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Systematic Review

Smart Adaptive Homes and Their Potential to Improve Space Efficiency and Personalisation

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Abstract: Over the last decades, population growth in urban areas and the subsequent rise in demand for housing have resulted in significant space and housing shortages. This paper investigates the influence of smart technologies on small urban dwellings to make them flexible, adaptive and personalised. The study builds on the hypothesis that adaptive homes and smart technology could increase efficiency and space usage up to two to three times compared to a conventional apartment. The present study encompasses a comprehensive semi-systematic literature review that includes several case studies of smart adaptive homes demonstrating various strategies that can be employed to enhance the functionality of small spaces while reducing the physical and psychological limitations associated with them. These strategies involve incorporating time-dependent functions and furniture, as well as division elements that can adapt to the changing needs of users in real-time. This review further categorises types of flexibility and adaptation regarding the size of the moving elements, the time that the transformation takes and whether it is performed manually (by a human) or automatically (by a machine). Results show that smart and adaptive technology can increase space efficiency by reducing the need for separate physical spaces for different activities. Smart technology substantially increases the versatility and multifunctionality of a room in all three dimensions and allows for adaptation and customisation for a variety of users.

Keywords: adaptive homes; efficient spaces; flexibility; home automation; interactive architecture; micro-living; personalisation; resilience; smart homes; space shortage

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1. Introduction

Over the recent decades, the population growth in urban areas and rising demand for housing have been accompanied by a sharp increase in space shortage and a loss of identity and personalisation in urban homes. According to the RIBA [1], the most prevalent cause of discontent with one's home in the UK is lack of space. In major cities such as London, the housing demand is hardly met with adequate supply, leading to unaffordable rents, urban sprawl, transportation problems and sustainability issues [2]. Increasingly, 'Micro-living' concepts have been proposed as a possible solution for affordable residential spaces, when combined with smart technology and automation. Smart technology can help increase the quality of life, especially regarding the increase of functionality and personalisation [3]. By doing so, housing can overcome fixed layouts for specific functions and have the potential to become smart, adaptive as well as easy to personalise. This will allow homes to solve problems, alter furniture and layouts, make decisions and predict what users might require in advance [3]. The objective can be achieved by introducing actuators and forms of Artificial Intelligence (AI) such as a Bidirectional Associative Memory (BAM) neural network, which is a type of recurrent neural network that is commonly used for pattern recognition and associative memory. Bifurcations in a fractional-order BAM neural network can have important implications for the network's behaviour and performance, and research in this area [4–7] influences several fields, including pattern recognition, computer vision, speech recognition, signal processing, optimisation, associative memory, etc., that could play a vital role in smart adaptive homes and automation.

According to Oosterhuis [8], architecture can become the science of dynamic structures and environments running in real time. The intersections of different concepts that contribute to a space that acts and reacts in real time such as smart, adaptive, etc., are illustrated in Figure 1 below. Adaptive architecture combines the research areas of automation (making changes with the help of actuators and machines) and smart technology and includes areas such as interactivity or reactivity.

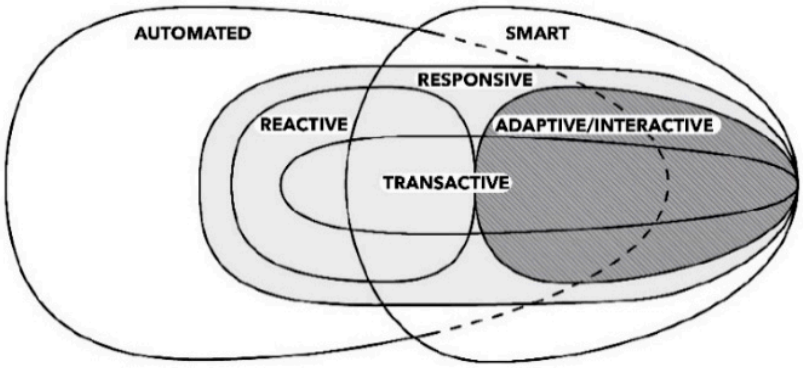

Figure 1. Terminology. Source: Author (adapted from Jaskiewicz [9]).

"Smart" in this context means the integration of sensors, databases, and wireless access to collaboratively sense, adapt, and provide services for users [10] in the home environment. The term "adaptive architecture" (aA) is used to describe an environment capable of continual self-adaptation to the constantly changing circumstances of its surroundings while also being referred to as "interactive architecture" (iA) by Beesley and Khan [11] and Oosterhuis [8], among others.

The research inquiry at hand pertains to exploring the following underlying research question: What are the enablers and barriers for different strategies of adaptation to overcome the physical and psychological limitations of small spaces?

The research is novel, as it concentrates on small residential spaces and addresses the lack of systematisation and categorisation of adaptive systems throughout the literature. The paper contributes to the body of knowledge of making small spaces adapt in real time to achieve maximum functionality and space efficiency according to personal preferences with the uptake of smart technology and links related theories with real-world products. It also presents different options and categories of architectural concepts that can be utilised.

2. Materials and Methods

The methodology employed in this study involves a semi-systematic review of literature and case studies, aimed at identifying potential research opportunities to enhance the efficiency, functionality, and personalisation of urban dwelling units. The literature review includes a body of 410 peer-reviewed articles, working papers, case studies and reports which were gathered and compiled through the use of EthOS, Science Direct, ResearchGate and Google Scholar as search engines and databases. A three-stage approach was deployed: First, deduplication of the various sources was carried out Then, abstracts were reviewed using a Critical Appraisal Skills Programme (CASP) protocol. Finally, when full texts were available, the papers were thoroughly analysed. The review is considered semi-systematic, since after the initial systematic scoping, the selection of the literature and projects was based on the researcher's judgement regarding relevance to the research focus. The search terms that were used are" cybernetic architecture", "adaptive architecture", "adaptive interior", "cybernetic architecture", "home automation", "interactive architecture", "micro-living", "smart furniture", "smart home", and "space saving furniture". The search terms were used individually without further combinations. In this paper, the criteria for inclusion stipulate that the work was published in the time between 2010 and 2022 and contains information that is relevant to the architectural perspective of adaptive spaces. This led to a reduction in the body of work to 81 articles, papers and conference proceedings. Additionally, space standards and national statistics were considered.

Given the significant role that projects and technology play in the architectural discipline, this review will also take into account a range of selected smart furniture and home designs to supplement the existing literature. The comparison of theoretical strategies aimed at achieving increased space efficiency and personalisation in adaptive smart homes with real-world examples enables their evaluation. A semi-systematic literature and project review create the theoretical framework for further research. This paper is part of a PhD research project and only a selection of the literature and case study reviews are included. The procedure implemented for this systematic literature review is presented in Figure 2.

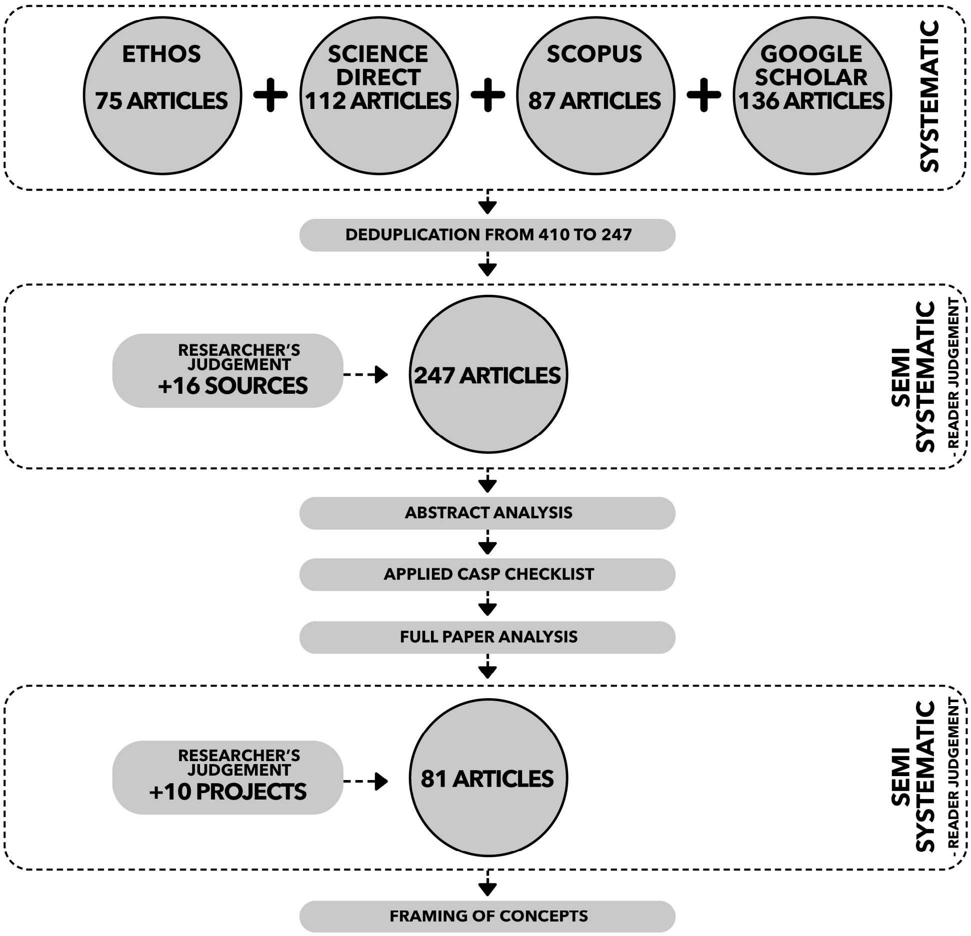

Figure 2. Literature review protocol. Source: Author.

3. Literature Review

This review examines a variety of concepts relevant to small adaptive homes through different lenses, namely the architectural perspective dealing with the concept of a home, including the significance of space for well-being as well as micro living as a strategy to improve space usage, and secondly the role that technology plays to make space more interactive and efficient. The combination of these sections forms the state of the art of adaptive and interactive environments, which consequently allows for the classification of adaptive space concepts in the research results.

3.1. The Home

From an architectural point of view, the concept of a home consists of physical space, the function that a space enables and the meaning of space which considers the home as a space of relationships, memories and as a representation of the resident [12]. The literature indicates that personalisation and higher-level needs such as self-actualisation have to be incorporated to achieve user satisfaction [13]. Today's smart homes that improve energy usage, security, remote control, automation and comfort [14] are especially attractive to young people pursuing a technology-supported neo-nomadic lifestyle characterised by their digital dependence and location independence [15].

3.2. Reasons for Adaptive Micro Living Spaces

Adaptive micro-living homes have been gaining attention in recent years due to various reasons such as increasing urbanisation, rising housing costs, technological advancements, changing demographics, and a growing awareness of sustainable living. Most of the analysed research papers focus on needs regarding space shortage or are linked to a change in society where especially young people want to live in flexible, smart environments. According to the United Nations [16], an estimated 55.3 per cent of the world's population lived in urban settlements in 2018, and by the year 2030, that number is expected to rise to 60 per cent. This rapid growth and the inability of many metropolitan areas to keep up with the resulting demand cause housing shortages in many of the world's largest cities. London's population has increased by 25 per cent from 1999 to 2019, yet the number of dwellings has only increased by 15 per cent, which leads to unaffordable rents, house prices and housing dissatisfaction [2]. Well-intended legislation such as a 37 m^2—minimum [17] for new-build flats in London are political attempts to improve the situation. However, such legislation is criticised for making the situation worse by architects such as Patrick Schumacher [18] or researchers such as Kichanova [2] who argued that "smart micro-housing" is the better choice for some people. Reducing size can decrease living costs, be a driver for sustainability and allow people to live in urban areas while focusing more on social life and leisure activities [2]. The literature suggests that, young individuals are particularly adept at utilizing micro-homes, or will be in the near future [3].

Historically, labour has been geographically bound, while the introduction of teleworking has brought the freedom to work from anywhere for a group of people who are often referred to as digital nomads [19]. Some studies have estimated that the number of digital nomads will continue to rise and reach over 1 billion in 2035 [20]. Especially young professionals who are working digitally while living a location-independent and often travel-reliant lifestyle are looking for co-living, micro-living, or smart living solutions [21]. Research findings by Omar et al. [22] showed that personalisation is another important factor for housing satisfaction. Their findings indicate that modifying homes does not necessarily signify user dissatisfaction. Instead, it suggests that people desire to make their homes unique and personal.

Currently, mass-produced homes are not designed to adapt with respect to residents' individual needs. Although research conducted by organisations such as RIBA [1] demonstrates that insufficient space is the primary source of housing discontent, Foye [23] argues that moving to a "larger accommodation" has no positive long-term impact on subjective well-being. Similar results are shown by other user surveys [24,25]. Jansen [26] explained this outcome by stating that an increase in living space will initially close the gap between one's preferred housing situation and reality, leading to an initial increase in housing satisfaction. However, this gap re-emerges over time and causes the uplift in housing satisfaction to diminish [26]. In the literature, the concept of micro-living is discussed mainly positively as a hub for aesthetic and functional refinement and innovation. The size of a micro living space can vary depending on different contexts and definitions, but it is generally considered to be a living space with a total floor area of approximately 15 to 37 square metres [2]. Critics say that instead of constituting sustainable liveable space, micro homes are sold above market price to increase profits [27,28]. According to Arcilla [24], this is due to efficiency becoming a modern obsession in all facets of life, good marketing and design that sells micro-homes as more sustainable, but more importantly due to capitalism and market interests. The literature above suggests that when all basic needs such as security, safety and physical needs such as warmth and hygiene are available, housing satisfaction is influenced by the functionality of a space, the flexibility that it offers and only to some extent the actual size per person. New technology has the potential to increase space efficiency and personalisation and can be used to achieve real-time adaptation.

3.3. Technology (Automation and Smartness)

Most adaptive smart home concepts build on technological advancement as a driving force for adaptive spatial design, which is addressed succinctly in the following paragraphs. The state-of-the-art technology is highly influenced by the progress in sensors, actuators, materials and AI. The role of these factors in adaptive architecture is illustrated in Figure 3.

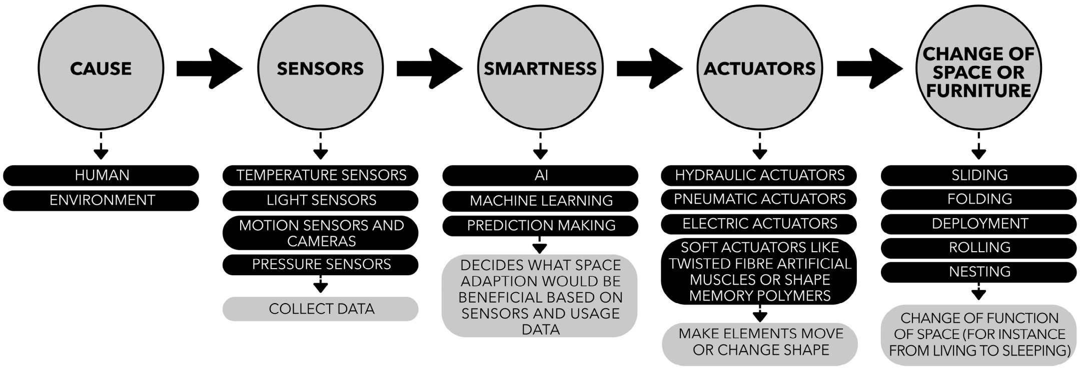

Figure 3. Technology for adaptive spaces. Source: Author.

Progress in AI allows machines to learn, recognise what users are doing and make predictions with very high accuracy [29]. Machines are becoming context-aware and more ambiently intelligent [29]. Ambient Intelligence is used as a term for a collection of technologies that smoothly blend into their environment to produce an unnoticeable user interface [30]. Sensors are already very elaborate in collecting multitudes of data, from temperature, humidity, solar radiance, or energy usage to human activity, sound or spatial recognition of objects [31]. The trend progresses toward cableless microsensors or wearables that detect human activity with high accuracy [32]. Cutting-edge actuators can achieve almost any motion and vary from engines to artificial muscles. Soft actuators which are materials that can perform tensile and torsional actuation are becoming increasingly elaborate and cost efficient [33]. They include twisted fibre artificial muscles, shape memory polymers, hydrogels, liquid crystal polymers, electrochemical actuators utilising conducting polymers, and certain natural materials [34].

To alter space visually, lights, screens and materials allow the ambience and colour of a room to change in real time [13]. Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR) are advanced enough to offer an immersive experience that can be a solution to expand the physical space [35]. Hermund and Klint [36] showed with a questionnaire that was answered by participants experiencing a real space compared to a group of people experiencing a digital copy in VR that virtual space can convey all the information that physical space can, namely size, ambience and atmosphere. While the literature indicates that technology is advanced enough to alter architectural space physically or virtually, the big question in the architectural discipline concerns the best way of adaptation and transformation to suit individual needs. Integrated technology opens up many opportunities to achieve these individual preferences from a selection of possible options.

3.4. Adaptive Space Theories

According to Jaskiewicz [9], adaptation, which is the change in architectural space over time (both regarding the building shell and the interior layout) is in the first aspect linked to human needs and follows cycles of daily routines and external factors. Environments adapt to human activity, while at the same time, through a feedback loop, human activity is influenced by the spatial characteristics of the human habitat [8]. According to Jaskiewicz [9] and Yiannoudes [29], adaptation can be achieved by different means depending on the time necessary for the change (Figure 4) and the entity (human or machine) making the change. Adaptation can be divided into the following components: First is reconfiguration of space, which is reassembling or changing parts of a building manually (for instance, installing/removing a partitioning wall), which is time- and labour-intensive. Second is flexibility, which means leaving margins in the space or creating open spaces that allow users to reconfigure spaces manually. However, over-dimensioning leads to inefficiency [29]. Third is adaptation, which is achievable in real time by utilizing automation with intelligent systems, sensors, and actuators [9]. The main emphasis of this paper is on the third aspect.

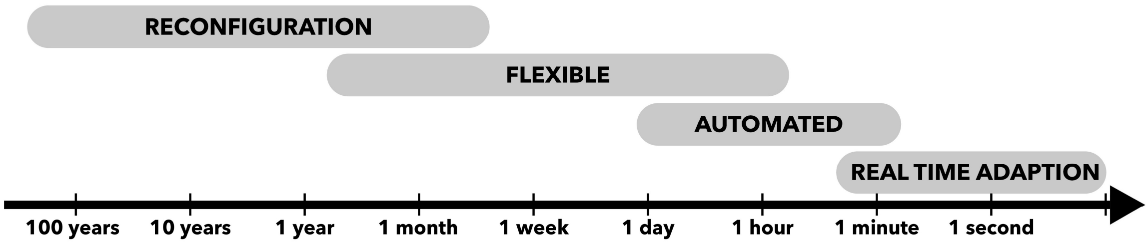

Figure 4. Time-dependent space change. Source: Author.

An alternative approach to exploring the concepts of adaptation is to consider the scale of components, ranging from an entire city down to a single structure, individual furniture pieces, and constituent materials. Historical concepts remain highly pertinent within contemporary literature that is built up on cybernetic and Metabolist ideas from the 1950s and 1960s. Pask [37] proposed that cybernetics could make buildings adapt, learn, and respond according to the interaction with users. In his work, "The Architectural Relevance of Cybernetics" from 1969, Pask [37] described cybernetics as a transdisciplinary area that permeates divergent domains such as engineering, biology, sociology, economics, and design. He puts forward that the architect's "aim is to provide a set of constraints that allow for certain, presumably desirable modes of evolution" [37] (p. 75) and to determine the relevant properties between humans and systems.

Archigram, an avant-garde architectural group drawing inspiration from technology, had a more iconographic and theoretical approach towards adaptive architecture [38], and they envisioned flexible and functionally indeterminate spaces where the "push of a button or a spoken command, a bat of an eyelid will set transformation in motion—providing what you want where and when you want it" [39] (p. 146). While Archigrams' concepts were futuristic, on the other end of the spectrum, the works of Price [40], Friedman [41] and Zenetos [42] were more elaborate examples that marked a shift towards adaptive user-centric designs [29].

Today, user-centric studies by Radha [3] and the MIT Media Lab [43] have shown that, due to the technological advancements, moving furniture elements and adaptive spaces are re-emerging in the public interest and are no longer futuristic ideas. The research project *CityHome* [43] conducted in Cambridge/USA revealed that this smart furniture system has the potential to increase the functionality of a small apartment to that of two or three times its size. The MIT Senseable City Laboratory [44], which is a successor of the *CityHome* project, continues to examine methods for studying the built environment as layers of networks as well as digital information and the machine becoming the city [45].

According to the findings by Radha [3] who conducted user surveys regarding adaptive smart home prototypes in Iraq, smart houses with moving room elements have better internal space efficiency and functionality since they make better use of time and space for a variety of activities using smart technologies and are more likely to be accepted by younger people. The paper concludes that by "incorporating smart architectural elements, an increased degree of design versatility was achieved, and it was discovered that changing size, shape, reference, and layout became easier, faster, and allowed more options for organising spaces in smart homes" [3] (p. 15). Together, the above studies show great potential and user acceptance for adaptive elements to be integrated into existing as well as new buildings. Yiannoudes [29] examined architectural designs that employ computational technology to adapt to changing environments together with human demands and emphasised that intelligence is needed for adaptive spaces acting in real time. Ambient Intelligence is concerned with intelligence in the built environment that allows smart environments to proactively respond to the needs and activities of people by utilising adaptive systems, ubiquitous computing, and user-friendly interfaces [29]. Although the analysis of the literature under consideration indicates that only a limited cohort of scholars focus on the user-centric design of spaces, the reviewed literature suggests that there is substantial potential and related technology to optimise spatial utilisation and save space.

In prospect, research that examines the use of swarm robotics and room bots as a prospective remedy for achieving almost infinitely adaptable spaces has demonstrated some encouraging outcomes in preliminary studies and experiments. The Hyperbody Research Group under the lead of Kaas Oosterhuis at TU Delft conducted research regarding adaptive spaces, for instance, the *Muscle Project* that attempted to create a space that can change shape by contracting and relaxing artificial muscles and stretchable materials [46]. According to Oosterhuis [8], buildings are subject to the digital revolution and architects have to play with the potential of the new media invading the built environment. Especially swarm architecture (a self-organised system consisting of smaller elements) that is at the same time e-motive, transactive, interactive and collaborative is seen as the future of buildings adapting in real time [8]. Companies such as Festo were able to create small robots (resembling, for instance, ants) that can work together like a real-world colony [47]. Currently, constructing furniture and walls with all of their inherent qualities (such as the suppleness of a couch) poses a significant hurdle and is not realistically attainable.

Concerning automation and unrestricted indeterministic adaptability, Szot et al. [48] developed a virtual environment to train robots to arrange objects and furniture in an apartment with reinforcement learning, which shows that re-arranging ability can be achieved with independent robots. Working towards a similar goal, Suzuki et al. [49] developed the prototype of a room-scale dynamic haptic environment called *RoomShift* that creates haptic experiences by rearranging physical spaces with the help of a tiny swarm of shape-changing robots that can freely move a variety of furniture. Spröwitz et al. try to "imagine a world in which our furniture moves around like legged robots, interacts with us, and changes shape and function during the day according to our needs" [50] (p. 15). An additional approach entails enhancing functionality through the integration of virtual content. Although overlaying physical and virtual space using technology such as VR (Virtual Reality), AR (Augmented Reality) or MR (Mixed Reality) is currently feasible and individuals are increasingly conducting their social lives within virtual spaces, it is questionable whether these technologies can or should fully replace the physical space [29]. The mentioned literature indicates that technological advancement combined with architectural design opens many possibilities.

3.5. Real-World Systems

Many aspects of interactive and adaptive architecture have not yet found their way into commercial applications despite having been initially tried in experimental installations or being applied to specific parts of buildings such as facades or furniture. Examples of adaptive kinetic facades like the *Ocean Pavilion* by Soma from 2012, the *Shed* by Studio

Diller Scofidio + Renfro completed in 2019, the *Shanghai Theatre* by Heatherwick and Foster from 2017 or the *Polish House* by Robert Konieczny from 2017 are becoming more and more common today and might be further developed for use in interiors. Products by Expand Furniture [51], Candra [52], Dror [53], or the foldable and smart furniture lines by Ikea [54] are contributing to space-saving.

Smart furniture by Ori Living [55] and Bumblebee [56] are considered to be state of the art and show that furniture can be made adaptive and movable with actuators. ORI furniture emerged from MIT Media Lab's [43] *CityHome* project where furniture, storage, exercise equipment, lighting, office equipment, and entertainment systems are all integrated into a transformable wall system. The product range includes the *Cloud Bed*, a ceiling-mounted bed, as well as the *Pocket Studio* and *Pocket Office*, which are smart walls with an integrated bed or office table [55]. Although smart walls are often considered the most highly anticipated feature, it is worth noting that both ceiling-mounted and floor-mounted moving furniture options are currently available on the market and offer significant space-saving benefits. The systems from ORI and Bumblebee (Figure 5) have the same goal, namely, to increase the functionality of residential spaces with furniture that is multi-functional, smart and can change the inner layout of space automatically in real time.

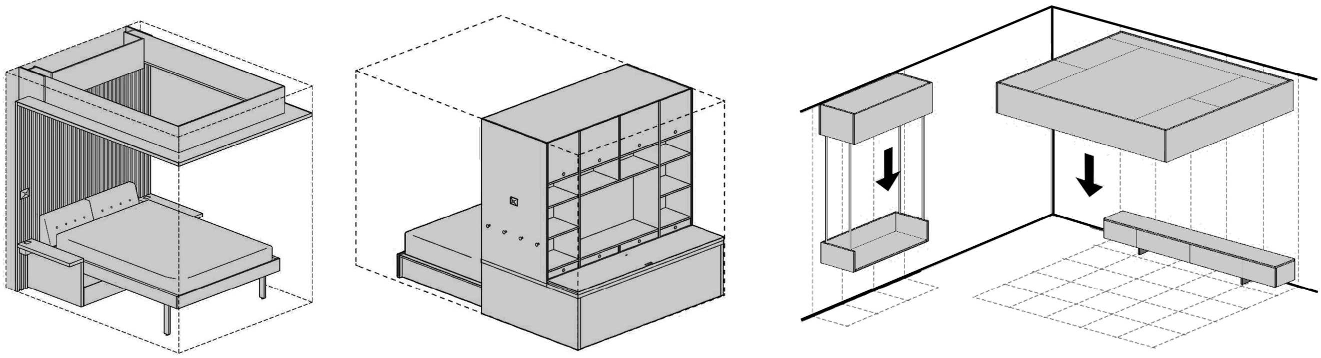

Figure 5. From left to right: ORI Cloud Bed, ORI Pocket Studio, Bumblebee Bed and Table. Source: Author.

Both systems provide a bed, a table, and storage, although one of their principal distinctions is their respective mounting configuration: while ORI is floor and wall-mounted, Bumblebee is a ceiling-mounted system. The advantage of the latter is its heightened adaptability, as the bed and storage can be situated in the middle of a room. Nonetheless, the Bumblebee solution appears to be more costly, owing to the more intricate cable-based movement mechanism. Regarding the bed options from ORI and Bumblebee, they can both almost free up the whole space of about 5 m^2 that a standard bed would use. Regarding storage, ORI can save about 50 per cent of space usage compared to a conventional cupboard because the access area can be minimised. Systems like this become more efficient if more rows of storage are staggered, like in the *Domestic Transformer* by Chang [57]. In comparison, the Bumblebee system does not need any floor space. However, due to the small volume of the ceiling-mounted boxes, there is a larger area of the ceiling necessary to achieve a similar volume and a certain room height is necessary to make the system feasible. Products such as the *Pocket Studio* by ORI combine a variety of functions, which can save up to 9 m^2 compared to the same elements without adaptiveness [55,56]. Looking at these examples, it seems feasible that a 35 m^2 studio can function like a 50 m^2 home.

Regarding visual adaptation, art installations such as *Ada* by Microsoft from 2019 show that light and sound can change in real time according to people around the installation [58]. There are also more advanced visual personalisation options such as colour-changing materials (for instance, *ChroMorphous* [59], a material that changes colour and appearance on demand, developed by researchers at the University of Central Florida), and invisible screens. According to Yiannoudes [29], the functionality of an ambient intelligent system depends on the design of the space that is supposed to host it. Architectural design and immersive smart technologies must be linked and thought of as a concise system. Combining those has the potential to make our life happier, healthier, sustainable, and more comfortable [9].

4. Results

The findings from the literature and project reviews suggest that the initial wave of intelligent furniture systems available in the market hold great potential, despite their current limited prevalence. Smartness has become an important factor in every related product. Evident reasons why people would not buy such systems are high costs, system compatibility issues and concerns regarding data security [60]. The avant-garde British author J.G. Ballard in his short tale *Billennium* from 1962 [61] envisioned a dystopian future metropolis that is overcrowded, where people have become accustomed to living in cramped cellular rooms with a legal maximum size of just 3.5 square meters per person. In future scenarios where space is scarce and expensive, these challenges [61] need to be addressed and the goal to make most out of the available space emphasised [29].

The available evidence suggests that there is potential to increase functionality and diminish the physical and psychological limitations of small spaces by making functions time-dependent and interiors adaptive and personalised. Research works by Jaskiewicz [9] and Radha [3], among others, attempt to build a new framework for such architecture to establish a solid foundation for designing interactive architecture. Such a move away from simply exploring theoretical concepts of complexity in architecture could help make these concepts more accessible for both designers and users.

Adaptability often implies anticipating and planning to allow for unforeseen events, while flexibility can be more immediate and situational, often with a need to accommodate other factors. These two concepts sometimes interchange, and it can be difficult to differentiate between them in relation to the broader framework of a home interior. This study tries to classify strategies of adaptation and flexibility and divide them into categories (Figure 6) that can enable planners to create spaces that can easily adapt to changing user needs while increasing space efficiency. In summary, flexibility leaves margins and open spaces to allow for the movement of furniture and is closely linked to manual adaptation that introduces movable or transformable elements such as walls, furniture, and partitions that are manually transformed by the user. The strategies depicted on the right half of Figure 6 use technology for change, such as automated real-time adaptation that automates changes of layouts and functions and can include artificial intelligence or the extension into cyberspace that is replacing an actual function with a virtual alternative [33]. Figure 6 also illustrates Representatives and Authors related to these concepts as well as real-world examples.

Different strategies have different levels of multifunctional space, which is illustrated in a simplified manner in Figure 7 based on a 37 m^2 home. It is noteworthy that elements such as kitchens or bathrooms, which rely on pipework and similar infrastructure, possess a limited potential for adaptability across the strategies. The graphic is intended as a general illustration of types of adaptation based on estimations and represents conventional, manually adapting and automatically adapting furniture graphically. Further research is carried out to determine the level of adaptability for each option.

The subsequent sections provide a comprehensive account of each approach, with Figures 8–12 providing a simplified representation of these categories based on a 37 m^2 apartment.

4.1. No Adaptation—Standard Apartment

The most common apartment type today is a conventional apartment that has room separation and loose furniture. The minimum allowable space standard for newly built flats with one occupant in the UK is 37 m^2 according to the *Technical housing standards* [62] and everything smaller is considered micro-living. The replacement of furniture presents an easy means of achieving personalisation. However, due to the spatial limitations of many minimum apartments, reconfiguration and relocation of furniture may not be feasible in practice. As a result, structural reconfiguration is necessary for severe functional change. While standard furniture is the cheapest option, the usability of the space cannot be increased, and functions are difficult to stack.

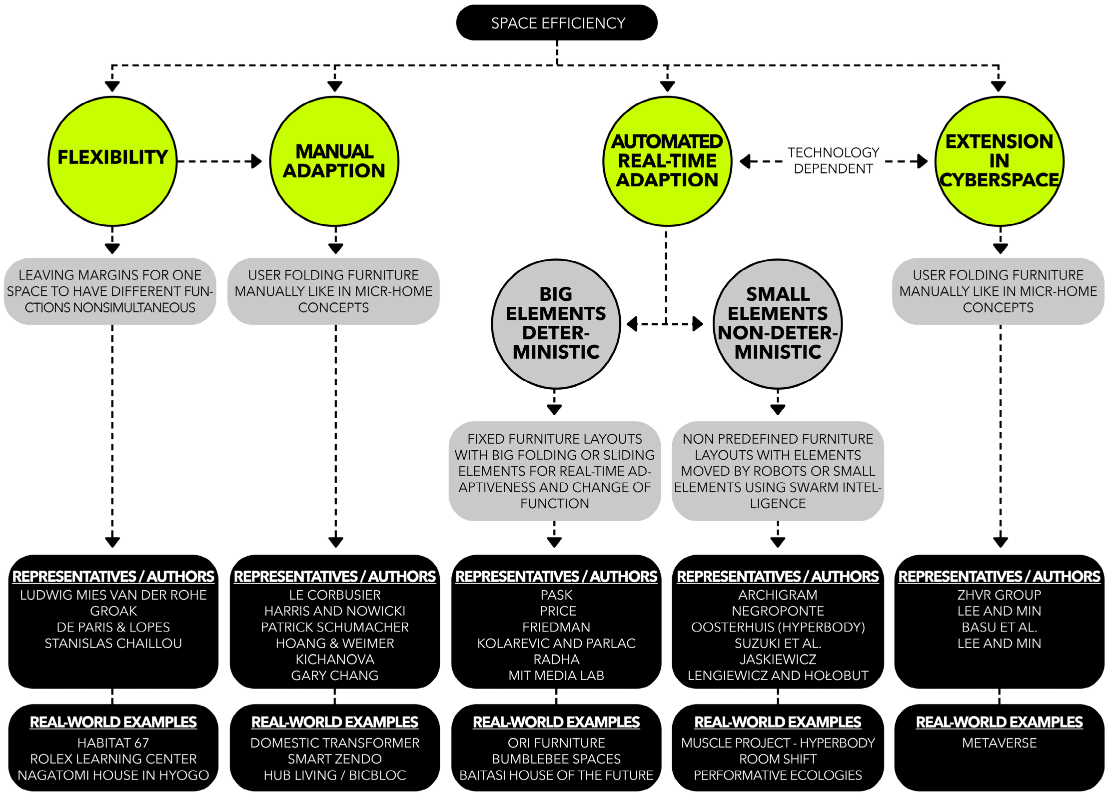

Figure 6. Systematisation of concepts of adaptation, Key authors, and Real-world examples. Source: Author.

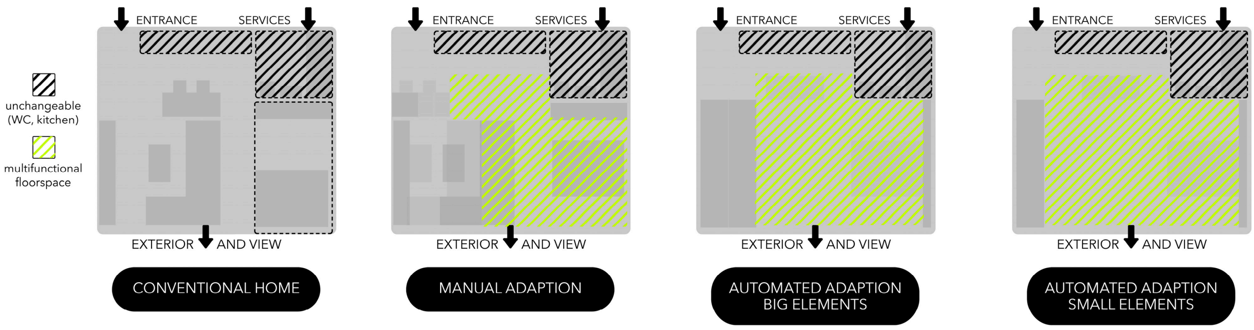

Figure 7. Estimation of spatial adaptability. Source: Author.

4.2. Manual Adaptation (Transformable Micro-Living Apartment Incorporating Flexibility)

Micro-living spaces that use movable or folding elements have become common to make space more efficient. In comparison to a standard apartment, space is much more flexible and can serve multiple purposes within a single area. There are relatively cheap products such as wall-mounted folding beds (Murphy beds), sofa beds, stackable chairs, expandable tables or simply furniture with wheels on the market. More elaborate, often individually designed examples also use the floor and the room height to maximise space usage with split levels or under-floor storage. While cost and space efficiency are the big advantages, the disadvantage is that changing layouts is often time and labour-intensive.

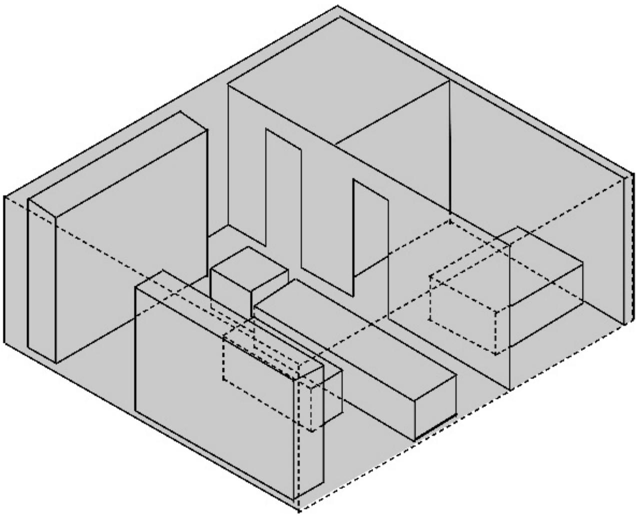

Figure 8. Standard apartment. Source: Author.

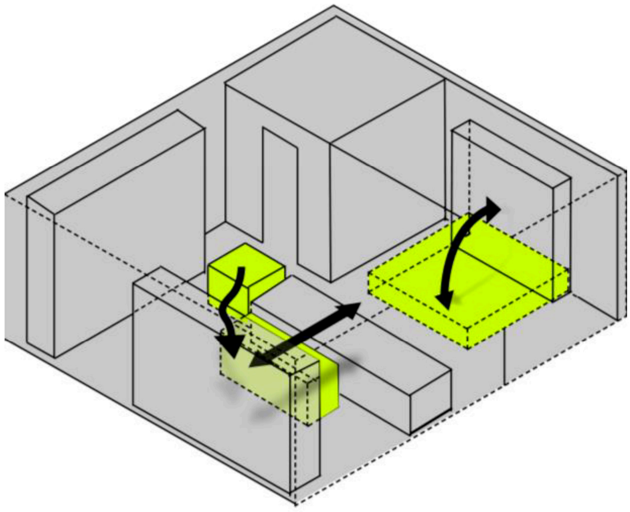

Figure 9. Manual adaptation (micro living). Source: Author.

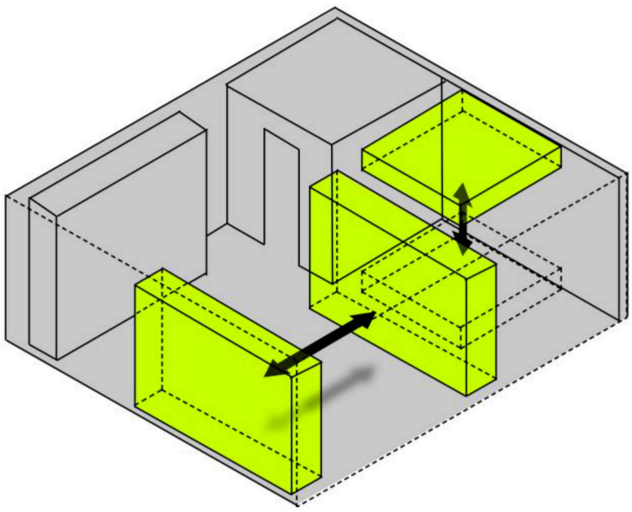

Figure 10. Automated adaptation big modules. Source: Author.

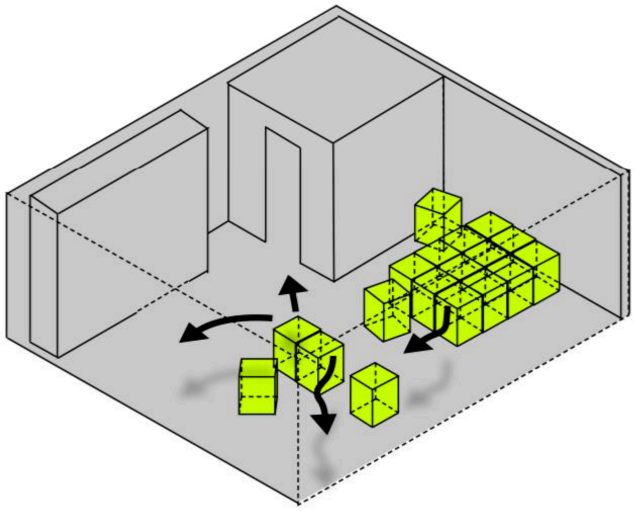

Figure 11. Automated adaptation small modules. Source: Author.

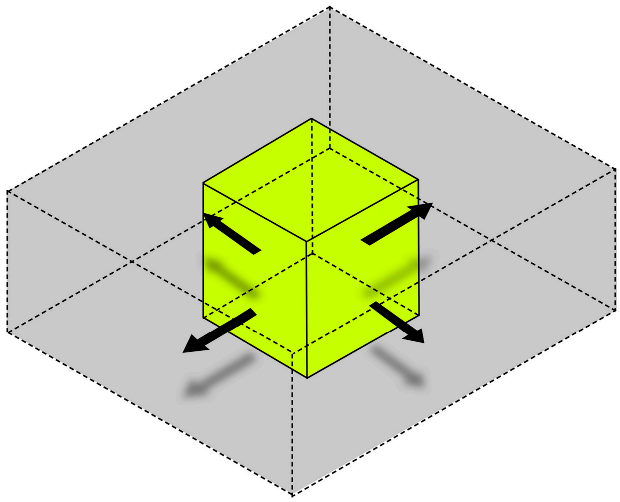

Figure 12. Virtual space. Source: Author.

4.3. Automated Adaptation with Fixed Layout Options (Large Modules)

Building upon theories by Radha [3] and the MIT Media Lab [43], this approach provides a variety of predetermined configurations that the apartment can transform into, resulting in highly predictable outcomes. It is adopted by real-world furniture such as Bumblebee or ORI which automates the movement of elements with actuators. The elements can be ceiling-mounted storage, beds or tables, movable smart walls and expandable elements. Automated adaptive systems offer the advantage of being able to place furniture in areas that are difficult for users to access manually, such as ceilings. While furniture elements come at a higher cost than furniture that does not transform automatically, it has the benefit of increased flexibility and convenience. In the future, space will be able to adapt by itself and do so without any user input with machine learning and activity prediction, if wanted by the user.

4.4. Automated Adaptation without Fixed Layout Options (Small Modules)

This approach builds upon methods that use small robots, bio-inspired organic systems or other small building elements. Theoretical projects such as the muscle projects by Oosterhuis [63] as well as research by Lengiewicz and Hołobut [64] or Suzuki et al. [49] show the potential of small robots and intelligent materials in test environments. The concept has the advantage of the smaller elements always increasing freedom and spatial adaptiveness, allowing for the possibility of nearly any modification. Due to complexity, technological limitations and costs, these systems are harder to achieve and are less accessible.

4.5. Virtual Space

The cultural shift towards digital space influences architecture on many levels. Extending space virtually while only having the bare minimum in the real world has limitless options and allows users to live and play in a shared, permanent, and self-sustaining world due to the metaverse ecology. Early examples of this trend such as the *Metaverse* show both opportunities and problems [65]. While this approach has the problem of dystopian connotation, both physical boundaries and location are irrelevant since everyone is connected with everyone else and can be anywhere [66].

5. Discussion and Conclusions

This paper presents a review of existing research studies, links them with projects in the field of smart adaptive homes and attempts to categorise strategies in terms of time that the system needs to reconfigure the space and the type and size of the elements. The literature review shows that today, there are both the need (regarding space shortage) and the necessary technology for many concepts to be realised as well as the user acceptance (especially among young people) to make adaptive homes successful.

Even though a lot of research is carried out in relation to smart homes, they concentrate predominantly on technical improvements [67], while there is a gap in design-related research, functional maximisation and real-world implementation as already pointed out by some researchers [3]. A complex adaptive system has a boundary and a finite number of components, just like any other system. All the abovementioned strategies enable increased space efficiency. Smart interior design refers to the most efficient ways to satisfy inhabitants' sometimes complex and intricate expectations. The goal of many researchers is to create an ideal model, which results in a variety of approaches and theories that suit the majority.

Pursuing the need for better space efficiency, more user-centric studies need to be executed, considering different locations of the world to explore whether results might be different. Most studies agree that modular smart house architecture should have changeable flexible or adaptive physical areas. While the lack of space is undoubted, and technology should not be the excuse to make spaces smaller per se, there is little available literature indicating the amount of space that is enough to prevent claustrophobic conditions. This space requirement can also vary according to location, economic status, and socio-cultural differences.

The role of technology has transcended the mere production of amusement, leisure, or lifestyle gadgets, and it is imperative to remain abreast of alterations in customer desires and ambitions. Thus, architecture and interior design must employ appropriate solutions to work with, incorporate and benefit from the mentioned technologies. Increasing adaptiveness and reducing fixed residential space layouts can prevent the need for renovations and construction work for possible additions and changes which can be a driver for sustainability and resilience. Adaptive space anticipates and accommodates change from the outset and allows occupants to reconfigure the space to meet their evolving needs without requiring major renovations or structural changes. For example, if a family grows and needs more space, they can simply reconfigure their existing living area or add temporary partitions rather than building a whole new room or even moving to a larger house. Other systems that are more focused on increasing efficiency in a minimal space correlate with the trend towards living as a service, where residents could use the same housing model in different places. Models driven by spatial efficiency are more sustainable and resilient in the sense that they use less space and resources to provide the same functionality. However, the question of what makes a smart adaptive space successful remains unanswered to some extent. The analysis of the smart furniture systems from ORI and Bumblebee shows that while saving floor space, they lack interactivity and have high costs. At a theoretical level, the nomenclature employed to describe models of adaptability is not clearly defined and overlaps. Common terminology includes expressions such as "adaptive", "automated", "cybernetic", "interactive", "reactive" and "smart", among others. The categorisation of strategies for the improvement of space efficiency can help future research to test different solutions with users (for instance, in VR models).

In traditional building design, the relationship between indoor and outdoor space is often fixed and inflexible, with clear boundaries between the two. However, adaptive architecture recognizes that these boundaries can be fluid and that adaptive building envelopes can change this division both visually and physically. Although this paper focuses on residential interiors and presents a single apartment module as an example, it is essential to acknowledge that adaptive elements and dwellings cannot be considered independently of their impact on an urban scale. As multiple environmental and communication flows, as well as networks such as water, energy, transport, or building systems, become interconnected and continuously adapt [68], it is imperative to incorporate multi-disciplinary research developments that seek to make entire cities adaptive, resilient, and sustainable.

The limitation of a semi-systematic literature review is that it is restricted in the scope of depicting the whole picture since progress in the field is happening fast. For this ongoing research, surveys and experiments with users will be conducted to better understand the user perspective regarding these technologies and resulting living spaces. Specifically, experimental research in micro homes and living labs could provide further information regarding the future of housing.

The consolidation of the existing body of knowledge also shows that these new forms of urban living (together with micro-living and co-living) can and should be reflected in contemporary housing policies and practices. In the UK, for instance, the allowed minimum floor area of 37 m^2 for newly built apartments has been criticised, since the quality of the space and its functionality might be more important than its size on paper. Mainstreaming such novel and innovative concepts will require mind, attitude and behavioural changes and many more real-time examples for lessons to be learnt. Therefore, research in the area of smart adaptive and interactive micro homes is essential and has the potential to improve living quality in urban areas and needs to be advanced to reflect the development of technologies.

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