusses the various requirements that a software platform for smart cities should fulfill. These requirements include interoperability, scalability, security, data management, service management, and user interface design. Meeting these requirements is essential for the successful development and integration of smart city applications.
5. Reference Architecture: Based on the analysis of existing platforms, architectures, and systems, the authors propose a reference architecture for software platforms for smart cities. This architecture provides a framework for implementing the necessary components and technologies to support the development of scalable integrated smart city applications.
6. Challenges and Opportunities: The paper highlights the challenges and open research problems in developing software platforms for smart cities. These challenges include interoperability between multiple systems, guaranteeing citizens' privacy, managing large amounts of data, and dealing with a variety of sensors. The authors also discuss future opportunities for advancing smart city platforms.

In the paper of Alampalli and Pardo [23], a comprehensive analysis of the factors influencing the development of complex systems is presented, highlighting the intricate balance between social and technical elements. At its core, the research underscores the significance of both these aspects in ensuring successful outcomes in system development.

This is not just about the technology itself but also about the people and processes behind it. One of the key insights from the study is the critical role played by diverse stakeholders in the development process. The involvement of a wide group of individuals, each bringing their own unique perspectives, interests, and expectations, is pivotal. However, what stands out is the commitment these stakeholders have towards collaboration, despite their differing viewpoints. This collaborative spirit is further enhanced by effective communication, which not only improves relationships but also positively influences the work environment. The research also sheds light on the importance of management support and the skillset of the team members. It is interesting to note that while team members are generally equipped with the necessary technical skills, they often lack specific knowledge and experience related to the complex system at hand. This gap highlights the need for a more rounded skillset that encompasses both technical and non-technical aspects. One of the more striking conclusions of the study is the identification of challenges in development, particularly the unanticipated administrative tasks that often pose significant hurdles. Teams, while generally prepared for technical challenges, find these administrative aspects more daunting. This is compounded by the dynamic nature of project requirements,

as well as time and budget constraints. In conclusion, the research provides a nuanced understanding of the complex interplay between technical and social factors in system development. It advocates for development methodologies that effectively bridge these two aspects, ensuring a more holistic approach to system development. The ongoing research in this area is poised to further evaluate existing methodologies, ensuring they are robust enough to encompass the diverse range of factors that influence the development of complex systems.

The paper titled "*Everything You Wanted to Know About Smart Cities*" by Mohanty et al. [26] provides a comprehensive introduction to the concept of smart cities, which is an emerging area of interest in both academia and practical applications. The article serves as a single-source introduction to the concept of smart cities, aiming to familiarize researchers with the vast scope of research possibilities in this domain. A smart city is a place where traditional networks and services are made more efficient, flexible, and sustainable through the use of information, digital, and telecommunication technologies. The paper outlines various components that make a city 'smart', including smart infrastructure, transportation, energy, healthcare, and technology. These components are enabled primarily by Information and Communication Technology (ICT), with the internet of things (IoT) and big data being key drivers. The growing world population and urbanization have led to increased resource and energy consumption, contributing to environmental challenges. Smart cities are seen as a strategy to mitigate problems arising from rapid urbanization, aiming to reduce energy consumption, carbon emissions, and waste. The paper provides a thorough understanding of the concept of smart cities, emphasizing the role of technology in enhancing the efficiency and sustainability of urban environments. It highlights the need for smart cities in the context of global challenges like urbanization and environmental impact and discusses the various components and characteristics that define a smart city.

The paper titled "*Digital Twin: Enabling Technologies, Challenges and Open Research*" by A. Fuller et al. [16] delves into the concept of digital twins, their enabling technologies, and the challenges faced in their implementation and research. The paper provides an in-depth look at digital twins, a technology that creates digital replicas of physical systems, and explores the challenges and potential research areas in this field. The paper distinguishes between a (1) Digital Model, which is a static digital representation without automatic data exchange between the physical and digital model; (2) Digital Shadow: a digital representation with a one-way data flow from the physical to the digital object; and (3) digital twin: a fully integrated digital and physical object with a two-way data flow. The main challenges in digital twin implementation are the necessity of a robust infrastructure for effective operation, obtaining high-quality, consistent data for accurate performance, and concerns about data privacy and security: managing vast amounts of sensitive data poses significant risks. A common misconception derives from the high expectations of AI and IoT technologies, often without a full understanding of their capabilities and limitations. The paper emphasizes the need for a deeper understanding of these technologies to fully realize their potential.

The paper titled "*Characterizing the Digital Twin: A systematic literature review*" by David Jones et al. [28] provides a comprehensive analysis of the digital twin concept. The paper aims to consolidate the understanding of the digital twin concept through a systematic literature review, addressing the varied definitions and characterizations in industry and academia. The research involved a thematic analysis of 92 digital twin publications from the past ten years. The paper identifies 13 characteristics of the digital twin, including Physical Entity/Twin, Virtual Entity/Twin, Physical Environment, Virtual Environment, State, Realization, Metrology, Twinning, Twinning Rate, Physical-to-Virtual Connection/Twinning, Virtual-to-Physical Connection/Twinning, Physical Processes, and Virtual Processes. A complete framework of the digital twin and its operational process is presented. Seven areas for future research 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. The origin of the digital

twin is attributed to Michael Grieves and John Vickers of NASA in 2003. The concept has evolved significantly, driven by advancements in related technologies like IoT, big data, and Industry 4.0. The paper provides a thorough characterization of the digital twin, identifying key areas for future research and addressing the need for a unified understanding of the concept.

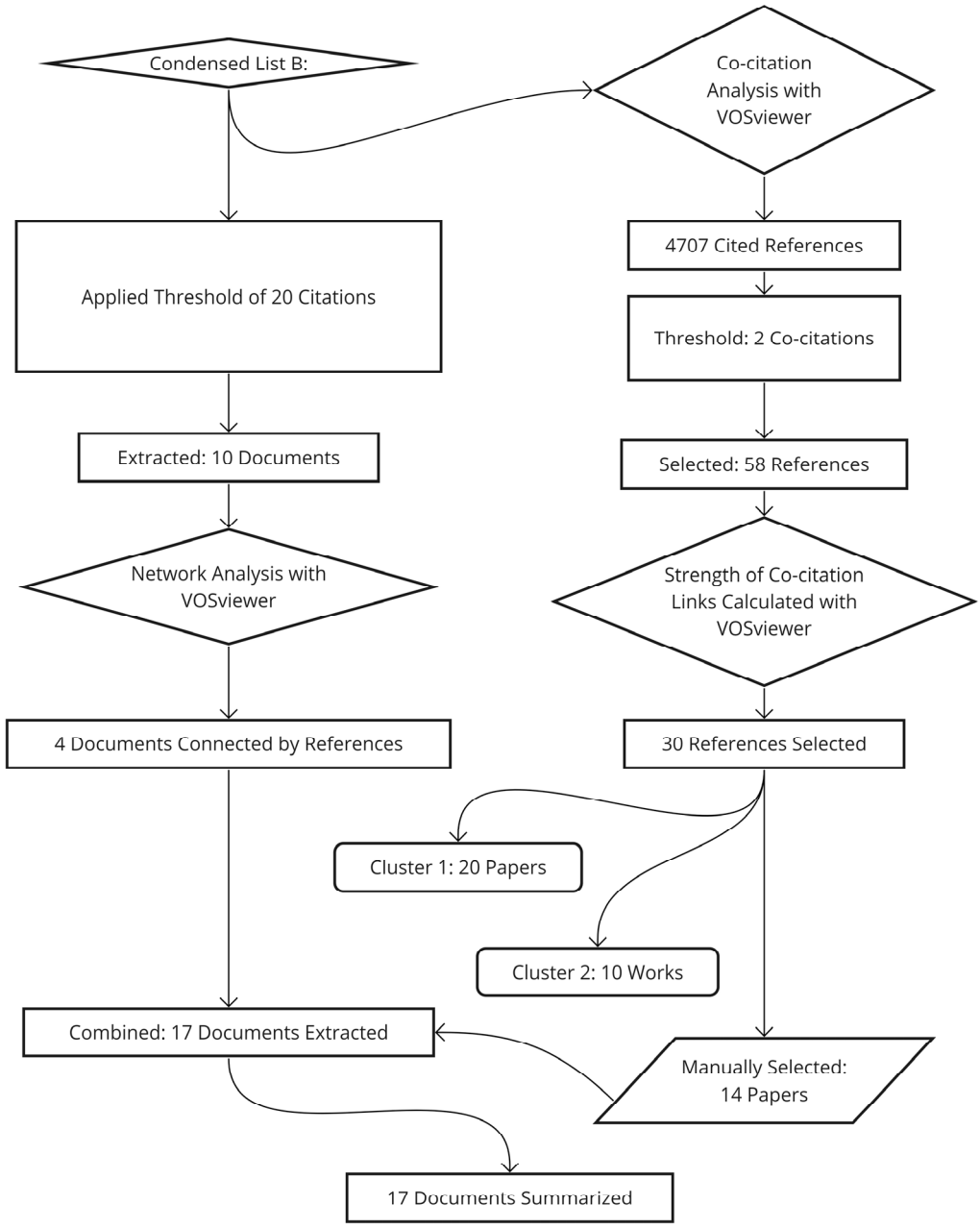

Figure 8. The process to obtain the relevant 17 documents discussed in this section.

The paper titled "*City Digital Twin Potentials: A Review and Research Agenda*" by Ehab Shahat et al. [29] provides an insightful review of the current state and future potential of city digital twins. The paper aims to clarify the potential of city digital twins and highlight the challenges that may hinder their full utilization by conducting a review of the state of the art of city digital twins and by identifying current and prospective benefits and challenges. The city digital twin is anticipated to reflect all city domains and systems on a digital platform, improving the city's visibility, realization, and operability. It is expected to enhance city management and operations, leading to smarter and more sustainable

cities with a higher quality of life for citizens. The paper distinguishes digital twins from traditional 3D models and BIM (Building Information Modeling) in architecture, engineering, and construction (AEC). Digital twins offer mutual interaction between physical reality and the virtual model in real time, unlike BIM, which requires manual data insertion for updates. The complexity of city systems, including integrating social and economic functions, poses significant challenges to realizing a fully mirrored digital twin. The paper also discusses the need for the explicit identification of prospective benefits, challenges, and requirements for developing digital twin cities. A research agenda is proposed to guide future research on city digital twins, focusing on enhancing data processing efficiency, including socio-economic components, and developing mutual integration between digital and physical counterparts. The paper emphasizes the importance of city digital twins in the context of smart city development. It highlights the need for a clear understanding of their potential benefits and challenges, proposing a research agenda to advance digital twin technology and enhance city management and sustainability.

The paper "*Smart cities with digital twin systems for disaster management*" by Ford et al. [30] explores the integration of smart cities with digital twins (SCDTs) in the realm of community disaster management. It emphasizes the need for a holistic approach that combines sensing, simulation, and community management to effectively utilize SCDTs. The paper proposes a conceptual model for SCDTs in disaster management, highlighting its potential to enhance community resilience and response. It identifies two primary threats to SCDT development: the complexity of integrating diverse infrastructure systems and the need for effective information loops. Communities are complex systems comprising built and social infrastructures, such as roadways, governance, and health systems. Disasters disrupt these interdependent systems, stressing the need for effective disaster management strategies that consider both systems and their interactions. The paper outlines the four phases of disaster management: mitigation, preparation, response, and recovery, each evolving over different time horizons. Effective disaster management requires understanding the unique characteristics of a community during a specific disaster and anticipating post-disaster evolution. SCDTs combine smart city technologies and digital twins to improve community management, especially in disaster scenarios. The integration of real-time data from smart technologies and the predictive capabilities of digital twins can optimize disaster management strategies. The paper presents a model of an iterative community disaster management cycle, emphasizing continuous adaptation to changing conditions. SCDTs can enhance all four phases of disaster management, from mitigation to recovery, by providing tools for decision-making and resource allocation. The work contributes to SCDT development by providing improved definitions for SCDT components, describing synergies between SCDTs and disaster management, introducing a new model for information flows in SCDT systems, and identifying and addressing risks to SCDT development. The development and use of SCDTs in disaster management can significantly enhance both fields, with smart city digital twins benefiting from a disaster management focus and vice versa. In summary, the paper concludes that SCDTs hold great promise for improving disaster management in communities, and their development can be accelerated by focusing on this area. The work lays a foundation for future research and development in this domain.

The paper titled "*Disaster City Digital Twin: A vision for integrating artificial and human intelligence or disaster management*" by Fan et al. [31] presents a comprehensive vision for a Disaster City Digital Twin (DCDT) paradigm, aimed at enhancing disaster management through the integration of various technological and interdisciplinary approaches. The DCDT paradigm aims to enable convergence in crisis informatics and ICT in disaster management. It seeks to integrate disciplines for a unified approach to disaster management. AI algorithms and approaches are proposed to improve situation assessment, decision-making, and coordination among stakeholders. The goal is to enhance visibility into the complex network dynamics of disaster management and humanitarian actions. The increasing frequency of natural and man-made crises has escalated the need for effective

disaster management. Current research across various disciplines focuses on ICT and AI solutions but often lacks a common, converging vision. The proposed DCDT includes four main components:

1. Multi-Data Sensing: For data collection from various sources in disaster situations.
2. Data Integration and Analytics: To draw insights from heterogeneous data using AI.
3. Multi-Actor Game-Theoretic Decision-Making: For improving disaster response training and coordination.
4. Dynamic Network Analysis: Capturing interactions among various networks for performance assessment.

The paper discusses challenges in integrating different types of information and AI solutions like knowledge graphs and network embedding. It also explores AI's role in serious game learning environments and dynamic network analysis for disaster management. The DCDT aims to provide predictive insights into planning and response operations in humanitarian actions, and it focuses on improving coordination among various humanitarian and emergency response actors, including robot–human teaming. In summary, the paper advocates for a Disaster City Digital Twin paradigm that integrates AI and ICT to enhance disaster management, emphasizing the need for interdisciplinary convergence and the effective use of AI in various aspects of disaster response and coordination.

4. Discussion of Additional Works

The Google Scholar research tool was used to identify more recent documents that might not have been yet included in the Scopus database. Five documents were found and are listed in Table 4 where the number of citations was established using Google Scholar (the following documents have been published very recently):

The paper "*A Review of Digital Twin Applications in Civil and Infrastructure Emergency Management*" by Cheng et al. [38] discusses the role of digital twins (DTs) in enhancing emergency management of civil infrastructure (EMCI) in the face of natural disasters and human-caused hazards. It acknowledges the severe damages and economic losses caused by such disasters and the need for intelligent technology in emergency response. The paper identifies digital twins as an emerging interdisciplinary paradigm that integrates intelligent technology across various stages of emergency management. However, it notes that current applications of DTs in EMCI are limited and often case-specific, lacking generalizability. To bridge this gap, the paper conducts a systematic literature review using a scientometric approach to analyze the latest progress and research deficiencies in DTs. It proposes a framework explaining how DTs can be applied to the mitigation, preparation, response, and recovery stages of EMCI. The study aims to promote research and development of more viable DTs for emergency management in civil infrastructure. The conclusions highlight the advancements in digital twins and smart cities, particularly in the context of EMCI. The paper addresses how developments in DT construction and exploitation can improve emergency management for civil infrastructure. The systematic literature review identifies three main research topics: development of DTs, critical technologies in DTs, and resilience and emergency management of civil infrastructure. A proposed framework details how DTs facilitate various stages of emergency management, including life-cycle reinforcement, virtual planning, real-time assessment, and collaboration for recovery. The study foresees challenges and prospects in DT applications for EMCI, such as fast modeling, knowledge management techniques, and addressing cybersecurity and data quality issues. The research provides systematic knowledge on DT applications in EMCI, offering insights for academics and practitioners to develop feasible DTs that meet the growing needs of emergency management in infrastructure.

Table 4. List of additional recent works.

Additional Works	Citations
R. Cheng, L. Hou, e S. Xu, «A Review of Digital Twin Applications in Civil and Infrastructure Emergency Management», *Buildings*, vol. 13,5, p. 1143, apr. 2023, doi: 10.3390/buildings13051143. [38]	4
S. Shaharuddin, K. N. Abdul Maulud, S. A. F. Syed Abdul Rahman, e A. I. Che Ani, «Digital twin for indoor disaster in smart city: a systematic review», Int. Arch. Photogramm. *Remote Sens. Spat. Inf. Sci.*, vol. XLVI-4/W3-2021, pp. 315–322, gen. 2022, doi: 10.5194/isprs-archives-XLVI-4-W3-2021-315-2022. [39]	5
M. R. M. F. Ariyachandra e G. Wedawatta, «Digital Twin Smart Cities for Disaster Risk Management: A Review of Evolving Concepts», *Sustainability*, vol. 15, 15, p. 11910, ago. 2023, doi: 10.3390/su151511910. [17]	0
S. Yu, Q. Lei, C. Liu, N. Zhang, S. Shan, e X. Zeng, «Application research on digital twins of urban earthquake disasters», *Geomat. Nat. Hazards Risk*, vol. 14, 1, p. 2278274, dic. 2023, doi: 10.1080/19475705.2023.2278274. [40]	0

The paper "*Digital twin for indoor disaster in smart city: a systematic review*" by Shaharuddin et al. [39] presents a systematic review of the application of digital twins (DTs) in indoor disaster management within smart cities. It explores the integration of Building Information Modeling (BIM), big data, and sensors to create digital twin smart cities. The review identifies a gap in current research, particularly in addressing indoor emergencies and disasters. The study involves analyzing 39 articles from various databases, focusing on smart cities, digital twins, BIM, and disaster management. The findings lead to the proposal of a workflow for smart city digital twins and a conceptual framework for indoor disaster management. The paper suggests that establishing smart city digital twins for indoor emergencies can significantly benefit urban areas in terms of enhanced situation assessment, decision-making, coordination, and resource allocation. The review concludes that there is limited research on indoor disaster management in the context of smart cities and digital twins. This gap is attributed to the digital twin's requirement for real-time data rather than static information. The paper highlights new insights such as data conversion, technology enablers, and data security importance in developing smart city digital twin systems for indoor emergencies. However, it acknowledges that the proposed workflow and conceptual framework are based on the literature and may not fully represent actual industrial practices. In conclusion, the establishment of smart city digital twins focused on indoor emergencies offers significant benefits for urban areas, including improved situation assessment, decision-making, coordination, and resource allocation.

The paper "*Digital Twin Smart Cities for Disaster Risk Management: A Review of Evolving Concepts*" by Ariyachandra and Wedawatta [17] discusses the escalating impact of natural hazard-induced disasters on buildings, infrastructure, and communities, emphasizing the need for effective disaster risk management systems. Digitalization, particularly digital twins (DTs) and smart cities (SCs), is identified as a key enabler for enhancing disaster resilience. The paper reviews the evolution of Digital Twin Smart Cities (DTSCs) and their role in disaster risk management, analyzing 312 titles and abstracts and 72 full papers. It assesses the intelligence technologies used in DTSCs and evaluates their benefits and technical feasibility in disaster risk management. The review finds that while DTSCs offer significant potential benefits, they also introduce new complexities and challenges to disaster risk management. Understanding the process of utilizing DTSCs is crucial for effective disaster risk reduction and sustainability. The introduction highlights the severe impact of natural hazard-induced disasters, with economic losses and casualties on a global scale. The paper underscores the importance of improving disaster risk management systems at various levels, from local to international. Digitalization, including DT and

SC technologies, is seen as a promising avenue for enhancing disaster risk management. DTs provide a digital replica of real-world assets, while SCs connect various aspects of city life to improve quality of life and sustainability. The paper aims to clarify the potential of DTSCs in disaster risk management and proposes recommendations for future research. The paper concludes that digital transition is increasingly impacting society, with DT and SC technologies offering potential solutions for socio-economic and environmental challenges, particularly in disaster risk management. Despite the benefits, DTSCs add complexities to disaster risk management, necessitating a comprehensive understanding of their implementation and impact. The paper identifies challenges such as funding for DTSC projects, technical sustainability, and the need for improved methods to capture spatial and temporal disruptions. The review contributes to understanding the current status of DTSC technologies in disaster risk management and highlights the need for future research to address challenges and opportunities in this field. The findings have broader implications beyond disaster risk management, potentially benefiting various domains.

The paper "*Application research on digital twins of urban earthquake disasters*" by Yu et al., which is not just a review, discusses the use of digital twin technology in creating a digital twin of an earthquake disaster city. This technology enables the reflection of different stages of an earthquake disaster in virtual space, ensuring high synchronization and simulation with the real world. This approach aims to improve the safety of emergency rescue personnel and the decision-making ability of decision-makers. The method involves using oblique photogrammetry and LiDAR data to create a high-precision three-dimensional model of the city. The model is used to calculate seismic intensity, assess building seismic response, and visualize seismic damage. Real-time monitoring of earthquake disasters through sensors and analysis in the digital twin model provides optimal schemes for earthquake emergency rescue and accurate disaster evaluation. China frequently experiences natural disasters, particularly earthquakes, which are sudden and cause severe damage and secondary disasters. Traditional approaches to earthquake disaster management often lead to increased destruction due to their unpredictability. Digital twin technology offers a solution by providing real-time synchronization, accurate rescue, and iterative optimization of decision-making processes in earthquake disaster management. This technology integrates real and virtual interactions to improve earthquake disaster prevention and control. The study proposes the application of digital twin technology in earthquake disaster scenarios. It establishes an urban digital model using a three-dimensional real-scene model and a white model, providing data support for urban digital twins. The study verifies the applicability of the shortest-fault-distance intensity attenuation model for calculating seismic intensity and uses elastic–plastic time history analysis to determine building seismic responses and damage. The main conclusions are as follows:

- The study effectively addresses issues of data volume, iterative updates, and high costs by using a three-dimensional real-scene model for key places and a white model for non-key areas.
- In extreme earthquakes, the seismic capacity of buildings is insufficient, leading to significant damage and losses.
- Digital twin technology can monitor, analyze, and manage earthquake disasters, providing valuable experience for future emergency rescue efforts.

The study highlights the importance of pre-earthquake risk assessment and post-earthquake emergency rescue. However, it also notes limitations, such as the large amount of data required and dependence on network connectivity, which can be compromised during an earthquake. Future research aims to improve the three-dimensional expression ability of the digital world while reducing data volume to achieve diversified real-time digital twins.

5. Discussion on the Risk Mitigation Potential of Digital Twins in Disaster Management and Prevention

5.1. Discussion Introduction

In this section, the different risks that our cities could face are discussed in detail: man-made hazards, floods, earthquakes, and general disaster management are discussed separately in different subsections. A specific discussion of how better evacuation management could mitigate the risks is added for each subsection. The integration of digital twins in disaster management and prevention has shown significant potential in the various studies above indicated. Digital twins, which are virtual replicas of physical entities, can play a crucial role in reducing risks associated with different types of disasters, such as floods, earthquakes, and other natural or man-made hazards.

Moreover, digital twins can help professionals in training and also in better managing risks by enhancing situation awareness and by optimizing resources:

Enhanced Situation Awareness: Digital twins provide a comprehensive view of the disaster's impact on the cityscape, including critical infrastructure and key resources. This enhanced situational awareness is crucial for effective decision-making during disasters.

Resource Optimization: In disaster scenarios, efficient allocation of resources like medical aid, food, and shelter is critical. Digital twins can help in optimizing these resources by predicting demand and coordinating logistics.

Training and Preparedness: Digital twins can be used for training emergency personnel by simulating disaster scenarios. This helps in preparing response teams for various situations, improving their efficiency and effectiveness during actual disasters.

A better evacuation management of risks translates into optimized evacuation plans, significantly enhancing disaster management by ensuring rapid, safe removal from hazardous area [41–46]. Moreover, the use of advanced simulations offers a clear view of the disaster's scope, enabling precise deployment of resources and evacuation routes [47–50]. Additionally, digital twins facilitate targeted training for emergency personnel, heightening preparedness and response efficacy. Collectively, these measures drastically reduce risks to life and infrastructure during disasters.

5.2. Discussion of Specific Risks

In this section, a discussion on how digital twins can be utilized to mitigate risks in various disaster scenarios with special attention dedicated to risk exposure reduction obtained with proper risk mitigation is presented.

5.2.1. Man-Made Hazards

Industrial Accidents: For industrial facilities, digital twins can monitor system health in real time, predict equipment failures, and prevent accidents. In the case of incidents like chemical spills, digital twins can model the spread and guide containment strategies.

Urban Security: In urban environments, digital twins can enhance security measures by simulating scenarios like building evacuations or responses to terrorist threats.

It must be noted that handling the large volume of data required for accurate digital twins is a challenge. Efficient data processing and management are essential for real-time applications. Moreover, digital twins rely heavily on network connectivity. In disasters that disrupt communication networks, the effectiveness of digital twins can be compromised.

Risk reduction with better evacuation management: Enhancing evacuation procedures with digital twin technology significantly mitigates risk by providing precise, real-time simulations of emergency scenarios. This enables the optimization of evacuation routes and strategies, ensuring faster, safer exits from hazardous zones. By accurately modeling crowd dynamics and potential bottlenecks, digital twins facilitate informed decision-making, reducing the likelihood of injury during evacuations. Ultimately, improved evacuation planning minimizes exposure to danger, safeguarding both individuals and communities in times of crisis.

5.2.2. Floods

Flood Prediction and Response: Digital twins can simulate various flood scenarios based on historical data and current environmental conditions. This helps in predicting flood-prone areas, enabling authorities to implement flood defenses and evacuate residents in a timely manner.

Urban Planning and Infrastructure Design: By integrating hydrological data, digital twins can aid in designing flood-resilient urban infrastructure and effective drainage systems, reducing the long-term risk of flooding.

Risk reduction with better evacuation management: Implementing advanced evacuation strategies for flood risk management, guided by digital twin simulations of both roads and flood events, can markedly reduce the impact of flooding and the evacuation process. These two combined simulations (logistic dynamics and flood dynamics) not only pinpoint optimal evacuation routes but also refine flood response strategies, ensuring minimal human and economic losses.

5.2.3. Earthquakes

Real-time Monitoring and Simulation: Digital twins allow for the real-time monitoring and simulation of seismic activities. By creating accurate 3D models of urban areas, digital twins can predict the impact of earthquakes on buildings and infrastructure, enabling preemptive measures to reinforce structures or evacuate areas at risk.

Seismic Intensity and Damage Assessment: As seen in the studies, digital twins can calculate seismic intensity using models like the shortest-fault-distance intensity attenuation model. This helps in assessing potential building damages and visualizing seismic impacts, thereby guiding emergency responses and resource allocation.

Emergency Rescue Management: By simulating earthquake scenarios, digital twins provide valuable insights for emergency rescue operations, helping to identify the most affected areas and optimize rescue efforts.

Risk reduction with better evacuation management: Simulations can assist in the strategic deployment of emergency services, focusing on severely impacted regions for efficient rescue operations. Ultimately, leveraging digital twins for earthquake preparedness ensures faster, safer responses, significantly reducing the disaster's impact on communities.

5.3. Conclusions

In this section, a discussion of the different risks and mitigation strategies has been presented. Challenges and future directions for research activities in this field are discussed in the next section.

6. Challenges and Future Directions

6.1. Introduction to Challenges and Future Directions

According to the papers listed above, there are many challenges for the implementation of digital twins in urban risk reduction. Challenges connected with data management and processing are generated from the difficulty of managing the vast amount of data generated by digital twins, including real-time data from sensors and historical data. Processing these data efficiently to provide timely insights is crucial. For this reason, research into advanced data processing algorithms and efficient data storage solutions is needed. The development of edge computing and distributed processing techniques could be explored to handle data more effectively.

The following points are discussed in the following subsections: data transmission networks and connectivity issues, interoperability and standardization, reliability and accuracy, scalability and customization, cybersecurity and privacy concerns, costs and resource intensiveness, and user training and adoption.

6.2. Data Networks and Connectivity Issues

Digital twins rely heavily on network connectivity for data transmission and real-time monitoring. In disaster scenarios, network infrastructure might be compromised, limiting the effectiveness of digital twins. The future directions of this research appear to be alternative communication methods, such as satellite communication or decentralized networks; this type of solution could provide backup connectivity solutions in disaster scenarios.

6.3. Interoperability and Standardization

Interoperability and Standardization in the implementation of digital twins are also important issues. The challenge is to integrate digital twins with various existing systems to ensure interoperability among different platforms and data formats. Future research could develop universal standards and protocols for digital twins in disaster management. Collaborative efforts between industry, academia, and government agencies might help to establish these standards.

6.4. Reliability and Accuracy

Digital twins should be accurate and reliable to generate useful information; ensuring the accuracy and reliability of the simulations and predictions made by digital twins is critical, especially in high-stakes disaster management scenarios. The solution to this accuracy issue are to push toward a continuous improvement and validation of simulation models based on real-world data and outcomes. Research could take advantage of advanced modeling techniques and AI algorithms for more accurate predictions.

6.5. Scalability and Customization

Digital twins need to be scalable to different sizes of cities and adaptable to various types of disasters; this challenge might foster research into scalable architectures and customizable solutions for digital twins that can be adapted to different urban environments and disaster types.

6.6. Cybersecurity, Privacy Concerns, and Cross-Border Cooperation

With the increasing amount of sensitive data used in digital twins, cybersecurity and privacy concerns become paramount. Research on developing robust cybersecurity frameworks and privacy-preserving technologies for digital twins could rely on blockchain and other secure data-sharing methods.

The Oak Ridge National Laboratory has published a report on "*Regulatory criteria applicable to the use of digital twins*" [51]. In this report, some issues regarding the necessity for cross-border cooperation and data privacy issues are addressed. In detail, it is affirmed that existing policies and regulations play a significant role in shaping the adoption and implementation of digital twin technology in urban risk management. Policy-makers need to consider factors such as data-sharing agreements, cross-border data flows, privacy regulations, and cybersecurity measures when formulating policies related to digital twins. By analyzing the current policy landscape, policy-makers can identify gaps, challenges, and opportunities for promoting the responsible use of digital twins in urban risk management. Moreover, regulatory frameworks provide the legal and institutional structures within which digital twin technology operates. Understanding the regulatory context is essential for ensuring compliance with data protection laws, privacy regulations, and other relevant guidelines. By examining existing regulatory frameworks in different jurisdictions, policy-makers can develop harmonized approaches that facilitate cross-border cooperation while safeguarding data privacy and security.

By synthesizing insights from this report with empirical studies, policy analyses, and regulatory contexts, stakeholders can gain a comprehensive understanding of the opportunities and challenges associated with applying digital twin technology to urban risk management.

In this optic, it is clear that there is a need for cross-border cooperation and that a lot has to be achieved.

Blockchain technologies can help in both cross-border cooperation and data privacy and security. Blockchain technology, in fact, has the power to create trust between different stakeholders and also to secure data that can be encrypted according to the requirements of different entities.

6.7. Costs and Resource Intensiveness

Moreover, the development and maintenance of digital twins require significant resources and investment, and digital twin implementation requires cost-effective solutions and resource optimization. It could be also interesting to explore public–private partnerships and innovative government funding models.

6.8. User Training and Adoption

Ensuring that emergency personnel and decision-makers are adequately trained to use digital twin technology effectively might require the development of comprehensive training programs and user-friendly interfaces, fostering research into the human–technology interaction aspect of digital twins.

6.9. Other Future Research Directions

Other future research directions that have been suggested by the papers outlined in the literature review are as follows:

- Exploring AI and machine learning techniques for predictive analytics in digital twins to anticipate disaster impacts more accurately.
- Developing real-time decision support systems integrated with digital twins to aid emergency responders and decision-makers during disasters.
- Research on integrating digital twins with IoT devices and other emerging technologies like drones and robotics for enhanced disaster response.
- Studying the long-term sustainability of digital twins and their environmental impact, particularly in the context of climate change and urban development.
- Exploring ways to involve the public in the digital twin process to enhance community resilience and disaster preparedness.
- Addressing the ethical and legal implications of using digital twins in disaster management, including issues related to data ownership and usage rights.

6.10. Conclusion

In this section, the potential challenges and future directions of research have been presented.

By addressing these challenges and exploring these future research directions, the field of digital twins in disaster management can continue to evolve, offering more robust, efficient, and effective solutions for mitigating the risks of disasters.

7. Conclusions

7.1. Key Findings and Limitations

Integrating digital twins with existing disaster management systems and ensuring interoperability among various data sources and platforms is crucial.

Digital twins offer a transformative approach to disaster management and risk mitigation. By providing accurate, real-time data and predictive insights, they enable authorities to make informed decisions, optimize resources, and enhance the overall effectiveness of disaster response and recovery efforts. However, realizing their full potential requires addressing technical challenges and solving the relative problems.

The main contribution of this paper is the presentation of both the opportunities and challenges in the context of urban risk management and digital twin applications with a complete literature review.

Moreover, as emerges from the listed relevant papers, many systems are proposed, and yet not many real-world implementations have been achieved with clear success in reducing disaster risks.

7.2. Research Objectives and Practical Implications

The objectives of this paper have been addressed with a detailed procedure to extract a relevant bibliography that claims how digital twins can be integrated into urban planning and disaster management processes to improve the resilience, response mechanisms, and overall sustainability of urban areas.

This study's findings have practical implications for urban planners, policy-makers, and practitioners involved in urban risk management; it is essential to highlight the great potential of integrating digital twins into decision-making processes. By leveraging digital twin technology, urban stakeholders can gain a comprehensive understanding of urban dynamics, anticipate potential risks, and optimize resource allocation strategies. The real-time simulation capabilities of digital twins enable stakeholders to visualize various scenarios, assess the impact of interventions, and make informed decisions to enhance urban resilience and sustainability. Furthermore, the integration of digital twins can facilitate proactive risk management strategies, improve emergency response planning, and streamline infrastructure maintenance practices. Ultimately, by embracing digital twin technology, urban planners and policy-makers can foster more adaptive, efficient, and sustainable urban environments that are better equipped to address emerging challenges and uncertainties.

7.3. Call to Action

In conclusion, the integration of digital twins in urban risk management presents a transformative opportunity for enhancing resilience and sustainability in urban environments. The application prospects of digital twins extend beyond traditional risk assessment methods, offering real-time insights, predictive capabilities, and scenario modeling for proactive risk mitigation strategies. Urban planners and policy-makers can leverage digital twins to visualize and simulate complex urban systems, enabling informed decision-making, resource optimization, and effective response planning in the face of diverse risks. By harnessing the power of data analytics, simulation, and predictive modeling embedded in digital twins, cities can enhance their disaster preparedness, infrastructure management, and overall risk reduction efforts. The main conclusion is that it is imperative for stakeholders to recognize the potential of digital twins as invaluable tools in urban risk management and to actively incorporate them into planning processes. By embracing digital twin technology, urban planners and policy-makers can navigate uncertainties, improve response mechanisms, and foster sustainable urban development practices that prioritize resilience and safety in the face of evolving risks.

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