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A Critical Review of Building Adaptability Assessment Models

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ABSTRACT

This study examines existing qualitative and quantitative models developed to understand and evaluate adaptability in buildings, aiming to provide a comprehensive reference for future research on both adaptive reuse of existing structures and the design of adaptable new buildings. The existing literature offers numerous frameworks—both qualitative and quantitative—for assessing building adaptability. However, while studies include comparative analyses of these models, they have generally overlooked the inherent strategies that outline a roadmap for achieving adaptability and the relationships between these strategies. Recognizing that the interrelationships between strategies have significant implications for the development of integrated adaptability solutions, this research comparatively reviews these models based on criteria such as publication year, scope, function, focus, evaluation criteria, methodology, output, and strategies.When viewed over time, an analysis of the temporal distribution of these models reveals that interest in adaptability assessment has remained consistent over the past two decades. Among the various evaluation methods, criterion-based scoring emerges as the most commonly applied approach.Although their intended purposes differ, many of these models share similar features, including rating or classification systems, conceptual decision-support tools for adaptive reuse, and analyses of relationships among key variables. Furthermore, the evolving definition of adaptability and the expanding scope of related research have led to a diversification of strategies proposed to achieve adaptability in buildings. The most frequently cited strategies include disassembly or deconstruction, flexibility, scalability, movability, durability, accessibility, and layering.

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1. Introduction

The traditional understanding of construction does not adequately account for the changes that occur in buildings throughout their lifespan (Russell and Moffatt, 2001). However, buildings are not static entities; they remain incomplete and subject to transformation until the day they are demolished (Milwicz and Pasławski, 2018). Changes within a building arise from internal factors, such as physical and functional conditions, as well as from external influences, including economic and legal conditions (Douglas, 2006). Both the pace and scope of these changes have accelerated compared to earlier periods.

In light of current global challenges, it is hypothesized that 21st-century phenomena—such as climate crises, environmental disasters, migration, and large-scale population movements—will have distinct impacts on buildings and the urban environment, compared to those of the past (Russell and Moffatt, 2001). In particular, the scale and speed of technological innovation make it difficult to predict long-term shifts in user needs, thereby increasing uncertainty (Keymer, 2000; Russell and Moffatt, 2001). As a result, this uncertainty, driven by rapid technological development, complicates efforts to plan for the future built environment and heightens the risk of premature obsolescence (Ellison and Sayce, 2007).

Against this backdrop, obsolescence and abandonment are critical design challenges that must be addressed by a wide range of stakeholders, including large corporations, public institutions, homeowners, and users (Slaughter, 2001). Due to various factors—such as declining building performance, functional obsolescence, and evolving user expectations—buildings may lose their capacity to meet both initial and future requirements. Consequently, buildings that cannot adapt to new demands become inadequate for future users (Keymer, 2000). Despite their potential for long physical durability, such buildings often face premature demolition due to limited service life. Taken together, these conditions underscore the ongoing need for change in the built environment and the continuous search—both historically and in the present—for ways to extend building lifespans (Milwicz & Pasławski, 2018).

In response to these challenges, adaptability emerges as an effective strategy for ensuring the continued use of the built environment. It also represents a building's future viability, as reflected in its long-term utility value, which is a key prerequisite for sustainability. Adaptability, which accounts for the social benefits of a building's future use, considers not only the current user and owner but also future generations of users (Geraedts, 2008). Through periodic assessments of the existing building stock and evolving user requirements, timely measures can be implemented via adaptive reuse to address factors such as obsolescence and vacancy. Moreover, in the context of new building design and construction, adaptive strategies can be developed to respond proactively to changes in individual and societal structures (Gijsbers and Lichtenberg, 2014). Ultimately, to ensure resilience in the face of future change, it is essential to achieve a high degree of robustness, modifiability, and efficiency, while minimizing demolition costs and waste (Sinclair et al., 2012).

Building upon this foundation, the issue of adaptability in the built environment continues to be a relevant and evolving topic, prompting the development of numerous qualitative and quantitative models designed to understand, evaluate, and measure adaptability. Theoretical studies have sought to discuss and compare these models, aiming to illuminate how the definition, scope, and methodologies related to adaptability in buildings have shifted over time. Rockow et al. (2019), for example, analyzed a set of studies presenting quantitative or potentially quantifiable methods and identified ten distinct models. These were evaluated based on factors such as their focus—initial design, adaptability decision points, and building life cycle—as well as the types of features considered (e.g., physical and contextual attributes) and the degree and nature of validation. Similarly, Unver et al. (2022) compared the seven most frequently used models by examining structural focus (existing versus future buildings), the type of adaptability relationship (direct or indirect), methodology, and dependent matrices—including scenario planning, physical lifespan, openness, functional use, barriers, and obsolescence.

Although the topic is widely addressed in the literature on adaptability and flexibility—often through various strategic and methodological approaches—previous comparative studies have largely overlooked the specific strategies embedded within the models themselves. While this study shares certain comparative parameters with earlier works, it distinguishes itself through the broader range of models analyzed, the identification of the adaptability strategies employed, and the investigation of the interrelationships among these strategies.

Within this context, the research is structured around the following research questions:

1. How do existing adaptation assessment models in the literature systematically address the adaptability potential of buildings, in terms of their fundamental approaches and criteria?
2. When evaluating adaptability, how do these models differentiate the building context, employed methodologies, and resulting main outputs?
3. What are the most commonly used design strategies in adaptability assessment models, and what critical factors in achieving adaptability do the prevalence of these strategies indicate?
4. What network of relationships exists among different design strategies, and what implications do these relationships offer for the development of integrated adaptability solutions?

1.1 Building Adaptability Terminology

Adaptability is the capacity of a building to respond to emerging demands (Schmidt et al., 2010). It is a socio-technical concept that concerns buildings' ability to adjust to their inhabitants and the surrounding environment (Schnädelbach, 2017). Adaptability involves changes in function, capacity, performance, and spatial flow to accommodate new conditions, user goals, and expectations over a building's lifespan (Keymer, 2000; Slaughter, 2001; Douglas, 2006; Kostourou & Psarra, 2017). Eguchi et al. (2010) define adaptability as a design decision informed by the dimensions of 'time' and 'layers'. The term 'time' refers to the building as a dynamic system capable of accommodating various types of change, whereas 'layers' refer to components belonging to different periods of use and function within the building (Eguchi et al., 2010).

Building upon this foundation, the discussion of adaptive systems—those that resist change by adapting and persisting over time—across various disciplines has led to a diversification of terminology. This terminology has become blurred due to the interchangeable use of different terms, which often obscure important distinctions in meaning (Pinder et al., 2017). As a result, in the relevant literature, a wide range of terms are used in reference to adaptability, including adaptation, adaptive design, adaptive reuse, adaptive capacity, flexibility, and resilience. Among these, flexibility is the most frequently used in architectural discourse, often alongside adaptability. However, while some sources use flexibility and adaptability interchangeably, others emphasize clear distinctions between the two.

In addition to these conceptual variations, building adaptability has also been defined in terms of the effort, cost, and extent of change required (Lynch, 1958; Ellison & Sayce, 2007); functional efficiency (Geraedts & Prins, 2016); functional change (Maccreanor, 2008; Langston, 2011); or multifunctionality (Maccreanor, 2008; Zee, 2014; Saarimaa & Pelsmakers, 2020).

Taking all of these perspectives into account, adaptability can be defined as the ability or capacity of the built environment to respond—at minimal effort and cost—to social, economic, physical, technical, and environmental changes, within the framework of all human and non-human actors, as well as building, urban, and environmental systems.

2. Methodology

In this study, the interrelationships among qualitative and quantitative models and tools developed to understand, guide, and evaluate the degree of building adaptability are examined, with the aim of contributing to future research on adaptive reuse and the design of adaptable new buildings.

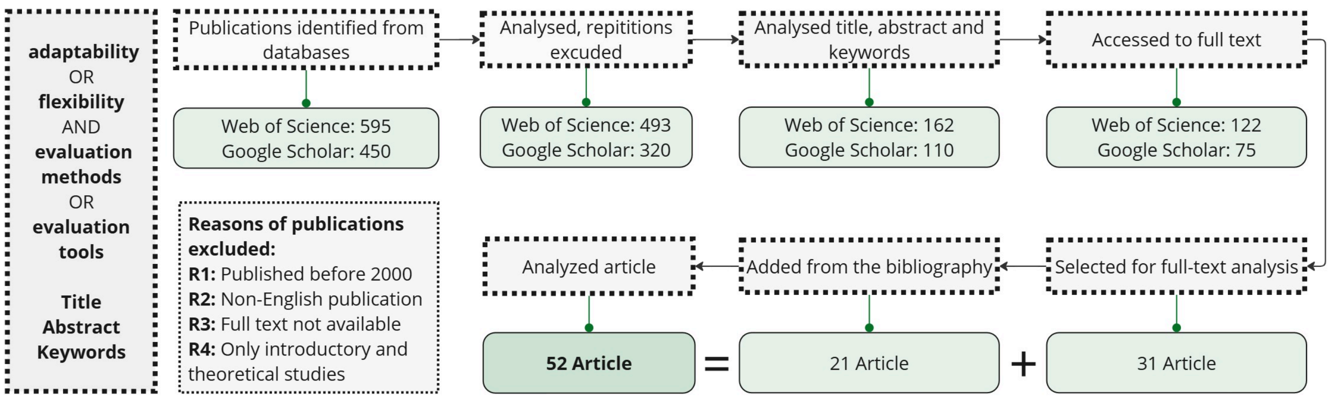


Figure 1 Literature Review: Steps of Database Search.

In the first stage, research was conducted using online databases (WOS and Google Scholar) with the keywords 'adaptability', 'flexibility', 'evaluation methods' and 'evaluation tools' to determine which qualitative and quantitative models, frameworks, or tools were recommended in the literature for measuring the adaptability of buildings (Figure 1).

In the second stage of the study, the models were analysed comparatively from a systematic point of view under the headings of year, scope (existing building/new building), building function, focal point (design, use, life cycle process), criteria (structure, context), method, type of validation (case study, database) and output. Finally, the strategies employed in the models to define and achieve adaptability were analysed. The strategies were then grouped according to their frequency of occurrence in the models and their effects. This process revealed the relationship between the strategies (Figure 2).

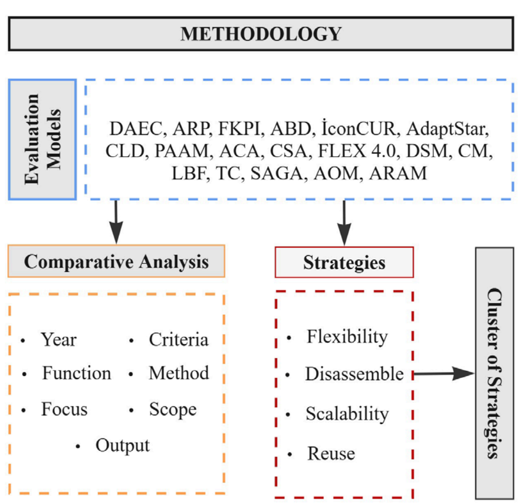


Figure 2 Research Flow Chart

3. Results and Discussion

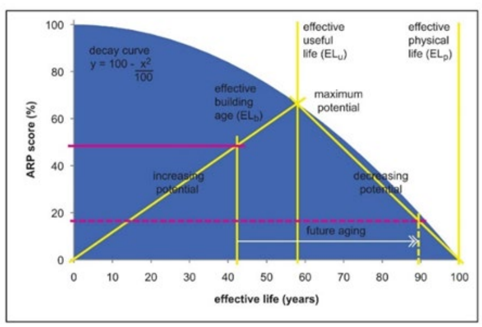
3.1 Models and Tools For Assessing Adaptability In Buildings

Many models have been developed to evaluate the adaptability of buildings. The following section presents a chronological analysis of 18 adaptability assessment models and tools for assessing adaptability in buildings, published between 2002 and 2021.

DAEC Model: The DAEC assessment tool constitutes a component of the 'Sustainability of Buildings' research programme. The DAEC tool can be employed to develop a design brief for new building designs, set objectives, evaluate different design options, compare the life cycle costs of design options, and provide decision support in the management process of existing buildings, such as maintenance, repair, rehabilitation, and reuse (Langford et.al., 2002). Despite the creation of a scoring and weighting system within the DAEC tool, no score was assigned to the criteria in contrast to the approach employed in similar evaluation models.

ARP Model: Langston et al. (2007) presented a model based on ranking the reuse potential of existing buildings and providing decision support to decision makers (Figure 3). The model (Langston et al., 2008), which was developed as a tool for stakeholders in the Hong Kong market to assess the potential of buildings for reuse in the decision-making process and to identify those with high conversion potential, has a general application (Langston et al., 2008).

The model is founded on a graphical algorithm that elucidates the interrelationship between effective useful life, effective physical life, and obsolescence (Langston et al., 2013). When the useful life of a building is approaching or equal to its current age, it can be considered to have lost its original function. This represents the maximum ARP value for the current stage of the building life cycle, indicating that planning activities for adaptive reuse should be initiated (Langston and Shen, 2007). The ARP value, which expresses the adaptive reuse potential of buildings as a percentage, indicates the type of buildings that should be transformed. A value above 50% is indicative of a high level of potential, between 20% and 49% is indicative of a medium level of potential, and a value between 1% and 19% is indicative of a low level of potential (Langston et al., 2008). As the model is algorithm-based, its application may require expertise.



$$\text{ARP (increasing)} = \frac{100 - \frac{EL_u^2}{100} \cdot EL_b}{EL_u} \qquad \text{ARP (decreasing)} = \frac{100 - \frac{EL_u^2}{100}}{100 - EL_u} \cdot (100 - EL_b)$$

Figure 3 Adaptive reuse potential model (Langston et al., 2008).

FKPI Model: The Flexibility Key Performance Indicators (FKPI) model is a tool that measures flexibility using four key indicators (Figure 4). These indicators are used to score the flexibility of existing building installation systems and determine the flexibility requirements of new buildings. In FKPI, the core indicators of partitionability, adaptability, extensibility, and multifunctionality are derived from the clustering of 23 subcategories of flexibility. In FKPI, each core indicator is scored by multiplying the degree assigned to the subcategories by the weighting factor. The basic indicator class of a building is determined based on the total score derived from the subcategories. The general flexibility score and class are determined by summing the scores obtained by multiplying the basic indicator class by the weighting factor (Geraedts, 2008). However, the subcategories are not clearly explained, and the weighting criteria are not specified, making the relative importance of both categories and subcategories unclear within the tool.

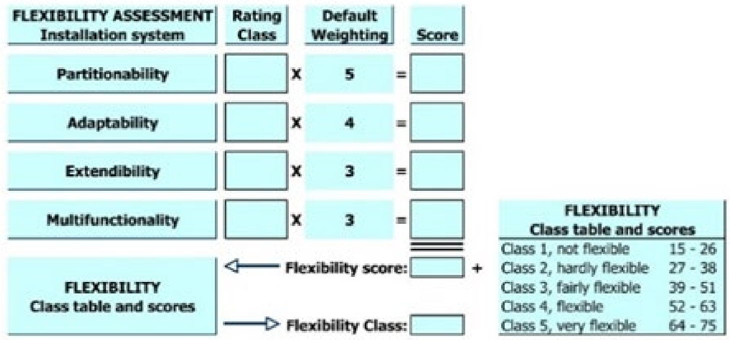


Figure 4 Layout of form for assessment flexibility (Geraedts, 2008).

ABD Model: The concept of adaptive building design (ABD) provides a framework for managing future demand uncertainties and for enhancing building flexibility (Figure 5). ABD comprises four stages: (1) the identification of uncertainties; (2) the identification of flexibility options and their embedding into the design/building system; (3) the formulation of design rules that determine the timing of implementation of possible options; and (4) the analysis of the adaptability value using real options analysis (ROA) and Monte Carlo simulations that validate the initial design solutions (Allahaim et.al., 2010). The ABD does not undertake an evaluation of the physical condition of the building; rather, it assesses the process of change of function based on demand, capacity and income. Consequently, the applicability of the evaluation tool may be limited to commercial buildings.

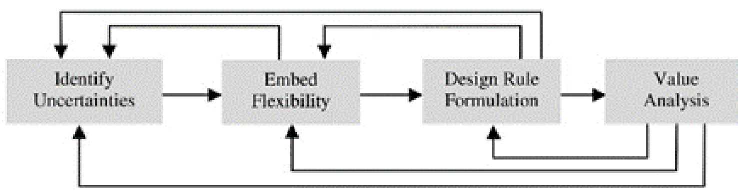


Figure 5 The framework for adaptable buildings (Allahaim et.al., 2010).

IconCUR Model: The IconCUR model is a multi-criteria decision-making (MCDA) model that employs a visual representation of the property's current condition in three-dimensional space and a weighted matrix methodology (Langston, 2013). The decision-making criteria in the model are organised on a scale from 0 (low) to 5 (high), with conditions on the X-axis, use on the Y-axis and reward on the Z-axis. The value of the new decision is determined by the difference between the coordinates of the building in its original state and in its new state (Figure 6).

The greater the distance between the old and new coordinates, the greater the impact of the decision and the greater the expected success. The main alternatives proposed, depending on the location of the building in the 3D space, are as follows: low condition and low utilisation (reconstruction or dmolition), high condition and high utilisation (conservation or extension), low condition and high utilisation (renovation or conservation), and high condition and low utilisation (reuse or adaptation) (Langston and Smith, 2012). The details for the sub-criteria, for which the importance degree is given in percentages, are not provided in sufficient detail in the model. This deficiency may consequently lead to inconsistencies in the evaluation process of the buildings as perceived by the evaluators, resulting in varied assessments for a given building.

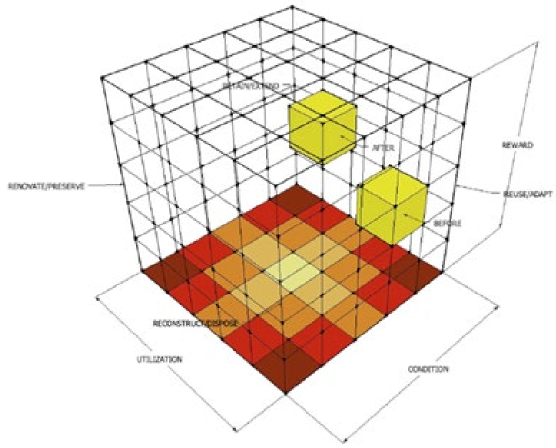


Figure 6 Before and after intervention effects in iconCUR (Langston and Smith, 2012).

AdaptSTAR Model: The Adaptstar method was developed by reverse engineering the ARP model proposed by Langston (2008) (Figure 7). This enables the provision of optimised building recommendations and facilitates improvements to the potential for future reuse (Conejos et al., 2017). In developing the model, a mixed research methodology was employed, comprising a combination of case study analysis, expert interviews, and practitioner surveys (Conejos and Langston, 2010). The structure of the model is hierarchical with 7 weighted design categories (physical, economic, functional, technological, legal, social and political), totalling 100 and 26 sub-criteria grouped according to each category (Conejos et al., 2017). The future-proofing performance of new and existing buildings is quantified through a standardised five-star rating methodology (Conejos and Langston, 2010; Conejos, 2013). Thanks to its clear scoring method and defined criteria, the model is accessible and does not require expert knowledge for implementation.

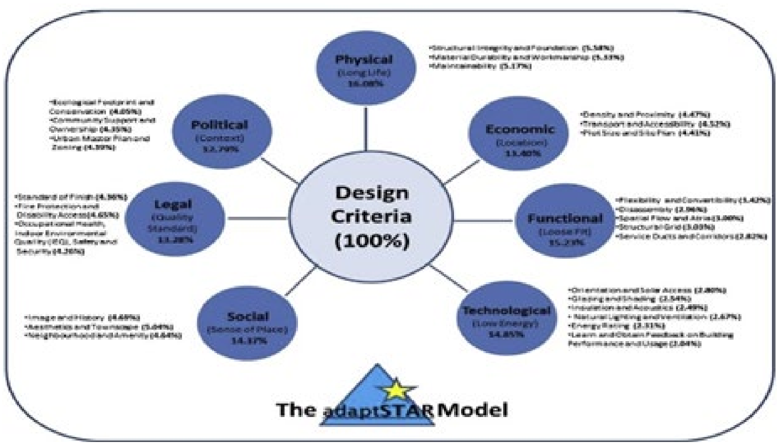


Figure 7 The adaptSTAR model (Conejos and Langston, 2010; Conejos, 2013).

CLD Model: The CLD model is a system model developed to visualise and rationalise adaptability in order to contribute to the sustainable construction agenda. The adaptability intervention subsystem is composed of two fundamental variables, design flexibility and process flexibility, as well as the relationships between these variables (Figure 8). With regard to design flexibility, the following variables have been defined: interchangeable components, level of uncertainty, layering and deconstruction design. In the case of process flexibility, the following variables have been defined: flexibility in the planning/project process, supply chain integration, and supply chain flexibility. In the CLD model developed using system dynamics techniques, the variables expressed by the nodes are connected by arrows indicating causal effects. The direction of the causal relationship (positive or negative) is determined based on the nature of the relationship (proportional or inverse) between the dependent and independent variables (Gosling et al., 2013). While the CLD model helps to understand factors influencing adaptability, it is not designed for evaluation purposes and has not yet been validated.

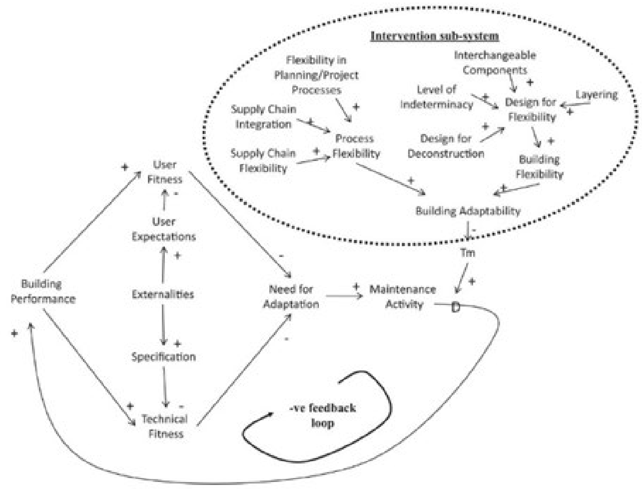


Figure 8 Building adaptation system (Gosling et al., 2013).

PAAM Model: The Preliminary Assessment Adaptation Model (PAAM) was informed by Chudley's (1981) decision model, which was taken as a reference point. The environmental, technical and political difficulty categories, which were excluded from Chudley's model, were incorporated into PAAM, and the existing order of the difficulty categories was altered and reorganised. In PAAM, the relative importance of the categories (physical, social, economic, environmental, legal, technological) decreases from the current physical condition of the building to the technological condition. A building that is not physically suitable is not considered for adaptability even if other conditions are met (Mehr and Wilkinson, 2021). A quantitative data set was constructed using principal component analysis (PCA) with data obtained from the literature (Wilkinson et al., 2014). PAAM is the sole model that utilises a substantial data set.

CSA Model: In the CSA model, potential change scenarios are transformed into functional requirements, suitable measures are selected, compatibility with the existing structure is evaluated, and the optimal solution is finally selected by comparing the efficacy of the proposed adaptability measures. It is recommended that the design be tested over a range of scenarios to enhance the likelihood of extending the building lifespan. The efficacy of the design scenarios developed in accordance with the CSA method is assessed through the measurement of the resources, financial costs, and environmental impacts necessitated by the adaptation process. Given that each stakeholder has different priorities, such as reducing costs, shortening construction time, and extending building lifetime, the adaptability measure is calculated separately for these three sub-scores, allowing the optimised option to be determined (Gijsbers and Lichtenberg, 2014).

ACA Model: The Adaptability Capacity Assessment Model (ACA) was developed to provide a quantitative measure of the adaptability level of existing buildings. The fundamental stages of the adaptability assessment capacity evaluation model are the formulation of change scenarios, the identification of space organisation alternatives compatible with the scenario, the assessment of the benefit value of the alternatives for users and the burden value for change and the determination of the adaptability capacity in accordance with the proportion or correlation between the relative scores of the benefit and burden of the alternatives. The AHP method was employed to determine the relative importance weights of the benefit and burden values associated with the alternatives devised for the change scenarios. (Savaş, 2014). The design alternatives in the ACA model are subject to variation according to the evaluated example and the modeler's design experience and attitude. Consequently, the model is expected to undergo changes during each evaluation process.

FLEX 4.0 Model: FLEX 4.0 is the latest version of the tool (Geraedts et al., 2014, Geraedts and Prins 2015, Geraedts and Prins 2016) developed as part of a research project conducted at Delft University in 2014 to assess the adaptive capacity of buildings (Figure 9). The 44 performance indicators that form the basic framework of FLEX 4.0 are divided into two categories: support and fill. The author assigned weights ranging from 1 to 4 to each of the general and specific indicators, with reference to other indicators, and scored the evaluation level of each indicator from 1 to 4. The total flexibility score was calculated by summing the scores calculated per indicator (weighting x evaluation), and the flexibility class of the building was determined according to the score range (Geraedts, 2016). Strengths of the model include its detailed, function-specific criteria, a clear scoring system, and practical usability. However, its main limitations are the lack of spatial planning considerations and insufficient integration of contextual data.

Assessment Form 12 Generally Applicable Flexibility Indicators						
Layer	Sub-layer	Nr	Flexibility Performance Indicator	Weighting	Assessment	Score
1. SITE		1.	Expandable site / location	1	1	1
2. STRUCTURE	Measurements	2.	Surplus of building space / floor space	4	3	12
		3.	Surplus of free floor height	4	2	8
	Access	4.	Access to building	2	4	8
	Construction	5.	Positioning obstacles / columns in load	3	1	3
3. SKIN	Facade	6.	Facade windows to be opened	1	4	4
		7.	Daylight facilities	2	3	6
4. FACILITIES	Measure/Control	8.	Customisability/controllability facilities	3	2	6
	Dimensions	9.	Surplus of facilities shafts and ducts	4	3	12
		10.	Modularity of facilities	2	1	2
5. SPACE PLAN	Functional	11.	Distinction between support - infill	4	1	4
	Access	12.	Horizontal access to building	3	1	3

Example of total Flexibility Score: 69

Flexibility Class: 2

CLASS TABLE FLEXIBILITY SCORES	Score range
Class 1: Not flexible at all	12 - 48
Class 2: Hardly flexible	49 - 85
Class 3: Limited flexible	86 - 122
Class 4: Very flexible	123 - 159
Class 5: Excellent flexible	160 - 192

Figure 9 Assessment form of generally applicaple flexibility indicators (Geraedts, 2016).

DSM Model: Schmidth and Austin (2016) developed DSM models of design strategies and building characteristics for adaptive design (Figure 9). By monitoring the dependencies established within the DSM, the diffusion of change was monitored and the impact was analysed. A DSM modeller and a system expert were tasked with rating each scenario and the number of components affected by the propagation in terms of feasibility. The feasibility levels are indicated as follows: (1) feasible, (2) partially feasible, (3) not feasible, and (x) uncertain, where additional information is required for analysis (Schmidt and Austin, 2016). The DSM model is subject to variation according to the experience of the modeler, which can result in a subjective utilisation of the tool. One of the proposed DSM models is related to the design strategies and building character for adaptive design, as illustrated in Figure 10

.

	Design strategies	1	2	3	4	5	6	7	8	9	10	11	12
1	Modularity		O		X	X	O		O	O			
2	Design 'in' time	O								O			
3	Long life				O	O			O				
4	Simplicity and legibility	X		O		O	X		O				
5	Loose fit	X		O	O		X	X	X	X	X	O	O
6	Spatial planning	O			X	X			O	O	O		
7	Passive techniques					X					X		O
8	Unfinished design	O		O	O	X	O			O			
9	Maximise building use	O	O			X	O		O				X
10	Increase interactivity					X	O	X				X	O
11	Aesthetics					O					X		
12	Multiple scales					O		O		X	O		

Figure 10 Connectivity between design strategy (Schmidt and Austin, 2016).

Conversion Meter Model: The Conversion Meter is a series of checklists, ranging from general to specific, that are used to assess the potential for the conversion of vacant office buildings into housing and the feasibility of conversion projects (Figure 11). The initial stage of the process involves the creation of a market supply inventory of unused or expected vacant office buildings within municipal, regional, and property portfolios. Subsequently, veto criteria are established under the headings of market, stakeholders, location and building to facilitate rapid screening of the transformation potential. The conversion potential of the buildings that have been deemed suitable following the preliminary assessment is calculated according to the weighted sum of the criteria. The building is then assigned to one of the following five conversion classes (not suitable for conversion, to be converted, to be converted with modifications, to be converted with significant modifications, or perfectly suitable) according to the conversion score. The financial viability of the conversion project is evaluated through an assessment of key parameters, including conversion costs and rental income (Geraedts et al., 2017). However, the model does not consider spatial planning criteria.

Step	Action	Level	Outcome
Step 0	Inventory market supply of unoccupied offices	Stock	Location of unoccupied offices
Step 1	Quick Scan: initial appraisal of unoccupied offices using veto criteria	Location Building	Selection or rejection of offices for further study; Go / No Go decision
Step 2	Feasibility scan: further appraisal using gradual criteria	Location Building	Judgement about transformation potential of office building
Step 3	Determination of transformation class	Location Building	Indicates transformation potential on 5-point scale from excellent to not transformable
Further analysis (optional, and may be performed in reverse order if so desired):			
Step 4	Financial feasibility scan using design	Building	Indicates financial/economic feasibility Sketch and cost-benefit analysis; Go / No Go decision
Step 5	Risk assessment checklist	Location Building	Highlights areas of concern in transformation plan; Go / No Go decision

Figure 11 Conversion meter process (Geraedts et al., 2017).

LBF Model: The LBF provides a framework for the quantitative measurement of design-based adaptability (DBA) within the context of structural systems, facades and foundations, offering designers a means of making informed decisions during the initial design and construction phases. The LBF is analogous to the flexibility key performance indicator (FKPI) model proposed by Geraedts (2008). This model determines flexibility based on the total value of weighted key indicators and sub-indicators, which is essentially the same as adaptability. The study identified four key factors: longevity, layer separation, reduced uncertainty, and loose fit (Figure 12). These factors were equally weighted. The system weighting factor (S) is determined based on the relative importance of the building systems and the system cost. The degree of presence (D) is a measure of the probability of adaptation of the system based on prior analysis theory and the degree of presence of the enabler type within the system (Ross, 2017). However, the model only presents adaptability-related sub-criteria as headings, without offering specific decision-making or design guidance.

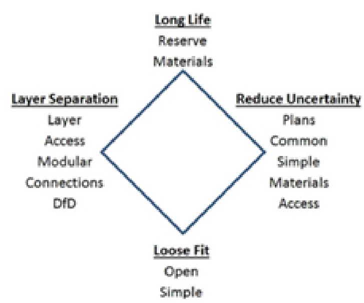


Figure 12 Four dimensions of enabling adaptability (Ross, 2017)

TC Model: The TC (Transformation Capacity) Information Model, which provides a visual representation of the deconstruction potential of buildings, refers to eight key themes of deconstruction: functional decomposition, cluster systemisation, assembly sequences, interface geometry, open versus closed hierarchy, connection type, base element specification and life cycle coordination (Figure 13). In addition to the aforementioned deconstruction themes, the information model incorporates two design criteria (independence and exchangeability) and three transformable configuration domains (material, technical composition and physical integration). The model demonstrates a hierarchical relationship between independent and dependent variables at four distinct levels of dependency. The relationship between variables, expressed by nodes, is a feed-forward structure, where lower-order nodes exert influence over higher-order nodes. The quantity of waste produced during demolition is less than 25% in buildings with high dismantling potential, between 20% and 80% in buildings with medium dismantling potential, and in excess of 80% in buildings with low dismantling potential (Durmisevic, 2006). Since adaptability is evaluated through dismantling capacity, the model focuses on the selection of building systems and components.

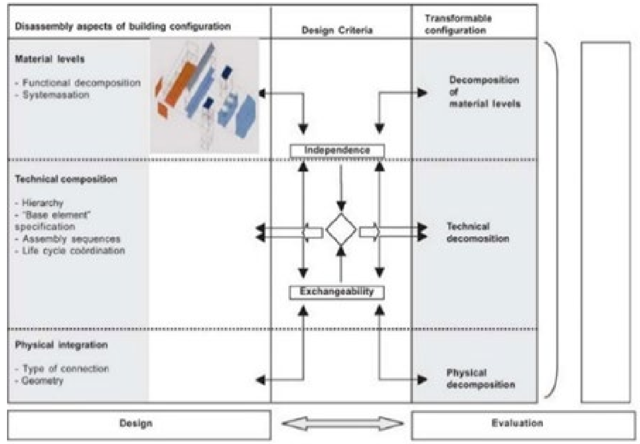


Figure 13 A conceptual framework of the decision support evaluation model (Durmisevic, 2006)

SAGA Model: The spatial assessment of generality and adaptability is a quantitative assessment method that expresses the general and adaptable nature of a space in terms of its graphic permeability. The measure measures the extent to which the spatial connectivity network and spatial area distribution provide generality as passive support for change and adaptability as active support. In the model, floor-plan permeability is calculated with reference to existing and potential connections. The SAGA method represents a reinterpretation of the JPG method, which was previously used in spatial sequence theory to examine the connections between interspatial relationships and social behaviour patterns (Herthogs et al., 2019). The SAGA computational approach can be essentially distilled into two indicator categories. These are the spatial configuration and spatial area indicators employed by SAGA. The spatial configuration indicators calculate the mean permeability (MP) of the various layout graphs, that is, the mean normalised distance of all areas to other areas (Figure 14). Space area indicators examine the potential uses of different space sizes (Herthogs et al., 2019). However, SAGA is limited to plan-level relationships and does not account for structural systems, façades, or service volumes, all of which are crucial to a comprehensive assessment of adaptability.

Mean Permeability (MP; %) *k = number of nodes*	$MP = \frac{\sum_{n=0}^{n=k-1} 1 - RA(n)}{k}$
Relative Asymmetry (RA; %)	$RA = (2(MD-1))/(k-2)$
Mean Depth (MD)	$MD = TD/(k-1)$
Total Depth (TD)	Total step depth or total shortest path distance from one node to all other nodes.
Normalised Generality (G_n)	$G_n = (G - 1/3)/(MA - 1/3)$
Normalised Adaptability (A_n)	$A_n = (A - G)/(MA - G)$

Figure 14 Spatial configuration indicator formulas (Herthogs et al., 2019).

AOM Model: The areal openness model (AOM), developed with reference to SAGA concepts, is a quantitative assessment tool that measures existing floor plans and the change potential of buildings through spatial openness. While SAGA uses graphical theory to examine the arrangement and relationship of spaces, AOM uses basic arithmetic and algorithms to examine the presence and effect of barriers between spaces (Rockow and Ross, 2021). Generality (G), adaptability (A) and normalised adaptability (An) in SAGA correspond to OS, WOS, and OP, respectively, in AOM. OS is the state where there are no obstacles such as walls, projections, and columns separating spaces; WOS measures the number of obstacles and their ability to change; and OP measures the potential for the floor plan to be more open or to improve. According to the equation, OS is inversely proportional to the area density of obstacles, and WOS is inversely proportional to the area density and difficulty of changing obstacles. OP is a function of the difference between WOS and OS (Rockow and Ross, 2021). In earthquake-prone regions, where structural systems are typically more robust and dense, OS and OP values may be lower. Therefore, adaptation threshold values defined by the model should be adjusted according to the specific conditions of each building.

ARAM Model: The ARAM model has been developed with the objective of providing all stakeholders with the information required to make informed decisions regarding the adaptive reuse of heritage buildings at different stages of their life cycle. The development of the model is based on a critical analysis of existing assessment and decision-making models. Previous models have neglected consideration of political aspects, heritage values, and specific characteristics of heritage buildings. In addition, other models have the option of demolishing or leaving vacant buildings that cannot withstand different categories of challenges, which prevents heritage buildings from being preserved and passed on to future generations (Mehr and Wilkinson, 2021). Therefore, the range and prioritisation/order of challenges faced by stakeholders in adaptive reuse may vary depending on the type and characteristics of the building being assessed.

3.2 Comparative Analysis of Models and Tools for Assessing Adaptability in Buildings

A review of the literature on adaptability reveals the existence of numerous models designed to evaluate the adaptability of buildings. In this study, in addition to the models that directly evaluate adaptability, models that address adaptability through the attributes that contribute to adaptability (ARP, AOM, FLEX 4.0, TC) and adaptability as a sub-heading (DAEC, FKPI) were also analysed (Figure 15). The models were subjected to comparative analysis according to the following criteria: year, scope (existing building/new building), building function, focus (design, use, life cycle process), criteria (building, context), method, validation and purpose/output (Table 1).

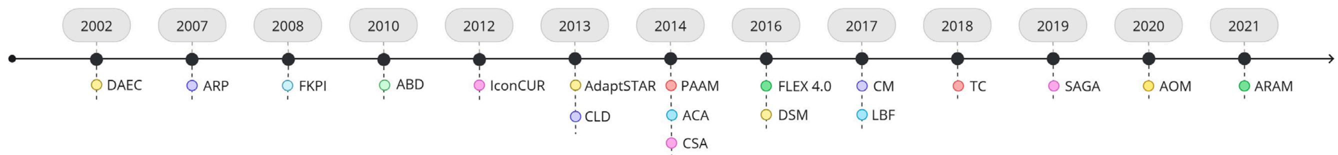


Figure 15 Review of the adaptability assessment models according to year of publication (Authors own work)

A comparison of the evaluated models in terms of scope reveals that approximately half of them address adaptability for both existing buildings and new building designs. Most of the models developed for adaptability approach this issue in a general manner, without making a functional distinction.

These models also vary in terms of which stages of the building life cycle they address. Models focusing on the design phase aim to incorporate adaptive strategies and building features into the planning of new buildings in order to enhance their adaptability from the outset. Models that emphasize the use phase are intended to help decision-makers choose between adaptation, demolition, or maintaining the status quo for existing buildings that were not originally designed with adaptability in mind.

In contrast, models that address the entire life cycle of a building—including design, construction, use, alteration, and demolition—take a more comprehensive view of adaptability. Although many models span multiple stages, it is evident that those assessing the feasibility of adapting existing buildings tend to focus on the use stage. Meanwhile, models offering a general system framework for designing adaptable new buildings typically remain at the design stage.

The criteria evaluated by the models were analysed in terms of both contextual and building-related factors. While most models assessed adaptability using a combination of building and contextual criteria, a few focused only on building-related aspects.

A variety of analytical methods were employed across the models, including criterion scoring, mathematical algorithms, graphical algorithms, multi-criteria decision making, space syntax, principal component analysis, model comparison, real options analysis, Monte Carlo simulation, boundary value methods, DSM matrix, causal loop diagrams, analytic network hierarchy, AHP analysis, and correlation methods. Among these, criterion scoring was the most commonly used method. Model validation and real-life applicability were predominantly demonstrated through case studies. The PAAM has been the sole validated model, with its validation being achieved through the utilisation of a substantial data set and case studies. In contrast, the ABD, CLD, and LBF models have not yet been validated.

Although the output of each model developed for assessing adaptability differs according to its purpose, some models produce similar types of outcomes. These include:

- Rating or classification systems for evaluating structures (e.g., AdaptSTAR, FLEX 4.0, TC, CM, FKPI),
- Conceptual decision support tools for the adaptive reuse phase (e.g., ARP, iconCUR, PAAM, ARAM, CSA),
- Models that assess the level of interrelationships between variables (e.g., DSM, CLD, TC).

Table 1 Comparative analysis of adaptability assessment models (Authors own work)

MODEL	YEAR	SCOPE		FUNCTION	FOCUS			CRITER		METHOD	VALIDATION		OUTPUT
		E	N		D	U	L	B	C		CS	DB	
DAEC	2002	X	X	Educational	X		X	X	X	Criterion Scoring	X		Comparison of durability, adaptability, and energy-saving design options
ARP	2007	X		General		X		X	X	Mathematical Algorithm Graphical Algorithm	X		Percentage expression of adaptive reuse potential/ARP index

ABD	2010		X	Office Commercial	X		X		X	Real Options Analysis Monte Carlo Simulation			Life cycle planning
IconCUR	2012	X		General		X		X	X	Criterion Scoring Multi-criterion decision making	X		Conceptual decision support visualised on a 3D plane
AdaptSTAR	2013	X	X	General	X			X	X	Criterion Scoring	X		5 star rating system for assessing adaptability
CLD	2013		X	General			X	X	X	Causal Loop Diagram			Visualising the impact of the variables that make up the adaptability system on each other
PAAM	2014	X		Office Commercial		X		X	X	Criterion Scoring Model Comparison Principal Component Analysis	X	X	Ranking the potential of small-scale adaptation actions and conceptual decision-making support
ACA	2014	X		Residential				X	X	AHP Analysis Correlation Method	X		Quantitative measurement of the adaptability of a building to different use scenarios
CSA	2014		X	General	X		X	X	X	Boundary Value Method	X		Conceptual decision-making support to bridge the demand–supply gap
FLEX 4.0	2016	X	X	General Office Residential	X		X	X		Criterion Scoring	X		5 star rating system for assessing flexibility
DSM	2016	X	X	General	X		X	X	X	DSM Matrix (N*N dependency matrix)	X		Revealing the complex relationships and dependencies between adaptive features and building systems
CM	2017	X		Office Residential		X		X	X	Criterion Scoring Boundary Value Method	X		5 grade classification system for transformation potential
LBF	2017	X	X	General	X			X		Criterion Scoring			Quantitative measurement of design-based adaptability
TC	2018	X	X	Office Residential Educational	X		X	X	X	Analysis Network Hierarchy	X		3-grade classification system for dismantling potential
SAGA	2019	X	X	Residential	X		X	X		Mathematical Algorithm Space Syntax	X		Quantitative analysis of adaptability and generality using the graph permeability formula
AOM	2020	X	X	General	X			X		Mathematical Algorithm Model Comparison	X		Quantitative analysis of spatial openness through the effects of barriers
ARAM	2021	X		Heritage		X		X	X	Model Comparison	X		Conceptual decision-making support for the reuse of heritage buildings

***E:** Existing building,* ***N:** New building,* ***D:** Design,* ***U:** Use,* ***L:** Life cycle process,* ***B:** Building,* ***C:** Context,* ***CS:** Case study,* ***DB:** Database*

A comparison of the models in terms of their weaknesses, strengths, and potential reveals that Flex 4.0, and AdaptSTAR are among the most practical models, as they do not require specialised expertise either in understanding their criteria or during their application process. Consequently, it is anticipated that these models can be readily utilized by non-expert users. In contrast, ARP, SAGA, and AOM—models based on mathematical algorithms—are considered the least practical, due to the need for technical expertise in their implementation.

The ABD, LBF, and CLD models are regarded as the least developed, primarily because of their lack of validation and limited content detail. While most models assess adaptability based on defined criteria, SAGA and AOM take a spatial planning-based approach, which positions them as potentially pioneering frameworks for future research in this field.

The innovative and comprehensible 3D visual expression technique of IconCUR, a feature not present in alternative models, is hypothesised to exert a positive influence on the decision-making process in the adaptable reuse of existing structures.

3.2 Strategy Used in Adaptabılıty Assessment Models

The majority of the models developed to understand and evaluate the adaptability process address this concept through a variety of strategic approaches (Table 2). The diversity in research scope and the evolving definition of adaptability have contributed to a wide range of strategies aimed at achieving adaptability. Among the most frequently employed strategies are disassembly, flexibility, scalability, mobility, durability, accessibility, and layering.

Table 2 Strategy used in adaptability assessment models (Authors own work)

MODEL	STRATEGY
DAEC	Durability, Adaptability
FKPI	Partitionable, Adaptable, Extendable, Multifunctional, Universal, Accessible, Adjustable
ICONCUR	Recycle, Reuse/Adapt, Renovate
ADAPTSTAR	Durability, Accessibility, Disassembly, Flexibility, Convertibility, Maintainability
CLD	Interchangeable, Indterminacy, Deconstruction, Flexibility, Layering
ACA, CSA	Senaryo Based Design
FLEX 4.0	Layering,Extendible, Multifunctional, Rejectable, Disconnectable, Mobility, Removable, Accessibility
DSM	Adjustable, Versatıle, Refıtable, Scalable, Movable, Convertıble
LBF	Long Life, Loose Fit, Layer Seperation, Reduce Uncertainty, Flexibility
TC	Independance, Exchangeability, Decomposition-Disassembly, Transformable
SAGA	Permeability, Disassembly, Generality, Adaptability
AOM	Openness, Disassembly, Removable

Disassembly, which relates to the connections between building elements, is an important strategy that facilitates repair and maintenance processes while reducing construction and demolition waste. Flexibility refers to minor, short-term alterations in the interior spatial configuration, allowing for easy adaptation to changing needs. Scalability is defined as the capacity of a building to accommodate volumetric changes, typically through the addition or subtraction of building components.

Mobility pertains to the modification of interior space by means of movable partition walls and furniture, enabling spatial reconfiguration without structural intervention. Durability is characterised by the long-term design of building elements with a low rate of change, such as structural systems, and emphasises resilience and longevity. Accessibility is defined as the ease and speed of access to building services for maintenance and repair, contributing to lower demolition rates and improved building performance. Layering refers to the hierarchical organisation of building components based on their expected lifespans, promoting flexibility by allowing certain layers (e.g., finishes or services) to be altered without affecting others (e.g., structure). While these strategies are conceptually distinct, they are often interrelated and can be grouped based on the degree of their interaction and influence within the adaptability framework.

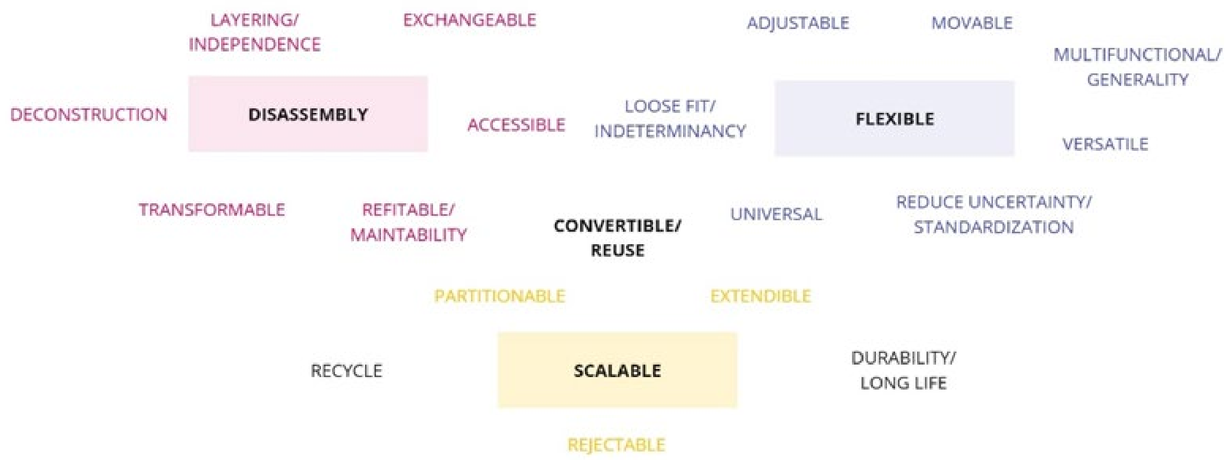


Figure 16 Relationship clusters of adaptable strategies (Authors own work)

Three distinct clusters emerge around the main strategies, based on the relationships among them (Figure 16). Disassembly, flexibility, and scalability—which are the most frequently applied strategies in the reviewed models—are identified as the core strategies. The prevalence of these core strategies indicates that facilitating component manipulation (disassembly), accommodating internal reconfigurations (flexibility), and enabling volumetric adjustments (scalability) are considered critical factors for achieving adaptability in buildings. Each of these core strategies is supported by a set of sub-strategies:

- Sub-strategies supporting disassembly include transformability, deconstruction, accessibility, layering, refitability, and interchangeability.
- Sub-strategies aligned with flexibility are mobility, generality, adjustability, loose fit, universality, and standardisation.
- Sub-strategies closely related to scalability comprise partitionability, extendibility, and regetability.

Reuse, which is associated with scenario-based design, is positioned at the centre of the strategic framework, as it involves large-scale transformations and is directly linked to all three main strategy groups.

4. Conclusion

Adaptability is defined as the ability of the built environment to respond efficiently and cost-effectively to changes in social, economic, physical, technical, and environmental contexts, considering all relevant actors and factors. This study comparatively analyses qualitative and quantitative adaptability assessment models. It provides a foundation for future model development by identifying their strengths, weaknesses, practicality, applicability, and the strategies employed along with their interrelationships. Despite its comprehensive analysis, this study acknowledges certain limitations. The comparative analysis focused on models developed between 2000 and 2022. While this period reflects significant activity in the field, neither more recent nor historical models outside this timeframe were included. Additionally, the present study focuses solely on the description and categorization of the strategies inherent in the models. Consequently, the correlation between strategy grouping and model effectiveness is excluded from the scope of the study. Furthermore, the practical application and detailed impact of these strategies in real-world projects were beyond the scope of this theoretical comparative analysis. The study's focus on academic models means that informal or industry-specific adaptability assessment practices, which may also contribute to the field, were not systematically reviewed. The main findings, offering a overview of existing adaptability assessment models, are as follows:

Context-Specific Adaptability Frameworks: Considering that each building has a specific design problem within the scope of its user, function, and context, drawing a general adaptability framework may lead to the development of an incorrect vision for the future and thus unsustainable adaptability solutions. The adaptive solutions should be proposed during the initial design process of the buildings, taking into account the building context, function, current and potential future users, which can facilitate the adaptability process. Thus, a more reasonable adaptability vision for the future can be developed. However, most of the models presented for existing and future buildings assess the adaptability of buildings in general without considering building function, although they assess the adaptability of buildings based on both structural and contextual criteria. This highlights a significant limitation, indicating a need for new models and tools that can propose specific, function-oriented adaptability frameworks.A function-oriented methodology can be developed based on different scenarios of existing and potential building uses, allowing for a more nuanced and effective approach to adaptability.

Holistic Assessment of Building Potential: In most models, the potential for change of the building is considered through building elements, neglecting spatial parameters. Considering that a building is a whole with respect to its context, technology, and spatial characteristics, existing models focus on only a part of the whole. In this context, this study underscores the necessity of creating a comprehensive reference for new building designs by employing models that address adaptability from a holistic perspective, integrating context, technology, and space throughout the design process. In this way, the impact of changing social, economic, environmental, and natural conditions on the built environment can be mitigated through new building designs with improved adaptive reuse potential.

Integrating Context, Structure, and Space in Quantitative Models: Although quantitative assessment models have been developed in recent years to evaluate adaptability spatially, they evaluate adaptability only through floor plans and neglect contextual and structural features. To provide a truly holistic view of building adaptability, there is a clear demand for new models that comprehensively assess context, structure, and space in an integrated manner.

Core Design Strategies for Adaptability: In the models evaluating adaptability, many design strategies have been proposed according to the scope and priority of the study. Among these, flexibility, disassembly and scalability are considered to be core strategies in planning, design, construction and demolition processes to ensure adaptability, and are thus of critical importance. It is therefore believed that following these strategies during the building production process will enhance the adaptability of the constructed environment. Applying strategies synergistically, rather than in isolation, can lead to more comprehensive and effective outcomes. This interconnectedness enables designers to combine the strengths of various strategies in order to address complex adaptability challenges in a holistic manner. As the emphasis was on the conceptual organisation of strategies, the relationship between strategies and model effectiveness was not analysed. In future research, the impact of various strategy groupings on model performance could be measured quantitatively.

Adapting to Evolving Trends and Technologies: In the 21st century, developments in digital design software, robotics, information and communication technologies, building construction technologies, and materials continue to transform the meaning and scope of adaptability and its impact on urban and architectural spaces. It is therefore vital that a comprehensive and up-to-date adaptability framework is established. This framework must keep pace with the accelerating rate of change in current trends and innovations, providing essential guidance to developers, designers, policymakers, and other stakeholders responsible for the production of adaptive built environments.

Although adaptive solutions in architectural practise are a natural part of prehistoric architectural forms and premodern traditional building culture, they were first discussed theoretically in conjunction with modernism. An analysis of the literature on assessing the adaptability of buildings shows that the concept of assessing the adaptability of the built environment has maintained its continuity and currency However, a critical gap exists in current assessment tools: among the models that examine contextual data alongside the building, none specifically reflect Turkiye's unique ecological, economic, social environment, architecture, and building culture. Climatic changes, technological developments, economic conditions, and changes in social conditions such as working and living conditions will have different impacts on different countries. Therefore, a future research direction and direct implication of the findings of this study is the need to develop a new adaptability assessment model tailored specifically to local conditions in Turkey. Such a model would provide guidance for sustainable urban development and architectural practice within the Turkish context. This local focus would also contribute to the broader discourse on adaptability, introducing a regionally sensitive framework and enriching the global understanding of how adaptability can be assessed and implemented effectively across diverse cultural and environmental landscapes.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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