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A CRITERIA- AND CASE STUDY-BASED APPROACH TO EVALUATE ADAPTABILITY IN BUILDINGS

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Abstract

Buildings may become functionally obsolete before they reach the end of their service life due to changing social, economic, and technological contexts. A building may undergo one or more transformations during its service life since decreased utility, vacancy, or demolition are not economically, socially, culturally, or environmentally viable options. Buildings with adaptable capacities offer effective solutions for responding to change and creating a sustainable built environment. The present study sought to clarify concepts related to adaptable architecture and develop a criteria-based evaluation approach to assess adaptability parameters in existing buildings. A criteria set was developed based on the literature to define adaptability strategies and parameters and their interconnected spatial, functional, and structural relationships that facilitated change. The magnitude of potential change was weighted and converted to adaptability scores. The adaptability evaluation criteria set was used to assess the adaptability scores of several architectural examples and the findings indicated that the criteria set could be used as both a quantitative and a qualitative evaluation tool.

Keywords: **Building adaptability; Strategies, Parameters; Criteria-based evaluation; Case study.**

1. INTRODUCTION

Global issues such as rapid technological advancements, environmental concerns, economic and social imperatives, and an increase in globally competitive work practices place new demands on the built environment at various scales [1]. Changes in user demands and needs, as well as changes in the social, economic, and physical environment, all have an impact on the urban and architectural environment [2]. The built environment constituents that are unable to respond to such changes have a negative impact on the natural environment through increased material use for new construction and waste from demolition due to obsolescence [3]. Dynamic and long-term approaches are required for sustainable built environment practices. As a result, architecture should be viewed as a *temporal* concept that promotes the continuity of interaction with the context and responds to change, rather than a *static* concept that relies solely on *form and function* [4, 5].

The effective use of existing building stock, as a part of the financial, physical, and cultural assets, makes it possible to construct a sustainable society [2]. Despite structural durability, the number of vacant buildings in a building stock may increase due to shorter function/lifespan estimates [6]. Increased urban density and the use of public transportation are considered a more sustainable option; thus, the adaptive reuse of buildings becomes preferable [7]. Inadequate use of existing building stock, demolition waste, and new constructions linked to resource consumption all contribute to urban problems, resource scarcity, and ecological crises [2, 8]. From an economic and social perspective, adaptability thus falls within the scope of durability and sustainability approaches [9]. Buildings with multiple functions are important for resource efficiency and the development of the built environment because they can better respond to unforeseen programmatic changes in the future [3]. Kendall [10] argued that a stable and adaptable building stock was strongly linked to issues of environmental ethics, embodied energy, recycling and efficient material use, and other sustainability issues. Given this context, adaptability emerges as a novel, viable, and practical countermeasure to the uncontrolled expansion of the building stock [11, 12].

Building adaptability necessitates a multifaceted approach due to the complex structural, functional, and service systems in buildings. In economic, environmental, and social terms, both the building occupants and the urban environment benefit from adaptability [13]. Adaptability in architecture can be assessed economically by the financial benefits that stakeholders receive from the building, socially by welfare, and environmentally by sustainable qualities [14]. Despite the high initial construction costs, adaptive buildings have a shorter return on investment because the long-term costs of operation, maintenance, renovation, service upgrade, and function adjustment are lower than in traditionally designed buildings. According to Keymer [15], the demand for buildings that adapt to change is growing because of the added value of adaptability in both the long and short term. Furthermore, Pinder, Schmidt III, and Saker [16] argued that adaptability should be considered within the scope of green building and performance assessment certification systems due to its contribution to sustainability as well as the added market value and recognition. Socially, adaptable buildings reinforce urban space requirements such as safety since they are rarely vacant [14]. The adaptive reuse of obsolete buildings for new purposes has the potential to create new forms of urban interactions [17] while maintaining social and cultural consistency to preserve the identity of the place [13]. The multifaceted nature of these approaches lends a certain level of strength to the concept of building adaptability in achieving a socially, environmentally, economically, and culturally sustainable built environment.

The possibility of functional adaptability, on the other hand, is primarily the result of an imbalance between the supply of obsolete space and the demand for a specific function (eg., office space, residential use) [7]. Hence, such possibility of adaptability is linked to the demographic, economic, social, and technological changes that affect the urban configuration. Significant shifts in the balance of supply and demand are common over the life of any building, according to Kincaid [1]. An economic recession may result in reduced demand for workspace, while a boom period may result in a demand that exceeds supply [1]; thus, such change may occur more than once during the service life of a building. Therefore, adaptive refurbishment of existing buildings becomes a financially and environmentally sustainable option for responding to change and emerging global trends.

Given the scope above, the ability of a building to change, or its *adaptability potential* [1], emerged as a current research area that is closely related to achieving a sustainable built environment. The present study, therefore, aims to clarify the concepts related to adaptability in architecture and to develop an evaluation tool for adaptability classifications and applications. The study focuses on developing an adaptability concept based on spatial, physical, and technical aspects of adaptability; economic, social, and legal aspects of adaptability were not considered within the scope of the present study. Given such aim and scope, criteria set for adaptability strategies and parameters were developed through a literature review. To develop the criteria set, histograms/Pareto diagrams were used for the strategies and parameters based on their frequency of use in the literature. Based on their frequency and strength, adaptability strategies and parameters, as well as their inherent relationships, were identified and included in the criteria-based evaluation tool. A weighted score system was assigned to the selected strategies and parameters. The developed criteria-based evaluation tool was used to test well-known adaptable examples such as the Schröder House, Farnsworth House, and Genter Strasse.

2. LITERATURE REVIEW

The review of the literature includes the definitions of change and change types, the definitions of the concept of adaptability, and the approaches considered to increase the adaptability level of buildings. The developed criteria-based evaluation tool was based on these key emphases in the literature.

2.1. Change and Types of Change

Buildings and urban environments that are occupant-oriented, recyclable, and adaptable to changing demands are essential for a sustainable future. A thorough examination of the rate and scope of change, as well as an effective assessment of the existing building stock based on alternate uses, facilitate the design of adaptable buildings and urban environments. The need for spatial change is caused by a variety of internal and external factors. Internal factors are defined as the building's inability to meet the initially defined requirements or a decrease in the building's capacity to meet these requirements due to aging and performance changes, even though the occupants' requirements did not change [15,18]. External factors are defined as a building's inability to meet changing demands and needs and increasing spatial and functional requirements [12]. Although a building's physical life is long, once it cannot meet the demand for change and revisions, the building will inevitably be subject to obsolescence and abandonment, which is a design problem for all stakeholders, particularly property owners [19].

To prevent or delay building aging, the factors should be analyzed, and the necessary measures should be implemented on time. According to Lemer, [20] as cited in [15], technological changes affecting infrastructure services and requirements, shifts in regulatory processes, economic and social change, and changes in occupant requirements and behaviors are the factors that cause obsolescence. Graham [21] categorizes these factors based on service and value requirements. Service requirements are related to poor design of building components, lack of maintenance and repair of these components, inadequate indoor environmental quality, spatial dimensions that do not meet ergonomic conditions, alterations in regulations, and changes in occupant requirements. Value requirements, on the other hand, are the factors related to cost and financial value, such as a decrease in the building's financial value, an increase in operation and maintenance costs, changes in aesthetic quality perceptions due to current trends, and the emergence of comparatively more valuable alternatives [21].

Building modifications for reuse, functional and physical upgrades, and other alterations are carried out by altering the building's function, capacity, performance, and operation throughout its service life. In terms of building adaptability, functional change refers to assigning diverse functions to the building rather than using it with the designated function [12]. The volumetric change of the building due to factors such as occupant and functional load is referred to as the change in building capacity [15, 19]. Performance change is carried out through refurbishment and/or rehabilitation or renovation and/or restoration [12]. Changes in occupant density and movement, furnishing/equipment use in or around the building, and climatic or physical environmental conditions may occur over time. For instance, replacing a fixed window with a retractable window may result in a change in the building's indoor environmental conditions due to the changes in occupant control. Similarly, a building expansion may necessitate additional circulation elements to improve circulation [15, 19].

Overall, an effective assessment of building change and types of change is becoming increasingly important for the adaptive reuse of existing buildings and the design of new buildings that achieve a certain level of adaptability. Hence, a building that fails to meet the demand for change and potential revisions is likely to become obsolete and abandoned. Therefore, adaptive reuse and functional and physical adaptability in buildings necessitate a certain potential for change in the building's function, capacity, performance, and operation. A shift from rigid functionalism to the use of capacity-for-change as a guiding principle, from centralized to distributed control, is nonetheless becoming evident.

2.2. The Adaptability Concept in Architecture

Adaptability discourse in literature is founded on diverse perspectives in different disciplines. Schnädelbach [22] defined adaptability as an interdisciplinary concept encompassing architecture, art, engineering, and computer science. Due to terminological differences based on context, there is no universal definition that applies to all disciplines. The ambiguity in the definition and scope of adaptability increases the possibility of a misconstrued concept [23]. Friedman [24], as cited in [23] also mentioned the wide range of definitions as a factor that contributed to misconceptions about adaptability. Such ambiguous definitions of adaptability in architecture could be attributed to – *what adaptability means to different stakeholders in disparate contexts and at varying points in time* [25]. Therefore, it is essential to briefly review different definitions to clarify the relative meanings of adaptability in architecture based on the context. Adaptability was defined as an extended benefit obtained from a product within the context of product/service development [26]. Given Tschumi's [27] discourse on the inclusion of uncertainties of function, event, and movement in architecture as an ability to accommodate social change, such a definition partially applies to architecture. The architectural product must somehow transcend the defined design boundaries, extending the *benefit* (or *utility*) it provides to its occupants. Gu, Hashemian, and Nee [26] distinguished two types of engineering/product development approaches: design adaptability and product adaptability. Design adaptability refers to a set of design principles that allow for product modification (adaptation) [26]. Product adaptability, on the other hand, enables the same product to be used for multiple functions by modifying its existing features [28]. In the architecture domain, design adaptability entails modularity and mass customization approaches [28] with limited building functionality (warehouses, factories, etc.). As a result, the former, design adaptability, may be irrelevant for unique architectural functions and contexts where design decisions are different from other designs. The latter, product adaptability, is more relevant to architectural discourses, where adaptability is defined as the *ability of a space to be modified for uses other than the one originally designed for* [29].

Definitions of adaptability in architecture have been broadened to include designs that are appropriate for changing social uses [30] or that can change function, capacity, or performance to adapt to changing conditions and needs [12]. Schmidt III et al. [5] define adaptability in architecture as the ability of a building to meet new requirements. Furthermore, current research on adaptive facades is linked to building adaptability, which occurs when parts of a building manually or automatically respond and adapt to environmental stimuli and/or occupant activities [22]. Orhon [31] similarly defines adaptability, as the ability to change the features of a building to adapt to the environment, occupants, and social context. Given the various approaches to defining adaptability in architecture, the present study focused on the AIA's definition [29], which is related to product adaptability [26, 28] and focuses on a space's ability to transform a new function. Even though adaptability and flexibility are closely related concepts in architecture and often used interchangeably, in the present study, we refer to adaptability as a governing concept that includes flexibility. Several studies indicated that expressions such as *adaptability, flexibility*, and *polyvalence* had multiple and often overlapping definitions that led to confusion and ambiguity [5, 23, 32, 33, 34, 35]. Flexibility in architecture refers to the ability of a space or building to accommodate change through the modification of physical elements such as movable and/or modular partitions, dry connections, etc. [36]. Flexible designs allow for different configurations or uses over time, providing options for users to adapt the space to their needs [9, 37, 38]. Adaptability, on the other hand, encompasses a broader range of factors beyond physical flexibility. It refers to the capacity of a building or space to respond effectively to changing **conditions** [30], **requirements** [39], or **contexts** over **time** [23, 40]. This may include changes in function, occupant needs, technological advancements, environmental considerations, or social dynamics. Adaptability involves not only the physical attributes of a building but also its ability to evolve and remain relevant in different circumstances [23, 35, 39, 41]. Therefore, the view of adaptability we focus on in the present study extends beyond mere physical flexibility, addressing a wide range of changes that may emerge over the course of a building's lifetime.

2.3. Adaptability Approaches in Architecture

Historically, adaptability became prevalent during the modernist movement through the work of architects such as Le Corbusier, Frank Lloyd Wright, and Mies van der Rohe, as a result of increased social change following the mid-nineteenth-century Industrial Revolution [28]. The modernist movement also pioneered a *functionalist* approach, emphasizing the *new objectivity* [42], which resulted in simple forms that expressed a building's structural and mechanical systems [10, 28, 32]. A certain degree of freedom in spatial design was introduced as a result of the adaptability approaches facilitated by frame construction [43]. Studies in literature that focused on adaptability strategies based their conceptual frameworks on the *Open Building* approach of Habraken [44], as *a viable alternative to the prevailing conventional practice of adopting a single program based on unsubstantiated projections through time, wrapping the result in built form and then knitting mechanical and structural systems into and around the functions,* [45] and the *Shearing Layers* approach of Brand [46], which assumed that the buildings were composed of several layers (site, structure, skin, services, space plan, and stuff) with different hierarchies and lifespans [32]. Schneider and Till [30] also proposed a governing principle of "hard" and "soft" elements in the building, with the former referring to the use of services and technology and the latter to the space itself, as the foundations for integrating adaptability strategies into the building. These three main approaches, which underpin the adaptability in buildings, in other words, *the shift from rigid functionalism to the capacity-for-change as a guiding principle* [47], were briefly discussed in the following subsections.

2.3.1. Open Building Approach

Mass housing constructed after the Second World War failed to adapt to social, economic, and technological changes due to their standard and rigid designs [48]. According to Dutch architect N. John Habraken [44], such a design approach stemmed from the was due to the perspective that the building industry needed to adopt methods based on standardization and repetition similar to the automobile industry, which led to the development of the alternative approach, that *supports theory* or the *open building* by Habraken in 1961 with the non-profit research group SAR (Stichting Architecten Research). They argued that the *housing problem* could be solved only when buildings accounted for change over time and inhabitant control was taken into consideration as a separate design task [44]. Later, the *open building* approach, which succeeded the *supports theory*, became an international movement based on the organization of levels in buildings and their technical and decision-making processes (Figure 1) [45]. Habraken argued that there existed a connection between the physical layers of the building and the hierarchical order of the environment [38]. The open building approach identified distinct levels of intervention in the built environment [49], from the macro to the micro levels, namely land use, fabric, support, support infill, layout, and planning (Figure 1). The changes at the macro levels impacted the lower levels of the hierarchy, however, a certain level of flexibility and change potential existed at the micro-levels [48]. The concept of levels distinguished control between support, which was not determined by occupants, and infill, which was determined by individual building occupants [50]. In other words, occupant control, which could be more flexible and responsive at the micro level (spaces), accommodated a greater potential for change (thus, adaptability), but had no influence on administrative decisions at the district, area, or block level [6], and vice versa. Therefore, the open building concept was considered a transformation mechanism that addresses adaptability through individualized characteristics [51].

The levels in the open building approach consider not only control and decision-making capacities but also long and short service life as a principle [6]. Building elements/components with long service lives, such as the structural system, building envelope, service systems, shafts, and circulation elements, were included in the support level and were required to be simple to construct, economical, and to allow flexibility at the infill level. Support level (with a lifespan of 100 to 200 years) is also common to all building occupants and any change at the infill levels

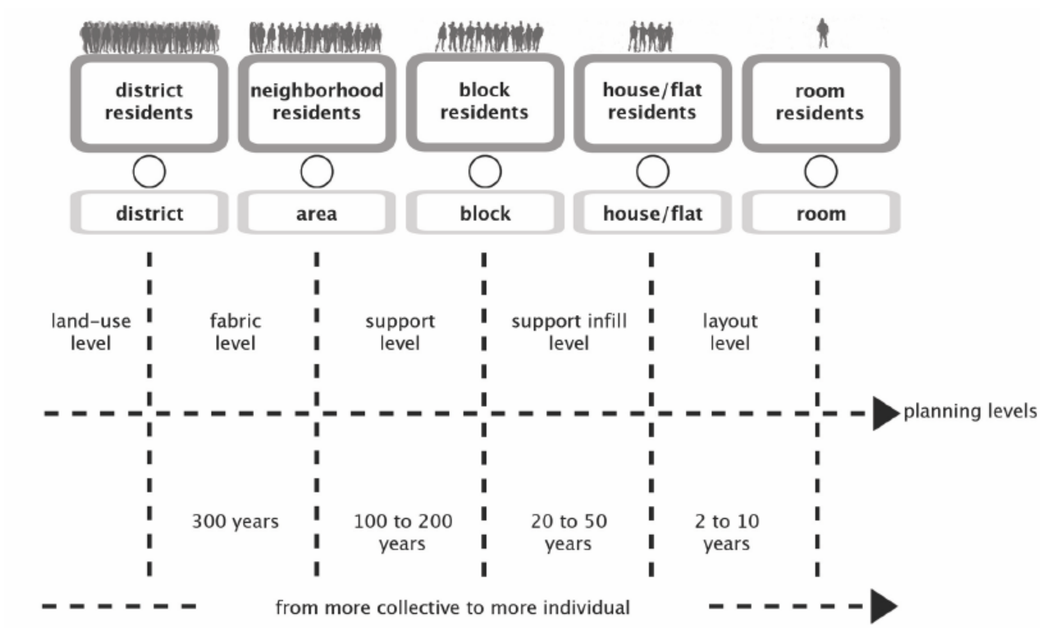

Figure 1.
Principle of Levels (Source: Authors. Adopted from Open Building Research Group, TU Delft, [50])

should not affect the support level [43]. Higher levels (i.e., support) also offer the degree of freedom for implementing adaptability at the infill level, which includes elements with shorter life spans, such as partitions, doors, finishings, circulation, and horizontal installations [39, 52]. Aside from the structural system and the options it provides for organizing the infill layers, other decision-making processes are involved in the building construction process. Examining the relationship between occupant control and the physical environment allows for the inclusion of the relationship between boundaries and occupant behavior [5] via decision-making at multiple levels, from collective to individual [6]. Contrary to the conventional approach, the open building approach seeks a balance between supply and demand [6, 10].

Since the 1970s, the open building approach has been popular in Japan, due to the shift in the construction technique from the traditional Japanese wooden structure to the reinforced concrete skeletal systems [53]. Several open building systems, such as the Kodan Experimental Project (KEP) [4, 53], Century Housing System [54], and open building schemes such as 'skeleton-infill' (SI) have been developed in Japan since the adoption of the open building approach [4]. Today, the CIB W104 working group and MANUBUILD maintain the open building approach on a global scale [48]. Although many projects have been carried out in various parts of the world using the approach, Schmidt III et al. [5] criticized the fact that open building was more focused on the design and utilization phases and did not take uncertainties such as time and change into account. As a result, despite its limitations in constraining adaptability primarily to the infill level [5], Habraken's method had a significant impact on adaptable architectural design [38].

2.3.2. The "Shearing Layers" Approach

A building is a collection of systems comprised of layers with variable service lives [21] and the individual building components are only partially interconnected [15]. Habraken's open building approach only considers levels of support and infill. Other approaches were also developed, such as categorizing building elements based on their degree of deterioration and assessing buildings hierarchically through layers. Frank Duffy [55] pioneered the "shearing layers" approach, arguing that the economics of a building change drastically over its service life. According to Duffy [55], building components should be classified based on their service life, as physical and temporal layers: *shells* (50 years), *services* (15 years), *scenery* (5 to 7 years), and *sets* (every day). Later, Brand [46] expanded on the *shearing layers* concept and identified six layers, namely the Site, Structure, Skin, Services, Space Plan, and Stuff (Figure 2), based on their differences in service life and overall effects. Of these six layers, *site* refers to the boundaries and context, which are *eternal* Duffy [55], as cited in [46], *structure* included foundation and load-bearing elements with a service life between 30 and 300 years, *skin* referred to the elements of the building envelope with an approximate service life of 20 years, services include the building installations with a service life between 7 and 15 years, *space plan* refers to the interior spatial layout with a service life between 3 and 30 years depending on the building function and *stuff* refers to furnishing with no definite service life (Figure 2) [46].

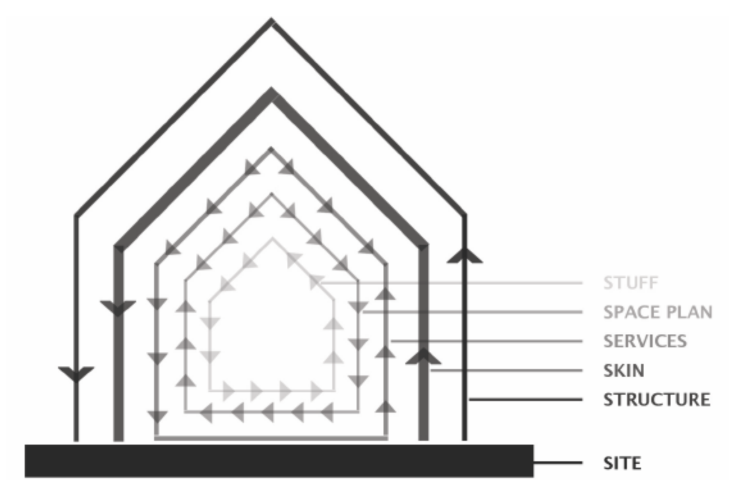

Figure 2.
The shearing layers approach (Source: Authors. Adopted from [46])

Sub-components within layers were also considered as building elements that could be changed without affecting the related layer. Layers can be physically separated or intersected through certain components. For instance, a roof as a building envelope component (part of the layer, *skin*) can also be a part of the *structure* layer or rely on the structural framework [19]. The characteristics and hierarchical order of the components and layers can be used as data in the analysis of a building's capacity to change.

The shearing layers approach was used and transformed by other researchers. The literature indicates varying scopes, systems, and subsystems for the layers approach, depending on the context and framework of the studies. Table 1 presents examples of the alternate uses of the shearing layers approach in literature. Slaughter, Sause, and Pessiki [56] investigated and characterized the interactions between building layers and components in 1997 to propose structural floor framing systems to accommodate nonstructural requirements such as installations. They included *structure, enclosure, service*, and *spatial/functional* layers (Table 1) as critical criteria concerning their performance indicators, such as strength, stability, serviceability, capacity, and versatility [56]. Ashbolt [57] adopted Brand's layers [46] with the inclusion of *circulation* as an additional layer. Abdullah and Al-Alwan [58] approach adaptability in architecture from the standpoint of smart material systems and the adaptive response of building components to the architectural environment, hence, the authors included "ambient" as an additional layer to Brand's shearing layers approach [46]. Ambient did not refer to a physical component but rather referred to internal environmental conditions such as illumination levels, thermal comfort, etc. [58].

Table 1.
Example studies that interpreted Brand's shearing layers approach [46]

Duffy [55]	Brand [46]	Slaughter, Sause, and Pessiki [56]	Ashbolt [57]	Abdullah and Al-Alwan [58]
	Site		Site	
	Structure	Structure	Structure	Structure
Shell	Skin	Enclosure	Skin	Outfit
Services	Services	Service	Services	Services
			Circulation	
Scenery	Space Plan	Spatial/ Functional	Space Plan	Infill
Sets	Stuff		Stuff	Interior
				Ambient

The changes that a building goes through over its service life are related to the organization of these layers and the level of flexibility and durability of the building elements. Elements with shorter service life are expected to have a higher flexibility level, whereas the elements with longer service life (i.e., structure) are expected to have a higher durability level [21]. Brand's *shearing layers* [46] were intended to increase a building's adaptability potential starting from the design phase. Given the potential for adaptability to contribute to the sustainability of the built environment [16], design decisions that facilitate building adaptability and flexibility towards change become critical.

2.3.3. Hard and Soft Use Approach

Schneider and Till [30] and Till and Schneider [59] introduced another approach to adaptability to enable social and physical change in the residential sector. They proposed a classification for different scales, from the block to the individual unit; however, did not delineate strict rules for designers and occupants. Schneider and Till [30] argued the design process of the buildings should be informed by occupant participation to achieve flexibility and adaptability in housing. Hence, the proposed classification was designated as *use (hard and soft) and technology (hard and soft)* [30]. Building use is related to occupancy characteristics and the layout's flexibility capacity. Soft use is a design approach that allows for uncertainties in space organization. The provision of a partible space in which standard modules are obtained through the centralized allocation of accessibility elements and specifically designated or distributed spaces for services is referred to as soft use [59]. The examples include the Britz in Berlin, designed by Taut and Wagner, with changing residential uses at different times of the day, and the Letna, a classic example of Czech Modernism, with its services located independently from other units and similar-sized spaces [59]. The approach was also used during Modernism due to the advances in structural systems and technologies that allowed structural clarity and open plans [60]. An early example was Mies van der Rohe's Weissenhof apartment building in Stuttgart, which was built in 1927 [59,61]. Later examples were Montereau by Les Frères Arsène-Henry (built in 1971), with a centralized service space and identical-sized apartments [62], and the 1953 Järnbrott Experimental Residence by Tage and Olsson in Sweden [59].

While soft use allows a degree of control for the inhabitants both during the design phase and service life of the building, hard use refers to a design approach largely determined by the architect. Hard use, as defined by the architect's control, is associated with the approaches of several twentieth-century architects, including Le Corbusier [59]. Le Corbusier's detached house project Maison Loucheur was designed for adaptability with transformable furnishing for day-night configurations [63]. Other examples for hard use were Wells Coates' The Lawn Road Flats with movable components and certain configurations, Gerrit Rietveld's Schröder House, and Carl Fieger's Kleinwohnung [59].

The other category, technology, which also included *hard* and *soft* aspects, was concerned with the effects of construction techniques, structural, and building service systems [59]. Hard technology refers to the layout organization of technologies (structure, installations, etc.) specifically to achieve flexibility. It has similarities with Habraken's open building approach, which focuses on technology and its applications in the building [59]. Contrary to the deterministic approach of hard technology, soft technology is considered as the *stuff* in the shearing layers approach, which enables spatial adaptability without the control of construction techniques Frame structural systems, flexible allocation of service systems, accessibility, elevated floors, suspended ceilings, installation walls are common approaches to soft technology [59]. An example is the Wohnanlage Genter Strasse by Otto Steidle, which allowed inhabitants to customize their flats before occupancy through a prefabricated reinforced concrete structural frame with ceiling panels called "Elementa" [59, 64].

Soft use and soft technology were considered an appropriate combination for adaptability and occupant participation in spatial change [37, 59]. A structural system that allows for long spans reduces the need for load-bearing walls while also allowing for soft use [59]. Multispace [65] is a soft use approach that meets a set of rules and, in particular, various functional demands, with designer and inhabitant control [5]. GlaxoSmithKline's Newways kit of parts concept, on the other hand, is a pre-configured component system to design the required building type [66] and is an example of the hard use approach, where the control is only available for the designer [5].

2.4. Overview

Despite a short overview presented in this section, building adaptability is highly studied within the context of the 21st century's social, environmental, and economic changes, with a more recent emphasis on sustainability [66]. However, Habraken questions why "after more than a century of attempts by architects to design with flexibility in mind, the issue is still marginal to the profession at large" [33]. The abovementioned approaches were well-known attempts to frame adaptability and flexibility in buildings, especially in housing. However, there is still a lack of applied frameworks for adaptability and flexibility in existing buildings. Commonly, adaptability approaches propose a theoretical framework through which they assess the fixed and flexible parts of a building [33]. Despite their differences in categorizing parts/components of a building based on their adaptability potentials, the abovementioned approaches also bear a strong similarity in their descriptive nature. Most approaches consider adaptability on the layout level and do not scrutinize the adaptability potentials three-dimensionally. Given the scope above, the present study presents an attempt to create a quantitative approach via a scoring system that can be used in evaluating the adaptability potential of existing buildings. The latter sections explain the methodology and the related case studies.

3. METHODOLOGY

The present study aims to develop an evaluation tool to assess the adaptability level in buildings, therefore, criteria set for adaptability strategies and parameters were developed based on an analysis of the literature. The building adaptability discourses and concepts in literature were identified and interpreted based on their frequency of use. The initial findings of the review indicated that the studies on building adaptability were structured around two levels of evaluation: strategies and parameters. Therefore, we examined strategies and parameters separately based on their potential to explain the concept of adaptability and frequency of use, and a criteria set was obtained by revealing their sub-relationships.

Figure 3 presents the methodological construct of the present study. An analysis of the literature was conducted to determine the studies that focused on at least one adaptability strategy and/or parameter and 33 studies that referred to the adaptability approaches and were frequently cited were identified. These studies referred to a total of 45 strategies in their discourses/conceptual frameworks (Table 2). We identified 17 structural/physical parameters taken into consideration in 19 of the 33 studies. The selected strategies and parameters were associated with developing the criteria set to assess the adaptability level in

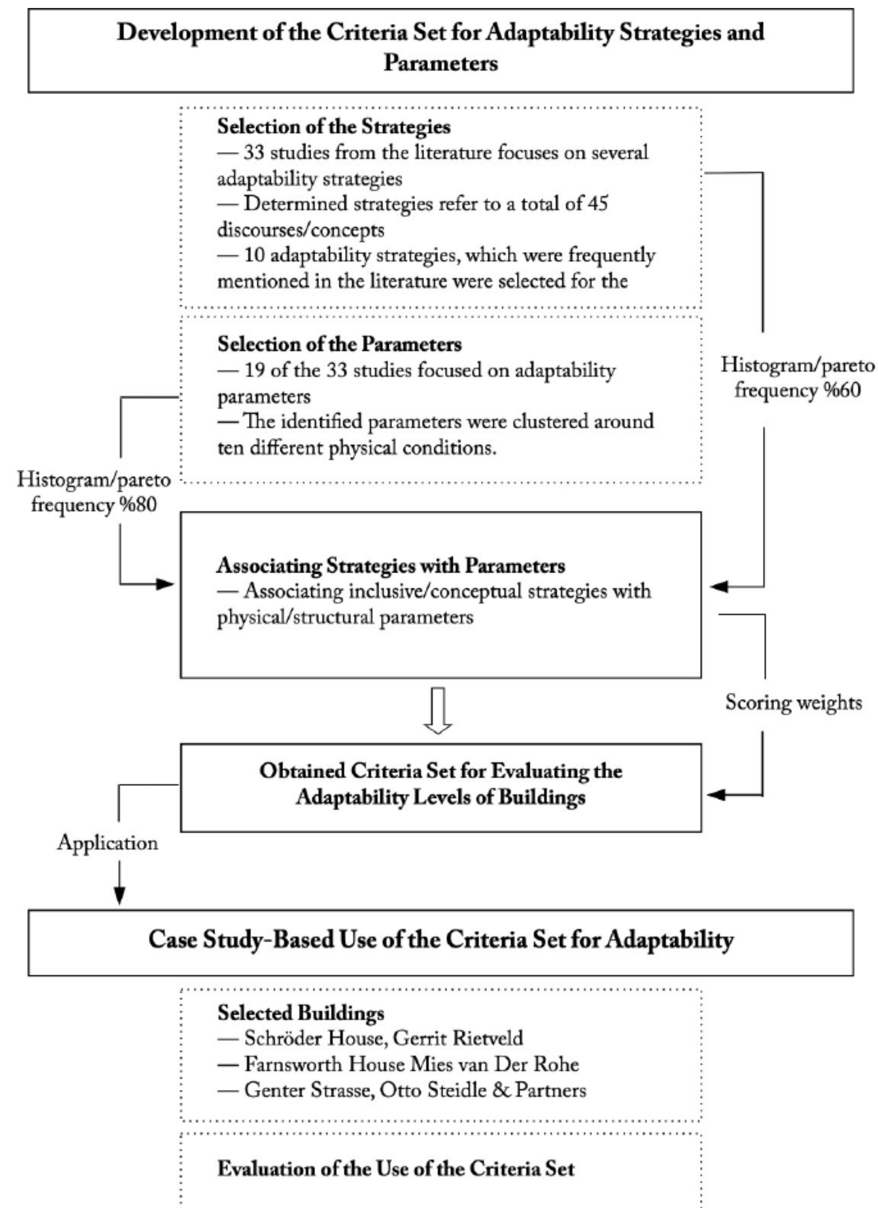

Figure 3.
The methodological framework of the study (Source: Authors)

buildings. The developed criteria-based evaluation tool was then demonstrated for its use in well-known adaptable examples such as the Schröder House, Farnsworth House, and Genter Strasse.

3.1. Development of the Criteria Set for the Evaluation of Adaptability in Buildings

The present section explains the approaches in selecting the adaptability strategies and parameters from the literature and in establishing their associations based on an expanded version of the shearing layers approach of Brand [46]: location (*site*), *structure*, layout (*space plan*), *services*, envelope (skin), elements, and reinforcements (*stuff*).

The scope of Manewa et al.'s [14] analysis was expanded based on the 33 selected studies, and a total of 45 strategies, specified 199 times, were identified (Table 2). The selected strategies for the evaluation criteria set were determined using histogram/Pareto analysis, which revealed the distribution of the frequency of use for the identified adaptability strategies (Figure 4). The cumulatively analyzed values revealed that ten strategies explained

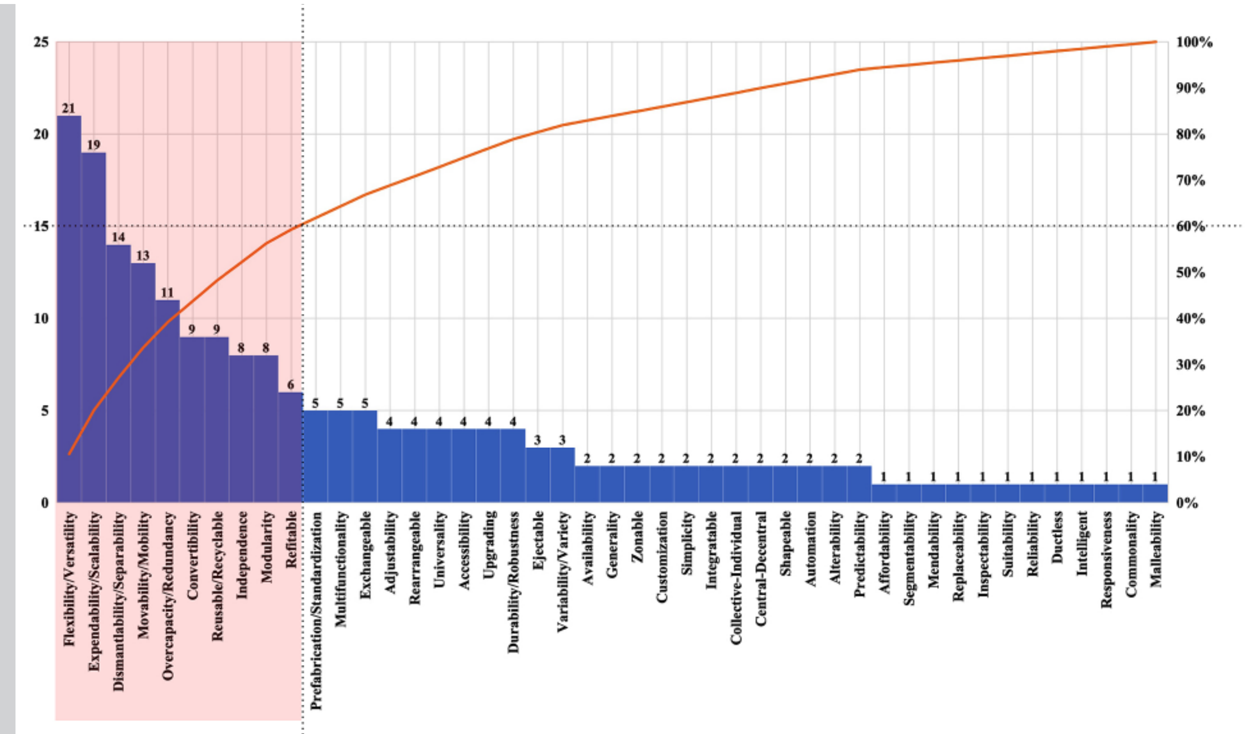

Figure 4.
Histogram/Pareto diagram for the frequency distribution of the identified adaptability strategies (Source: Authors)

more than 60% of the total variance, and these adaptability strategies were chosen for the evaluation criteria set. Since there existed no discriminating data to choose between the equally frequent strategies, the lower rate was determined as 60%. Strategies selected for the evaluation criteria set were *Flexibility/Versatility* (21; 10.6%), *Expandability/Scalability* (19; 9.5%), *Dismantlability/Separability* (14; 7.0%), *Movability/Mobility* (13; 6.5%), *Overcapacity/Redundancy* (11; 5.5%), *Convertibility* (9; 4.5%), *Reusable/Recyclable* (9; 4.5%), *Independence* (8; 4.0%), *Modularity* (8; 4.0%) and *Refitability* (6, 3.0%), respectively (Table 2, Figure 4).

Flexibility/Versatility was defined as the ability to transform the interior space [79, 80, 81] and to make small-scale changes to the interior space [2] for different uses. Schmidt III et al. [5] used *flexibility* in a similar sense to the concept of *versatility*. The ability of a building to expand horizontally or vertically [76], as well as the potential for change in building dimensions [57, 79, 80]were defined as ***Expandability/Scalability***. The ability to quickly and safely disassemble a building [12, 70] was referred to as ***Dismantability/Separability***, with an emphasis on the reuse of building components and the reduction of construction wastes [2, 75]. ***Movability/Mobility*** refers to the mobile or portable building components [57, 70, 78, 79, 80]. ***Overcapacity*** is defined as the excessive design of structural systems [75], floor heights, circulation, and service spaces [17] that are unlikely to be renewed. The continuation of a building with a function other than its original function is referred to as ***Convertibility*** [2, 5, 14, 57, 78]. ***Reusable/Recyclable*** are terms that refer to the reusability and recyclability of building components and elements [5,79]. The physical and functional separation of building components and systems in such a way that other components are not damaged during replacement is referred to as ***Independence*** [19, 75]. In a building, ***Modularity*** refers to independent modules, and clustering methods are used to systematize the module hierarchy and sub-relationships [26]. ***Refitability*** refers to the interchangeability of building parts [70].

Parameters include the spatial and structural features of a building and refer to tangible building elements, compared to the conceptual descriptions of adaptability strategies. The scope of Manewa et al. [14] was expanded for 19 selected studies, and a total of 17 parameters, specified 140 times, were identified (Table 3). Histogram/Pareto analysis was used to select the frequently used parameters for the evaluation criteria set (Figure 5). The cumulative analysis of the values revealed that 11 parameters explained more than 80% of the total expressions, and these

Table 2.
Distribution of adaptability strategies across 33 studies based on [14]

	Sources																																	
Strategies	[67]	[68]	[39]	[12]	[69]	[65]	[70]	[71]	[72]	[73]	[58]	[26]	[74]	[57]	[19]	[15]	[75]	[17]	[6]	[76]	[77]	[5]	[78]	[79]	[80]	[66]	[81]	[2]	[82]	[21]	[83]	[84]	[85]	Total
Generality			x																								x							2
Flexibility/Versatility			x	x	x	x		x	x	x		x	x	x								x	x	x	x	x	x	x	x	x		x	x	21
Expendability/Scalability		x	x	x		x	x	x	x					x					x	x	x	x	x	x	x	x	x	x	x	x				19
Convertibility				x		x		x	x					x							x	x	x					x						9
Dismantlability/Separability		x		x			x		x	x					x	x	x		x	x	x							x	x	x				14
Prefabrication/Standardization	x								x		x				x	x																		5
Overcapacity/Redundancy	x						x						x		x	x	x	x	x	x									x	x				11
Movability/Mobility	x					x	x		x		x			x					x	x		x	x	x	x	x								13
Rearrangeable	x						x												x	x														4
Reusable/Recyclable		x		x		x			x		x						x						x	x	x					x				9
Refitability						x																x	x	x	x	x								6
Multifunctionality							x						x						x	x									x					5
Integratable		x																	x															2
Universality							x							x					x	x														4
Modularity			x				x		x			x		x			x		x	x														8
Ejectable							x								x	x																		3
Exchangeable							x								x	x			x	x														5
Customization												x																					x	2
Upgrading												x																x	x				x	4
Variability/Variety												x		x																			x	3
Zonable																			x	x														2
Availability																								x	x	x								3
Adjustability																			x	x		x	x											4
Durability/Robustness																				x								x	x		x			3
Accessibility															x	x	x											x						4
Simplicity																												x	x					2
Independence					x						x				x	x	x											x	x	x				8
Collective-Individual																			x	x														2
Central-Decentral																			x	x														2
Shapeable																			x	x														2
Automation											x								x															2
Alterable																			x	x														2
Predictability															x	x																		2
Affordability																													x					1
Segmentability																																	x	1
Mendability																															x			1
Replaceability																															x			1
Inspectability																															x			1
Suitability																																x		1
Reliability																																x		1
Ductless																			x															1
Intelligent																			x															1
Responsiveness														x																				1
Commonality																	x																	1
Malleability																					x													1

were selected for the evaluation criteria set: Structural design/slabs/loads (14; 10.0%), plan organization (14; 10.0%), floor height (12; 8.6%), technical span (11, 7.9%), core/vertical circulation (11, 7.9%), service spaces (10; 7.1%), envelope design (10; 7.1%), building dimensions and height (9; 6.4%), mechanical, electrical, IT and HVAC installations (8; 5.7%), location/accessibility/orientation/proximity (7; 5.0%), and partitions/walls (7; 5.0%).

Table 3.
Distribution of adaptability parameters across 19 studies, adopted from [14]

Layers	Parameters	Sources																			
		[86]	[67]	[87]	[15]	[7]	[2]	[76]	[81]	[39]	[88]	[59]	[65]	[72]	[89]	[13]	[79]	[57]	[78]	[90]	Total
Location	Location/accessibility/ orientation/proximity							x	x				x		x	x		x		x	7
Structure	Building dimensions and height		x			x		x		x			x		x		x	x		x	9
	Structural design/slabs/loads		x		x	x		x	x		x		x	x	x	x	x	x	x	x	14
	Floor height	x		x			x	x	x	x		x	x		x	x	x			x	12
	Technical span				x		x		x	x		x			x	x	x	x	x	x	11
	Core/vertical circulation	x	x		x	x	x					x	x		x	x		x		x	11
Layout	Plan organization	x	x		x	x	x	x		x		x		x		x	x	x	x	x	14
	Circulation (horizontal)	x			x	x										x					4
	Plan depth		x			x							x		x			x			5
	Partitions/walls				x		x		x			x				x	x		x		7
Services	Service spaces				x		x		x	x	x	x			x	x	x		x		10
	Mechanical, electrical, IT, and HVAC installations	x	x		x	x			x	x	x				x						8
	Fire safety design		x		x					x	x		x								5
Envelope	Envelope design	x	x		x	x	x				x		x			x		x		x	10
Elements	Connection types						x	x						x		x	x		x		6
	Selection and availability of building elements/standard/ prefabricated/product family/Plug-and-play construction elements									x						x	x		x		4
Reinforcements	Furnishings/stackable and movable units/non-fixed objects															x	x		x		3

Structural design/slabs/loads are significant for the adaptability of the buildings based on their type, dimensions, and layout. The capacity to compensate vertical and lateral attachments [12,13]; connections that prevent collapse, electrical and mechanical service distribution schemes to adapt to different uses [2]; dry connections, partitionable structural design [13]; and the establishment of new service layouts [67] are all related to the structural design, slabs and loads. Multifunctionality, horizontal and vertical overcapacity of spaces [2, 13], increased spatial efficiency and continuity of spaces, buffer zones, modular design [13], loose fit approach in interior design [2, 59], and locating main functions around service spaces [67] are issues considered in **plan organization**.

Function, structural system, service spaces, and height limitations in the building codes are the factors [65]that are related to **floor height**. Buildings with increased floor height and structural spans are easier to adapt to different functions [2, 59, 76]. According to Kincaid [74], increased floor height may be uneconomical in the short term but beneficial for adaptability in the long term. **Technical span** refers to the axial arrangement in the structural system. In terms of providing subdivisions and responding to different uses [65], grid structural designs without uneconomical long spans [2] are preferable. Stairs, service cores, and entrances are all part of the **core** and **vertical circulation** design. Service and circulation areas, as well as core locations, should be designed so that the structure can expand vertically or horizontally and be divided into various functional units [13]. Locating cores at building ends provides an uninterrupted and spacious interior [15], whereas the central core allows spatial transformations along the façade line [59] and makes spatial changes while maintaining structural integrity [2]. The capacity of circulation spaces is determined by the density of occupants and the function of the building [67]. **Service spaces** accommodate building service systems. Modular and/or detachable installation systems [13], ducts for vertical service elements [59], raised floors, and/or suspended ceilings for the horizontal distribution of service elements [15, 59] increase the adaptability level of buildings. **Envelope design** should ensure that changes in the interior do not affect the façade (such as double façade systems), allow for different uses, properly control the interaction between façade modules and physical and visual access [13], should be accessible from the interior and exterior space, independent from the structural system [2, 13], and allow retrofit and maintenance [15]. **Building dimensions and height** influence the number of units and occupant density, as well as a building's adaptability in terms of function and density [67]. Overdesign of vertical shafts to accommodate additional mechanical and electrical services [15], sizing of drainage and pipelines to meet additional

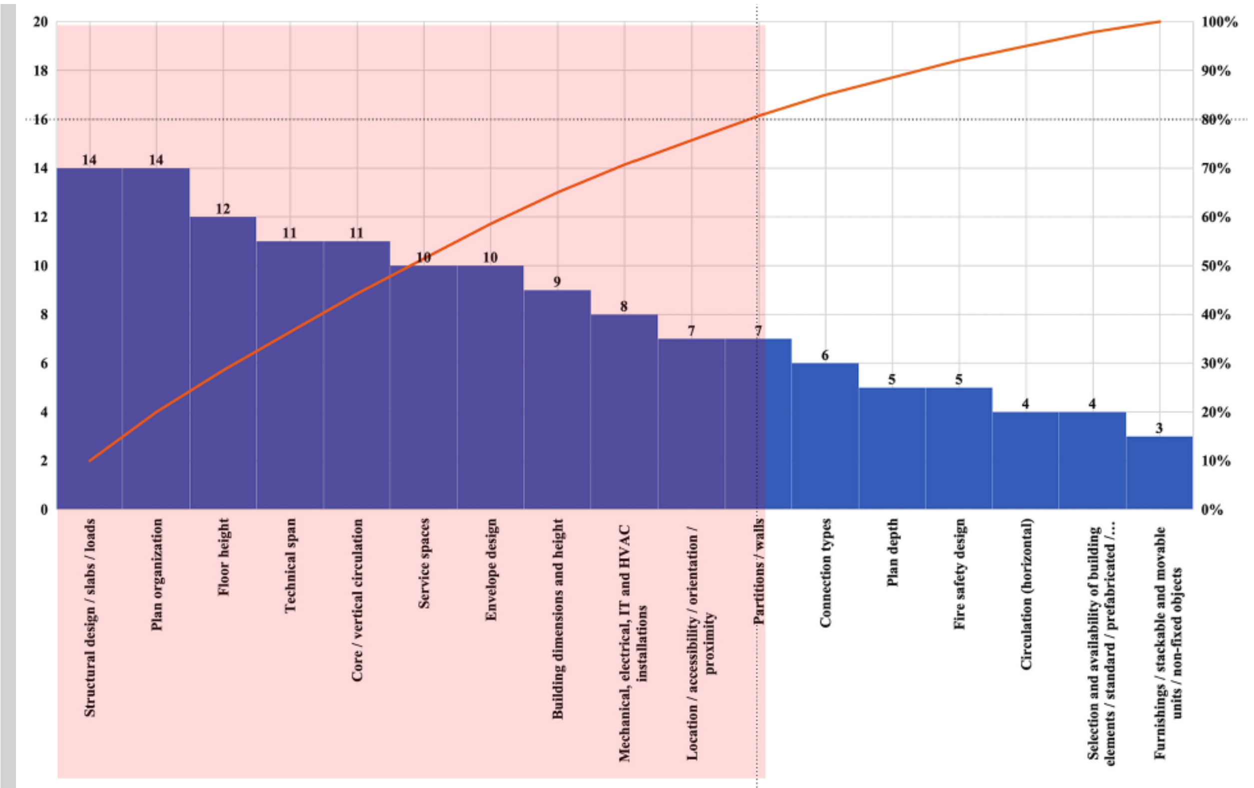

Figure 5.
Histogram/Pareto diagram for the frequency distribution of the identified adaptability parameters (Source: Authors)

uses [12], mechanical ventilation in deep-plan buildings [67], and decentralized distribution of service spaces to accommodate system control in the event of further spatial divisions [79] are **mechanical, electrical, IT, and HVAC installation** decisions that contribute to the adaptability of buildings. Building **location, accessibility, orientation**, and **proximity** include spatial requirements around the building to accommodate future facilities such as parking, pedestrian and vehicle access [12], and to prevent interruption during major works [13]. To support building adaptability, interior **partitions/walls** should be non-loadbearing [59], removable, reusable, and lightweight [2, 13].

3.2. Associating Strategies and Parameters: Determination of the Scoring System

The literature explains the relationships between adaptability strategies and parameters based on a building's spatial and structural features [14]. The present study focuses on the relationships between the 10 adaptability strategies and the 11 adaptability parameters included in the evaluation criteria set. Therefore, 5 of the *shearing layers* [46], respectively, location, structure, layout, services, and envelope, were used as the grouper of the relationship matrix, and the 11 physical parameters were classified under the layers (Table 4). The ***location*** layer included building location/accessibility/orientation/proximity, the ***structure*** included building dimensions and height, structural design/slabs/loads floor height, technical span, and core/vertical circulation, the ***layout*** layer included plan organization and partitions/walls, ***services*** included service spaces and installation elements, and the ***envelope*** layer included double skin facades, modular/panel systems, independent, universal, and irregular systems.

Parameters were studied to delineate their physical equivalents as building features, which were covered in the literature. The physical attributes of a building were then associated with the strategies (Table 4). Steel structural systems (9), modular and panel facade systems (8), prefabricated reinforced concrete frame systems (7), steel stairs (7), raised floors (7), and suspended ceilings (7) were the physical attributes that were frequently associated with the selected 10 strategies (Figure 6). Movable/rearrangeable and fixed partitions and double skin facades were also

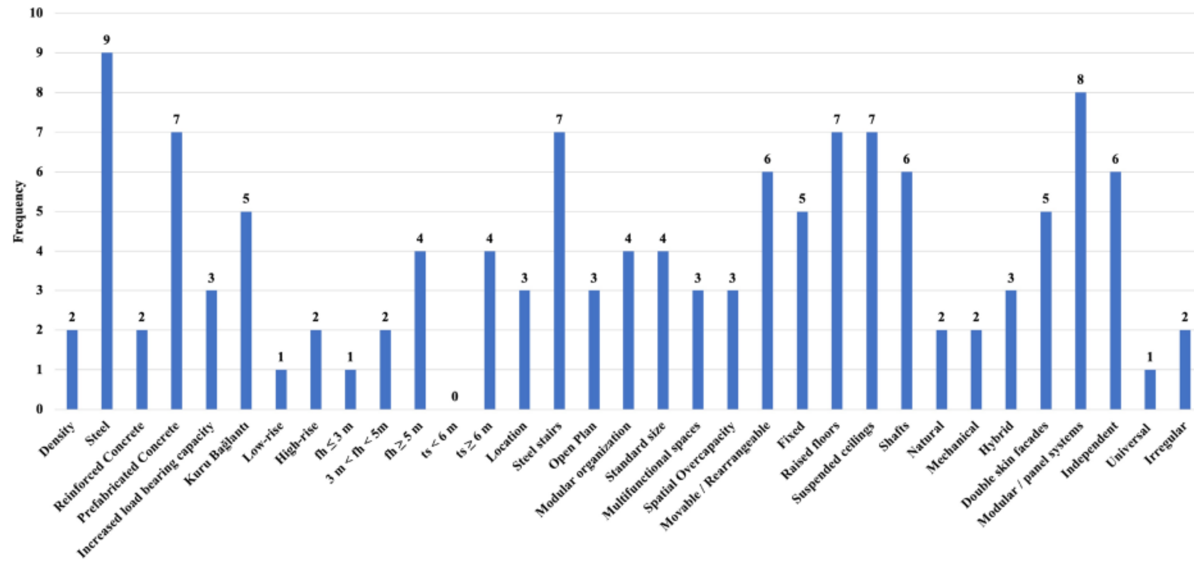

Figure 6.
Frequency of physical attributes of buildings within the scope of adaptability strategies (Source: Authors)

other physical attributes associated with the strategies (Figure 6), while shafts and independent facades were associated with 5 strategies. Table 4 indicates the strategies that were highly associated with the physical attributes; Flexibility/Versatility (26/33), Convertibility (26/33), Scalability (15/33), and Independence (15/33), respectively.

The score matrix presented in Table 4 was obtained by a simple weighted scoring system based on the frequency of adaptability and strategies in the literature. The frequency of adaptability strategies and parameters (X) was converted into a score of X/10. For instance, Flexibility/Versatility, with a 10.6% frequency in literature was assigned as $k_{strategyFlex} = 10.6/10 = 1.06$ points, or location/accessibility/orientation/proximity, with a frequency of 5%, was assigned as 0.5 points. The physical attribute/parameter score was calculated by multiplying the parameter scores separately with the associated adaptability strategies' scores. Total attribute scores were obtained via the sum of values for each attribute/strategy score. The maximum adaptability score for a building is 65.63, but this is only possible if the building meets all of the sub-parameters/physical attributes. If a building has an open plan, modular organization, and multifunctional spaces, the total floor plan/space organization parameter score is the sum of the scores of 1.91, 2.96, and 1.91, respectively. Flexibility/Versatility (a total of 21.84 points) explained 33.28 percent of the total score, Scalability (a total of 11.25 points) explained 17.14 percent of the total score, and Convertibility (a total of 8.81 points) explained 13.42 percent of the total score.

The main goal of the evaluation criteria set is not to score structures and assign them adaptability levels such as low, medium, or high; rather, the goal is to reveal the relationship between strategies and parameters through scoring by assessing physical parameters and determining which strategies contribute to adaptability and to what extent. In this respect, the adaptability evaluation criteria established in the present study is a qualitative assessment tool rather than a quantitative scoring system.

4. CASE STUDIES: THE USE OF THE ADAPTABILITY EVALUATION CRITERIA SET

In this section, an evaluation was conducted on Gerrit Rietveld's Schröder House, Mies van der Rohe's Farnsworth House, Otto Steidle & Partners' Genter Strasse, Alejandro Aravena and Elemental's Quinta Monroy Housing Project, and ANA Architecten's Het SchetsBlok using the developed adaptability evaluation criteria set. Table 5 provides a summary of the scores assigned to the selected examples. The assessment of the case studies was based on the weighted adaptability strategy and parameter scores established within the adaptability evaluation criteria set. The following subsections delve into the use of the adaptability evaluation criteria set in the adaptability evaluation of the abovementioned architectural examples from different eras and traditions.

Table 4.
Weighted scores of the associated adaptability strategies and parameters ($k_{strategy}$ x $k_{parameter}$)

			Strategies										
Layers	Parameters	Physical Attributes	Flexibility/Versatility 1.06P]	Expandability/Scalability [0.95P]	Dismantlability/Separability [0.70P]	Movability/Mobility [0.65P]	Overcapacity/Redundancy [0.55P]	Convertibility [0.45P]	Reusable/Recyclable [0.45P]	Independence [0.40P]	Modularity [0.40P]	Refitability [0.30P]	Sub-parameter Score
Location	Location/accessibility/ orientation/proximity [0.50P]	Low-density		0.48				0.23					0.71
Structure	Building dimensions and height [0.64P]	Low-rise						0.29					0.29
		High-rise					0.35	0.29					0.64
	Structural design/slabs/loads [1.00P]	Steel	1.06	0.95	0.70	0.65	0.55		0.45	0.40	0.40	0.30	5.46
		Reinforced Concrete	1.06							0.40			1.46
		Prefabricated Concrete	1.06		0.70	0.65			0.45	0.40	0.40	0.30	3.96
		Increased load-bearing capacity		0.95			0.55	0.45					1.95
		Dry connections		0.95	0.70				0.45	0.40		0.30	2.80
	Floor height [0.86P]	fh < 3 m	0.91										0.91
		3 m fh < 5m	0.91					0.39					1.30
		fh 5 m	0.91	1.01			0.47	0.39					2.78
	Technical span [0.79P]	ts < 6 m											0.00
		ts 6 m	0.84	0.75			0.43	0.36					2.38
	Core/vertical circulation [0.79P]	Centralized	0.84	0.75				0.36					1.95
		Steel structure stairs	0.84		0.55	0.51			0.36	0.32	0.32	0.24	3.14
Layout	Plan organization [1.00P]	Open plan	1.06					0.45		0.40			1.91
		Modular organization	1.06	0.95				0.45			0.40		2.86
		Standard size	1.06	0.95				0.45			0.40		2.86
		Multifunctional spaces	1.06					0.45		0.40			1.91
		Spatial Overcapacity	1.06					0.45					2.06
	Partitions/walls [0.50P]	Movable/ Rearrangeable	0.53	0.48				0.23		0.20	0.20		1.97
		Fixed	0.53	0.48				0.23		0.20		0.15	1.59
Services	Service spaces [0.71P]	Raised floors	0.75					0.32		0.28	0.28	0.21	2.80
		Suspended ceilings	0.75					0.32		0.28	0.28	0.21	2.80
		Shafts	0.75	0.67				0.32		0.28		0.21	2.62
	Mechanical. electrical. IT. and HVAC installations [0.57P]	Natural	0.60					0.26					0.86
		Mechanical	0.60					0.26					0.86
		Hybrid	0.60	0.54				0.26					1.40
Envelope	Envelope design [0.71P]	Double skin facades	0.75	0.67				0.32		0.28	0.28		2.30
		Modular/panel systems	0.75	0.67				0.32	0.32	0.28	0.28	0.21	3.33
		Independent	0.75					0.32	0.32	0.28		0.21	2.38
		Universal	0.75					0.32					0.32
		Irregular	0.75					0.32					1.07
		TOTAL	21.84	11.26	4.65	3.06	3.29	8.81	2.35	4.8	3.24	2.34	65.63

4.1. Adaptability Evaluation of the Schröder House

The Schröder House was designed by Gerrit Rietveld in 1924 in Utrecht and was considered one of the iconic examples of the De Stijl movement and modern architecture with its spatial organization, furniture design, and façade [91]. The house was built next to traditional three-storey row houses [92].

The Schröder House accommodates spatial transitions via distinct planar elements, and the interior space's continuity was articulated and adapted to different uses via sliding and pivoted surfaces (movable partitions, Figure 7), which allowed the occupants to perform spatial transformations [91]. The lower level has a traditional layout, whereas the upper level of the Schröder House (Figure 7) was designed as a relatively open and multi-purpose space with movable partitions situated between the fixed partitions and the exterior walls and structural elements [93]. Hence three different spaces could be combined during the day and used in an open plan and the closing of the partitions allowed spatial privacy when required [93]. Non-load-bearing and movable partition walls contribute to the *Flexibility/Versatility, Independence, Separability, Scalability, Convertibility*, and *Refitability* of the Schröder House.

Vertical circulation was centralized on the layout and

Table 5.
Scoring of the case studies based on the weighted adaptability strategies and parameters

Layers	Parameters	Physical Attributes	The Scröder House Gerrit Rietveld 1925	The Farnsworth House Mies van der Rohe 1951	Genter Strasse Otto Steidle & Partner 1972	Quinta Monroy Alejandro Aravena 2003	Het SchetsBlok ANA Architecten 2018
Location	Location/accessibility/orientation/ proximity	Low-density	0.71	0.71	0.71	0.71	0.71
Structure	Building dimensions and height	Low-rise	0.29	0.29	0.29	0.29	
		High-rise					0.64
	Structural design/slabs/loads	Steel	5.46	5.46			
		Reinforced Concrete	1.46	1.46		1.46	1.46
		Prefabricated Concrete			3.96		
		Increased load-bearing capacity			1.95	1.95	1.95
		Dry connections			2.80		
	Floor height	fh < 3 m				0.91	
		3 m ≤ fh < 5m	1.30	1.30	1.30		1.30
		fh ≥ 5 m					
	Technical span	ts < 6 m			0.00	0.00	
		ts ≥ 6 m	2.38	2.38			2.38
	Core/vertical circulation	Centralized	1.95		1.95	1.95	1.95
		Steel structure stairs			3.14	3.14	
Layout	Plan organization	Open plan	1.91	1.91		1.91	1.91
		Modular organization		2.86	2.86	2.86	2.86
		Standard size			2.86	2.86	
		Multifunctional spaces	1.91	1.91		1.91	
		Spatial Overcapacity			2.06	2.06	2.06
	Partitions/walls	Movable/Rearrangeable	1.97			1.97	1.97
		Fixed	1.59	1.59	1.59	1.59	1.59
Services	Service spaces	Raised floors					
		Suspended ceilings	2.80	2.80			
		Shafts	2.62		2.62		2.62
	Mechanical. electrical. IT. and HVAC installations	Natural	0.86	0.86	0.86	0.86	0.86
		Mechanical					
		Hybrid					
Envelope	Envelope design	Double skin facades					2.30
		Modular/panel systems	3.33		3.33		3.33
		Independent	2.38	2.38	2.38	2.38	2.38
		Universal	0.32	0.32	0.32	0.32	0.32
		Irregular			1.07	1.07	1.07
		TOTAL	33.24	26.23	33.67	30.20	31.71

the main spaces were situated along the façade line, thus, there was no need for mechanical ventilation. Vertical shafts and the horizontal distribution of the installation elements ensured via the suspended ceiling facilitated maintenance and repair without affecting other building elements (Figure 7). The façade was designed with an independent structural system from the structure of the building and with a modular arrangement of the transparent envelope surfaces, which facilitates change in the facade (Table 5). The structural system of the Schröder House consists of reinforced concrete slabs and steel profiles [92, 93].

The Schröder House was scored based on its physical attributes (Table 5). For instance, the low-density

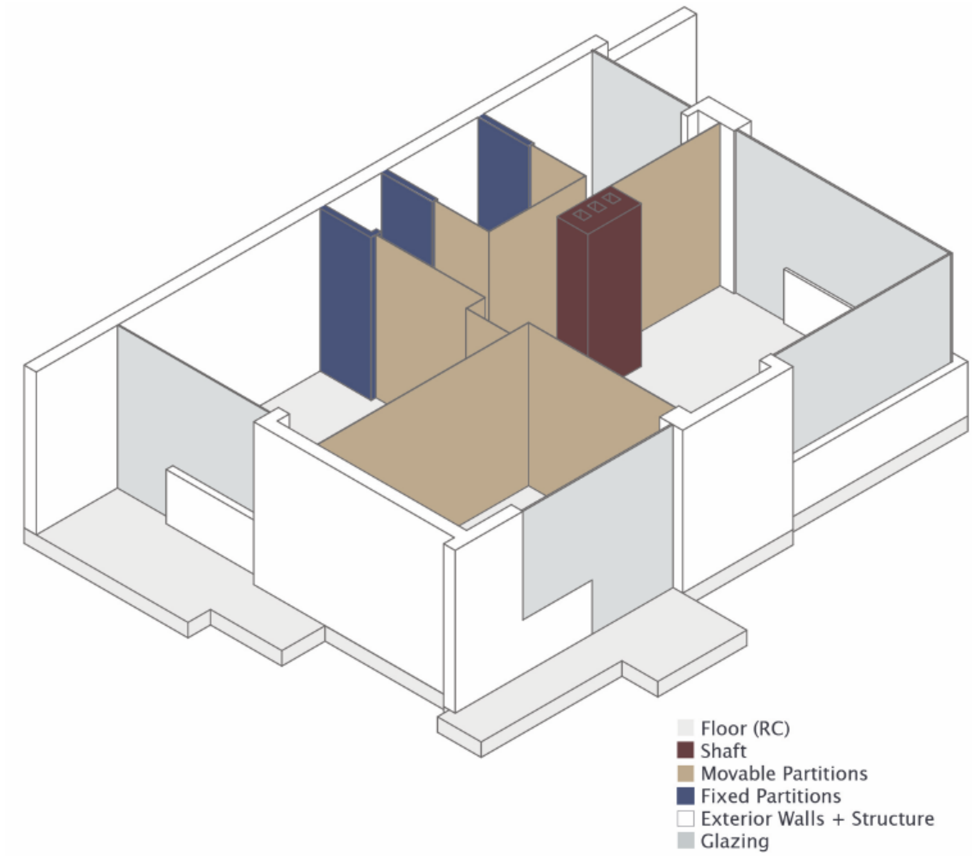

Figure 7.
The layers that augment the adaptability characteristics of the Schröder House (Source: Authors)

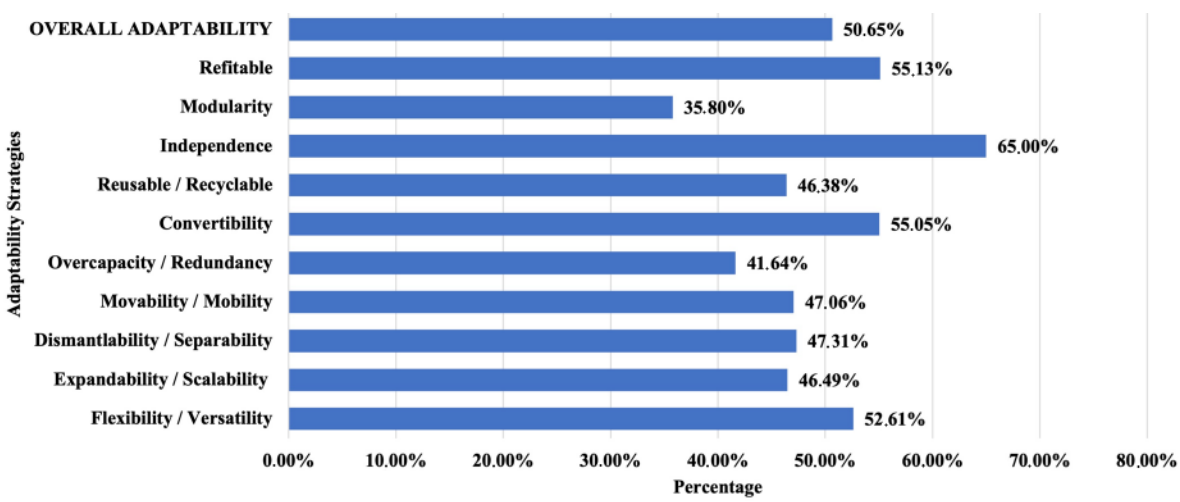

Figure 8.
The overall adaptability score and strategy scores of the Schröder House (Source: Authors)

score is a function of the adaptability parameter "location/accessibility/orientation/proximity" and adaptability strategies "scalability" and "convertibility" (Table 3). Therefore, the open space on three sides of the building corresponded to the *low-density* score, while the *low-rise* score was assigned based on the two-storeys of the building. Structure scores were based on the *steel* and *reinforced concrete* slabs used in the structural design of the building, and *floor height* was scored based on the three-meter height. The

Figure 9.
The Farnsworth House (Source: Author, Basak Gucyeter)

technical span was seven meters, and the centralized layout of the vertical circulation was scored as well. The *open plan* approach and spatial *multifunctionality* were scored separately to address both the spatial and the functional aspects of adaptability; hence, the partition elements, *fixed* and *movable*, were scored within the same scope. For services and installations, the *suspended ceiling* system, *shafts*, and *natural ventilation* were scored. The glazing and opaque elements of the envelope were scored for their *modularity, independence*, and *universality* (Table 5).

Figure 8 presents the percentage of score distribution for individual adaptability strategies and the overall adaptability of the Schröder House. The overall adaptability score of the Schröder House was 33.24 over a total score of 65.63 (50.65%, Figure 7). For individual adaptability strategies, the highest score was identified for Independence, as 3.12 over a total score of 4.80 (65.00%, Figure 8), based on the following physical attributes: steel and reinforced concrete construction, open plan and multifunctional spaces, movable/rearrangeable and fixed partitions, suspended ceiling and shafts, modular, panel, and independent envelope systems. *Refitability* and *Convertibility* were scored as 1.29 (55.13%, over a total score of 2,34) and 4.85 (55.05%, over a total score of 8.81), respectively (Figure 8, Table 3). *Flexibility/Versatility* was scored as 11.49 over a total score of 21.84 (52.16%, Figure 8). The adaptability strategy with the lowest score was *Modularity*, with a score of 1.16 over 3.24 (35.80%, Figure 8).

4.2. Adaptability Evaluation of the Farnsworth House

The Farnsworth House was built in Illinois by Mies van der Rohe between 1945 and 1951 and became one of the most prominent symbols of 20th-century modern architecture due to its structural clarity and minimalist approach [94]. Two rectangular planes of different sizes, one of which is an open terrace and the other enclosed by transparent surfaces, are offset from the ground by steel columns (Figure 9). The interior space was designed as an open plan around a central core (Figure 10) and the fixed interior partitions between the core and the main space were used as furniture [95]. The structure of the Farnsworth House was designed with a precast concrete floor and roof supported by steel frame elements [96]. A suspended ceiling is attached to the steel beams that support the roof slab [97]. The steel frame structure, centralized service spaces, and the limited use of partition elements increased the *Flexibility/Versatility*, *Convertibility*, and *Independence* of the building. The envelope is designed with transparent elements which were arranged independently of the building function (Figure 10).

The Farnsworth House was scored based on its physical attributes (Table 5). The freestanding building was scored for *low-density* and *low-rise* based on its contextual and massing decisions. The steel frame and reinforced concrete slabs were scored for *structure*, and the *floor height* score was based on the three-and-a-half meters height. The *technical span*

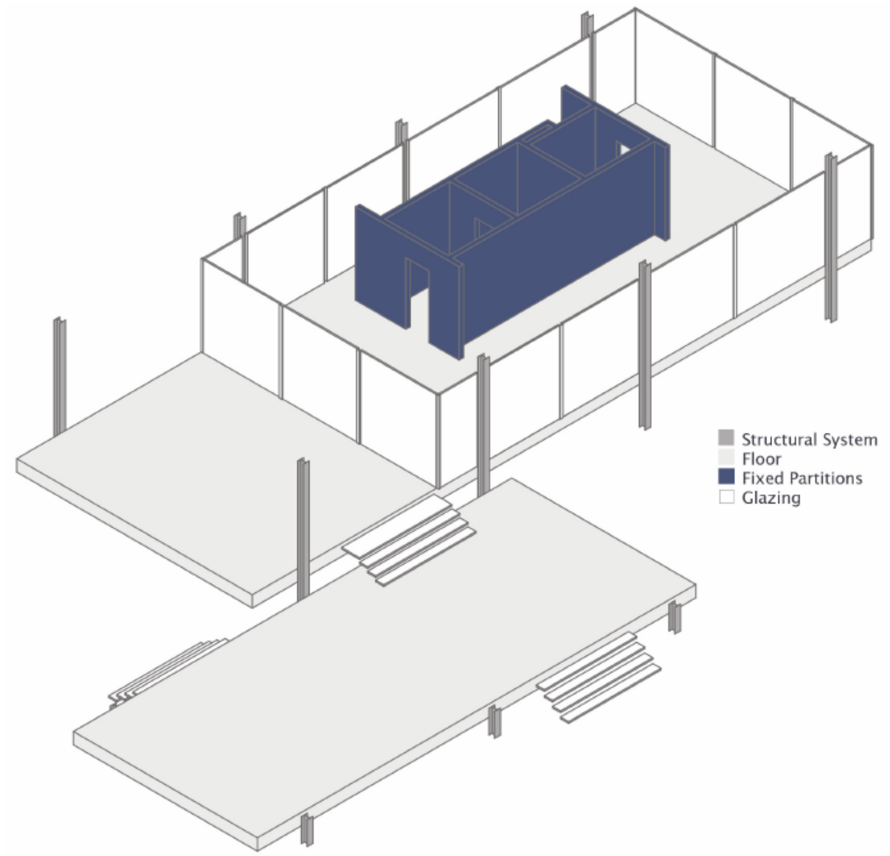

Figure 10.
The layers that augment the adaptability characteristics of the Farnsworth House (Source: Authors)

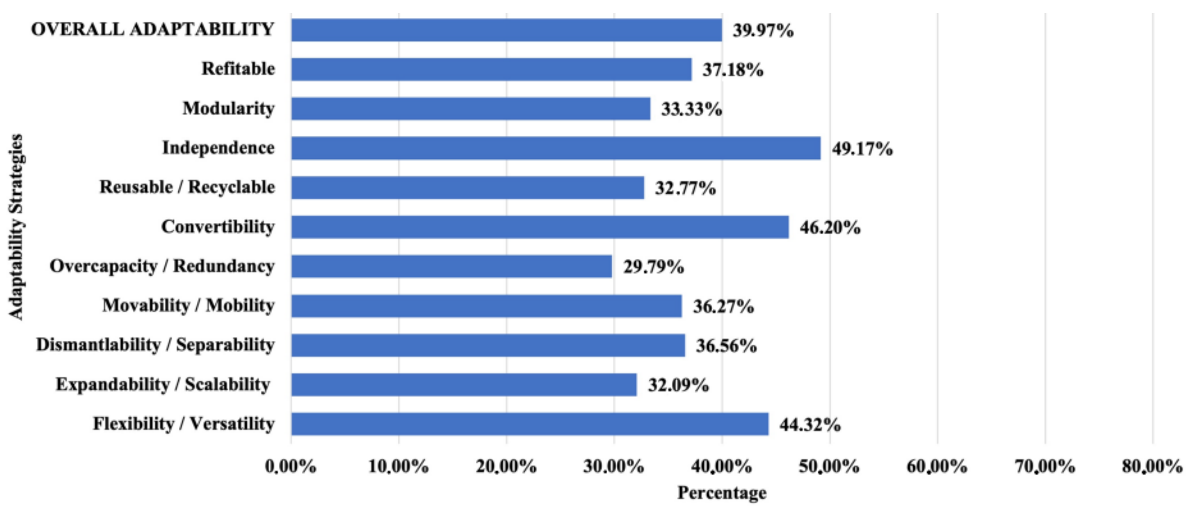

Figure 11.
The overall adaptability score and the adaptability strategy scores of the Farnsworth House (Source: Authors)

was nine meters and allowed *open plan*, *modularity*, and spatial *multifunctionality*, which were separately scored to address the spatial adaptability potentials of the Farnsworth House. The partition elements were limited in number and *fixed* to enclose the service spaces. Suspended ceiling was the main design decision to accommodate installations and the building was *naturally ventilated*. The envelope was fully glazed and was scored for *independence* and *universality* (Table 5).

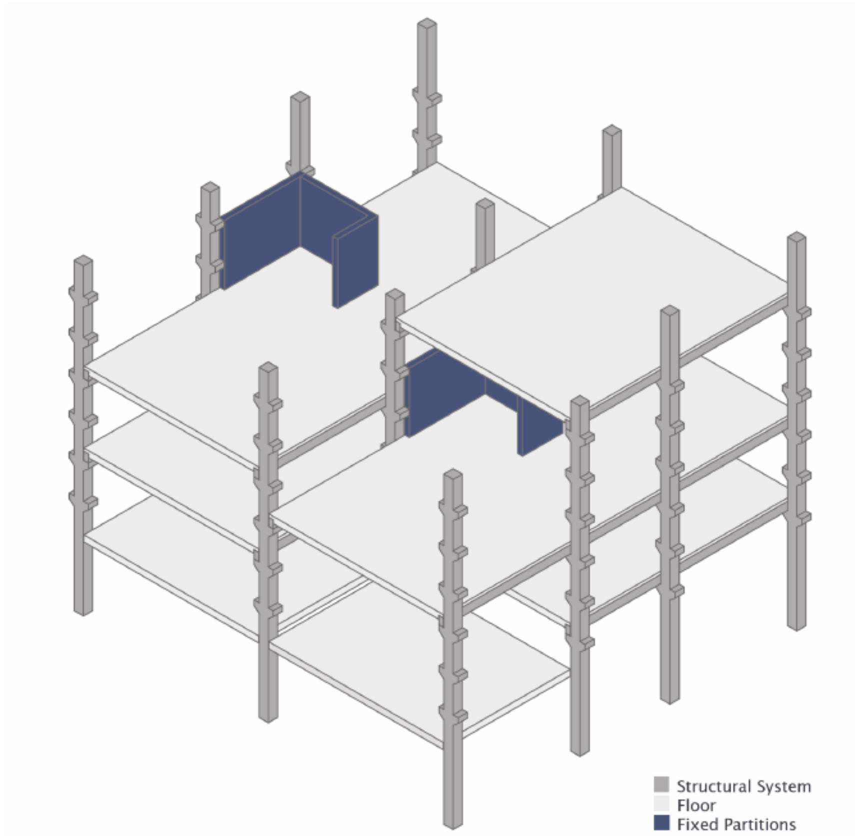

Figure 12.
Layers that augment the adaptability characteristics of the Genter Strasse (Source: Authors)

The percentage of score distribution for individual adaptability strategies and overall adaptability of the Farnsworth House is presented in Figure 11. The overall adaptability score of the Farnsworth House was 26.23 over a total score of 65.63 (39.97%, Figure 11). The highest score for individual strategies was identified for *Independence*, 2.36 over a total score of 4.80 (49.17%, Figure 11), and the scored physical attributes were steel and reinforced concrete construction, open plan, and multifunctional spaces, fixed partitions, suspended independent facade elements. *Convertibility* and *Flexibility/Versatility* were scored as 4.07 over a total score of 8.81 (46.20%) and 9.68 over a total score of 21.84 (44.32%), respectively (Figure 11). The adaptability strategy with the lowest score was Overcapacity, with a score of 0.98 over 3.29 (29.79%, Figure 11). The Farnsworth House is a single-storey building; hence, the adaptability score is lower due to the lack of shafts and vertical circulation elements. The steel frame structure and the suspended ceiling support multiple adaptability strategies such as *Flexibility/Versatility, Convertibility, Independence*, and *Refitability*.

4.3. Adaptability Evaluation of the Genter Strasse

Otto Steidle's Genter Strasse houses were constructed between 1967 and 1972 in a densely populated area of Munich. In the first phase of the project, Steidle collaborated with Doris Thut, Ralph Thut, and Jens Freiberg; in the second phase, he collaborated with Eckardt Böck and Gerhard Niese; and in the third phase, he collaborated with Roland Sommerer and Jens Freiberg. The project employed a variety of methods and solutions, with lightweight construction and prefabrication being the most important design approaches [98]. Load-bearing and non-load-bearing elements are visually distinguished in the building. Occupants can transform the spaces to meet their changing needs [99]. The adaptable organization of the prefabricated structural elements and the fixed partitions were partially presented in Figure 12.

The structural system is a prefabricated modular reinforced concrete frame. Mezzanine floors and 1.5-story spaces are possible due to the distribution of console beams in the columns at half-story

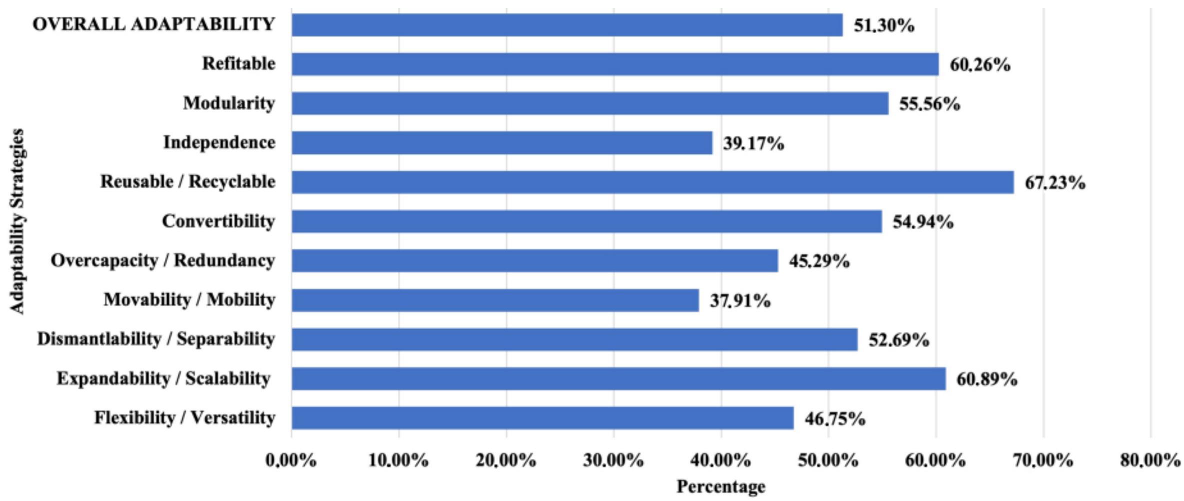

Figure 13.
The overall adaptability score and the adaptability strategy scores of the Genter Strasse houses (Source: Authors)

height [100]. The frame structure is completely or partially filled with spaces of varying floor heights and layouts, depending on the occupants' requirements (Figure 12). The structure's rigidity is provided by the in-situ concrete core spaces with service areas. The free-standing structural elements left during construction allowed the house to be more adaptable to potential changes [101]. Dry connections allow for simple and quick changes to the prefabricated structural system and facade, floor, and ceiling panels without causing damage to other building elements [102]. The modular facade design also allows for different use of envelope materials.

Figure 13 presents the percentage of score distribution for individual adaptability strategies and the overall adaptability of the Genter Strasse houses. The overall adaptability score of the Genter Strasse houses was 33.67 over a total score of 65,63 (51.30%, Figure 13). For individual adaptability strategies, the highest score was identified for *Reusable/Recyclable*, as 1.58 over a total score of 2.35 (67.23%, Figure 13), based on the following physical attributes: prefabricated reinforced concrete structure and dry connections, use of steel stairs and modular panel systems in the façade. *Expandability/Scalability* and *Refitability* were scored as 6.85 (60.89%, over a total score of 11.25) and 1.41 (60.26.05%, over a total score of 2.34), respectively (Figure 13, Table 3). *Movability/Mobility* was the least scored adaptability strategy, with 1.16 over a total score of 3.06 (37.91%, Figure 13). Genter Strasse houses received above-average scores for several individual adaptability strategies based on the adaptability evaluation criteria. The majority of the adaptability parameters related to façade design, structural design, core design, and spatial organization were fulfilled by Genter Strasse. As a result, the aforementioned parameters significantly improved the adaptability of the building.

4.4. Adaptability Evaluation of the Quinta Monroy Housing

In 2003, Alejandro Aravena and the Elemental Group designed Quinta Monroy Housing in Chile as a social housing project. The row house-style housing units were constructed in an unfinished state, a result of budget constraints and parcel limitations, thereby allowing occupants to undertake essential future extensions. The formal construction included the ground floor and upper floor apartments designed to 36 m^2 each, with different sizes of future extension possibilities of 9 and 18 m^2 (Figure 14) [103, 104, 105]. The formal construction of 36 m^2 incorporated structural system elements, sanitary spaces, and circulation elements that necessitated professional construction decisions [106, 107, 108]. Quinta Monroy Housing was constructed using a reinforced concrete structural system, featuring a total height of 8 meters across three storeys [109]. Independent units arranged within a three-meter structural grid exemplified an open plan design, enabling occupants to modify spatial characteristics according to their specific requirements [110].

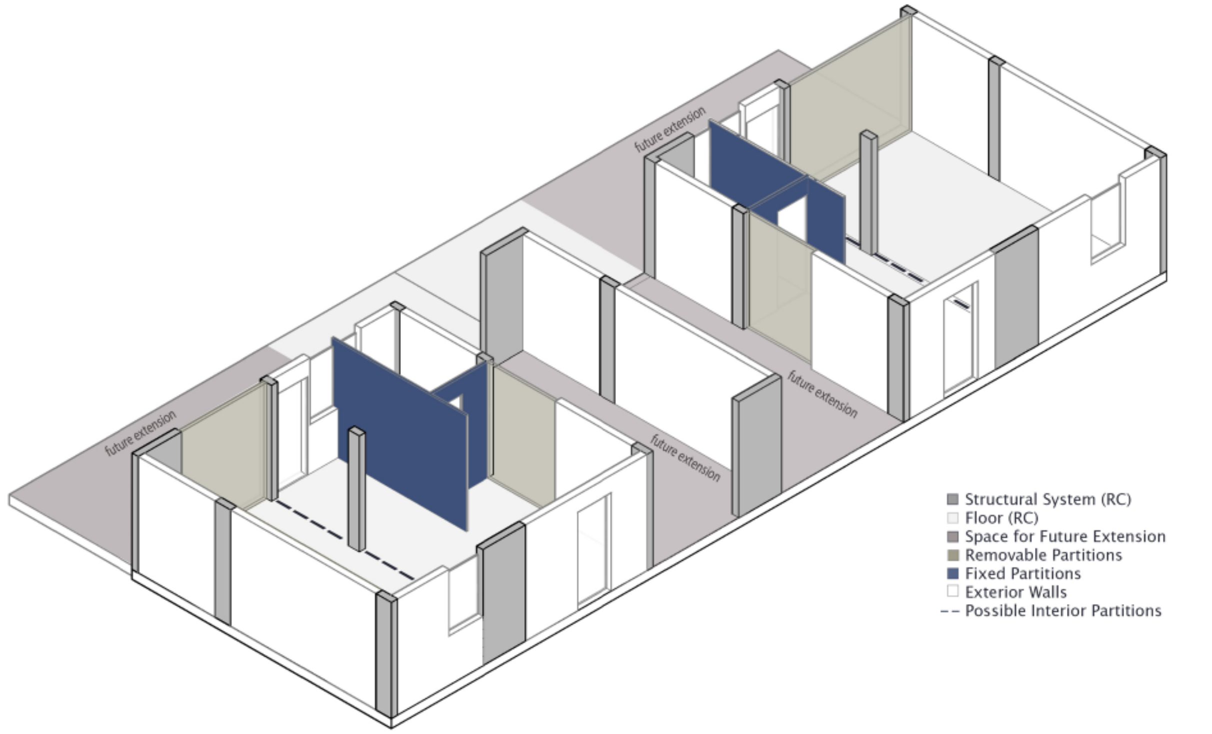

Figure 14.
Layers that augment the adaptability characteristics of the Quinta Monroy Housing (Source: Authors)

The Quinta Monroy Housing project was scored based on its physical attributes for *low-density* and *low-rise* based on its contextual and massing decisions (Table 5). For *structural design/slabs/loads*, the building complex was scored for *reinforced concrete and increased load-bearing capacity* due to the possibility of future extensions. The building complex was also scored for floor height ($fh < 3\ m$) and technical span ($ts < 6\ m$). For *core/vertical circulation*, the *centralized* layout of the vertical circulation and *steel structure stairs* were scored as well. The *open plan* approach, *modular organization, standard size*, spatial *multifunctionality*, and *overcapacity* were the parameters that the Quinta Monroy Housing project received scores for *plan organization* (Table 5, Figure 14). For the parameter, *partitions/walls*, the building complex was scored for the physical attributes, *fixed* and *movable*. The building complex received no score for *service spaces* and received only a score for *natural ventilation* for the parameter, *installations*. The glazing and opaque elements of the envelope were scored for their *independence, universality*, and *irregularity* (Table 5).

The percentage of score distribution for individual adaptability strategies and overall adaptability of the Quinta Monroy Housing is presented in Figure 15. The overall adaptability score of Quinta Monroy Housing was 30.20 (Table 5) over a total score of 65,63 (46.02%, Figure 15). *Convertibility* was identified as the individual strategy with the highest score, 5.26 (Table 4 and 5) over a total score of 8.81 (59.70%, Figure 15), and the scored physical attributes were *low-density, low-rise, increased load-bearing capacity, reinforced concrete* construction, *cent realized core, open plan, modular, standardized, multifunctional* plan organization, *spatial overcapacity, moveable/rearrangeable and fixed* partitions, *natural ventilation, independence, universality, and irregularity* of the envelope elements. Flexibility/Versatility was scored as 12.11 over a total score of 21.84 (55.45%) (Figure 15). The adaptability strategy with the lowest score was *Dismantlability/Separability*, with a score of 1.05 over 4.65 (22.58%, Figure 15).

The Quinta Monroy Housing project accrued fewer adaptability scores than expected, mainly due to the floor height being below 3 meters (2.6 m) and the technical span below 6 meters (maximum 5.80 m). The incorporation of structural steel circulation elements elevated the *Independence, Movability/Mobility, Flexibility/Versatility* levels [106]. As the building lacks service volumes such as shafts and raised floors, which typically segregate systems from other layers

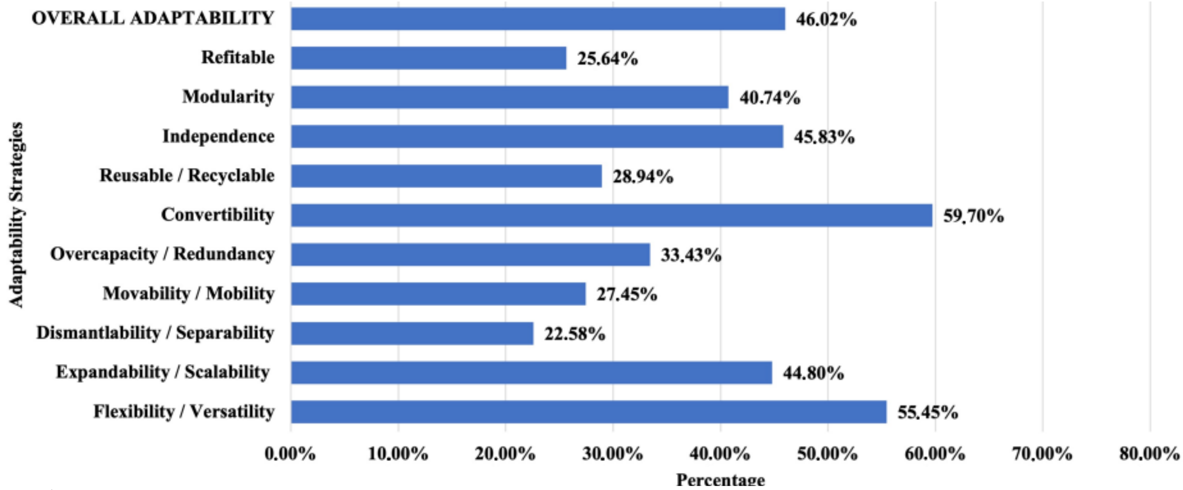

Figure 15.
The overall adaptability score and the strategy scores of the Quinta Monroy Housing (Source: Authors)

and facilitate repairs, it accrued lower scores in the *Flexibility/Versatility, Convertibility, Independence*, and *Refitability* strategies. Due to the Quinta Monroy structural system not being steel, prefabricated, or prestressed, and featuring low technical clearance and floor height, along with the absence of dry connections, the building layer received low scores. Additionally, the lack of service volumes led to diminished scores in the services layer. The facade layer similarly received lower scores due to the absence of a double facade system and modular layout. However, the design is quite prominent in terms of facilitating the spatial expansion of housing units in multiple directions, proving crucial not only for individual development but also for collective progress, as it fosters neighborhood interaction, self-regulation, and diversity in collective spaces and applications [111].

4.5. Adaptability Evaluation of the Het SchetsBlok

Constructed in Amsterdam in 2018 and designed by ANN Architecten, Het SchetsBlok encompasses 25 apartments with varied floor areas ranging from 46 m^2 to 150 m^2 (Figure 16) [112]. Tailored to specific occupant demographics, each apartment features unique sizes, floor plans, and facade designs. The residential complex emphasizes individual occupant preferences by incorporating modular layouts and facade designs for the apartments [113, 114]. The ground-level apartments are configured as duplexes, while two penthouse apartments occupy the 6th floor [112]. Habraken's open building was embraced in the design process, characterized by distinct layers for land use, fabric, support, support infill, layout, and planning [113]. The structural framework integrates a central reinforced concrete core, perimeter columns, and reinforced concrete slabs. Shafts are positioned at the corners of the core, adjacent to the apartment walls. Thus, a flexible floor area of 350 m^2 exists between the core and the facade, allowing unrestricted modifications. Non-load-bearing partition walls were designed to be demountable and/or movable, facilitating future adjustments based on the demand for different apartment sizes (Figure 16). The facade design is independent of the load-bearing structure and consists of a primary grid and a secondary grid adaptable to various apartment layouts, facilitating interior reconfigurations [114]. The opaque elements of the facade feature an inclined concrete composite grid and are clad with expanded aluminum panels [113].

Het SchetsBlok was scored based on its physical attributes for low-density and *high-rise* based on its contextual and massing decisions (Table 5). The building complex was scored for *reinforced concrete* and *increased load-bearing capacity* for the *structural design/slabs/loads* parameter since it allows future modifications for the number and size of apartments in the building. The building complex was also scored for floor height ($3\ m < fh < 5\ m$) and technical span ($ts \geq 6\ m$). The *centralized* layout of the vertical circulation was scored for the core/vertical circulation parameter. The *open plan* approach, *modular organization*, and *spatial overcapacity* were the parameters that the Quinta Monroy Housing project received scores for *plan organization* (Table 5, Figure 16). Het SchetsBlok was scored for the physical attributes, *fixed* and *movable*, for the parameter *partitions/walls*,

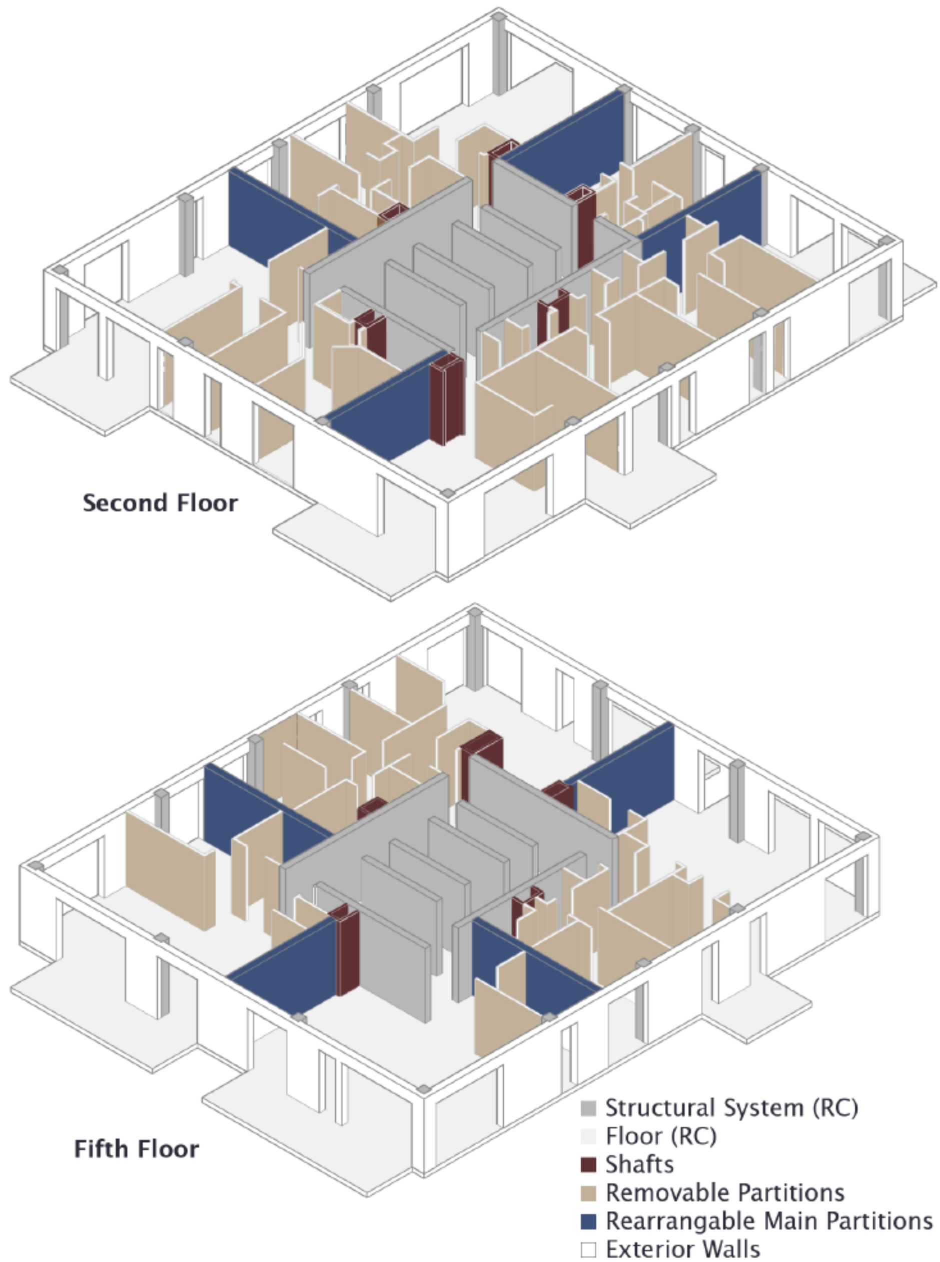

Figure 16.
Layers that augment the adaptability characteristics of Het SchetsBlok (Source: Authors)

for the *shafts* for the *service spaces* parameter, and *natural ventilation* for the *installations* parameter. The glazing and opaque elements of the envelope were scored for all physical attributes within the envelope design parameter (Table 5).

Figure 17 presents the percentage of score distribution for individual adaptability strategies and overall adaptability of Het SchetsBlok. The overall adaptability score of the building was 33.66 (Table 5) over a total score of 65.63 (51.29%, Figure 17). *Convertibility* and *Overcapacity/Redundancy* were identified as the strategies with the highest scores, respectively, 6.07 and 2.27 (Table 4 and 5) over total scores of 8.81 and 3,29 (68.90% and 69.00%, Figure 17). *Expandability/Scalability* was the other strategy that stood out for Het SchetsBlok with a score of 6.85 over a total score of 11.25 (60.89%, Figure 17). *Flexibility/Versatility* was scored as 12.24 over a total score of 21.84 (56.04%) (Figure 17). The adaptability strategy with the lowest score was

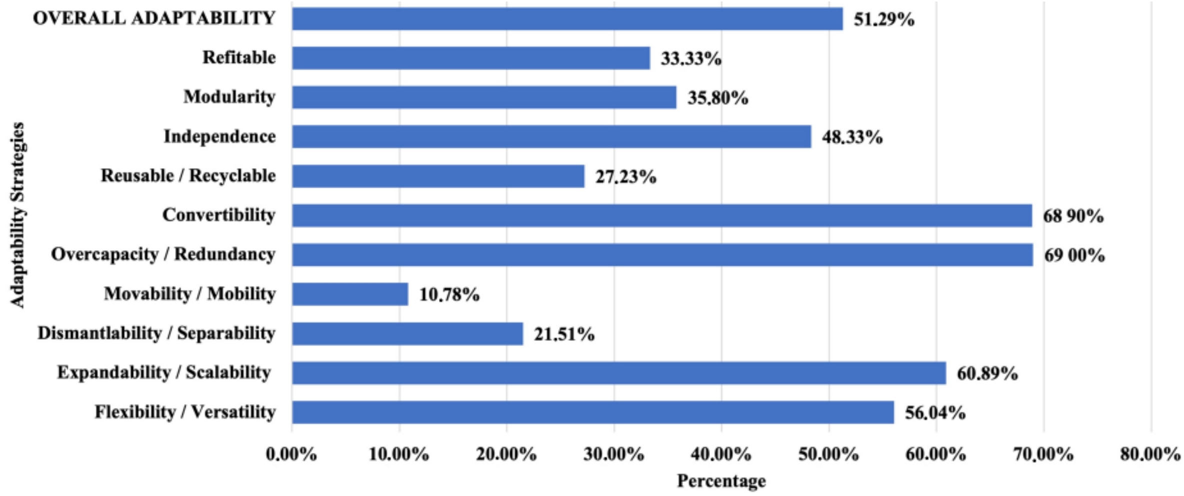

Figure 17.
The overall adaptability score and the strategy scores of the Het SchetsBlok (Source: Authors)

Movability/Mobility, with a score of 0.33 over 3.06 (10.78%, Figure 17).

Het SchetsBlok accrued higher adaptability scores for *Flexibility/Versatility, Expandability/Scalability*, and *Convertibility* strategies compared to the other studied examples, mainly due to its technical span larger than 6 meters and the use of a double skin façade. Given that Het SchetsBlok is situated in a low-density area there is a chance for horizontal expansion and the building, spanning a total of 7 floors, maintains an average floor height of 3.30 meters and a technical span of approximately 8 meters. The primary focus of Het SchetsBlok was to achieve flexibility that accommodates a wide range of unit sizes and to allow freedom in layout, addressing certain adaptability characteristics in meeting the requirements of the varied demographic groups of urban residents [112]. Adopting an open plan approach around the central core enhanced the building's flexibility, convertibility, independence, and expandability. Furthermore, the building received scores for spatial overcapacity due to the potential closure of the terrace floor for future inclusion in the flat. The modular organization parameter also contributed to the scores, given the modular layout of the flats within the interior.

Het SchetsBlok attained higher adaptability ratings in *Flexibility/Versatility, Expandability/Scalability*, and *Convertibility* strategies compared to other examined examples. This was primarily attributed to its technical capabilities, including a span exceeding 6 meters and the implementation of a double-skin facade. Situated in a low-density area, Het SchetsBlok presents opportunities for horizontal expansion. With a total of 7 floors, the building maintains an average floor height of 3.30 meters and a technical span of approximately 8 meters. Its primary objective was to achieve flexibility accommodating various unit sizes and allowing layout freedom, addressing adaptability characteristics to meet the needs of diverse urban resident demographics [112]. Embracing an open plan approach around the central core bolstered the building's *Flexibility/Versatility, Convertibility, Independence*, and *Expandability/Scalability*. Additionally, the building acquired a spatial overcapacity score due to the potential closure of the terrace floor for future inclusions in flats. The modular organization parameter also contributed to its scores, reflecting the modular layout of flats within the interior.

5. DISCUSSION

The adaptability evaluation criteria set included ten strategies and eleven parameters, which explained 60% and 80% of the adaptability considerations in the literature, respectively. The selected adaptability strategies were *Flexibility/Versatility, Expandability/Scalability, Dismantlability/Separability, Movability/Mobility, Overcapacity/Redundancy, Convertibility, Reusable/Recyclable, Independence, Modularity*, and *Refitability* (Table 2, Figure 4). The selected adaptability parameters were *structural design/slabs/loads, plan organization, floor height, technical span, core/vertical circulation, service spaces, envelope design, building dimensions and height, mechanical, electrical, IT and HVAC installations, location/accessibility/orientation/proximity*, and *partitions/walls*. Finally, the frequency of use for the strategies and parameters in the literature was used to develop a scoring system (Table 3). In parallel with the frequency of strategies and parameters in the literature, a simple weighted scoring system was developed. The frequency of adaptability strategies and parameters (X) was converted to a score of X/10. For example, with a 10.6 percent frequency in the literature, *Flexibility/Versatility* was assigned as $k_{strategyFlex}$ = 10.6/10 = 1.06 points. The physical attributes were also identified based on literature and were classified based on an expanded version of the shearing layers approach of Brand [46].

The findings presented in Section 4 offer a comprehensive assessment of adaptability in architecture, achieved through the examination of five distinct case studies: Gerrit Rietveld's Schröder House, Mies van der Rohe's Farnsworth House, Otto Steidle & Partners' Genter Strasse, Alejandro Aravena and Elemental's Quinta Monroy Housing Project, and ANA Architecten's Het SchetsBlok. These case studies span different epochs and architectural styles, providing valuable insights into the treatment of adaptability across diverse contexts. Each case study reflects the prevailing architectural principles of its era. For example, the Schröder House embodies the ethos of the De Stijl movement, prioritizing simplicity, abstraction, and geometric forms. In contrast, the Farnsworth House epitomizes the modernist ideals of minimalism and structural transparency. Understanding the historical backdrop is essential for contextualizing the design decisions and adaptability features integrated into these examples.

The evaluation system used in the present study adopted a comprehensive criteria-based approach to assess the adaptability of buildings. Instead of merely assigning scores, the focus was on identifying the strengths and weaknesses of each building in terms of adaptability. This approach allowed for a nuanced understanding of how different strategies and parameters contributed to the overall adaptability of buildings. Figure 18 shows the percentage scores of individual adaptability strategies as well as the overall adaptability scores for these examples. Genter Strasse and Het SchetsBlok received the highest overall adaptability scores (respectively, 51.30% and 51.29%, Figure 18). Genter Strasse stood out in adaptability scores due to the prefabricated reinforced concrete structural system and the dry connections, which were designed for spatial expansion when necessary. Het SchetsBlok on the other hand received higher scores due to a higher number of storeys, larger technical span, centralized design of shafts, double skin, and modular façade grid. A structural core and an independent façade structure, such as the system used in Het SchetsBlok was promising in terms of the adaptable use of interior partitions for diverse programmatic requirements and in managing vertical distribution of services and installations, which provide the occupant freedom in adapting the size and the program of the building units (12.81% of the overall adaptability score). All analyzed buildings have different circulation layouts, yet most are centralized and accounted for 2.97% of the overall adaptability score. The Schröder House received an overall adaptability score of 50.65% (Figure 18) especially due to the Independence (65.00%, Figure 18) provided by the steel structure and the multifunctional and open plan layout with movable partitions. Quinta Monroy Housing Project received an overall adaptability score of 43.01% (Figure 18). Less than 3 meters (2.6 m) floor height, less than 6 meters (maximum 5.80 m) technical span, and lack of distinctive service volume such as shafts were the main reason for Quinta Monroy Housing Project to receive a lesser score compared to the other examples. Despite the

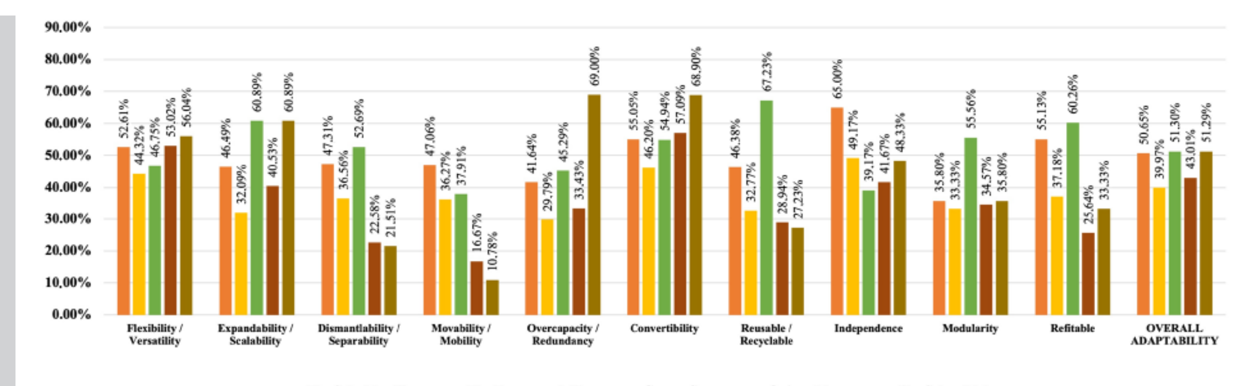

Figure 18.
Comparison of percentage scores of individual adaptability strategies and the overall adaptability scores (Source: Authors)

similarities in most physical attributes between the Farnsworth House and the Schröder House, The Farnsworth House received an overall adaptability score of 39.97% due to being single-storey, hence, was not scored for physical attributes such as core/vertical circulation, vertical distribution of services (shafts), etc. (Figure 18).

The evaluation criteria set out specific parameters for assessing adaptability, encompassing physical attributes such as location, structure, layout, services, and envelope design. The case studies demonstrated diverse approaches to addressing these parameters, ranging from flexible spatial arrangements and movable partitions to modular construction systems and innovative facade designs. Each case study scored based on its adherence to adaptability criteria and resulted in overall adaptability scores indicated that strategies such as *Independence, Convertibility*, and *Flexibility/Versatility* emerged as key strengths in enhancing adaptability. Overall, *Flexibility/Versatility* was identified as the main strategy that contributed to adaptability (33.28%) and was followed by *Expandability/Scalability* and *Convertibility*, by 17.16% and 13.42%, respectively. *Structural design, plan organization, floor height, technical span*, and *core/vertical circulation* were identified as the five parameters with the highest scores. *Steel structure, prefabricated reinforced concrete structure, modular/panel envelope systems, steel stairs, modular spatial organization*, and *standard-sized spaces* were identified as the most important physical attributes that defined adaptability strategies and parameters. However, the case studies exhibited that the scores varied based on the detailed approach to structural design, spatial organization, and service provisions.

6. CONCLUDING REMARKS

The multidisciplinary nature of adaptability, as well as its unpredictable emergence due to temporal factors and the demand for change, lead to various interpretations and definitions. Clear expressions of the concept of adaptability, as well as demonstrating its distinction and relationship to the interchangeably used terms for adaptability, may aid in the design and construction of adaptable buildings. Aside from clarifying the concept of adaptability, the definition of an adaptability evaluation criteria set is also critical to achieving a sustainable built environment. As a result, the present study attempted to develop a literature-based adaptability evaluation method for the classification and practical application of adaptability strategies and spatial, technical, and functional adaptability parameters. The main aim of the evaluation system was not to assign adaptability scores to buildings but to reveal the strengths and weaknesses of a building for adaptability through a criteria-based approach and identify to what extent strategies and/or parameters contributed to adaptability.

The adaptability evaluation criteria set proposed in this study allows for multiple scoring based on a building's physical adaptability attributes. Since the physical parameters can be scored for multiple strategies, the coexistence of spaces with different floor heights, different numbers of storeys, structural systems, or spaces with a technical span of more than 6 meters may result in higher adaptability scores.

While the case studies exhibited notable adaptability features, the scoring approach also highlighted the challenges of attaining high levels of spatial adaptability. For instance, limitations in floor height and technical span were identified as the main constraints to spatial flexibility and future modifications. Similarly, the lack of service volumes such as shafts and raised floors was anticipated to limit adaptability in terms of system segregation and maintenance. Despite these challenges, the case studies demonstrated innovative solutions and design strategies to enhance adaptability. From prefabricated modular construction to flexible floor plans and facade systems, architects continuously thrived to extend the boundaries of adaptability in response to evolving needs and contexts. Our overall findings underscored the importance of a holistic design approach that integrates adaptability considerations from the onset of the design. Flexible spatial layouts, modular construction techniques, and adaptable service layouts should be prioritized to future-proof buildings and accommodate evolving user needs. Furthermore, adaptability approaches should be tailored to the specific context, taking into account factors such as location, climate, cultural preferences, and socio-economic dynamics. By aligning design interventions with contextual realities, architects can improve adaptability outcomes and enhance the overall resilience of built environments. Another shared aspect of the studied examples was to engage occupants as active agents who can customize their spatial environment and develop a sense of ownership to ensure long-term usability through taking initiative in change. Designing for diversity and inclusivity can further enrich the adaptability of architectural interventions and promote social cohesion.

The adaptability evaluation criteria set, which was developed based on an analysis of the adaptability literature, is both a quantitative and qualitative evaluation tool, as it reveals the relationship between strategies and parameters through scoring. It provides a framework for assessing the adaptability levels of architectural work. However, it is essential to continuously refine and update these criteria based on emerging trends, technological advancements, and lessons learned from real-world applications. Regular evaluation and iteration can drive innovation and improve the effectiveness of adaptability strategies. In conclusion, the findings offer valuable insights into the multifaceted nature of adaptability in architecture and highlight the critical role of design in shaping resilient and responsive built environments. By embracing adaptability as a guiding principle, architects can contribute to sustainable urban development, enhance the quality of life, and ensure the longevity of architectural interventions in an ever-changing world.

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