

Review

A Review of Smart Materials in 4D Printing for Hygrothermal Rehabilitation: Innovative Insights for Sustainable Building Stock Management

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Abstract: There is an issue in the building stock, especially in Europe, concerning energy efficiency and climate change adaptation. Due to insufficient thermal insulation and passive solutions, the majority of the existing buildings are not only ill-prepared for the negative effects of climate change, but they also contribute to higher energy consumption. The combination of smart materials and 4D printing for hygrothermal rehabilitation of building facades is the main topic of this review paper. The paper examines the application of smart materials in construction to overcome problems with moisture and heat transfer and other issues in the building envelope. It discusses numerous instances of this printing technology's applications, such as particular responsive elements, identifies trends and draws attention to knowledge gaps in the field, and assesses environmental and economic impacts. The objective is to offer comparable data to aid in upcoming studies concerning the creation of 4D-printed building façade solutions. Additionally, the paper can be interpreted as a collaborative attempt to influence the direction of future hygrothermal building rehabilitation practices. It also aims to assist designers and other relevant parties in understanding the advantages, restrictions, and difficulties related to 4D printing and smart materials for the sustainable management of buildings.



Citation: Farham, B.; Baltazar, L. A Review of Smart Materials in 4D Printing for Hygrothermal Rehabilitation: Innovative Insights for Sustainable Building Stock Management. *Sustainability* **2024**, *16*, 4067. <https://doi.org/10.3390/su16104067>

Academic Editors: Antonio Caggiano, Marianovella Leone and Alessia Monaco

Received: 13 March 2024

Revised: 13 April 2024

Accepted: 9 May 2024

Published: 13 May 2024

Keywords: smart materials; 4D printing; hygrothermal rehabilitation; responsive construction

1. Introduction

This literature review focuses on the intersection of smart materials and 4D printing technology, which offers an innovative approach to the hygrothermal rehabilitation of building stock. Four-dimensional printing, an evolution of 3D printing, introduces the temporal dimension of time, enabling dynamic material responses to stimuli. This technology, which is particularly influential in medicine and aerospace, offers self-assembly, self-repair, and multifunctionality. This comprehensive review examines technologies, materials, applications, and challenges, and highlights the superiority of 4D printing. The analysis includes innovative techniques, such as automated fibre placement, and highlights the transformation of composite materials [1]. Framed as revolutionary, the review underscores the enduring importance of 4D printing and sets the stage for in-depth research on the subject.

Over the years, 3D printing has taken major steps forward in engineering and health, opening the door to the more sophisticated 4D printing sector. Unlike its predecessors, 4D printing involves transforming a 3D-printed object into a different structure under the influence of external stimuli, such as temperature, light, or other environmental factors. This innovative technology has the potential to transform construction processes, product assembly, and overall performance by relying on smart materials with shape-changing capabilities. Used in various fields, including engineering and medicine, 4D printing introduces a transformative dimension where printed elements change shape independently in response to external stimuli [2]. This review aims to provide a thorough exploration of



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the potential implications of these technologies for sustainable building rehabilitation and repair by exploring the background, highlighting the significance, and tracing the evolution of these technologies. A sustainable building is one that is constructed with materials that are designed to minimize its impact on the environment, including energy consumption, throughout its life cycle. Building Information Modelling (BIM) emerges as a valuable tool for virtually analyzing building performance when designing [3]. Energy efficiency is a growing concern, as buildings have a significant impact on the environment, mainly through the consumption of non-renewable energy. Most of the current building stock in Europe is not only ill-prepared to handle the adverse impacts of climate change but also contributes significantly to escalating energy consumption, primarily due to inadequate thermal insulation and passive solutions. At present, designers face challenges in assessing building characteristics and performing mandatory energy performance calculations. Several studies have demonstrated the effectiveness of integrating BIM methodology to improve building sustainability during the design phase. For example, case studies modeled in Autodesk Revit are subjected to energy simulation analysis. The results are linked to the SBToolPT-H system for a comprehensive assessment. The results provide a robust BIM-based framework to assist design teams in improving the energy performance of buildings and promoting sustainability [4].

Building materials are constantly exposed to environmental factors that cause wear and degradation over time. A significant threat to the longevity and performance of buildings is posed by hygrothermal phenomena, resulting from the combined effects of moisture, temperature variations, and the particularities of the microstructure of each material. To provide durable and sustainable solutions, conventional repair methods often fall short, so advanced technologies are needed that can provide innovative and sustainable approaches. The background to this research is the understanding that smart materials, with their responsive and adaptive properties, can play a key role in improving the hygrothermal performance of buildings. These materials can adapt to changes in temperature and moisture, providing a flexible solution to climate change [5]. The integration of 4D printing technology adds a dynamic dimension to the design process, allowing structures to adapt over time. This synergy has immense potential to transform the way buildings are rehabilitated, making them more efficient, durable, and environmentally friendly. The hygrothermal performance of buildings, which includes phenomena such as moisture diffusion, internal and/or surface condensation, and temperature gradients, can make a significant contribution to building pathologies. These pathologies not only affect the durability of building components but also contribute to energy inefficiency, indoor air quality problems, and increased maintenance costs. Overcoming hygrothermal problems is essential to creating healthier and more sustainable living and working environments.

In the context of climate change, where extreme weather events are becoming more frequent, the importance of hygrothermal rehabilitation is even more pronounced. The need for resilient building materials is increasing as global temperatures rise, humidity levels increase, and precipitation patterns change. For example, the use of hydrogel-based smart materials can help regulate moisture contents in building elements and provide an adaptive response to varying moisture concentrations [6]. By focusing on hygrothermal rehabilitation, this review also aims to open the way for the development of strategies that enhance the adaptability and longevity of buildings in the face of climate change scenarios.

A transformative era in construction and materials science is dawning with the development of 4D printing technology. Traditional 3D printing has already demonstrated its ability to produce complex structures with precision. The fourth dimension in 4D printing introduces a temporal aspect that allows printed structures to change their shape or properties in response to external stimuli, such as changes in temperature or levels of humidity. Initially developed in the field of additive manufacturing, 4D printing has rapidly expanded its applications. Examples include self-folding structures that adapt to environmental conditions, such as those developed using shape memory alloys [7]. Understanding the evolution of 4D printing technology is crucial for grasping its potential in the

field of hygrothermal rehabilitation, where dynamic responses to changing environmental conditions can be harnessed for sustainable building solutions.

The result of the present review is an overview of the state of the art, identifying gaps in the literature and possible new smart constructive materials/solutions that can be materialized using 4D printing, to be considered and studied in the context of hygrothermal rehabilitation of facades of existing buildings in Portugal and Euro-Mediterranean countries. This paper used a systematic literature review (SLR) approach to rigorously synthesize the existing knowledge on the integration of smart materials and 4D printing in hygrothermal rehabilitation within the building stock. The SLR methodology provides a structured and transparent process for systematically collecting, reviewing, and analyzing relevant literature to ensure a comprehensive overview of the state of the field [8]. The SLR began by formulating a well-defined research question: “How are smart materials and 4D printing technologies integrated into the hygrothermal rehabilitation of building stock?” This question guided the subsequent stages of the review.

Reputable academic databases, such as IEEE Xplore, ScienceDirect, and Google Scholar, were systematically searched. The search terms included combinations of keywords like ‘smart materials’, ‘4D printing’, and ‘hygrothermal control’. The aim was to capture a wide range of relevant studies within the defined scope through this broad yet focused search strategy. Strict inclusion and exclusion criteria were established to maintain the quality and relevance of the literature reviewed. Inclusion criteria included studies published within the last decade in refereed journals, conference proceedings, and books to ensure currency and relevance. In addition, only studies available in English were included to facilitate accessibility and comprehension.

Studies were excluded if they did not directly address integrating smart materials and 4D printing in hygrothermal rehabilitation. Opinion articles, editorials, and works lacking empirical evidence were also excluded from upholding the academic rigor of the review. Applying these criteria, we aimed to ensure the inclusion of high-quality studies directly contributing to understanding the research question. Upon identifying relevant studies, a systematic data extraction process was implemented to gather essential information for analysis. The extracted data included publication details, study objectives, research methods employed, smart materials utilized, 4D printing applications, and outcomes related to hygrothermal rehabilitation. The extracted data underwent a qualitative content analysis, a methodical approach for systematically categorizing and interpreting textual information. This analysis aimed to identify recurring themes, patterns, and key insights within the reviewed literature.

Here, we aimed to provide a comprehensive understanding of the role and significance of the materials in the context of hygrothermal rehabilitation for concrete structures. These images will visually illustrate the structural changes, chemical reactions, and performance enhancements facilitated by the use of specific materials, thus enhancing the clarity and depth of our discussion. Additionally, the accompanying analysis will offer insights into the properties and effects of these materials under hygrothermal conditions, further elucidating their importance in concrete rehabilitation strategies. Overall, this approach will strengthen the presentation of materials for hygrothermal rehabilitation and enhance the overall quality of this study.

2. Smart Materials

Smart materials, often called responsive or adaptive materials, represent a paradigm shift in the construction and building materials sector. They have unique properties that enable them to respond in a controlled and predictable manner to external stimuli, such as changes in temperature, radiation exposure, or moisture content. Their ability to dynamically adapt and change their response, contributing to improved performance, longevity, and sustainability in building applications, is the heart of smart materials. Shape memory polymers (SMPs) are a classic category of smart materials. These polymers have the noteworthy ability to “remember” and return to a shape when triggered by an external

stimulus. This property allows structures to self-repair or adapt to changing environmental conditions [5,8], which has significant implications for building rehabilitation. In addition, the incorporation of piezoelectric materials into structures enables the generation of electrical charges in response to mechanical stress. This provides opportunities for energy harvesting and structural health monitoring [9].

The use of smart materials in construction is becoming increasingly common and diverse, covering different stages of a structure's life cycle, from new construction to rehabilitation of existing buildings. A good example is self-healing concrete, in which microcapsules containing a healing agent are embedded in the concrete matrix. When cracks form, these capsules rupture, releasing the healing agents and allowing the concrete to repair itself [10]. This advance has the potential to extend the life of concrete structures and reduce maintenance costs.

Still, in the field of building structures, the use of shape memory alloys (SMAs) in seismic-resistant structures is gaining traction. SMAs can absorb and dissipate energy during seismic events. This application increases the resilience of buildings in earthquake-prone regions, demonstrating how smart materials contribute to the safety and durability of structures [11]. Another example, but this time in the area of building energy performance, is the use of thermochromic materials in building facades. These materials enable adaptive energy-efficient designs. These materials change color in response to changes in temperature, regulating heat absorption and reducing the need for artificial heating or cooling [11].

The hygrothermal performance of buildings is a critical aspect that has an impact on both the structural integrity of the building and the comfort of the occupants. Hydrogels, for example, are a type of smart material that can absorb and release water in response to changes in humidity. Incorporating hydrogels into building materials helps to regulate moisture levels, preventing problems such as condensation and mold growth [12]. Thermal control in buildings can also be achieved by managing temperature variations using phase-change materials (PCMs). PCMs absorb or release heat during a phase change, providing passive temperature control within a building. Incorporating PCMs into building materials improves energy efficiency and occupant comfort by reducing temperature swings and, consequently, energy consumption for heating and cooling [13]. The synergy between smart materials and hygrothermal control is evident in the development of adaptive building envelopes that respond dynamically to environmental conditions, optimizing both energy use and indoor comfort.

Given these examples, there is no doubt that smart materials can play a key role in addressing the hygrothermal performance of buildings, among several other aspects beyond the scope of this review.

3. A Paradigm Shift to 4D Printing Technology

Four-dimensional printing, an innovative technology, introduces a temporal dimension to the established principles of 3D printing, allowing structures to change or adapt over time in response to external stimuli. This transformative potential opens up new frontiers in construction, enabling the creation of adaptive and responsive construction solutions tailored to specific environmental or functional requirements [14].

Unlike traditional 3D printing materials, smart materials used in 4D printing include piezoelectric, electrostriction, thermoelectric, and shape-memory alloys and hardware, and modeling software plays an important role in the 4D printing process, and it facilitates the use of 4D printing in many structures and landscapes. Essential to 4D printing technology, smart components include sensors, actuators, and control systems. They enable sensing, processing, and self-control, expanding programming possibilities and enabling new practical applications. Intelligent systems, including sensors and self-healing systems, can easily adapt to stimuli and change their behavior. They offer solutions for vibration control and synthetic design, representing major advances in materials science and manufacturing. Multifunctional materials, such as magneto-mechanical and opto-mechanical materials,

exhibit overlapping responses to a wide range of stimuli, highlighting the interdisciplinary nature of research in this area [15].

The technology offers several advantages, including the ability to create structures that can adapt to changing environmental conditions, potentially revolutionizing the building industry. It also allows for self-assembly, simplifying construction processes and contributing to the feasibility of constructing intricate designs [16]. Additionally, 4D printing enables the integration of multiple materials within a single element, expanding the range of applications and creating multifunctional and dynamic structures with different properties. However, some challenges hinder widespread adoption, such as ensuring fresh state properties of materials, achieving precise and reliable shape change, and addressing concerns about durability, cost-effectiveness, and environmental impact. Scalability is also an issue, limiting practical application in large-scale construction projects.

The application of 4D printing technology extends beyond new construction, with potential uses in building rehabilitation, adaptive building facades, and heritage conservation. These applications demonstrate the technology's potential to significantly extend the life of buildings, optimize energy efficiency, and provide non-invasive and reversible solutions to conservation interventions [16].

4. Implementation Strategies for Sustainable Practices

Hygrothermal challenges arise from the complex dynamics of moisture diffusion and heat transfer mechanisms within the building envelope. Moisture infiltration, condensation phenomena, and temperature variations are the main contributors to these challenges. Moisture ingress occurs through capillary action and/or moisture adsorption mechanisms, resulting in problems such as high levels of moisture in materials, leading to mold growth, material degradation, and poor indoor air quality, the combination of which is technically known as sick building syndrome [17]. Condensation can form on surfaces or within building components as a result of temperature differences and high relative humidity. This increases the thermal conductivity of materials, accelerates material deterioration, and provides a favorable environment for mold and fungi. Temperature variations further stress building materials, potentially leading to mechanical damage. Understanding these interactions is essential for effective hygrothermal retrofitting [17–19].

The impact of hygrothermal phenomena on the durability and performance of buildings is extensive, affecting both structural integrity and functionality. Moisture absorption and/or adsorption can lead to the decay of wood and deterioration of concrete, compromising overall durability, undermining thermal insulation effectiveness, increasing energy consumption, and reducing overall building performance [20–22].

Hygrothermal rehabilitation techniques, which aim to improve durability, energy efficiency, and the indoor environment, include the installation of vapor barriers (where necessary), waterproofing, improved drainage, and improved thermal insulation. However, vapor barriers can trap moisture and waterproofing may not prevent rising dampness or internal condensation. Insulation upgrades require careful installation to avoid trapping moisture. Interventions in old buildings, where moisture levels tend to be high, require even greater care in the techniques and materials used than in modern buildings. The limitations of current methods highlight the need for innovative approaches; in this sense, integrating smart materials and technologies, such as 4D printing, promises to create adaptive building envelopes that respond dynamically to hygrothermal conditions, mitigating the shortcomings of traditional rehabilitation [17,23].

5. Smart Materials in Building Rehabilitation

Smart materials have revolutionized various fields, and their incorporation into building rehabilitation signifies a significant advancement. This section delves into the current state of smart materials, offering a comprehensive examination of their characteristics, uses, and potential impact on the hygrothermal rehabilitation of buildings. Smart materials encompass a broad spectrum of substances with responsive properties, enabling them

to dynamically adjust to environmental changes. Table 1 shows a diverse array of smart materials, outlining their attributes and applications in building rehabilitation. Each entry offers insights into the material's distinct capabilities and its potential to enhance the hygrothermal performance of buildings.

Table 1. Overview of State-of-the-Art Smart Materials in Building Rehabilitation.

Smart Material	Characteristics	Applications in Building Rehabilitation	Reference
SMPs	Reversible shape transitions, adaptive to temperature changes	Structural adaptation, façade permeability adjustment	[5]
Hydrogels	Absorb and retain water, responsive to humidity changes	Moisture management in construction, adaptive coatings, and panels	[24]
Piezoelectric Materials	Generate electrical charges in response to mechanical stress	Energy harvesting, structural health monitoring	[9]
Magnetostrictive Materials	Change shape in response to a magnetic field	Adaptive components in building structures, vibration control	[25]
Conductive Polymers	Exhibit electrical conductivity in response to stimuli	Integration in smart windows, sensing structural health	[26]
Phase-Change Materials	Absorb or release heat during phase transitions	Thermal regulation in building components, energy-efficient design	[27]
Electroactive Polymers	Change shape in response to an electric field	Artificial muscles, dynamic architectural components	[28]
Thermochromic Materials	Change color with temperature variations	Smart windows, indicating thermal conditions	[11]
Self-Healing Polymers	Repair damage autonomously when triggered	Increased durability, reduced maintenance costs	[29]
Photomechanical Polymers	Change shape in response to light	Light-driven actuators, dynamic architectural elements	[30]
Ferroelectric Polymers	Exhibit spontaneous electric polarization	Sensing and actuation in response to external stimuli	[31]
Polymer Nanocomposites	Enhance properties through the incorporation of nanoparticles	Improved strength, durability, and functionality in building materials	[32]

Smart materials play a crucial role in the advancement of building rehabilitation. Among these, shape memory polymers (SMPs), hydrogels, and piezoelectric materials stand out for their unique properties and potential applications:

Shape memory polymers (SMPs): SMPs have the remarkable ability to 'remember' a specific shape and return to it when exposed to external stimuli, particularly temperature changes. This adaptability makes SMPs well-suited for applications in exterior building elements, positioning them as transformative agents in hygrothermal rehabilitation [5]. The most common SMPs utilized in the previous studies are listed in Table 2. Various polymers play crucial roles in 4D printing, enabling the fabrication of smart objects with dynamic functionalities. For instance, polycaprolactone (PCL) enhances self-healing abilities and significantly improves mechanical performance when added to 4D-printed structures [33]. Polyurethane (PUR) demonstrates reliable shape memory polymer (SMP) programming, enabling self-bending features through experimental and numerical validation [34,35]. Polylactic acid (PLA) exhibits thermal shape memory behavior and maintains these properties when combined with nylon fabric, allowing temporary shape programming followed by shape recovery upon heating [36]. PLA also offers opportunities for novel applications, such as wind blade design with reversible bend-twist coupling and the development of shape memory stents for vascular stenosis treatment [37,38]. Additionally, PLA-based 4D-

printed models showcase control over elastic wave propagation, demonstrating potential applications in wave manipulation [39]. Through these diverse polymers, 4D printing continues to evolve, offering innovative solutions across various fields, from healthcare to advanced engineering [40].

Table 2. The most recent SMPs materials can be utilized for 4D printing.

Polymer	Structure	Feature	Application	Characterization
Polycaprolactone (PCL)	Linear polymer	Imparts self-healing ability; improves mechanical performance	Structural components requiring self-repair capabilities	Mechanical testing, self-healing assessment
Polyurethane (PUR)	Not specified	Reliable shape memory polymer (SMP) programming	Smart actuators, shape-adaptive structures	Experimental and numerical validation
Polylactic acid (PLA)	Thermoplastic	Exhibits thermal shape memory behavior	Temporary shape programming, wind blade design, shape memory stents	Thermal analysis, shape memory behavior assessment
High-impact-polystyrene (HIPS)	Not specified	High shrinkage strains; good shape transformation response	Prototyping, intricate structure fabrication	Shrinkage strain measurement, mechanical testing
Acrylonitrile-butadiene-styrene (ABS)	Not specified	Moderate shrinkage strains; shape transformation response	Functional prototypes, end-use parts	Shrinkage strain measurement, mechanical testing
Nylon	Thermoplastic	Durable, high tensile strength	Functional prototypes, flexible components	Tensile strength testing, impact resistance assessment
Polytetrafluoroethylene (PTFE)	Linear polymer	Low friction, chemical resistance	Bearings, seals, non-stick coatings	Friction coefficient measurement, chemical resistance assessment
Polystyrene (PS)	Linear polymer	Low shrinkage strains; limited shape transformation response	Packaging, insulation	Shrinkage strain measurement, mechanical testing

Hydrogels: These materials can absorb and retain water, offering a unique solution for moisture management within building elements. Hydrogels are smart materials that respond to changes in humidity levels, making them ideal for addressing hygrometric buffers. Incorporating hydrogels into building materials provides a dynamic response to moisture fluctuations, contributing to the resilience and sustainability of building envelopes. This adaptive moisture management not only enhances the longevity of building materials, but also addresses indoor air quality concerns associated with moisture-related issues [24].

Thermo-responsive hydrogels (TRHs) are among the most versatile materials utilized in 4D printing due to their ability to change shape and structure in response to temperature fluctuations. Typically characterized by the presence of hydrophobic groups, TRHs exhibit diverse behaviors based on temperature changes, including swelling or shrinking. They can be derived from natural polymers, like chitosan and cellulose, or synthetic polymers, such as poly(N-isopropylacrylamide) (PNIPAAm) [40]. The choice of monomer significantly influences TRH behavior, with PNIPAAm being extensively studied for its temperature-controlled phase transition properties. Additionally, TRHs offer potential applications in bioprinting, drug delivery systems, and tissue engineering, owing to their excellent printability, cell compatibility, and ability to mimic natural environments [41,42].

Table 3 presents conditions and parameters that outline various synthesis methods used for the production of poly(N-isopropylacrylamide) (PNIPAAm), a thermo-responsive polymer with applications in drug delivery, tissue engineering, and other biomedical fields. Each synthesis method has a unique temperature, fluid, crosslinkers, and reagents, resulting in different properties of PNIPAAm hydrogels.

Table 3. Conditions for PNIPAAm hydrogels synthesis.

Synthesis Method	Synthesis Temperature	Fluid	Crosslinkers	Reagents	Effect on PNIPAAm Properties	Ref.
Free radical polymerization	22 °C	DI water	MBAAm	APS and TEMED	Increased sensitivity to temperature triggered controllable drug release and improved mechanical properties	[43]
Surfactant-free emulsion polymerization	70 °C	DI water	MBAAm	KPS	Improved crosslinks, charge distribution impact and temperature-responsive deswelling behavior	[44]
Free radical polymerization	10, 15, 20, or 25 ± 0.2 °C	DI water	MBAAm	APS and TEMED	The transition towards a turbid substrate became more gradual (at 33.5–34.5 °C) which consequently had an influence on the light scattering behavior in response to temperature	[45]
Free-radical precipitation copolymerization	70 °C	DI water	MBAAm	SDS, APS	The particle size can be influenced by controlling the concentration of the free radical initiator, which is a crucial factor for drug delivery	[46]
Sedimentation polymerization	80 °C	Silicone oil	MBAAm	KPS, TEMED	The swelling rate of the resulting hydrogel beads was directly influenced by the morphology (especially porosity in the structure) of the gel delivered by the applied polymerization	[47]

Piezoelectric Materials: These materials generate electrical charges in response to mechanical stress, presenting opportunities for sustainable energy harvesting in building renovation. By integrating piezoelectric materials into structural elements, such as floors or facades, buildings can harvest energy from ambient vibrations. This harvested energy can be used to power low-energy sensors, lighting systems, or other components, thereby improving the overall sustainability of the structure. The dynamic nature of piezoelectric materials aligns with the theme of responsiveness in the hygrothermal context [9].

Magnetostrictive Materials: These materials change shape in response to a magnetic field, offering the potential for adaptive components in building structures and vibration control. By integrating magnetostrictive materials into 4D printing processes, structures can be designed to dynamically adjust their shape and properties in real-time, optimizing their performance in various conditions [25].

Conductive Polymers: With the ability to exhibit electrical conductivity in response to stimuli, conductive polymers find application in smart windows and sensing structural health. Incorporating them into 4D printing allows for the creation of structures that can monitor their own integrity and respond to changes in their environment, enhancing both safety and energy efficiency [26].

Phase-Change Materials: These materials absorb or release heat during phase transitions, making them ideal for thermal regulation in building components and energy-efficient design. By integrating phase-change materials into 4D printing, structures can adapt to temperature variations, improving comfort levels and reducing energy consumption [27].

Electroactive Polymers: Known for changing shape in response to an electric field, electroactive polymers enable the creation of artificial muscles and dynamic architectural components. In 4D printing, these polymers offer the potential for structures that can move, adjust, and respond to electrical signals, opening up new possibilities for interactive and responsive designs [28].

Thermochromic Materials: These materials change color with temperature variations, making them suitable for smart windows and indicating thermal conditions. Incorporating thermochromic materials into 4D printing allows for the creation of structures that can visually communicate changes in temperature, enhancing both functionality and aesthetics [11].

Self-Healing Polymers: With the ability to repair damage autonomously when triggered, self-healing polymers contribute to increased durability and reduced maintenance costs in building materials. Integrating them into 4D printing processes enables the fabrication of structures that can self-repair in response to damage or wear, prolonging their lifespan and sustainability [29].

Photomechanical Polymers: These polymers change shape in response to light, serving as the basis for light-driven actuators and dynamic architectural elements. In 4D printing, photomechanical polymers offer the potential for structures that can move and transform in response to changes in light conditions, enabling innovative and adaptable designs [30].

Ferroelectric Polymers: Exhibiting spontaneous electric polarization, ferroelectric polymers are suitable for sensing and actuation in response to external stimuli. When integrated into 4D printing, these polymers enable the creation of structures that can sense and respond to electrical signals, opening up new avenues for interactive and functional design [31].

Polymer Nanocomposites: By enhancing properties through the incorporation of nanoparticles, polymer nanocomposites offer improved strength, durability, and functionality in building materials. In 4D printing, these composites can be tailored to meet specific performance requirements, allowing for the fabrication of structures with enhanced mechanical properties and performance characteristics. These smart materials offer innovative solutions for addressing various challenges in building rehabilitation, from adaptability to moisture management and sustainable energy harvesting [32].

The integration of smart materials in building rehabilitation represents a significant advancement in construction practices, demonstrating transformative potential in practical applications. Unlike traditional materials, smart materials offer dynamic and responsive solutions to address the evolving challenges posed by environmental factors. This shift from static to dynamic solutions aligns with the broader objectives of sustainability, energy efficiency, and resilience to climate change. Smart materials play a crucial role in bridging the gap by providing adaptive and responsive properties to building components, thereby enhancing their performance in changing conditions. This evolution signifies a progressive shift towards materials that can dynamically adapt to environmental challenges, marking a significant advancement in building science.

6. Future Perspectives for 4D Printing in Building Rehabilitation

Given the consensus on the importance of using sustainable materials in the building industry, the focus is on sustainable schemes for existing buildings to aid designers in achieving rehabilitation performance. The proliferation and standardization of sustainable materials in the building sector can enhance sustainability communication and technical knowledge among stakeholders [48]. Recent studies supported the assessment processes for standard practice certification [49]. Mass use of sustainable materials can also facilitate compliance with regulatory frameworks and technical standards [50]. Insights from recent strategies to tailor sustainable materials to building stock need the adaptation of 4D printing to research findings and sector priorities with professional feedback from academic research.

Design-based assessments for existing buildings mostly regarding their landscapes and furniture can enhance their performance and condition [51]. Finding the absence of superior methods and tools can act as a bridge for linking effectiveness, efficiency, and utility in assessment protocols to evaluate sustainability effectively. Highlighting efficiency, interventions should prioritize measures requiring minimal effort and resources [52]. Feasibility evaluation should be integral to sustainability analyses for any intervention in existing buildings, includ-

ing deep renovations and maintenance actions. A comprehensive approach across sustainable dimensions ensures long-term building performance and condition.

The adoption of smart materials in hygrothermal rehabilitation presents significant challenges despite their potential. Technological and economic considerations need to be addressed to ensure seamless integration into existing building practices. Developing smart materials with optimal properties for specific applications remains a challenge, particularly in fine-tuning responsiveness, durability, and cost-effectiveness [53].

The cost of manufacturing and integrating smart materials can be a barrier to their adoption, but it is expected to improve with technological advances and economies of scale. Regulatory challenges also exist, and establishing standards and guidelines for the use of smart materials in construction is essential to ensure safety, durability, and compliance with building codes. Despite these challenges, the future of smart materials in hygrothermal retrofitting appears promising. Ongoing research to refine these materials and their applications is expected to lead to breakthroughs in sustainable building practices. The integration of smart materials with emerging technologies, such as 4D printing, is poised to redefine the landscape of building rehabilitation [53].

In addition, the field of 4D printing, which integrates stimulus-responsive materials, is emerging as a revolutionary manufacturing paradigm, producing intelligent 3D structures with dynamic behavior. This review focuses on addressing critical gaps in understanding the full potential of 4D printing. It highlights the lack of a universal formula for modeling the temporal dimension in the design phase and proposes a bi-exponential formula. The need to establish 4D printing as a robust manufacturing process, with a focus on energy efficiency, is also addressed. Furthermore, the challenge of demonstrating real-world applications is met by presenting groundbreaking applications, such as wind turbine blades and smart solar concentrators, showcasing the transformative potential of 4D printing. This abstract sets the stage for a comprehensive exploration of 4D printing, emphasizing critical gaps in design, manufacturing, and product development.

The parts below will provide a full knowledge of the limitations and opportunities of the 4D printing technology [54]. Exploring 4D printing applications in building rehabilitation offers new opportunities for dynamically responding to environmental stimuli over time. The next paragraphs highlight how 4D printing can address hygrothermal challenges and transform standard construction processes:

- Responsive architectural components are a pioneering application of 4D printing. Four-dimensional-printed materials can be used to create building elements, such as facades and roofs, that respond to environmental conditions like temperature and humidity. This adjustability enhances structural integrity and energy efficiency by enhancing ventilation and thermal insulation [55,56].
- Four-dimensional printing allows for self-assembling structures where components reconfigure or assemble autonomously based on external stimuli. This capability has significant implications for building construction, enabling buildings to respond to changing environments like temperature fluctuations [12,57].
- Four-dimensional printing can be used to create smart building envelopes that adapt to changing hygrothermal conditions. Shape-memory materials can adjust the permeability and insulation of a building envelope in response to environmental stimuli. This response enhances energy efficiency and occupant comfort [12,41,42,58].
- Using 4D-printed elements in interior design creates dynamic and adaptable settings. Furniture and interior constructions can adapt to user preferences, functions, and environmental conditions. Four-dimensional-printed partitions can vary transparency based on lighting or user preferences, creating adaptable and responsive interior spaces [12,24,59].
- Four-dimensional printing allows for environmentally friendly gardening in outdoor locations. Weather-responsive elements, like 4D-printed pavements, kinetic sculptures, and adaptive flora, can create visually beautiful and useful outdoor spaces [2,12].

- Four-dimensional printing provides new possibilities to retrofit and rehabilitate old structures. Shape memory components can enhance building performance, adapt to changing environmental conditions, and increase structural life [60,61].

Despite promising synergies, integrating smart materials and 4D printing in building restoration presents obstacles and considerations. Successfully implementing this novel strategy requires understanding and mitigating these limitations. Ensuring the compatibility and durability of smart materials during 4D printing is a significant problem. Printing circumstances and post-printing procedures can impact the properties of smart materials, thereby reducing their flexibility and performance over time. Balancing printing conditions and maintaining the integrity of smart materials is a tough task [62].

The challenges include optimizing printing techniques for various smart materials and ensuring they perform cohesively within the greater structural context. Cost and accessibility are important issues for new technologies. Currently, the cost of producing smart materials and advanced 4D printing procedures may limit mainstream adoption. Achieving a balance between creativity and economic viability is crucial for expanding the use of this strategy in building repair interventions. Incorporating smart materials and 4D printing in building retrofitting holds significant potential, with promising opportunities ahead. Standardization and recommendations for integrating smart materials and 4D printing in buildings are vital for future advances. Standardization promotes consistency, interoperability, and the adoption of best practices. Regulators and industry stakeholders are critical in shaping these standards.

Advancements in research and development are projected to broaden the variety of applications. Smart materials and 4D printing are likely to be used in new construction projects, not just for building repair. This could involve creating façade structures that adjust to changing conditions or user needs, ushering in a new era of dynamic and responsive architecture. Integrating smart materials and 4D printing involves collaboration among researchers, engineers, architects, and industry people. Collaboration and knowledge sharing will speed advances in materials science, printing technologies, and rehabilitation procedures.

7. Discussion

This study's comprehensive literature evaluation reveals the diverse landscape of using smart materials and 4D printing for hygrothermal rehabilitation in building stock. The literature review found promising uses for these technologies in addressing hygrothermal rehabilitation issues. The paper highlights promising improvements in using smart materials, including piezoelectric and hydrogels, with 4D printing methods. These applications represent a significant shift towards dynamic and responsive structures, beyond traditional construction approaches. Sustainability is now a crucial aspect of modern construction, taking into account environmental, social, and economic factors. The building sector, known for resource-intensive operations, is shifting towards sustainable practices to minimize environmental effects [63]. The building industry contributes greatly to environmental degradation by consuming natural resources, energy, and waste. Sustainable construction practices strive to reduce negative impacts. Sustainable building approaches prioritize energy efficiency, eco-friendly materials, and waste minimization, reducing the industry's carbon footprint [64]. Sustainability in buildings extends beyond environmental issues to include social and economic factors. Sustainable construction techniques promote tenants' health, comfort, and productivity. Sustainable building promotes employment creation, local economic development, and long-term cost savings via energy-efficient designs and materials [65].

Green building standards and tightened restrictions represent a global shift towards sustainability. Governments and regulatory agencies are demanding sustainable practices, encouraging the construction industry to use eco-friendly technologies and materials. Green building certifications, like LEED (Leadership in Energy and Environmental Design), are becoming more common [51,66,67]. Integrating smart materials and 4D printing is cru-

cial for improving building resilience, sustainability, and efficiency [2,52,53]. The literature suggests that hydrogel-based smart materials are being used for effective hygrothermal management. Hydrogels have been a popular alternative for moisture buffering in construction materials [2,68,69]. Research suggests that 4D printing has the potential to revolutionize buildings by adding a temporal dimension [70]. This ability allows for the construction of adaptable structures that align with sustainability and resilience concepts [71].

Responsive architectural components have advanced the use of smart materials and 4D printing. Four-dimensional-printed facades and roofs can adjust to external variables, including temperature and humidity. This improved structural integrity and increased energy efficiency by optimizing ventilation and insulation [72]. The literature research revealed that 4D printing has expanded beyond construction to other applications. Four-dimensional-printed structures are adaptable and can be used in interior design and gardening. These applications demonstrated the adaptability of 4D printing technology and its potential to transform numerous industries [73].

Existing literature lacks information on the long-term performance and durability of structures made with smart materials and 4D printing in real-world contexts. Many studies have concentrated on the technical aspects of these technologies, but there is a need for comprehensive assessments of their long-term practical ramifications. Future studies should assess the real-world performance of these new solutions, including maintenance, resilience to environmental stressors, and structural integrity. The scalability and economic feasibility of using smart materials and 4D printing technology on a broader scale are key areas for research. Assessing cost-effectiveness, life-cycle costs, and resource availability is crucial for successful large-scale implementation [74].

Several researchers have examined the use of smart materials and 4D printing in new buildings [71,75,76]. However, there is a lack of study on integrating these technologies with existing building stock. Future research should focus on integrating smart materials and 4D printing into older buildings to enhance performance and sustainability, as they present unique challenges for rehabilitation and conservation.

The literature review did not adequately investigate human-centered design issues for building elements using smart materials and 4D printing technology. Future research should examine how these advances affect occupant wellness, comfort, and overall user experience. Understanding the human elements connected with building technologies is crucial for developing creative solutions that meet the demands and preferences of building occupants. The literature discusses the possible environmental benefits of smart materials and 4D printing technology. Further research is needed to examine the environmental impact of these technologies, including energy use, material sourcing, and trash generation. Understanding environmental implications is crucial for implementing sustainable construction strategies. It also highlights the revolutionary potential of using smart materials and 4D printing for the hygrothermal rehabilitation of buildings.

The scalability and cost issues for various large civil engineering projects involving 4D printing are currently promising, but are still in an evolving phase. Four-dimensional printing capabilities could create dynamic, shape-changing structures over different time spans and potentially provide many benefits for large civil engineering projects, such as the concept of adaptive components, enhanced resilience, and optimized fabrication. Many factors affect the scalability and cost issues for implementing 4D printing in large civil engineering projects. Although 4D printing has still been limited to scales of only a few centimeters, there has been increased development of more efficient printing techniques, increased scalability of production processes, and advanced materials, which are improving 4D printing scalability, especially for large civil engineering applications. Moreover, increasing the level of automation, optimizing the printing parameters, and increasing printer size will continue to improve 4D printing scalability. Lastly, increasing sophistication in computational modeling and simulation tools is helping designers optimize the structure's performance by predicting the outcome on a larger scale [77–79].

Cost feasibility remains a significant consideration for large civil engineering projects involving 4D printing. While the cost of 4D printing technologies has been decreasing over time, it still presents challenges for widespread adoption in large-scale projects. Material costs, equipment expenses, and labor requirements contribute to the overall cost of 4D printing, and optimizing these factors to achieve cost efficiency is an ongoing area of research and development. Additionally, the integration of 4D printing into existing construction workflows and regulatory frameworks may require investment in training and infrastructure, further influencing project costs [80,81]. To enhance the scalability and cost feasibility of 4D printing in large civil engineering projects, ongoing research and development efforts focus on improving printing speed, material properties, and process reliability.

8. Challenges and Concerns

The process of 4D printing is complicated due to the numerous steps to construct smart objects, including fabrication, stimulation, actuation, and recovery, which can occur consecutively or in a nested manner. In particular, the training step can function as a pre-stimulation and actuation phase, taking place either after [82] or concurrently with the material deposition step [83]. The effectiveness of actuation and recovery steps directly influences the performance of the final printed objects, with certain limitations observed in processes, techniques, and stimulation stages that integrate materials and physics considerations. The current process limitations within this complex transformation process can be stated as the availability and quantity of materials (powder, resin, filament, fiber, and pellet) required a tuning step and change capacity degradation after multiple cycles, multi-scale behaviors, composite synthesis, and combinational process, material compatibility with the technologies, anisotropy induced by the layer-by-layer deposition mode, the associate of a post-processing step, temporal application of the conduction/diffusion in the structure, weak actuator efficiency due to energy issues for the stimulation, and the high amplitude of the required signal [84].

However, employing more sophisticated heterogeneous 4D printing methods enables the realization of multi-material and multi-voxel systems through one or more 3D printers, potentially achieving industrial-grade performance in the future. To attain high industrial performance, future activities must transcend a bottom-up logic approach and embrace a top-down, requestor-and-designer-driven complex logic. This transition represents the necessary evolution to achieve industrial excellence.

9. Conclusions

This literature analysis highlights the potential for integrating smart materials with 4D printing technology to improve building hygrothermal performance. Synthesizing various studies and trends has led to significant insights. For instance, combining smart materials, like hydrogels and shape memory polymers, with 4D printing technologies can provide dynamic and responsive solutions, representing a paradigm shift in building practice. The presentation highlighted the transformative power of 4D printing technology by introducing responsive architectural components that produce dynamic and adaptive parts. Four-dimensional printing has expanded beyond construction to include interior design, infrastructure, and landscape. This demonstrates how 4D printing technology has revolutionized industries outside buildings. The evaluation found gaps in the available literature, which have important implications for future research. Addressing these gaps is vital for the practical deployment and widespread adoption of breakthrough technology. Future studies should focus on the endurance and performance of smart materials and 4D-printed structures in real-world applications. To estimate the environmental impact of using smart materials and 4D printing in construction, a thorough impact evaluation is necessary. To ensure sustainable construction techniques, life-cycle assessments take into account energy use, material sources, and waste generation. Finally, the future of hygrothermal retrofitting in existing structures lies in the integration of smart materials

and 4D printing technologies. These technologies have the potential to address present difficulties and provide a more adaptable, efficient, and sustainable built environment. The future of construction depends on the collaborative efforts of academia, business, and policymakers to create smart and responsive buildings.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

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