smart cities

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Review

How 3D Printing Technology Makes Cities Smarter: A Review, Thematic Analysis, and Perspectives

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Highlights:

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 cities.

What is the implication of the main findings?

- Three-dimensional printing or additive manufacturing (AM) offers potential pathways for sustainable urban development.
- 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, is provided.

Abstract: This paper presents a comprehensive review of the transformative impacts 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 (DTs), 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, designers, 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; urban

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1. Introduction

Rapid urbanization, resource shortages, 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 a growing market for smart buildings from USD 97 billion in 2023 to around USD 400 billion in the next 7 years [2]. From this perspective, the ubiquitous use of 3D printing technology in various industries today has the potential to transform urban development [3]. The concept of mass customization effectively shortens the time between design creation and prototyping, allowing for the production of goods closer to the consumer as needed [4]. This review work examines how 3D 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 in real time, including transportation, waste management, energy usage, and public safety. "3D printing" or "additive manufacturing" is a critical breakthrough that can enhance urban infrastructure, reduce waste, achieve zero-net carbon neutrality, and empower communities [5–7], aligning with 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]. Three-dimensional printing uses the 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 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 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. Figure 1 presents the key benefits of using 3D printing for construction to reduce various costs during construction.

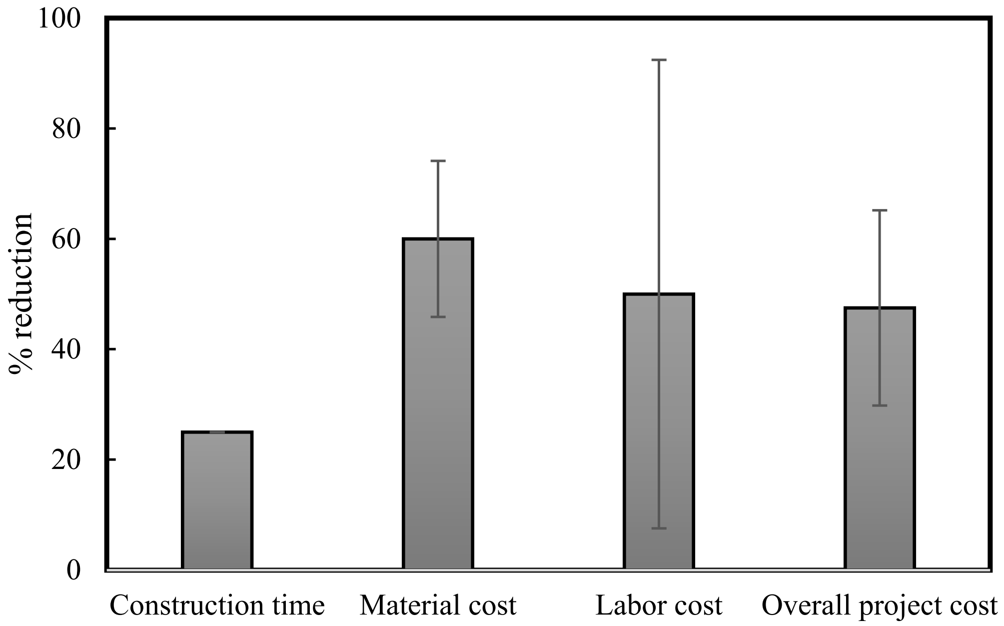


Figure 1. Cost reduction of using 3D printing for construction (source: by author).

Local production with 3D printing reduces transportation, which 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]. Three-dimensional printing allows quick prototypes 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 printed 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, and food-related 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 visualization technique. Strong positive attitude levels of around 64% were obtained when 3D printing was involved in industries in Egypt [18]. Additionally, 3D printing in schools may also raise understanding of urban planning procedures and encourage civic engagement, especially for STEM, social science, and history students [19,20]. Additionally, a notable feature of a garden project in Kenya is the cost. It produced a two-bedroom house at an estimated price of USD 28,000, which is considerably cheaper than the typical price of similar houses by 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. Three-dimensional printing with recycled or bio-based materials supports a circular economy and sustainable development (e.g., with emissions as low as 0.0524 $kgCO_2eq/kg$) [22,23]. This value is notably low, as compared to the CO_2 emission of ordinary Portland cement of approximately 1 $kgCO_2eq/kg$. Recycling plastics or organic materials into 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, research is ongoing [24–27]. Innovative energy-efficient designs like buildings that utilize natural light as well as 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 have been implemented for cities to become smarter within the contemporary improvement domain for the purpose of improving quality of life [30], including which innovations that are vital for smart cities and those that are beneficial. The literature search revealed the absence of a development summary in existing articles. 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 and Meta-Analyses (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: a qualitative study based on the keywords used and systematic review of existing literature. The systematic review followed PRISMA principles, which have been created for several research domains. The PRISMA process is shown in Figure 2. Studies were retrieved from Scopus, PubMed, and Google Scholar databases. The search terms used were the contexts presented in the titles, abstracts, and keywords of the literature. The terms included "smart city" or "smart building," together with the term "3D printing" or "additive manufacturing." Due to very fast 3D printing development [32], the scope focused on the articles published from 2015–2024. Research from before this decade may be obsolete, and their review may not represent current developments. After the review, it was found that 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:

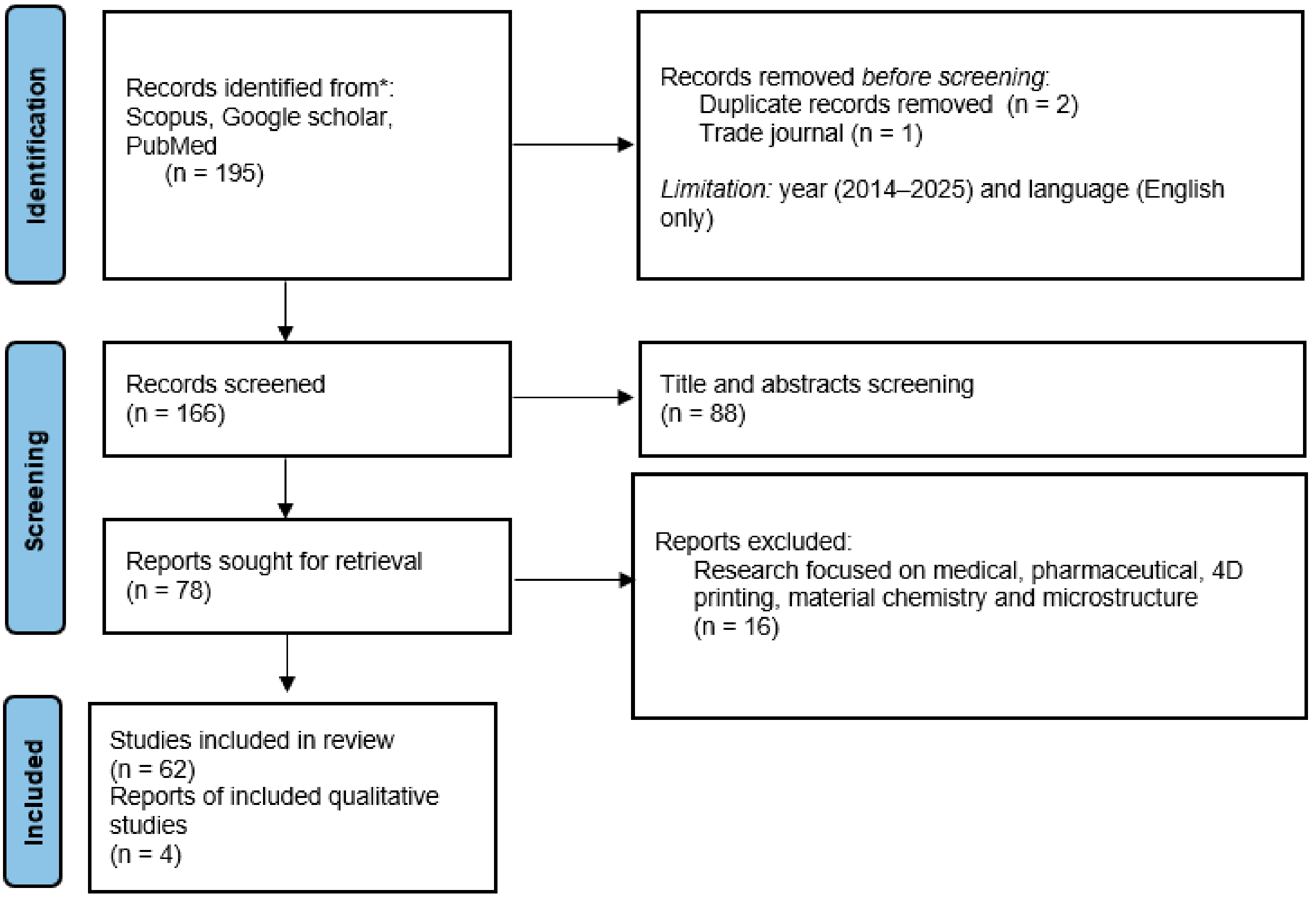


Figure 2. The review approach obtained using the PRISMA guidelines (source: by author). * sources from Scopus, Google scholar, and Pubmed databases.

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")).

2.1. In-/Exclusion Criteria

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

2.1.1. Inclusion Criteria

- Regarding the utilization of 3D printing from a smart city perspective;
- Including current 3D printing technologies with a published date later than 2015;
- Providing a detailed explanation of the effectiveness that each technology offers;
- Must be in a smart city setting;
- Only English language used.

2.1.2. Exclusion Criteria

- Excluding topics focused on medical, pharmaceutical, automative, 4D printing, material microstructure applications;
- General argument;
- Trade article;
- 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 are also subsequently addressed for each section. This review study highlights the significance and prospects for academic communities to understand and adhere to the issues raised in this context for future research.

3. Review Analysis and Discussion

3.1. Thematic Analysis on Keywords

Sixty-two pertinent publications were identified from the literature search and screened articles, as given in Table 1. From the thematic analysis, Figure 3 illustrates the number of articles released per 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 AI, machine learning (ML), and digital twin (DT) technology integration. The frequency of terms utilized more than twice was aggregated and is depicted in Figure 4. 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, is the most often utilized term. 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, AI has been addressed in most other topics, so the discussion of AI/3D printing for smart cities is not mentioned here. After examining 10 important aspects in this thematic analysis, as illustrated in Figure 5, each section is discussed to elaborate on its role in contributing to smart cities. Such technological aspects related to 3D printing can offer a contribution to how the current development of such aspects can benefit the smart city context. The subsequent sections present contributions and significance for the stated aspects.

Table 1. Existing literature determined in this review (source: by author). ✓presents the topic related to the publication.

Topic	Year																																																												
	2024								2023									2022														2021									2020						2019							2018	2017					2016		2015
	[2]	[33]	[34]	[35]	[36]	[37]	[38]	[39]	[40]	[41]	[42]	[43]	[44]	[45]	[46]	[47]	[48]	[49]	[50]	[51]	[52]	[53]	[54]	[55]	[56]	[57]	[58]	[59]	[60]	[61]	[62]	[63]	[64]	[65]	[66]	[67]	[68]	[69]	[70]	[71]	[72]	[73]	[74]	[75]	[76]	[77]	[78]	[79]	[80]	[81]	[82]	[83]	[84]	[85]	[86]	[87]	[88]	[89]	[90]	[91]	[92]	[93–95]
Smart material		✓										✓	✓	✓	✓			✓		✓		✓	✓	✓								✓				✓						✓						✓									✓				✓	✓ ✓
Digital twin	✓		✓			✓			✓							✓											✓		✓																								✓									✓
Smart manufacturing				✓													✓														✓														✓	✓	✓		✓	✓					✓	✓		✓		✓		
Structural health monitoring					✓																														✓			✓						✓								✓							✓			
Industry 4.0						✓													✓		✓				✓					✓																					✓											
Machine learning							✓																																				✓																			
Wire arc additive manufacturing							✓																						✓																																	
Soft robotic								✓																									✓	✓																												
Artificial intelligence										✓	✓															✓		✓									✓			✓														✓								
Repair																																							✓		✓																					

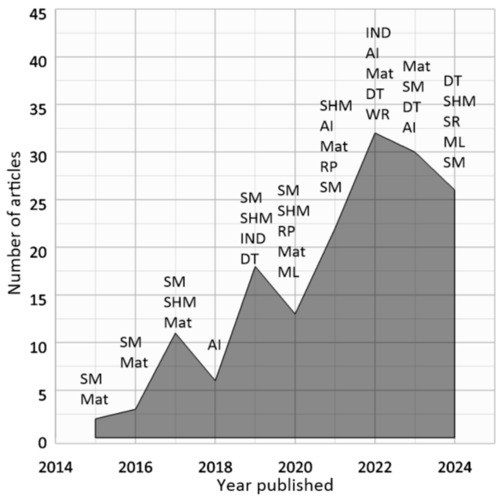


Figure 3. Number of publications published and keywords used each year from 2015–2024 (SM = smart manufacturing; Mat = smart material, SHM = structural health monitoring, AI = artificial intelligence, IND = Industry 4.0, DT = digital twin, RP = repair, ML = machine learning, and WR = wire-arc additive manufacturing) (source: by author).

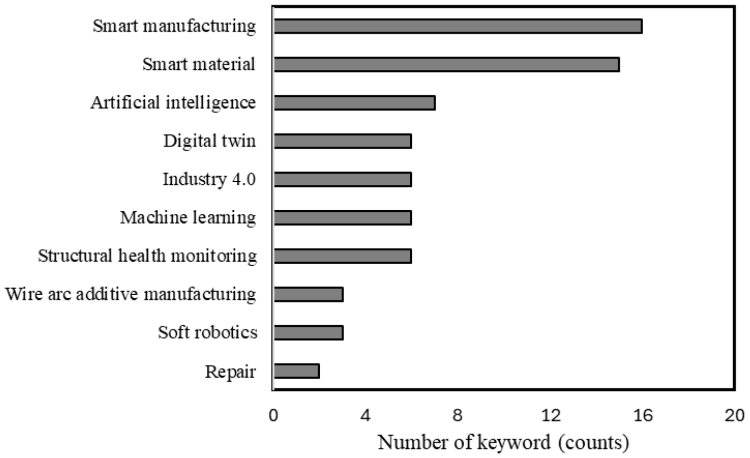


Figure 4. Count of keywords used in this literature review (source: by author).

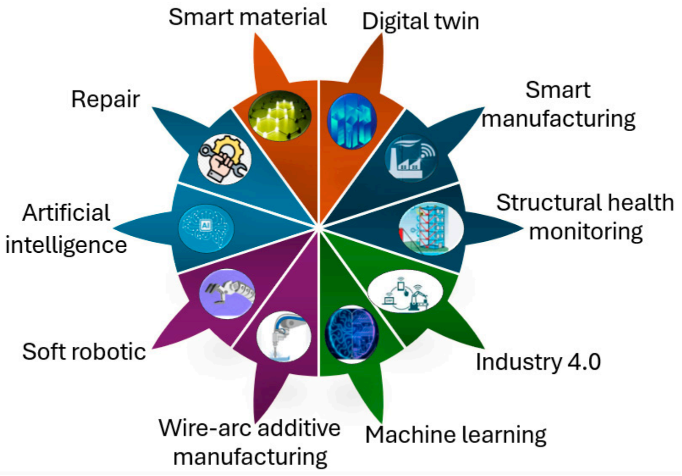


Figure 5. Current technological aspects related to 3D printing for smart city context (source: by author).

3.2. Digital Twins (DTs) in 3D Printing for Smart Cities

DT technology is defined as a virtual representation of physical entities that disclose, forecast, and enhance their tangible counterparts [95]. The term "twin" evokes a simpler framework and implies an equitable relationship between the two "twins." The term "twin" serves as a metaphor, conveying both a relationship of similarity (the digital representation possesses identical properties to the physical thing) and a relationship of parity (the digital representation corresponds to the physical entity as an equal). DTs are delineated into five components, entailing physical, data, analytical, virtual, and connection environments [96].

DT technology is progressively used to model the performance of intricate systems, including those employed in the building and manufacturing industries. Integrating AI enhances the accuracy of these simulations and their capacity to manage extensive data, facilitating predictive maintenance and process optimization. Rojek et al. [37] examined the influence of digital transformation on enhancing 3D printing methodologies using DT virtual representations of physical entities and mentioned that it facilitates real-time surveillance and enhancement of industrial operations. This research emphasizes that DTs serve as a potent instrument for forecasting and alleviating challenges in 3D printing, including flaws and inefficiencies. In terms of construction technology, DTs can be used in interior design and fabrication of architectural and building elements in existing buildings, as depicted in Figure 6. This DT adoption can reduce survey time, errors, and inspectors since the operating process can be performed in a digital file. In addition, DTs can be used in the simulation stage before printing actual buildings. The wall panels, flat slabs, and other structural components can be efficiently printed and fabricated with other construction additives 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-weight ratios of 3D printed wall panels can be enhanced more than 200% compared to the original design [98].

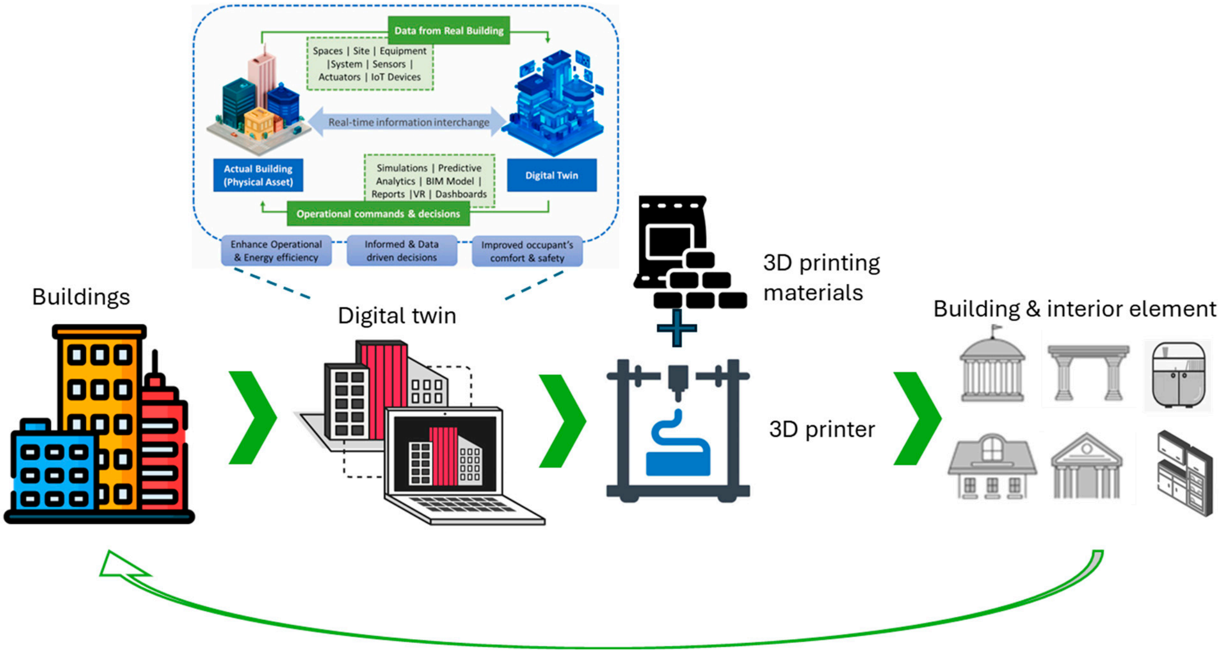


Figure 6. Three-dimensional printing process with DTs, where the DTs can be implemented in the renovation and interior of existing buildings (source: by author).

In the contexts of urban planning for smart cities, DTs generally support 3D city simulations regarding several factors, such as environmental, spatial, historical, and in situ collected data [99,100]. The 3D printing can be modeled and used as a preliminary study from the data obtained from geographical information systems (GISs). This benefits continuous 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 DTs in 3D printing appears promising, there remain obstacles to their broad adoption. DTs necessitate 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 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]. DTs can be augmented with several technologies for smart cities such as virtual reality, geographic information systems, life cycle assessment, parametric design, generative design, and building/city information models [95,106–112]. Indeed, 3D printing with DTs also offers another promising technology as a smart tool for mass-customized manufacturing.

3.3. Three-Dimensional 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, cyberphysical 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—along with the mentioned technologies grows more substantial [113–116].

Three-dimensional printing revolutionizes built environments within the framework of Industry 4.0 in the era of “fab cities” and “maker cities” [117]. 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 previously prohibitively expensive or challenging to construct using conventional techniques. As a specific example, Rimmer [117] mentioned that maker cities projects have been initiated worldwide, such as in the US, Spain, and the UAE. This 3D printing policy has been utopianly established, especially in Dubai, where construction sector products, consumer products, and medical products were aimed to be made by 3D printing technology.

In the creation of smart cities, 3D printing can expedite the building of infrastructure using IoTs and wireless systems, including on-demand houses [118,119], on-demand bridges [120], and on-demand urban furnishings [121], as shown in Figure 7. 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 have shown potential in delivering inexpensive housing alternatives in metropolitan environments for developing countries like Brazil [122]. Although technology readiness levels are 7–8 for an unreinforced 3D printing house where the development of research gap still has to be conducted [122], advancements in robotics and artificial intelligence can fully automate 3D printing systems to create complete structures autonomously, significantly leading to decreased construction time and labor expenses to achieve city livability [123]. Additionally, it should be noted that recycled concrete and nanomaterials can be added to the 3D printing material to improve the sustainability of the holistic construction process [124].

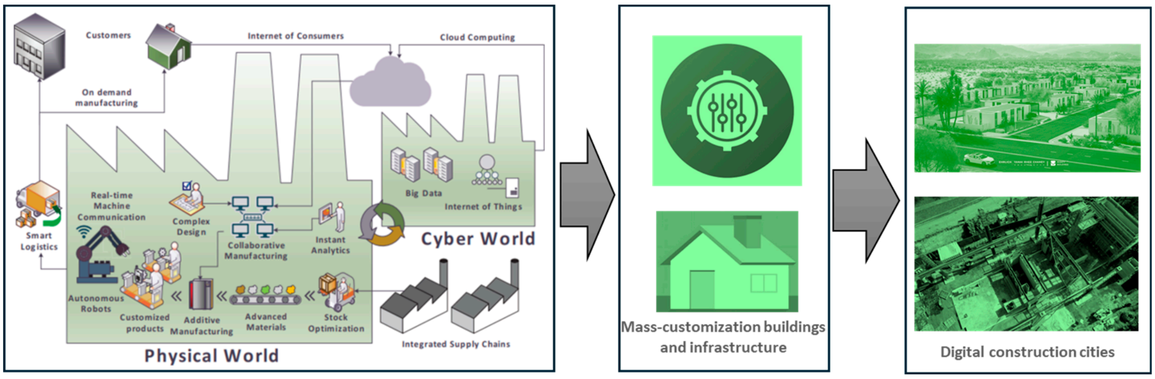


Figure 7. Outline of 3D printing in smart city in Industry 4.0, where mass customization is the key for the future of digital construction cities (source: by author).

Numerous metropolitan areas experience traffic challenges, including congestion, pollution, scheduling difficulties, infrastructure deterioration, and cost reduction concerns for public transportation [125–129]. 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 GPSs 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 [130,131]. These real-time data are 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, they can be used for the fast mass customization of manufacturing parts and on-demand attachment of GPSs/sensor devices for systems. Demir et al. [132] advocated that the combined manufacturing and logistics processes of medical 3D printing products and services can be effectively completed during the daytime (8 a.m.–6 p.m.), mitigating the logistic challenge in urban areas.

Nonetheless, the present progress continues to face pragmatic hurdles since the technology is still in its infancy [106]. It is believed that a primary challenge is ensuring effective communication and data exchange across many technologies and platforms. Three-dimensional printing, DTs, 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 conservative R&D [133,134]. 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 in adopting digital technologies, such as AI, robotics, and data analytics [135,136]. The industry must invest in training and upskilling staff to effectively maximize the benefits of these technologies. Finally, governments and industry leaders must devise strategies to alleviate these challenges, potentially through subsidies, incentives, or cooperative platforms [106,137]. Political challenges can be a key parameter for such successful 3D printing technology adopted in the Industry 4.0 context. Indeed, 3D printing can have the main roles in smart manufacturing for smart cities in the context of Industry 4.0.

3.4. Smart 3D Printing Materials for Smart Cities

Smart materials are objects that perceive environmental circumstances and respond accordingly by processing the acquired information [138–140]. The awareness of the environment allows smart materials to be appropriately responsive and reactive. Conversely, non-smart advanced composites often consist of multistructural solid parts that offer multifunctionality. Smart materials can be classified into two categories [141]: the first comprises materials that exhibit a sensing effect in response to external stimuli, referred to as sensing materials, which can be utilized to create various sensors for detecting environmental changes or gathering information. Sensing materials are now utilized as various sensors, including acoustic emission materials, resistance strain materials, photosensitive materials, moisture-sensitive materials, heat-sensitive materials, and chemical-sensitive materials. The other category comprises materials that react to alterations in external environmental conditions or internal states, sometimes referred to as actuating materials [142–144].

These smart materials often implemented in 3D printing are mainly adopted in filament or ink components, and they are utilized for smart cities and infrastructure as shape memory alloys (SMAs) [145–149], photovoltaic materials [150–155], self-healing materials [156–160], thermochromic materials [161–166], and piezoelectric materials [87,167–174].

The discussion of such 3D printed smart materials is provided herein. For example, 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 the 3D printing process, therefore creating new opportunities to improve material efficiency in smart infrastructures, where multifunctionality and customization are essential.

Tuloup et al. [174] elucidated their research on the application of 3D printed lead zirconate titanate (PZT) transducers in SHM systems, which were 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 printed PZT transducer can be made from a digital file and subsequently printed and fabricated onsite, where accessibility can be limited. With this customized production and fabrication, the transducer can perform more accurately, even on miniaturized scales. The growing complexity of contemporary infrastructure necessitates regular and non-intrusive SHM to uphold safety and performance criteria in smart cities.

Three-dimensionally printed hydrogels are moisture-responsive materials that may expand or shrink in response to humidity levels for self-healing purposes. These materials exhibit intelligence by adapting or responding to their environmental conditions, enhancing the functioning of passive buildings and rendering them more dynamic and responsive [175,176]. Three-dimensionally printed urethane diacrylate and linear semicrystalline polymers have been formulated for a self-healing polymer ink capable of stretching up to 600% [177].

Smart materials are gaining traction in the 3D printing construction industry, where their unique properties can be applied to improve building performance, improve electrical performance, reduce energy consumption, and enhance the longevity and functionality of infrastructure. Many additives for smart cities can be added to intelligent concretes and asphalts, such as graphite/graphene oxides [178–181], graphene nanomaterials [182–186], and graphene quantum dots [187–190]. The electrical conductivity of the resulting concrete notably increased up to 100% when graphene additives were added [187], with the potential to be adopted in 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. Three-dimensionally printed thermochromic windows can change their transparency based on temperature or sunlight intensity [162,191]. When exposed to bright sunlight, these windows become opaque, reducing the amount of heat entering a building and thus lowering cooling costs [192]. 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 and heat islands in urban areas into electricity [193–195]. 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.

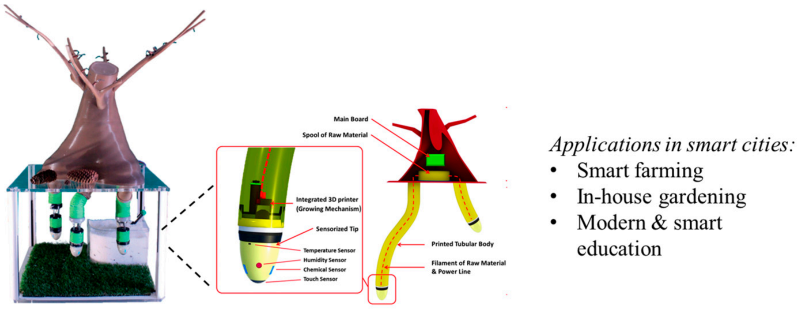
- In terms of the economic aspect, smart materials can be costly to produce and may be difficult to scale for large construction projects [196,197]. Hence, a scaling up of production should be performed and find an ameliorative solution.
- Regarding durability performance, some smart materials, such as hydrogels, may degrade over time or under certain environmental conditions, limiting their self-healing effectiveness in long-term applications [198,199]. Fillers or coatings can mitigate the degradation issue.
- Regarding the policy setup, integrating smart materials into existing construction processes requires new proper standards and protocols to ensure compatibility with other materials and systems [200]. This requires collaboration between inventors, city planners, and policymakers to deliberate on the progressive development of future smart cities.

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 infrastructure.

3.5. Three-Dimensional Printing in Soft Robotics for Smart Cities

Robots frequently face challenges while functioning in unstructured and densely populated situations. A diverse array of soft robots resembling plant and animal species demonstrate intricate locomotion utilizing pliable frameworks without hard elements [201]. A soft robot relies on the pliability of its subsystems, including the power generator, actuator, sensor, controller, and body including artificial muscles and tissues [202–207].

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 [208]. 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 and attracting visitors. The plantoid robot shown in Figure 8 possesses distributed sensors, actuators, and intelligence. Roots are the plant organs that obtain 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 collection and develops a more harmonious interaction between technology and nature in urban environments. The model can be applied in several applications in smart cities, including smart farming, in-house gardening, and modern/smart classrooms.



3D printed Plantoid robot model 3D printed soft robot systems

Figure 8. The 3D printed plantoid robot and its systems (source: by author).

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 [209,210]. Another instance is the soft robotic grasper, which is advantageous because of 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 [211]. 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. Three-dimensional 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 technological 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 [212,213]. Although flexible materials provide distinctive capabilities, they may also jeopardize durability, especially in dense metropolitan regions. To address these problems, continuous research and development programs are necessary to enhance material characteristics and robotic designs, guaranteeing that soft robots can endure the challenges of urban environments. A further problem is the necessity for multidisciplinary collaboration among engineers, urban planners, and policymakers [214–216]. The success of the plantoid robots (in Figure 8) necessitates complex coordination among customers, agricultural specialists, mechatronics engineers, programmers, and product designers. The aforementioned stakeholders play a crucial role in each component. Furthermore, for the advancement of successful urban smart farming, urban planners and landscape designers must consider land utilization and propose the most effective and urban-friendly configurations for future agricultural, recreational, and tourism locations. 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 [217,218]. 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. Ultimately, the breakthrough of soft robotic 3D printing represents a sophisticated vital technology for cutting-edge biological applications in our present and future smart cities.

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

WAAM is an innovative 3D printing process that uses an electric arc as a heat source to melt wire material, facilitating the layer-by-layer fabrication of metallic components such as steel, aluminum, alloys, and titanium [219]. Relative to other metal additive manufacturing techniques, due to 3D freeform fabrication, WAAM has reduced cooling rates and increased heat input [220]. This is advantageous for the majority of commercially accessible materials. Moreover, the deposition rates and part dimensions can be enhanced due to the decreased complexity and surface quality of the component when compared to powder-bed-based 3D printing methods.

This novel methodology, as shown in Figure 9, is gaining prominence in the realm of smart cities, where there is an urgent demand for sustainable building methods and sophisticated manufacturing procedures.

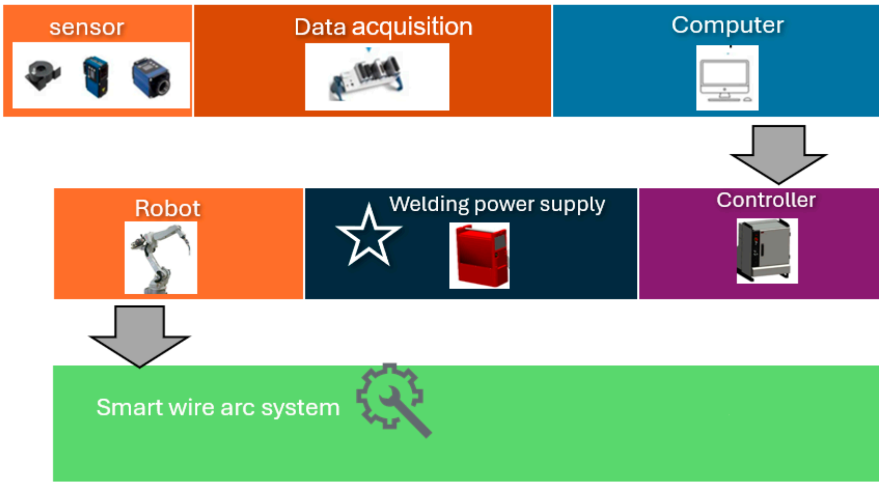


Figure 9. Generic smart wire-arc systems using 3D printing process (source: by author).

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 [221–223]. The capacity to fabricate intricate geometries with WAAM can result in creative freeform designs that improve structural performance [224,225]. 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 [226]. 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 [224,227]. WAAM facilitates expedited prototyping, 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 [228]. 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 [229]. 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 [230]. 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. In addition, partnerships among educational institutions, businesses, and governments may cultivate a workforce skilled in modern manufacturing processes, promoting innovation and economic development in metropolitan regions [117,231–233]. Many structural applications such as 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 abilities 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

ML demonstrates the experiential "learning" characteristic of human intelligence, while also possessing the ability to enhance its analysis using computing methods, and it is employed to instruct machines on managing data more effectively [234,235]. Occasionally, after analyzing the data, we are unable to derive the extracted information. In that instance, ML is implemented. The proliferation of datasets has led to an increasing demand for ML. Numerous businesses utilize it to retrieve pertinent data with the key objective of deriving insights from existing data. ML employs many techniques to address data-related issues. Data scientists emphasize that there is no universal method that is optimal for every situation. ML algorithms for smart cities can be effectively employed due to the large datasets and their selection is contingent upon the specific problem to be addressed, the quantity of variables involved, and the most appropriate model to utilize, among other factors.

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 [74,236,237]. 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 [238,239]. 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 [240,241]. Conventional quality assurance techniques frequently depend on manual inspections and established criteria, which can be labor-intensive, time-consuming, and susceptible to human error [242–244]. 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 [245,246]. As 3D printing technology becomes more integrated into urban infrastructure, the necessity for continuous maintenance and repair of printed components is paramount. ML algorithms can 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 ML with 3D printing might enable the creation of intelligent, sustainable, and recycled materials that react adaptively to environmental variations [247–250]. For instance, ML algorithms can be employed to engineer materials that alter their characteristics in response to external stimuli, such as temperature, humidity, or mechanical stress. This breakthrough facilitates the development of adaptable structures in smart cities, such as buildings that can optimize temperature and energy consumption or bridges capable of self-repairing small amounts of damage. Since the self-repairing or self-heating system is dependent on time, ML can gather the conditional data from the sites, train, and accurately predict the future variables like the crack width or thickness covering, the strengths, bonding, and surface condition of the repair areas, as well as the timing of the subsequent maintenance. 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 datasets to train ML models efficiently [251–255]. 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, businesses, and governments 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. 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. Indeed, ML concepts to analyze the large data of 3D printing processes in smart cities can be applied and integrated well together.

3.8. Three-Dimensional Printing in Structural Health Monitoring (SHM) for Smart Cities

SHM provides valuable insights into a system's behavior by examining its reactions and assessing its present mechanical condition [256,257]. A system may comprise a skyscraper, a bridge, an infrastructure network, or a basic beam. Initially, SHM was utilized for damage detection in airplanes within the field of aerospace engineering and industry. In the past two decades, it has significantly evolved due to sophisticated sensor technologies, substantial improvements in computing, and the integration of structural control methodologies. A conventional simple harmonic motion system has three principal components: (1) sensors, either touch or non-contact, (2) a processing unit (comprising data gathering, transmission, and storage), and (3) a data interpretation system (consisting of diagnostic procedures and information management) [258]. Its purpose in structures is to not just convey its structural integrity, initiating automatic protocols or, if required, requesting human aid, but also to anticipate potential future occurrences [259,260].

SHM denotes the assessment of the state of structures—such as bridges, buildings, and roads—utilizing diverse sensing technologies to guarantee their safety and integrity [261–263]. Conventional SHM frequently depends on integrated sensors and routine evaluations, which are typically labor-intensive and expensive. The use of 3D printing in 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 [264].

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 [265]. Three-dimensionally printed sensor systems can be included in printed structural components, facilitating smooth integration and reducing interruption to the overall structure. This capability enhances the effectiveness of monitoring systems by ensuring the strategic placement of sensors to gather crucial data. The collected data from 3D printed sensors can be loaded into monitoring or environmental datasets [266–268]. For instance, Kim et al. [267] developed 3D printed vorticella-kirigami-inspired sensors and revealed that these 3D printed wireless sensors can perform 3 times better in terms of out-of-plane strain compared to conventional spring structures with only around 25% strain. In terms of signal detection, the sensors had a sensitivity of 0.80 $\mathrm{pF/ms^{-2}}$ through the message queuing telemetry transport protocol, which can be adopted in wireless smartphones and personal computers. This adaptability is especially significant in the realm of smart cities, where the fluidity of urban settings demands prompt reactions to evolving IoT 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, like seismic, tornado, and tsunami failure, by integrating real-time data from 3D printed sensors with sophisticated analysis tools [269–272]. Li et al. [273] developed a 3D printed tilt sensor with electrical time domain reflectometry used for SHM in railway level crossings and found promising results with a conservative estimate of sensors' accuracy of $\pm 0.16^{\circ}$, better than the conventional sensor systems. 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. In summary, 3D printing is appropriate for the fabrication of SHM sensors and structures, as its mass customization capabilities enable the manufacturing of objects with efficiency and reduced prices.

3.9. Repair Strategies in 3D Printing for Smart Cities

Current infrastructure and buildings have been in service for decades. Many projects have been designed regarding their serviceability design limits like structural and durability performance. This service life of concrete structures, for instance, is stated in "EN 206: Concrete—Requirements, Properties, Production and Compliance" [274] as the duration during which the concrete's condition in the structure meets the operational specifications. The necessity for maintenance seemingly contradicts the belief in the durability of concrete. Numerous manuals on concrete durability and the construction of resilient buildings typically conclude with a chapter titled "How to make repairs" [275]. The seeming contradiction is further demonstrated by the fact that repairs, contingent upon conditions, aim to preserve or restore the durability of a building's construction [276,277]. Hence, repair strategies are key activities of restoration of buildings and infrastructure. This can be integrated with new innovation 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. Three-dimensional printing enables a prominent repair strategy that involves the on-demand production of replacement components [278,279]. Conventional supply chains sometimes entail extended lead times and significant logistical difficulties, especially for specialty components. Conversely, 3D printing allows towns to produce components locally, therefore diminishing transportation emissions and expenses [280]. 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 as lamps, benches, or signage, therefore reducing service disruptions and improving the overall efficacy of public places [281]. Engineers may develop components that are more resilient and better equipped to endure environmental difficulties by leveraging modern and ecologically adaptive materials and implementing design optimization methods. Alongside on-demand manufacture, adaptable design methodologies are essential to the efficacy of 3D printed repairs. In this on-demand repair, new 3D printing materials with faster hardening are required [282,283]. As examples of cement-based materials, alternative binders and chemical additives like calcium aluminate, calcium sulfoaluminate, and accelerator were introduced for such applications [284–287]. Kumar [288] also used polyvinylidene fluoride (PVDF)–graphene–manganese (Mn)-doped zinc oxide (ZnO) and PVDF-based 3D printable solutions for smart maintenance of non-structural cracks of heritage structures.

Predictive maintenance enabled by the IoT enhances the efficacy of repair solutions in 3D printing [289–291]. 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 [292,293]. 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 [10,294]. The circular economy paradigm, which prioritizes reuse and recycling, may be included in 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 [295,296]. Another example is adding polymer and additive waste [297–299] or using low-energy intensive binders [230–302] and reinforcement [72,303–308] in 3D printed concrete/polymer matrix in concrete structures for increasing flexibility and promoting a circular economy. This method not only reduces trash but also fosters a culture of sustainability in urban environments. WAAM is an innovative 3D printing process that uses 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 8, is gaining prominence in the realm of smart cities, where there is an urgent demand for sustainable building methods and sophisticated manufacturing procedures. Without doubt, 3D printing repair strategies with freeform printing and adaptive fabrication serve well for restoring and maintaining buildings and infrastructure for smarter cities.

4. Conclusions

The article conducted qualitative analysis and a systematic review of the contribution of 3D printing to smart cities, which underscores the substantial contributions of the study to academic debate and practical understanding from state-of-the-art publications.

- The review elucidates the interaction of DTs, smart materials, Industry 4.0, soft robotics, ML, SHM, WAAM, and repair strategies for construction, urban planning, smart infrastructure, and environmental sustainability through the integration of many views. All of the mentioned areas have research gaps and roadmaps to notably improve the future of smart cities.
- DTs and 3D printing can be utilized in producing building elements in existing buildings.
- Industry 4.0 presents the future of mass-customized digital construction.
- Smart materials in 3D printing offer distinct benefits like improved building, electrical, and functional performance, reduced energy consumption, and enhanced durability.
- ML can evaluate past performance data from diverse components from existing smart buildings to forecast maintenance requirements as well as predict and control environmental conditions and cities for more livable communities.
- Soft robotics are key for human interaction with automated machines, with implementation varying from medicine to gardening and farming.
- SHM is the key to inspecting and maintain safety in cities with less cost and more security regarding unpredictable, diverse events.
- Repair strategies of existing building structures can be made easier and more effective by the WAAM approach, yielding strategized planning of repairs for communities, minimizing the possibility of failure, and enhancing resource distribution.

The analysis delineates synergies, obstacles, constraints, and research gaps while providing prospective recommendations to enhance future investigations. Academics, practitioners, and policymakers can follow the recommendations and insights of this work to implement powerful technology for local communities. 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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