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Ten questions concerning the future of intelligent buildings

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ABSTRACT

Buildings face growing pressure to reduce energy use and carbon emissions while maintaining healthy, resilient indoor environments. Conventional automation often optimises isolated functions and cannot coordinate environmental, operational, and occupant requirements across building systems and lifecycles. Intelligent buildings (IBs) can address these limitations through integrated sensing, analytics, adaptive controls, and responsive materials, but effective implementation remains essential. This paper examines how IBs address these pressures and identifies the conditions required for responsible building intelligence. The ten questions are organised into four thematic clusters covering foundations, technologies, performance, and ethical and social implications. The paper examines these questions across building information modelling and digital twins, ubiquitous technologies, smart materials, operational systems, grid flexibility, Industry 5.0, and data responsibility. The discussion demonstrates that these technologies can improve coordination, energy flexibility, maintenance, indoor environmental quality, and lifecycle decision-making. However, technology alone does not make a building intelligent or guarantee measurable environmental and human outcomes. Effective IBs require interoperable systems, reliable data, clear performance objectives, cybersecurity, maintainability, accountable governance, and meaningful occupant participation. Neighbourhood coordination is important because shared energy assets, local grid constraints, and environmental exposures cannot always be managed by individual dwellings. Accordingly, IBs should be assessed through measurable outcomes, including comfort, health, safety, energy flexibility, resilience, privacy, and long-term value. The resulting research agenda supports human-centred, low-carbon, grid-responsive, resilient, and ethically governed intelligent buildings.

1. Introduction

Buildings increasingly face changing climatic conditions, extreme weather, variable renewable generation, episodes of poor outdoor air quality, and shifting occupancy patterns [1,2]. These pressures alter heating and cooling loads, ventilation requirements, grid interactions, envelope performance, and the risks experienced by occupants [3,4]. Failure to adapt can increase energy use and emissions, weaken indoor environmental quality, strain energy networks, and expose occupants to unequal risks [5]. Conventional building automation often optimises predefined setpoints within isolated systems, limiting its ability to manage interacting and rapidly changing demands [6]. Intelligent buildings (IBs), in contrast, offer a more adaptive approach by integrating sensing, data analytics, and control systems to respond dynamically to changing environmental, energy, and occupant conditions. Yet, the challenge lies in how IBs respond to these changes and adapt

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building operations without compromising comfort, health, autonomy, or privacy [7].

The idea of IBs emerged in the early 1980s, initially centred on building management systems, centralized control, and energy-efficient operation [8,9]. Over time, the concept expanded with advances in information and communication technologies, sensing, automation, and digital platforms [10] and more recently with developments in artificial intelligence (AI) and digital twins [11–13]. These advances have extended the role of IBs beyond automated building operation towards broader goals related to energy and carbon performance, safety, occupant comfort, health, and well-being [14]. However, technological capability alone does not ensure that IBs can adapt effectively. Their performance also depends on how well different systems are integrated, maintained, and governed, as well as the occupants' acceptance and interaction with these systems [9]. The future of IBs therefore depends not only on what these technologies can do, but also on how effectively they can be integrated into buildings and accepted by the people who occupy them [15].

As IBs become more technologically sophisticated, understanding their environmental and social implications becomes increasingly important [16]. These implications cannot be considered independently of building context, as appropriate technology configurations vary with typology, occupancy, climate, lifecycle stage, operational capacity, and scale [17]. Different building types have distinct environmental priorities, privacy risks, operating schedules, and acceptable control strategies [6]. Residential settings make this particularly important, as intelligent technologies operate within people's everyday living spaces, where comfort, routines, privacy, and control are closely intertwined.

The performance of intelligent technologies is also shaped by the scale at which they operate. Component control, whole-building optimisation, neighbourhood coordination, and grid services involve different technical, information and governance arrangements [18]. Their effectiveness can also vary across building types, climates, operating contexts, meaning that evidence from one setting may not be directly applicable to another. Yet, available evidence is fragmented across technologies, disciplines, building types, lifecycle stages, and spatial scales [19,20]. The challenge, therefore, is not simply to determine whether intelligent technologies work, but to understand where, when, and under what conditions they deliver meaningful benefits.

This paper examines the future of IBs through ten questions that consider their technological development, performance, interaction with occupants, and wider environmental and social implications. The discussion centres on residential buildings, from detached and attached homes to multi-unit housing. Where relevant, it also considers how IBs interact with neighbourhoods and the wider energy grid. Particular attention is given to the issues that ultimately shape residential performance, including indoor environmental quality, energy and carbon performance, resilience, occupant control, privacy, and performance over the building lifecycle. Evidence from other building types is also drawn upon where it provides useful insights that can be applied to such IB settings.

The ten questions are organised to build the discussion, starting with what defines an IB and why it matters, before considering the technologies involved, their performance, interaction with occupants, and questions around governance and data responsibility. In doing so, the paper sets out a research agenda for the future development of IBs, with a particular emphasis on adaptability, evidence of performance, and responsible integration into people's everyday lives. The ten questions are discussed in Section 2, with the main conclusions and priorities for future research presented in Section 3.

2. Ten questions and answers concerning the future of IBs

Fig. 1 organises the ten questions into four thematic clusters. The first cluster defines the concept of IBs and distinguishes them from related concepts such as smart, green, sustainable, and high-performance buildings. The second cluster examines key technologies supporting IBs, including BIM, digital twins, ubiquitous information technologies, digital design and delivery processes, and smart materials. The third cluster focuses on building operation, renewable energy integration and grid flexibility, and the role of Industry 5.0 in supporting human-centred and resilient performance. The final cluster considers the ethical responsibilities associated with intelligence-gathering technologies, including surveillance, privacy, freedom, and professional accountability. Collectively, the four clusters examine the future of IBs from technological, operational, human, and ethical perspectives.

2.1. Question 1: what is an IB and how has its definition evolved?

The concept of an IB has been defined in different ways over time,

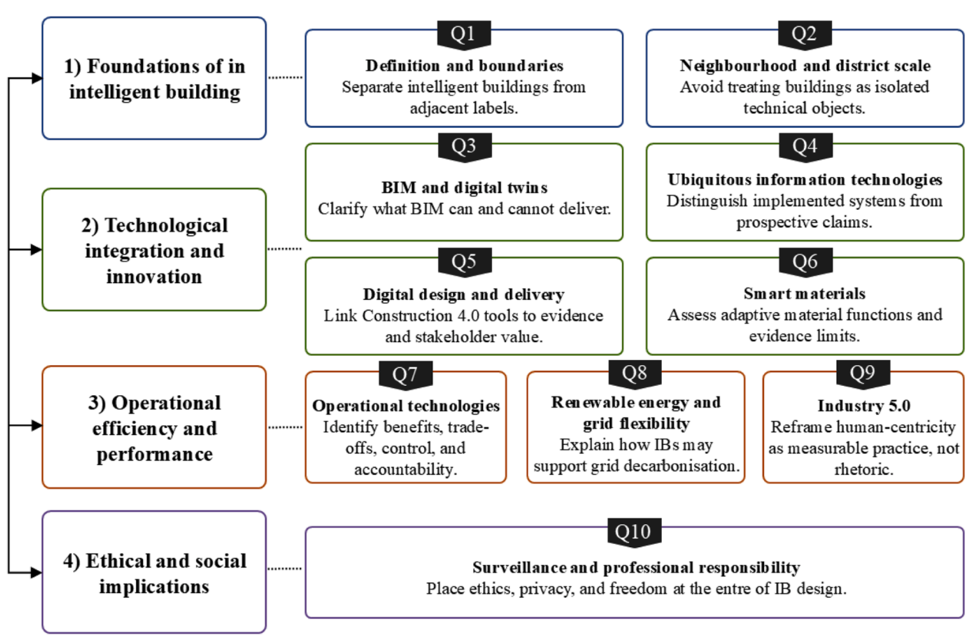

Fig. 1. Conceptual framework of the ten questions.

reflecting changes in technological, geographical, policy, and stakeholder priorities [21,22]. Some definitions emphasise automation and systems integration, whereas others prioritise resource efficiency, sustainability, adaptability, occupant well-being, or measurable performance [23,24]. These perspectives often overlap, with some terms used interchangeably in the literature. Fig. 2 presents the dominant emphasis of each era and the evolving definition of IBs.

1980s: techno-centric automation. Early definitions emerged from high-technology commercial buildings and associated intelligence with automated services, telecommunications, centralised management, and operating efficiency [8,25]. The building was treated mainly as a technical product. Occupants were largely recipients of centrally controlled conditions rather than active participants in building operation [10].

1990s: systems integration and responsiveness. During the 1990s, attention shifted from installed technologies toward coordinating building fabric, services, management, occupants, and organisational requirements [26]. Powell associated intelligence with environmental control, while Kroner developed the idea of responsive architecture [27]. Derek and Clements-Croome [28] connected intelligence with organisational performance, productivity, and the management of building resources. Arkin and Paciuk [29] treated systems integration as an assessable level of service rather than a binary technological attribute.

2000s: resource optimisation and performance assessment. Definitions became more performance-oriented and geographically differentiated during this period. The Asian perspective explicitly connected building intelligence with user requirements, environmental quality, building facilities, and long-term value [30]. The Intelligent Building Index subsequently translated these principles into a quantitative assessment method [31]. Wong, Li [10] found that definitions increasingly included learning, adjustment, and responsiveness to individual, organisational, and environmental requirements. Energy and resource efficiency therefore became explicit criteria for evaluating intelligence rather than assumed outcomes of automation [24].

2010s: smart-building convergence and sustainable urbanism. The terms "smart building" and "intelligent building" increasingly overlapped around IoT, interoperability, integrated design, adaptability, and predictive control. Buckman et al. distinguished smart buildings through integrated adaptability rather than simple technological reactivity [32]. Ghaffarianhoseini, Berardi [25] combined technological awareness with economic efficiency, social sensitivity, and environmental responsiveness. Sustainable urbanism also widened the unit of analysis beyond individual buildings to their relationships with energy, information, mobility, and community systems. However, the increasing number of technological and sustainability criteria did not produce a universally accepted definition [32].

2020s: measurable and human-centred intelligence. Current definitions increasingly describe intelligence as the capacity to sense, interpret, communicate, and respond to occupants, technical systems, external conditions, and energy grids [6]. The EU Smart Readiness Indicator measures energy performance, occupant responsiveness, and grid flexibility, making building intelligence more explicitly assessable [23]. ISO 37,173 provides guidance for smart-building information systems, while ISO 37,176 extends responsiveness assessment to community infrastructure [33]. These frameworks connect intelligence with information quality, interoperability, performance measurement, and interactions across spatial scales.

Human-building interaction research has added health, well-being, occupant agency, equity, privacy, and sustainability to contemporary interpretations of building intelligence [6]. Occupants are therefore treated as active participants whose needs, preferences, and actions influence building performance. However, recent professional evidence continues to show ambiguity between technological capability, sustainability, and responsiveness [22]. Technological sophistication alone therefore remains an inadequate basis for classifying a building as intelligent.

The historical divergence reflects changing purposes rather than a simple progression from incorrect to correct definitions. Automation remains necessary, but it is insufficient unless integrated systems produce verifiable environmental, operational, and human outcomes. Although IBs were historically associated mainly with large commercial buildings and centrally managed systems, the underlying concept is not limited to this typology. Here, residential buildings are treated as a specific application of the broader IB concept, with greater emphasis on occupant comfort, personalisation, and household-level interaction. An IB is defined here as an occupied dwelling or multi-unit housing system with integrated sensing, interoperable data, analytics, and adaptive control. These capabilities coordinate the envelope, building services, household appliances, distributed energy resources, and shared residential systems. The building interprets indoor, outdoor, resident, and

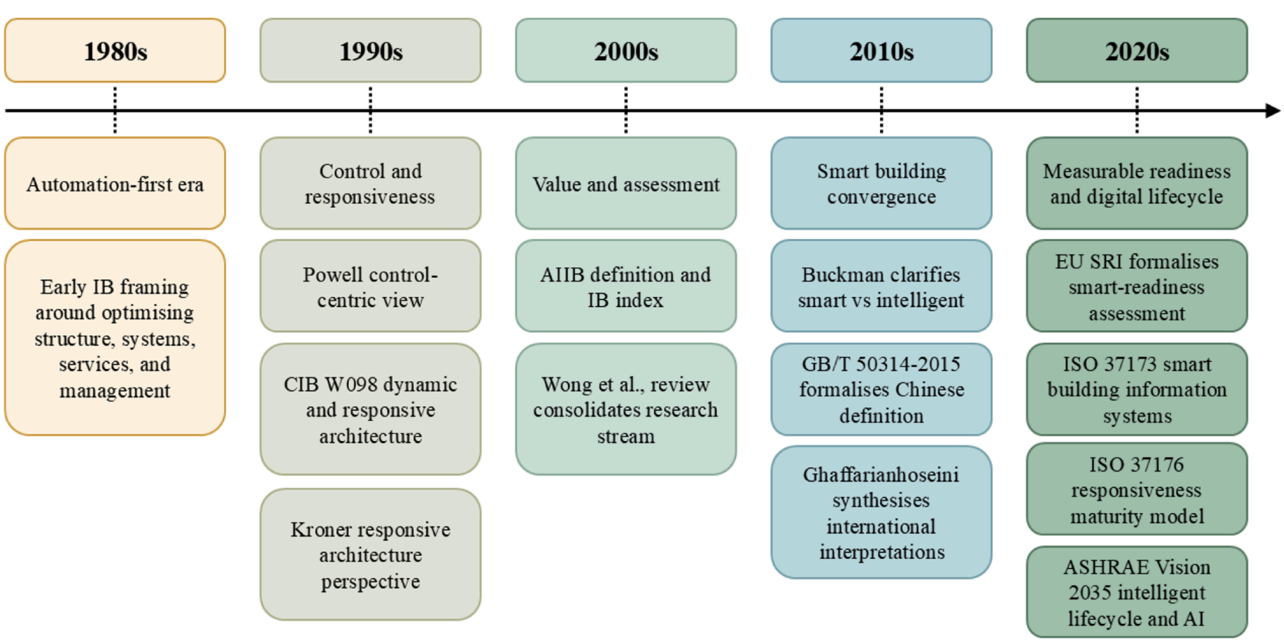

Fig. 2. Evolution of building-intelligence concepts, from automation-centred control to measurable, responsive, and lifecycle-oriented intelligence.

grid conditions and adapts its operation over time. Intelligence is demonstrated through measurable improvements in health, comfort, safety, energy and carbon performance, resilience, and lifecycle value, while preserving resident agency and privacy [6,34]. It is not determined by the number or novelty of installed technologies. This definition provides the conceptual basis for the remaining nine questions.

2.2. Question 2: why do we need to move towards IBs?

2.2.1. Neighbourhood-scale residential intelligence

The role of residential IBs increasingly extends beyond individual dwellings. Household energy demand, rooftop generation, shared storage, electric-vehicle charging, and outdoor environmental conditions can all involve neighbourhood infrastructure. Individual homes may optimise comfort and energy use, but they cannot independently coordinate shared network capacity or collective responses to disruption. This makes neighbourhood-scale intelligence increasingly relevant to the operation and performance of residential IBs [35,36]. At the neighbourhood scale, homes can connect with shared energy networks, mobility infrastructure, outdoor spaces, digital services, and community organisations. These connections can influence household energy costs, environmental quality, service availability, resilience, and residents' ability to make informed decisions.

2.2.2. Household outcomes, mobility, and health

The value of neighbourhood coordination should be judged through outcomes experienced by households. Coordinated residential systems may support local renewable-energy use, shared storage, air-quality information, emergency communication, and access to essential services. However, these services do not automatically improve residential well-being. Their benefits depend on affordability, accessibility, infrastructure quality, resident participation, and the distribution of costs and risks [37].

Residential transport electrification provides a direct example. Uncoordinated charging across many homes can create coincident demand and increase pressure on local electricity networks. Neighbourhood-scale charging management can coordinate household demand, network capacity, tariffs, and renewable availability [38]. The analysis should remain focused on household charging, shared residential parking, apartment charging, and local grid effects. Discussion of municipal fleets and public transport is outside the defined scope unless it demonstrably affects residential performance [39].

Health-related services also matter when they connect directly with the home. Remote assistance, telemedicine, environmental alerts, and emergency communication may help older residents, people with disabilities, and households exposed to disruption. These services make the dwelling part of a wider support network rather than an isolated technological unit. However, their effectiveness depends on reliable connectivity, accessible interfaces, consent, service capacity, and protection of sensitive household data [40].

2.2.3. Governance, privacy, cybersecurity, and social legitimacy

Neighbourhood coordination can aggregate energy, mobility, security, health, and behavioural data from multiple homes. Such integration can support shared services, but it can also increase surveillance, cybersecurity exposure, and uncertainty about data ownership. Top-down platforms controlled by governments, utilities, housing providers, or technology companies may leave residents with limited knowledge or control over how household data are used [41,42].

Governance must therefore specify who collects residential data, who can access them, how long they are retained, and who is responsible for failures. Residents, housing providers, property managers, utilities, service providers, and local authorities may have different interests and levels of authority. Neighbourhood intelligence should be developed through resident participation rather than imposed as a finished technological system [43,44].

2.2.4. Context-specific residential neighbourhoods

No universal smart-neighbourhood model will suit every residential setting. Detached homes, attached dwellings, apartment buildings, and multi-unit housing differ in ownership, shared infrastructure, maintenance capacity, resident control, and energy flexibility. Climate, tenure, income, digital access, and network reliability further influence which technologies are appropriate. Neighbourhood-scale intelligence should therefore remain adaptable and should be evaluated through measurable household outcomes rather than technological connectivity alone [45,46].

2.3. Question 3: what would be the significance of BIM in developing IBs over the next decade?

BIM can provide an important information foundation for IBs by organising geometric, material, system, and performance information across design, construction, handover, operation, and retrofit [47,48]. Digital twins can build on this information by connecting digital representations with operational data from occupied dwellings [49]. Together, they can support design coordination, performance simulation, commissioning, fault detection, maintenance planning, and lifecycle decisions [50].

The strongest residential use of BIM is as a shared information structure rather than a three-dimensional model. During design, BIM can support energy modelling, apartment-layout coordination, prefabrication, cost estimation, and communication with clients and prospective residents. At handover, structured asset information can help homeowners, housing providers, property managers, body corporate representatives, and maintenance contractors understand and maintain building systems. This continuity may reduce information loss between design, construction, occupation, and refurbishment [46].

However, these benefits are often not realised. Models may be developed for design coordination or regulatory compliance without being prepared for residential operation. Information may be incomplete, outdated, inaccessible to residents and property managers, or locked into proprietary platforms [51]. A residential information record requires defined ownership, maintenance responsibility, version control, cybersecurity, and accessible formats. Software alone cannot create a reliable information record across the housing lifecycle [52,53].

Digital twins face similar limitations. They can support residential decisions when sensors are reliable, models are calibrated, assumptions are validated, and outputs are linked to specific actions [54,55]. A visually detailed interface is not evidence of intelligence or improved residential performance [56]. Many digital-twin projects demonstrate technical feasibility without independently establishing long-term energy savings, improved comfort, affordability, resident acceptance, or resilience under system failure [57].

Residential research should therefore ask which information is needed for each decision and who is responsible for maintaining it. It should examine whether residents understand the system, whether tenants can access relevant information, and whether household data are collected proportionately. It should also determine how errors are detected and how residents can challenge decisions derived from digital models. BIM and digital twins can provide infrastructure for residential intelligence, but they do not constitute intelligence by themselves [19,58,59].

2.4. Question 4: how will ubiquitous information technologies influence IBs?

UIT as the embodiment of ubiquitous computing (ubicomp) refers here to the combined use of pervasive computing, ambient intelligence and IoT and related data services to monitor, analyse, and control buildings across locations. With most of UIT instances, computing, sensing, and network intelligence are woven invisibly into the physical environment so that IT capability becomes available everywhere, all the time, and without demanding explicit user attention. The value of UIT is that building information no longer needs to remain inside a plant room, a local workstation, or a single building management interface. It can be collected, processed, visualised, and acted upon across distributed systems [48]. As a result, UIT transforms building from a passive construct into a context-aware, self-adaptable environment that constantly responds to who are inside, what they are doing, what they desire, and how conditions are changing.

Applying UIT to IBs provides a new paradigm-based expectations beyond conventional "smart home" automation by supporting critical functions of ambient assisted living. Aging in place and seamless health monitoring is one of them. Ubiquitous sensing (embedded in floor, rooms, furniture) enables continuous, non-intrusive wellness/fall monitoring so that older adults can live independently longer. Silent and non-invasive energy, comfort, and indoor-air stewardship would be another function. Multi-sensor context awareness converges with building energy systems (i.e. HVAC, lighting) so the intelligent house optimizes energy use and indoor air quality in real time per detected occupancy load. Above all, occupant-centred calm interaction is the most critical aspect of an UIT based IBs. In this regard, provision of automation is to be proactive and invisible so that the occupant is never required to control a device. User experience could be enhanced to context-aware personalization rather than mere device management. As a summary, UIT could migrate towards "intelligent building" from plain device automation to environment-level intelligence that has the knowledge on the current context and the delegated authority to take decisions on behalf of the occupant.

For instance, in a dwelling or apartment building, information can be processed through local controllers, shared-building gateways, cloud services, or resident interfaces. Residents, housing providers, property managers, and service contractors can then receive alerts and interact with residential systems.

Several UIT components are already in use. IoT enabled ambient sensors can measure temperature, humidity, carbon dioxide, particulate matter, occupancy, illuminance, energy use, equipment status, and security events [59,60]. Cloud platforms can store and process large datasets and allow remote access, while edge computing can support lower-latency and more distributed decision-making close to the data source [47]. As a recently emerged technology, Digital twins can link operational data with digital representations of physical assets. Mobile interfaces and diversified Human Machine Interfaces (HMI) could allow facility managers, occupants, or service providers to receive alerts and interact with building systems. These technologies are no longer purely speculative, although their maturity varies by application and market Stopps and Touchie [61].

Independent residential field studies provide stronger evidence than vendor demonstrations. Stopps and Touchie [61] tested connected thermostat strategies in 49 suites across two high-rise residential buildings, occupancy-responsive thermostat control, and load shifting. The study found an average cooling-season HVAC runtime reduction of about 5.9%, although variability between suites was very large, and the load-shifting strategy did not consistently reduce aggregate peak-period HVAC demand. The load-shifting strategy did not consistently reduce aggregate peak demand [62–64]. Jiang, Andrew Ejenakevwe [65] implemented model-predictive precooling through smart thermostats in residential buildings, linking field measurements, predictive models, and automated HVAC control. These studies demonstrate technical feasibility while showing that outcomes depend on dwelling characteristics, climate, control settings, system integration, and occupant responses.

Low-power wide-area network technologies, including LoRaWAN, can connect distributed residential sensors over relatively long distances while limiting device energy use. Their suitability depends on transmission range, data rate, interference, battery life, network density, and required response time [66]. These examples should be treated carefully. They show that implementation is technically possible, but they do not always provide independent evidence of energy savings, improved comfort, better maintenance outcomes, or social acceptance. Vendor case studies are useful for understanding capabilities, but they should not be confused with third-party evaluation [67].

UIT can support IBs in at least four ways. First, it can improve visibility by making building conditions and faults easier to detect [68,69]. Second, it can improve responsiveness by linking data to control actions. Third, it can support remote and portfolio-level management through cloud-based data access and distributed analytics. Fourth, it can enable feedback loops between design assumptions and real operational performance through BIM–IoT integration and digital-twin workflows. These benefits depend on data quality, sensor calibration, cybersecurity, interoperability, semantic consistency, and organisational capacity to respond [19,58].

Multiple instances of UIT associated residential building prototypes have been introduced world-wide. “TRON Intelligence House” in Tokyo tried to integrate computers, sensors and actuators and intuitive Human -Machine Interfaces into a demonstrative house environment. “Aware Home” at Georgia Tech demonstrated instrumented residential testbed studying ambient sensing, activity recognition, and digital technologies for aging-in-place. As a part of MIT House_n project associated living lab construction and operation effort, “Place Lab” explored privacy sensitive ambient monitoring of residents with ubiquitous computing devices and interpretation techniques in which experiment participating residents wear body-state sensors while the environmental layer tracks real-time activity and context through the monitored datasets which were widely used for activity recognition. Fig. 3 shows an example of a residential IB, where interactive built-in components are integrated with smart appliances for coordinated and customized services for the residents.

Steeply emerged advancement of delicate IoT devices as well as noticeable innovations in information processing by exponentially enhanced AI capability, UIT-based IB implementation becomes highly instrumented, recently. Nevertheless, major risks are also being recognized due to its intensive data and network dependency. Data management considering validity, privacy, security as well as processing efficiency is, therefore, the key for minimizing potential risks. The main risk is that monitoring becomes an end in itself. More sensors do not automatically produce better buildings. Data must be connected to decisions, responsibilities, and outcomes. Future research should therefore ask not only whether UIT can collect data, but whether the data are accurate enough, interpreted correctly, acted upon responsibly, protected securely, and evaluated independently [70,71].

2.5. Question 5: how will emerging digital technologies impact the design and delivery of IBs?

Digital technologies are changing how homes are designed, constructed, handed over, operated and refurbished. Construction 4.0 brings together technologies and processes such as BIM, IoT, cloud computing, simulation, automation, offsite manufacturing, data analytics, and cybersecurity within connected delivery processes [72,73]. In residential projects, these technologies can support performance modelling, coordination of prefabricated components, construction-quality monitoring, cost control, and structured information transfer [74]. Ultimately, their value should be reflected in housing quality and occupied performance, not simply in more efficient construction.

Visualisation and analytical technologies can improve residential decision-making before construction. BIM, VR, and AR can help clients and prospective residents examine layouts, accessibility, daylight, environmental conditions, and proposed control interfaces [75,76]. AI and optimisation can compare alternatives involving energy demand, comfort, cost, maintainability, and material use [77,78]. These applications are useful when they reveal trade-offs and allow affected users to influence decisions. They are less valuable when they merely make

Fig. 3. Example of an IB where interactive and customizable built-in components (lighting, tabletops) are integrated with smart appliances (refrigerator, cooking oven).

predetermined proposals appear more persuasive.

Digital delivery also affects what residents, and housing managers receive at handover. Asset records, operating instructions, control settings, warranties, and maintenance information should remain usable after contractors and designers leave the project. Distributed ledgers have been proposed for product traceability, procurement, payment, and asset-information management [79,80]. However, technical traceability does not guarantee understandable information, fair contracts, or accountable decisions.

Emerging technologies should therefore be evaluated through a residential value test. The relevant questions are whether they reduce the difference between predicted and occupied performance, improve construction quality, support resident understanding, simplify maintenance, and protect household data. A technology should not be considered transformative if it only accelerates fragmented design and construction practices [36,81].

2.6. Question 6: how do smart materials support IBs?

Smart materials can support IBs by giving envelopes, surfaces, and structural components adaptive, responsive, or sensing capabilities. Unlike conventional materials, smart materials can change their properties or generate useful information in response to external stimuli such as temperature, light, moisture, stress, pressure, electricity, or chemical exposure [82–84]. Their significance lies in making intelligence partly material, rather than only digital. In this sense, smart materials can complement sensors, controls, BIM, digital twins, and building management systems by enabling the building envelope, structure, and surfaces to participate directly in performance regulation [85,86].

Energy efficiency is one of the most important areas in which smart materials can contribute to IBs. Thermochromic, photochromic, and electrochromic materials can modify their optical or thermal behaviour in response to temperature, sunlight, or electrical signals, helping to manage solar heat gains, daylight availability, glare, and cooling demand [87,88]. For example, smart glazing can reduce unwanted solar gains in warm conditions while supporting daylight access and visual comfort [89]. However, its real energy benefit depends on climate, orientation, baseline glazing, control strategy, occupant behaviour, and integration with HVAC systems. Therefore, smart windows and adaptive façades should not be evaluated as isolated products, but as components of a whole-building environmental control strategy [90,91].

Embedded materials and sensors may also support structural and envelope monitoring in apartment buildings and other multi-unit housing. Piezoelectric materials, fibre-optic sensors, and related systems can detect stress, strain, vibration, deformation, or damage [92,93]. However, much of the available evidence comes from bridges, long-span structures, and critical infrastructure rather than occupied homes. These findings should not be transferred directly to residential buildings. Residential studies must show whether such systems improve detection of structural movement, façade deterioration, moisture-related deformation, or damage under realistic maintenance conditions. Their value depends on durability, calibration, replacement access, interpretation, and clear responsibility for responding to warnings [82,83,94].

Adaptive building components provide another important application. Shape-memory alloys, shape-memory polymers, and related responsive systems can change form or mechanical behaviour when exposed to environmental triggers [85,95]. These materials can be used in dynamic façades, shading systems, vents, or responsive envelope components that adjust to solar position, temperature, wind, or resident preferences and household requirements. In principle, such systems can improve comfort while reducing operational energy demand. In practice, their performance depends on robustness, control logic, maintenance requirements, cost, and user acceptance. A dynamic façade that is poorly controlled may increase complexity without improving comfort or energy performance [96].

Smart materials can also contribute to sustainability and indoor environmental quality. Photocatalytic and self-cleaning coatings, particularly titanium-dioxide-based systems, can help reduce surface soiling and decompose some pollutants under suitable light conditions [97]. These materials may reduce cleaning effort and maintenance demand, particularly on apartment façades and difficult-to-access multi-unit housing surfaces. However, their effectiveness depends on exposure conditions, pollutant type, light availability, surface ageing, and maintenance context [98,99]. Similarly, hygroscopic materials can buffer moisture by absorbing and desorbing water vapour, helping to moderate indoor humidity fluctuations. This can support comfort and reduce short-term humidity peaks, but it should not be treated as a substitute for ventilation, moisture source control, insulation, drainage, or good building maintenance [92,93,100].

This distinction is important because smart materials are often described as if their benefits are automatic. They are not. A smart coating may work well in one environmental context but provide limited benefit in another. Moisture-buffering materials may help regulate humidity but cannot solve persistent dampness or mould risks alone. Embedded sensors can improve safety but also raise questions about data ownership, replacement, interoperability, and long-term reliability. Smart materials should therefore be assessed as part of integrated building systems, not as standalone technological innovations [48,101].

The strongest residential contribution of smart materials may lie in passive adaptation, moisture management, responsive glazing, fault detection, and reduced maintenance demand. The main research need is not simply to develop new materials. These materials must be tested in occupied homes under realistic climate, use, maintenance, ageing, and failure conditions. Studies should compare them with conventional alternatives using energy, comfort, durability, health, maintenance, life-cycle cost, and environmental indicators.

2.7. Question 7: what are the key technologies enabling the operation of IBs?

The operation of residential IBs depends on several interconnected technologies and systems. These can be grouped into six functions: home sensing and automation, residential energy management, data analytics, interoperability, safety and security, and resident interaction. Fig. 4 summarises these functions. The effectiveness of these technologies also depends on reliable data, maintainability, cybersecurity, understandable controls, and their practical use by residents and housing providers [24,102].

Home sensing and automation: Smart thermostats, indoor environmental sensors, smart meters, appliance controls, lighting controls, and resident interfaces provide the operational foundation of intelligent homes. These technologies can monitor temperature, humidity, air quality, occupancy, energy use, and equipment condition [103,104]. In multi-unit housing, dwelling-level systems may also interact with shared ventilation, heating, energy, and access systems. Automation creates value only when controls are understandable and residents retain appropriate authority over conditions inside their homes [1,105].

Residential energy management: Smart meters, heat pumps, domestic hot-water systems, photovoltaic generation, batteries, and electric-vehicle charging can coordinate household demand with energy prices, renewable availability, and grid conditions. These systems may reduce peaks or shift demand, but their performance depends on climate, dwelling characteristics, tariffs, equipment capacity, and household routines [106]. Demand flexibility should not reduce comfort or transfer costs and risks to households with limited ability to respond [47,75].

Data analytics and decision-making: Analytics can forecast household energy demand, identify equipment faults, detect unusual consumption, and support predictive control. Digital twins and BIM-IoT integration can connect operational data with information about residential systems and components [53]. However, household data may reveal occupancy, routines, health conditions, and appliance use. Analytics should therefore be evaluated through measurable outcomes, data minimisation, interpretability, and accountable decision-making [48,66,107,108].

Connectivity and interoperability: Residential technologies require communication protocols, shared data structures, and grid interfaces to connect devices that would otherwise operate independently. Interoperability is particularly important when dwelling-level controls interact with shared systems in apartment buildings or community-energy networks. A home containing many connected devices is not intelligent if those devices cannot exchange reliable information or continue operating when a proprietary platform fails [109,110].

Safety, security, and privacy: Connected alarms, leak detection, access controls, security cameras, and video doorbells may improve household safety and emergency awareness. They also create risks involving surveillance, cybersecurity, consent, and observation of neighbours and passers-by [6]. Security should therefore include physical protection, cyber-physical resilience, privacy safeguards, and clear responsibility for data access.

Resident interaction and control: Dashboards, mobile applications, local controls, alerts, and feedback systems determine how residents experience building intelligence. Interfaces should explain automated actions, provide accessible choices, and allow residents to override decisions within safe operating limits. Housing providers may require aggregated information for maintenance, while residents require control over their dwelling and protection against unnecessary monitoring. A residential building cannot be considered intelligent when its systems

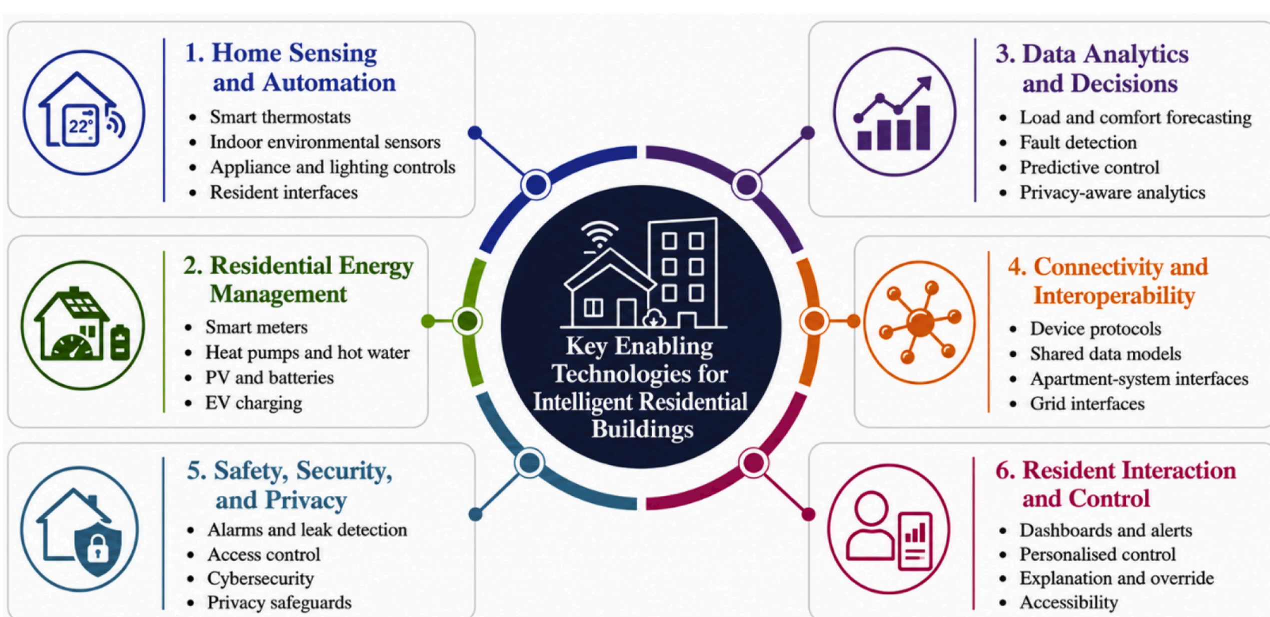

Fig. 4. Key enabling technologies for IBs.

are intrusive, difficult to understand, or unresponsive to household needs [111].

2.8. Question 8: how can IBs enable the inclusion of renewable energy on the grid?

As electricity systems decarbonise, buildings become more important to grid operation. Electrification of heating, cooling, domestic hot water, transport, and appliances can reduce direct fossil-fuel use in buildings, but it can also increase electricity demand and peak loads. At the same time, solar and wind generation are variable. Many grids already operate with substantial renewable generation, but higher shares increase the need for flexibility in demand, storage, and control [112]. IBs can contribute to this flexibility because many building loads can be shifted in time. Residential HVAC systems can pre-cool dwellings within acceptable comfort limits. These strategies use the thermal inertia of the building as short-term energy storage, shifting electricity demand away from peak periods [113]. Their effectiveness depends on climate, envelope performance, tariff structure, control strategy, and occupant comfort requirements [114,115]. Batteries can shift electricity use across time, while photovoltaic systems can reduce grid demand during periods of solar generation. Electric vehicles can act as flexible loads and, where vehicle-to-grid systems are available, potential distributed storage. Heat pumps can be operated in ways that respond to prices, emissions signals, or grid constraints [116,117]

However, the contribution of IBs should not be overstated without local evidence. The amount of flexibility available depends on building thermal characteristics, climate, occupancy schedules, comfort requirements, equipment capacity, control algorithms, electricity tariffs, emissions factors, and occupant acceptance [116,118]. A result from one housing type and climate may not apply to other residential contexts. Similarly, pre-cooling may be useful in some cases but unacceptable where it causes discomfort or shifts emissions to dirtier generation periods [119,120]. The strongest role for residential IBs is not simply to consume less electricity. It is to consume electricity at better times, within clear comfort, health, and operational constraints. This requires buildings to respond not only to price signals, but also to carbon signals, grid conditions, and indoor environmental quality. It also requires safeguards so that demand response does not become a hidden reduction in occupant comfort or a burden shifted to vulnerable groups [116,118]. Fig. 5 illustrates the interactions between the home, neighbourhood, and grid, alongside residential demand flexibility and community energy sources.

At a wider system level, residential IBs can increasingly operate as multi-vector energy hubs rather than as collections of independently controlled technologies. Electricity from on-site PV can be coordinated with batteries, electric vehicles, heat pumps and, at district scale, hydrogen production and storage to balance generation and demand across different timescales [121]. Batteries are particularly suited to short-term balancing, whereas hydrogen-based storage can provide longer-duration flexibility when renewable generation and demand are temporally mismatched. Recent optimisation studies of residential energy hubs show that coordinating these technologies can increase local renewable utilisation, energy autonomy and emissions mitigation while reducing uncontrolled grid exchange [122]. However, the optimal configuration depends on trade-offs between storage capacity, renewable penetration, grid interaction, life-cycle cost and future climate and demand conditions. IB control therefore increasingly involves deciding not only when energy should be consumed, but also when it should be generated, stored, converted, exported or recovered across different energy vectors [123].

The boundary of IBs energy management is also expanding beyond the building itself. In particular, EVs can be integrated with building energy systems so that EV charging is coordinated with on-site PV generation, battery storage, electricity tariffs, and grid conditions. Rather than acting as an uncontrolled additional load, EVs can therefore provide schedulable demand and, where bidirectional charging is available, potentially contribute storage capacity. Recent studies have extended this concept from individual PV–battery residential buildings to multi-vector urban energy districts in which building loads, EV demand, renewable generation, batteries, and hydrogen storage are jointly optimised [124]. Such integration can increase renewable self-consumption and improve peak management, although its effectiveness depends on mobility patterns, charging availability, infrastructure, and control objectives [125].

2.9. Question 9: how can industry 5.0 assist the future of IBs?

Industry 5.0 builds on Industry 4.0 by bringing greater attention to human-centredness, sustainability, and resilience alongside technological development [126–128]. Applied to IBs, these principles challenge the assumption that greater automation necessarily produces better homes. Reviews show that smart-home research has often prioritised technological performance over resident experience. Evidence for aggregate household energy savings also remains uncertain and sensitive to rebound effects [129]. Residential intelligence should therefore

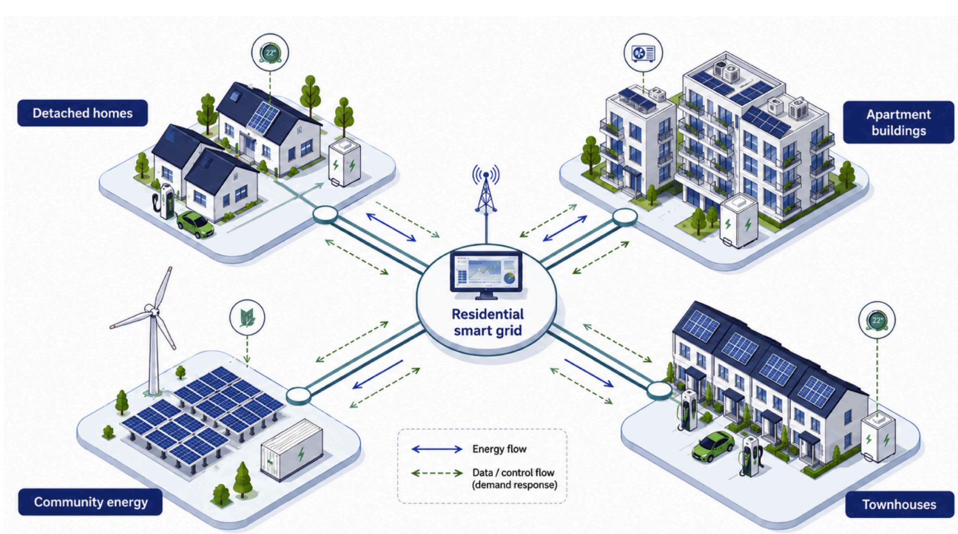

Fig. 5. Residential smart-grid coordination across housing types and community energy systems. Solid blue arrows represent bidirectional energy flows, while dashed green arrows represent data and control signals supporting demand response.

be assessed through observed effects on comfort, health, autonomy, accessibility, privacy, affordability, trust, and participation [130].

A human-centred approach must recognise the different needs of residents, housing providers, property managers, service providers, and other stakeholders. Research on smart residential environments, public housing, ageing in place, and disability shows that needs and risks vary substantially across these groups [131]. They do not have equal decision-making authority, technical knowledge, or capacity to bear financial and privacy risks [132]. Technologies should therefore be selected and governed around the needs and rights of people affected by automated decisions, rather than around data availability or technical feasibility alone [133].

Sustainability and resilience require a broader evaluation of connected residential systems. Smart-home technologies can support household energy management and carbon reduction, but these outcomes vary with adoption levels and occupant practices [134]. Their benefits must be verified in occupied homes and assessed against rebound effects, cybersecurity risks, software obsolescence, maintenance burdens, and limited repairability [135]. Systems should remain adaptable and usable during power, network, or service disruptions. Residents require intelligible interfaces, effective manual controls, and clear procedures for questioning or overriding automated decisions. A system that performs efficiently under normal conditions but loses essential functions during disruption does not satisfy the resilience principle [133].

Industry 5.0 remains largely aspirational unless its principles change what researchers and practitioners measure. Describing a system as human-centred does not demonstrate that residents retain meaningful control. Likewise, the technical capacity to reduce energy use does not establish sustained environmental performance under occupied conditions [136]. Evaluation should therefore cover occupied performance, resident acceptance, the distribution of costs and benefits, cybersecurity, maintenance, accessibility, and unintended consequences [137].

Data governance is another condition for human-centred and resilient IBs. Connected residential systems generate and exchange substantial amounts of operational and occupant data, making data availability, integrity, ownership, privacy, and cybersecurity central design issues. Distributed technologies such as blockchain have been proposed for IoT-enabled building and smart-grid applications because they can provide traceable and tamper-resistant records of energy transactions and support decentralised energy exchange without relying entirely on a single intermediary. However, their value depends on appropriate governance, interoperability, regulation, and stakeholder participation; blockchain does not itself resolve poor data quality, privacy concerns, or inappropriate data collection [138]. Fig. 6 links Industry 5.0 principles with governance, residential technologies, household applications, measurable outcomes, and evaluation. It does not predict that these outcomes will occur. Instead, it identifies the conditions and evidence required before an IB can be described as human-centred, sustainable, or resilient.

2.10. Question 10: IBs and data collection: what are the responsibilities of designers?

IBs collect data through smart meters, thermostats, environmental sensors, appliances, access systems, video doorbells, and shared-building platforms. These data can support comfort, safety, maintenance, and energy flexibility, but they can also reveal occupancy, routines, health conditions, relationships, and appliance use. The central ethical issue is whether collection is necessary, proportionate, transparent, secure, and contestable, not merely whether it is technically possible. Designers share these responsibilities with residents, housing providers, property managers, technology vendors, utilities, and service contractors.

In 1785, Jeremy Bentham set out the principles underpinning his Panopticon Building. There he sought to describe how 'intelligence' gathering could be incorporated into the design of a building through manipulation of the geometry of its plan form and section [139]. A watcher, placed at the centre of its radial layout could directly and constantly observe the behaviour of its occupants throughout the whole building. The idea of constant, overbearing surveillance is certainly unsettling, but the panopticon and its central inspection principle would, Bentham argued, have multifarious benefits:

> *Morals reformed-health preserved-industry invigorated-instruction diffused-public burthens lightened-Economy seated, as it were, upon a rock-the gordian knot of the Poor-Laws not cut but untied-all by a simple idea in Architecture!* [140].

For the next two hundred years, manipulation of architectural form remained a major means of intelligence gathering in buildings. Then, in the 1970s, with the rise of micro-electronics, a new and powerful technology became available - BMS. These were originally introduced to take control over energy consumption away from individual occupants and place it centrally in the hands of building managers [141]. Today BMSs are sold as integrated platforms for automating and streamlining a vast array of building operations, allowing control of a building's whole

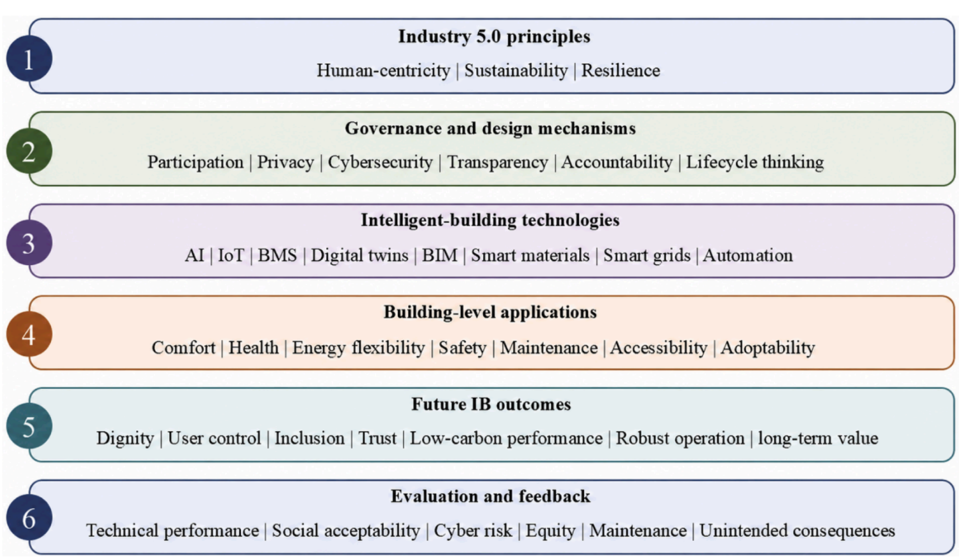

Fig. 6. Industry 5.0 framework for the future of IBs.

infrastructure from one point [142]. Now, when aligned with the IoT, they can be used to store, share and analyse data collected by myriad widely distributed devices [143,144].

Residential surveillance can extend beyond the dwelling through connected video doorbells and neighbourhood platforms that record visitors, neighbours, and passers-by. Research on Ring's Neighbours platform shows how privately owned cameras can form wider participatory surveillance networks [109]. When video systems incorporate facial recognition, they can also support persistent identification and tracking, raising concerns about privacy, discrimination, consent, and public legitimacy [145]. These developments raise ethical dilemmas for building and urban designers. What role, if any, can and should they play in increasing the penetration and span of surveillance technologies while maintaining the integrity and privacy of people's everyday lives and protecting them from online hackers? The increasing spread of BIM models and the arrival of building and city digital twins may simply increase pressures on built environment practitioners, especially in an era of calls for a new, more socially engaged, professionalism. Or has our heedless addition of digital services to the architecture of surveillance already delivered us into Bentham's dream of being inescapably watched?

These principles are derived from established ethical and legal frameworks rather than proposed independently. UNESCO grounds responsible AI in human rights, proportionality, privacy, fairness, transparency, human oversight, accountability, sustainability, and inclusive participation [146]. The GDPR provides more specific requirements for purpose limitation, lawful processing, data minimisation, and data protection by design [147]. Recent architecture-specific research similarly identifies privacy, bias, transparency, accountability, professional integrity, and environmental effects as central concerns when AI enters design practice Winner [148].

On this basis, ethical governance of data-intensive and AI-enabled IBs can be organised around eight principles. First, purpose limitation: household data should be collected only for explicit and legitimate purposes. Second, proportionality: intrusive monitoring should not be used when a less intrusive method can provide the required function. Third, transparency: residents should know what data are collected, how they are analysed, who can access them, and how long they are retained. Fourth, consent and legitimate authority: data collection and automated use require a lawful basis and must recognise unequal control among affected parties. Fifth, data minimisation: systems should collect and retain only the information required for the stated purpose. Sixth, human oversight and contestability: residents should be able to understand, challenge, and override consequential automated decisions where this is safe and practicable. Seventh, equity and accessibility: benefits, burdens, and failure risks should be assessed across tenure, age, disability, digital capability, and household circumstances. Eighth, accountability: named organisations and professionals must remain responsible for failures, misuse, cybersecurity, maintenance, data sharing, and long-term governance.

These principles are necessary but insufficient. Their effectiveness depends on enforceable procurement requirements, privacy-protective technical defaults, independent audits, resident participation, accessible redress, and named accountability. warned that information technologies can strengthen actors who already hold institutional and economic power. In residential settings, this risk arises when landlords, platform providers, utilities, or housing managers control data and automated decisions while residents cannot refuse, inspect, or challenge them. Ethical performance should therefore be assessed through the actual distribution of control, benefits, and risks rather than the presence of a published framework.

3. Conclusions and future research directions

In this paper, we discussed the evolution of IBs, with particular attention to the residential sector. It was inferred that the roles of automation, and subsequently digitalisation, were substantial in defining the primary identity of IBs towards creating increasingly intelligent and responsive environments. Today, in an era of rapid AI emergence, this evolution is increasingly moving towards buildings that go beyond automating predefined functions. IBs are becoming intertwined with new capabilities to learn from diverse data, optimise performance in real time, monitor and respond to end-user needs and environmental conditions, and adapt their operation to changing requirements. AI's growing potential across the building lifecycle, from the conceptual design stage to design optimisation and, particularly, at the operational level, through energy management, predictive maintenance, occupant monitoring, and real-time environmental control, is evident and deserves greater attention from researchers. But more importantly, the future role of AI-enabled IBs, especially in residential buildings, remains difficult to predict. As AI-led technological initiatives, new patterns of living, more pressing environmental challenges, and societal expectations continue to change, designing spaces around fixed technologies, with limited adaptability and flexibility, may eventually limit their capacity to remain truly intelligent.

Together, the ten questions show that residential intelligence extends beyond the presence of connected technologies and should ultimately be judged by demonstrated outcomes in real residential settings. Across these questions, sensing and adaptation are considered alongside health, comfort, resident agency, environmental performance, resilience, and lifecycle value. This shifts attention to who benefits, under what residential conditions, and with what risks.

This paper provides a residential-focused definition of building intelligence and uses the ten questions to connect technological capabilities with outcomes in occupied homes. It also highlights housing type, climate, tenure, household characteristics, system maturity, and study duration as important factors when evaluating these outcomes. Together, these contributions help distinguish technological capability from demonstrated performance in different residential contexts.

The discussion also shows that IBs are not inherently socially beneficial. They may support healthier, lower-carbon, and more resilient homes, but they can also concentrate control, weaken privacy, and distribute costs and risks unequally. These outcomes depend on who controls the technologies and data, who participates in decisions, and how much control residents retain over their homes. Without enforceable safeguards and meaningful resident participation, residential intelligence may reinforce inequalities and weaken democratic control over housing decisions.

Human-centred residential intelligence can improve indoor environmental quality, comfort, accessibility, safety, and trust when systems respond to diverse household needs. Energy performance may also improve when residents understand automated decisions, retain meaningful control, and establish acceptable limits for demand flexibility. Opaque or over-automated systems can instead reduce agency, create discomfort, and encourage residents to bypass controls. These effects require longitudinal evaluation in occupied homes.

IoT provides an operational foundation by connecting sensors, controls, appliances, energy assets, maintenance information, and resident feedback. In homes, these technologies may support personalised comfort, fault detection, energy management, demand response, safety, and security. They also collect behavioural data and create privacy, cybersecurity, interoperability, and governance risks. More connected devices should not be interpreted as greater intelligence unless their sustained benefits exceed their financial, environmental, and social costs.

Neighbourhood coordination is relevant when shared energy, mobility, health, emergency, or resilience systems alter dwelling performance and household experience. Such coordination can redistribute costs, comfort, privacy loss, and operational risks among households, housing providers, utilities, and public authorities. Research must identify who receives the benefits, who bears the burdens, and how residents can contest decisions affecting their homes. Participatory governance and privacy-preserving system design are therefore necessary at both dwelling and neighbourhood scales.

Despite of all potentially critical risks and challenges, IB emerged as a new breed among all constructed artifacts, could be evolved into an autonomous "robot to live in" with which ambient multi-modal sensing, AI enabled context awareness and customized and yet optimized action planning as well as delicately tunned actuation to satisfy multi-dimensional criteria would demonstrate a visionary anthropogenic form of habitat based on highly selected and coordinated information and materials(bits & atoms) in the way that has never been realized in the past. As a matter of fact, we are now witnessing its evolutionary path accelerated especially by the combination of IoT and AI that could lead us to a house similar to a self-aware living creature for us to live in.

Future IBs should also avoid equating intelligence with technological standardisation. The increasing use of globally available digital platforms, sensors, automation systems, and algorithmic control could encourage similar technological solutions across very different climatic, cultural, and architectural contexts. Building intelligence should therefore integrate digital capabilities with climate-responsive design, passive strategies, local materials, cultural expectations, and established architectural knowledge. Digital intelligence should complement rather than replace architectural intelligence. Future research should examine how advanced building technologies can be adapted to local conditions while preserving architectural diversity, cultural identity, and place-specific responses instead of producing increasingly uniform buildings across different regions.

Future research should prioritise longitudinal studies in occupied detached homes, attached dwellings, apartments, and multi-unit housing. Comparisons should account for climate, tenure, household characteristics, system maturity, and study duration. Evaluations should combine energy, carbon, resilience, and lifecycle indicators with comfort, health, autonomy, accessibility, privacy, trust, and distributive equity. An IB should be considered intelligent only when its connected systems produce verifiable, inclusive, and durable benefits while preserving meaningful resident control.

Future IBs should also prioritise adaptability, not only through flexible spaces or infrastructure, but, more importantly, through intelligent systems capable of rapidly and consciously evolving with their occupants and emerging technologies. Thus, IBs of the future may be defined less by the embedded technologies with which they are incorporated today, and considerably more by their overall capacity to adapt to what comes next.

CRediT authorship contribution statement

Amirhosein Ghaffarianhoseini: Conceptualization, Project administration, Investigation, Validation, Writing – original draft, Methodology. **Hossein Omrany:** Writing – original draft, Methodology, Investigation, Conceptualization, Writing – review & editing. **Ali Ghaffarianhoseini:** Supervision, Investigation, Conceptualization, Writing – original draft, Writing – review & editing. **Ian Cooper:** Writing – review & editing, Supervision, Investigation, Conceptualization, Writing – original draft. **Abdollah Baghaei Daemei:** Visualization, Resources, Methodology, Investigation, Writing – review & editing. **Farzad Rahimian:** Supervision, Investigation, Conceptualization, Writing – original draft. **Seongju Chang:** Writing – review & editing, Methodology, Investigation, Conceptualization, Writing – original draft. **Kody Merlin Powell:** Supervision, Investigation, Conceptualization, Writing – original draft. **Hind Bril El Haouzi:** Methodology, Conceptualization, Writing – original draft. **Husam AlWaer:** Methodology, Conceptualization, Writing – original draft. **Umberto Berardi:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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