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*Review*

# A Review and Thematic Analysis of How 3D Printing Technology Makes a City Smarter

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**What are the main findings?**

- Key benefits of 3D printing include reducing construction time and material waste, lowering costs, and enabling the creation of scalable, affordable housing solutions.
- Existing challenges remain in terms of cost, scalability, and the need for interdisciplinary collaboration among engineers, urban planners, and policymakers for smart city.

**What is the implication of the main finding?**

- This 3D printing or additive manufacturing (AM) offers potential pathways for sustainable urban development
- Roadmap for future research and practical applications of 3D printing in smart cities, contributing to the ongoing discourse on sustainable and technologically advanced urban development is provided.

**Abstract:** This paper presents a comprehensive review of the transformative impact of 3D printing technology on smart cities. As cities face rapid urbanization, resource shortages, and environmental degradation, innovative solutions such as additive manufacturing (AM) offer potential pathways for sustainable urban development. By synthesizing 66 publications from 2015 to 2024, the study examines how 3D printing improves urban infrastructure, enhances sustainability, and fosters community engagement in city planning. Key benefits of 3D printing include reducing construction time and material waste, lowering costs, and enabling the creation of scalable, affordable housing solutions. The paper also addresses emerging areas such as the integration of 3D printing with digital twins (DT), machine learning (ML), and AI to optimize urban infrastructure and predictive maintenance. It highlights the use of smart materials and soft robotics for structural health monitoring (SHM), and repairs. Despite the promising advancements, challenges remain in terms of cost, scalability, and the need for interdisciplinary collaboration among engineers, urban planners, and policymakers. The findings suggest a roadmap for future research and practical applications of 3D printing in smart cities, contributing to the ongoing discourse on sustainable and technologically advanced urban development

**Keywords:** 3D printing; smart cities; additive manufacturing; digital twins; machine learning; sustainable development; smart material; structural health monitoring; repair; artificial intelligence

## 1. Introduction

Rapid urbanization, resource shortage, environmental deterioration, and the need for sustainable development have plagued cities worldwide in recent years. Innovative solutions to improve urban living conditions and solve the inefficiencies of traditional urban planning and building methods are needed as the world's urban population grows to 68% by 2050 [1]. This yields the growing market for smart building from $97 billion in 2023 to around $400 billion in the next 7 years [2]. In this perspective, 3D printing technology, which is nowadays ubiquitously used in several industries, can change urban development [3]. Its concept of mass customization ascribes to effectively reducing the interval between design creation and prototyping, enabling things to be manufactured in proximity to the consumer as required [4]. This review work examines how 3D

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printing innovation makes cities smarter by improving infrastructure, resource management, and community participation.

Smart cities use technology to improve quality of life, sustainability, and resilience. They use several digital technologies and data-driven solutions to improve service delivery, resource utilization, and public engagement in decision-making. Smart cities use cutting-edge technologies to monitor and control urban processes including transportation, waste management, energy usage, and public safety in real time. "3D printing" or "additive manufacturing" is a critical breakthrough that can improve urban infrastructure, decrease waste, offer zero-net carbon neutrality, and empower communities [5–7], which follows the 2023 United Nations (UN) sustainable development goals (SDGs) [8].

One of the biggest benefits of 3D printing is resource management, which is crucial to smart city development. Material waste from traditional building processes degrades the environment and raises expenses [9]. 3D printing uses additive manufacturing concept to build items layer by layer using just the resources needed. Precision cuts material waste and construction's environmental impact. Ahmed [10] reviewed the 3D printing technology in 2023 and asserted that it provided a solution that significantly diminishes building expenses compared to conventional construction methods: it reduced construction time by 25% for equivalent houses; minimized material costs by decreasing waste; lowered manpower expenses by 50–70%; cut labor costs by 50–80%; decreased labor accidents and injuries by requiring only a team of 3–5 individuals to complete the structure; eliminated costs associated with human errors during construction; and crucially saved 35–60% of the overall project cost by eliminating false-work.

Local production with 3D printing reduces transportation, that can boost local economies and reduce carbon emissions. Cities may improve efficiency and community response by creating local 3D printing hubs to make construction components on demand once the solution can be practically implemented [11]. 3D printing allows quick prototype and experimentation, which can improve urban infrastructure. Before making adjustments, traditional urban planning requires extensive design procedures and major infrastructure expenditure. However, 3D printing lets city planners and designers quickly construct scale models and prototypes for iterative design testing and modification [12]. Smart city efforts require adaptation; thus flexibility is key. Cities can use 3D printing to test public space, transportation, and emergency shelter designs before building them. For example, temporary 3D printing concrete walls and structural self-supported pavilions can be built and fabricated onsite [13–15]. Planners may receive real-time input from citizens and stakeholders to ensure that developments meet community requirements via experimentation.

Housing is another important area where 3D printing can make cities smarter. Many cities have housing shortages, worsening homelessness and affordability. By building affordable homes quickly and cheaply utilizing 3D printing technology, these issues may be addressed. Several projects have shown that 3D-printed structures may be practical and attractive. Smart cities can reduce housing instability and improve quality of life by offering scalable affordable housing alternatives [16]. In addition to infrastructure and housing, 3D printing promotes urban community participation and participatory planning. Cities may guarantee their developments meet community requirements by including individuals in planning and construction. In workshops, tourism, travel, food-engaged, and community activities, citizens may design public areas, parks, and community buildings using 3D printing [17]. Participants and tourists feel empowered and proud of their urban surroundings with this participatory visualized technique. The strong positive attitudes were obtained around 64% when the 3D printing were involved in their industries in Egypt [18]. Besides, 3D printing in school may also raise understanding of urban planning procedures and encourage civic engagement, especially for STEM, social science, and historical students [19,20]. Additionally, a notable feature of another garden project in Kenya is the cost. It has produced a 2-bedroom house at an estimated price of $28,000, which is considerably cheaper than the typical price of similar houses around 35.7%. Furthermore, the initial 10 residences were produced in under 2.5 months [21].

The use of 3D printing in smart cities can help improve sustainability. As cities lessen their environmental effect, 3D printing may help create eco-friendly materials and construction methods.

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3D printing with recycled or bio-based materials supports circular economy and sustainable development (e.g. as low as 0.0524 kgCO2eq/kg) [22,23]. Recycling plastics or organic materials in 3D printing filaments such as recycled polylactic acid (PLA), polyethylene terephthalate (PET), glycol-modified PET (PET-G), ABS, and high-impact polystyrene (HIPS) minimizes waste and encourages sustainable building, thus study is ongoing [24–27]. Innovative energy-efficient designs like buildings that utilize natural light, and ventilation can be created using 3D printing. de Rubeis [28] examined the thermal performance of a PLA construction using 3D printing cavities by infrared thermography and a hot box method. His findings indicated that insulating the voids with wool results in thermal uniformity. In addition, Sun et al. [29] conducted an examination of the thermal performance of a 3D-printed prototype structure utilizing infrared thermography. The investigation suggested an irregular temperature distribution throughout the cross-section and elevation of the building, signifying disparities in thermal characteristics. The average U-value varied from the U-value at certain sites by as much as 58%.

Since digital technology is expanding rapidly, new innovations implemented our city to become smarter with the contemporary improvement domain with the aim to improve quality of life [30], thus summarizing which innovation is vital for our smart city is beneficial. According to the literature search, the development summary from existing articles is missing. The main research question of this work is shown below:

Research question: How does 3D printing make cities smarter?

The preferred reporting items for systematic reviews (PRISMA)-based qualitative technique for keywords of screened articles is used to identify relevant characteristics [31], which will be explained in depth.

## 2. Methodology

The review covers two parts: qualitative study based on the keyword used and systematic review of existing literature. The systematic review followed PRISMA principles for systematic reviews and meta-analyses, which have been created for several research domains. PRISMA is shown in Figure 1. Studies were retrieved from Scopus, Pubmed, and Google Scholar. Due to very fast 3D printing development [32], the scope focused on the articles published during 2015–2024. Research from before this decade may be obsolete, and the review may not represent current developments. After review, 3D printing in smart cities is underrepresented, thus this article reviews it for smarter cities and smarter buildings. Thus, the study searched Scopus using title, abstract, and keywords in text:

TITLE-ABS-KEY((Smart city OR Smart build*) AND (3D printing OR Additive Manufact*)) AND PUBYEAR > 2014 AND PUBYEAR < 2025 AND ( LIMIT-TO ( LANGUAGE,"English" ) ) AND ( LIMIT-TO ( SRCTYPE,"j" ) OR LIMIT-TO ( SRCTYPE,"p" ) OR LIMIT-TO ( SRCTYPE,"b" ) )

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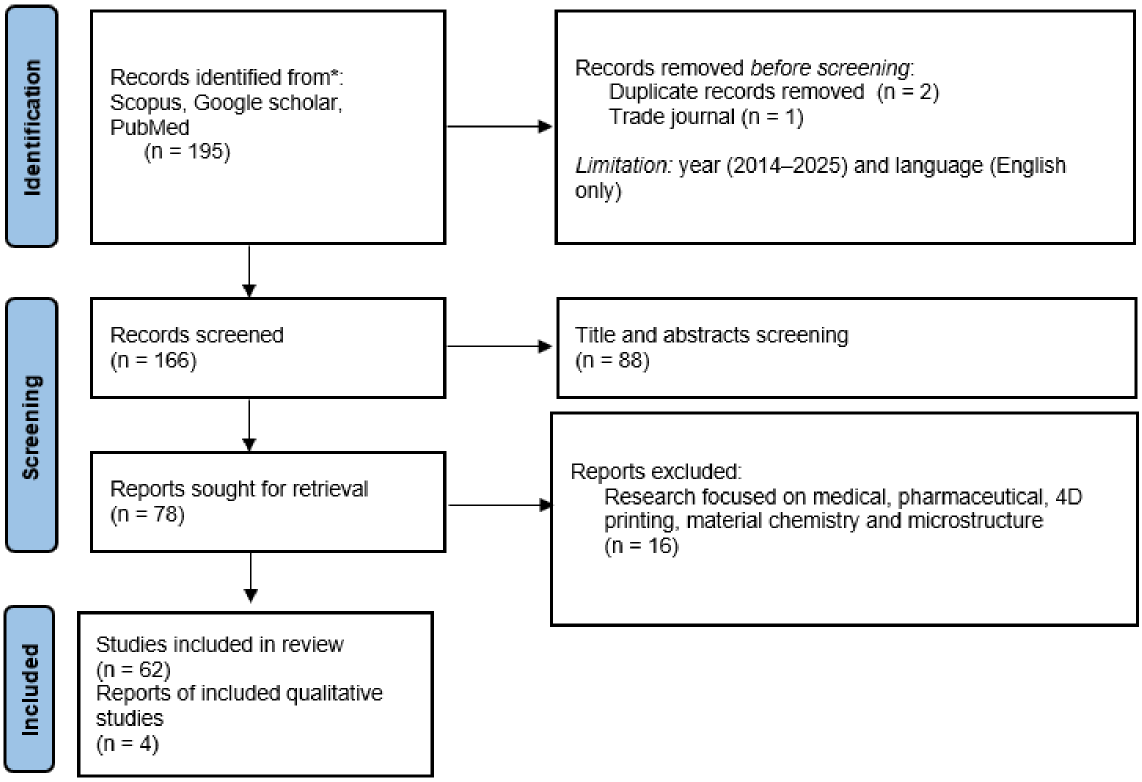


**Figure 1.** The review approach obtained using the PRISMA guidelines. (source by author).

### *2.1. In-/Exclusion Criteria*

The present systematic review incorporates the subsequent criteria for inclusion and exclusion.

Inclusion criteria

- Regarding the utilization of 3D printing for smart city perspective
- The paper needs to use current 3D printing technologies with a published date later than 2015
- Provide a detailed explanation of the effectiveness of each technology offers
- Must be occurred in the smart city settings
- Only English language used

Exclusion criteria

- Exclude the topics focused on medical, pharmaceutical, automative, 4D printing, material microstructure applications
- General argument
- Trade article
- The paper is based on another study
- The investigation lacks adequate information regarding the AR/VR technology

### *2.2. Data Extraction*

During the manuscript evaluation process, the title, abstract, and keywords were examined to verify that the submissions conform to established requirements. This process entails the systematic extraction of several critical core components following a keyword analysis search. After screening, 62 articles were analyzed for this review. The importance of 3D printing was examined. The challenges and prospective research directions subsequently are also addressed for each section. This review study highlights the significance and prospects for academic communities to understand and adhere to the context for future research.

## 3. Review Analysis and Discussion

### *3.1. Thematic Analysis on Keywords*

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Sixty two pertinent publications were identified from the literature search and screened articles, as given in Table 1. From the thematic analysis, Figure 2 illustrates the number of articles released year from 2015 to 2024. Analysis indicated that the trend of 3D printing in smart cities is fast escalating. The interests around this issue are growing increasingly pronounced. During the initial stage, extensive research focused on developing smart materials and smart manufacturing. Subsequently, the research advances to the AI, machine learning (ML), and digital twins (DT) technology integration. The frequency of terms utilized more than twice was aggregated and depicted in Figure 3. When ranking the frequency of these keywords from most to least common, the investigation indicates that 3D printing in smart cities, in relation to smart manufacturing, comprises the most often utilized terms. This is succeeded by smart materials, DT, industry 4.0, soft robotics, AI, SHM, and wire-arc additive manufacturing (WAAM). The keywords were subsequently examined for each segment. The phrases "3D printing," "additive manufacturing," and "smart city" were omitted as they are already contextual to the study. Also, the AI has been addressed in most other topics, so the discussion of AI/3D printing for smart cities is not mentioned here.

**Table 1.** Existing literature determined in this review.

| Title | Year | Journal | Field of study | | Source |
|---|---|---|---|---|---|
| 3D printed architected shell-based ferroelectric metamaterials with programmable piezoelectric and pyroelectric properties | 2024 | Nano Energy | Smart materials | | [33] |
| Online distortion simulation using generative machine learning models: A step toward digital twin of metallic additive manufacturing | 2024 | Journal of Industrial Information Integration | Digital twin | | [34] |
| Selection of digital fabrication technique in the construction industry—A multi-criteria decision-making approach | 2024 | Frontiers of Structural and Civil Engineering | Smart manufacturing | | [35] |
| Printed PZT Transducers Network for the Structural Health Monitoring of Foreign Object Damage Composite Panel | 2024 | 11th European Workshop on Structural Health Monitoring | Structural health monitoring | | [36] |
| Digital Twins in 3D Printing Processes Using Artificial Intelligence | 2024 | Electronics | Digital twin | Industry 4.0 | [37] |
| Monitoring and control the Wire Arc Additive Manufacturing process using artificial intelligence techniques: a review | 2024 | Journal of Intelligent Manufacturing | Machine learning | Wire arc additive manufacturing | [38] |
| Digitalization for sustainable buildings: Technologies, applications, potential, and challenges | 2024 | Journal of Cleaner Production | Digital twin | | [2] |
| Cure-on-demand 3D printing of complex geometries for enhanced tactile sensing in soft robotics and extended reality | 2024 | Materials Today | Soft robotic | | [39] |
| Environmentally Friendly Smart Construction—Review of Recent Developments and Opportunities | 2023 | Applied Sciences | Digital twin | | [40] |

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|---|---|---|---|---|
| Exploring Spatial Patterns in Sensor Data for Humidity, Temperature, and RSSI Measurements | 2023 | Data | Indoor climate | [41] |
| 3D Printed Hemispherically Radiating Antenna for Broadband Millimeter Wave Applications | 2023 | IEEE Open Journal of Antennas and Propagation | Artificial intelligence | [42] |
| Smart-substrate: a novel structural design to avert residual stress accretion in directed energy deposition additive manufacturing | 2023 | Virtual and Physical Prototyping | Smart material | [43] |
| Hybrid direct ink writing/embedded three-dimensional printing of smart hinge from shape memory polymer | 2023 | Manufacturing Letters | Smart material | [44] |
| One-shot additive manufacturing of robotic finger with embedded sensing and actuation | 2023 | International Journal of Advanced Manufacturing Technology | Smart material | [45] |
| Material Extrusion on an Ultrasonic Air Bed for 3D Printing | 2023 | Journal of Vibration and Acoustics | Smart material | [46] |
| Toward a smart wire arc additive manufacturing system: A review on current developments and a framework of digital twin | 2023 | Journal of Manufacturing Systems | Digital twin | [47] |
| Identifying the feasibility of 'travelator roads' for modern-era sustainable transportation and its prototyping using additive manufacturing | 2023 | Sustainable Operations and Computers | Smart manufacturing | [48] |
| Smart Thermoplastics for Maintenance and Repair of Heritage Structures | 2022 | Encyclopedia of Materials: Plastics and Polymers | Smart material | [49] |
| Additive manufacturing of a passive, sensor-monitored 16MnCr5 steel gear incorporating a wireless signal transmission system | 2022 | Procedia CIRP | Industry 4.0 | [50] |
| A critical review on Classification of materials used in 3D printing process | 2022 | Materials Today: Proceedings | Smart material | [51] |
| 3D Marketplace: Distributed Attestation of 3D Designs on Blockchain | 2022 | Proceedings - 2022 IEEE International Conference on Smart Computing | Industry 4.0 | [52] |
| Comprehensive Study on Materials used in Different Types of Additive Manufacturing and their Applications | 2022 | International Journal of Mathematical, Engineering and Management Sciences | Smart material | [53] |
| Particle-resin systems for additive manufacturing of rigid and elastic magnetic polymeric composites | 2022 | Additive Manufacturing | Smart material | [54] |
| Origami-Based Design for 4D Printing of 3D Support-Free Hollow Structures | 2022 | Engineering | Smart material | [55] |

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| | | | | | |
|---|---|---|---|---|---|
| Examining the influence of big data analytics and additive manufacturing on supply chain risk control and resilience: An empirical study | 2022 | Computers and Industrial Engineering | | Industry 4.0 | [56] |
| Electronics - A First Course for Printed Circuit Board Design | 2022 | ASEE Annual Conference and Exposition | | Artificial intelligence | [57] |
| Numerical simulation and evaluation of the world's first metal additively manufactured bridge | 2022 | Structures | | Digital twin | [58] |
| Luminaire for Connected Lighting System with Spectrum that Mimics Natural Light | 2022 | 2022 Opportunity Research Scholars Symposium | | Artificial intelligence | [59] |
| Context awareness in process monitoring of additive manufacturing using a digital twin | 2022 | International Journal of Advanced Manufacturing Technology | Wire Arc Additive Manufacturing | Digital twin | [60] |
| Screen-Printed FSS Plasterboard for Wireless Indoor Applications | 2022 | Mediterranean Microwave Symposium | | Artificial intelligence | [60] |
| A Campus Prototype of Interactive Digital Twin in Cyber Manufacturing | 2022 | Proceedings of the 20th ACM Conference on Embedded Networked Sensor Systems | | Industry 4.0 | [61] |
| Additive manufacturing (3D Printing)-applied construction: Smart node system for an irregular building façade | 2022 | Journal of Building Engineering | | Smart manufacturing | [62] |
| Molds with advanced materials for carbon fiber manufacturing with 3d printing technology | 2021 | Polymers | | Smart material | [63] |
| Modular design principle based on compartmental drug delivery systems | 2021 | Advanced Drug Delivery Reviews | | Soft robotic | [64] |
| Remotely triggered morphing behavior of additively manufactured thermoset polymer-magnetic nanoparticle composite structures | 2021 | Smart Materials and Structures | | Soft robotic | [65] |
| Fiber optic sensors embedded in textile-reinforced concrete for smart structural health monitoring: A review | 2021 | Sensors | | Structural health monitoring | [66] |
| Bulk Ferroelectric Metamaterial with Enhanced Piezoelectric and Biomimetic Mechanical Properties from Additive Manufacturing | 2021 | ACS Nano | | Smart material | [67] |
| 3D Printing Deformation Estimation Using Artificial Vision Strategies for Smart-Construction | 2021 | Industrial Electronics Conference | | Artificial intelligence | [68] |
| Reproducibility and embedding effects on static performance of 3D printed strain gauges | 2021 | IEEE International Workshop on Metrology for Industry 4.0 and IoT | | Structural health monitoring | [69] |

| | | | | |
|---|---|---|---|---|
| Introduction to additive manufacturing | 2021 | Additive Manufacturing | Repair | [70] |
| Digital technology and the world of the future: implications for the management of technology | 2021 | Proceedings of the 30th International Conference of the International Association for Management of Technology | Artificial intelligence | [71] |
| 3D printed temperature-sensing repairs for concrete structures | 2020 | Additive Manufacturing | Repair | [72] |
| The effects of additive manufacturing and electric poling techniques on PVdF thin films: Towards 3D printed functional materials | 2020 | ASME 2020 Conference on Smart Materials, Adaptive Structures and Intelligent Systems | Smart material | [73] |
| Machine learning for advanced additive manufacturing | 2020 | Matter | Machine learning | [74] |
| Smart build-plate for metal additive manufacturing processes | 2020 | Sensors | Structural health monitoring | [75] |
| Realtime control-oriented modeling and disturbance parameterization for smart and reliable powder bed fusion additive manufacturing | 2020 | Proceedings of the 29th Annual International Solid Freeform Fabrication Symposium | Smart manufacturing | [76] |
| Disrupting from the Inside: UK Archipreneurs | 2020 | Architectural Design | Smart manufacturing | [77] |
| Multi-Nozzle Pneumatic Extrusion Based Additive Manufacturing System for Fabricating a Sandwich Structure with Soft and Hard Material | 2019 | Proceedings - International Conference on Machine Learning and Cybernetics | Smart manufacturing | [78] |
| A review of the current progress and application of 3D printed concrete | 2019 | Composites Part A: Applied Science and Manufacturing | Smart material | [79] |
| Additive manufacturing of cementitious composites: Materials, methods, potentials, and challenges | 2019 | Construction and Building Materials | Smart manufacturing | [80] |
| SMP Prototype Design and Fabrication for Thermo-responsive Façade Elements | 2019 | Journal of Facade Design and Engineering | Smart manufacturing | [81] |
| 3D printing for sustainable construction | 2019 | Proceedings of the 2nd International Conference on Sustainable Smart Manufacturing | Industry 4.0 | [82] |
| Direct-Write Printed Current Sensor for Load Monitoring Applications | 2019 | IEEE Power and Energy Society Innovative Smart Grid Technologies Conference | Structural health monitoring | [83] |
| QUILT: Quality inference from living digital twins in IoT-enabled manufacturing systems | 2019 | Proceedings of the 2019 Internet of Things Design and Implementation | Digital twin | [84] |
| A Wireless Triboelectric Nanogenerator | 2018 | Advanced Energy Materials | Artificial intelligence | [85] |

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| | | | | |
|---|---|---|---|---|
| Intelligent nozzle design for the Laser Metal Deposition process in the Industry 4.0 | 2017 | Procedia Manufacturing | Smart manufacturing | [86] |
| A prelimiary study on 3D printed smart insoles with stretchable piezoresistive sensors for plantar pressure monitoring | 2017 | ASME International Mechanical Engineering Congress and Exposition Proceedings | Smart manufacturing | [87] |
| Integrating Fiber Fabry-Perot Cavity Sensor into 3-D Printed Metal Components for Extreme High-Temperature Monitoring Applications | 2017 | IEEE Sensors Journal | Smart material | [88] |
| Digital Manufacturing- Applications Past, Current, and Future Trends | 2017 | Procedia Engineering | Smart manufacturing | [89] |
| 3D printed strain gauge geometry and orientation for embedded sensing | 2017 | 58th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference | Structural health monitoring | [90] |
| Overview of the oak ridge national laboratory advanced manufacturing integrated energy demonstration project: Case study of additive manufacturing as a tool to enable rapid innovation in integrated energy systems | 2016 | ASME International Mechanical Engineering Congress and Exposition, Proceedings | Smart manufacturing | [91] |
| Multifunctional and multiphasic materials as load-bearing structural components | 2016 | Proceedings, Annual Conference - Canadian Society for Civil Engineering | Smart material | [92] |
| Advanced ceramic components with embedded sapphire optical fiber sensors for high temperature applications | 2016 | Materials and Design | Smart material | [93] |
| 3D-Printed Origami Packaging with Inkjet-Printed Antennas for RF Harvesting Sensors | 2015 | IEEE Transactions on Microwave Theory and Techniques | Smart manufacturing | [94] |
| Combined 3D printing technologies and material for fabrication of tactile sensors | 2015 | International Journal of Precision Engineering and Manufacturing | Smart material | [95] |

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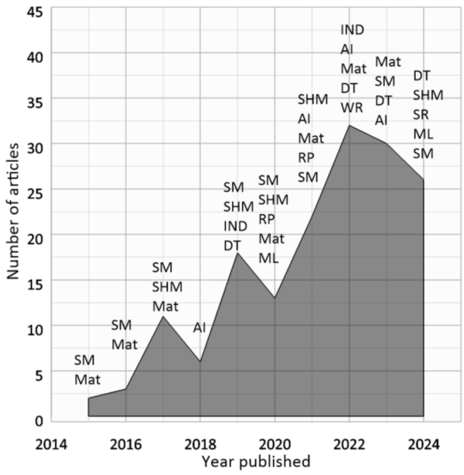


**Figure 2.** Number of publications published, and keywords used each year during 2015–2024 (SM = smart manufacturing; Mat = smart material, SHM = structural health monitoring, AI = artificial intelligence, IND = industry 4.0, DT = digital twin, RP = repair, ML = machine learning, and WR = wire arch additive manufacturing). (source by author).

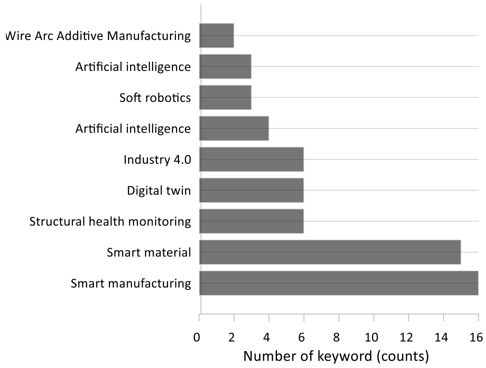


**Figure 3.** Count of keywords used in this literature review. (source by author).

### *3.2. Digital Twins (DT) in 3D Printing for Smart Cities*

DT technology is progressively used to model the performance of intricate systems, including those employed in building and manufacturing industry. Integrating AI enhances the accuracy of these simulations and their capacity to manage extensive data, facilitating predictive maintenance and process optimization. Rojek et al. (2024) examined the influence of digital transformation on enhancing 3D printing methodologies using DT virtual representations of physical entities and mentioned that it facilitate real-time surveillance and enhancement of industrial operations. This research emphasizes that DT serve as a potent instrument for forecasting and alleviating challenges in 3D printing, including flaws and inefficiencies. In terms of the construction technology, DT mainly serves with process of simulation stage before printing actual buildings, as depicted in Figure 4. The wall panels, flat slab, other structural components can be efficiently printed and fabricated with other construction additive to improve their performance and functionality such as ultra-high strength (more than 100 MPa) as well as thermal and acoustic insulations [96,97]. For instance, with different printing configurations, the structural performance to the weight ratios of the 3D printing wall panels can be enhanced greater than 200% from the original design [98].

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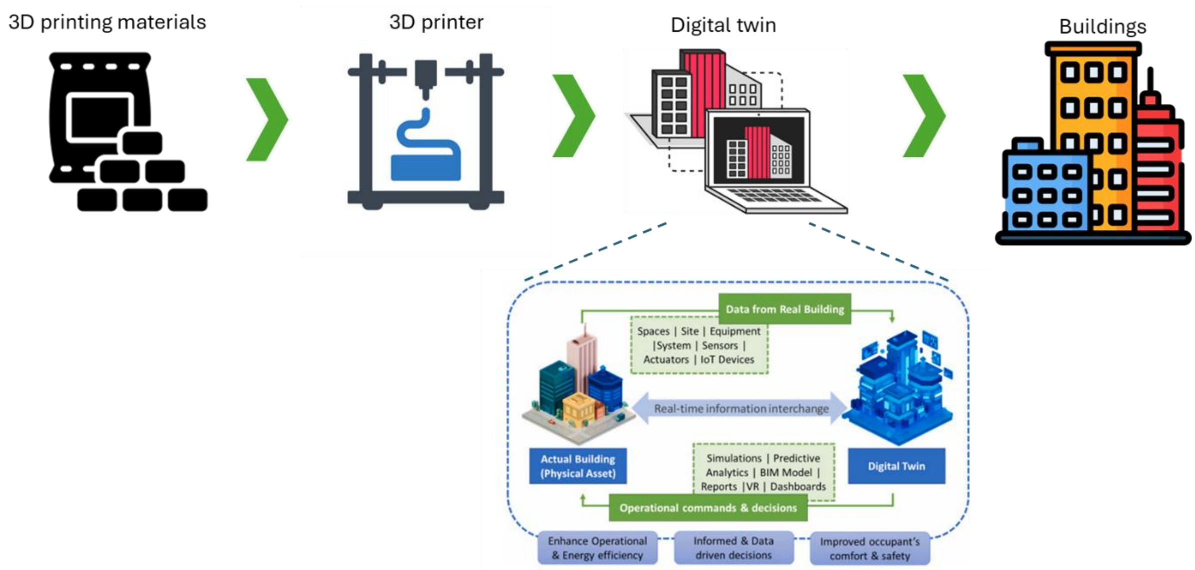


**Figure 4.** 3D printing construction process with DT (source by author).

In the contexts of urban planning for smart cities, DT general support the 3D city simulations from several factors such as environmental, spatial, historical, and in situ collected data [99,100]. The 3D printing can model and used as preliminary study from the data obtained from Geographical Information Systems (GIS). This benefits for continuously learning and adaptation, providing more accurate predictions and facilitating better decision-making processes for urban planning such as categorization of the land use [101]. This approach is particularly valuable in built environments, where the optimization of resources and reduction of downtime are critical for maintaining competitiveness and sustainability [102].

Although the future of DT in 3D printing appears promising, there remain obstacles to its broad adoption. DT necessitates considerable initial investment in technology and training, potentially posing a barrier for smaller enterprises. Furthermore, the integration of digital twins with 3D printing necessitates defined data protocols and enhanced compatibility among software systems [37]. As "smart city" project projects gain traction globally, it is imperative for governments, international organizations, and significant businesses to advocate for these standards, therefore enabling more seamless integration [103–105].

### *3.3. 3D Printing in Industry 4.0 for Smart Cities*

Industry 4.0, commonly known as the Fourth Industrial Revolution, signifies a radical change in industrial operations via the integration of modern digital technology in manufacturing and other sectors. Industry 4.0 is defined by the integration of physical and digital realms, utilizing technologies such as the Internet of Things (IoT), AI, cyber-physical systems, cloud computing, and big data to establish highly automated, efficient, and linked industrial ecosystems. As Industry 4.0 progresses, its impact on industries such as building, manufacturing, and urban development—especially in smart cities—grows more substantial [106,107].

3D printing revolutionizes built environments within the framework of Industry 4.0 in the era of "Fab Cities" and "Maker Cities" [108]. It facilitates the fabrication of intricate structures with exceptional precision and minimum waste through the methodical stacking of materials. It enables architects and engineers to expand the limits of design, producing distinctive, tailored buildings that were before prohibitively expensive or challenging to construct using conventional techniques. In the creation of smart cities, 3D printing can expedite the building of infrastructure using IoTs and wireless systems, including on-demand houses [109], on-demand bridges [110], and on-demand urban furnishings [108], as shown in Figure 5. The adaptability of 3D printing facilitates on-demand manufacturing, obviating the necessity for extensive warehousing of pre-manufactured components and enhancing supply chain efficacy. Projects such as 3D-printed dwellings are shown potential in delivering inexpensive housing alternatives in metropolitan environments for developing countries like Brazil [111]. Although technology readiness levels are 7–8 for an unreinforced 3D printing house where the development room still has to be conducted [111], advancements in robotics and artificial intelligence can fully automated 3D printing systems to create complete structures autonomously, significantly leading to decreased construction time and labor expenses to achieve City Livability [112].

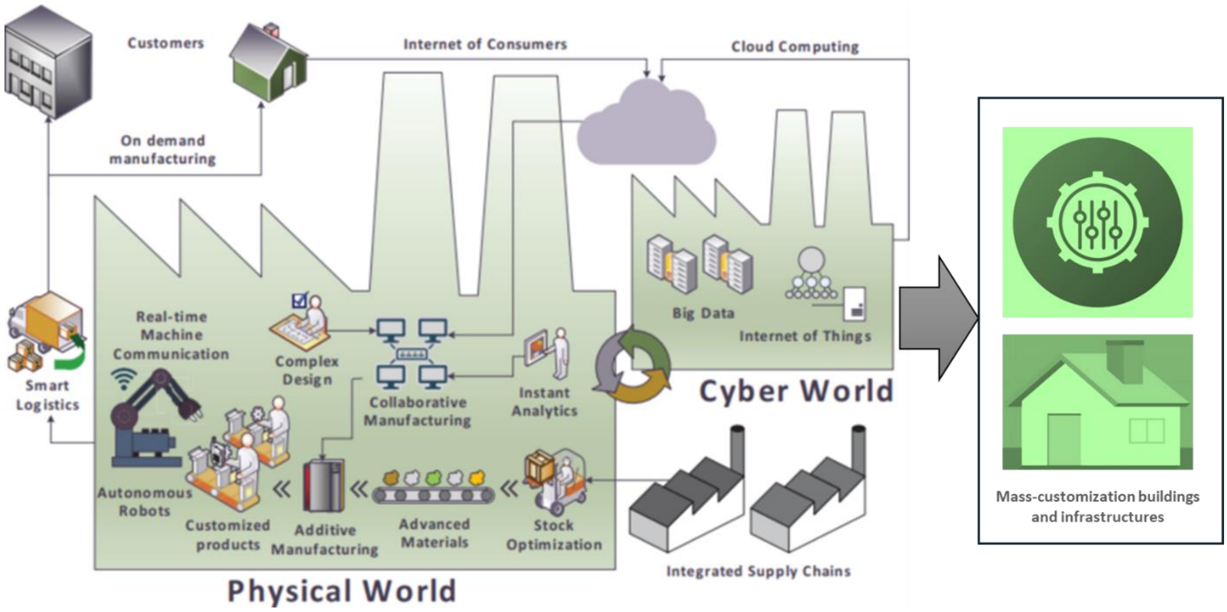


**Figure 5.** Outline of 3D printing in smart city in Industry 4.0. (adapted from [113–115]).

Numerous metropolitan areas experience traffic challenges, including congestion, pollution, scheduling difficulties, infrastructures' deterioration, and cost reduction concerns for public transportation [116]. The swift advancement and deployment of novel IoT technologies have rendered Vehicle-Infrastructure-Pedestrian communication ubiquitous. Technologies such as Vehicle to Vehicle (V2V), Vehicle to Infrastructure (V2I), Vehicle to Pedestrian (V2P), and Pedestrian to Infrastructure (P2I) have facilitated the development of intelligent transportation systems. Given the prevalence of GPS and sensor devices in vehicles and the ubiquity of smartphones among drivers, several methodologies utilize GPS data to monitor driver behavior and analyze traffic trends [117–119]. This real-time data is utilized for route planning in programs like Waze and Google Maps, as well as for trip scheduling in public transportation. However, in the context of 3D printing, it can advocate the fast mass-customized manufacturing parts and on-demand attachment of GPS/sensor devices for the systems. Demir et al. [120] advocated that the combined manufacturing and logistics processes of medical 3D printing products and services can be effectively completed within a daytime (8 AM–18PM), mitigating the logistic challenge in urban areas.

Nonetheless, the present progress continues to face pragmatic hurdles since the technology still in the infancy stage [106]. It is believed that a primary challenge is ensuring effective communication and data exchange across many technologies and platforms. 3D printing, DT, and IoT devices must connect seamlessly to provide accurate, real-time insights into building performance. The integration of industry 4.0 technologies into existing processes may be expensive, especially for smaller construction firms due to smaller budgets and more conservation in R&D [121,122]. Additionally, as construction and smart city initiatives grow more digitized, they are increasingly vulnerable to cyberattacks [123]. Ensuring the security of IoT devices, data networks, and key infrastructure is imperative to prevent interruptions. The execution of industry 4.0 requires a workforce skilled to adopt digital technologies, such as AI, robotics, and data analytics [124,125]. The industry must invest in training and upskilling staffs to effectively maximize the benefits of these technologies. Finally, governments and industry leaders must devise strategies to alleviate these challenges, potentially

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through subsidies, incentives, or cooperative platforms [106,126]. The political challenges can be a key parameter for such successful 3D printing technology adopted in the industry 4.0 context.

### *3.4. Smart 3D Printing Materials for Smart Cities*

Smart materials are engineered substances that have properties that can change in response to external stimuli. These smart materials often implemented in 3D printing are mainly adopted in filament or ink components, and their utilization for smart cities and infrastructure such as shape memory alloys (SMA) [127–131], photovoltaic materials [128,132–137], self-healing materials [128,138–142], thermochromic materials [143–147], and piezoelectric materials [135,148–154].

The discussion of such 3D printed smart materials is provided herein. For examples, Shi et al. [33] illustrated that shell-based ferroelectric metamaterials maintained a high piezoelectric constant at low densities, resulting in enhanced sensitivity to mechanical forces and temperature variations. These materials can be crucial in the advancement of smart city infrastructure, especially in energy-efficient building systems, where immediate reactions to environmental alterations are vital. They also presented an innovative methodology for the design and manufacture of 3D printed ferroelectric metamaterials. These engineered shell-based structures, encompassing spinodoids and diamond shellulars, have programmable piezoelectric and pyroelectric characteristics, rendering them suitable for applications in energy storage, pressure sensing, and thermal systems. This research integrated ferroelectric materials with 3D printing process, therefore creating new opportunities to improve material efficiency in smart infrastructures, where multifunctionality and customization are essential.

Tuloup et al. [155] elucidated their research on the application of 3D printed lead zirconate titanate (PZT) transducers in SHM systems, which produced by sophisticated 3D printing methods. The materials are integral to a broader network intended for the real-time detection of structural problems. This method is particularly advantageous in extensive constructions, such as bridges and skyscrapers, where ongoing surveillance is essential to maintain structural integrity and avert disasters. The authors emphasized the advantages of employing printed PZT transducers in comparison to traditional sensors, indicating that they contributed no weight to the construction, were simple to manufacture, and yielded very precise data. The growing complexity of contemporary infrastructure necessitates regular and non-intrusive SHM to uphold safety and performance criteria in smart cities.

3D printed hydrogels are moisture-responsive materials that may expand or shrink in response to humidity levels for the self-healing purpose. These materials exhibit intelligence by adapting or responding to their environmental conditions, so enhancing the functioning of passive buildings and rendering them more dynamic and responsive [156,157]. 3D printed urethane diacrylate and linear semicrystalline polymers have been formulated for 3D printing a self-healing polymer ink capable of stretching up to 600% [158].

Smart materials are gaining traction in the 3D printing construction industry, where their unique properties can be applied to improve building performance, improved electrical performance, reduce energy consumption, and enhance the longevity and functionality of infrastructure. Many additives for smart cities can be added in intelligent concretes and asphalts such as graphite/graphene oxides [137,159–162], graphene nanomaterials [137,163–167], and graphene quantum dots [168–171]. The electrical conductivity of resulting concrete notably increased up to 100% when the graphene additives were added [171] with the potentials to be adopted as energy autarkic buildings, self-charging pavements for electric vehicles, and energy storage foundations for green wind turbines and tidal power stations.

One of the key applications of 3D printed smart materials in construction is their potential to improve energy efficiency in buildings. 3D printed thermochromic windows can change their transparency based on temperature or sunlight intensity [143,172]. When exposed to bright sunlight, these windows become opaque, reducing the amount of heat entering a building and thus lowering cooling costs [173]. On cloudy days or during winter, they remain transparent, maximizing natural light and reducing the need for artificial lighting. Moreover, 3D printed photovoltaic building materials, such as solar panels or solar tiles, are already being used to convert sunlight into electricity

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[174,175]. However, new developments in smart photovoltaic materials promise even greater integration with building facades, roofs, and other surfaces, turning buildings into mini power plants that produce clean energy. These materials contribute to the development of zero-energy buildings, a critical goal in smart city planning, where the need for sustainable, energy-efficient infrastructure is paramount.

While 3D printed smart materials hold significant promise, there are several challenges that need to be addressed for widespread adoption such as cost, scalability, durability, lifespan, standardization, and integration. Smart materials can be expensive to produce and may be difficult to scale for large construction projects [176,177]. Some smart materials such as hydrogels may degrade over time or under certain environmental conditions, limiting their self-healing effectiveness in long-term applications [178,179]. Integrating smart materials into existing construction processes requires new proper standards and protocols to ensure compatibility with other materials and systems [180]. Despite these challenges, the future of smart materials in construction and smart cities is ameliorative. As material science advances and costs decrease, we can expect to see these 3D printed smart materials play an increasingly important role in creating adaptable, sustainable, and intelligent buildings and infrastructures.

### *3.5. 3D Printing in Soft Robotics for Smart Cities*

Soft robotics possesses several applications in smart cities, particularly in infrastructure maintenance, environmental monitoring, and human-robot interaction. Their devices can be utilized for the examination and repair of infrastructure. Conventional inspection techniques frequently utilize inflexible robots or human personnel, which can be unwieldy and pose risks in restricted or intricate settings [181]. Conversely, soft robots can maneuver through confined areas and conform to uneven surfaces, facilitating more effective and safer examinations of bridges, tunnels, and pipelines. Cities can employ 3D printing to create bespoke soft robots that are lightweight and specifically intended for inspection jobs, therefore improving the upkeep of urban infrastructure. Their 3D-printed, pliable shapes provide seamless integration into urban settings, reducing interruption while gathering essential data. For instance, 3D-printed soft robotic systems may be engineered to emulate plant life, including sensors for environmental surveillance while enhancing urban aesthetics, so attracting visitors. The planetoid robot, as shown in Figure 6, possess distributed sensors, actuators, and intelligence. Roots are the plant organs that get nutrition and provide anchorage. Roots, endowed with multiple sensors at their tips, efficiently investigate their surroundings while continuously adapting, avoiding barriers, penetrating soil, and selectively extracting vital nutrients and water for plant life. Roots mitigate friction and elevated pressures in soil by proliferating new cells at the apical area of the root tips and subsequently absorbing water from the surrounding environment. This capacity increases data collecting and develops a more harmonious interaction between technology and nature in urban environments.

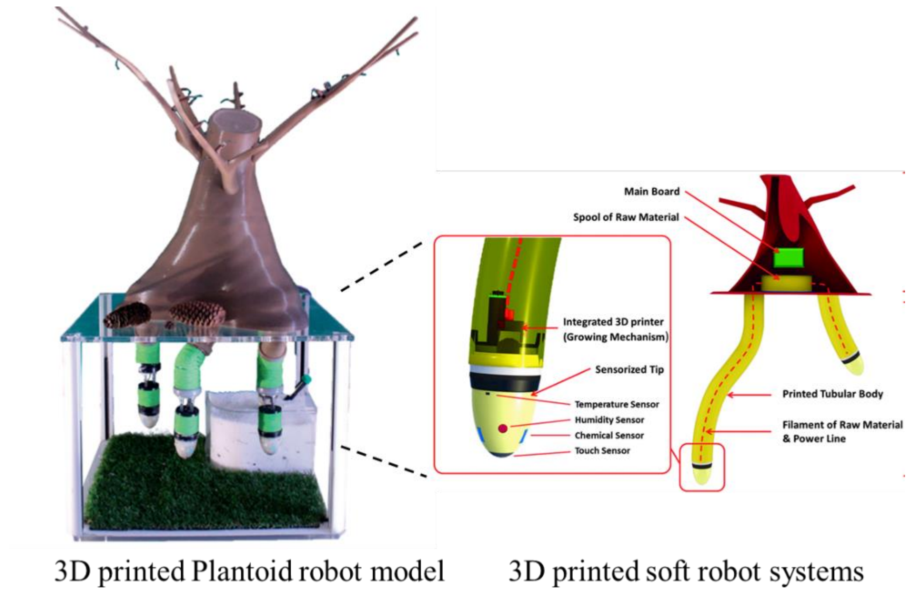


**Figure 6.** The 3D printed Plantoid robot and the systems. (adapted from [182–184]).

Furthermore, soft robotics can enhance human-robot interaction in public environments. Robots intended for social interaction—such as those offering information or help in public spaces—can advantageously utilize soft materials to enhance their approachability and safety for users [185,186]. Another instance is the soft robotic grasper is advantageous because to its lightweight nature compared to conventional stiff graspers, and it may streamline the control method for gripping mechanics. A drone capable of flight and perching was constructed, inspired by the resting behaviors of birds and bats in nature, utilizing 3D-printed landing gear [187].Cities may utilize 3D printing technology to provide visually appealing and functionally efficient soft robotic systems, therefore improving the user experience in public areas.

The incorporation of 3D printing in the advancement of soft robotics has several benefits. A primary advantage is the capacity to fabricate intricate, tailored geometries that conventional manufacturing techniques may find challenging to produce. Soft robots sometimes need complex designs to optimize flexibility and functionality. 3D printing enables designers to swiftly develop and refine ideas, resulting in more inventive and efficient robotic systems customized for specific jobs in urban settings. Furthermore, 3D printing facilitates the utilization of sophisticated materials, such as elastomers and composites, which can improve the functionality of soft robots. These materials may be engineered to offer different levels of flexibility and rigidity, allowing robots to adjust their behavior based on the specific tasks required. A soft robot designed to grasp fragile things can be constructed with a pliable, compliant exterior, yet the same robot can become rigid to execute structural functions as necessary. This adaptability is especially advantageous in smart cities, where the requirements for robotic systems might fluctuate considerably depending on the setting. The cost-effectiveness of 3D printing in soft robotics is a significant benefit. Conventional manufacturing techniques can include substantial setup expenses and extended production lead times. Conversely, 3D printing might diminish production expenses and duration, enabling communities to swiftly implement and modify robotic systems as requirements change. This adaptability is crucial in the dynamic contexts of smart cities, where fast technology progress and evolving urban dynamics may need prompt changes.

Notwithstanding its myriad benefits, the use of 3D printing in soft robotics for smart cities encounters certain hurdles. A primary problem is the longevity and dependability of soft robotic systems [188,189]. Although flexible materials provide distinctive capabilities, they may also jeopardize durability, especially in severe metropolitan settings. To address these problems, continuous research and development are necessary to enhance material characteristics and robotic designs, guaranteeing that soft robots can endure the challenges of urban environments. A further

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problem is the necessity for multidisciplinary collaboration among engineers, urban planners, and policymakers [190–192]. Creating efficient soft robotic solutions for smart cities requires an in-depth comprehension of urban dynamics, infrastructural requirements, and community anticipations. Collaborative initiatives may promote innovation and guarantee that soft robotic systems are developed with the end-users' needs in consideration, hence improving their acceptance and efficacy in urban environments. Finally, ethical and social implications accompany the implementation of robotic devices in public areas [193,194]. It is essential that soft robots are created and executed to uphold privacy and improve public safety to ensure their acceptability and success. Involving communities and stakeholders during the design and implementation phases helps mitigate these issues, promoting confidence and collaboration between technology suppliers and urban inhabitants.

*3.6. Wire Arc Additive Manufacturing (WAAM) for Smart Cities*

WAAM is an innovative 3D printing process that use an electric arc as a heat source to melt wire material, facilitating the layer-by-layer fabrication of metallic components such as steel, aluminum, and titanium. This novel methodology, as shown in Figure 7, is gaining prominence in the realm of smart cities, where there is an urgent demand for sustainable building methods and sophisticated manufacturing procedures.

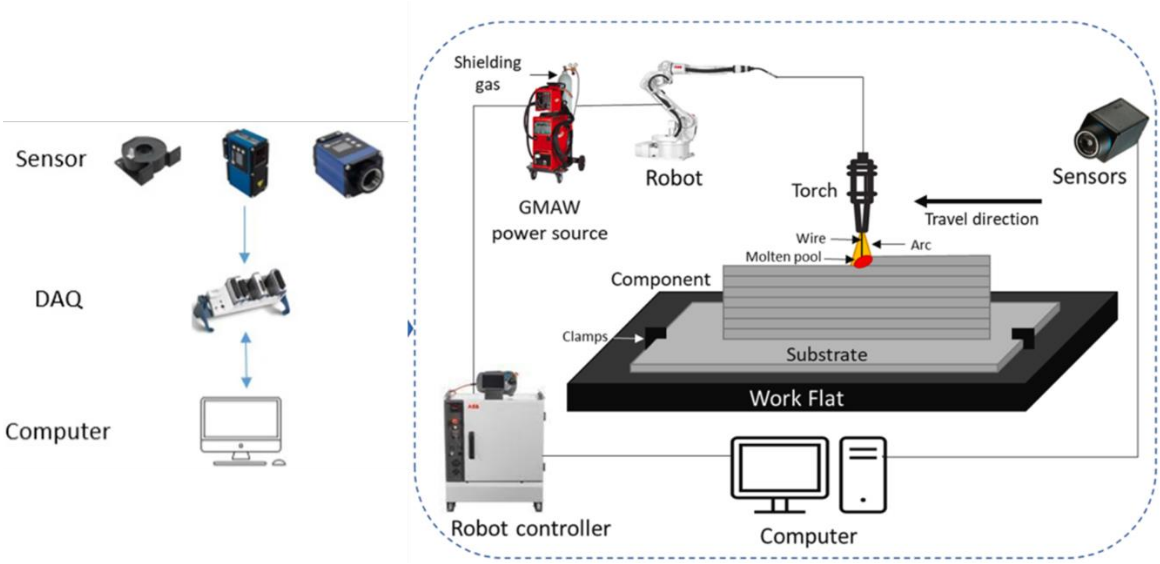


**Figure 7.** WAAM systems for smart process. (adapted from [47,48,195]).

One of the primary advantages of WAAM is its capacity to effectively manufacture large-scale components. In contrast to conventional subtractive manufacturing methods that often result in significant waste and prolonged production times, WAAM produces minimum material waste, hence adhering to the concepts of sustainability and circular economy essential for smart city programs [196–198]. The capacity to fabricate intricate geometries with WAAM can result in creative free-form designs that improve structural performance [199,200]. The layer-by-layer process facilitates the creation of complex forms that are frequently challenging or unattainable by conventional production techniques. This design flexibility is especially advantageous in smart cities, where architects and engineers are prioritizing the optimization of structures for sustainability and efficiency. Furthermore, WAAM can enable the incorporation of multifunctional components, integrating characteristics like thermal insulation or structural reinforcements directly into the produced pieces for smart and greener buildings [197,201]. The quick prototyping capabilities of WAAM significantly augment its attractiveness for smart city applications. The capacity to rapidly generate and evaluate components facilitates a nimbler design process, enabling engineers to improve designs based on empirical performance data. This iterative methodology is crucial in the dynamic context of smart cities, where infrastructure demands may swiftly evolve owing to variables such as population expansion, technology progress, and climate change [199,202]. WAAM facilitates expedited

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prototyping, so considerably diminishing the time necessary to introduce new designs to the market, thereby improving the overall agility of urban infrastructure development.

Notwithstanding its myriad advantages, WAAM has problems that must be resolved for effective adoption in smart cities. A major challenge is the quality monitoring of printed components [203]. Although WAAM can rapidly manufacture large-scale components, it is essential to ensure the mechanical characteristics and structural integrity of these parts. Inconsistencies in the printing process, including fluctuations in heat application and cooling rates, may result in faults that undermine the efficacy of the final product [204]. To alleviate these concerns, continuous research is essential to provide standardized protocols for process monitoring and quality assurance in WAAM systems. A further problem is the necessity for proficient workers to run WAAM systems efficiently [205]. The technique necessitates a profound comprehension of welding and additive manufacturing concepts, which may not be readily accessible within the existing workforce. As smart cities develop, there will be an increasing need for training programs that prepare professionals to run and maintain WAAM systems. Besides, partnerships among educational institutions, business, and government may cultivate a workforce skilled in modern manufacturing processes, promoting innovation and economic development in metropolitan regions [192,206]. The incorporation of WAAM into current urban infrastructure presents logistical difficulties. Urban settings frequently encounter spatial limitations, necessitating the investigation of modular building techniques to enable the implementation of WAAM technology in confined areas.

WAAM offers a significant possibility for the advancement of smart city development via efficient, sustainable, and creative building methodologies. WAAM can significantly contribute to addressing the changing requirements of urban infrastructure by utilizing its expertise in large-scale component production, fast prototyping, and design adaptability. Addressing issues associated with quality control, workforce development, and logistical integration will be essential for optimizing the technology's potential. As urban areas progress and encounter intricate obstacles, the adoption of WAAM and analogous technologies will be crucial for developing resilient, sustainable, and adaptable urban ecosystems.

### *3.7. Machine Learning (ML) in 3D Printing for Smart Cities*

The convergence of ML and 3D printing technology is poised to revolutionize various sectors, including construction and urban infrastructure, particularly in the context of smart cities. As urban environments become increasingly complex, leveraging ML in 3D printing can significantly enhance efficiency, sustainability, and adaptability in urban development. One of the primary applications of ML in 3D printing is in the optimization of design and manufacturing processes [98,207,208]. ML algorithms can examine extensive datasets produced during the design process, deriving insights from prior designs and production results to recommend ideal configurations. This data-centric methodology can enhance geometry, material utilization, and structural efficacy. By examining the structural integrity of various designs, ML can forecast which configurations would excel under diverse loads and climatic conditions. [209,210]. This feature is especially significant in smart cities, where adaptable infrastructure is essential for addressing evolving urban dynamics. Furthermore, ML algorithms like XGBOOST can effectively improve the quality control procedures in the 3D printing process [211,212]. Conventional quality assurance techniques frequently depend on manual inspections and established criteria, which can be labor-intensive, time-consuming, and susceptible to human mistake [213–215]. Manufacturers may utilize ML algorithms to monitor printing operations in real time, identifying and predicting abnormalities and faults as they arise. This proactive strategy allows prompt modifications to the printing settings, guaranteeing that the final 3D printed products conform to the specified requirements.

Another critical area where ML can contribute to 3D printing in smart cities is predictive maintenance [216,217]. As 3D printing technology becomes more integrated into urban infrastructure, the necessity for continuous maintenance and repair of printed components is paramount. ML algorithms may evaluate past performance data from diverse components to forecast maintenance requirements based on usage patterns and environmental variables. This predictive capacity prolongs the durability of printed buildings, diminishes downtime and maintenance expenses, and eventually fortifies the resilience of urban infrastructure. Moreover, the amalgamation of machine learning with 3D printing might enable the creation of intelligent materials that react adaptively to environmental variations [130,218]. For instance, ML algorithms may be employed to engineer materials that alter their characteristics in response to external stimuli, such temperature, humidity, or mechanical stress. This breakthrough facilitates the development of adaptable structures in smart cities, such buildings that can optimize temperature and energy consumption or bridges capable of self-repairing small damages. These characteristics correspond with the objectives of sustainability and resilience in urban development.

The integration of ML in 3D printing for smart cities presents several obstacles. A primary problem is the necessity for high-quality, sufficient number of datasets to train ML models efficiently [219–221]. In several instances, the data necessary for the development of strong algorithms may be scarce or challenging to acquire. To surmount this obstacle, collaboration among academics, business, and government can facilitate the creation of extensive datasets that accurately represent real-world conditions in metropolitan contexts. Moreover, uniformity is required in the amalgamation of ML and 3D printing technologies [211]. As both domains progress swiftly, the formulation of best practices and standards will be essential for guaranteeing interoperability and dependability in smart city applications. Involving stakeholders from many sectors—such as urban planners, engineers, and policymakers—will be crucial for establishing a unified framework to incorporate new technologies into urban infrastructure.

### *3.8. 3D Printing in Structural Health Monitoring (SHM) for Smart Cities*

SHM denotes the assessment of the state of structures—such as bridges, buildings, and roads—utilizing diverse sensing technologies to guarantee its safety and integrity [222–224]. Conventional SHM frequently depend on integrated sensors and routine evaluations, which is typically labor-intensive and expensive. The use of 3D printing into SHM methods provides novel options to tackle these difficulties. Through the application of 3D printing, municipalities may create bespoke sensors and monitoring apparatus that are lightweight, economical, and simple to install for smart city purposes [225].

A notable benefit of 3D printing in SHM is the capacity to fabricate intricate geometries and structures customized for particular monitoring requirements. Conventional manufacturing techniques may constrain the design of sensor enclosures or supporting structures, but 3D printing facilitates the production of more complex designs [110,225]. 3D printed sensor systems can be included into printed structural components, facilitating smooth integration and reducing interruption to the overall structure. This capacity improves the efficacy of monitoring systems by guaranteeing that sensors are strategically placed to collect essential data. The collected data from 3D printed sensor can be loading monitoring or environmental datasets [226–228]. This adaptability is especially significant in the realm of smart cities, where the fluidity of urban settings demands prompt reactions to evolving circumstances.

The amalgamation of 3D printing with data analytics and AI significantly augments the efficacy of SHM systems in smart cities. Municipalities may obtain significant insights into structural performance and possible failure risks by integrating real-time data from 3D-printed sensors with sophisticated analysis tools [229]. AI systems can analyze extensive datasets, detecting patterns and abnormalities that may signify underlying problems. This data-centric methodology facilitates anticipatory maintenance plans, enabling municipalities to tackle possible issues prior to their escalation into substantial safety risks.

### *3.9. Repair Strategies in 3D Printing for Smart Cities*

As urban areas confront issues associated with deteriorating infrastructure, resource depletion, and sustainability, 3D printing provides novel repair methodologies that improve resilience and efficiency. A prominent repair strategy enabled by 3D printing is the on-demand production of replacement components [230,231]. Conventional supply chains sometimes entail extended lead

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times and significant logistical difficulties, especially for specialty components. Conversely, 3D printing allows towns to produce components locally, therefore diminishing transportation emissions and expenses [232]. This localized production strategy accelerates maintenance operations and enables towns to retain a supply of essential components customized to their individual requirements. Urban regions can utilize 3D printing to manufacture replacement components for public infrastructure, such lamps, benches, or signage, therefore reducing service disruptions and improving the overall efficacy of public places [233]. Alongside on-demand manufacture, adaptable design methodologies are essential to the efficacy of 3D-printed repairs. Engineers may develop components that are more resilient and better equipped to endure environmental difficulties by leveraging modern and ecological-adaptive materials and implementing design optimization methods.

Predictive maintenance enabled by the IoT enhances the efficacy of repair solutions in 3D printing [234–236]. IoT sensors may be integrated into infrastructure to perpetually assess performance and identify possible faults prior to their escalation. This proactive strategy allows communities to plan repairs effectively, minimizing the chances of unforeseen failures and enhancing resource distribution. For instance, intelligent streetlight systems with sensors may notify maintenance personnel when components need repair, facilitating prompt and precise interventions. The collaboration of 3D printing and IoT technology highlights the potential for a data-centric approach to urban infrastructure management [237,238]. Furthermore, promoting collaboration among stakeholders is essential for the development and execution of successful repair plans in 3D printing. Involving city planners, engineers, architects, and the local community cultivates an atmosphere conducive to the flourishing of ideas and inventions. Sustainability constitutes a crucial element of repair solutions in 3D printing for smart cities [10,239]. The circular economy paradigm, which prioritizes reuse and recycling, may be included into the design and repair processes. For example, wasted plastic trash may be transformed into filament for FDM 3D printing, diminishing landfill contributions by >90% while offering a useful resource for infrastructure restoration [240,241]. Another example is adding polymer waste into 3D printing concrete for increasing flexibility and promoting circular economy to the concrete structure [242–244]. This method not only reduces trash but also fosters a culture of sustainability in urban environ WAAM is an innovative 3D printing process that use an electric arc as a heat source to melt wire material, facilitating the layer-by-layer fabrication of metallic components such as steel, aluminum, and titanium. This novel methodology, as shown in Figure 7, is gaining prominence in the realm of smart cities, where there is an urgent demand for sustainable building methods and sophisticated manufacturing procedures.

## 4. Conclusions

The article conducted qualitative analysis and systematic review from contribution of 3D printing for smart cities, which underscores the substantial contributions of the study to academic debate and practical understanding from the state-of-the-art publications. The review elucidates the interaction of DT, AI, smart materials, industry 4.0, soft robotics, SHM, and repair strategy for construction, urban planning, smart infrastructure, and environmental sustainability through the integration of many views. All of the mentioned areas has the research gaps and roadmap to notably improve for our future of smart cities.

The analysis delineates synergies, obstacles, constraints, and research gaps, while providing prospective recommendations to enhance future investigations. These insights facilitate the development of more resilient, technologically sophisticated, and ecologically sustainable urban landscapes. Despite the promising advancements, ubiquitous challenges remain in terms of cost, scalability, established policies and regulations, and the need for interdisciplinary collaboration among engineers, urban planners, and policymakers. This paper offers a detailed framework for academics, practitioners, and policymakers to inform the development of more intelligent, sustainable urban environments. These insights have profound implications for researchers, practitioners, and policymakers, providing a roadmap for fostering resiliently designed, technologically advanced, and environmentally conscious urban environments.

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