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Review article

Comprehensive review and comparative analysis of building condition assessment models

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ABSTRACT

Building Condition Assessment (BCA) is an important part of Facility Management (FM) since it involves strategic planning and decision-making to optimize the performance, longevity, and value of facilities. This paper aims to provide a review and a comparison of published research in the field of BCA, especially in the context of the developed models for this purpose. The methodology for reviewing and comparing the selected models involved a systematic approach to identifying, filtering, and extracting relevant studies from recently published scientific papers and conference papers indexed in reputable databases such as Web of Science and Scopus. The selected models were systematically reviewed and analysed to assess the types of buildings for which the models were developed, the purpose of their development, methods of data collection, software or tools used for data analysis, model strengths weaknessess and limitations. The findings from the data analysis were synthesized to identify patterns, trends, and insights across these selected models.

1. Introduction

Studies have revealed that many buildings rapidly deteriorate due to aging and overloading despite their significant cultural, economic, and historical significance [1]. It is highlighted in the literature that in the context of Facility Management (FM), building maintenance is generally recognized as the main activity since more than 65 % of the total cost of FM comes from facility maintenance management [2,3]. Also, 75–80 % of the costs of a building are realized during the operation and maintenance phase of its life cycle [4–6]. Given that expenses typically rise steadily because of either ineffective maintenance techniques or a lack of regular maintenance, this is a serious concern, especially for buildings with a 50-year service life [7–10]. In addition, there is a global trend toward an aging building stock and an increase in the number of existing buildings [7]. Building maintenance stakeholders, including governments for their public buildings, have responded by significantly increasing their budget for building maintenance as they recognize the need to sustain existing facilities [11–13]. Furthermore, it is widely acknowledged that the building life cycle's operation and maintenance phase has the most significant environmental impact [7]. These factors underscore the importance of proactive measures to ensure a building's continued functionality and minimize resource consumption throughout its lifespan. The quantitative assessment of the building degradation is done by Building Condition Assessments (BCAs), which gather information to decide when and what kind of predictive, preventative, or corrective actions are needed to maintain the intended level of service [14]. A BCA, in general, is an analysis that pinpoints significant flaws in every system in the structure [15]. Mechanical systems, external building envelope components, structural assemblies, roofing systems, fire and security systems, electrical systems, transportation systems, interior finishes, plumbing systems, and occasionally installations, equipment, and furniture are among the systems that may be covered by the assessment [16]. A quick overview of the building's condition is given by the BCA enabling the creation of a capital budget for significant maintenance and replacements over a predetermined time frame [17]. As a result, in case of FM, financial resources for maintenance and replacements are prioritized. Also, understanding the current state of a building, including its physical components and systems is provided [18]. This information is crucial for developing effective maintenance plans, ensuring that necessary repairs and upgrades are addressed in a timely manner [19]. Besides, identifying potential risks and vulnerabilities in a building through a condition assessment helps in implementing preventive measures [20]. The likelihood of unexpected failures, safety hazards, and disruptions to operations are reduced by that proactive approach [21]. Additionally, for asset owners, a thorough BCA contributes to accurate property valuation. Since consumers

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demand strategies for predicting events instead of reacting to difficulties, prospective buyers and investors are more likely to have confidence in a building with a documented and well-maintained state [3,22]. Also, a significant factor influencing building condition is the long-term performance of its materials [23,24] and BCA models play a critical role in proactively evaluating this performance. These models allow for identifying of potential issues early on, enabling timely interventions that can prevent costly repairs, extend the building's lifespan, and ensure continued functionality [25].

Literature gives various definitions of BCA covering a period from 1993 to 2023 which are shown in Table 1.

A common element across these definitions is the systematic evaluation of the technical performance and state of buildings, systems, or organizations. The emphasis is on assessing operational effectiveness, structural soundness, and compliance with predetermined goals, frequently to preserve or return the evaluated entities to their original state. The analysis of the definitions has led to a conclusion that the key elements of these procedures include information systems, data management, and the discovery of deficiencies, highlighting an organized and thorough method of assessing and maintaining physical assets. However, a wide range of perspectives, methods, and professional backgrounds is included in the field of BCA leading to varying interpretations based on details, changing industry standards, and the particular emphasis each author places on different aspects of building or system evaluation. For this reason, various authors use various approaches with respect to define the term.

BCA models are essential for construction and maintenance industries, offering structured frameworks for assessing built infrastructure [40]. They aid stakeholders throughout a building's lifecycle, from design and construction to ongoing maintenance and renovation. During construction, these models inform decision-making, anticipate maintenance needs, and optimize resource allocation. In maintenance, they help prioritize tasks and extend asset lifespan through proactive planning [41]. BCA models also enable predictive maintenance, utilizing historical data and analytics to address issues before it is too late [42]. Additionally, they support industry goals like resilience and sustainability by identifying opportunities for resource optimization, retrofitting, and energy efficiency improvements. Overall, BCA models are indispensable tools for efficient infrastructure management, benefiting industries and society [43].

Table 1
Various definitions of BCA from the literature.

Definitions	Year	Ref.
A systematic process of assessing an organization's capital assets to determine what needs to be replaced, renovated, or repaired to maintain their capacity to carry out the tasks they were designed for	1993	[26]
A professional service wherein building evaluations are carried out, mainly to report building problems, and the goal is to restore the building's performance to its initial "new" level	1995	[27]
An examination and reporting procedure for assessing the structural soundness and operational efficiency of structures, infrastructure systems, and parts	1996	[28]
Evaluation of the condition of a working system that achieves intended objectives	1996	[29]
An information system for entering, storing, modifying, and reporting building-related data	1997	[30]
An organization's systems, parts, and subparts are evaluated according to their state	2001	[31]
A method for assessing a building's technical performance to support long-term maintenance expectations.	2002	[32]
System inspection to determine the system's current state using predetermined condition metrics.	2003	[33]
A process for compiling an exhaustive inventory of a building's shortcomings by carefully assessing the building's current state of repair and functionality and its installations, machinery, and surroundings.	2004	[34]
Using a systematic process to generate appropriate, important, and helpful information to conduct a technical evaluation of the assets' physical state	2007	[35]
Enhancing knowledge of asset management and monitoring, along with improving asset information management techniques	2017	[36]
Establishment of the basis for determining the suitable frequency of regular maintenance for building facility components	2021	[37]
Physical inspection and diagnosis of the health of a building	2021	[38]
Integration of diverse data types including building characteristics, element/system properties, and maintenance records	2022	[3]
A systematic process that should analyse the facility conditions to identify and prioritize the maintenance work required to restore and maintain the desired conditions	2023	[39]

Even though the topic is familiar, the database related to previous research is not as extensive as in some of the often-researched topics regarding FM. Most of building assessment research deals with green building rating which is a rating system that evaluates the environmental performance and sustainability of a building. These ratings are designed to assess and promote environmentally friendly and resource-efficient construction and operation practices [44–46]. Only one review paper in the field of building condition assessment was found [47] and it deals with building component rating systems.

This paper aims to provide a review and a comparison of published research in the field of BCA, especially in the context of the developed models. The goal of the paper was to analyse.

- the types of buildings for which such models were developed,
- the purpose of their development,
- methods of data collection,
- software or tools used for analysing the collected data,
- strengths of the models,
- weaknesses of the models, and
- limitations of the models.

Based on the analysed research, the paper aims to provide the main elements for developing an efficient BCA framework and propose recommendations for future research directions and practical applications based on the identified gaps and opportunities.

The next chapter refers to the methodology used for conducting the review, following the review, which comprises 101 referenced sources, the structure of the remaining sections of the paper is outlined as follows: section 3 explores the definition of BCA and introduces some of the first condition assessment systems; section 4 introduces the building hierarchies and explores linguistic/numerical representations in condition assessment; section 5 conducts an analysis of condition assessment models over the past 20 years; section 6 provides a comprehensive discussion, and in section 7 conclusions are drawn based on the findings.

2. Methodology

The methodology for reviewing and comparing the selected models involved a systematic approach to identifying, filtering, and extracting relevant studies from recently published scientific papers and conference papers indexed in reputable databases such as Web of Science and Scopus. The primary objective was to comprehensively assess the state-of-the-art models in the field of BCA, with a focus on key areas such as asset management, building maintenance, performance evaluation, and facility management. The analysis contained the types of buildings for which such models were developed, the purpose of their development, methods of data collection, the software or tools used for analyzing the collected data, and their strengths, weaknesses, and limitations.

The process of data collection began by selecting the main keywords, namely "condition assessment," "asset management," "building maintenance," "performance evaluation," and "facility management," to initiate the research process. Search filters were applied to narrow down the results and ensure the incorporation of recently published scientific papers and conference papers. Studies that met the predefined criteria for relevance and quality were extracted for further analysis and comparison.

The selected models were systematically reviewed and analysed to assess the types of buildings for which the models were developed, the purpose of their development, methods of data collection, and software or tools used for data analysis were analysed. Also, the analysis included their strengths, weaknesses, and limitations. Finally, the findings from the data analysis were synthesized to identify patterns, trends, and insights across the selected models.

3. Building condition assessment

3.1. Optimal frequency and data collection

Given that the more time passes between inspections, the more thorough the inspections become, it is recommended that the optimal frequency for evaluating the condition is once a year. However, the expense of the inspection is a manageable issue when considering frequency of performing condition assessments. In addition, proper detailed information needs to be gathered during on-site inspections. It is redundant to collect overly extensive data that is never used, but a lack of depth also wastes resources because the data may need to be more beneficial due to inadequate information [31].

Experts advise creating an asset management program in decision-making processes. This program begins with policies, goals, and strategies and then moves into detailed asset management plans. Since Asset Management Information Systems (AMIS) deal with technical, financial, and historical asset data, they are an important topic in this context. These systems range in complexity, from widely used basic tables to sophisticated systems that use particular models to forecast future situations [48]. These models offer the most accurate analytical and forecasting skills [49]. Nevertheless, facility managers encounter challenges that make it difficult to put these predictive models into practice. The inability to gather data related to the present state of assets prevents the development of such predictive models [50], which also makes it impossible to use a broad method to evaluate building subcomponents [35]. A number of studies have suggested methods for evaluating infrastructure elements and ranking the importance of their maintenance [50]. Nevertheless, these attempts fail to consider how this evaluation might be implemented at the building level and fail to offer a deeper analysis of the structure. This emphasizes the necessity of a thorough yet user-friendly method for evaluating the state of components that may be used at the construction level [51].

3.2. Assessment methods and Building Condition Index (BCI)

Conducting a condition assessment can be done in a variety of ways. It can be done at the component level, where each piece of equipment is assessed to determine its worth and remaining lifespan [52]. It can also be done at the system level, where the emphasis is on evaluating the state of the system and assigning a value to it, as opposed to evaluating each of its constituent parts. Additionally, there are statistical techniques like parametric methods which include gathering data for a subset of organizational assets and extrapolating the findings to the complete building inventory. Following a BCA, the information gathered is examined and converted into an index known as the Building Condition Index (BCI) which serves as a measure of the building's condition. BCI is regarded as a standard tool in FM and is used to compare building conditions and assess whether it would be financially feasible to replace an existing building or completely modernize and renovate an existing one [16].

BCI is calculated by taking the ratio of the cost of repairing deficiencies (or deferred maintenance) to the Current Replacement Value (CRV) of the building [16]:

$$\text{BCI} = \text{cost of deficiencies repair / CRV}$$

The cost for deficiencies repair represents the estimated total cost to repair all deficiencies throughout the lifecycle and maintenance, while the replacement value is the cost of replacing the existing building with a new one of the same dimensions at the same location, which can be calculated as follows [53]:

$$\text{Current Replacement Value of the building} = \text{Gross area of the existing building} * \text{Estimated cost per square meter for designing and constructing a new building}$$

Yet, the method used to calculate BCI differs throughout institutions and consulting firms. When comparing buildings owned by various companies or within the same community, where BCAs are conducted by different consultants using different formulae for computing BCI, the measurement scale also varies, making BCI less trustworthy as a tool for comparison [54]. Cost is the main limiting factor when deciding who will do the assessment or condition evaluation. The assessment can be carried out by an internal staff member or an external consultant. While larger firms can hire numerous specialists specifically for this purpose, smaller ones might not be able to afford one. Nonetheless, in order for the assessment team to complete the assignment effectively, they must have sufficient time and an elementary knowledge of building maintenance and operations [55].

3.3. Specific systems for building condition assessment

Since the 1980s, condition assessment systems have been developed for specific types of construction and components. For example, PAVER was developed for asphalt management [22], RAILER for railways [23], BRIDGER for bridges [24], ROOFER for roofs [25], and GRIPPER for underground gas pipes [24]. For buildings, various systems have been developed.

- BUILDER was created at the Engineer Research and Development Centre by the U.S. Army Corps of Engineers. Engineers and building managers can use BUILDER as a tool to help them decide when, where, and how best to maintain buildings and their essential components. Its features, which are based on the Windows® system, include form-based inspections, condition assessments, functionality evaluations, and predictive capabilities in addition to an inventory of the main building components [56,57].
- RECAPP®, or Re-Engineering the Capital Asset Priority Plan, was initially created to assist clients who were going through audits with data collecting and reporting. It consists of condition assessments, form-based inspections, and an inventory of the principal building components. School boards, municipal infrastructure managers, and airport owners use it extensively [16].
- The European Commission created TOBUS as a component of the JOULE II initiative, and it assesses the level and scope of physical deterioration as well as the labour required to renovate office buildings [58].

Every component in the RECAPP system has a unique list of specific flaws, each of which is weighted to indicate how much impact it has on the condition. Inspectors evaluate each possible deficiency in the field, and RECAPP computes the condition index based on their findings [16]. BUILDER use its 20 standard damage categories during the evaluation procedure. An inspector assesses the quantity and extent of damages in the field by evaluating each subcomponent considering those 20 damage types. It takes a lot of time and it is very complex to complete this process since an inspector must provide $20*2*3 = 120$ subjective measures, for example, in order to evaluate a component that has only three subcomponents where those data are used to construct the condition index [56,57]. TOBUS uses a direct assessment method to determine how well construction components are performing. Four degradation codes are used by TOBUS to evaluate the current condition and determine the building's physical deterioration degree [58]. The disadvantage of this approach is that parts are not dissected as they are in BUILDER and RECAPP. Furthermore, TOBUS does not have a numerical scale like BUILDER and RECAPP, therefore the evaluation of its components is quite subjective [55].

4. Building hierarchies and linguistic/numerical representations in condition assessment

4.1. Hierarchical component breakdown

Uzarsky and Burley underline that breaking down a structure into its constituent parts in a hierarchical manner is an essential part of conducting a condition evaluation. These elements can be categorized and grouped into different groups using hierarchy. For example, a structure can be broken down into many systems or disciplines such as mechanical and electrical, which can then be broken down into more specific levels of components (ceilings, windows, doors on the inside, exterior). It is possible to group components into a branch of the hierarchy to represent related qualities (like materials) or inspection requirements [56]. According to Straub, a precise and hierarchical classification of a building's components is required for a fair evaluation of the structure [59]. When creating a building's hierarchy, a uniform and consistent format can help departments within an organization to share data more easily. To align with the Organizational Breakdown Structure (OBS) of an educational organization (such as school boards), Elhakeem combined the advantages of existing hierarchies and proposed a building hierarchy with five levels (system, subsystem, component, type/element, and instance) in his doctoral dissertation. The primary benefits of the suggested hierarchy include the following: it is easier to review the components that have been assessed, each department is assessed for how much they are doing at keeping its components safe and in good working order, and it allows the organization to distribute funds across various systems in accordance with organizational preferences [48].

4.2. Component assessment methods

Uzarski emphasizes that when assessing the condition of a single instance of a building component, two approaches can be combined: damage inquiry and direct condition assessment. Since the damage investigation method creates a record of the things that need to be fixed in the analysed instance, it is marked as an accurate and repeatable procedure. The direct condition evaluation approach involves visually inspecting each component and evaluating it according to a set of criteria, and that is much faster but less accurate. The author also points out that knowing the goal of the assessment is necessary when deciding whether to employ the damage investigation approach or direct condition evaluation. Direct condition evaluation is adequate if the only objective is to determine the state of a component. However, the damage inquiry approach should be used if the goal is to discover current issues [57]. The building hierarchy of different assessment methods is presented in Table 2 [47]. The Portuguese method of condition assessment divided the entire building into 3 groups and 37 elements [60], while the Dutch method utilized 4 categories and 17 elements [59]. Eweda et al. [61] categorized the building into 4 groups and 17 components, while Ho et al. [62] proposed an assessment method that divided the building into 2 branches, 5 categories and 17 components.

Table 2
Component display in building hierarchies [47].

Reference	Year	Building type	Hierarchy
NCES [53]	2003	Educational	11 systems and 106 components
Ho et al. [62]	2005	Residential	2 branches, 5 categories and 17 components
Pedro et al. [60]	2008	Residential	3 groups and 37 elements
Straub [59]	2009	Residential	4 categories and 17 elements
Eweda [61]	2015	Educational	4 categories and 17 components

It is clear from the information given that there is the absence of a uniform, accepted hierarchy of building components in use. A vast building's components may be easily tracked when there is a consistent and logical hierarchy in place. In order to create an effective and trustworthy evaluation system, a suitable mechanism for evaluating building components should be used in conjunction with a thorough building hierarchy [47]. To make it easier to locate and manage each component unit throughout the building evaluation process, building hierarchies break down the entire structure into smaller pieces. According to earlier research, the creation of a building hierarchy is a crucial step in the building component assessment process. While different building types may have different components, most structures share many basic building components such as mechanical, electrical, and structural parts. Variable condition assessments could result from reviewing the same building component problems with various hierarchies while utilizing the same assessment procedures. Considering the building hierarchy when combining component assessments to estimate overall building conditions might have important consequences. Inspection staff will need a clear hierarchical classification of building components in order to achieve an objective assessment [47].

A great amount of research has been done with the aim to find appropriate standards for assessing the performance of building components. The correctness of the subjective on-site inspection procedure, however, has a significant impact on the outcomes of the evaluation process, independent of the criteria employed and their degree of detail. Current methods frequently require an experienced inspector to evaluate the state based on a variety of criteria while the inspection is being conducted. As a result, these inspections are frequently expensive and time-consuming [63]. There are several problems with on-site inspections, regardless of the technique employed with the aim to document a structure's condition. A primary issue noted in the literature is the inspector's subjectivity when evaluating the state of building systems or components [64]. The inspector's particular experience, attitude toward risk, dependence on "rule of thumb" procedures, and bias can all contribute to this subjectivity [65,66]. Traditionally, professionals with knowledge related to building systems—such as the structural, mechanical, electrical, and architectural—conduct visual inspections to evaluate the condition. Although many FM systems incorporate measures to ensure uniformity, such as staff training and the use of quantitatively based rating systems, the current condition assessment procedure is still very subjective. A significant factor in determining its accuracy is the knowledge and experience of on-site inspectors and assessors [16].

Faqih and Zayed 2021 compared the methods that are now in use for building components' state evaluation by critically examining and comparing the methods' advantages and disadvantages. The analysis of various assessment systems such as rating the severity of building deficiencies using a scale, evaluating the building's condition by breaking it down into smaller components within a hierarchy, and using weight coefficients to determine the relative significance of each component in the overall assessment showed that similarities were found between assessment systems. The primary distinctions between the various systems were found to be the scope and aims of the assessments, as well as the diverse approaches, instruments, and strategies employed to arrive at the ultimate evaluation of the complete structure. Additionally, it was discovered that the methods used to evaluate building components are quite subjective because most assessment systems rely on inspection staff interpretation and visual observation. The authors highlight that in order to cut costs, limiting subjectivity in the evaluation of building components and shortening the amount of time needed should improve current inspection processes and assessment methods [47].

The fact that so few industrialized nations have made the system of evaluating building components legally obligatory also motivates building owners and building managers to use it. If a BCA assessment system is not legally mandated, building managers may nevertheless be discouraged from using it due to the subjectivity of assessments that only rely on visual inspection, the time and expense involved in examining numerous components. In order to accomplish sustainable management, the authors stress the necessity of creating a low-cost, dependable system for evaluating building components that employs standard procedures and measurements, minimizes inspection expenses, and takes the required amount of time [47]. The authors offered suggestions for creating a new, effective method for evaluating building components based on the study that was done [47].

- Consistency: Building hierarchies that are consistent should serve as the foundation for the assessment system, and the evaluation findings should be repeatable using the same standardized process.
- User-Friendly: To be accepted by the expert community, the assessment process should be simple to use and have grading scales that are easy to grasp.
- Objectivity: The human factor in component evaluations makes it difficult to eliminate subjectivity, but efforts should be made to minimize subjectivity as much as possible and establish an objective method.
- Modularity: The evaluation method should include provisions for future improvements while also capturing the current state of constructing components with existing knowledge and limits. It is advised to use a modular strategy that allows the assessment system to be expanded with new modules in the future.
- Transparency: To make it simple to spot any mistakes that might happen during an inspection, the assessment and evaluation process should be transparent and open to future review.

4.3. Linguistic and numerical representations

Any system's BCI values provide a means of comparing the current conditions of different components. The BCI for building components typically has a range from 0 to 100, where 100 represents a new condition and 0 represents a critical (failed) condition [51]. Regardless of the scale used, a linguistic representation can be derived from numerical values [55]. Fig. 1 shows an example of a recent research and how the component condition rating state can be related to the condition index, colour code, linguistic depiction and action that is required.

In Table 3, the authors present a thorough review of the condition scale with detailed linguistic representations that describe various conditions. It is essential to highlight that the information within Table 3 doesn't solely rely on pre-existing sources, notably [16,47,55,67] but is instead expanded by extensive additional research. The selection process of expanding the table involved identifying a wide range of condition scales; focusing on sources that provided detailed linguistic representations alongside the numerical scales, offering a clearer understanding of each condition state; and including references from a wide time span (1995–2024) to capture the evolution of condition scales and terminology over time.

According to the analysed research findings, a diverse range of condition scales is employed within the field of BCAs, as depicted in Fig. 2.

The representation of these condition scales provides insights into the methodologies and frameworks utilized across different studies. Notably, the most prevalent condition scale observed is the 1–5 scale, utilized in approximately 32 % of all analysed research. This scale, characterized by its simplicity and ease of interpretation, offers straightforward categorizing of the condition of buildings and their components. In addition to the 1–5 scale, the analysis reveals the frequent adoption of the 0–100 scale, which is evident in approximately 21 % of the analysed research. The utilization of these various scales underscores the diversity in approaches employed within BCAs.

5. Review of the building condition assessment models

5.1. Early advancements (1997–2008)

Maintenance requirements frequently surpass budget according to Pitt's study from 1997. He underlined that a typical issue is that the BCA's categories are too broad to produce a sensible maintenance schedule. He pointed out that adding more categories is the obvious answer. However, one disadvantage is that there must be concerns regarding the consistency and dependability of the data if more than six or seven categories are utilized as it is believed that people find it difficult to discern between more than those numbers. Another disadvantage is that there would still be challenges in aligning needs with budgets, particularly in case of borderline values, even when there are twice as many categories. Logistically, handling a large number of categories is difficult because the majority of condition assessment systems were designed for manual sorting [81].

According to Elhakeem and Hegazy's conclusion from a 2005 study, a visual guiding system might be used to help the BCA process, making it more efficient, less subjective, and suitable for staff members with less expertise. In order to design the system, they analysed past BCA reports of Toronto District School Board school buildings and created a visual database with photographs of buildings in various situations [73].

In his doctoral dissertation, Langevine examined the weights of building components to establish a mechanism for evaluating their condition in 2006. Based on the extensive inspections created at the base of the building's hierarchy, he evaluated the relative importance of every element at every level of the hierarchical structure. He also evaluated the state of the building using a consolidation procedure and highlighted that the Analytic Hierarchy Process (AHP) model, when developed, could accurately calculate the relative weight factors of building systems and their constituent parts. The BCI of buildings and systems was then evaluated using the "roll-up" technique by combining the distributed weights with the BCI values of the building components. The authors emphasize that for buildings of the same type, the model

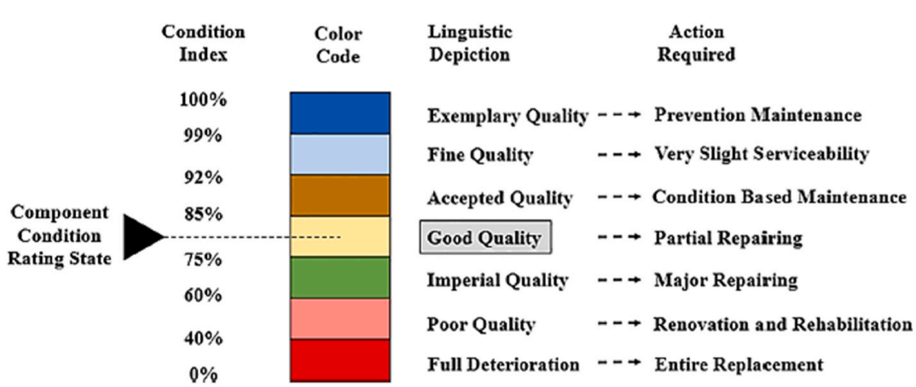

Fig. 1. Component condition rating scale, linguistic depiction and action required [50].

Table 3
The condition scale and related linguistic representations [16,47,55,67].

Reference	Year	Structure type	Condition scale	Linguistic representation
Pontis database [68, 69]	1995	Bridges	1–5	Decay: (1 = protected, 2 = exposed, 3 = sensitive, 4 = attacked, and 5 = damaged)
ADOE [55]	1997	Buildings	1–4	Condition Category: (1 = good, 2 = satisfactory, 3 = poor, 4 = unacceptable)
Greimann et al. [70]	1997	Dams	0–100	Maintenance Need: (0–39 = further investigation only, 40–69 = if economically feasible only, 70–100 = no action required)
Lee and Aktan [14]	1997	Buildings	1–4	Deterioration: (1 = none, 2 = slight, 3 = moderate, and 4 = severe)
Lounis et al. [71]	1998	All	1–7	Condition category: (1 = failed, 2 = very poor, 3 = poor, 4 = fair, 5 = good, 6 = very good, and 7 = excellent)
WSDOT [55]	2000	Buildings	1–5	Condition category: (1–2 = meets current standards, 3–4 = adequate, 4–5 = poor)
Teicholz et al. [27]	2001	Buildings	0.05-1.0	Condition category: (less than 0.05 = good, 0.05–0.10 = satisfactory, more than 0.10 = poor)
NCES [53]	2003	Buildings	1–8	Condition category: (1 = excellent, 2 = good, 3 = adequate, 4 = satisfactory, 5 = poor, 6 = non-operational, 7 = critical condition, 8 = emergency)
DfES [72]	2003	Buildings	A-D	Condition category: (Grade A = good, Grade B = satisfactory, Grade C = poor, Grade D = bad)
Elhakeem and Hegazy [73]	2005	Buildings	0–100	Deterioration: (0–20 = none, 20–40 = mild, 40–60 = moderate, 60–80 = severe, and 80–100 = critical)
Abbott et al. [35]	2007	Hospital buildings	1–5	Condition category: (5 = excellent, 4 = good, 3 = satisfactory, 2 = poor, 1 = very poor)
Ho et al. [74]	2008	Residential buildings	0–1	Rating: (1 = satisfactory, 0.75 = above average, 0.5 = acceptable, 0.25 = inadequate, 0 = poor)
Pedro et al. [60]	2008	Residential buildings	1–5	Deficiency: (5 = minor, 4 = mild, 3 = moderate, 2 = severe, 1 = critical)
Straub [59]	2009	Residential buildings	1–6	Condition category: (6 = very poor, 5 = poor, 4 = fair, 3 = satisfactory, 2 = good, 1 = excellent)
Salim and Zahari [75]	2011	Office buildings	1–5	Condition category: (1 = good, 2 = minor repairs, 3 = general maintenance, 4 = major repairs and replacement, 5 = extensive repairs and replacement)
Eweda [76]	2012	Educational buildings	0–100 %	Condition category: (A (90–100 %) = excellent, B (75–89) = very good, C (60–74) = good, D (40–59) = satisfactory, E (20-39) = poor, F (0-19) = failure)
Adcock and Wilson [77]	2016	Residential buildings	A-J	Hazard rating: (A = 5000 and above, B = 2000–4999, C = 1000–1999, D = 500–999, E = 200–499, F = 100–199, G = 50–99, H = 20–49, I = 10–19, J = 9 or fewer)
Mohamed and Marzouk [50]	2021	Buildings	0–100	Condition category: (0–40 = complete decay, 40–60 = poor quality, 60–75 = imperial quality, 75–85 = good quality, 85–92 = acceptable quality, 92–99 = excellent quality, 99–100 = exemplary quality)
Piaia et al. [78]	2021	Buildings	1–6	Condition category: (1 = very good, 2 = good, 3 = acceptable, 4 = marginal, 5 = poor, 6 = very poor)
Lendo-Siwicka et al. [79]	2023	Heritage buildings	0–70	Classification of the technical condition of an element/building: (0–15 = very good, 16–30 = satisfactory, 31–50 = average, 51–70 = bad)
Bucoń and Czarnigowska [80]	2024	Residential buildings	1–5	Building criteria: (5 = very good (BD), 4 = good (D), 3 = average (S), 2 = poor (Z), 1 = very poor (BZ))

can be adjusted to the revaluations of weights for systems and components [82].

It was the same year when Langevine, Allouche and AbouRizk developed the Building Maintenance Decision Support System (BMDSS) which can monitor and model the deterioration of building components and systems. Upon prioritizing building systems and components, each component's estimated remaining service life is calculated. The approach uses a consolidation process and extensive inspections performed at the base of the building hierarchy to determine the building's condition grade. A framework for prioritizing maintenance, rehabilitation and replacement projects based on financial analysis and optimization techniques with the goal of optimizing benefits within a limited financial budget is also provided by the BMDSS. To help building managers assess their current maintenance management procedures and make wise decisions about their assets, the BMDSS framework compiles a wide range of tools. Most of the necessary cost-related data is available through computerized maintenance management systems utilized by Canadian government organizations [83].

Moreover, in 2006, by means of information obtained from component inspections, Grussing et al. used the Weibull probability distribution function model to predict the reliability and state of components throughout the course of their whole life cycle. To precisely forecast the distinct deterioration pattern for each component's lifespan in the building, the prediction model self-adjusts using property data acquired during recent and past inspections [84].

A five-tiered, color-coded rating system for a South African hospital was created by Abbott et al., in 2007. Condition levels are represented by colours, where red denotes extremely good condition, while blue represents a very poor condition. Cyan, green and yellow indicate intermediate grades for good, satisfactory, and bad circumstances, respectively. Evaluations are carried out at the element level, and associated maintenance tasks and expenses are computed. The budget at the building level is determined by the combined components which are then further combined at the building level. Color-coding makes reports easier to understand for non-experts, thus improving accessibility. Sustainability requires periodic inspections, and although the physical visits required for assessments generate costs, data entry should be simplified [35].

In her doctoral dissertation in 2008, Ahluwalia proposed a novel framework that simplifies, expedites, reduces subjectivity, and lowers the cost of the BCA process. The author's system, intended for large enterprises with limited resources, automates procedures related to BCA with the goal to increase productivity and cut expenses. It provides a distinct condition indication system based on maintenance data that may be utilized to address capital replacement problems and was developed by analysing two years of reactive maintenance data from 88 Toronto schools. With its user-friendly interface and low training requirements, the integrated prototype was successful in automating the field data collection, making use of digital drawings, reducing the amount of work that needed to be inspected, and setting priorities. The costs are reduced by means of empowering internal teams and facilitating improved decision-making through diversified data [55].

In the same year, in Portugal, Pedro et al. suggested a system for BCA that involved breaking the building down into its component parts and rating the building's shortcomings using predetermined standards. Building identification, characterisation, functional element inadequacies, evaluation, observations, evaluator information, and a maintenance coefficient are all covered in eight components of the checklist used by the model. Three categories exist for functional elements: the building as a whole, common areas, and individual units. The

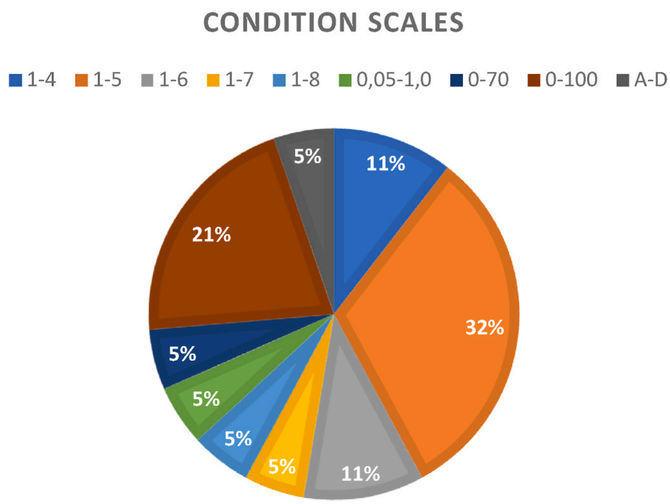

Fig. 2. Condition scales used in analysed research.

ranking system goes from 1 for serious flaws to 5 for minor ones. Ratings are determined in a way that points related to deficiency levels are multiplied by weight coefficients. The total amount of points and weights for relevant functional elements is taken into account for the deficiency index and then divided into condition kinds [60].

5.2. Standardizing the approach (2009–2018)

Based on the Dutch standard NEN 2767, Straub in 2009, as well as Kuijper and Bezemer in 2017, examined the application of BCA [59,85]. Using a scale from 1 to 6, this assessment model looks for functional element weaknesses while taking into account the functional components' importance, scope, and severity [59]. Eighty to ninety percent of common building elements in residential and other structures are covered by a defined list of building components and defects included in the Dutch standard. Defects are found and evaluated by on-site inspectors who use the standardized list and rank them according to severity and scale [85]. Defect detection is the first step in the assessment which is then followed by the importance categorization, intensity, and scope determination. According to the Dutch standard, deficiency intensity is classified into three classes: 1 (low), 2 (medium), and 3 (high). Class 2 is progressive, Class 3 has high intensity and is unable to advance, and Class 1 has hardly perceptible, low-level inadequacies. Ratings, which go from 1 (excellent) to 6 (very poor), are used to compare buildings, prioritize resources, schedule maintenance, and evaluate the state of buildings [59].

In 2010 Che-Ani et al. introduced an efficient model - the Condition Assessment Protocol (CSP) Matrix 1 - for efficient BCA. To derive an overall rating, this matrix multiplies two criteria—building condition and deficiency severity, and that requires concise explanations of identified deficiencies while saving inspection time. Building condition and deficiency severity are the two sets of data gathered by the system to provide an overall condition assessment. Named after its basis in Protocol 1 (visual inspection), CSP 1 is a versatile tool adaptable to various building types that provides a practical approach to property condition assessment. CSP1 Matrix's main objectives are as follows [86].

i) Efficient data collection without textual descriptions during fieldwork.
ii) Recording of existing building deficiencies by assessing conditions and assigning priorities to each identified deficiency.
iii) Attaining an overall building condition rating.
iv) Utilizing the numerical rating from assessments for statistical analysis.

Condition ratings and priority are among the data required by the CSP1 matrix. Based on evaluated building maintenance requirements, a scale value and explanation are assigned to each numerical rating (1–5). A total rating is calculated by multiplying the condition and priority ratings given to deficiencies. A hue (green, yellow, or red) denotes the rating in planned maintenance (1–4), condition monitoring (5–12), and significant attention (13–20). This overall rating is compared to a matrix (1–20). Once every shortcoming has been evaluated, the building's overall rating is determined by dividing and adding the ratings. In that way a final rating is enabled and can be classified as good, satisfactory, or poor [86].

The CSP1 matrix was used in a case study to evaluate the state of a smart school in Malaysia, and it turned out to be a trustworthy and useful assessment technique. It is stressed by the authors that additional testing is necessary to assess the applicability of this model for medium to large-scale building inspections. Moreover, it is also stressed that it is limited in situations where thorough deficiency descriptions are needed, particularly when creating building inspection reports [87]. When Malaysian public primary schools were evaluated using the CSP1 Matrix, 4725 inadequacies were found in 24 schools with an overall rating of 9.71 which is acceptable but needs further observation. The study verified that the building's age and its deficiencies are related. Additionally, it was utilized to inspect 72 recently built homes in Selangor where the results showed 2119 deficiencies and a total grade of 13.05 which is indicative of urgent maintenance required to meet buyers' standards for quality [88].

In 2010 Eweda et al. proposed a model for assessing Canadian educational buildings integrating physical and environmental aspects. AHP and Analytical Network Process (ANP) were used to analyse "spaces" within buildings. Space conditions were computed using Multi Attribute Utility Theory (MAUT), while integrated conditions were found using K-means clustering. The model provided a condition index (0–100) with corresponding letter grades (A-F) which indicated the overall building condition. Indexes 90–100 were graded as A (excellent), 0–19 as F (complete failure), and intermediate conditions (75–89, 60–74, 40–59, 20–39) as very good, good, satisfactory, and poor [89]. In his doctoral dissertation, Eweda (2012) introduced an integrated condition evaluation technique for educational buildings in Canada, emphasizing "spaces" within structures. By using MAUT and grouping based on means, the model combined the environmental and physical elements for each location. Attribute weights were determined using ANP and AHP based on expert opinion gathered via questionnaires. Additionally, Building Information Modelling (BIM) was incorporated into the technique as a platform for data sharing and storage, which enhanced the review process. Validated by professionals in FM, the concept showed great potential when tested in a Montreal educational institution [76]. The author and associates have carried out more research in later papers, building it upon the model developed in the dissertation [61,90].

In 2011, Integrated Building Indicator System (IBIS), an assessment system for assessing Malaysia's existing buildings prior to refurbishment, was proposed by Salim and Zahari. Factors such as building type, function, gross floor area, number of problems, and repair costs are considered by IBIS. The algorithm yields a rating based on the ratio of total defect costs to gross floor area. A scale of 1–5 is used to rate defect costs, with 5 being the lowest. A higher rating indicates fewer mistakes and less expensive corrections [75].

A framework for Egyptian educational buildings was proposed by ElSamadony et al., in 2013. In it maintenance data are integrated to speed up the assessment of interconnected building components and enable reliable inspection preparation [91]. The requirement for on-site monitoring is reduced by combining a deterioration model that makes use of neural network techniques to anticipate many repair procedures within a planned period. Data used for network training, testing, and validation include calculated maintenance data, average school utilization, school type, geographic data, and age—the most crucial factor influencing decay prediction. Data related to repairs and reactive maintenance, including two types of data for the last three repair plans, were acquired from the Egyptian Educational Buildings Agency and applied to 25 schools [91].

(1) general information from geographic departments such as details on the location, year of construction, area (measured in square meters), kind of school (elementary or high school), as well as classroom capacity, and
(2) particulars from the repair department that include details on prior fixes, such as the type of work done, the code, the amount of work done, the cost per unit, and the total cost of the repairs.

The authors highlight that gathering the information was a difficult conduct. They claim that when deciding which solutions are ideal for maintenance, repair, and renovation of educational buildings, decision-makers could find value in using such approach [91].

The technical index and the document index are two Key Performance Indicators (KPIs) that Dejaco et al. suggested for evaluating construction conditions in Italy in 2014. The building's condition in terms of aging and anomalies in its components is evaluated by the technical index, whereas the document availability which needs to meet with the legal requirements is evaluated by the document index. Three sub-indexes make up the technical index: one evaluates anomalies (A), two compare component lifespan with reference values (D+ and D-), and one compares both. Document assessments have an availability score of 1 and a non-availability score of 0. For a certain building, the weighted ratio of predicted to available documents is determined by the document index [67]. Expanding on their earlier findings, in 2017, Dejaco et al. discovered that a single building index that combines the technical index and the document index provides a KPI that is easier to comprehend. The technical index and the document index are added together to create this combined index, which is computed as the simple average of both indexes [36]. Regardless of the approaches or procedures used, the availability of documentation for existing structures has a major impact on on-site inspections during the condition assessment process. The authors highlight that a document availability index can be helpful for both, a more thorough inspection and adhering to local building codes.

In 2016, Grussing et al. presented a model that makes use of inspection data for construction components to generate a transitional matrix that can be used to predict Markov processes for condition, reliability, and predicted lifespan. A generalized framework for condition development over time is provided by that approach assuming pure degradation in the absence of maintenance interventions. For both individual components and complete buildings, better activity selection and cost optimization are facilitated by the model. The best time to conduct inspections by taking reliability and state into account are enabled by it. Additionally, a dependability metric for risk management is produced by accommodating varying time intervals in condition assessments. In order to improve predicted abilities and job planning procedures, future studies will investigate regional divisions in transitional matrices for environmental variability and create matrices based on types of repairs [92].

In the same year, Marzouk and Award developed a model which included program, building, package, and item levels of performance evaluation to assess the state of schools using the AHP which is useful for school administrators. An AHP-fuzzy model represents property conditions through language expressions. For each of the three levels—item, package, and building—the model produces standard indexes that, when combined, offer a realistic evaluation of the situation for a collection of buildings (program). Every building has distinct physical areas with a specified purpose, location, and kind. These areas consist of the flooring, doors, windows, and other components that should be examined. A case study was carried out utilizing information from 21 schools in the Giza governorate, Egypt, in order to assess this approach [93]. The authors believe that administrations may use the results as a part of a decision support system, so they propose extending the model to include more elements like external fences, light posts, and roads. They also recommend looking into how the environment affects educational institutions [93].

BCIs and their functions in BCA were examined by Karanja in 2017. The goal of the study was to understand the procedures used in BCA surveys—including data gathering, reporting guidelines, presentation styles, and BCI computations. A group of experts in educational FM provided their opinions through a Delphi survey. The format of the institutions varied significantly, as indicated by the results, and depended on ownership and mission. Responses from the Delphi panel revealed that asset classification was not standardized and was frequently done by the institution's owner. The panellists concurred that a database was necessary for the analysis, monitoring, reporting, and prioritization of the data gathered, and the study suggested performing BCAs every three to five years [16].

52 classrooms in newly constructed, renovated, and non-renovated schools were assessed by Sadick and Issa in 2018 as part of their research related to the development of a tool for building-level condition assessments. They found significant differences between recently constructed and non-renovated schools, with the latter demonstrating the strongest correlation ($r = 0.86$) between relative humidity and the condition of the building envelope. The study draws attention to the obvious link between increasing building envelope defects and elevated relative humidity, which in turn affects perceived air temperature [94].

5.3. Recent advancements (2019–2023)

In 2019, Mohd Noor et al. conducted a BCA of a cultural heritage building, emphasizing the preservation of original construction materials, functionality, safety, and sustainability of structural and architectural aspects. By means of in-depth notes and a thorough visual assessment, the research assesses each shortcoming according to its state and maintenance requirements. Energy-dispersive X-ray spectroscopy is used in material assessment to determine the chemical composition of samples in order to preserve authenticity throughout restoration and upkeep [95].

A model was developed by Linggar, Aminullah and Triwiyono in 2019 to evaluate important elements of Indonesian student housing. The model analyses building conditions floor by floor, determining the quality of each floor according to its distinct attributes. Component importance was approved by use of confirmatory factor analysis and expert questionnaires. The student residence at Gadjah Mada University served as the case study for applying the idea. The findings provide managers and owners with recommendations for improving student housing maintenance and redevelopment plans [96].

To improve and expedite building inspections and maximize preservation and maintenance planning, Piaia et al. presented a framework in 2020 that makes use of currently available BIM data. With a focus on sustainable conservation, the solution is especially helpful for decision-making related to historical building repair, preservation, and upkeep and it also facilitates expert condition evaluations [78].

In 2021, Mohamed and Marzouk offered a novel approach for assessing the physical state of educational buildings that are currently in use. Their approach integrates an Artificial Neural Network (ANN) forecasting model with Structural Equation Modelling (SEM). Building component condition ratings are predicted by the ANN model, and proportional weights are determined by SEM. The authors used data from an Egyptian faculty at Cairo University that they visually inspected over a period of five years. The study examines the effects of several parameters and ranks building components in order of importance for maintenance. Scan-to-BIM, condition prediction, proportional weight determination, and overall space value evaluation are the four modules used. An analysis was conducted on six internal components (wooden floor tiles, gypsum ceiling panels, wooden doors, wooden windows, heat pump air conditioners and desk computers). The general coefficient of determination (R^2) for developed ANN models for the predicted states of six components was 0.99, 0.99, 0.927, 0.88, 0.97, and 0.972 respectively. The outcomes of the case study validated the suitability of the suggested approach in helping facility managers and clients decide what maintenance is necessary by performing BCA. As future research directions, the authors suggest that the proposed model could be expanded to consider different types of buildings and consider various challenges, considerations, and issues. Furthermore, by taking into account the uncertainties and difficulties related to the deterioration of building components over the course of their life cycle, the condition forecast might be further enhanced [50].

In their 2021 study, Faqih and Zayed introduced an innovative defect-based condition assessment model tailored for existing concrete buildings. The model considers both physical and environmental conditions. The authors implemented a grading scale to evaluate the severity of construction flaws. Additionally, ANP was employed to determine the weighting coefficients for these defects. The researchers conducted a questionnaire to compare environmental and physical deficiencies in pairs. Fuzzy membership functions were utilized to quantify the degree of belief in assessments, accommodating the inherent uncertainty in the judgment of inspection staff. The authors demonstrated the implementation of the model on Block Z at the Hong Kong Polytechnic University campus. The findings emphasized the potential of organized inspection data management through a shared BIM platform. This approach can expedite the inspection process and efficiently handle a large volume of data accessible on a portable tablet [38].

With the ability to digitally manage a building's entire life cycle—-from design to maintenance—BIM presents the construction sector with many opportunities [97]. In this perspective, authors Matos et al. developed a framework for using BIM as a supplementary tool for BCA and maintenance management to evaluate the performance of the building and prioritize maintenance tasks using KPIs. A methodology was presented and implemented in a case study that included the following steps to accomplish these goals: 1) gathering building data, 2) estimating building life cycle costs, and 3) automatically calculating building performance indicators. The authors stress the significance of BIM's function in FM, highlighting how it enables the model to update information continuously, prioritizes building maintenance tasks, and extends the life of its materials—all of which help create a sustainable built environment. The framework was developed in the Civil Engineering Department of Aveiro's University. As further research directions, the authors propose improving and testing the prototype application on several Aveiro's University Campus case studies [43].

A 3x3 matrix was created by Kejeh, Nwaogazie and Samuel in 2022 to evaluate the upkeep state of medical and educational buildings. The CSP matrix, which is frequently employed for assessing the state of buildings, served as an analogy for the model's design. The building's current condition and the maintenance unit's maintenance management procedures are the two evaluation criteria included in the maintenance assessment matrix. The authors state that there are four components or questions associated with maintenance management that make up the maintenance management practice [98].

i) Does the hospital/school have a maintenance schedule?
ii) Is there a database where maintenance actions are kept at the hospital/school?
iii) Is there a robust quality assurance framework?
iv) Management of human resources (sufficient maintenance personnel)

The authors used a checklist to assess maintenance management practices by examining the availability and functionality of elements through a physical inspection. The maintenance practice score was calculated using the average scores of four maintenance components. Each condition received a grade from 1 to 3 based on the present status of distinct elements, and the building's current state was determined by averaging the ratings of 10 components. This approach was applied in Nigeria to evaluate maintenance conditions in general hospitals and two public schools. The maintenance condition rating for the case study buildings involves combining evaluations of the current state and maintenance practices. After obtaining the maintenance condition rating, the building maintenance rating can be determined using the following equation [98]:

Maintenance Condition Rating = Current Building Condition Rating x Maintenance Management Practice Rating

In relation to the original CSP1 matrix, a rating from 1 to 4 indicated the need for planned maintenance, a rating from 5 to 12 indicated the need for condition monitoring, and a rating from 13 to 20 indicated a major concern. It was found that 25 percent of the buildings were in "good condition" and just needed planned maintenance, as indicated by the research findings; 68.75 % of the buildings were in "satisfactory condition," and required condition monitoring, while 6.25 % of the buildings were in "serious attention condition" [98].

In 2022 Hassan et al. proposed a model to determine the BCI for building elements, utilizing an ANN for predicting element deterioration. The three-layer backpropagation ANN model was compared with an Ordinary Least Squares (OLS) model to validate its predictive accuracy. The study which was conducted on internal and external wooden doors in an educational institution aimed to confirm the approach's feasibility and cover a range of input variations in the prediction model. The effectiveness of the model was assessed by contrasting the results of OLS with the expected CI values. The ANN model showed dependability in a case study on wooden doors, with R^2 values of 0.99, 0.98, and 0.99 for training, cross-validation, and validation sets, respectively. In contrast, with an R^2 value of 1.00, the OLS model showed a small advantage over the other model despite both having strong predictive ability. The potential of the technique for decision-making in preventive maintenance planning across many elements was highlighted by the authors. They did, however, recognize certain drawbacks, such as the lack of maintenance reports that interfere with trustworthy model validation and training. The authors also highlighted that the prediction of the overall state of a building necessitates the use of models that may introduce mistakes and require large amounts of data, high computer capability, and data storage [51].

To close the current gap and inconsistencies in the assessment process and assist the work of building inspectors, in 2022 Lupășteanu, Lupășteanu, and Chingălată proposed a new BCA model that is based on the broad guidelines given in the Romanian national norm with a high degree of applicability. The method known as PEST (the Romanian acronym for Method of Assessing the Technical Condition) is constituted by conducting site investigations and using a methodology to assess damages and determine the building's degradation classes for structural and non-structural components. Sixty-two buildings of different types, ages, and construction systems underwent condition assessments to verify the model's effectiveness and application. The authors stated that the site investigations have been completed methodically, quickly, and with great results using the suggested approach. As a primary benefit, the authors highlight its applicability to various types of buildings because a standard national procedure is absent [40].

Authors Tijanić Štrok, Car-Pušić, and Marenjak developed a system in 2023 for evaluating school building conditions. A questionnaire survey distributed to principals based on the division model created in this study for school buildings was used to assess the condition of the buildings. Building components and a methodical visual condition evaluation scale are presented in the model. It was discovered that the mechanical components of the schools are in the worst shape, with the space-cooling system having the lowest rating and the beams having the highest rating among the building's structural components. The primary findings indicated that the schools under examination are generally in

Table 4a
A review and comparison of BCA studies based on [47].

Ref.	Year	Building purpose	Assessment criteria	Assessment purpose	Data collection	Data processing and used tools	Strengths	Weaknesses	Limitations
Abbott et al. [35]	2007	Healthcare	Maintenance, renovation, replacement costs	Maintenance budget allocation	Visual inspection	Form and Markov model	Sustainability consideration, refined rating system	Reliance on past assessments, subjectivity	Lack of flexibility, implementation challenges, uncertainty in predictions
Ho et al. [74]	2008	Residential	Based on hazards that may jeopardize the safety and health of resident	Building health and safety	Visual inspection and survey questionnaires	Form and AHP	Comprehensive assessment scheme, identification of critical factors	Subjectivity in assessment, limited generalizability	Resource-intensive data collection, implementation barriers
Pedro et al. [60]	2008	Residential	Based on the severity of building deficiencies	For determining the rental amount	Visual inspection	Form and website	Comprehensive development process, balancing accuracy and feasibility	Limited validation period, subjectivity, resource requirements	Lack of stakeholder involvement, scope, and generalizability
Straub [59]	2009	Residential	Based on the intensity and scope of building deficiencies	Maintenance costs	Visual inspection	Form	Standardization, potential for benchmarking	Reliance on inspector expertise	Generalizability, adoption challenges
Salim and Zahari [75]	2011	Office	The type, age of the building, deficiencies, and repair costs	Repair and maintenance	Visual inspection	Form	Comprehensive approach, cost-effectiveness analysis	Subjectivity in rating assignments	Reliance on historical data, context-specific applicability
Eweda [76]	2012	Educational	Based on the space and deficiencies of the building	Asset management	Visual inspection	BIM and statistical analysis	Use of advanced techniques, integration with BIM	Complexity, reliance on expert input	Validation scope, resource requirements
Dejaco et al. [67]	2014	Residential	Aging of building components and document availability	Asset management	Visual inspection	Computer software	Decision support, standardization	Subjectivity in KPI selection, complexity of implementation	Validation and applicability

good condition. Furthermore, the findings indicate that financial constraints and deterioration have the most significant impact on the state of school buildings. The primary disadvantage of the research, according to the authors, is that the their BCA system does not offer information about the specific type, location, source, and effect of the damage [39].

An innovative condition assessment framework that uses several Artificial Intelligence (AI) approaches appropriate for the condition data analysis of various building components was proposed by authors Ahmed, Mostafa, and Hegazy in the same year. The framework has been used on a dataset comprising more than 2000 roof and HVAC (heating, ventilation, and air conditioning) system maintenance requests from a portfolio of 600 villas. Convolutional neural networks were used on photos of roof flaws, and enhanced data mining was utilized to gather textual information on HVAC systems to meet their different needs. To repair 203 HVAC systems, work packages containing degraded components were identified, and a 60-day schedule was created. The authors emphasize that AI can help facility management with condition assessment, rehabilitation planning, and resource allocation as the model's primary strength [99].

In 2024, Bucoń and Czarnigowska developed a methodology to assist in residential building modernization planning, from evaluating the structure to determining the ideal extent of renovation. Four phases comprised the multi-criteria evaluation of the building's condition: 1. Choosing the criteria (technical, cultural, social, economic, and environmental) to evaluate a building's state 2. Using the AHP approach to determine the weights of the adopted criterion. 3. Assessing the construction criteria using a 5-point rating system, with 5 points awarded for very good (BD), 4 points for good (D), 3 points for average (S), 2 points for poor (Z), and 1 point for very poor (BZ). 4. Evaluating the building's condition using multiple criteria. The primary benefit of the study, according to the authors, is that the established model offers managers a useful and adaptable tool for use during the maintenance phase of residential structures. The primary drawback, however, is that the model is deterministic and ignores changes brought on by the building's aging as well as variations in the pre-estimated cost of repairs [80].

6. Discussion

Tables 4a and 4b presents a review and comparison of the previously mentioned studies on the subject in the last 17 years and examine the assessment criteria, the goal of the evaluation, the technique for gathering data, and the tools used to process the data concerning the type of building. Table 4a is adopted from research presented in Ref. [47] and adapted with added information on strengths, weaknesses, and limitations of analysed references, while Table 4b is made solely by authors inspired by the previous table but contains many additional research not covered in Table 4a.

When analysing purpose of the buildings that the models were developed for, 12 (44 %) out of the 27 studies analysed in the table refer to the educational type of buildings, highlighting the significance of such analysis since inadequate educational buildings influence everyday building operations, staff and student health and safety, and the efficacy of teaching and learning, especially due to the fact that people spend a large amount of time in such buildings [100]. The poor quality of educational buildings could be a result of poor management and operation, as well as maintenance [101]. Fig. 3 presents the statistical proportion of each of the mentioned building types from Tables 4a and 4b in the total number of analysed research.

When it comes to assessment criteria, the criterion based on building deficiencies prevails in 13 (48 %) of the analysed studies, since evaluating them is a fundamental part of BCAs. A broad range of issues is covered by it, such as structural difficulties, functional deficiencies, and any deterioration or defect that may impact the building's overall performance and safety. Effective maintenance, renovation, and decision-making procedures also depend on detecting and resolving issues.

Table 4b
A review and comparison of building condition assessment studies.

Ref.	Year	Building purpose	Assessment criteria	Assessment purpose	Data collection	Data processing and used tools	Strengths	Weaknesses	Limitations
Langevine, Allouche and AbouRizk [82]	2006	All	Arbitrary	Maintenance decision-making	Visual inspection	Computer software and Markov model	Deterioration modelling and forecasting, prioritization framework	Complexity and usability	Uncertainty in forecasting
Ahluwalia [55]	2008	Educational	Based on the building defects	Improvement of maintenance processes	Visual inspection and survey questionnaires	Form and statistical analysis	Visual guidance system, location-based inspection process	Initial setup and implementation, data accuracy and reliability	Generalizability
Che-Ani [86]	2010	Educational	Based on the age of the school and its deficiencies	Increased inspection efficiency	Visual inspection	Form and matrix	Quantitative approach, overall rating	Reliability testing, subjectivity	Lack of comprehensive evaluation, dependency on user expertise
ElSamadony et al. [91]	2013	Educational	Maintenance data, average school utilization, school type, geographic information, and age	Planning inspections	Database	ANN	Utilization of neural network tools, restructured inspection efforts	Limited scalability	Maintenance of predictive models, generalizability
Wilson [77]	2016	Residential	Probability of hazards that may pose a risk to the health and safety of occupants	Security risk assessment	Visual inspection	Computer software	Risk-based assessment, tenure neutrality	Complexity, focus on private rented housing	Compliance issues
Grussing [92]	2016	All	Type of component, year of installation, type and age of the building, geographic location	Asset management	Database of past inspections	Computer software and Markov model	Standardized approach, rigorous analysis method	Complexity of analysis method	Assumptions and uncertainties, interpretation challenges
Marzouk and Awad [93]	2016	Educational	The criteria for comparison between elements are sustainability priorities	Improvement of maintenance processes	Database of past inspections	Form, AHP and „fuzzy“ logic	Standardized assessment, case study validation	Complexity of modelling approach, interpretation challenges	Context-specific applicability, scalability, and generalizability
Sadick and Issa [94]	2018	Educational	The building characteristics and user adaptations	Determining the physical condition and building's health	Database	Form and statistical analysis	Statistical analysis, practical implications for school divisions	Limited scope of assessment	Short-term assessment, reliance on self-reported data
Mohd Noor et al. [95]	2019	Cultural heritage	The functionality, safety, sustainability, and maintenance of the building	Setting maintenance priorities	Visual inspection	Form and energy-dispersive X-ray spectroscopy	Integration of advanced techniques, systematic recording method	Subjectivity in rating determination, reliance on single assessment method	Sample size and representativeness, interpretation of results
Linggar, Aminullah and Triwyiono [96]	2019	Educational	Based on the building deficiencies	Improved planning and implementation of renovation and maintenance strategies	Survey questionnaires	Form, confirmation factor analysis, SEM and MAUT	Utilization of established guidelines, data-driven methodology	Subjectivity in expert opinions	Practical implementation challenges
Piaia et al. [78]	2020	Cultural heritage	Information from the BIM model	Improved inspection efficiency	Database	Computer software	Integration of BIM, user friendly	Dependence on BIM data, complexity of implementation	Validation and testing, long-term sustainability
Mohamed and Marzouk [50]	2021	Educational	Based on the building deficiencies	Decision-making regarding maintenance	Survey questionnaires	ANN and computer software	Integration of advanced predictive models, high predictive accuracy	Complexity of implementation	Generalizability, long-term performance prediction
Faqih and Zayed [38]	2021	All	Based on the building deficiencies	Identifying defects and evaluating building's health status	Survey questionnaires	Fuzzy sets, ANP and evidential reasoning	Utilization of BIM, efficiency, and speed	Complexity of implementation, dependency on data quality	Resource constraints, validation requirements
Matos et al. [43]	2021	Educational	Based on the building deficiencies	Prioritize maintenance tasks based on KPIs	BIM data	Continuous updating of	Integration of BIM, utilization of KPIs	Limited testing on Campus case studies	Scalability and generalizability of

(continued on next page)

Table 4b (*continued*)

Ref.	Year	Building purpose	Assessment criteria	Assessment purpose	Data collection	Data processing and used tools	Strengths	Weaknesses	Limitations
						information through BIM			the framework to other contexts
Kejeh, Nwaogazie and Samuel [98]	2022	Healthcare and educational	Building appearance, functionality of water supply and drainage system	Predicting maintenance conditions	Visual inspection and survey questionnaires	Form and matrix	Practical matrix model	Lack of flexibility	Small sample size, subjectivity in ratings
Hassan et al. [51]	2022	Educational	Based on the building deficiencies	Decision-making in developing a preventive maintenance plan	Visual inspection	Checklist, ANN, and OLS	Holistic approach, integration of ANN	Lack of scalability	Specificity of results
Lupășteanu, Lusitano, and Chingălată [40]	2022	Various	Evaluating the damages and establishing the degradation classes of the building	Assist inspectors, reduce assessment gaps	Visual inspection	Checklist, PEST method	Novel methodology, compliance with national norms	Subjectivity of evaluation, lack of comparative analysis	Regional specificity, scalability
Tijanić Štrok, Car-Pušić, and Marenjak [39]	2023	Educational	Based on the building deficiencies	Evaluating school building conditions	Visual inspection and survey questionnaires	Systematic visual condition rating scale	Practical Framework, statistical analysis	Subjectivity in assessment, potential response bias	Regional specificity
Ahmed, Mostafa, and Hegazy [99]	2023	Residential	Condition data of various building components	Assessment, rehabilitation planning, and resource allocation	Gathering textual information on HVAC systems, photos of roof flaws	Convolutional neural networks, enhanced data mining techniques	Integration of AI techniques, practical application	Interpretation challenges	Technical complexity, ethical considerations, maintenance of AI models
Bucoń and Czarnigowska [80]	2024	Residential	Technical, cultural, social, economic, and environmental criteria	To assist in modernization planning and determine the ideal extent of renovation	Visual inspection	AHP and 5-point rating system	Utilization of decision tree model, quantitative measurements	Subjectivity in criteria selection, complexity,	Generalizability, validation

Furthermore, concentrating on shortcomings is in line with the larger objective of BCAs, frequently comprehending and improving the building's environmental overall performance and health.

Asset management is found to be the prevailing purpose of the assessment indicating a common emphasis on using BCAs for effective asset management since it involves strategic planning and decision-making to optimize the performance, longevity, and value of assets, which is in line with the broader goals of maintenance, renovation, and resource allocation. That purpose, which has been expressed differently by authors in each research study, can be found in all the examined publications.

Visual inspection is the most frequently mentioned data collection method, used in 17 (63 %) of the analysed studies, indicating its widespread use in BCAs in various research, as can be seen in Fig. 4. It allows for a direct examination of building's physical condition and its components, providing valuable information for the assessment process. Nevertheless, despite its widespread application, it has drawbacks such as subjectivity, a shallow depth of analysis, time consumption, inaccurate quantitative data, and applicability related only to the present.

The prevailing data processing methods and tools include a variety of approaches with a notable emphasis on computer software (27 %) which is frequently mentioned in conjunction with other tools and models such as Markov models, statistical analysis, BIM, and ANN. It is driven by its efficiency, automation capabilities, and its capacity to integrate diverse data sources. The use of software facilitates advanced modelling, visualization, and standardization which is in line with the evolving technological demand for precise and comprehensive analyses in building assessments.

The analysed models showed multiple strengths. Many models offer comprehensive decision support by considering multiple criteria, integrating various decision-making methods, and providing structured frameworks for analysis. Furthermore, several models include case studies or real-world examples to demonstrate the practical application of the proposed approaches in solving real problems. Also, many models

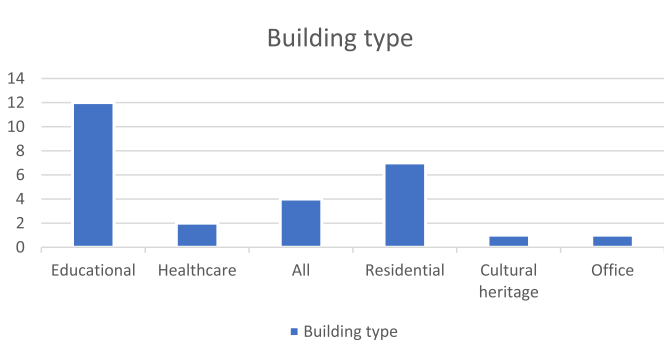

Fig. 3. Statistical proportion of building types in the total number of analysed research.

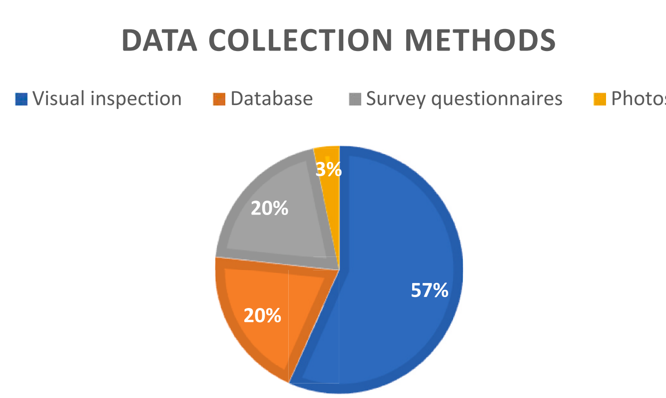

Fig. 4. Data collection methods of analysed research.

utilize quantitative measurements and data-driven approaches to enhance the objectivity of decision-making processes. Several models are specifically developed to address the needs and challenges of specific domains or industries, increasing their relevance and applicability. Finally, some models incorporate innovative techniques, such as AI, machine learning, or advanced data analytics, to improve decision-making processes and outcomes.

Besides strengths, models have also shown some weaknesses such as the fact that many models may overlook certain important criteria or factors that could influence decision outcomes, leading to incomplete evaluations. Furthermore, the integration of multiple methods and frameworks may introduce complexity into decision-making processes, making them difficult to navigate and interpret. The effectiveness of many models relies heavily on the availability and accuracy of data, which may not always be readily accessible or reliable. As one of the main limitations it was observed that despite the use of quantitative measurements, subjectivity may still exist in criteria selection and decision-making processes. Additionally, implementing some models may require significant resources in terms of time, expertise, and computational power, posing challenges for organizations with limited resources.

Finally, the models have also shown several limitations such as generalizability since the applicability of many models may be limited to specific contexts or domains, and their effectiveness may vary across different scenarios. Also, some models may lack extensive validation or empirical testing, raising questions about their reliability and generalizability.

7. Conclusion

The strategies that depend on visual inspection and basic data processing techniques (such as matrices and forms) are clearly more user-friendly since they are straightforward and do not require high technical expertise. However, the degree of subjectivity in visual assessment is extremely troubling, as was already indicated. However, approaches that use databases and sophisticated techniques like ANN or BIM might require more specialist knowledge and resources. As a result, the usability of these approaches is depended on the level of user competence and the accessibility of relevant hardware and software.

Ultimately, the choice of the most user-friendly approach should consider the users' expertise, available resources, and the specific goals of the BCA. However, the survey questionnaires provide a realistic perspective on the building manager and users' opinions, especially when collecting more significant amounts of data since they give non-subjective results on such a large sample. Also, whether the database is created throughout the questionnaires, or the existing one is used, it must contain data from several years to enable creation of a model for predicting future asset management needs in the analysed building. In that perspective, statistical methods including ANN are beneficial for maintaining large amounts of data and providing a well-trained model. Ultimately, many of the analysed studies have persisted at the component level and do not provide the perspective that a building-level analysis may.

Throughout the review, it was noted that there is a growing trend towards the integration of technology, such as BIM and AI in BCA processes. Also, many BCA models are increasingly incorporating sustainability criteria, reflecting a broader industry trend towards sustainable building practices. This includes assessing environmental performance, energy efficiency, and resilience to mitigate the impact of climate change. Besides, there is a recognition of the importance of stakeholder engagement in BCA processes. Stakeholders, including building owners, facility managers, and end-users, are increasingly involved in decision-making and prioritizing maintenance tasks.

However, one of the primary challenges identified is the availability and quality of data for BCA. Many studies highlighted issues with incomplete or outdated data, which can impact the accuracy and reliability of assessment results. There is also a lack of standardization and interoperability among BCA models, making it challenging to compare results across different studies or implement integrated assessment frameworks. In addition, limited resources, including financial, human, and technological resources, pose challenges for organizations undertaking building condition assessments.

The need for a comprehensive but approachable technique for BCA that may be utilized at the building level is highlighted by the authors. To address this gap in research, the authors propose the development and implementation of an integrated building-level assessment framework. Such framework would not only encompass the detailed analysis of individual components, but also consider their collective impact on the overall performance and resilience of the entire building. In this perspective, the authors recommend creating new mathematical models relying on data from at least five to ten years including detailed costs spent on maintenance and repairs in educational buildings to predict future costs and improve decision-making.

Based on the conducted analysis the main elements in developing the framework for BCA include.

- To develop a technique that is comprehensive yet simple, allowing for thorough assessment of building conditions while being practical and user-friendly.
- To design the framework to integrate various components and systems within a building, considering their interdependencies and collective impact on overall performance and resilience.
- To conduct detailed analysis of individual components and systems, considering factors such as functional performance, environmental sustainability and operational efficiency.
- To utilize data from at least five to ten years, including detailed costs spent on maintenance and repairs, to inform decision-making and predict future costs accurately.
- To focus the framework on educational buildings, recognizing their significance and the impact of inadequate conditions on building operations, staff and student health and safety, and teaching and learning efficacy.
- To develop new mathematical models to predict future costs based on historical data, facilitating proactive maintenance planning and resource allocation.
- To ensure that the framework is user-friendly and accessible to stakeholders involved in building management and maintenance, including facility managers, maintenance personnel, and building owners.
- To develop the framework for practical implementation in real-world scenarios, considering factors such as feasibility and compatibility with existing processes and systems.

Despite the potential benefits of utilizing BIM data in building assessment, its widespread adoption is hindered by the lack of BIM models for many school buildings. For older school buildings that were constructed before the widespread adoption of BIM, there may not be a BIM model readily available. However, efforts might be made to create a BIM model where existing building data is captured and converted into a BIM-compatible format. Therefore, future research could focus on overcoming this challenge by exploring methods to develop BIM models for school buildings or adapting existing models from similar building types. Additionally, investigating alternative approaches to leverage available data sources, such as facility management databases or digital building documentation, could provide valuable insights for developing a BIM-integrated framework.

In addition to visual inspection, future research could explore alternative data collection methods that complement traditional approaches. Sensor technologies, remote sensing techniques, and IoT devices offer opportunities to gather real-time data on building performance, condition, and occupancy patterns.

While the literature review identified limited research on the use of

AI in BCA, there is potential for leveraging advanced data processing techniques to analyse building data and identify defects. Machine learning algorithms, AI-driven analytics, and pattern recognition methodologies can augment human decision-making processes and improve the accuracy and efficiency of BCA. Future research could explore applying these techniques in BCA, considering factors such as data quality, model interpretability, and scalability across different building types and contexts.

CRediT authorship contribution statement

Hana Begić: Writing – original draft, Visualization, Investigation, Data curation, Conceptualization. **Hrvoje Krstić:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis.

Declaration of competing interest

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

Data availability

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

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