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Smart Architecture: Case Studies and Breakthrough Applications of Advanced Materials in Buildings

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Keywords: Smart Architecture, advanced materials, building envelopes, biomimicry, smart materials, kinetic elements, 3D printing.

Abstract. Buildings have become experimental grounds for architectural technology, sustainable practices, and human-centered design principles to be tested and refined. This paradigm shift has not only transformed the physical aspects of urban environments but has also redefined the relationship between architecture, end-users, and the built environment.
Advancements in technology paved the way for a revolutionary approach to architecture, that involves responsiveness and adaptability to the environment, leading to the spread of the so-called Smart Architecture, buildings able to fit in with their ever-changing surroundings. Smart buildings present, in general terms, a global enhancement of their performance features, having the potential to impact the built environment in a new interacting, and engaging way, making architecture more accessible, performant, and user-friendly.
This paper summarizes the results of a study aimed at identifying and classifying a sample of applications of advanced materials and technologies in the context of building envelopes, considered representative of relevant Smart Architecture solutions. The categorization will be done according to four categories: biomimicry, smart materials, kinetic elements, and 3D printed solutions. This results in a database of Smart Architecture case studies that collects brief details of each application and working principles, together with data regarding design practice, technology readiness, and economic aspects, among others.

Introduction

The history of Architecture has been profoundly influenced by technological advancements, societal needs, and environmental concerns.

In recent years, there has been a notable shift toward the adoption of most recent innovations within the built environment, leading to the development of the so called "Smart Architecture", an approach that emphasizes the integration of advanced materials and technologies to create buildings that are responsive, adaptive, and environmentally sustainable. This has not only reshaped the urban landscape but has also redefined the way architects, engineers, and designers conceptualize and engage with the built environment.

In this definition of the concept of Smart Architecture, building envelopes play a central role as outer layer of buildings that serve as primary interface with the external environment. Therefore, the integration of advanced materials and technologies within building envelope domain holds the potential to revolutionize the way buildings are designed, constructed, and operated, improving their sustainability, efficiency, and responsivity, according to the needs of their occupants.

Objective of the Study and Methodology

The paper aims to give a broad overview about the diverse range of applications of advanced materials and technologies within the building envelope domain, focusing on their role in shaping the emergence of Smart Architecture.

Through a systematic categorization of case studies – here presented only via a reduced sample, for synthesis purposes – the contribute seeks to identify common themes, challenges, and opportunities associated with the integration of advanced materials and technologies in building design. By combining insights from the sample analyzed indeed, the paper aim is to contribute to a deeper understanding of the potential implications of Smart Architecture for the built environment and society at large.

The methodology employed provides for the systematic identification and classification of case studies according to different categories, recognized as relevant "approaches" to reach smartness in Architecture through the application of building advanced materials and technologies. A comprehensive literature review was conducted to identify a number of relevant case studies from books and journals, academic sources, conference proceedings, and industry reports. The case studies were then categorized, and, for each case study, relevant information was extracted, including details of the application's working principles, design practices, technology readiness, economic aspects, and other pertinent factors. This information was then compiled into a database (Fig.1), allowing for systematic analyses and comparisons across different case studies. Additionally, qualitative analysis techniques, such as thematic analysis, were employed to identify common themes, challenges, and opportunities emerging from the case studies.

#	Case-study		Use	Develop.	Scale	Type	Scope	Function	Operation	Trigget	Response	Adaptability
01		2001 **QUADRACCI PAVILLON** Milawaukee, Wisconsin (USA) Santiago Calatrava	S	R	I	SS	Cv	C	A	V	E	G
02		2002 **MUSEUM OF PAPER ART** Shizuoaka, Giappone Shigeru Ban Engineer(s)	S	R	I	IT	IC	C	A	a	U	OF
03		2002 **LUMENHAUS** Madrid, Spagna Virginia TECH Team	R	P	C	SS	Ct	C	A	O	E	OF
04		2002 **ESPLANADE** Singapore DPA Architects, Atelier One. Michael Wilford	S	R	I	SS	Cv	C	P	Rs	U	G
05		2003 **LA CHIESA DEL DIO PADRE MISERICORDIOSO** Roma, Italia Richard Meier	S	R	M	a	IAQ	C	P	Rs	I	OF
06		2003 **SMART WRAP PAVILLON** New York, USA Kieran Timberlake Associates	S	P	I	a	Ct	A	P	Rs	I	OF
07		2004 **ARTICULATED CLOUD** Pittsburgh, USA Ned Khan	S	R	M	SS	Cv	C	P	a	I	G

Fig. 1. Extracted from the database created for data collection related to the case- studies analyzed.

Smart Architecture definition

Although the use of the term "intelligent" in the context of building regulation is relatively recent, some of the principles underlying this concept (such as the use of Building Automation and Control Systems), as well as their interaction with installations or other technical devices (Technical Building Systems), are well-known and already largely integrated, and have been addressed in last energy efficiency regulations. The concept of "smart buildings" indeed, so as the references to "smart technologies" are included in the Directive 2018/844/EU **[1]**, published in 2018 as an amendment of the EPBD; in the context of a strong digitalization trend and the rapid development of related markets, smart building technologies, and Information and Communication Technologies (ICTs) as well, are seen as drivers for energy efficiency in buildings. The technologies on which these systems are based have also existed for some time, implemented in various services with varying levels of possible control.

However, there is no commonly accepted definition of “smart buildings” or even “smart technologies” in the regulatory context, despite various initiatives being promoted in this direction, both nationally and internationally.

In its early stages, the smart concept referred more to automation than intelligence **[2]**; even if, the real spread of the concept of smartness came in the 21^{st} century, alongside the soaring of new materials and innovative technologies experimentations **[3]**.

In general terms, we can say that Smart Buildings present improved performance characteristics that, in most cases, aim to confer them some degree of adaptability, concerning both the surrounding environment and their end-users, contrasting the main deficiency of “*traditional buildings*” which stands in their static behavior **[3]**.

Simplifying, the concept of building intelligence underlying the one of smart architecture, can be substantiated according to two different approaches: the first aimed at acting on technical devices, to optimally monitor and manage the building-plant system; and the second aimed at implementing the performance of the building envelope, through the use of innovative materials, techniques, and technologies capable of providing buildings with the aforementioned capabilities, even in a passive manner. Increasingly frequent, of course, are examples where these approaches converge towards a common goal: creating buildings that are not only intelligent, capable of adapting to the continuously changing needs of the current context, but also interactive and engaging for the users, making architecture high-performing, accessible, and inclusive.

Smart buildings, understood in the broadest sense of the term – that is to describe both intelligent and adaptive systems **[4]** – can therefore be considered one of the latest frontiers of technological research, linked to the desire to design increasingly high-performing envelope models which, with the help of advanced devices (such as, but not limited to, sensors or smart materials), give rise to systems capable of reducing the building's energy consumption, managing its various related variables to usage, user preferences, external conditions, and, more generally, the complexity of the building. Technological progress has indeed paved the way for an entirely new approach to architecture, which considers change as an essential part of the process, embracing the concepts of reactivity and adaptability towards the spread of so-called intelligent architecture, made up of buildings capable of dynamically adapting to a continuously evolving surrounding environment.

Categorization

The paper aims to briefly depict the results of a study aimed at identifying and classifying a sample of applications of advanced materials and technologies within the building envelopes’ domain, considered representative of relevant smart architecture solutions.

In an attempt to categorize the various design possibilities capable of giving buildings the required "intelligence", it seems possible to refer to different groups that encompass significant solutions or approaches that "enable" the capacities for reaction and adaptation to change, helping building envelope to be more responsive towards both external and internal conditions. Therefore, the “categories” identified are: biomimicry, smart materials, kinetic elements, and 3D printed solutions.

The first category is *biomimicry* (from the Greek, *βίος*, life, and *μίμησις*, imitation), a discipline that aims to transfer the principles that regulate and define the functioning of natural organisms to the field of architecture. Specifically, the term *biomimetics* refers to building envelope solutions inspired by nature **[5]**, where it is possible to find a vast database of adaptive, multifunctional, and reactive strategies, whose observation is a great source of inspiration for the conception of adaptive technological systems **[6]**.

Fig. 2. Details of the stairwell of the Gaudi's Sagrada Familia in Barcelona, doubling a seashell, example of how natural forms can be used as design inspiration. Source: Brendan Baker via Flickr under the CC BY-NC-ND 2.0 license.

Biomimetic solutions can develop, through different mechanisms of adaptation, functional surfaces, dynamic movements, or material development based on biomimetic design **[7]**, or, again, new building envelope systems able to provide multifunctional highly advanced responsive technology in a new adaptive form **[8]**. Sometimes, biomimetic adaptive envelopes are characterized by low-tech technological solutions, capable of passively adapting to external conditions and thus limiting the energy consumption of the buildings that house them **[5]**.

However biomimetics is a rapidly growing discipline in engineering and architectural design **[9]**, it's scarcely applied in architecture; the majority of applications are still limited to prototypes or small-scale pavilions **[5]** since transforming natural strategies into technologies for the adaptivity of building envelope is still a great challenge.

Another possibility to lend building smartness is given by using materials with unprecedented characteristics, such as the so-called *smart materials*, able to react and/or change their properties according to the stimuli they receive **[10]**. In response to various changes, whether or not of environmental nature (temperature, humidity, or light, to name a few), smart materials enable the creation of dynamic and interactive building envelopes, based on different control strategies.

Fig. 3. Aerogel is one of the best examples of smart material thanks to its extreme lightness and strength. Source: Courtesy NASA/JPL-Caltech, Public domain, via Wikimedia Commons

Within literature, smart materials are described as intelligent or active materials, or more in general, as a group of material systems with unique properties **[11]**. Among them are: *piezoelectric materials*, which release an electric charge when they undergo deformation or, conversely, deform when subjected to an electric voltage; *shape-memory materials*, such as alloys or polymers that deform due to temperature changes but that can return to their original shape; *magnetostrictive materials*, which can change shape when subjected to a magnetic field or generate a magnetic field when subjected to mechanical deformation; *chromogenic materials*, which change their optical and transparency characteristics in response to thermal, optical, or electrical changes; *photomechanical materials*, *self-healing materials*, or *dielectric elastomers*. The application of these materials allows to exploit their unique capabilities to endow architecture with the much-desired ability to adapt.

Among the wide scope of possibilities related to their adoption, of particular interest is their application to transparent building envelope systems, due to the potential they offer in terms of controlling and managing incident solar radiation, by changing transparency, color, or shapes. For instance, photochromic materials such as smart glass, able to adjust their color and transparency, can respond to light changes to regulate the amount of light entering a building, allowing for privacy within interior spaces, and light control for exterior windows.

Thanks to their sensing abilities, smart materials can be considered the best allies of advanced architecture, enabling building envelope with a responsive function, able to regulate temperature, solar radiation, and, in general, properly behave in different climatic conditions, properly reacting to variable environmental parameters. The use of smart materials indeed, favors the adaptability of the building envelope to environmental conditions and improves not only the resilience of buildings but also that of urban areas thanks to the use of environmental triggers for their activation that do not require additional energy consumption **[12].**

Kinetics architecture, on the other side, involves reactivity and movement at the macroscopic scale, since this approach usually refers to the dynamicity of building components **[3]**. It refers, indeed, to a design concept in which building components can move and transform in response to environmental conditions, user needs, or functional requirements.

Kinetic systems, or responsive components in general, have been used in architecture for thirty years, primarily for aesthetic purposes or environmental control **[13]**, becoming commonplace in contemporary architecture **[14]**. They integrate mechanical, electronic, and structural systems to create dynamic and adaptable structures that go beyond static functionality.

Kinetic devices can then be described as responsive elements that offer to the architectural design of building envelopes new performance, contributing to thermal comfort, mitigating the environmental impact, avoiding thermal overheating and glare, providing shade, and enhancing illuminance control. Besides adaptability and sustainability, kinetic architecture often incorporates interactive elements that engage users, allowing them to influence buildings' behavior through manual or automated controls. Examples of kinetic devices for building envelopes are systems and components that enable parts of the shell to move or change in response to various stimuli, and range from simple operable components – such as adjustable louvers – to complex systems like movable facades, solar tracking panels, transformable shading systems, retractable roofs and, more in general, transformable space in their whole.

Fig. 4. Eskenazi Hospital parking structure, Rob Ley Studio (2014). Source: Rockinrollblues, CC BY-SA 4.0, via Wikimedia Commons

As a corollary to the previous paragraphs, it is essential to briefly discuss the matter of *sensors* and *control and actuation devices*, which enable the intelligence of buildings, transforming the built environment into an increasingly connected and smart space. Sensors are one of the fundamental technologies supporting the current digitization process and are particularly important for gaining awareness of the surrounding environment. They provide assistance in terms of security and surveillance while allowing the monitoring of various parameters **[15]**. The most common use of sensors is to control and manage parameters such as lighting, temperature, and air quality, or to use them for the activation/deactivation of appliances or various devices, as well as to automatically operate building components (e.g., opening or closing windows, adjusting solar shading systems, etc.).

Sensors in use within buildings comprehend:

- *IoT sensors*, used to monitor the environment in terms of “things” such as temperature, motion, light, air quality, and more. The sensors communicate with an access point in the building, and that information is shared with a gateway which gathers all the data and stores it in the cloud, to be accessed when needed.
- *Analytics software*, which, starting from the information gathered by the sensors, show how to turn information into actions to improve building behavior.
- *User interface*, which considers things such as displays, computer screens, and language options that ensure the systems are understood and utilized by buildings’ users.

In the end, connectivity is the key factor that allows for it all to be stored, shared, analyzed, and used. All the above components are needed for smart building architecture to provide its full value.

Another alternative that is quickly gaining ground in the construction sector is the use of *3D-printed materials and components*, specifically created for each project and particularly suitable to overcome traditional constraints associated with the construction of complex structures. Through 3D printing indeed, it is possible to create unique shapes that explore intricate geometries using unconventional textures and materials. Printing architecture in 3D means saving on material usage (employing only what is truly necessary for structural strength), thereby reducing environmental impact and related costs. Another fundamental advantage of 3D printing is the speed of execution: the transition from design to construction is practically immediate, allowing for every process to be conceived during the design phase and then directly realized during printing (e.g., the creation of ducts or channels for systems, pipes, and ventilation conduits).

3D printing processes are currently mainly based on stratification (additive manufacturing) even if other techniques exist, including powder-based techniques. However, extrusion processes are more flexible and offer a variety of shapes to suit the geometry. Materials used are primarily cementitious materials/concrete based but include thermoplastics and photopolymer as well, even if their strength properties are weaker; for this reason, they are generally used for rapid prototyping. Some interesting trials are being conducted using nature-based materials (Fig.5), especially for remote housing, to offer fast recovery in post-disaster scenarios.

Fig. 5. WASP (Italy’s pioneering specialists in 3D printing) has completed the printing phase of the TECLA supporting structure, the first and unique fully 3D printed construction based on natural materials and made with multiple 3D printers operating at the same time. The innovative habitat model engineered by WASP and designed by MCA - Mario Cucinella Architects was conceived as a new circular model of housing entirely created with reusable and recyclable materials, sourced from local soil, carbon-neutral and adaptable to any climate and context. Source: Alfredo Milano, CC BY 2.5 <https://creativecommons.org/licenses/by/2.5>, via Wikimedia Commons

Generally, construction applications of 3D shapes (e.g. for walls) require reinforcement to improve mechanical properties and the bond between printing layers, placed in different ways according to structural demand (they can be pre-incorporated - either fiber or bars, online incorporated or post processed). Nevertheless, 3D printed concrete can achieve strength results similar to traditionally built elements. Concerning the specific applications of 3D printing to architecture, it is preferable to create non-standard designs because simple shapes (e.g. bricks) are cheaper to manufacture using conventional methods).

Despite the rapid and numerous developments in recent years, 3D printing in buildings is still at an early stage; research remains primarily focused on printability and structural capacity. There is still a gap in physical aspects (such as thermal and acoustic behavior) **[16]**, which could also become an interesting field of investigation, by acting for instance on the element's structure.

Case-Study Analyses

The previous considerations have allowed to build a matrix for the evaluation and analysis of a sample of architectural case studies considered "smart" according to different points of view. The case studies analyzed come from the whole world, in a period that ranges from the mid-late '90s (1970) till nowadays. Details collected regarding each application are primarily focused on general approaches and working principles, together with data regarding design practice (scale of applications, type, scope, functioning, trigger, adaptive, response, and adaptability), technology readiness, and economic aspects, if available. Some of them presents also deeper insights into challenges, limitations, and future applications of the technologies adopted.

Here following, for synthesis purposes, only one case study considered representative of each category previously presented has been briefly discussed. Common themes, challenges, and opportunities emerging from the case studies' analysis are summarized in the conclusive section of the paper.

BIOMIMETIC | Eye Beacon Pavilion, UNStudio (2017) Amsterdam Light Festival [17]. The Eye Beacon Pavilion is a lightweight, temporary structure designed by UNStudio in collaboration with the textile manufacturer MDT-tex. Its design features a fluid, organic shape that creates an immersive experience thanks to the pavilion's form, inspired by the surrounding marine environment and combining the meaning of a beacon, symbolizing guidance and illumination, with the bioluminescence typical of marine organisms.

Eye Beacon visually represents the festival's theme of connectivity and interaction, using choreographed light sequences to signal its presence to visitors, serving both as an architectural sculpture and an information point for the festival. The cubic forms, constructed from modular components, are connected by parametrically modeled surfaces to optimize the fabrication and installation of the various components. The result is a structure composed of 250 uniquely sized panels made from specially designed tensile textile modules. The overlapping panels reveal glimpses of the interior spaces, displaying LED projections, and give the pavilion an ever-evolving aesthetic.

The pavilion structural framework consists of lightweight aluminum and steel, ensuring stability while allowing for ease of assembly and disassembly. The exterior is clad with translucent panels that diffuse light, creating a glowing effect that enhances the visual impact. LED lights integrated into the structure change color and intensity based on movement and interaction: as visitors move through and around the pavilion, the lights react in real time, fostering a sense of engagement and participation. This interactive lighting system is controlled through a combination of motion sensors and responsive algorithms.

The pavilion exemplifies an innovative fusion of architecture and light art, creating a dynamic and interactive public space that serves as a captivating landmark within the festival, characterized by its striking form, advanced lighting technology, and interactive elements.

SMART MATERIALS | HydroSKIN, Eisenbarth and Haase (2022), University of Stuttgart [18]. Developed by the University of Stuttgart to address the issues of extreme climate events (specifically, overheating and flooding) in urban surroundings, HydroSKIN is a lightweight textile-based façade element designed to harvest rainwater and utilize evaporation for cooling both building interiors and surrounding urban areas. It is composed of a spacer fabric, consisting of two textile layers separated by threads to ensure adequate ventilation. This structure facilitates efficient air circulation, enhancing the evaporation process and thereby increasing the cooling effect of the façade on which it is applied. The outer layer of the fabric is a water-permeable textile, allowing rainwater to penetrate while blocking insects and debris. An inner film directs the collected water to a lower profile system, where it can be stored in a reservoir or directly used within the building. During hot weather, the water is redirected to the façade element to evaporate, providing a cooling effect. Moreover, thanks to their lightweight, HydroSKIN elements can be retrofitted to any façade, making them a valuable addition to both new and existing buildings.

Enhancing resource efficiency and climate protection in urban areas through the evaporative cooling principle, HydroSKIN mimics the natural cooling provided by parks and green areas, where approximately 60% of rainwater evaporates, compared to only 10% on sealed surfaces like roads and buildings. This innovative system is currently being tested on the world's first adaptive high-rise building at the University of Stuttgart's Vaihingen Campus; preliminary results are promising, with laboratory tests demonstrating a temperature reduction of about 10° due to evaporation.

KINETIC ARCHITECTURE | The Shed, a Center for the Arts (2015), Diller Scofidio + Renfro, New York [19] (Fig.6). The Shed is a groundbreaking example of adaptable architecture that reimagines the traditional arts center. Located in the Hudson Yards area in New York City, it redefines the concept of a cultural space through its innovative design, flexible spaces, and commitment to technological integration. The building indeed allows for various formal transformations to accommodate different public activities thanks to the presence of a retractable roof which permits the physical transformation of the built space, enabling changes in geometry and internal layout to host different artistic visions. The movement of the facade also impacts the immediately adjacent external space.

The building is composed of two primary components: a fixed base structure and a movable shell. The base, a six-level building, houses traditional performance spaces, galleries, and rehearsal rooms. This part of the structure is cladded with a glass and steel facade, allowing natural light to penetrate and providing transparency to the activities within. The most striking feature of The Shed is its telescoping outer shell, which is a steel-frame structure clad in translucent ETFE panels. Advanced acoustics and lighting systems are incorporated throughout the building, ensuring optimal conditions for diverse artistic presentations. This shell can be deployed over the adjoining plaza to create a vast, climate-controlled space known as the McCourt. When extended, the shell offers an additional 17,000 square feet of programmable space, capable of hosting large-scale performances, installations, and events. The movable shell operates on a sophisticated system of rails and wheels, powered by a combination of mechanical and hydraulic systems. This kinetic system is inspired by the industrial past of the High Line and the West Side Railyard. This flexibility is further enhanced by the modular interior spaces, which can be reconfigured thanks to movable walls and stages to host different types of events concurrently.

Fig. 6. The Shed @ Hudson Yards in 2019. Source: Ajay Suresh, CC BY 2.0, via Wikimedia Commons

3D PRINTING | The Striatus bridge (2021), Zaha Hadid Architects in collaboration with incremental3D, Holcim, and Block Research Group, Venice [20, 21]. Striatus is a complex structured concrete bridge entirely 3D-printed, the first of its kind as it stands solely by mutual compression without additional structural reinforcements. This maximizes the properties of the material used (concrete) exploiting its strength while reducing material usage by about 50% compared to similar conventional structures, without compromising performance. Its design indeed, draws inspiration from traditional masonry arches, employing modern computational design to optimize the structure for load-bearing efficiency and material usage. The bridge spans 16 meters and is composed of 53 hollow, 3D-printed concrete blocks. These blocks are printed with an advanced, layered method that ensures precision and structural integrity. The concrete used is a specially formulated, low-carbon mixture specifically developed.

The bridge's form-finding process, based on principles of compression and equilibrium, results in a highly efficient structure that requires no additional support elements. Further, thanks to the homogeneity of the whole components, given the absence of reinforcements, adhesives, or binders, the block can be disassembled and reused indefinitely or easily recycled.

Located in Venice, Italy, the Striatus Bridge was inaugurated during the Venice Architecture Biennale, symbolizing a forward-thinking approach to architectural design and construction. It provides a model for future projects that seek to integrate cutting-edge technology with sustainable practices.

Conclusions and Future Research's Perspectives

The results of this study try to provide a general overview of the diverse applications' range of advanced materials and technologies within the building envelope domain, counterposed to traditional static design that too often fall short in adapting to the dynamic indoor and outdoor conditions of buildings [**22**].

The analysis of the vast sample of case studies analyzed, here only very briefly presented for synthesis purposes, so as their categorization, has facilitated a nuanced understanding of the various approaches and techniques employed in the design and construction of smart buildings, revealing common themes and trends among them: above all, the need to control parameters that are responsible of building efficiency and internal comfort in buildings, with a particular attention towards sustainability. On the other side, the examination of economic aspects has highlighted the potential cost implications associated with the adoption of advanced materials and technologies in building design, underscoring the need for careful consideration of cost-effectiveness and long-term value.

Cost control surely represent a challenge; demonstrating the economic viability of advanced building technologies means to promote their wider market adoption and implementation since addressing the cost-effectiveness issue is crucial for the widespread application of smart building envelopes. Although smart envelopes can significantly improve energy efficiency and reduce operational costs, their initial investment and maintenance costs remain major barriers to their widespread adoption [**22**].

On the other hand, the integration of advanced materials and technologies in building envelopes offers exciting opportunities to enhance the sustainability, efficiency, and resilience of buildings, thereby contributing to the creation of more livable and environmentally conscious urban environments. However, the widespread adoption of smart architecture also poses challenges, including concerns related technological complexity and societal acceptance/awareness of their applications in the current context.

Technical integration challenges that advanced technologies may encounter in practical applications probably requires a conceptual shift toward the understanding that each design is a prototype; so, rather than focusing merely on manufacturing techniques of these materials or on the complexity of the production and installing process, the priority must be to develop the ability to design tailor made solutions, based on individual conceptual model **[23].**

In parallel, there is the need to push forward research on system integration and interoperability, and to investigate user acceptance and behavioral responses to smart building envelope technologies, designing systems able to better meet user needs [**22**].

Future directions for extending emerging application area can be raising awareness about specific topics (e.g. media façades) [**23**] or to engage people even closely, toward an improvement in cities' life quality as well [**24**].

Moving forward, it is essential for architects, engineers, policymakers, and other stakeholders to collaborate closely to address these challenges and unlock the full potential of Smart architecture. By fostering innovation, promoting interdisciplinary collaboration, and embracing principles of sustainability and inclusivity, it is possible to create buildings and urban environments that are not only smarter but also more resilient, equitable, and responsive to the needs of all members of society.

The findings of this study underscore the transformative potential of smart architecture in shaping the future of the built environment and highlight the importance of continued research and innovation in this field.

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