Prototyping Smart City Solutions with Metaverse and Digital Twins: A Systematic Literature Mapping

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Keywords: Smart Cities, Digital Twins, Metaverse, Prototype, Prototyping.

Abstract: The concept of Smart Cities (SC) has emerged as a strategic approach to address contemporary urban challenges. The integration of innovative technologies, such as Digital Twins (DT or DTs), the Metaverse, prototyping, and stakeholder participation, offers promising solutions for improving urban management. This paper presents a systematic mapping of the main approaches and research on prototyping solutions in Smart Cities, exploring how the metaverse and Digital Twins contribute to these advancements. Based on a detailed analysis of relevant articles, this work investigates key trends and challenges, providing a consolidated view of the state-of-the-art in these emerging areas.

1 INTRODUCTION

In recent decades, as noted by (Iliuţă et al., 2024), the concept of Smart Cities (SC) has gained prominence in urban studies and municipal governance. With urbanization and increasing demand for sustainable solutions, cities face challenges in mobility, energy, infrastructure, and social interaction. The adoption of technologies like Digital Twins (DT or DTs) and the Metaverse offers promising solutions for integrating various urban dimensions (Hu et al., 2023).

One key advancement in SC is the use of DT, which creates virtual replicas of urban systems for real-time simulation, monitoring, and optimization (Iliuţă et al., 2024). When combined with the Metaverse, a 3D virtual space, it enables real-time interaction among citizens, authorities, and stakeholders with digital city representations (Adnan et al., 2024). This integration supports prototyping urban solutions, allowing virtual tests before real-world implementation (Tupayachi et al., 2024).

DT represents a leap in urban system design and management by connecting physical and digital worlds. Powered by sensor data, DTs allow real-time analysis of urban scenarios and simulate future conditions, such as infrastructure performance during natural disasters or the impact of policies (Hu et al., 2023). Their predictive abilities help prevent failures and improve decision-making by balancing efficiency, sustainability, and citizen well-being.

Prototyping is crucial in creating and evaluating SC solutions, as it enables early-stage testing and refinement through iterative processes (Saeed et al., 2023). Using DT and the Metaverse, prototyping becomes more agile, allowing faster experimentation and validation at lower costs (Salminen and Aromaa, 2024). This process improves user feedback, enhances scalability, attracts investments, and fosters stakeholder engagement (Dane et al., 2024).

The combination of DT and the Metaverse addresses dual aspects of SC prototyping. DTs align prototypes with real city data, while the Metaverse enhances interactivity between stakeholders and prototypes, promoting collaboration.

A Systematic Literature Mapping (SLM) investigated how DT and the Metaverse are applied to SC prototyping, mapping contributions, trends, and challenges in using these tools for complex urban systems. This study highlights opportunities to integrate these technologies effectively.

Digital twins and the Metaverse have transformed smart city prototyping by enabling immersive, data-driven simulations. DTs provide real-time virtual replicas of city components for testing and refining systems without disrupting real environments. The Metaverse adds immersive capabilities, fostering col-

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Rizzatto, M. R., L'Erario, A. and Maganha de Almeida, E.
Prototyping Smart City Solutions with Metaverse and Digital Twins: A Systematic Literature Mapping.
DOI: 10.5220/0013279200003929

In *Proceedings of the 27th International Conference on Enterprise Information Systems (ICEIS 2025) - Volume 2*, pages 193-200
ISBN: 978-989-758-749-8; ISSN: 2184-4992

laborative design through augmented and virtual reality. This integration enhances decision-making, improves resource efficiency, and reduces costs by identifying issues early. Together, DTs and the Metaverse enable sustainable, resilient, and human-centric solutions, bridging the gap between concept and implementation.

2 BACKGROUND

The evolution of Smart Cities (SC) is tied to advancements in technologies like IoT, AI, and big data (Alaeifar et al., 2024). Recently, Digital Twins have gained prominence for virtually replicating cities and infrastructures, enabling efficient management and accurate resource predictions (Li et al., 2023). The Metaverse, with its XR capabilities, extends this evolution by offering a collaborative platform for urban visualization, testing, and optimization (Rojek et al., 2024; Papadopoulos et al., 2023). Prototyping within the Metaverse fosters agility and enhances communication among stakeholders (Chen and Ruan, 2024).

Smart Cities apply ICT (Information and Communication Technologies) to improve urban quality of life by optimizing services like transportation, energy, waste management, and safety (Hu et al., 2023). They use real-time data and sensors for informed decision-making, creating more sustainable and responsive environments (Gilman et al., 2024). Beyond infrastructure, SC aim to promote economic and social innovation, ensuring equity and resilience (Gilman et al., 2024).

Digital Twins are virtual replicas of physical objects, systems, or processes connected via real-time data (Iliuţă et al., 2024). They simulate physical behavior, enabling monitoring, analysis, and optimization. In SC, DTs replicate urban infrastructure, predicting failures, improving processes, and testing enhancements before real-world implementation (Perisic and Perisic, 2024; Rojek et al., 2024). This technology transforms urban planning and resource management efficiency (Iliuţă et al., 2024).

The Metaverse is a shared 3D virtual space for real-time interaction (Rojek et al., 2024). While rooted in entertainment, it now spans education, healthcare, and urban planning. For SC, it enables immersive city simulations, facilitating collaboration among architects, planners, and citizens to explore scenarios and improve decision-making (Li et al., 2023).

A prototype represents an initial solution design, allowing for functionality testing and refinement before final production (Iliuţă et al., 2024). In SC, prototypes validate concepts, identify flaws, and enhance design efficiency. They range from infrastructure models to policy simulations, ensuring solutions address population needs effectively (Iliuţă et al., 2024).

Prototyping, the iterative creation and evaluation of prototypes, is essential in SC (Iliuţă et al., 2024). Virtual environments like DTs and the Metaverse accelerate prototyping by enabling scenario exploration and reducing risks before implementation. Digital prototyping allows for cost-effective innovation and agile development, transforming SC solutions (Salminen and Aromaa, 2024).

3 RESEARCH METHOD

A systematic literature review is a method to collect and analyze multiple studies in a structured way. This research applied the approach outlined by (Kitchenham et al., 2007).

Following the guidelines of (Kitchenham et al., 2007; Petersen et al., 2015), the study investigated the use of DT and the Metaverse for prototyping smart city solutions. The adapted protocol ensured a rigorous and reproducible systematic review process.

The research question is: **"How are digital twins and the Metaverse used to prototype solutions for smart cities?"**

This question explores the application, trends, challenges, and gaps in the literature surrounding these technologies.

The study examined five scientific databases:

- SCOPUS;
- Elsevier ScienceDirect;
- IEEE Xplore;
- ACM Digital Library;
- MDPI.

The articles addressed the key terms: smart cities, digital twins, Metaverse, prototype, and/or prototyping. The search string: **"smart cities" AND "digital twins" AND "metaverse" AND ("prototype" OR "prototyping")**.

This string was applied across databases for the period 2020–2024, ensuring recent and relevant articles, as noted by (Sampaio and Mancini, 2007). "The scarcity of relevant articles necessitated stricter inclusion criteria. Limiting the period to 2020–2024 increased the number of relevant results, as no pertinent studies before 2022 were identified."

The following inclusion and exclusion criteria were outlined:

- Inclusion Criteria (IC):
  - IC1 - Articles in English;
  - IC2 - Articles published between 2020 and 2024;
  - IC3 - Complete articles;
  - IC4 - Articles published in journals, periodicals, and scientific conferences in the field of computing and peer-reviewed;
  - IC5 - Articles with studies that discuss or demonstrate the use of digital twins and the Metaverse for prototyping solutions in smart cities.
- Exclusion Criteria (EC):
  - EC1 - Duplicate articles;
  - EC2 - Articles that do not fit the scope of this work;
  - EC3 - Articles that only mention the Metaverse or DT.

The study selection process was conducted in two phases, as described in the Petersen Protocol (Petersen et al., 2015):

1. **First Phase of Article Inclusion.** Articles were initially numbered in ascending order by title, including details such as identifier, BibTeX key or code, type (article, etc.), title, authors, publication source (Scopus, IEEE, etc.), year, and relevant terms or keywords (Smart Cities, Digital Twins, etc.). Titles, abstracts, and keywords were analyzed to check for relevant keywords, excluding references and non-informative content (e.g., tables, graphs). Articles meeting the inclusion criteria advanced to the next phase, while duplicates were marked and excluded. Figure 1 illustrates the inclusion criteria applied during the selection process.
2. **Second Phase of Article Classification.** In this phase (see Figure 2), the full texts of pre-selected articles were analyzed in depth. Relevant terms were noted in the text, excluding references or simple citations. Articles were prioritized based on the presence of keywords in the following order: ”smart cities,” then ”prototype” or ”prototyping,” followed by ”digital twins” and/or ”metaverse.” Irrelevant articles were excluded. A new final table was created, retaining the structure of the initial table but including only relevant articles, with a new ascending numbering system. Figure 2 illustrates the inclusion criteria applied during this phase.

The studies were categorized by their approaches and contributions to the research theme. Categories included digital twin-based prototyping for smart cities, metaverse applications for urban interaction, and studies combining digital twins and the metaverse for smart city prototyping. These classifications helped identify key research areas, trends, and gaps in the literature.

3.1 Data Extraction

The data extracted from the selected articles were organized in a table that includes the following information:

Authors and Year of Publication Article Title Source (Journal/Conference) Methodology Used Main Conclusions Relevance for Prototyping Solutions in Smart Cities using Digital Twins and/or Metaverse The data extraction was performed systematically and in a standardized manner to ensure consistency in the results and facilitate comparative analysis between the studies.

3.2 Classification of Studies

The studies were classified into categories based on their approaches and contributions to the research topic. The categories included:

1. Prototyping based on DT for SC;
2. Use of the Metaverse in urban interaction and simulation;
3. Studies combining DT and the Metaverse for prototyping in SC.

These categories allowed us to map the main research areas and identify trends and gaps in the literature.

4 RESULTS AND DISCUSSIONS

The selected studies were synthesized to identify trends, gaps, and future research opportunities. From 41 articles identified, 18 met the inclusion criteria.

The articles reveal strengths and weaknesses. The paper (Hu et al., 2023) highlights geospatial intelligence for urban digital twins, addressing technical challenges like small object detection. However, ethical issues and practical applications are underexplored.

The article (Gilman et al., 2024) examines smart city data challenges, proposing a ”systems of systems” framework and practical applications like Seoul’s data use. However, it lacks focus on equity, digital twins, and stakeholders.

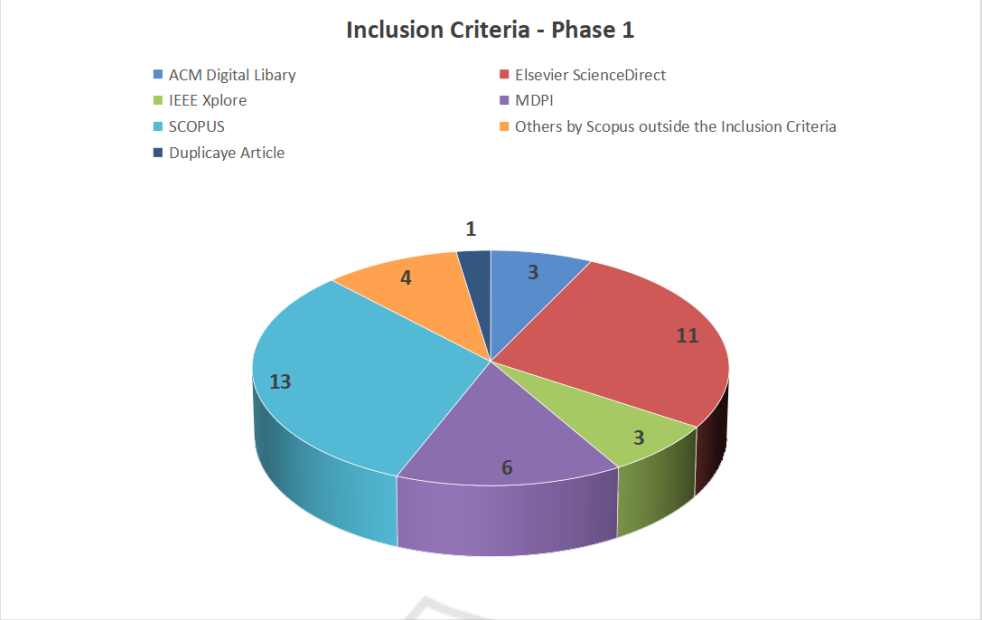

Figure 1: First Phase of applying the inclusion criteria for the articles selected with the search string by publication.

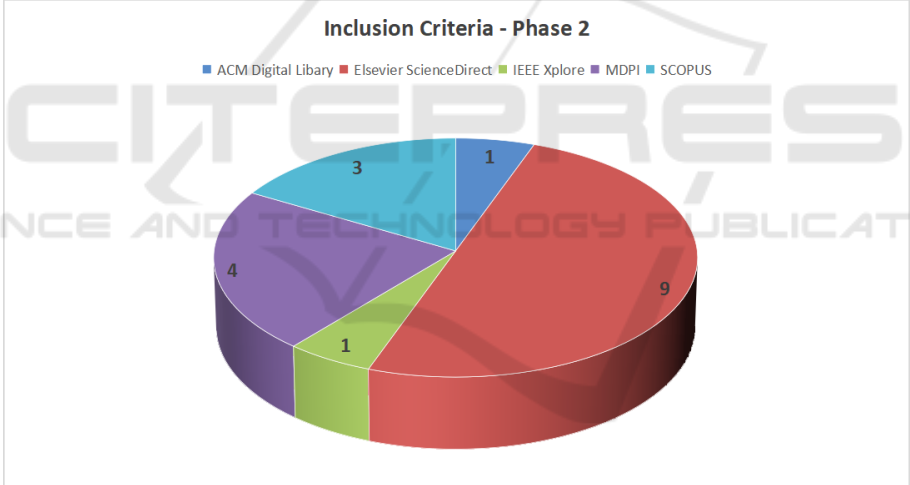

Figure 2: Second Phase of applying the inclusion criteria for the articles selected in this phase by publication.

The study (Alaeifar et al., 2024) explores cyber intelligence sharing, emphasizing IoT and blockchain synergies. However, its focus on cybersecurity overlooks smart city contexts and stakeholder engagement.

The paper (Rojek et al., 2024) defines digital twins for manufacturing, emphasizing efficiency and sustainability. Yet, it offers limited insights into smart city applications and social impacts.

The study (Iliuţă et al., 2024) outlines the evolution of digital twins, analyzing healthcare and industrial uses. However, challenges in urban implementation are minimally addressed.

The article (Dane et al., 2024) proposes a virtual reality framework for participatory urban planning, focusing on stakeholder engagement. Its scope, however, is limited to public spaces.

The paper (Adnan et al., 2024) explores technological convergence in smart grids, proposing resource management models. However, practical urban links are minimal.

The article (Salminen and Aromaa, 2024) examines metaverse applications for road safety education with interactive learning examples. Yet, its focus is narrow, and empirical validation is limited.

The study (Chen and Ruan, 2024) investigates

the metaverse in healthcare supply chains, addressing barriers with blockchain solutions. Complexity and lack of validation are notable challenges.

The paper (Alsamhi et al., 2023) integrates drones and the metaverse into cyber-physical-social systems, offering practical applications. However, complexity and costs limit real-world feasibility.

The article (Papadopoulos et al., 2023) explores mixed reality and IoT synergies but lacks emphasis on smart city applications and privacy concerns.

The paper (Schmitt, 2023) addresses AI for cybersecurity in smart city infrastructure but relies heavily on emerging technologies, limiting accessibility.

The study (Qu et al., 2024) introduces "microverses" for task-specific smart city applications, using blockchain and IoT. However, technical complexity and costs are challenges.

The paper(Tupayachi et al., 2024) applies language models to urban planning, improving data integration. Yet, adoption is limited by technological dependence and lack of social focus.

The article (Hasan et al., 2023) discusses NFTs (Non-Fungible Tokens) for digital twin ownership, proposing decentralized, validated solutions. However, its focus is primarily on manufacturing, with limited smart city relevance.

The papers (Iliuţă et al., 2024), (Saeed et al., 2023), (Schmitt, 2023), (Tupayachi et al., 2024), (Hasan et al., 2023) report on the use of prototypes in DT environments to create a virtual copy of the physical version. The studies (Hu et al., 2023), (Gilman et al., 2024), (Papadopoulos et al., 2023), (Li et al., 2022), (Qu et al., 2024) do not explicitly discuss or use the terms "prototype" and "prototyping." The articles (Alaeifar et al., 2024), (Perisic and Perisic, 2024), (Rojek et al., 2024), (Dane et al., 2024), (Adnan et al., 2024), (Salminen and Aromaa, 2024), (Chen and Ruan, 2024), (Alsamhi et al., 2023) discuss or use the terms "prototype" or "prototyping" but do not explore them in depth.

Thus, the results of applying the protocol resulted in Table 1 with the included articles.

Generating a Table 2 with the included articles and applying this data in VOSviewer [1], a line chart is obtained for a better understanding of Table 2, as presented in Figure 3.

Figure 3 presents the publication of articles by year, and for this reason, the search string was applied for the time frame from 2023 to 2024 to obtain the most recent and relevant works, due to the scarcity of articles in previous years that met the inclusion and exclusion criteria for this study.

The relationship between the names of the publications of the accepted articles, their citations, and citation averages can be observed in Table 3, generated by VOSviewer, for the accepted articles, which can be better understood through Figure 4.

The main findings in answering the research question 'How are DT and Metaverse technologies being used to prototype solutions for SC?' were identified from the 18 included articles. Three main themes emerged: (i) prototyping urban solutions through DT, (ii) the use of the Metaverse for urban visualization and interaction, and (iii) the integration of both technologies for SC solutions.

4.1 Prototyping with DT and Metaverse

DT are essential for creating virtual replicas of urban systems and infrastructure. According to (Perisic and Perisic, 2024), this technology enhances planning by predicting failures and optimizing resources. Additionally, (Iliuţă et al., 2024) note that DT enables agile, iterative testing, offering controlled and cost-effective environments for prototyping.

The integration of DT and the Metaverse is a promising approach for SC prototyping. (Iliuţă et al., 2024) suggest that combining these technologies allows real-time modeling and validation of citizen behavior and infrastructure. Moreover, (Salminen and Aromaa, 2024) emphasize exploring urban scenarios to mitigate risks before physical implementation.

The Metaverse, highlighted by (Adnan et al., 2024) and (Rojek et al., 2024), is a 3D environment for visualization, simulation, and collaboration in SC projects. It enables stakeholders to virtually experience and evaluate proposed changes, fostering transparency and public participation.

4.2 Challenges and Gaps

Despite advances, the reviewed studies highlight challenges, particularly in prototypes and prototyping. Most research focuses on technical aspects, with limited attention to social and ethical factors. Digital prototyping, though powerful for testing, faces difficulties transitioning to practical implementation due to urban complexity.

Adapting virtual prototypes to the physical world efficiently and scalably remains challenging (Iliuţă et al., 2024). The lack of empirical studies validating DT and the Metaverse in real SC environments limits its understanding of their practical impacts (Qu et al., 2024). Integration with public policies and addressing

[1] VOSviewer is a free tool for constructing and visualizing bibliometric networks, available at https://www.vosviewer.com/

Table 1: Results of included articles.

ID	Reference	Smart Cities	Digital Twins	Metaverse	Prototype	Prototyping
1	(Hu et al., 2023)	yes	yes	yes	yes	no
2	(Gilman et al., 2024)	yes	yes	yes	yes	no
3	(Alaeifar et al., 2024)	yes	yes	yes	yes	no
4	(Perisic and Perisic, 2024)	yes	yes	no	yes	yes
5	(Rojek et al., 2024)	yes	yes	no	yes	yes
6	(Iliuţă et al., 2024)	yes	yes	yes	yes	yes
7	(Dane et al., 2024)	yes	yes	no	yes	no
8	(Adnan et al., 2024)	yes	no	yes	yes	no
9	(Saeed et al., 2023)	yes	yes	yes	no	yes
10	(Salminen and Aromaa, 2024)	yes	yes	yes	no	yes
11	(Chen and Ruan, 2024)	yes	yes	yes	yes	no
12	(Alsamhi et al., 2023)	yes	yes	yes	yes	no
13	(Papadopoulos et al., 2023)	yes	yes	yes	yes	no
14	(Schmitt, 2023)	yes	yes	yes	no	yes
15	(Qu et al., 2024)	yes	yes	yes	yes	no
16	(Tupayachi et al., 2024)	yes	yes	no	yes	yes
17	(Hasan et al., 2023)	yes	yes	yes	no	yes
18	(Li et al., 2022)	yes	yes	yes	yes	no

Table 2: Articles included by year.

Year	2020	2021	2022	2023	2024
Publications Accepted (total)	0	0	1	6	11

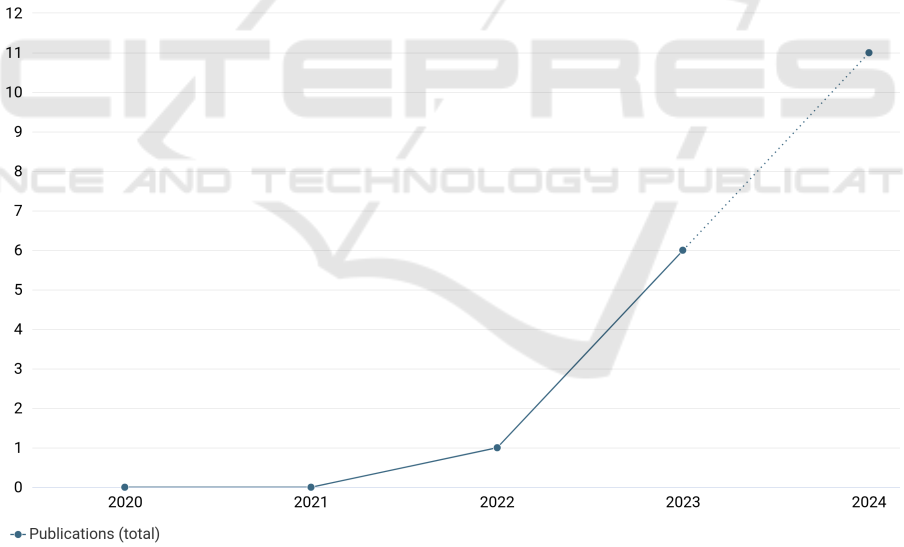

Figure 3: Articles included by year according to Table 2.

accessibility and equity issues are also underexplored (Gilman et al., 2024).

Prototyping requires methodologies that ensure solutions are effective, sustainable, and adaptable to diverse urban contexts. A holistic approach, encompassing technical, social, ethical, and practical aspects, is critical for successfully applying these technologies in SC.

5 FINAL CONSIDERATIONS

The SLM analyzed how DT and Metaverse technologies are applied to prototype SC solutions. These technologies show great potential to transform urban planning, enabling precise simulations and stakeholder collaboration. DT optimize systems and predict failures, while the Metaverse enhances visualiza-

Table 3: Citations per Publication.

Name	Publications	Citations	Citations median
IEEE Internet of Things Journal	1	119	119
Journal of Industrial Information Integration	1	45	45
Future Internet	1	10	10
Future Generation Computer Systems	1	8	8
Engineering Applications of Artificial Intelligence	1	7	7
Smart Cities	1	5	5
Virtual Reality and Intelligent Hardware	1	3	3
Applied Sciences	1	3	3
Advances in Engineering Software	1	2	2
Procedia Computer Science	1	1	1
ACM Transactions on Intelligent Systems and Technology	1	1	1
Computers and Electrical Engineering	1	1	1
Journal of Information Security and Applications	1	1	1
Electronics	2	1	1
Computers Environment and Urban Systems	1	0	-

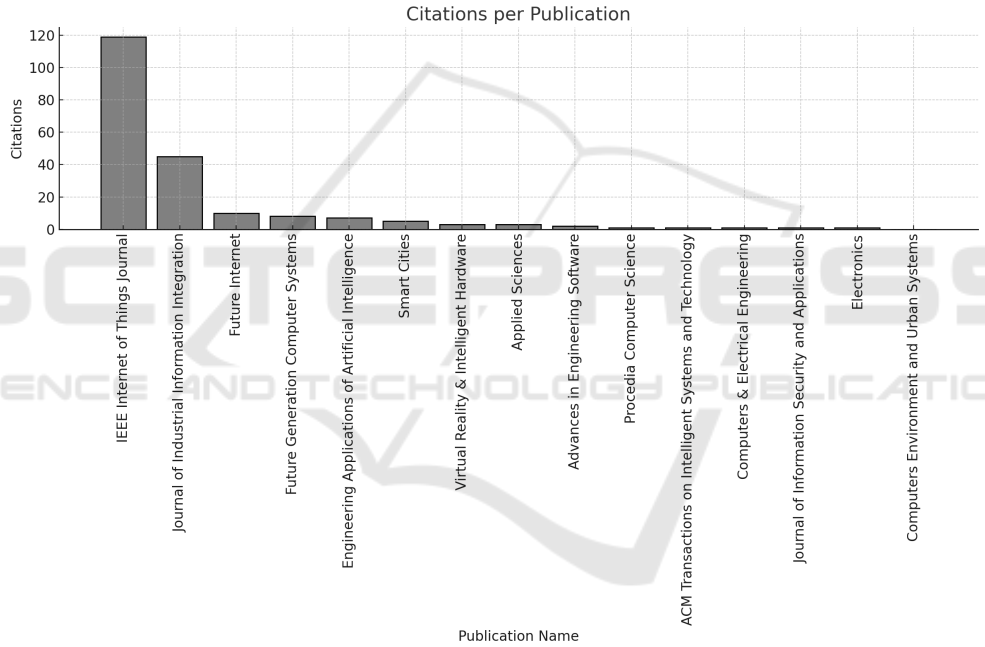

Figure 4: Citations per Publication of the included articles.

tion and communication among managers, citizens, and developers.

Challenges remain, including social, ethical, and equity issues. Implementation requires adequate infrastructure and integration with existing urban systems.

Future research should address:

- **Validation in Real Environments.** Empirical studies to evaluate solutions in real cities, measuring efficiency and public acceptance;
- **Social and Ethical Aspects.** Ensuring inclusivity and benefits for all communities;
- **Integration with Public Policies.** Aligning these technologies with policies for sustainability and equity;
- **Digital Accessibility.** Making DT and Metaverse platforms accessible to all, including people with disabilities.

In conclusion, DT and Metaverse technologies hold transformative potential for SC. They enable collaborative and efficient prototyping of urban solutions. Addressing social, ethical, and accessibility issues, along with policy integration, is essential to ensure inclusivity and sustainability. Continued research will drive progress towards more connected,

responsive, and inclusive cities, benefiting society as a whole.

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