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From smart cities to self-healing cities: the role of 4D printing in urban resilience

Antreas Kantaros[1,*], Theodore Ganetsos[1], Zoe Kanetaki[2], Constantinos Stergiou[2] and Michail Papoutsidakis[1]

[1] Department of Industrial Design and Production Engineering, University of West Attica, 12244 Athens, Greece
[2] Department of Mechanical Engineering, University of West Attica, 12244 Athens, Greece

* Correspondence author; E-mail: akantaros@uniwa.gr.

Highlights:

- 4D printing enables autonomous repair in urban infrastructure.
- Shape-memory polymers and hydrogels support self-healing structures.
- Bio-based and capsule-triggered systems restore structural integrity.
- Pilot-scale demonstrations guide safe, scalable deployment in cities.
- Integration with sensors and digital twins enhances urban resilience.

Abstract: Urban infrastructure is increasingly challenged by aging components, environmental stresses, and dynamic operational demands, highlighting the need for autonomous, adaptive repair strategies. This perspective paper explores the potential of 4D printing technologies to transform conventional smart cities into self-healing urban systems capable of real-time structural and functional restoration. Stimuli-responsive materials, including shape-memory polymers, hydrogels, and bio-based or capsule-triggered healing agents, are examined for their mechanisms, fabrication compatibility, and potential deployment in structural elements, utility networks, and environmental protection systems. Insights from biomedical, aerospace, and maritime sectors are analyzed to identify translational opportunities and limitations for urban applications. Integration challenges, encompassing sensor-actuator coordination, compatibility with existing construction and maintenance practices, scalability, environmental robustness, and manufacturing standardization, are discussed to provide a comprehensive view of the system-level considerations required for reliable operation. Policy, regulatory, and lifecycle assessment aspects are addressed to outline requirements for certification, safety, liability, economic, and environmental evaluation. Pilot-scale demonstration projects and interdisciplinary collaboration are highlighted as critical means to validate material performance, system functionality, and operational feasibility. Finally, research priorities, including accelerated testing, dual-stimuli control, hybrid repair mechanisms, and predictive monitoring strategies, are proposed to guide the development and deployment of resilient, autonomous urban infrastructure. The integration of these approaches is envisioned to enable cities capable of continuous adaptation and self-repair, offering enhanced

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resilience, extended service life, and sustainable maintenance. This bibliometric analysis (2015–2026) highlights the rapid growth of research on 4D printing and its role in developing self-healing and adaptive systems. From 991 keywords grouped into four thematic clusters, findings reveal strong foundations in material science and additive manufacturing, with emerging trends in bio-based materials, autonomous repair, and urban resilience. Despite significant advancements, limited integration between materials research and large-scale infrastructure applications signals the need for interdisciplinary approaches toward smart and sustainable cities. By synthesizing current advances and future perspectives, this work provides a context for utilizing 4D printing to create self-healing cities and establishes a foundation for ongoing research, policy development, and practical implementation.

Keywords: 4D printing; self-healing urban infrastructure; stimuli-responsive materials; autonomous repair systems; shape-memory polymers; hydrogels; capsule-triggered healing; smart cities; urban resilience; additive manufacturing

1. Introduction and scope

Urban environments have increasingly been managed through Smart City initiatives, in which advanced information and communication technologies are employed to monitor, analyze, and optimize urban systems [1,2]. Data streams generated by sensors, Internet of Things (IoT) devices, and centralized control platforms are leveraged to enhance the efficiency of transportation networks, energy distribution, water management, and emergency services [3–5]. Despite these technological advancements, the physical adaptability of urban infrastructure has largely remained unaddressed, and vulnerabilities associated with structural degradation, environmental stressors, or unanticipated damage have persisted. Reliance on data-driven monitoring alone has limited the capacity of cities to autonomously respond to evolving challenges, while reactive maintenance strategies continue to dominate the management of urban assets [6,7].

The limitations inherent in conventional Smart City frameworks have motivated the exploration of infrastructure systems capable of autonomous adaptation and self-repair. Analogous to biological systems, urban infrastructure could be engineered to detect damage, trigger responsive mechanisms, and restore functionality without external intervention [8]. Such integrative BIM-based workflows are expected to mitigate risks related to structural and energy performance deficiencies, minimize operational disruptions during retrofitting processes, and extend the functional lifespan of existing building assets [9]. Moreover, resilience against both acute events, such as natural disasters, and long-term chronic stressors, including material aging and climate-induced degradation, could be significantly enhanced through the integration of autonomous repair mechanisms [10].

Within this context, the potential role of 4D printing in enabling self-healing urban infrastructure is examined [11]. Emphasis is placed on materials and design strategies that facilitate autonomous repair, on the identification of functional requirements for self-healing systems, and on the assessment of relevant stimuli-responsive materials [12]. Integration challenges at the system level are analyzed, and research, implementation, and policy considerations are discussed to provide a comprehensive understanding of the opportunities and limitations associated with translating 4D printing technologies from laboratory-scale demonstrations to operational urban infrastructure applications [13,14].

In this work, the term “4D printing” is used in accordance with its contemporary definition in the materials and additive manufacturing literature, referring to 3D-printed structures that exhibit programmed, stimulus-responsive, time-dependent behaviour. Although self-healing materials constitute a well-established field, our focus is on cases where self-repair mechanisms are embedded, spatially patterned, or functionally activated through additive manufacturing techniques. In such systems, the printed architecture itself contributes to the timing, localization, or efficiency of the healing response, aligning them with the broader category of 4D-printed, programmable material systems. This clarification ensures that conventional self-healing materials are not conflated with 4D printing, while highlighting the unique role of additive manufacturing in enabling autonomous, adaptable behaviour in urban infrastructure applications.

The article is organized to provide a logical progression from conceptual foundations to applied considerations. Definitions and functional requirements for self-healing urban systems are presented in the following section, followed by a review of state-of-the-art 4D printing materials and adaptation strategies. System-level integration challenges, including sensor-actuator coordination and environmental robustness, are subsequently analyzed. Considerations related to implementation, policy, and research priorities are then discussed, and perspectives on future development, long-term vision, and concluding remarks are provided in the final section.

2. Literature review

In order to focus on the most recent scientific developments in the research field, a bibliometric analysis of keywords has been performed for defining the research gap.

2.1. Bibliometric analysis of keywords methodology

An initial step before reviewing the related works consists on an advance document search in Scopus database, based on a set of targeted keywords. The specific query includes keywords derived from the manuscripts ‘title, combined with additional keywords and limitations in the time period that this search is limited.

The query returning 1270 related articles has been launched as follows:

(TITLE-ABS-KEY (“4D Printing”) AND (TITLE-ABS-KEY (“Smart Cities”) OR TITLE-ABS-KEY (“Urban Resilience”) OR TITLE-ABS-KEY (“Self-Healing”) OR TITLE-ABS-KEY (“Autonomous Repair Systems”) OR TITLE-ABS-KEY (“Stimuli-Responsive Materials”) OR TITLE-ABS-KEY (“Shape-Memory Polymers”) OR TITLE-ABS-KEY (“Hydrogels”))) AND PUBYEAR > 2014 AND PUBYEAR < 2027.

The time period has been limited from 2014 to 2026 in order to refine the results and focus on the most recent advances in the field. Scopus analysis of results shows the prominence of China, United States, India and United Kingdom as pioneers in the literature activity. The annual distribution of documents from 2015 to 2026 demonstrates a steadily increasing research interest in the field.

A RIS file has been exported from Scopus database, which was inserted to VOSviewer (2023) software in order to analyze bibliographic data of various scientific publications and journals as well as the link strength, and the occurrence [15–17]. A keyword co-occurrence analysis has been conducted for the specific time period [18–20]. Network maps have been generated as shown in Figure 1, indicating

the frequency or co-occurrence identifying five research clusters based on the weight of the keywords. The links and weights of the clustered items in the mapping represent all core components.

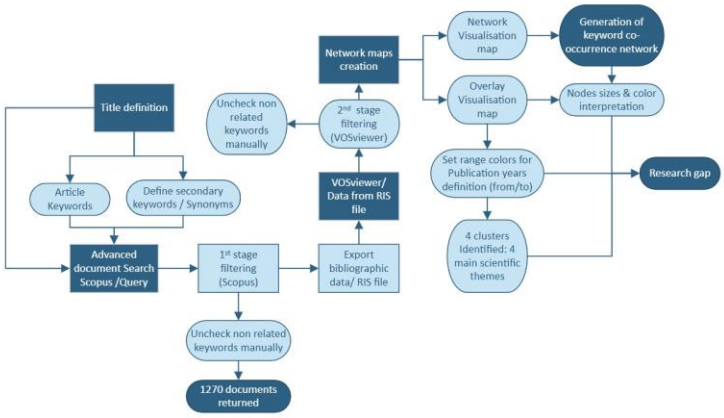


Figure 1. Bibliometrics analysis methodology.

2.2. Bibliometric analysis: networks maps of keywords

The network visualization map reveals a keyword co-occurrence network where nodes represent keywords and their size their co-occurrence. The size of the nodes reveals the strength of the keywords. The size of each circle (node) shows its frequency of occurrence within the dataset. The color coding (as shown in Figure 1) represents distinct clusters of related terms, identified through co-occurrence analysis.

An overlay visualization of the imported data is presented in Figure 2, including similar information as shown in Figure 3, with the addition of the color bar indicating the color mapping in the selected time period of publication. The legend bar on the bottom of Figure 2 indicates the time period within the query has been launched in Scopus database (from 2014 to 2026). Keywords (nodes) in yellow and vivid green col-or derive from the most recent publications (2020–2026), therefore representing the most recent trends. Those keywords are “self-memory polymer”, “four dimensional printing”, “digital printing”, “thermal printing”, “4D printing”; “4D/3D printing”; ”4D bioprinting”; “bio-based”; bio-based materials; “shape-memory polymers”; “stimuli-responsive materials”; “active material”; “blending”; “adhesion”; “bond strength”.

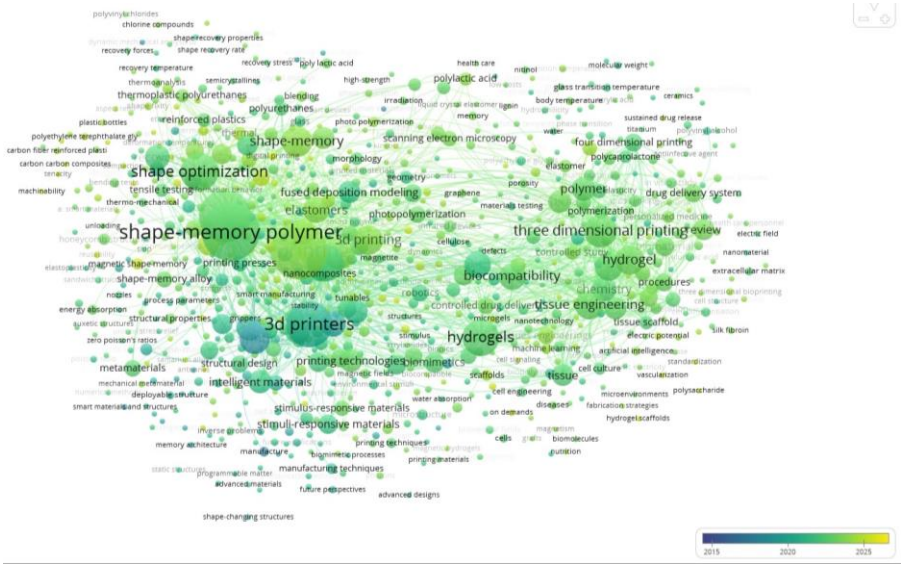


Figure 2. Overlay visualization map of keywords from the time period 2010–2026.

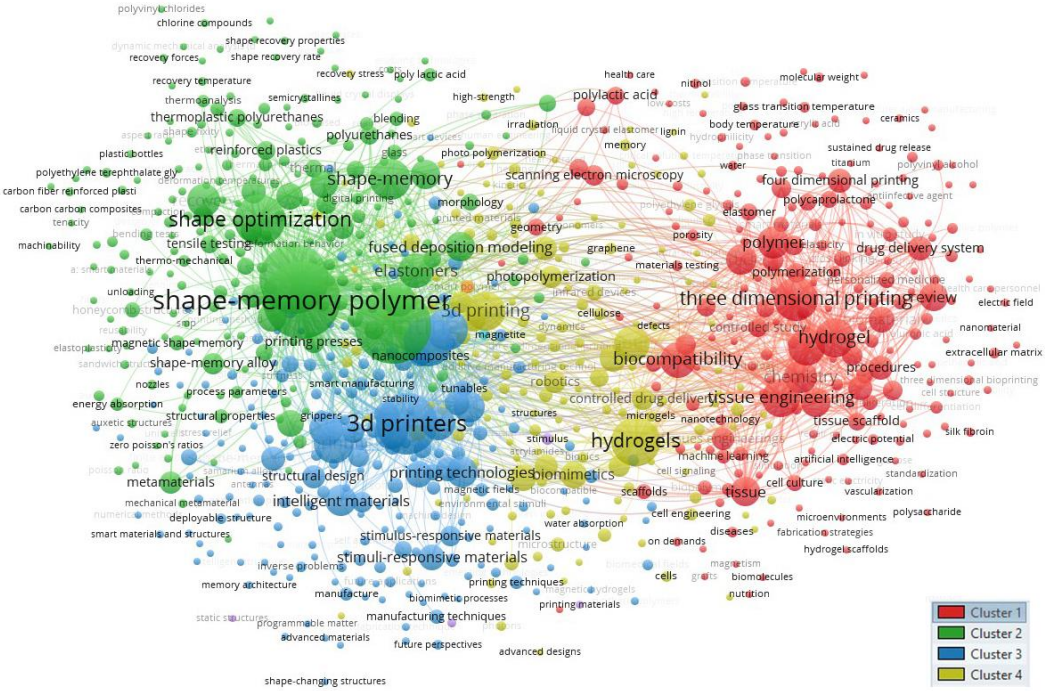


Figure 3. Network visualization map of keywords indicating four clusters.

Dark green and purple nodes indicate keywords from older publications (2010–2015). Larger nodes with darker or mid-green tones represent continued re-search over a long period of time. The keywords such as “3D printing”, “additive manufacturing”, “shape-memory polymers”, “biocompatibility”; “biomaterials”; “hydrogels”; “bioprinting”; “smart materials”; “stimuli-responsive materials” and “aero-space applications” are represented in large green nodes, indicating a continued research trend over a longer period.

The bibliometric analysis of keywords revealed dominant terms represented as nodes of bigger diameter which include “three dimensional printing”, “tissue engineering”, “hydrogel”, “procedure” and “biocompatibility”, “polymer”. Those keywords of red color belong in the primary thematic area.

From the interpretation of the overlay visualization, the spatial overlay of key-words and their distribution during the last decade (time period set from 2014 to 2026) indicate a research acceleration from the year 2021 revealing emerging trends in the themes “4D/3D printing”, “bio-based materials” and “cell viability”, themes actively expanding since 2021.

Green circles (nodes) indicate specialized topics such as “shape-memory polymer”, “shape optimization”, “shape memory”, “elastomers”, “fused deposition modeling”. Those green nodes (circles of smaller diameter) are linked to the dominant nodes but represent subfields of research. Lighter colored and smaller sized circles represent distinct subfields which are also connected to each other and to the core (red) nodes, such as “bioprinting”, “stimuli-responsive polymers”, “hydrogel-based composites” and “biofabrication processes”.

2.3. Cluster analysis of keywords

Consequently, a cluster analysis has been performed, identifying four clusters bringing to light four scientific themes, research themes or subject areas. The keywords are represented as “items” in the cluster analysis. 991 items are contained in the VOSviewer database extracted from the bibliometric

data—Scopus RIS file (titles and author keywords) that meet the occurrence threshold as set in VOSviewer ≥ 5 occurrences.

Distinct research directions are revealed with the cluster analysis of keywords: An overall pattern may be distinguished for the four clusters generated by the cluster analysis:

Cluster 1: Bioprinting & Biomedical Materials, including keywords such as "4D bioprinting", "biocompatibility", "biopolymers", "biofabrication" and "tissue engineering.

Cluster 2: Smart & Active Materials including keywords such as "4D printing", "shape-memory polymers", "stimuli-responsive materials" and "composites".

Cluster 3: Additive Manufacturing & Engineering Applications including keywords such as "3D printing", "3D modeling", "active structures" and "aerospace applications".

Cluster 4: Hydrogels & Chemical Materials including keywords such as "hydrogels", "alginate", "biomaterials", "biomedical applications", "adhesion".

2.4. Defining the research gap

Keywords positioned around the dominant ones, demonstrate their limited integration the core keywords (red nodes), which may lead us to conclude to their limited integration in the red nodes of bigger diameter and consequently to define the research gap. It may be district that keywords positions in the periphery such as "urban resilience", "smart cities", "self-healing infrastructure", and "autonomous repair systems" appear less densely linked to the core technological and material-oriented clusters. The above-mentioned observation suggests that, although the technological foundations for 4D printing and stimuli-responsive materials are well-established, their application within urban and infrastructural contexts yet remains underexplored. More specifically, connecting material innovation studies with large-scale urban infrastructure, adaptive infrastructure design with "self healing" systems, and resilience planning reveals a research gap in the recent literature.

3. Definitions and functional requirements for self-healing urban systems

The design and implementation of self-healing urban infrastructure require a clear understanding of the underlying terminology, concepts, and performance criteria that define such systems. Self-healing systems are intended to respond autonomously to damage or environmental stimuli, restoring functionality without external intervention [15]. To ensure rigorous scientific assessment, it is necessary to establish precise definitions, distinguish between adaptive, responsive, and self-repairing mechanisms, and identify the functional requirements that urban components must satisfy to qualify as self-healing [16]. These foundational concepts serve as a framework for evaluating the potential of 4D printing technologies and other stimuli-responsive materials for practical deployment in urban infrastructure applications. In addition, the characterization of performance metrics, target application domains, and operational constraints is essential for establishing a consistent basis for comparison between different materials, design strategies, and system configurations.

3.1. Terminology and conceptual framework

The term self-healing has been employed across multiple scientific disciplines, including materials science [17], civil engineering [18], and biomedical engineering [19], to describe systems capable of

autonomous restoration following damage. In the context of urban infrastructure, self-healing is defined as the ability of a component or system to detect mechanical or environmental perturbations, activate a reparative response, and restore structural or functional integrity without human intervention [20]. This concept is distinct from adaptive systems, which modify their behavior or configuration in response to external stimuli but do not necessarily repair or restore lost functionality [21]. Similarly, self-sensing systems are capable of detecting changes in state or performance but lack mechanisms for autonomous repair [22]. A comprehensive conceptual framework is therefore established in which urban infrastructure components can be classified along a continuum of sensing, adaptation, and repair capabilities, providing a basis for systematic evaluation of emerging 4D printing solutions.

Within this framework, the design principles of self-healing systems are further delineated by material-level and system-level considerations. At the material level, healing mechanisms may involve reversible deformation, shape-memory activation, microcapsule rupture, or bio-mediated repair, and these mechanisms are characterized by activation thresholds, response rates, and durability under repeated stimuli [23]. At the system level, the integration of sensing, actuation, and control elements must be considered, along with operational constraints imposed by structural loads, environmental exposure, and safety standards [24]. Functional requirements are thus defined in terms of efficiency, repeatability, reliability, and compatibility with urban deployment scenarios [25]. By establishing such a conceptual framework, the evaluation of 4D printing technologies can be grounded in quantifiable criteria that allow for rigorous comparison, identification of research gaps, and guidance for future implementation strategies.

3.2. Performance criteria

The assessment of self-healing urban systems is fundamentally dependent on clearly defined performance criteria, which establish the effectiveness and reliability of autonomous repair mechanisms. Healing efficiency is typically quantified as the degree to which structural or functional properties are restored following damage [26]. In the case of 4D-printed materials, this may be expressed as the percentage recovery of mechanical strength, stiffness, or geometric integrity relative to the undamaged state [27]. High healing efficiency is critical for ensuring that repaired components can continue to perform their intended functions under operational loads and environmental conditions. Moreover, it is essential that healing mechanisms are effective across the range of expected damage scenarios, including micro-cracks, localized fractures, and more extensive structural failures.

Activation triggers represent another critical criterion, as the responsiveness of the system must be precisely controlled to avoid premature or unintended activation. Stimuli such as temperature variations, moisture exposure, mechanical stress, or chemical signals may be employed to initiate self-repair, and the sensitivity of the material or component to these stimuli must be calibrated to match the anticipated urban environment [28]. Repeatability of the healing process is also essential, as multiple damage-repair cycles may occur over the lifespan of an infrastructure element. Materials and systems must maintain their reparative functionality after repeated activation without significant degradation [29]. Finally, load-bearing restoration is a key functional requirement, as repaired components must be capable of sustaining design loads without compromising structural integrity or safety [30]. Collectively, these performance criteria provide a quantitative and operational basis for evaluating self-healing

mechanisms, guiding the selection of suitable 4D printing materials, and informing the design of autonomous urban infrastructure systems.

3.3. Target application domains

The potential applications of self-healing urban systems can be categorized into three primary domains: structural elements [31], utility networks [32], and environmental protection systems [33]. In the case of structural elements, components such as bridges, pavements, building facades, and load-bearing frameworks are considered, as these elements are frequently exposed to mechanical stress, environmental degradation, and accidental damage [34]. The integration of self-healing materials or 4D-printed adaptive components into these structures allows for the autonomous restoration of mechanical integrity, crack closure, and dimensional stability, thereby extending service life and reducing maintenance requirements [35].

Utility networks, including water distribution pipelines, electrical conduits, and transportation infrastructure, represent a second critical domain [36]. Self-healing systems can be employed to restore fluid or electrical continuity following leaks, fractures, or partial failures, minimizing service disruptions and enhancing resilience [37]. Autonomous repair mechanisms embedded within these networks can detect localized damage, trigger restorative responses, and prevent the propagation of failures across interconnected systems [38]. Finally, environmental protection systems, encompassing flood barriers, stormwater management structures, and green infrastructure, can also benefit from self-healing capabilities [39]. Adaptive materials and components can be programmed to respond to environmental stimuli such as moisture, flow rate, or temperature, enabling proactive mitigation of extreme weather events and dynamic restoration of protective functionality [40]. Collectively, these application domains highlight the broad relevance of self-healing technologies and provide a practical framework for evaluating the potential impact of 4D printing in the urban context.

To consolidate the functional spectrum of self-healing requirements across urban infrastructures, the primary application domains of 4D-printed adaptive materials can be grouped into structural, utility, and environmental protection systems, with further relevance to protective surface layers and energy-related components. Each domain presents distinct operational stressors, activation conditions, and performance expectations, necessitating tailored material strategies rather than a one-size-fits-all solution. Table 1 summarizes representative use cases within these domains, the corresponding functional demands for effective healing or adaptation, and indicative classes of stimuli-responsive materials with potential suitability for deployment.

To clarify the operational distinction between adaptive, stimulus-responsive behavior and true autonomous self-healing in urban infrastructure, the decision logic underlying these mechanisms is illustrated in Figure 4. The flowchart outlines the sequential evaluation of environmental stimuli, damage detection, functional impairment, and material response, highlighting the conditions under which a 4D-printed component performs a genuine self-repair event versus a temporary adaptive transformation.

Table 1. Target application domains for 4D printing-enabled self-healing urban systems.

Application Domain	Representative Use Cases	Functional Requirements	Potential 4D Material Strategies
Structural Elements	Cracks in concrete pavements; bridge joints; expansion seals	Load-bearing restoration; long-term durability; cyclic fatigue resistance	Shape-memory polymers; capsule-triggered cementitious composites
Utility Networks	Leakage in water pipelines; cable insulation breaches; gas line micro-damage	Rapid sealing; chemical resistance; minimal flow disruption	Hydrogels for swelling-based sealing; bio-based polymer coatings
Environmental Protection Systems	Flood barriers; coastal erosion control; drainage channels	Moisture- or temperature-activated adaptability; resilience to UV and abrasion	Hydrogels and hydro-responsive fabrics; SMP-reinforced geomembranes
Surface Coatings and Protective Layers	Anti-corrosion coatings on metal infrastructure; façade cladding	Scratch repair; weathering resistance; self-replenishing surfaces	Microcapsule-based self-healing paints; polymer nanocomposite films
Energy and Smart Grid Components	Solar panel support frames; battery casings; sensor housings	Electrical insulation recovery; thermal stability	Conductive SMP composites; dual-stimuli responsive polymers

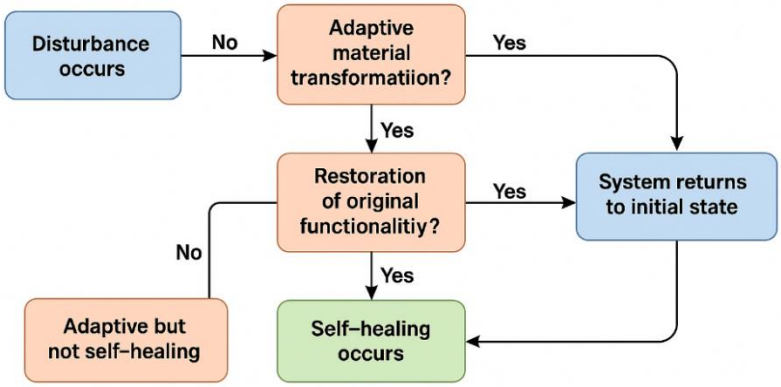


Figure 4. Decision-logic flowchart distinguishing adaptive stimulus responses from true self-healing events in 4D-printed urban infrastructure systems.

4. State-of-the-art in 4D printing for structural and functional adaptation

The utilization of 4D printing technologies for self-healing urban infrastructure has been increasingly explored due to their capacity to produce stimuli-responsive materials that change shape, mechanical properties, or functionality over time [41]. The integration of such materials into structural and functional components allows for autonomous adaptation to environmental or mechanical stimuli, providing a platform for urban systems capable of self-repair and resilience enhancement. A variety of 4D printing materials and mechanisms have been investigated, with particular attention to their fabrication feasibility, compatibility with existing additive manufacturing processes, and potential for integration into urban infrastructure applications [42,43]. In this chapter, the state-of-the-art of these technologies

is reviewed, emphasizing their material mechanisms, performance capabilities, and translational relevance to self-healing systems in the urban context.

4.1. Shape-memory polymers and composites

Shape-memory polymers (SMPs) and their composite variants have been extensively investigated for use in 4D-printed self-healing structures due to their inherent ability to undergo programmed deformation and recover predefined geometries upon exposure to specific stimuli, such as temperature, light, or electrical input [44]. The shape-memory effect is achieved through a combination of a permanent network that defines the ultimate shape and reversible domains that allow temporary deformation [45]. This mechanism enables the material to respond autonomously to environmental triggers, closing cracks, restoring structural alignment, or adjusting component geometry to maintain functional performance. The tunability of SMPs allows the activation temperature, recovery stress, and deformation kinetics to be precisely engineered to match the requirements of urban infrastructure applications [46].

Fabrication of SMPs and SMP-based composites has been demonstrated using multiple additive manufacturing techniques, including fused filament fabrication (FFF), stereolithography (SLA), and digital light processing (DLP), providing flexibility in producing complex geometries and customized components [47]. Incorporation of reinforcing fibers, nanoparticles, or fillers within the polymer matrix has been employed to enhance mechanical strength, thermal stability, and fatigue resistance, facilitating the use of SMPs in load-bearing urban elements. The potential of SMPs and their composites for urban infrastructure has been highlighted in studies involving self-closing cracks in pavements, adaptive façade elements, and temporary support structures, where autonomous shape recovery mitigates damage and prolongs service life [48]. Overall, SMP-based 4D printing provides a promising approach for embedding autonomous repair functionality into structural and functional urban components, bridging the gap between material-level responsiveness and system-level resilience.

4.2. Hydrogels and moisture/heat-responsive materials

Hydrogels and moisture- or heat-responsive materials have been investigated extensively for self-healing urban applications due to their ability to undergo volumetric changes, swelling, or deformation in response to environmental stimuli [49]. These materials are capable of absorbing water or responding to temperature variations, thereby enabling autonomous adjustments in shape or functionality that can be exploited for sealing leaks, filling cracks, or redirecting flows in infrastructure systems [50]. The swelling behavior of hydrogels, for instance, allows microcracks in concrete or polymer-based components to be autonomously sealed, mitigating water ingress and preventing the propagation of structural damage. Similarly, heat-responsive hydrogels can expand or contract to regulate gaps, adjust mechanical properties, or redirect fluid flow, making them particularly suitable for dynamic urban environments subjected to thermal fluctuations [51].

The fabrication of hydrogels and other responsive materials has been achieved through multiple 3D printing modalities, including extrusion-based bioprinting, inkjet printing, and photopolymerization techniques, allowing complex geometries and graded structures to be realized [52]. Material formulations can be tuned to achieve specific swelling ratios, response times, and mechanical strengths,

thereby enabling integration into structural elements, utility conduits, or environmental protection systems. Applications in urban infrastructure have demonstrated the potential for hydrogels to act as autonomous sealing agents in water distribution networks [53], adaptive components in stormwater management systems [54], and self-regulating barriers in flood protection structures [55]. The inherent responsiveness, combined with additive manufacturing capabilities, positions hydrogels and moisture- or heat-sensitive materials as a versatile class of 4D-printable components capable of enhancing the resilience and self-healing capacity of urban systems.

4.3. Bio-based or capsule-triggered healing systems

Bio-based and capsule-triggered healing systems have been increasingly explored as mechanisms for autonomous repair in 4D-printed urban infrastructure due to their ability to initiate restorative processes upon material damage [56]. In bio-mediated approaches, microorganisms such as bacteria are embedded within a structural matrix, where they remain dormant until mechanical stress, crack formation, or chemical changes activate their metabolic activity. Upon activation, these bacteria precipitate mineral phases, polymers, or other reparative agents that fill microcracks, restore mechanical integrity, and inhibit further degradation [57]. Similarly, microencapsulated healing agents can be incorporated into printable matrices, where the capsules rupture upon crack propagation, releasing reactive compounds that polymerize or bond with the surrounding material to restore functionality [58,59]. These strategies allow for localized, autonomous repair without external intervention, providing a biologically or chemically inspired pathway for self-healing urban components.

Fabrication compatibility for bio-based and capsule-triggered systems has been demonstrated using extrusion-based printing, stereolithography, and other additive manufacturing techniques capable of embedding living or reactive agents without compromising viability or activity [60–62]. Material matrices can be engineered to optimize capsule distribution, bacterial viability, and diffusion pathways, ensuring that healing agents are delivered precisely to damaged regions. Pilot studies have shown the effectiveness of these systems in concrete repair, polymer composites, and multifunctional coatings, highlighting their potential for restoring structural integrity in critical infrastructure elements such as pavements [63], utility conduits [64], and protective barriers [65]. The integration of bio-mediated or microencapsulated healing agents within 4D-printed components represents a promising strategy for autonomous, environmentally adaptive urban infrastructure, bridging the gap between material-level responsiveness and functional resilience at the system scale [66].

4.4. Insights from adjacent sectors (biomedical, aerospace, maritime)

Significant insights regarding the design and implementation of self-healing 4D-printed systems have been gained from adjacent sectors, including biomedical engineering, aerospace, and maritime applications. In the biomedical field, shape-memory polymers, hydrogels, and bio-based healing agents have been extensively applied in tissue scaffolds, implantable devices, and drug delivery systems, where autonomous responses to mechanical, chemical, or thermal stimuli are essential for functionality [67,68]. Techniques for embedding living cells, encapsulating reactive agents, and achieving precise, localized activation have been refined in these contexts, providing a valuable foundation for translating similar strategies to urban infrastructure components [69,70]. Likewise, aerospace and maritime industries have

employed 4D-printable composites and self-healing polymers to mitigate microcracks, fatigue damage, and environmental degradation in high-stress structural elements, demonstrating both the feasibility and effectiveness of autonomous repair mechanisms in demanding operational environments [71,72].

Despite the demonstrated potential in these sectors, several limitations have been identified that must be addressed when translating these technologies to urban infrastructure. Activation conditions optimized for biomedical applications may not be directly compatible with the variable and harsh environmental conditions encountered in urban settings, including temperature extremes, UV exposure, moisture fluctuations, and mechanical loads [73]. Scale-up challenges are also significant, as materials and fabrication methods developed for small or high-value components must be adapted for large-scale infrastructure elements while maintaining performance, reliability, and cost-effectiveness. Furthermore, regulatory, safety, and long-term durability considerations differ substantially between biomedical or aerospace applications and public urban infrastructure [74]. Nevertheless, the lessons learned regarding material design, stimuli-responsiveness, and autonomous repair strategies provide a valuable translational framework, highlighting both the opportunities and the constraints associated with deploying 4D-printing technologies to enhance resilience in self-healing cities [75].

The comparative analysis of biomedical, aerospace, and maritime applications demonstrates that while 4D printing concepts have reached high maturity in controlled and mission-critical environments, their adaptation to urban infrastructure demands broader functional versatility and environmental robustness. To synthesize the transferable insights from these adjacent sectors, the key operational contexts, demonstrated capabilities, and persisting constraints are systematically consolidated in Table 2. This cross-sector mapping highlights both the validated advantages of stimuli-responsive systems and the remaining research and engineering barriers that must be addressed before translation to large-scale civil infrastructure becomes feasible.

Table 2. Cross-sector insights from 4D printing applications in biomedical, aerospace, and maritime domains.

Sector	Demonstrated Use Cases	Relevant Mechanisms for Urban Translation	Key Limitations for Infrastructure Deployment
Biomedical	Self-expanding stents; tissue scaffolds; drug-release matrices	Precise shape recovery; biocompatible self-repair	Limited load-bearing capacity; narrow environmental range
Aerospace	Morphing wings; thermal-shielding components; deployable structures	High-performance shape-memory alloys and polymers	High fabrication cost; complex activation requirements
Maritime	Anti-fouling coatings; adaptive hull structures	Moisture-/pressure-responsive hydrogels and composites	Degradation in extreme salinity; scalability challenges

Although 4D-printed materials demonstrate impressive autonomous response capabilities, their current mechanical performance remains below the thresholds typically required for deployment in resilient urban infrastructure. For instance, shape-memory polymers commonly achieve high recovery ratios (> 90%) and moderate recovery stresses but still exhibit tensile strengths and fatigue resistance significantly lower than those demanded by load-bearing structural elements such as pavements, joints, and façades. Hydrogels and moisture-responsive systems offer excellent sealing behaviour and rapid

volumetric actuation but possess inherently low stiffness and poor long-term durability under UV exposure, drying–wetting cycles, and fluctuating mechanical loads. Similarly, bio-based and capsule-triggered healing systems successfully restore micro-damage at the material scale, yet their healing kinetics, repeated-cycle stability, and compatibility with cementitious or composite matrices remain insufficient for large-scale structural integration. These discrepancies highlight a clear performance gap between the physical and mechanical indicators of current 4D-printed materials and the operational requirements of resilient cities, particularly in terms of load-bearing capacity, environmental robustness, and multi-cycle reliability. Addressing this gap will require materials engineered with higher baseline mechanical strength, hybrid material architectures, and validated durability under realistic urban stressors.

5. Integration challenges: from material-level functionality to system-level deployment

The transition from material-level responsiveness to system-level deployment in self-healing urban infrastructure requires careful consideration of integration challenges. While 4D-printed materials demonstrate autonomous adaptation and repair capabilities under controlled conditions, their effectiveness in operational urban environments is constrained by the complexity of interacting components, environmental variability, and functional dependencies [76]. The successful deployment of self-healing infrastructure depends not only on the intrinsic properties of the materials but also on the coordination between sensing, actuation, and control systems, the compatibility with existing construction practices, and the resilience of components to long-term environmental stressors. In this chapter, key challenges are examined, highlighting constraints that must be addressed to enable reliable, scalable, and functional self-healing urban systems.

5.1. Sensor-actuator coordination

The effective operation of self-healing urban infrastructure is fundamentally dependent on the precise coordination of sensors and actuators integrated within structural and functional components. Activation thresholds must be rigorously defined to ensure that autonomous repair mechanisms respond exclusively to relevant damage or environmental stimuli [77]. Premature or unintended activation can compromise structural integrity, reduce material efficiency, and increase maintenance demands. Sensor networks are employed to continuously monitor mechanical, thermal, or chemical parameters, providing real-time data on the condition of the infrastructure. This information is processed through control architectures that determine the necessity, timing, and magnitude of the actuated response, thereby ensuring that self-healing processes are executed accurately and efficiently. The calibration of these thresholds must account for the variability of urban environmental conditions, the stochastic nature of damage events, and the intrinsic response characteristics of the 4D-printed materials.

Control architectures for sensor-actuator coordination can be designed as either centralized or distributed systems, depending on the scale, complexity, and criticality of the infrastructure components. Centralized systems enable comprehensive analysis of the entire network, allowing optimized decision-making for multi-component interactions, whereas distributed systems provide localized responsiveness, improving redundancy and fault tolerance [78]. Feedback loops and predictive algorithms are employed to enhance the reliability and adaptability of the self-healing process,

accounting for potential delays in material activation and variations in load distribution. Furthermore, integration of sensor-actuator networks must consider long-term operational factors, including durability under environmental stressors, ease of maintenance, and energy efficiency. By addressing these requirements, autonomous repair functionality can be reliably achieved, ensuring that self-healing infrastructure maintains structural and functional performance over its intended service life. The deployment of 4D-printed adaptive materials in urban applications requires a structured integration workflow from materials engineering to operational feedback. The following process diagram (Figure 5) illustrates the sequential progression from material selection to long-term lifecycle monitoring, emphasizing the interdependencies between fabrication, sensor fusion, and in-field activation.

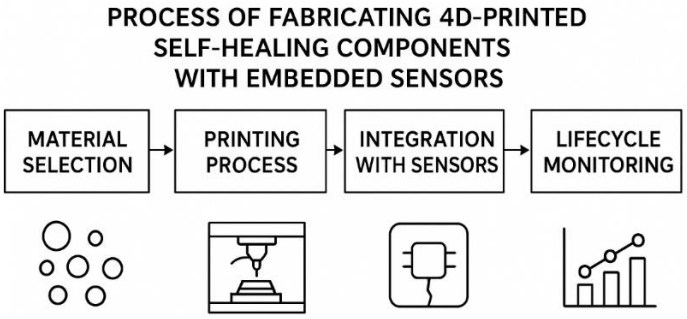


Figure 5. Sequential integration workflow for 4D printing in self-healing infrastructure applications, illustrating the transition from material selection to lifecycle monitoring. The process includes formulation of stimuli-responsive materials, additive manufacturing and component fabrication, incorporation of sensing and activation systems, deployment under operational conditions, and continuous performance assessment for adaptive maintenance.

5.2. Compatibility with construction and maintenance ecosystems

The integration of 4D-printed self-healing components into existing urban infrastructure necessitates careful consideration of compatibility with current construction and maintenance ecosystems. Retrofitting of existing structures with autonomous repair materials presents significant challenges, including the alignment of new components with pre-existing geometries, ensuring adhesion between old and new materials, and accommodating the mechanical and environmental loads already experienced by the infrastructure [79]. In addition, the long-term performance of self-healing elements must be evaluated in the context of legacy materials and construction techniques, as discrepancies in thermal expansion, stiffness, or chemical composition can affect the efficacy of autonomous repair. Implementation strategies must therefore be developed to optimize the interface between 4D-printed materials and conventional urban assets, ensuring that healing mechanisms function reliably without compromising structural integrity or operational continuity [80].

Direct fabrication *in situ*, while offering advantages in terms of design flexibility and integration, introduces its own set of technical and logistical considerations. Printing large-scale infrastructure components on site requires the adaptation of additive manufacturing equipment to urban environments, including handling of environmental variables, site constraints, and scalability of production processes [81]. Quality control, material deposition consistency, and curing protocols must be rigorously monitored to ensure that printed components meet structural, functional, and regulatory

requirements. Maintenance strategies must also be adapted to accommodate autonomous repair functionality, incorporating monitoring of material performance, activation cycles, and potential failure points. By addressing these factors, both retrofitting and *in situ* fabrication approaches can be optimized to enable the successful deployment of self-healing urban systems, bridging the gap between advanced 4D printing technologies and practical infrastructure applications [82].

5.3. Scalability and environmental robustness

The successful deployment of self-healing 4D-printed components in urban infrastructure is contingent upon both scalability and environmental robustness. Materials and structures must be engineered to maintain functional integrity under a wide range of outdoor stressors, including wind, precipitation, pollution, and mechanical loads associated with pedestrian or vehicular traffic [83]. The response of 4D-printed materials to these stimuli must be predictable and repeatable, ensuring that autonomous repair mechanisms activate only when required and that structural performance is preserved during and after activation. Scaling laboratory-validated self-healing mechanisms to infrastructure-sized elements requires careful consideration of material homogeneity, activation consistency, and the distribution of stimuli-responsive components across larger geometries [84].

Environmental factors such as ultraviolet (UV) radiation, fatigue from cyclic loading, and thermal cycling can significantly influence the long-term performance of self-healing systems. UV-induced degradation may alter polymer chemistry, reducing the efficiency of shape-memory or swelling mechanisms, while repeated mechanical stress can compromise the integrity of both the primary structure and embedded repair agents. Thermal fluctuations may also affect activation thresholds and recovery kinetics, potentially leading to delayed or incomplete self-repair. Recent advances also demonstrate that UV robustness can be intrinsically improved through material chemistry, including aromatic or siloxane-modified SMP networks, UV-stable crosslinkers, and nanocomposite formulations incorporating TiO_2, ZnO, graphene derivatives, or nanoclays. Similar strategies in hydrogel systems—such as zwitterionic matrices and nanoparticle-reinforced networks—enhance resistance to UV-induced chain scission, supporting long-term outdoor performance beyond conventional surface-coating approaches. To mitigate these challenges, material formulations, protective coatings, and structural design strategies must be optimized for resilience, and performance must be validated under accelerated aging protocols [85]. Resolving these environmental and scaling considerations is essential for ensuring that self-healing urban systems remain reliable, durable, and effective throughout their operational lifespan.

5.4. Manufacturing and standardization constraints

The fabrication of self-healing 4D-printed components for urban infrastructure is constrained by limitations in manufacturing capabilities and standardization protocols. Additive manufacturing techniques, while highly versatile, impose restrictions on print resolution, build volume, and material compatibility, which can influence the functional performance of stimuli-responsive elements [86]. In particular, the precise placement of healing agents, fibers, or sensors must be achieved to ensure consistent activation and repair functionality. Variability in layer adhesion, curing rates, and dimensional accuracy can lead to heterogeneous material behavior, potentially compromising the efficacy of

autonomous repair mechanisms when scaled to full-sized urban components. Consequently, process optimization and quality control measures are critical for achieving reproducible performance across multiple units and deployment scenarios [87].

Standardization represents an additional challenge, as regulatory frameworks, testing protocols, and performance metrics for 4D-printed self-healing infrastructure components are still in early development [88]. Certification procedures must be established to verify mechanical strength, durability, activation reliability, and environmental resistance under realistic operational conditions. Material characterization, component testing, and lifecycle assessment protocols need to be harmonized to facilitate comparison between different systems and to guide adoption in practical urban applications [89]. Furthermore, cross-disciplinary collaboration between materials scientists, additive manufacturing engineers, civil planners, and regulatory authorities is required to establish guidelines that ensure both safety and functionality [90]. Addressing manufacturing and standardization constraints is therefore essential for translating laboratory-scale demonstrations into deployable, reliable, and resilient self-healing urban infrastructure.

6. Implementation, policy, and research considerations

The translation of 4D-printed self-healing technologies from laboratory-scale demonstrations to operational urban infrastructure requires careful consideration of implementation, policy, and research aspects. Material capabilities and system-level integration alone are insufficient to guarantee functional deployment; legal, regulatory, and procedural frameworks must also be addressed. These considerations are critical to ensure that self-healing components are introduced safely, efficiently, and in a manner compatible with existing urban infrastructure and governance structures. Furthermore, research priorities must be defined to address knowledge gaps related to material performance, system reliability, and long-term operational sustainability. The following sections provide a comprehensive overview of these aspects, highlighting the interplay between policy, regulation, experimental validation, and interdisciplinary collaboration.

6.1. Policy and regulatory considerations

The deployment of self-healing urban infrastructure is contingent upon adherence to certification protocols, safety codes, and liability frameworks that ensure public safety and structural reliability. Certification procedures must be developed to verify the mechanical performance, autonomous repair functionality, and durability of 4D-printed components under realistic operational and environmental conditions [91]. These procedures are necessary to establish confidence among regulatory authorities, engineers, and end-users, and to facilitate compliance with existing building codes and material standards. In addition, safety regulations must account for potential failure modes, unintended activations, and interactions between novel materials and conventional infrastructure elements, ensuring that the introduction of autonomous repair systems does not compromise overall structural integrity [92].

Liability considerations are equally critical, as responsibility must be clearly defined in the event of system failure or insufficient repair performance [93]. Legal frameworks must address accountability for material manufacturers, construction contractors, and municipal authorities, including scenarios in which unforeseen environmental conditions or atypical loading events challenge the functionality of

self-healing systems [94]. Risk assessment and mitigation strategies, informed by experimental testing and predictive modeling, are essential to support decision-making and regulatory compliance [95]. By establishing robust policy and regulatory frameworks, the deployment of self-healing urban infrastructure can be conducted safely, responsibly, and with a clear understanding of operational limits, thereby facilitating the integration of advanced 4D-printed materials into the urban environment.

6.2. Reliability and lifecycle assessment

The reliability of self-healing urban infrastructure is fundamentally dependent on a thorough understanding of failure modes and the operational limits of 4D-printed materials and components. Potential failure scenarios include incomplete repair activation, material fatigue under repeated stress, environmental degradation, or interaction failures between embedded sensing-actuation networks and structural matrices [96]. These failure modes must be systematically identified and characterized through laboratory experiments, accelerated aging tests, and computational simulations. By doing so, predictive models can be developed to anticipate system performance over time and to inform design improvements that enhance the robustness and dependability of autonomous repair mechanisms [97].

In parallel, risk mitigation strategies and lifecycle evaluations are essential to support the adoption of self-healing technologies in urban environments [98]. Economic considerations, including material costs, fabrication complexity, installation, and maintenance expenses, must be weighed against potential savings achieved through reduced repair interventions, extended service life, and decreased downtime [99,100]. Environmental impacts, such as material recyclability, energy consumption during production, and the potential release of reactive agents, must also be assessed to ensure sustainable deployment [101]. Lifecycle assessment frameworks allow the holistic evaluation of both benefits and limitations, guiding research, policy, and implementation strategies. By integrating reliability analysis with economic and environmental evaluation, the functional, financial, and ecological sustainability of self-healing urban infrastructure can be systematically ensured.

6.3. Research priorities

The advancement of self-healing urban infrastructure requires the identification of short- and medium-term experimental priorities that can accelerate the translation of 4D-printed materials from laboratory studies to operational applications. Accelerated testing protocols are essential to evaluate material durability, repair efficiency, and activation reliability under controlled yet intensified environmental and mechanical stressors [102]. These protocols enable rapid characterization of performance, identification of failure mechanisms, and optimization of material formulations and structural designs. Emphasis must also be placed on the development of standardized testing methodologies that facilitate comparison across different material systems, enabling the establishment of evidence-based guidelines for urban deployment.

In addition to accelerated testing, research must focus on dual-stimuli control and hybrid repair mechanisms to enhance the versatility and robustness of self-healing systems. Materials capable of responding to multiple environmental triggers, such as temperature and moisture, can be engineered to address complex, dynamic damage scenarios commonly encountered in urban environments. Hybrid repair mechanisms, combining bio-based, capsule-triggered, and shape-memory strategies, may be

integrated within a single component to provide layered and redundant repair capabilities [103]. Experimental studies should investigate the interactions between these mechanisms, the kinetics of their activation, and the scalability of their fabrication. By addressing these research priorities, the performance, reliability, and applicability of self-healing infrastructure can be systematically enhanced, providing a solid foundation for future large-scale deployment.

To translate laboratory-scale demonstrations into reliable infrastructure-ready technologies, research efforts must be directed toward experimental standardization, multi-stimuli validation, and long-term performance quantification. The key short- and medium-term priorities can be structured into material-, system-, and evaluation-focused studies, as summarized in Table 3. These priorities are intended to guide coordinated efforts among materials scientists, additive manufacturing engineers, and civil infrastructure specialists toward deployable self-healing urban systems.

Table 3. Priority research areas for advancing 4D printing toward self-healing urban infrastructure.

Research Focus Area	Specific Objectives	Representative Methods or Approaches	Expected Outcomes
Accelerated Durability Testing	Assess long-term healing stability under cyclic stress and environmental exposure	UV/thermal cycling, salt fog aging, fatigue loading simulations	Predictive lifespan models for healing performance
Dual- or Multi-Stimuli Control	Enable activation through combined thermal, moisture, or mechanical triggers	Hybrid SMP-hydrogel formulations, layered activation architectures	Increased activation reliability in variable urban conditions
Hybrid Repair Mechanisms	Combine passive and active healing strategies within a single system	Capsule-triggered coatings with SMP overlays; bacterial agents with swelling polymers	Extended healing range and redundancy in failure recovery
Standardized Evaluation Protocols	Define consistent testing metrics for load-bearing restoration and healing efficiency	Benchmark tensile/compression recovery ratios; repeatability indexing	Cross-comparable datasets for materials and system assessment
Digital Twin-Integrated Monitoring	Couple repair mechanisms with predictive maintenance models	Embedded sensor networks, AI-assisted failure prediction	Closed-loop repair decision frameworks for infrastructure

6.4. Pilot-scale deployment and interdisciplinary integration

The transition from laboratory research to operational urban infrastructure necessitates the implementation of pilot-scale demonstration projects to validate the performance, feasibility, and scalability of self-healing 4D-printed systems. Such pilot projects allow for controlled evaluation under realistic environmental, mechanical, and operational conditions, providing critical data on material durability, repair efficiency, activation reliability, and integration with existing infrastructure elements. Demonstration projects can also reveal unanticipated challenges related to fabrication, installation, monitoring, and maintenance, enabling iterative refinement of both materials and system

designs. Examples of early-stage deployments in small-scale structural components, adaptive façades, or utility conduits have demonstrated the practical potential of autonomous repair mechanisms while highlighting the need for further optimization [104,105].

Successful pilot-scale deployment requires interdisciplinary collaboration among materials scientists, additive manufacturing engineers, civil planners, and regulatory authorities. Materials scientists are responsible for developing stimuli-responsive polymers, hydrogels, and bio-based healing agents, while engineers optimize fabrication methods, control architectures, and system integration. Civil planners ensure compatibility with urban design and infrastructure requirements, and regulatory authorities provide oversight on safety, certification, and operational compliance. Cross-disciplinary interaction facilitates the co-development of solutions that are both technically feasible and practically deployable, ensuring that experimental insights are effectively translated into operational frameworks. By coordinating expertise across these domains, pilot-scale projects can establish reliable models for large-scale implementation of self-healing urban infrastructure, bridging the gap between innovative material science and functional city-wide resilience [106,107].

6.5. Long-term perspective

The long-term evolution of urban infrastructure is expected to be increasingly influenced by the integration of autonomous, self-healing systems enabled by 4D printing technologies. Over extended operational periods, infrastructure components may be designed to continuously monitor structural integrity, detect incipient damage, and activate repair mechanisms without human intervention. The combination of stimuli-responsive materials, embedded sensing-actuation networks, and predictive maintenance algorithms can enable infrastructure systems to adapt dynamically to evolving environmental and operational conditions [108]. Digital twins and advanced simulation models may further enhance this capability by providing real-time monitoring, scenario analysis, and optimization of repair strategies, allowing urban assets to maintain resilience and service continuity over decades [109,110].

The realization of self-healing cities will also require the sustained alignment of material innovation, fabrication technologies, regulatory frameworks, and interdisciplinary collaboration [111,112]. Research and development must continue to focus on the creation of multifunctional, durable, and environmentally resilient materials, as well as scalable and cost-effective manufacturing techniques [113,114]. Policy and standardization efforts will need to evolve in parallel to accommodate new risk assessment methodologies, safety protocols, and certification procedures for autonomous infrastructure components [115]. Additionally, urban planners, engineers, and regulatory authorities must be engaged in long-term strategic planning to integrate self-healing systems seamlessly into city-wide networks. Through these concerted efforts, the vision of cities capable of autonomous, continuous repair and adaptation can be systematically approached, establishing a new paradigm in urban resilience and sustainability.

7. Conclusions

In this perspective paper, the role of 4D printing as a key enabler for self-healing urban infrastructure has been examined, highlighting its potential to transform conventional smart cities into autonomous, repair-capable urban systems. The integration of stimuli-responsive materials, including shape-memory

polymers, hydrogels, and bio-based or capsule-triggered healing agents, has been demonstrated to provide localized, adaptive repair mechanisms that enhance structural resilience and functional reliability. Lessons from biomedical, aerospace, and maritime sectors have been translated to urban infrastructure contexts, revealing both the opportunities for innovation and the constraints imposed by environmental, scaling, and regulatory considerations. Challenges associated with sensor-actuator coordination, construction compatibility, scalability, environmental robustness, and manufacturing standardization have been systematically addressed, providing a comprehensive framework for the deployment of self-healing systems in complex urban environments.

The bibliometric analysis revealed the rapid evolution and interdisciplinary expansion of research on 4D printing and its related technologies between 2015 and 2026. The steady growth in publications, peaking in 2024–2025, reflects the increasing global recognition of 4D printing as a transformative approach for developing adaptive, self-healing, and sustainable systems. The network visualization identified 991 keywords grouped into four main clusters: (1) Bioprinting & Biomedical Materials, (2) Smart & Active Materials, (3) Additive Manufacturing & Engineering and (4) Hydrogels & Chemical Materials.

Larger, darker nodes—such as 3D printing, additive manufacturing, shape-memory polymers, and biomaterials—represent long-established research domains that form the technological foundation of the field. In contrast, yellow and vivid green nodes—bio-based materials, autonomous repair systems, smart cities, and urban resilience—highlight emerging directions that bridge materials science with sustainability and infrastructure innovation.

Despite this progress, the limited integration between core material research and large-scale urban and infrastructural applications underscores a persistent research gap. Future studies should prioritize interdisciplinary collaboration to translate laboratory-scale advances in 4D printing into self-healing, intelligent, and resilient urban systems, contributing to the realization of truly smart and sustainable cities. Research priorities, including accelerated testing, dual-stimuli control, hybrid repair mechanisms, and lifecycle assessment, are expected to guide material innovation and system optimization. Through systematic integration of 4D printing technologies, predictive monitoring, and autonomous repair strategies, urban systems can be designed to respond dynamically to evolving environmental and operational challenges, establishing a new standard for resilient, future-ready cities.

Authors' contribution

Conceptualization, A.K., T.G., Z.K., C.S. and M.P.; methodology, A.K., T.G., Z.K., C.S. and M.P.; validation, A.K.; formal analysis, A.K. and Z.K.; investigation, A.K.; resources, A.K.; writing—original draft preparation, A.K.; writing—review and editing, A.K., T.G., Z.K., C.S. and M.P.; visualization, A.K.; supervision, T.G., Z.K., C.S. and M.P.; project administration, A.K., T.G., Z.K., C.S. and M.P.; All authors have read and agreed to the published version of the manuscript.

Conflicts of interests

The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Full Term
4D Printing	Four-Dimensional Printing
AM	Additive Manufacturing
SMP	Shape-Memory Polymer
UAV	Unmanned Aerial Vehicle (if referenced in pilot deployment or smart city monitoring)
IoT	Internet of Things
ECM	Extracellular Matrix (if referenced in bio-based systems)
UV	Ultraviolet
LCA	Lifecycle Assessment
SMAs	Shape-Memory Alloys (if referenced in hybrid materials)
RH	Relative Humidity (if relevant for hydrogel responsiveness)
4D Printing	Four-Dimensional Printing
AM	Additive Manufacturing
SMP	Shape-Memory Polymer

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