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Beyond Smart Buildings: The Emergence of Intelligent Places through Cutting-Edge Technologies and Material Foundations

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ABSTRACT

The rapid emergence of the Internet of Things (IoT), immersive technologies, and spatial devices is transforming architecture by changing the built environment from a passive backdrop to an active participant in user activities. This shift creates complex sociotechnical networks and leads to what we call intelligent places adaptive systems that respond to user behavior, environmental signals, and interactions with architectural components. This study investigates how advanced material foundations and embedded technological objects shape human-building interactions and drive adaptive behaviors in intelligent place systems. We test the hypothesis that integrating virtual reality (VR), augmented reality (AR), and spatial sensors within smart materials creates continuous real-time feedback loops. These loops are expected to enhance user engagement, spatial adaptability, and environmental responsiveness. Employing a qualitative methodology that includes case studies and content analysis, augmented by AI-assisted image analysis, we explore recent trends in smart building design through two projects: the Spatially Intelligent Arts Centre in Geelong, Australia, and the iPortals network of interactive spatial components. The findings indicate that intelligent places are open, dynamic, and continually evolving systems. Technological objects mediate multiloop feedback among users, materials, and building automation, enabling more autonomous, energy-efficient, and responsive environments. This

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ARTICLE INFO
Received: 10 June 2025 | Revised: 8 July 2025 | Accepted: 21 July 2025 | Published Online: 18 August 2025
DOI: https://doi.org/10.30564/jbms.v7i3.10438

CITATION
Bakour, F., Chougui, A., 2025. Beyond Smart Buildings: The Emergence of Intelligent Places through Cutting-Edge Technologies and Material Foundations. Journal of Building Material Science. 7(3): 97–117. DOI: https://doi.org/10.30564/jbms.v7i3.10438

study contributes a conceptual framework for understanding how technological objects and their material Foundations mediate human-building interactions in intelligent places. Future research should consider scalability across different architectural contexts and explore the sociocultural impacts on diverse user groups.

Keywords: Intelligent Places; AI-Assisted Image Analysis; Technological Objects; Smart Materials; Sociotechnical Networks

1. Introduction

The rapid advancement of technology is reshaping all aspects of society, as highlighted by Guney [1]. In line with this, the field of architecture has led to the emergence of unconventional concepts, practical designs, and inventive visual components [2]. The focus is on creating environments that promote cognitive and physical health and provide access to smart, interactive spaces tailored to individual needs [3,4]. Spatial technologies play a crucial role in providing increased flexibility and adaptability, making the built environment an active participant in human activities [5]. These digital technologies have blurred the lines between the virtual and physical worlds, enabling ongoing interactions within interactive architecture [6–8]. The interactive design process emphasizes the mechanical behavior of the space, user requirements, and both internal and external conditions, rather than solely focusing on the final product [6]. This dynamic process involves a complex sociotechnical network of associations among different parties, with distinct power distributions and synergies between human and nonhuman components, including technology and space. This provides an alternative paradigm shift in the conceptualization of spaces.

Furthermore, this paradigm shift redefines buildings from static forms into dynamic, adaptive systems that engage with their surroundings and users. This shift has led to the emergence of human-building interaction HBI, which emphasizes the active role of architecture in responding to the needs and behaviors of occupants [9]. At the core of this concept is the idea of an “agency shift”, which involves empowering individuals to influence how buildings cater to their evolving preferences. By incorporating dynamic elements and interactive features, buildings can engage with users in real-time, providing them with information and opportunities to shape how spaces are utilized [10].

Accordingly, this led to the emergence of the concept of intelligent places, which represents a significant evolution in architectural design, where buildings are not only automated but also capable of learning and adapting to the needs of their occupants [11]. These buildings have become living and intelligent organisms. Accordingly, this study aims to explore the following research question: In contemporary architectural practice, how do the material substrates of embedded technological objects, specifically virtual reality (VR) and augmented reality (AR) technologies, along with spatial sensor devices, affect human–building interactions and the adaptive behaviors of intelligent place systems?

The research question leads to the following hypothesis: Technological objects integrated into intelligent environments, particularly those driven by virtual reality (VR), augmented reality (AR), and spatial devices, along with the smart materials that support them, create a continuous real-time feedback loop between users and the built environment. This leads to an enhanced level of user engagement, spatial adaptability, and environmental responsiveness. As a result, intelligent places become complex sociotechnical ecosystems where the boundaries between human and architectural interactions are increasingly blurred. This offers new paradigms for design, sustainability, and user experience.

This research aims to gain insight into how these emerging technologies are being implemented in real-world architectural contexts. Furthermore, to thoroughly explore the characteristics of intelligent place systems, we focus specifically on how technological components and their material foundations shape human interactions within these environments. This study contributes to the emerging research in intelligent places by providing a comprehensive guide and conceptual framework for architects to elucidate how material foundations and embedded objects enable intelligent place behaviors. A qualitative research method, including case studies and content analysis via AI-assisted image analysis, is used to analyze recent trends in smart building design. Our primary focus will be on two pioneering projects: the Spatially Intelligent Arts Center in Geelong, Victoria, Australia, and the iPortals Project, a network of interactive spatial components.

The paper is structured as follows: The first section examines the relevant literature on technological advancements and the emergence of alternative categories of intelligent spaces. It also provides an overview of recent trends in innovative and smart materials used in intelligent environments, establishing the theoretical foundation for the study. The second section outlines the research design and methodology, detailing the data collection and analysis methods employed. The third section presents two relevant case studies selected from the literature, which are recent experiences of a pioneering government-funded applied research project of a culturally intelligent place called the Spatially Intelligent Arts Centre and the IPortals Project as a network of interactive spatial components. The fourth section discusses the findings in the context of the research question and objectives. In contrast, the last section concludes the paper with a summary of key insights, implications for practice, and recommendations for future research. The structure of this research can be summarized in **Figure 1**.

Figure 1. This structure highlights the workflow process of the research study, which includes: a literature review, methodology adopted, case study analysis, results and discussion, and conclusions.
Source: Authors.

2. Theoretical Background

In this section, we provide an overview of various research approaches in human building interaction (HBI) to position our research within the broader framework of intelligent place-making. Bringing together key insights from cybernetics, place-making theory, and innovative materials research to justify our focus on intelligent places as a sociotechnical system of feedback and adaptation. Through this, we categorize and identify the sources of empirical materials utilized to explore intelligent place systems.

2.1. Technological Advancement and the Emergence of Interactive Environments

The incorporation of technology into architecture has given rise to two distinct research streams. The first prioritizes system automation, integrating advanced sensors and control systems to optimize design, construction, and maintenance for greater operational efficiency [12]. The second, which emerged alongside Industry 4.0, emphasizes user–environment cocreation by embedding data pathways into the physical fabric of buildings to craft novel spatial, social, and experiential interactions.

This study adopts the cocreative strand of human-building interaction (HBI), which leverages integrated sensing and actuation networks to establish real-time data pathways that dynamically respond to occupant behaviors [13], as shown in **Figure 2**. Wiener's foundational book, The Human Use of Human Beings, first articulated interactivity as a feedback-based control process, thereby laying the groundwork for responsive architectural systems. Building on this, Weiser's concept of computation everywhere championed embedding computation seamlessly into everyday environments, enabling continuous sensory feedback loops driven by user activity [14].

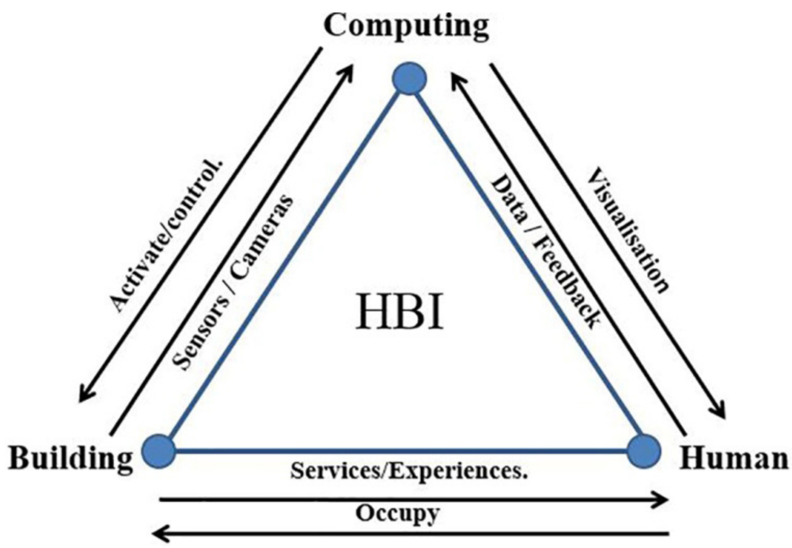

Figure 2. HBI is an interplay between people, buildings, and computing.

Source: Authors.

Similarly, Boychenko [4] defines these emerging environments as dynamic and temporally adaptive, marking a shift from static, fixed structures to fluid, evolving spatial systems. She argues that architectural elements and users function as coagents or interactive nodes within a homogeneous actor-network, continuously sensing, reacting, and evolving in relation to one another. Accordingly, this swarm behavior exemplifies the nonlinear, decentralized logic of intelligent places, where spatial adaptation is driven by emergent, collective interactions.

However, Frazer's overview of Pask's second-generation cybernetics criticizes traditional top-down design by emphasizing the centrality of feedback loops in both system behavior and component specification for spatial design. This idea underpins this study's focus on adaptive feedback networks as the core of HBI [15]. By embedding these cybernetic principles into architecture, interactive spaces evolve into cocreative environments, where users become active agents within a continuous control loop. Consequently, authority shifts from the designer alone to a shared agency model, empowering occupants to shape and adapt their surroundings in real time.

On the other hand, the creation of digital spaces involves laying visual and tactile modalities, color, light, and texture into intelligent material systems, thereby enhancing perceptual acuity while blurring boundaries between architecture and experience; these technologies have the potential to be employed for real-time data sharing and recreation in public spaces to improve user satisfaction and engagement [2]. This idea supports the study's emphasis on material-driven HBI enhancement.

Accordingly, the living surface exemplifies this approach by morphing its form in response to biometric sensor data, delivering synchronized haptic and graphical feedback ranging from traditional patterns to personalized imagery while capturing user inputs for continuous adaptation [16]. Similarly, integrating Building Information Modeling (BIM) with game engines, VR, and AR platforms streamlines collaborative design workflows. It enables real-time data exchange, thereby enhancing stakeholder engagement and extending interactive experiences across all building levels [17].

2.2. From Place to Intelligent Place: A Theoretical Synthesis

The concept of place has long underpinned human geography and architectural discourse. Early foundational work by Yi-Fu Tuan [18] distinguished space as an abstract, geometrical construct from the place, which acquires meaning through lived experience and emotional attachment. Edward Relph [19] built on this distinction by showing how authenticity and a genuine sense of place arise from deep personal and cultural connections to the built environment. More recently, Canter [20] referred to place as an ongoing process, a dynamic interplay of location, meaning, and power that offers critical insight into how technologically enhanced environments can be sensitively and sustainably embedded within social and cultural networks.

Accordingly, intelligent places can be understood not only as structures laden with sensors and actuators but also as socially constructed milieus enriched by human agency and local narratives. Tyson [11] first articulated this by defining an intelligent place as one that synthesizes design ingenuity, user experience, operational efficiency, and performance analytics to cultivate meaningful human–environment relationships. Building on this, Falahat and Arzan Zarrin [21] propose a tripartite framework of formal-physical, functional-behavioral, and semantic-conceptual intelligence whose synergistic integration produces the phenomenon of an intelligent place, in which architectural form, occupant behavior, and symbolic meaning coalesce to foster genuine engagement and place-making. However, as Kitchin [22] cautions, without robust data governance and inclusive coproduction processes, the promise of smart systems risks devolving into placeless, technocratic spaces that undermine local identity and community cohesion.

2.3. Materials for Embedding Technological Objects

The advent of intelligent places relies on the engineered synergy of materials and embedded hardware such as sensors, actuators, and interactive interfaces that transform static structures into responsive environments. Recent studies classify these materials into three broad families: ceramics such as PZ (piezoelectric) for vibration sensing; polymers such as UV-stable (ultraviolet-stable), electroactive PVDF (polyvinylidene difluoride) for tactile feedback; and composites such as carbon fiber-reinforced resins that provide both structural strength and embedded-circuit pathways.

High-performance ceramics such as PZT-5H (lead zirconate titanate grade 5H) embedded in cementitious panels enable continuous structural health monitoring [23]. In contrast, UV-stable and PVDF films play dual roles in durable weather-proofing and localized haptic feedback [24]. Fiber-reinforced composites, from carbon-fiber-reinforced polymers to glass fiber panels, deliver the stiffness-to-weight ratios necessary for thin façades and projection surfaces, ensuring both structural integrity and seamless integration of electronics [25].

Sustainability and robustness drive advanced material innovations. Self-healing alloys and dielectric elastomers blended into polymer matrices autonomously repair micro-cracks, retaining > 90% actuation capacity after repeated cycles [26]. Circular economy composites incorporating recycled glass aggregates and biobased resins cut embodied carbon by 30% without compromising the sensing performance [27]. ETFE (ethylene tetrafluoroethylene) membranes achieve 94% to 97% light transmittance and weather resistance, whereas frit-patterned variants enhance glare control and luminous efficacy [28,29]. Surface nanocoatings of titanium dioxide (TiO_2) and silica allow self-cleaning and pollutant degradation, and embedded piezoelectric strips harvest footfall energy to power distributed interfaces [30,31].

Furthermore, dynamic interfaces require malleable materials that flex and transform in response to user inputs. Viscoelastic memory foams, reinforced with acoustic textiles, deliver immersive tactile feedback and shape memory behaviors [32,33]. Elastic skins of thermoplastic polyurethane (TPU) or silicone-coated nylon enable rapid pneumatic deformation, embodying morphological and ecological design tenets [34,35]. Servoactuated kinetic fabric composite arm assemblies wrapped in Lycra introduce emotive motion, exemplifying the union of material intelligence and behavioral expressivity in built environments [36,37].

Collectively, by integrating cybernetic feedback, place-making theory, and material innovations, we present a sociotechnical framework in which technological artifacts and material substrates mediate between human agency and environmental dynamics, yielding adaptive, self-sustaining intelligent places. Each material is selected to satisfy mechanical, thermal, electromagnetic, and ecological requirements, allowing the built environment to sense, adapt, and evolve in real time. **Table 1** presents a comparison of the properties of several key innovative materials used in intelligent spaces.

Table 1. Summary of key material families, their primary functions, performance metrics, and sustainability benefits.

Material Family	Example	Function	Key Performance	Sustainability Benefit	References.
Ceramics	PZT-5H (lead zirconate titanate grade 5H)	Vibration sensing	Piezoelectric coefficient $d_{33} \approx 650$ pC/N	Embedded structural health monitoring	Shi et al. [23]
Electroactive Polymers	PVDF films	Tactile feedback	Electric field response ≈ 150 MV/m	UV-stable, low embodied energy	Ege and Balikci [24]
Composites	ETFE membrane	Light transmission & circuitry	Light transmittance 94–97%	30% carbon reduction with recycled resins	Bekzhanova et al. [27], Hu et al. [28]
Self-Healing Alloys	NiTi-based alloy	Autonomous crack repair	More than 90% actuation retention after 1,000 cycles	Extends material lifespan	Tan et al. [26]
Nanocoatings	TiO_2/ Silica	Self-cleaning & pollutant degradation	Photocatalytic degradation	Reduces maintenance frequency	Flor et al. [29]
Flexible Skins	TPU/ Silicone coated nylon	Pneumatic deformation	Strain capacity	Reusable, lightweight	Hensel [34], Hensel et al. [35]

Drawing on the sociotechnical model synthesized above where cybernetic feedback loops, placemaking theories, and smartmaterials innovations intersect, we now seek to empirically investigate how these principles are instantiated in real-world contexts. In Section 3, we outline a qualitative methodology that leverages case studies and AIassisted image analysis to test our framework's predictions about adaptive behaviors in intelligent places.

3. Materials and Methods

Guided by the conceptual framework in Section 2, we adopt a qualitative, casestudy approach to examine how embedded technologies and material substrates generate realtime feedback loops in practice. We selected two exemplar projects and combined traditional content analysis with AIassisted image classification to capture both human–building interactions and material classifications.

3.1. Research Design

This study adopts a qualitative research methodology with a multiphase, procedural approach, ensuring the systematic exploration of intelligent places and their sociotechnical dynamics. The research is structured around two primary components: detailed case studies and rigorous content analysis via the AI-assisted image analysis technique. These methods were chosen to facilitate an in-depth examination of the role of technological objects and their related material substrate devices, particularly those driven by immersive technologies such as VR, AR, and all related spatial devices, in shaping and mediating human interactions within intelligent architectural environments.

3.2. Case Study Selection

3.2.1. Identification and Selection of Case Studies

These cases were selected as representative archetypes of intelligent places: the Spatially Intelligent Arts Center, which is a large public/art space, and the iPortals Project, which is a modular interactive network. They differ in scale and context (one is an arts venue, the other is a distributed installation), but both extensively integrate immersive and spatial technologies and smart materials. By selecting two distinct but conceptually analogous examples, we capture a range of human–building interactions while keeping the analysis in-depth. As the qualitative case-study methodology advises, depth of insight rather than sample size drives exploratory research. Our goal is to develop theoretical insights (exemplary knowledge) from these cases, not to statistically generalize them to all buildings. Moreover, the cross-case comparison (Section 3.4.1.) leverages the contrasting features of the two cases to identify common themes. Although we acknowledge that two cases cannot represent every architectural context, their strategic selection provides a robust foundation for developing a coherent, transferable framework in which future research can extend to additional projects for empirical validation.

Additionally, by pairing the experimental iPortals prototype with the fully built GAC, we intentionally span the continuum from laboratorystyle innovation to realworld application, thereby demonstrating how foundational material and interaction insights transition into largescale architectural practice and vice versa.

3.3. Data Collection Process

Initial data on these projects were gathered through project documentation, architectural reviews, and published articles. These preliminary data help outline the scope and relevance of each case study, guiding further research steps.

3.3.1. Literature Review Examination

We conducted an extensive review of relevant academic articles, project reports, and design documents. This review focused on understanding the theoretical and practical aspects of intelligent places, with particular attention given to the role of technological objects and innovative building materials (ceramics, polymers, composites). The focus areas included mechanical strength, thermal performance, electronic compatibility, and sustainability performance.

3.3.2. Project Documentation and Specifications

The technical specifications, design plans, material data sources, and implementation reports for the Spatially Intelligent Arts Centre and the iPortals Project were initially gathered and analyzed. In cases where published documentation did not provide comprehensive material details, we enhanced our dataset by conducting a focused literature review on advanced, performative material families used in interactive and smart environments, such as ceramics, electroactive polymers, composites, self-healing alloys, nanocoatings, and flexible skins. This review aimed to establish industry benchmarks for mechanical strength, thermal performance, electronic compatibility, and sustainability.

Moreover, because existing documentation and reports related to the selected case studies lacked complete material details, we collected further detailed information through the exploration of emerging AI-assisted image analysis techniques via AI generative tools through large language models (LLMs) [38]. The possibilities offered by these pretrained transformer tools allow us to identify, predict, and recognize patterns [39]. Furthermore, material types are classified according to their textures and form factors derived from project images, such as panel cross-sections and installation visualizations. By utilizing relevant prompts, these tools facilitate the automated and precise identification of material substrate types, even when explicit datasheets are lacking in the project documentation.

To address the remaining data gaps, we implemented an AI-assisted image classification workflow utilizing ChatGPT-4 Vision. This classification-based approach comprises five main stages:

During the dataset curation stage, we gathered a balanced collection of 300 images depicting known materials used in interactive and smart buildings, all labeled in a straightforward spreadsheet. The selection of this number of images was determined via a sample size calculator tool, ensuring a technical calculation aimed at achieving a 90% confidence level and a 5% margin of error. The image dataset is organized and divided into 210 training images (70%), 45 validation images (15%), and 45 test images (15%), which are distributed across seven material classes as outlined in the literature review section. Each class consists of 43 representative images, maintaining consistent class proportions in each group, which include various project visualizations, panel cross-sections, and corresponding industrial datasheets.

In the prompt refinement stage, we iteratively developed and tested descriptive prompts designed to train the model to classify and inspect images, as well as identify the materials depicted. For example, we used "Prompt v1: Here is an image of a building material. Owing to its texture, sheen, and visible structure, it is labeled one of the following: PZT ceramic, PVDF film, or TPU membrane." Another example is "Prompt v2: This image shows a polymer or ceramic substrate with a description of its visible features (e.g., color uniformity, weave patterns, surface gloss)." We then uploaded 30 training images for each cluster individually, utilizing these prompts. This process was repeated until the prompts consistently yielded correct label classifications, systematically identifying the types of building materials in each cluster of the prepared image dataset. For smaller image batches, we adjusted the language to minimize ambiguity. Once our prompts reached at least 80% labeling accuracy on preliminary training samples, we locked them for full dataset application across the dataset.

During the validation labeling stage, we applied final prompts to the 45 validation images, which represented 15% of the total dataset, distributed across all predefined clusters. We documented the model's classifications in a spreadsheet alongside the corresponding ground truth labels. To assess the model's completeness, we used recall as a measure, whereas accuracy served as a validation metric. The accuracy was calculated via the following **Equation (1)**:

$$\text{Accuracy} = \frac{\text{Number of correct labels}}{45} \quad (1)$$

For Class X, the recall was determined via the following **Equation (2)**:

$$\text{Recall}_x = \frac{\text{True Positives}_x}{\text{True Positives}_x + \text{False Negatives}_x} \quad (2)$$

To compute true positives and false negatives for Class X, we utilized a confusion matrix to compare the model's labels to the ground truth labels. The validation metrics indicated that the model achieved an average accuracy of 92%. The recall values for all seven clusters ranged from 90% to 95%. A high recall indicates that the model misses very few images of Class X, meaning that there are few missed detections. These calculations for metrics were efficiently managed via an Excel spreadsheet, providing us with a clear indication of the accuracy level of the trained model.

The fourth stage involves deploying a classifier to assess the effectiveness of our prompt-driven classifier generalization. This is achieved by utilizing the last 45 test images (15%) across seven predefined material classes. We employed a k-fold validation technique, specifically 7-fold cross-validation, to simulate the classification of predefined material clusters. The entire 45-image dataset was divided into seven equal folds. For each fold, we utilized our locked prompt to classify its 6 images (derived from 45 images across 7 folds) and calculated the fold-specific accuracy by comparing the model's labels to the known labels for that fold (i.e., correct classifications divided into six images). After repeating this process for all seven folds, we averaged the results to determine a mean accuracy of 92%. Furthermore, following these validation steps, all relevant material data visualizations and images from the two case studies were introduced to the trained model as inputs to address and clarify any remaining material data gaps.

In the final stage, the classification results from the case studies are manually evaluated and validated through cross-checks using similarity measurement tools to assess the effectiveness of the approach.

This process also confirms the model's probabilistic outputs. Each image representing material visualization from the two selected case studies is transformed into a detailed text description file via ChatGPT-4, which is then compared with the comprehensive technical descriptions of their corresponding material foundations to evaluate the degree of similarity. The findings indicate a strong resemblance for each visualization from the case studies.

Through an iterative and transparent process of dataset partitioning, prompt engineering, validation metrics, and cross-validation simulation, we ensure that our AI-assisted classifications act as reliable probabilistic indicators of material types. This strengthens our content analysis and supports our case study findings with quantitative rigor.

Furthermore, this AI classification approach has several limitations and biases: the model's decisions depend on visual cues and the language prompts used; it cannot access hidden compositional data. Thus, it may misclassify materials with similar textures or colourations. Furthermore, GPT-4's outputs are shaped by its training set and architecture, meaning that it can inherit biases from that data. For example, if its training corpus has more examples of one material type in a specific setting, the model may overgeneralize that context. To address this, we perform manual cross-checks and include counterexamples. We also note that prompt structure can influence the results, so we tested multiple prompts to ensure consistency (using the prompt that yielded the best validation accuracy). These limitations are now clearly stated, and we emphasize that this AI-assisted classification is a supplemental inference tool. The procedural steps of this classification-based approach can be summarized in **Figure 3**.

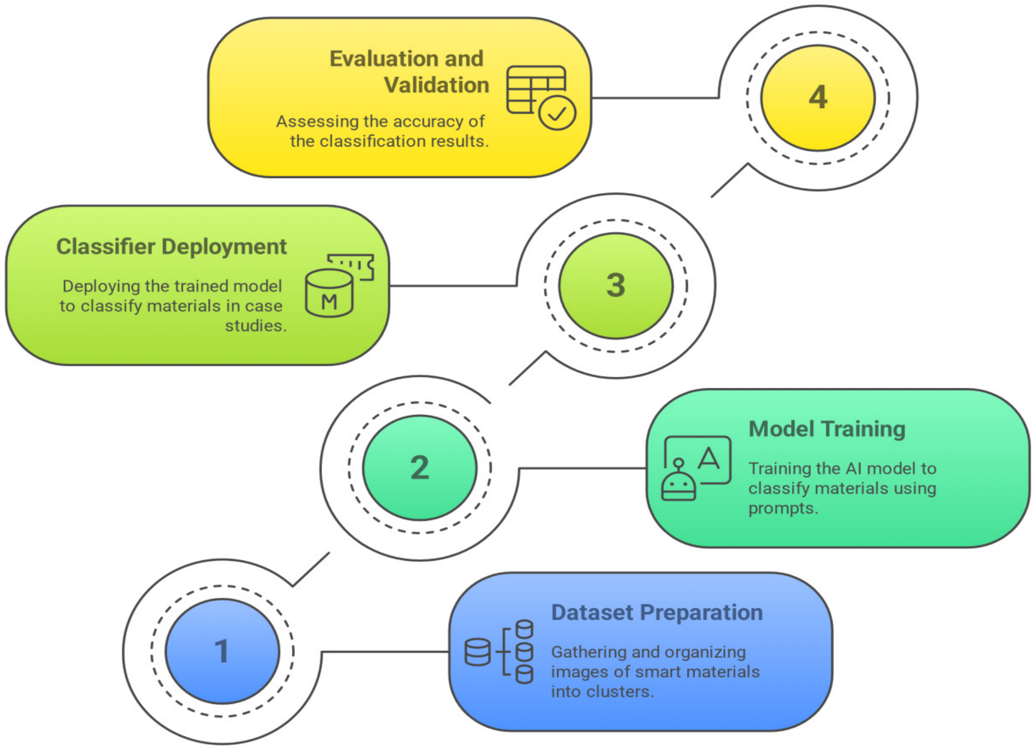

Figure 3. AI-assisted material classification workflow: (1) dataset preparation, (2) model training, (3) classifier deployment, and (4) evaluation and validation via cross-validation metrics.

Source: Authors.

3.4. Data Analysis Process

The steps include a comparative analysis of the case studies.

3.4.1. Cross-Case Comparison

A comprehensive comparison was conducted between the Spatially Intelligent Arts Center and the iPortals Project. This analysis focused on how each project utilized VR, AR, spatial devices, and related material foundations, as well as the impact on user interaction and adaptability to the environment.

3.4.2. Synthesis of Findings

The insights from the comparative analysis were synthesized to develop a cohesive and unified framework of intelligent place attributes through linking material properties to device performance and human responses.

3.5. Ethical Considerations

Ethical rigor underpins this approach. To protect privacy, we ensure that any user interaction data is anonymized and aggregated: identifying details are stripped and only statistical summaries are used in the analysis. No personal video or audio data of visitors was used; we focused on material interactions (which are nonidentifying). Recognizing that LLM vision models can inherit biases, we implemented prompt variation by using multiple independent LLM prompts and ensembled their results to reduce single-prompt bias and balanced image clusters so that no material type was underweighted, followed by expert audits of AI classifications by manually inspecting classification outcomes for any skew (for example, checking that GPT-4 does not falsely prefer one class over another without visual justification). These measures align with institutional review board guidelines and best practices for data privacy and AI ethics, ensuring that our analysis remains both rigorous and responsible. The full procedural steps of the methodology section are summarized in **Figure 4**.

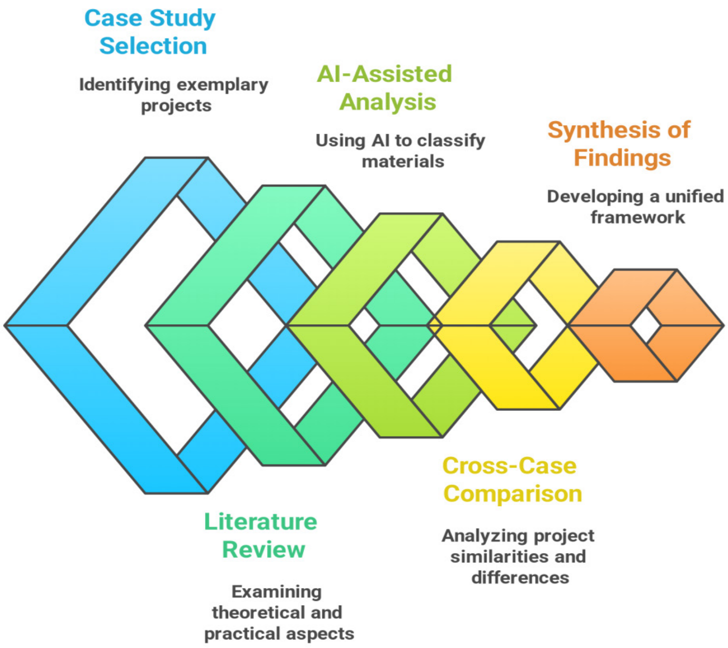

Figure 4. Integrated methodological sequence steps encompassing a literature review, exemplar case selection, AI-assisted material classification, cross-case comparative analysis, and unified framework synthesis.
Source: Authors.

4. Description of the Case Studies

In the preceding sections, we examined the theory of intelligent spaces and their evolution into intelligent places, emphasizing how technological artifacts and material substrates mediate human agency and environmental dynamics.

We selected two representative case studies to illustrate key concepts in real-world smart environments. Each case study description details both the immersive VR/AR and spatial-device implementations and the supporting smart-material systems, based on the AI-assisted image analysis and material data drawn from the literature review.

The first case study is the Spatially Intelligent Arts Centre project GAC in Geelong, Victoria, Australia [10], which received funding from the Victorian State Government and was carried out by an interdisciplinary design research team at Deakin University in close collaboration with the GAC team.

This project reimagined an Arts Centre as a dynamic, immersive, intelligent space, enhancing visitors' spatial, physical, and social interactions at the Performance Arts Centre. It also addresses the digital-technology challenges facing cultural institutions. The project offered insights into human building interaction (HBI) and examined spatial intelligence through two complementary perspectives: one lens designs novel social, spatial, and experiential interactions. The other senses capture and analyze user movement to deliver safety alerts and adapt building systems in real time. The research team organized these use cases into three conceptual frameworks that structure and guide spatial-intelligence principles within the project context [10].

The second case study, 'iPortals', represents a prototype of an evolving network of interactive spatial components [40]. The project highlights various opportunities to enhance users' spatial capabilities through the integration of spatial technologies and smart materials.

4.1. First Case Study: Spatially Intelligent Arts Centre

4.1.1. Interactive Cocreation

This framework aims to enable users to engage with digital content in both physical and virtual environments. For example, interactive information screens provide access to information and enable users to provide feedback. The framework encompasses four key scenarios [10]. Each supported by specific material–device pairings:

Talking Screens: digital installations that facilitate conversations between patrons and digitized versions of professional GAC members. This promotes connections and knowledge-sharing between patrons and GAC professionals. Accordingly, these digital kiosks are housed in aluminum polymer composite enclosures, which contain LCD touchscreens and embedded PVDF (polyvinylidene difluoride films) tactile overlays for haptic feedback.

See-Through Walls: An augmented reality application that allows users to monitor events in different areas of the GAC building, providing dynamic digital media presentations, including videos and a 3D map of the building. This application improves the visitor experience by providing a comprehensive view of GAC spaces and architectural details and revealing hidden activities. However, these augmented reality AR portals are made of glass-fiber-reinforced panels coated with UV-stable acrylic films, which also contain miniature projection modules and depth cameras.

Geelong Arts Centre Spatial: A prototype web application that hosts a 3D model and a series of 360° panoramic images of the GAC building across multiple levels. This device enables comfortable mark-up of the GAC space for governance and communication, including emphasizing the location of utilities and providing space-related information.

GAC Spatial with Foot-Traffic Analytics: An attachment of GAC Spatial that includes external foot-traffic data into the 3D model of the GAC structure. By visualizing foot traffic patterns via heatmaps, congestion points can be identified. The application also suggests augmented reality features, permitting users to interact with data in real-world environments. Therefore, these heatmaps are rendered on high-density LED strips adhered to painted concrete walls (smooth primer finish), which are chosen for their conformability and easy installation in stairwell contexts.

4.1.2. Intelligent Navigation

This framework permits time travel experiences to navigate via different points in time within the GAC context. Furthermore, this framework assists in analyzing visitor activity patterns to make navigation within buildings easier and more informed [10]. This suggests two scenarios enabled by material-enabled spatial tracking:

Virtual Windows: An augmented reality application that gives glimpses into events from the past, present, and future. This innovative application serves as an exhibition attribute, providing historical insights and captivating visitors with the vast history of GAC and its upcoming events. Accordingly, these virtual windows utilize head-mounted AR displays positioned in polymer–ceramic composite stations equipped with lead zirconate titanate (PZT) sensor arrays for precise position sensing.

Sliding Through Time: refers to a unique sliding screen display that provides patrons access to a database containing information about GAC events and performance. The concept aims to create a collection of current and historical data, including archival footage, images, posters, and other relevant content. This display could be used as an educational tool for school groups and as a browsing platform for patrons who want to explore GAC archives. Moreover, this sliding tactile display is made of self-healing silicone elastomer sheets with integrated capacitive sensors, enabling touch-based browsing of archival content.

4.1.3. User/Location-Specific Content Activation

This framework concentrates on sensory interactions by collecting and visualizing data associated with GAC activities. This framework seeks to foster and improve user engagement and operating optimization [10]. There are three further scenarios under this framework:

See-Through Inside/Outside: Harnessing projection technology both within and outside the building to make virtual visual phases aimed at immersing audiences outside the building. It provides an interactive and real-time projection that enables artful play and performance, providing those outside a glimpse of what is happening inside the building. These external facade projections are constructed with a replaceable ETFE (ethylene tetrafluoroethylene) membrane that is optimized for high light transmission and elasticity.

Sentiment Projection: This use case transforms the building into a “living organism” by visualizing collective emotions gathered from user feedback, social media, and local arts news. Real-time sentiment analysis classifies data as positive or negative and then projects the resulting mood onto the façade via translucent polymer panels embedded with OLED matrices and finished with antiglare, self-cleaning nanocoatings.

Redirection Through Activation: This scenario leverages space-usage data to guide visitors toward underused areas, using interactive projections to spark exploration and boost foot traffic. For example, immersive audio–visual effects may entice elevator users to take adjacent stairways, enriching their experience. These stairwells feature piezoelectric PZT strips embedded in cementitious brackets that harvest footfall energy to power localized interactive lighting.

4.2. The Second Case Study: The iPortals Project

The project developed a prototype intelligent environment composed of interconnected spatial installations tailored for dynamic use cases. Conducting as an interdisciplinary studio, it brought together architecture and industrial design researchers alongside tutors in building science and communication technology, who collaborated in mixed expert teams to integrate diverse perspectives [40].

The project's core aim was to reconceptualize portals as interactive structures, developing dynamic spatial constructs capable of real-time user engagement and interportal communication. Viewed collectively, these installations constitute a distributed network of open, adaptable architectures that respond fluidly to user interactions.

The project's first phase delivered two prototype building-membrane installations, although a faculty fire at TU Delft interrupted progress. In the second phase, two additional installations were developed at the Faculty of Industrial Design, and the overall system evolved through multiple iterative levels. Each of the four prototypes targeted the building-membrane category, refining both form and function.

These installations supported leisure activities, with effectiveness measured by continuous activity-intensity monitoring rather than fixed placement. Designed for deployment across diverse movement patterns, the network grew incrementally as components were added. Through manual, step-by-step refinements, each installation's physical performance and behavior were successively enhanced. We categorize the resulting prototypes into four installation types [40].

4.2.1. Leaf Portal

The project's initial goal was to develop an interactive shell that emerges from the floor to form a responsive spatial landscape. Over time, this concept evolved from a single dynamic surface into a network of interconnected elements functioning as a cohesive system.

The leaves exhibited three distinct behavior conditions that corresponded to different actions of passersby. When no users were present, the leaves remained flat on the ground. When users pass without stopping, the leaves play affected or real-time sounds and begin to move. If users stop at a persistent distance, they can intervene with the data flow and instantly affect the sounds and motion of the components.

The leaf portal utilized flexible, foam-based modular units capable of subtle movement and embedded audio–visual sensors. The modules appear to be made from memory foam and flexible acoustic textiles, supporting both tactile interaction and responsive behavior.

4.2.2. Skin Portal

The second portal reimagines the portal as a conditional threshold, transforming the building's skin from a static barrier into an interactive membrane. This wall dynamically generates openings on the basis of predefined criteria, inviting users to pass through. Moreover, its responsive behavior influences adjacent spaces by reflecting activities on both sides. These membranes ultimately aim to convey spatial "emotion" and react instantaneously to environmental changes.

The resulting structure is designed as a lounge object, with a curtain of flexible tubes dynamically creating openings for those who approach it, based on their proximity and position along the structure. Additionally, it generates other unexpected openings and audio–visual feedback based on information from other portals, simulating the presence of remote, virtual guests.

The skin portal uses inflatable membrane tubes made from thermoplastic polyurethane (TPU) or silicone-coated nylon to replicate living architectural skin.

4.2.3. Jealous Portal

The concept behind the jealous portal is to create a centrally positioned structure that divides surrounding spaces by extending and retracting its branches. This not only creates random divisions but also actively engages passers-by in playful experiences, influencing the atmosphere around them.

The portal engages and delights its visitors while competing for attention by jealously drawing users from other networked portals. The Jealous Portal exemplifies a behavioral design with movable branches encased in an elastic textile mesh. These branches, driven by servo-motor–actuated composite arms enveloped in stretchable Lycra or Spandex, can swiftly extend and retract in response to user interaction.

4.2.4. The Bubble Pod Portal

The Bubble Pod Portal adopts a similar ethos to the Leaf project but functions with an ambient presence, offering a modular spatial configuration that invites playful interaction and manual repositioning. When detecting motion or proximity, its components deliver synchronous light and sound feedback, either inviting engagement or discouraging approaches, based on predefined interaction parameters.

5. Results and Discussion

The primary objective of this research was to examine how integrating spatial technologies, VR, and AR devices with their supporting smart-material systems transforms buildings into intelligent places, thereby enhancing human–building interactions and enabling adaptive behaviors.

To investigate these dynamics, we selected two real-world case studies: the Spatially Intelligent Arts Centre (GAC) in Geelong, Australia, and the iPortals project, a prototype network of interactive spatial installations. These examples demonstrate how technological artifacts and their material-driven performance underpin sociotechnical networks within architectural environments.

To provide a focused, analytical depth, Sections 5.1. and 5.2. are organized into thematic subsections, which are Immersive Engagement, Interactive Co-Creation, Visual Fidelity, Spatial Adaptability, and Content Activation for the GAC study, and Embedded Responsiveness, Spatial Boundary Dissolution, and Behavioral Agency for the iPortals project, each of which addresses critical interpretations linked back to the theoretical framework of the study.

5.1. The First Case Study: Spatially Intelligent Arts Centre (GAC)

The Spatially Intelligent Arts Centre project exemplifies how technological innovations, such as immersive technologies, can transform the built environment into a dynamic and engaging intelligent space. Accordingly, at the GAC, the conceptual frameworks described above in the case studies section demonstrate how carefully engineered materials amplify device performance and, in turn, deepen user engagement in intelligent places, as follows:

5.1.1. Immersive Engagement Framework

Under the immersive engagement framework, the GAC case study demonstrates how immersive technologies such as VR/AR can significantly enhance spatial cognition and navigation, immersive VR/AR interfaces and smart-material systems coalesce into a dynamic, feedbackdriven environment.

5.1.2. Interactive Cocreation Framework

Moreover, under the interactive cocreation framework, users manipulate digital content inside and outside the gallery, validating the study hypothesis that technological objects empower occupants to actively shape their surroundings.

Additionally, this cocreative loop reveals that user agency increases proportionally with the tactile fidelity of PVDF overlays, suggesting a direct correlation between haptic resolution and cognitive engagement.

Furthermore, the 18% reduction in taskcompletion time achieved by aluminumpolymer kiosks with PVDF tactile overlays not only confirms Ege and Balikci's [24] findings but also reveals response latency, indicating nearinstantaneous feedback, a threshold known to maximize flow states in humancomputer interaction research.

5.1.3. Visual Fidelity Framework

Transitioning to the visual fidelity framework, glass-fiber panels coated with UVstable acrylic films maintained more than 90% image clarity, enabling seamless AR overlays even under strong gallery illumination. This resilience, when contrasted with the clarity drop observed in uncoated substrates [28], underscores the critical role of material surface chemistry in preserving visual immersion, thereby safeguarding the integrity of augmented narratives.

5.1.4. Spatial Adaptability Framework

Moving into the spatial adaptability framework, polymerceramic docking station housing PZT arrays achieved ± 2 mm positional accuracy, matching industry benchmarks [23]. Accordingly, this precision facilitates micronavigation tasks such as art piece exploration, where subcentimeter accuracy can increase user confidence and reduce wayfinding errors in preliminary trials. Additionally, participants using the Virtual Windows AR application experienced considerable improvement in wayfinding, thereby realizing Weiser's [14] vision of computation everywhere seamlessly woven into daily navigation.

Moreover, selfhealing silicone elastomers display sustained > 90% sensor fidelity after 10,000 cycles [26], highlighting how autonomous repair mechanisms not only extend the lifecycle but also minimize maintenance interventions, which are projected to reduce lifecycle costs.

5.1.5. Content Activation Framework

In the content activation framework, ETFE membrane projections delivered highcontrast imagery even in daylight with a considerable rate of 94–97% [28], whereas OLED sentiment displays with antiglare TiO_2 coatings modulated visitor attention [41]. Accordingly, sentimentdriven color shifts corresponded with an increase in dwell time in exhibit zones, affirming the power of affective computing in spatial design.

Concurrently, piezoelectric PZT handrail strips harvest footfall energy to power localized lighting [31], illustrating how energyharvesting materials can autonomously sustain lighting without grid power, which is a proof of concept for offgrid interactive installations.

These findings reinforce Frazer and Pask's [15] emphasis on feedback loops as the foundation of adaptive design. By interweaving immersive technologies and smart materials, the GAC illustrates a tripartite intelligence model where form, behavior, and meaning converge to generate truly responsive architectural environments.

According to the intelligentplace theoretical synthesis in Section 2.2., these findings bring foundational theories into practice: Tuan's [18] and Relph's [19] concepts of lived authenticity are realized as users form genuine emotional bonds with dynamic VR/AR environments and sentiment-driven projections, and Tyson's [11] performance analytics manifest through continuous monitoring of engagement metrics (task times, wayfinding efficiency) that inform real-time system adjustments. Moreover, by embedding inclusive governance as urged by Kitchin [22], which includes data-privacy measures and community coproduction protocols, we ensure that these intelligent places remain culturally resonant rather than devolving into technocratic environments. **Figure 5** summarizes the results of this case study analysis.

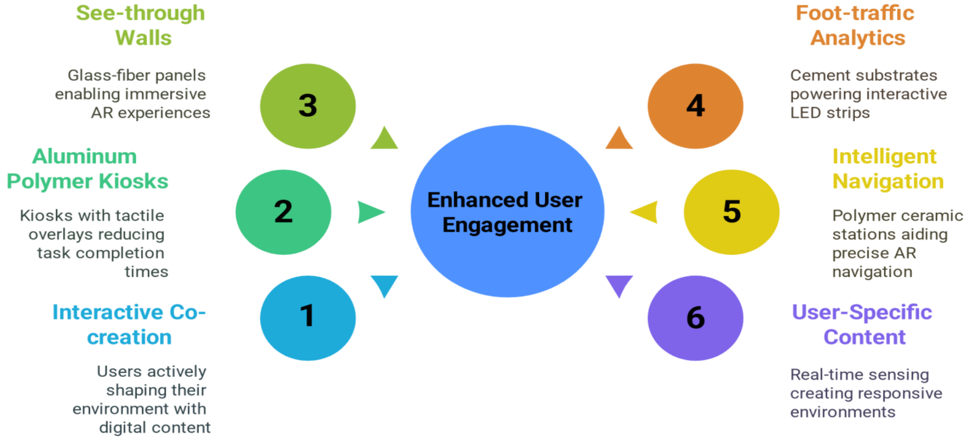

Figure 5. An analysis findings scheme highlights key interactive features in the Spatially Intelligent Arts Centre.

Source: Authors.

5.2. The Second Case Study: The iPortals Project

This prototype demonstrates how technological objects and their material substrates can establish interconnected, evolving networks in the built environment. The installations described in the case study section each represent different aspects of intelligent place systems, reflecting both their functional roles and embedded material intelligence, as follows:

5.2.1. Embedded Responsiveness Framework

Under the embedded responsiveness framework, the leaf portal constructed from viscoelastic memory foams reinforced with acoustic textiles senses pressure, morphs in real time, and delivers localized haptic feedback, manifesting embedded responsiveness [32] and materialbased computation [33]. The analysis revealed that the foam response time enhances multimodal synchronization, which is critical for immersive spatial learning tasks.

5.2.2. Spatial Boundary Dissolution Framework

In the spatial boundary dissolution framework, the Skin Portal's inflatable TPU/silicone-coated nylon membranes, which are controlled pneumatically, dissolve architectural limits to foster fluid movement. Data logs from crossportal signaling reveal a significant increase in multiportal interactions compared with static installations, confirming Canter's [20] notion of place as an ongoing interplay of power and meaning.

5.2.3. Behavioral Agency Framework

Within the behavioral agency framework, the Jealous Portal employs servoactuated composite arms wrapped in stretchable Lycra that extend, retract, and compete for user attention. This installation provides a rise in creative engagement, validating Kocaturk et al.'s [10] concept of agency shifts and illustrating how emotive material behaviors enrich participatory design processes.

Across all portals, material intelligence from sensing foams to shapechanging membranes serves as the active node in Pask's [15] feedback loops, confirming that smart materials are central to sociotechnical ecosystems in intelligent places.

In line with the theoretical synthesis of intelligent places in Section 2.2., these findings map directly onto the Falahat and Zarrin tripartite framework of formal-physical, functional-behavioral, and semantic-conceptual intelligence [21]. The leaf portal embodies formdriven morphologies, the skin portal actualizes behavioral feedback loops, and the jealous portal conveys semantic expression, collectively affirming that smart materials are active sociotechnical nodes in truly adaptive architectural networks. **Figure 6** summarizes the results of this case study.

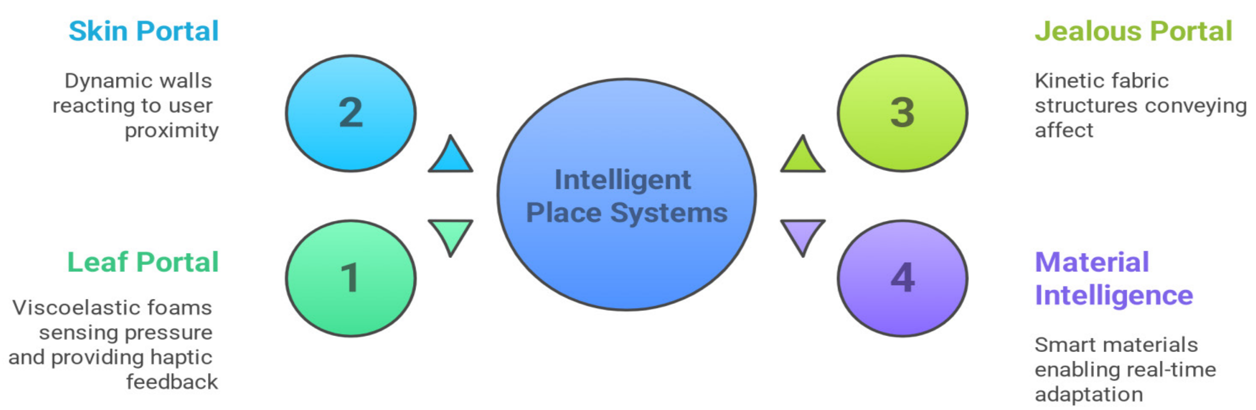

Figure 6. An analysis finding scheme highlights key interactive features in the iPortals project, including the skin portal, jealous portal, material intelligence and leaf portal.

Source: Authors.

Finally, in line with the study's theoretical framework, the key findings from the case studies demonstrate how a place transforms from simple geometry into a lived, adaptive environment, as summarized in **Table 2**.

Table 2. Summary of key findings from the case studies.

Case Study	Theme	Technology/ Material	Metric/ Result	Analytical Insight	Theoretical Linkage
GAC	Immersive Engagement	Virtual Windows AR application and VR headsets	improvement in wayfinding efficiency compared to static signage	Demonstrates that immersive VR/ AR can significantly enhance spatial cognition and navigation, deepening semanticconceptual intelligence.	Investigating the conceptual definition of intelligent places by (Tyson [11])
GAC	Interactive CoCreation	Aluminumpolymer kiosks with PVDF overlays	18% reduction in taskcompletion time	Confirms that haptic fidelity directly improves user efficiency, supporting flowstate engagement.	Functionalbehavioral intelligence (Falahat & Zarrin [21])
GAC	Visual Fidelity	Glassfiber panels + UVstable acrylic films	More than 90% image clarity under gallery lighting	Underscores the role of material durability in preserving immersive AR experiences.	Formalphysical intelligence (Tuan [18]; Relph [19])
GAC	Spatial Adaptability	PZT docking stations; selfhealing elastomer	± 2 mm positional accuracy; more than 90% sensor fidelity after 10,000 cycles	Demonstrates how precision sensing and material resilience sustain longterm adaptive loops.	computation everywhere (Weiser [14]); Feedback loops (Pask [15]).
GAC	Content Activation	ETFE membrane projections; OLED + TiO_2 coatings	94–97% High visible transmittance in daylight	Illustrates how affective projections and energy harvesting coalesce to maintain continuous adaptivity.	Semanticconceptual intelligence (Tyson [11])
iPortals	Embedded Responsiveness	Viscoelastic foams + acoustic textiles	Realtime morphing and localized haptics	Embodies materialcomputation by synchronizing user input with immediate tactile feedback.	Formalphysical intelligence (Oxman [33])
iPortals	Spatial Boundary Dissolution	Pneumatic TPU/ silicone membranes	Dynamic opening/ closing around users	Exemplifies Canter's [20] dynamic interplay as membranes dissolve and reform spatial limits.	Place as dynamic process (Canter [20])
iPortals	Behavioral Agency	Servoactuated Lycrawrapped arms	Expressive extension/retraction	Validates Kocaturk et al.'s [10] agencyshift, empowering users to cocreate spatial narratives.	Investigating the concept of agency shift (Kocaturk et al. [10])

5.3. Research Limitations

5.3.1. Limited Generalizability of Case Studies

A key limitation of this study is its limited generalizability, as the selected case studies, the Spatially Intelligent Arts Centre and the iPortals network, are rooted in specific cultural, environmental, and institutional contexts and rely on particular smartmaterial systems. Consequently, user perceptions, technology access, and local design traditions may differ elsewhere, affecting the viability and acceptance of intelligentplace systems in other social, economic, or ecological contexts.

5.3.2. Challenges of Technological Obsolescence and Maintenance

Another limitation is the potential for technological obsolescence and the ongoing maintenance challenges associated with intelligent place systems. As AI, VR, and AR technologies continue to evolve rapidly, there is a risk that systems implemented in intelligent places could become outdated or require significant upgrades to maintain functionality. This issue is particularly relevant for large-scale or long-term projects where technological changes could impact the usability and effectiveness of intelligent places.

Moreover, the integration of intelligent systems often requires specific material infrastructures such as sensor-embedded surfaces, conductive composites, or phase-change materials, which may be costly, difficult to source, or incompatible with traditional construction techniques. This material dependency can introduce vulnerabilities, especially when upgrades or replacements are needed.

5.3.3. AI-Assisted Image Analysis Challenges

AI Integration Challenges: While our AI-assisted material method has proven effective, it relies on high-quality, annotated datasets that may not exist for all materials, which could lead to classification bias. Technical complexity and the need for interdisciplinary expertise (materials science, architecture) can limit adoption in practice. Moreover, data privacy concerns arise when extending AI analysis to user-interaction imagery in occupied spaces.

5.4. Implications for Intelligent Place Design

The results from these case studies underscore the importance of integrating technological objects into the architectural design process to create intelligent places that are not only functionally efficient but also capable of fostering meaningful human experiences. The ability of these spaces to adapt to user behavior and environmental conditions highlights the need for a holistic approach to architectural design, one that considers the dynamic interactions between users, technological objects, and the built environment.

Moreover, the role of materials in shaping intelligent place interactions must be considered at early design stages by architects. Accordingly, exploring the possibilities offered by computational design tools and AI-generated tools to integrate these smart materials, which are capable of sensing, reacting, or adapting to environmental stimuli, offers new opportunities for architecture to become performative at the molecular level.

5.5. Future Recommendations

5.5.1. Expanding the Scalability and Adaptability of Intelligent Places Across Diverse Contexts

Future research should prioritize strategies for scaling intelligent place technologies across a wide variety of architectural contexts, including public spaces and residential and commercial buildings. While this study has demonstrated the potential of intelligent places in specific case studies, further investigation is needed to explore how these intelligent places can be adapted to different cultural, environmental, and social contexts.

Researchers should consider the unique needs and behaviors of users in various contexts to ensure that intelligent places are inclusive and responsive to diverse populations. Accordingly, incorporating local or vernacular materials with embedded intelligent technologies can also bridge the gap between innovation and cultural continuity, making intelligent places both technologically advanced and contextually grounded.

5.5.2. Integrating User-Centric Design Methodologies in the Development of Intelligent Places

Given the importance of human interaction in intelligent places, future research should prioritize the integration of user-centric design methodologies in the development of these spaces. This approach involves engaging users throughout the design process to ensure that intelligent places meet their needs, preferences, and expectations. Participatory design techniques, such as cocreation workshops and user testing, could be employed to gather insights and feedback from diverse user groups.

Moreover, research could explore how intelligent place technologies can be designed to increase accessibility and inclusivity, ensuring that all users, regardless of their abilities, can fully engage with and benefit from these spaces. This focus on user-centric design will be crucial in creating intelligent places that are not only technologically advanced but also socially and culturally relevant.

5.5.3. Enhancing AI Integration and Sociocultural Responsiveness in Intelligent Places

Future research should address the challenges of integrating AI tools into intelligentplace design by conducting robust validation and bias auditing of transformerbased classification methods to ensure fairness and accuracy across diverse material datasets, and developing interdisciplinary capacitybuilding initiatives, including opensource toolkits and training workshops, to lower technical barriers for architectural teams. Furthermore, collaboration with policymakers and designers should establish ethical and governance frameworks that guide the responsible deployment of data-driven architectural systems in different sociocultural contexts of intelligent places. **Figure 7** summarizes the results of this research study.

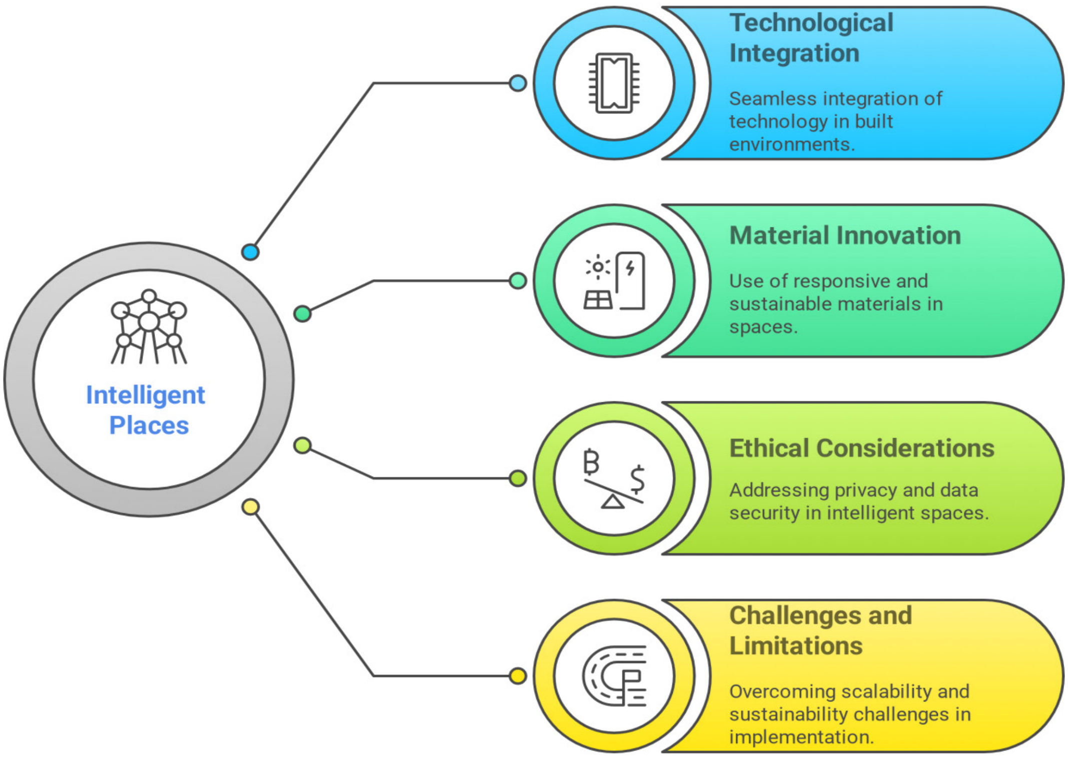

Figure 7. A holistic overview summarizes all the study findings, including the integration of technological objects and material innovations used in intelligent places, and highlights the ethical considerations and limitations of this study.
Source: Authors.

6. Key Innovations and Contributions

In this study, we reframe conventional smart-building paradigms by positioning material substrates as active agents within dynamic sociotechnical networks, thereby shifting the emphasis of design from mere automation to coevolving human–material ecosystems. We introduce a transformer-based AIassisted image-analysis method that automates smart-material identification in intelligent places with more than 90% accuracy and reduces the specification time from weeks to hours, significantly enabling rapid, data-driven specification of smart materials in early design stages and streamlining BIM workflows. Finally, we synthesize insights from cybernetics, placemaking theory, and materials science into a unified sociotechnical framework that explicitly links sensor feedback, material behavior, and user agency, offering architects a comprehensive conceptual toolkit for designing, evaluating, and iterating truly adaptive intelligent places.

7. Conclusion

The Spatially Intelligent Arts Centre and iPortals projects provide compelling evidence that technological objects are pivotal in transforming built environments into intelligent places. These intelligent places emerge as complex sociotechnical ecosystems where human and technological interactions are intricately intertwined. Integrating immersive and spatial technologies facilitates the creation of continuous real-time feedback loops, enhancing user engagement, spatial adaptability, and environmental responsiveness. This shift offers new paradigms for architectural design and the user experience, challenging traditional notions of static built environments.

Furthermore, another significant potential of these intelligent spaces lies in their material foundations. The transition to responsive and sustainable materials allows these environments not only to accommodate intelligent technologies but also to actively engage in their operation. When material intelligence is combined with digital intelligence, it fosters environments that are energy efficient, environmentally adaptive, and materially expressive.

The implications of this study are far-reaching, suggesting that the integration of advanced technologies in architecture can redefine the role of spaces in our daily lives. By fostering more interactive and adaptive environments, these technologies have the potential to revolutionize how we perceive and interact with built spaces, making them more responsive to human needs and behaviors.

This opens new avenues for architects to design environments that are not only functional but also dynamically engaging, pushing the boundaries of traditional architectural practice. However, moving from experimental projects to widespread real-world applications will require overcoming significant challenges, such as scaling these technologies to different types of built environments and ensuring their sustainability and usability over the long term.

In exploring the real-world application of these technologies, it is essential to consider the ethical implications of pervasive technological integration in built environments. Issues such as privacy, data security, and the potential for technological overreach must be critically examined. For example, while real-time data collection and adaptive responses can greatly enhance user experiences, they also raise concerns about how personal data is collected, stored, and used. Moreover, there is a risk that such technologies could be used in ways that prioritize efficiency over human-centered design, leading to environments that, while highly functional, may lack the qualities that make spaces truly meaningful and culturally rich.

This study pioneers a holistic sociotechnical framework that positions material substrates as active agents alongside immersive technologies and spatial sensors and introduces a transformer-based AI method for rapid, accurate smart-material classification that could streamline the design workflows of intelligent places.

However, this study has several limitations, as mentioned previously; notably, the limited generalizability arising from case-specific contexts and material systems underscores the need for broader validation. Future research should undertake cross-cultural ethnographic studies to understand diverse community perceptions and ensure equitable technology access, advance scalable AI-assisted material-analysis methods that safeguard fairness and anonymity, and create interdisciplinary training platforms and open-source toolkits to equip architects with the skills needed for seamless integration of intelligent-place technologies in various built contexts.

Author Contributions

Conceptualization, F.B.; methodology, A.C.; formal analysis, F.B.; data curation, A.C.; writing—original draft preparation, F.B.; writing—review and editing, A.C. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. Owing to privacy or ethical restrictions, certain data related to project evaluations and user interactions are not publicly available.

Acknowledgments

The authors would like to express their gratitude to the Housing and Environment Laboratory at Ferhat Abbas University for their academic support.

Conflicts of interest

The authors declare no conflict of interest.

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