Check for updates

Maintenance of Building Elements to Fulfill the Basic Requirements Buildings

Držislav Vidaković[1](✉), Marijana Nyarko-Hadzima[1], Naida Ademović[2], and Silva Lozančić[1]

[1] Faculty of Civil Engineering and Architecture Osijek, Josip Juraj Strossmayer University of Osijek, Vladimira Preloga 3, 31 000 Osijek, Croatia
dvidak@gfos.hr

[2] Faculty of Civil Engineering, University of Sarajevo, Patriotske lige 30, 71 000 Sarajevo, Bosnia and Herzegovina

Abstract. Regulations define the basic requirements for buildings, which ensure the safety and comfort of users. Fulfillment of these requirements depends on the buildings' condition, i.e. its elements, which are affected by the use and various planned and unplanned effects. In addition to physical wear and tear, the service life often is shortened due to the lag of the building behind technological and economic progress. Therefore, proper and timely maintenance is required, and sometimes capital renewal and reconstruction. The article provides an overview of maintenance measures for the main building elements, from control to repairs and eventually to replacement. Availability of financial resources dictates how and when these measures will be conducted. In this respect, the costs of measures for maintenance and improvement of building properties in line with the new requirements are analyzed. Lifelong maintenance costs should be taken into account from the conception and design stage, because then the basic characteristics of the building are determined and, as a rule, increasing capital investment in construction can reduce the maintenance costs that will be required for numerous years. In some cases, major renovations on buildings that are already in use are also cost-effective. By time-linking the reconstruction and renovation with regular building maintenance multiplication of some works and the costs required would be avoided, leading to higher profitability of such projects.

Keywords: Prescribed requirements · Building elements · Degrading impacts · Service life · Maintenance · Improvement · Cost-effectiveness

1 Introduction – Prescribed Requirements for Construction and Maintenance

In Croatia, the Construction Law [1] stipulates that each building must be designed and constructed in such a way that it meets the basic requirements for the building and other prescribed requirements, i.e. conditions that affect the fulfillment of basic requirements, during its lifetime, depending on its purpose. The basic requirements are in line with the

H. Glavaš et al. (Eds.): OTO 2021, LNNS 369, pp. 288–309, 2022.
https://doi.org/10.1007/978-3-030-92851-3_22

principles of European harmonization of technical legislation and are elaborated by the Technical regulations.

Meeting the basic requirements of buildings is subject to change over the life of their use. In order for the condition of the building to remain satisfactory for use, even with constant physical degradation, it is necessary to take appropriate maintenance measures in a timely manner.

The need for maintenance during usage is influenced by the definition of the building during design and the quality of performance, and proper maintenance assures the designed duration or even extends it. Furthermore, maintenance prevents an increase in operating costs (for example, water supply costs since there will be no leakage and heating costs because the thermal insulation will be adequate), and in some buildings, it will increase the productivity of processes that are taking place in or on them. The main goal of building maintenance is to avoid the deterioration and misfunctioning of its component pieces, as well as their replacement to fit the intended purpose within the normal, planned duration. Figure 1 illustrates the benefits of building maintenance.

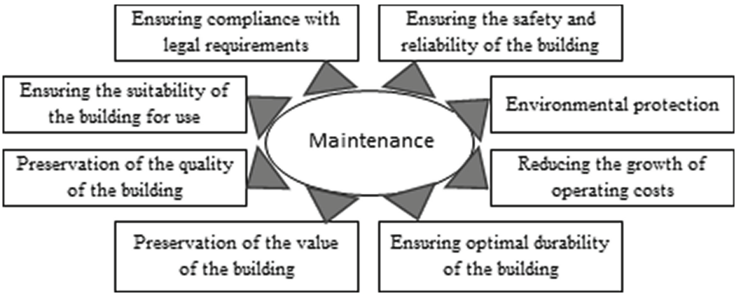

Fig. 1. Benefits of building maintenance

The contractor is obliged to compile a written statement on the performed works and conditions of maintenance of the building. The building owner is responsible for maintenance after construction and must preserve documentation on the maintenance and improvement of compliance with the basic requirements throughout its duration [1, 2]. The regulations established by the relevant standards, i.e. special rules prescribed by the Technical Regulation for various types of structures, are applied to the maintenance of buildings. The applied enforced standards at a specific time must be indicated in the design of the building structure, and there may be a technical specification that establishes stronger requirements than those from the standards [3].

New standards that develop during the use of a building usually impose stricter requirements, i.e., they demand that buildings have better properties. However, a building constructed in compliance with previously valid regulations is maintained in such a way that, during its lifetime, the technical properties are preserved and the requirements determined by its design and regulations are in compliance with which it was constructed are met [3].

Reconstruction of a building envisages the construction and other works on an existing building which, unlike maintenance, affect the fulfillment of basic requirements for that building or which change the building's compliance in respect to the location conditions under which it was built [1].

Published literature from 1994 to 2019 related to physical building conditions has increased approximately tenfold indicating the importance of the condition of buildings shows that a study of [4].

2 Impacts on the Condition and Durability of Buildings

2.1 Factors that Negatively Affect the Physical Condition of Buildings

Building's initial properties gradually deteriorate from the end of construction and the beginning of the use of buildings. For example, fatigue occurs with some materials, their strength decreases, deformations increase, metal corrosion, wood decay, surface delamination and flaking of concrete occur, air permeability and water permeability increase, etc. As a result, the structure of the building materials is destroyed, uneven deformations and settlement occur, as well as other negative consequences. Degrading changes are the result of the influence of many physical (e.g. freezing and thawing, wetting and drying), mechanical (static and dynamic loads), chemical (e.g. action of chlorides and sulfates on concrete, carbonization of concrete and mortar, etc.), and electrochemical factors (such as reinforcement corrosion). The intensity of these processes varies in a fairly wide range, and often there is a combined effect of several influences with a synergistic effect on the building. The result of the action depends on the state of the environment, the level of use (especially if some work processes take place in the building), the importance, and construction quality of the buildings. Figure 2 depicts the different influences from air and ground on a building, which degrade its elements. Other external influences, in addition to those indicated in Fig. 2, can be other, such as fire, earthquake, and other catastrophic events or demolition and construction of nearby buildings, especially during underground works.

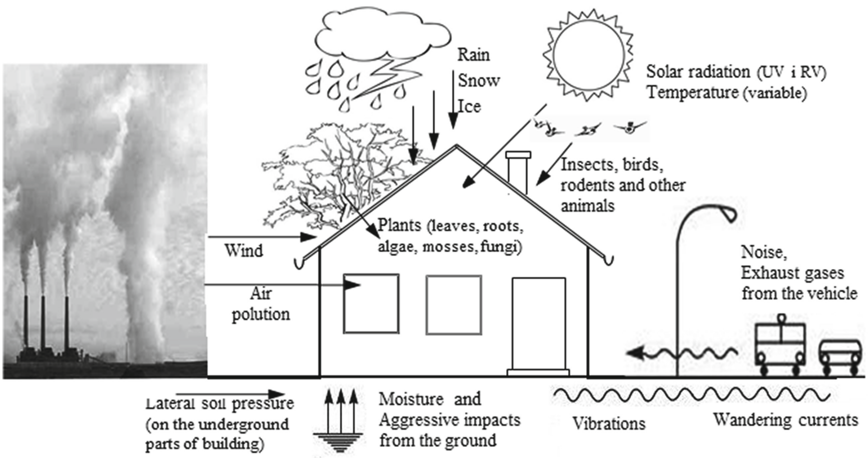

Fig. 2. Negative effects on the building which requires the maintenance of its elements.

One of the most dangerous and common negative effects on buildings is moisture. As the humidity increases, the thermal conductivity of the material increases, and the thermal protection properties deteriorate. In addition, with humidity change, the bulk density of the material increases, sand repeated wetting disrupts their structure and reduces durability [5]. Moisture in buildings (in the air, on the surface of walls, and condensed on windows) causes rot, fungi, and mold, which are harmful to health. Humid air is also more difficult to heat, resulting in higher heating costs. (If the humidity is twice as high as the ideal 45%, it takes almost 50% more energy to heat.) Moisture can come from a variety of sources; during construction, atmospheric precipitation (particularly if the building is poorly waterproofed), condensation of water vapor, groundwater, electroosmosis and capillary lifting, leakage from the water and sewage system, and floods. (Research of defects in wet areas of buildings has shown that the biggest problem is water leakage through joints [6].) Water leaks out of the water supply or sewerage system due to failures, feeding the foundation soil of buildings, causing erosion and, as a result, loss of stability [7]. Inadequate or unmaintained drainage of rainwater (discharge of rainwater from roof surfaces without gutters or vertical gutters discharging water adjacent to walls, damaged or clogged gutters, pipes, and sewers, etc.) is a common cause of softening and settlement of foundation soil, resulting in deformations and cracks in buildings. Poor, unmaintained surface drainage can also cause excessive softening of the foundation soil over time (neglect of drainage channels, overgrown terrain, unfavorable terrain slope). An increase in moisture can induce swelling and consequent damage to the building in soils that are particularly sensitive to shrinkage and swelling [8]. The influence of moisture increases with oscillations of temperature and humidity, as well as when the environment is polluted by aggressive impurities. Pollution from industrial plants enters groundwater, which spreads over large areas and often reaches the underground parts of buildings, destroying their foundations and the ground beneath them. Increases in the intensity of transportation flows, as well as the carrying capacity of machinery and rolling stock, results in increased vibration and shock strengths, which, when combined with changes in soil structure, can be extremely harmful. It is the increase in soil moisture content that leads to an increase in the rate of vibration propagation, leading to a decrease in the damping properties of the soil, and ultimately, to stronger dynamic effects on buildings.

Table 1 summarizes the main groups of factors of physical deterioration of buildings, some of which are random in nature and others which are caused by organizational and technological factors. In addition to the above, the weakening of some material properties and degradation of building elements occurs with aging (change in physical and/or chemical properties of materials regardless of the time of use [9]) and wear through normal use, in proportion to its intensity. Dilapidation or wear can lead to the failure of certain elements, which means the cessation of the ability to perform the required function.

These factors may have different degrees of influence in each specified situation (building). In 2017, Ledenyov and Yartsev [10] conducted a statistical analysis of the damage pattern and misfunctions of building structures, finding that 50% of all of them were caused due to construction errors, 20% due to the usage phase, 18–20% due to design errors and shortcomings, and 10–12% due to geological research.

Table 1. Classification of causes of building elements deterioration.

Causes of damage	Explanation - examples
Design and construction	Errors, i.e. omissions in the project documentation and during construction (especially with poor supervision) lead to insufficient load-bearing capacity and durability, and thus to damage to buildings. (For example, due to insufficient insulation of the attic floor, heat flows there from the heated floor below, causing snow and ice to melt on the roof and ice to form along the eaves.)
Violation of usage regimes and inadequate maintenance	Non-compliance with the rules of use and content of the building, which are provided by the project, lead to unplanned actions (loads, etc.) for which the building does not have sufficient capacity to withstand them (e.g. irregular, uneven load when filling the silo, excessive traffic load, unforeseen, unprofessional changes on the building or use of inappropriate heating fuel). Damage and an increase in damage are also results of improper and untimely repairs
Technological activities	Aggressive, polluted environment, mechanical actions, etc. from technological processes that take place in/on the building
External actions	Natural influences and human action (strong wind, sea salt in the air, groundwater, machine vibrations, vehicle shocks, and many other impacts)

2.2 Decay and Obsolescence of Buildings and Their Durability

Physical (material or technical) deterioration means partial or complete loss of the original qualities of the building, which can be sudden or gradual. The technical condition has steadily deteriorated since the completion of construction, although there may be some more immediate, more severe disruptions, such as floods, landslides, fractures, and so on. Susceptibility of building elements to physical wear depends on the quality of the materials from which they are made, usage, and technological processes in/on the building and external conditions. A building's physical deterioration cannot be reversed in full, but it can be controlled through maintenance to keep it above the project's compliance level.

Durability is the calendar time after construction during which the basic requirements and usability properties above the permitted level are met for buildings, with possible repair breaks. Figure 3 shows how without regular (planned) maintenance durability and the service life is reduced, and how service life can be prolonged further with the additional capital renovation and reconstruction interventions.

All elements of the building have a certain duration, and the duration of the building as a whole is primarily determined by the service life of the main load-bearing structures, i.e. elements that are not replaceable during major repairs. For example, in most countries, stone and concrete foundations are expected to last 100–150 years [7]; buildings with reinforced concrete (RC) frame structures, concrete and masonry with vertical ties, and massive floor structures are expected to last 120 years; and buildings with the same floor structure and walls of brick, concrete, concrete blocks, or stone without vertical ties are expected to last 100 years [14].

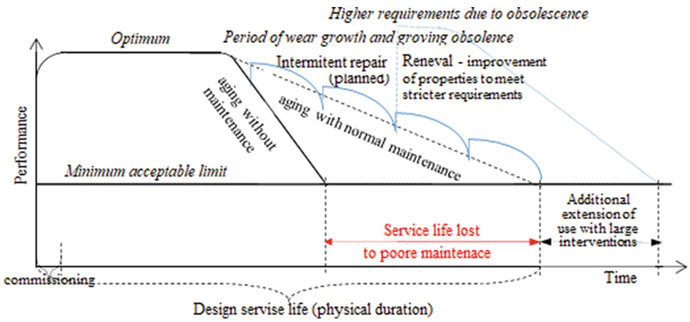

Fig. 3. Impact of maintenance on the expected service life of the building (combined according to [11–13]).

Predicting the duration of building elements is a complex procedure and there are deterministic and stochastic methods that can be applied [15]. It is most often calculated deterministically using factors defined by the standard ISO 15686:8 - Part 8: Reference service life and service-life estimation [16]. Factors categorized into groups from A to G provide the ability to take into account a lot of specific conditions [16] (quality of the material, level of workmanship, frost days index, temperature, relative humidity, heavy precipitation index, insects, surrounding activities, type of use, type of ownership, budget limitations, ease of maintenance, etc.). Loli et al. [17] believe that the planning of expected interventions on the renovation of buildings, especially buildings that are historical heritage, will be more accurate if long-term climate change is taken into account, i.e. their impact on building materials. The service life can change significantly depending on the method of use and the method of maintenance. Different scenarios of using one particular house show that the duration varies from −15% to 20% compared to the reference 63 years, depending on whether it is converted for commercial purposes (more people come and more damage), whether it is rented and not maintained according to actual needs or the owner uses it himself and additionally invests in the maintenance of the facade [17]. For this reason, Chow [18] provided data in 1990 for the durability of individual building elements and their renewal of cycles according to the purpose of buildings (condominiums, retail, public housing, hotels, office, and airports), and the differences between the duration of some types of elements in different buildings are multiple. Design Life is the period of time during which a building is predicted to remain in operation. Such durability should be achieved by the building, according to regulations and standards adopted by the project, with regular maintenance, but without unforeseen effects on the building (and unforeseen costs) and without large, expensive interventions (time due to durability/structural failure [19]).

All elements of the building must resist the negative influences and degrading processes described in Sect. 2.1. Their durability and reliability depend on the strength and duration (frequency) of these actions and the properties obtained by the design and execution. However, while some building elements are long-lasting (such as concrete and stone foundations, brick and RC walls, and RC floor slabs), some have much shorter durability than the building of which they are a part, so they need to be replaced or renovated one or more times during the service life of the building. For example, the expected service life for galvanized sheet metal cover is 25–40 years, for PVC floors 15–25 years, for softwood windows 20–30 years, for elevators 20–30 years, etc. [14, 20, 21]. While some buildings have a much longer lifetime (often with a change of original purpose) than the duration expected by the project, others, due to poor functionality and competitiveness compared to newer buildings of the same type, do not remain in use as long as they could due to structural elements and installed materials.

Physical lifetime is the period of the actual existence of a building in a functionally capable state before its demolition [22], but the actual service life does not always last as long as possible according to physical predispositions (especially in RC and steel buildings). There are cases in the world where buildings aged 15–20 are demolished to build new buildings on the same site [23]. This is because the duration of use depends on the obsolescence of the building and its technical equipment and on the conditions around the building (new or missing contents, which may be attractive or unsuitable) and the economic and political situation (living standards, taxes, tourism, market situation, large migrations, war, etc.). Obsolescence is the deviation of buildings from current standards and in general from current expectations for use (they change during long-term use). Obsolescence can be functional (lack of more favorable conditions for users, such as surface and spatial layout, sanitary facilities, elevators, insufficient thermal and sound insulation, etc.) or technological (when there is a mismatch between the service life of the building and progress in the development of technological equipment, which in its dimensions, weight, etc. does not fit into the existing building). With proper maintenance, buildings usually become obsolete faster than physical decay, and according to UNESCO, residential buildings have become obsolete every 8 years [7]. In Croatia, most buildings were built more than 40 years ago [24], and the housing stock is very old in most other European countries. These buildings continue to fulfill the function for which they were built, but at levels below modern standards. The global trend of awareness of the need to preserve the environment and energy and the recent earthquakes in Croatia and other countries have especially highlighted the requirements for improving energy efficiency and seismic safety. Even today some buildings are still in use in which some materials that are known to be dangerous today (such as asbestos and mercury-containing paints) have been installed, so it is imperative to replace them.

Figure 4 shows how the obsolescence of a building increases in a very steep stepwise manner as requirements, i.e. standards, change. In reality, there are micro-steps in the process of losing the physical and mechanical characteristics of the material (if no catastrophe occurs), but this can be approximated by a curve. Due to aging, buildings have a smooth change in the state of wear, while changes in working conditions and external influences contribute to a more sudden change in physical condition. Physical deterioration increases over time, but the parameters of physical wear are less pronounced (reduced) as a result of maintaining the building elements in normal technical condition. The curves of the growth of wear and tear of the building and its elements can be convex, concave, or combined depending on the conditions of maintenance (as shown in Fig. 4). The results of the research show that the wear of buildings, i.e. their individual elements occurs more intensively in the first 20–30 years of use and after 90–100 years [7], which is shown in Fig. 4.

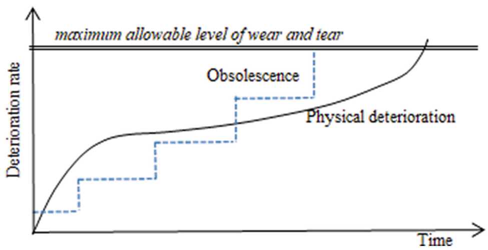

Fig. 4. Physical deterioration and obsolescence of buildings over time.

Obsolete buildings are less attractive and lose value, so it is questionable how profitable it is to invest in larger interventions just to prolong their physical life. It is possible to have a positive effect on the obsolescence of building the same as in the case of physical condition (i.e. physical lifetime) [22], i.e. it is possible to modernize them, by improving the characteristics compared to those envisaged before construction.

3 Building Maintenance Activities

3.1 Maintenance System

In addition to performing direct maintenance activities on the building, the maintenance system must include maintenance preparation (planning, contracting) and supervision of maintenance implementation, recording and reporting on maintenance and construction (databases), monitoring and analysis of costs of all maintenance activities, and development of measures for optimization of total operating/use and maintenance costs of the building.

HRN EN 13306 interprets maintenance in general as a combination of all technical, administrative, and managerial procedures during the life of an element with the aim of retaining or returning the element to a condition in which it can perform the required function [25]. Such an interpretation, in a broader sense than the Law on Construction, implies a complex system that performs a series of procedures and planned and unplanned activities, depending on the adopted maintenance strategy. These are inspections and monitoring to determine the condition of buildings, replacement of worn-out materials and elements, and repairs to restore the physical condition and preserve the physical life of buildings. For regular maintenance, cleaning, and maintenance of passable parts of the building are prescribed when the fulfillment of the basic requirements for it (e.g., for roads) or its durability depends on it [2, 26]. More recently, authors (e.g., Asaul [22], Olanrewaju et al. [27], Ihuah and Fortune [28] on building maintenance, and Radović et al. [29] on road maintenance) expand the maintenance activities on construction facilities improvements to meet current standards.

Building maintenance activities refer to the underground and aboveground elements of the building, to the elements of finishing works, installations, and equipment and devices [30]. In addition, this usually includes maintenance work on the building's surroundings, including external installations (roadside vegetation is mandatory on roads [26]).

According to the ISO 15686 standard [16], maintenance can be planned (according to the determined time period), preventive (to avoid malfunction, meaning to prevent the loss of the function envisaged by the project), corrective (reactive - removal of the malfunction after it has occurred), based on the condition of the elements (preventive, based on performance, parameter monitoring, and follow-up activities), based on prediction, delayed, urgent and unpredictable, and direct or indirect [9, 16].

Unplanned maintenance is a short-term corrective action necessary to return the building to service condition (associated with unforeseen maintenance costs). Planned maintenance can be prevention, corrective, and refurbishment [28]. For road facilities, preventive maintenance is usually applied if they are in good condition and have a long remaining service life, while reconstruction (work to improve or replace the entire part of the road) is undertaken when the structural efficiency of the existing facility is compromised [31]. For maintenance, it is necessary to make appropriate plans (different levels) for predictable activities, optimized according to determined priority criteria, available resources, and the lowest possible costs. Long-term, medium-term, and annual plans are made for road maintenance, and the operational maintenance program determines the time and schedule of individual works, their scope and technological procedure, the deadline for execution, as well as other conditions that are important for their execution [32]. Records must be kept on the implementation of plans and all performed activities, costs, and findings.

Maintenance planning should begin already at the stage of conception and design of the building when the characteristics important for later maintenance are determined (defining the location, position, dimensions, materials and equipment, availability of elements, etc.). With modern systems that help in the management process, such as Cloud computing, Internet of Things, Building automation system, and Building information modeling (BIM) further expands the application [33]. BIM's databases have been continuously expanded and improved since the graphic design (3D), and the last, the "seventh dimension" (7D) of BIM is the life cycle and maintenance (planning and management of maintenance operations throughout the building's lifecycle). This lifelong approach, with advanced computer support, effectively improves the quality and efficiency of building operation and maintenance, from construction to the removal of the building. There is a possibility of introducing BIM models also in the reconstruction projects. Then it is necessary to collect the data for existing buildings (mostly built a long time ago) so that they can be used in future situations to save money and time, and for such Perhavec and Vidaković [34] are showing an example of Knowledge management systems and Rules and Legislation Database and Building Database.

3.2 Inspection and Monitoring of the Condition of Buildings

In addition to the mentioned numerous factors that affect buildings and their elements, with a longer period of use, appropriate, professional control of their condition is required. An inspection is an assessment of the conformity of an element by observing, measuring, examining, or evaluating their relevant characteristics, while during monitoring the condition the parameters are constantly monitored over a period of time [9] (e.g., settlement, crack propagation, etc.). The actual loads determined during the use of the building can differ significantly from those envisaged by the project, both in size and in place of action. Therefore, in some cases, systematic monitoring of operating loads should be developed, being careful that they do not exceed the prescribed values [5].

Inspections of buildings are required in order to determine the need for certain maintenance measures (from emergency to delayed) to maintain safety, but also to prevent a significant deterioration (growth of spread) of damage due to delayed repairs. Inspections are focused on the physical condition of the building elements and its technical equipment - the degree of change in material properties, structural defects, i.e., wear, damage, defects, and malfunctions/faults. In addition, the causes of unplanned major deterioration should always be discovered.

During the inspections, certain parameters are detected in different ways, with standard methods (sometimes a combination of several of them) and suitable equipment, i.e., instruments, depending on the building element and its availability (inaccessibility of some parts of the building makes them much more difficult). Data important primarily for safety, but also for the efficiency and quality of use and durability of the building are checked, such as longitudinal dimensions and cross-section, stresses, deformations and displacements (deflections, slopes), cracks and other damage, material properties (strength, homogeneity, toughness, stiffness, humidity, etc.), impermeability (joints, wall panels, covers, etc.), cover thickness (as in concrete reinforcement and thermal or hydro insulation), vibrated property, humidity in the room, composition and airflow, resistance to heat transfer, functioning/malfunctions of technical equipment and compliance of devices (e.g. for heating) and equipment with the design of the building, etc. [2, 5, 7]. It is also necessary to examine the environmental conditions (physical, chemical, and biological).

Building inspection diagnostics are often based on a comparison of existing values with some reference or initial one, i.e., a deviation from the designed condition. Testing can be done by non-destructive and destructive methods. It can be visual (e.g. according to color, without instruments, or with a camera), touch, acoustic methods (it can be searching for cavities by knocking), scraping or notching (to check the strength, because the crushing of the material indicates poor hardness), measuring electrical resistance (for reinforcement corrosion), the radiographic testing of welded joints, pressure test (for chimneys and gas and plumbing installations), chemical analysis and other laboratory tests (e.g. swabs, sawdust or samples taken by sounding).

To help in obtaining a more complete picture of the building, *in situ* inspection is preceded by acquaintance with the technical documentation and other materials (documentation on previously performed inspections), if available. If such documentation does not exist or is incomplete, the initial (general) inspections will have to be more extensive, with complete measurements of the dimensions of the structures, determination of the construction scheme, and drafting. The entire work on the inspection is carried out at different levels of expertise, in stages, as shown in Fig. 5.

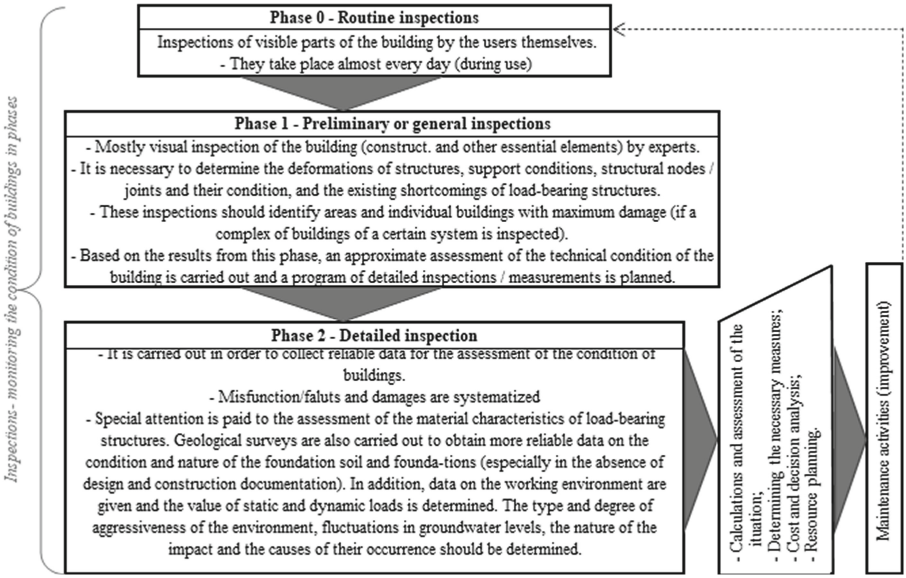

Fig. 5. Contents of all phases of testing the condition of buildings and further action.

A detailed inspection requires a lot of time and resources, so the need for it should be proven by a preliminary examination. If necessary, after a preliminary inspection, measures are taken to temporarily strengthen the structures. A detailed inspection can be selective (only individual elements) or complete (checking all essential elements). If during the examination of the sample a significant reduction in the load-bearing capacity of structures (inhomogeneous material properties, different load conditions, etc.) is found or significant deviations from the design are detected, a complete inspection is performed [7]. A complete measurement is also carried out in cases when there is no technical documentation. When performing all types of reviews, it is necessary to record the identified data because they are used for further calculations and databases for decision-making and planning.

According to the Croatian regulation, inspections can be [3]:

– regular - basic (every year or more often), main (at an interval of 5 years for bridges, towers, and other engineering structures and 10 years for buildings), and additional

(then the basic inspection identifies deficiencies that may affect the requirements of mechanical resistance and stability and fire resistance) or
– extraordinary (as soon as possible after natural or technical disasters or extraordinary loads).

In addition, an inspection of the buildings must be made in the following cases [5]:

– when the reconstruction of the building is required, ie a change that changes the spatial-planning solution, load, or working conditions or
– accidents on similar buildings.

Road inspections on the regular basis are carried out [26]:

– by the professional patrol service (at least once a month visual inspection of road facilities, primarily elements and parts related to stability, functionality, durability, and safety of traffic);
– seasonal (usually after the winter period and in the fall to check the condition of the roads and determine the extent of damage);
– annual (steel and wooden road structures are inspected at least once a year, other road structures are inspected at least once every two years);
– main (at least once in six years all parts of the facility are inspected and specialist measurements and tests are carried out).

Laws, regulations and norms, and a written statement of the contractor after the completion of the construction prescribe the content and inspection periods for some elements and equipment of the buildings. For installed equipment, devices, and installations, the service plan and deadlines are prescribed in the guarantees of their manufacturers [2]. For example, residential and public buildings require a series of inspections related to lightning protection and electrical installations, fire protection systems, chimneys and heating systems, air conditioners, elevators, etc. (usually for a period of 1 or 2 years).

The need for some inspections is dictated by the time of year, so the facades of buildings should be inspected in general by a professional in autumn (ie before winter) and in spring (together with that at least every 5 years in detail) [35], and chimneys always before the heating season.

For some buildings (e.g., bridges, waterworks, pipelines, steel structures, etc.) it is possible to apply the Risk-Based Inspection strategy. However, although these procedures are elaborated on a theoretical level, in practical use they become a significant problem in connection with complicated modeling of the structure (necessary before risk analysis). This is modeling in terms of dividing the building structure, according to different criteria (e.g., sensitivity, i.e., vulnerability, state of the structure, state of the environment, etc.), into different areas that should be treated as a whole according to the maintenance procedure [36].

After testing on the building, data processing and calculations of the condition and impact of damage on the reliability and load-bearing capacity of structures as a whole follow. Based on the test data, it is possible to define the degradation curve as it has been so far and assume its progress in the future [37] and determine the remaining service life of structures according to it. The determined level of physical degradation gives an objective idea of the technical condition of the structural elements and through them the building as a whole. The study of the overall building condition is an extremely important basis for building management and decision-making on maintenance [38] - on repairs and replacement of elements (urgency and scope of work and the necessary cost of restoration), reconstruction, modernization, or abandonment/demolition buildings.

The classification of condition assessments can be different, adapted to the specific type of building, but as a rule, it always goes from a good or fully usable condition, where all the requirements of the building are met (suitable for use with normal maintenance), to a condition that is not for use (if urgent actions are not taken there will be a collapse). Yacob et al. (2016) suggest the following types of maintenance activities depending on the five categories of building condition [38]:

- Very Good – Preventive maintenance;
- Good – Condition Based Maintenance;
- Fair – Repairs;
- Poor – Rehabilitation;
- Very poor – Replacement.

3.3 Repairs and Replacement of Elements and Improvement of the Condition of Buildings

If the technical properties of the building structure do not meet the requirements of regulations and rules according to which it is designed and constructed, it is necessary to replace individual elements, conduct periodical repairs, conduct repair or reconstruct by which the building structures to a level that meets the minimum requirements or remove the building [3]. Defining the type of maintenance work according to the Ordinance on maintenance of buildings is shown in Fig. 6.

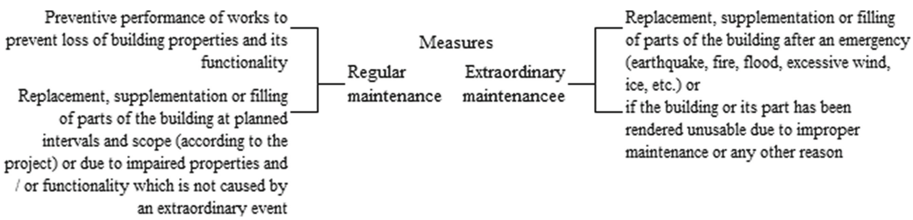

Fig. 6. Measures of regular and extraordinary maintenance.

Repairs are considered to be works on restoring worn-out, i.e., decaying, deteriorated, or in other ways damaged elements to a normal usable condition (the function provided by the project is returned to them). Repairs differ in the scope of work and the impact on the building. Minor repairs to buildings are, for example, replacement of individual roof tiles or battens, placing of fallen bricks and fixing with mortar, grouting, occasional repairs of plaster, etc. These are ongoing, routine repairs of a shorter duration (usually 1–2 days). They can be planned and in accordance with regular inspections or unplanned when the need for them is revealed by extraordinary inspections. Such repairs allow for further use and prevent deterioration and increasing of subsequent maintenance costs. Buildings require major repairs when satisfactory properties for use cannot be provided by small, ongoing repairs. The lost properties of the individual constructive building elements are selectively restored. Larger repairs extend the physical life but do not increase the economic value of the building because they do not improve it compared to the initial requirements. The application of new materials and technologies can significantly increase the reliability and durability of structures and buildings as a whole. In the complete renovation (overhaul) and reconstruction of buildings, some long-lasting structural elements, and the system of technical equipment are replaced as needed (it is modernized with modern equipment). This achieves the fulfillment of modern requirements and improves usability. Modernization extends the economic life of the building (duration until when the usage is profitable). For such large interventions, project documentation must be prepared in advance and special resources (contractors) are usually hired for them. Due to the high cost of these works, a quantitative assessment of the obsolescence of the building and verification of the cost-effectiveness of the project is required to justify them.

The urgency of eliminating the existing damage, i.e., detected defects in the building depends on their importance. The identified damages can be of different weight [7]:

– insignificant damage, which does not reduce the load-bearing capacity of structures and can be easily removed by routine (ongoing) repairs;
– significant damage, which reduces the load-bearing capacity and usability of buildings and their physical durability;
– critical (alarming) damage to structural elements due to which further use is unsafe and the condition is extraordinary.

In case of damage to the building, which endangers the life and health of people, environment, nature, and other buildings, as well as soil stability on the surrounding land, the owner of the building, is obliged to take urgent measures to eliminate the danger and mark the building as dangerous until such damage is eliminated [1]. In some cases when the usability reliability and durability are impaired, action is necessary, but if it is possible to use the building for some time and in that condition (no emergency intervention is required) repairs can be postponed until the planned date within the existing maintenance program. This is the so-called delayed maintenance. Repairs can also be temporary if they only allow the worn-out element to perform its function until the necessary repair is performed in full [9]. It is necessary to recognize whether the misfunction is primary or secondary, or caused by another misfunction or defect (which is quite common in buildings), and then be sure to eliminate the primary cause.

Long-lasting structural elements are not subject to replacement, but due to physical wear, they undergo regeneration procedures (e.g., bearing renewal), which restore their correctness and the ability to meet the necessary basic requirements. Elements, as well as parts of building equipment whose durability is less than the design life of the building when they were worn out, are replaced by similar ones [22]. Nowadays, improving the properties of residential buildings usually includes replacing windows and doors with better thermal insulation properties, increasing the thermal envelope of external walls, roofs, and ceilings to unheated space, replacing heating systems with more energy-efficient ones, replacing plumbing and other technical equipment and installation lines, etc. [7, 39].

Buildings protected as a cultural asset always require an individual approach and cost-effectiveness is not primary. Their protected monumental properties must not be disturbed [2] and therefore works on them may only be designed and carried out by a company with a permit to work on the heritage asset property [40]. In some cases, original materials that are more difficult to obtain on the market and more expensive must be used, and today it is very difficult to find craftsmen who know some of the necessary traditional works (e.g., restoration of decorations).

The main reason for the high degree of physical deterioration of the housing stock is the untimely execution of repairs and restorations, which is the result of the limited availability of funds [7]. The degradation of load-bearing structures in buildings generally goes from the stage of crack formation at the places of stress concentration, through their slow development to sudden destruction when critical stresses and deformations are reached. From that, it can be seen that longer interruptions in the necessary maintenance activities lead to emergencies and shorten the physical duration of buildings. Their restoration when the critical stage has already occurred requires very large works and the cessation of use until their completion. That means tens of times more costs than they would be for timely action. (They can even exceed the value of the structure, i.e., building a new one, so sometimes the renovation is abandoned [7].) Irregular maintenance of the water supply and sewerage network is also dangerous, and damage to it (due to water leakage) can lead to the deterioration of the structural elements of the building. One should always try to avoid situations when repairs should be performed immediately and inevitably because then it is the most expensive.

In conditions of limited financial resources and at risk of developing deterioration of the building, maintenance based on the risk of failure or multi-criteria decision-making is recommended, which takes into account some other criteria in addition to the risk. For this, it is convenient to use the Analytic Hierarchy Process method to determine the priority of maintenance activities (there are computer programs, such as various versions of *Expert Choice*, which greatly simplify the process). Such a need is particularly pronounced when managing the maintenance of large buildings or a multi-building complex, and the available maintenance budget should be allocated to a lot of different necessary replacements, repairs, and remediation of certain elements (not urgent interventions or major renovations). Cerić and Katavić [41] proposed the status of the building, physical condition, significance for use, impact on users, and impact on the building as criteria for such decisions when maintaining buildings. First, the criteria should be compared with each other to determine their weight, and then for each criterion, maintenance interventions are compared with each other as variants that should be ranked according to priority.

In some cases, for organizational and technological reasons and due to the same one-time costs of preparation and safety measures at work, it is more convenient to repair or renovate the entire building element or the entire structure (e.g. a reinforced concrete wall damaged by corrosion), although there is not the same degree of damage everywhere (e.g. if a scaffolding has already been installed or a crane has been hired, if the maintenance team is already on the site, it is better to do the whole job than to work part-time, etc.).

4 Analysis to Minimize the Total Cost

Maintenance costs are one of the Life-cycle costs (LCC) groups that are part of Whole-life costing [16]. Along with them, there are the costs of Construction, Operation, Occupancy, and End of life, and there is a connection between all these costs. Maintenance affects all other costs after construction (e.g., the costs of required energy and cleaning), and Construction, Operation, Occupancy affect the required maintenance (explained in the introduction). A review of research in different countries shows a large share of operating, maintenance, and refurbishment costs in LCC buildings [42]. This share is higher the longer the service life (according to Boussabaine et al. [43] more than 80%).

The structure of building maintenance costs according to [30] is shown in Table 2.

Table 2. Maintenance cost by type of activities.

Costs of expert inspections	Costs of preventive maintenance activities	Costs of replacing worn materials, elements, and techn. equipment	Reactive (corrective) maintenance costs
– the costs of periodic inspections prescribed by law for the purpose of taking measures necessary for the safety, health, and life of people. (These are various tests and inspections of individual parts of the building, devices, and installations.)	– the costs of those activities that are repeated at relatively the same time intervals in order to maintain a defined level of easement of the building	– costs of activities on changes of certain worn-out materials and elements of the building (according to the planned schedule or inspection determined by the condition)	– costs of repair and replacement of materials and elements and equipment in interventions after failures and damage. (The magnitude of these costs is unpredictable because it is impossible to predict all possible faults/malfunctions that may occur due to extraordinary impacts.)

Performing maintenance and other work on existing buildings can be very expensive. The reason for this is work in conditions of lack of space, which makes it difficult to engage optimal mechanization and a lot of manual work, sometimes very professional and in particularly dangerous conditions. Special work equipment may be necessary, and small amounts of individual works (relative to new construction) increase the unit price due to the share of fixed, one-off costs (mainly indirect labor costs that must be made regardless of the amount of work on the building). A special organizational problem is a work in the conditions of leaving the building in use, otherwise, there are costs of suspension of use (relocation of tenants, alternative traffic routes, etc.) and speeding up the completion of works as soon as possible, which also increases costs, (such as work in multiple shifts).

The required maintenance costs mainly follow the dynamics of the physical deterioration of the building. They become the largest in a period of intensive deterioration of a building, and then one should consider how economically justified the investment in further maintenance is, compared to the demolition and construction or purchase of a new building.

Cost analysis is aimed at minimizing them, through long-term (lifelong) planning of maintenance and other related activities of realization and use of the building. In order to analyze the costs, it is necessary to include all their types and carriers and determine the dependence with other activities on the construction and with the costs they require. The process of analysis and decision-making (costs are often the most important criterion) about the building is shown in Fig. 7.

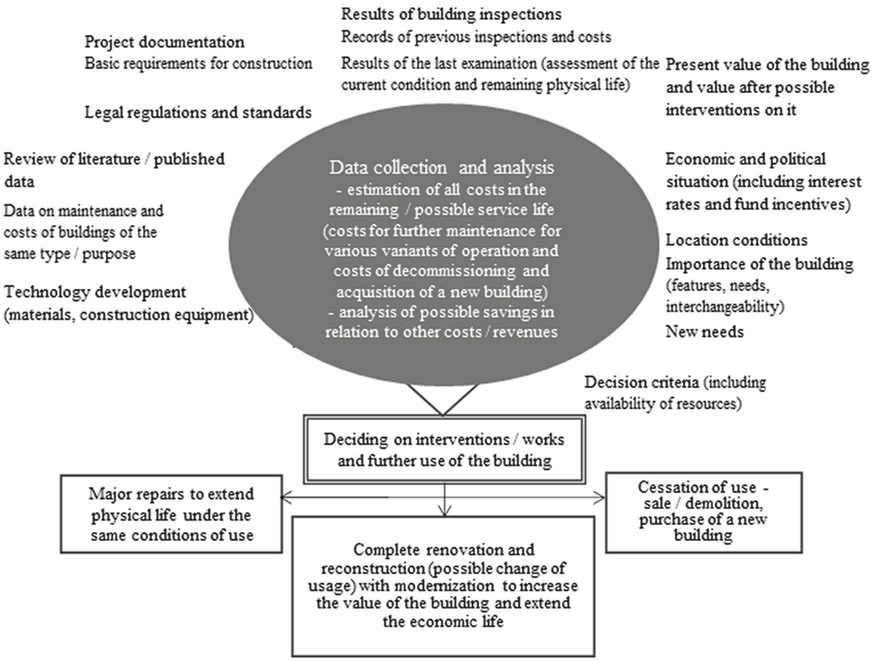

Fig. 7. Cost analysis and therefore decision making on building.

In the cost analysis, it should not be neglected that the maintenance of buildings has direct and indirect costs. Direct costs are the costs of materials, the labor of workers and machines, and all work equipment. Maintenance may involve an own workforce (from the one who manages the building) or it can be outsourcing to external companies/trades (especially for consultants, for highly specialized activities, or large amounts of work that is rarely done). Indirect costs are all costs of the maintenance team, logistics costs (e.g. IT systems, education, etc.), and penalties (inability to use the building or degradation of quality/performance) [30]. Reduced usability or unavailability of a building may result in many associated costs (depending on the type or purpose of the building and compensation for discontinuation of its use), such as the cost of providing alternative services, warranty costs, liability, lost revenue, and also with this can also affect the bad reputation of the building owner [9].

It has been shown that at the design stage operating, maintenance, and refurbishment costs can be predicted [43] and that these costs can be well influenced over the life cycle even before construction. Suitable location and design solutions, including materials that will require less maintenance, it can save significantly more over its useful life than it does to increase initial investment in construction. Today, there are many structural elements of reinforced concrete structures that are negatively affected by environmental factors, and the appropriate composition of concrete greater resistance can be achieved. For example, in concrete sidewalks, the addition of macrofibre reduces the potential cracking due to shrinkage and limits the movement of cracks, and the base gravel reduces the risk of lifting due to frost. According to the analysis of Czarnecki and Poon [19], the service life without macrofibre and substrate is 15 years. Appropriate composition of concrete and substrates increases the construction costs by 20–30%, but thus the service life is extended to 35–50 years, and the costs of necessary renovation and replacement are reduced. Preventive maintenance at 40% of assumed service life further reduces rehabilitation costs.

Improvements to meet the requirements of existing buildings should also be considered. As with replacing elements with better properties when the old ones expire lives, the cost-effectiveness is always higher in situations where some of the costs are reduced or avoided. This can be achieved if work on the complete reconstruction (overhaul) or improvement of the building's properties takes place in connection with another project (which requires the construction site formation, scaffolding, crane delivery, removal of some parts of the building, etc.). Thus, for example, the addition of floors or rearrangement of the attic into a living space can be combined with the complete renovation or replacement of some structural elements (e.g., the roof structure can be further strengthened and the ceiling with wooden beams replaced with reinforced concrete) and the installation of better equipment or installations. Likewise, the reconstruction of a building after an earthquake or fire can be well combined with energy efficiency improvements or interventions that increase the level of compliance with the basic requirements for resistance and stability and safety in the event of a fire. Table 3 highlights the types of costs of investors, i.e., building owners, and the costs of contractors that can be saved by such project conjugation.

With the increase in the volume of construction work, indirect costs (e.g., the establishment and management of the construction site, for cranes that serve everything, etc.) are distributed over a larger amount, so in terms of the unit of work, the costs are lower. Even greater savings are possible if maintenance works and other works are carried out simultaneously on several buildings that are close and well-coordinated according to the work schedule (if the types of works on the buildings are the same, then best tactfully).

Table 3. Costs that can be reduced by combining the necessary maintenance activities with the project of reconstruction and modernization of the building.

Investor/owner costs	Contractor costs
- for testing the condition of the building (harder to reach elements) - for the procedure of selection of contractors and contracting - for supervision of the execution of works - payment of the contractor (the price of works) - temporary unusability or reduced level of usability of the building (losses because it is not operational)	- Indirect construction site costs – preparatory works, dismantling and insurance, safety measures at the worksite, construction site management, internal supervision of works and communication with the investor, transports - Direct realization costs - hours of work of workers and machines, and there may be less material (In some cases they are reduced due to avoidance of double cleaning, demolition, and closing of the structure, due to the existing availability of elements with (insured for other works) and higher utilization of machines and workers for a larger amount of work on the construction site (especially universal workers)

This also increases the amount of work for the contractor, and the necessary resources can be easily exchanged (for which the requirements on individual projects are usually variable).

5 Conclusion

Many buildings show at first glance that their owners do not allocate enough funds for satisfactory maintenance. There can be many reasons for neglecting maintenance, but this has consequences whose correction in the end almost always exceeds the cost of omitted maintenance measures. In addition, failure to monitor the condition of buildings and failure to take appropriate maintenance measures can lead to catastrophic accidents, as exemplified in both the poorest and most developed countries. In addition to meeting the requirements of safety and reliability, the maintenance of buildings has other important goals, including financial and quality of use and regulation of service life.

Maintenance decisions are crucial for successful building management, and one of the fundamental decisions is choosing the most appropriate strategy. The maintenance strategy depends primarily on the importance and purpose of the building and the processes that take place through it and the risks that can lead to dismissals, and the available resources should be taken into account (including the availability of funds and people with relevant knowledge).

Maintenance activities should be planned (although some unforeseen activities will always be required), taking into account long-term, i.e., lifelong costs. Only by analyzing all maintenance costs and related building costs, it is possible to optimize the total costs of the owner and the management of the value of the property. That is why it is important to constantly collect data on maintenance and related costs (costs, causes of problems, measures taken, etc.), especially when one owner/manager has several buildings of the same type, and especially of a similar type (by construction, materials, etc.)

Savings are possible if improving the fulfillment of basic requirements and modernizing the properties of buildings (e.g., energy efficiency, better sound insulation, higher earthquake resistance, etc.) is associated with the implementation of major repairs (e.g., constructive renovation of buildings after earthquakes). Each construction project is unique and the possibility of avoiding the double performance of part of the construction and other works and procedures, and thus the size of the savings always depends on the specific case (must therefore be analyzed separately).

In order to ensure optimal maintenance, looking to minimize all costs throughout the life of the building and taking into account all the benefits that maintenance brings, even in the pre-construction stages, the issue of future maintenance of buildings should be considered. Lifelong maintenance care is provided by BIM, but its application requires a very serious interest in the "fate" of the building since the beginning of the development of the construction project.

Today, buildings are being built for a future of maybe 100 or more years, so the planning of their maintenance should be flexible and with the adoption of the latest knowledge and technologies.

References

1. Construction Law, Official Gazette 153, Croatia (2013). (in HR)
2. Ordinance on maintenance of buildings, Official Gazette 122, Croatia (2014). (in HR)
3. Technical regulations for building structures, Official Gazette 17, Croatia (2017). (in HR)
4. Faqih, F., Zayed, T., Soliman, E.: Factors and defects analysis of physical and environmental condition of buildings. J. Build. Pathol. Rehabil. **5**(1), 1–15 (2020). https://doi.org/10.1007/s41024-020-00084-0
5. Kazarnovsky, V.S., Grigoriev, P.Ya., Neustroev, A.Ya.: Technical Exploitation of Buildings and Facilities of Railway Transport. Training and Methodological Center for Education in Railway Transport, Moscow (2006). (in RU)
6. Chew, M.Y.L.: Defect analysis in wet areas of buildings. Constr. Build. Mater. **19**, 165–173 (2005)
7. Afanasyev, A.A., Matveev, E.P.: Reconstruction of Residential Buildings. JSC Center for Design Products in Construction, Moscow (2008). (in RU)
8. Jurić, A., Vidaković, D., Minažek, K.: Measures of preparation and maintenance in the construction and rehabilitation of buildings. In: Proceedings of the 6th Conference Maintenance 2020, pp. 105–114. University of Zenica, Faculty of Mechanical Engineering, Zenica (2020)
9. Frković, D., et al.: Maintenance and property management. ESUO manual. Croatian Maintenance Society, Zagreb (2016). (in HR)
10. Ledenev, V., Yartsev, V.P.: Inspection and Monitoring of Building Constructions and Structures. Publishing House TGTU, Tambov (2017). (in RU)
11. Building Research Board: Commission on Engineering and Technical Systems: National Research CouncilFourth Dimension in Building: The Fourth Dimension in Building: Strategies for Minimizing Obsolescence Studies in Management of Building Technology. National Academies Press, Washington, D.C. (1993)
12. Thomsen, A., van der Flier, K.: Understanding obsolescence: a conceptual model for buildings. Build. Res. Inf. **39**(4), 352–362 (2011)
13. Alexander, M.G.: Service life design and modelling of concrete structures – background, developments, and implementation. Revista ALCONPAT **8**(3), 224–245 (2018)

14. Željko, Ž.: Real Estate Sales; Real Estate Valuation. Handbook, Croatian Chamber of Commerce, Zagreb (2004). (in HR)
15. Ortega Madrigal, L., Serrano Lanzarote, B., Fran Bretones, J.M.F.: Proposed method of estimating the service life of building envelopes. J. Constr. **14**(1), 60–68 (2015)
16. ISO 15686-8:2008: International Organisation for Standardization, Geneva (2008)
17. Loli, A., Bertolin, C., Kotova, L.: Service life prediction of building components in the times of climate change. IOP Conf. Ser. Mater. Sci. Eng. **949**, 1–9 (2020)
18. Chow, K.F.: The Construction Agenda. Construction Industry Development Board, Singapore (1990)
19. Czarnecki, B., Poon, B.: Concrete sidewalk design analysis and optimization for improved life cycle and sustainability. In: Conference of the Transportation Association of Canada St. John's (2017)
20. Aničić, D.: Planning the service life of buildings - translation of ISO 1586 series standards. Građevinski godišnjak 03, HDGI, Zagreb (2004). (in HR)
21. Akmatov, A.K., Ryspaev, J.A., Ordobaev, B.S.: Technical Exploitation of Buildings and Construction. Faculty of Architecture, Design and Construction, Bishkek (2017). (in RU)
22. Asaul, A.N., Abaev, H.S., Molčanov, Y.A.: Management, Exploitation and Development of Property Complexes. Humanism, St. Petersburg (2007). (in RU)
23. Čaušević, A., Rustempašić, N.: Reconstructions of Masonry Buildings. Faculty of Architecture, Sarajevo (2013). (in BA)
24. Long-Term Strategy to Encourage Investment in the Renovation of the National Building Fund of the Republic of Croatia, Ministry of Physical Planning, Construction and State Assets, Zagreb (2020). (in HR)
25. HRN EN 13306, HZN e-Glasilo 12 (2017). (in HR)
26. Ordinance on road maintenance, Official Gazette 90, Croatia (2014). (in HR)
27. Olanrewaju, A.A., Khamidi, M.F., Idrus, A.: Appraisal of the building maintenance management practices of Malaysian Universities. J. Build. Apprais. **6**, 261–275 (2011)
28. Ihuah, P.W., Fortune, C.J.: Toward a framework for the sustainable management of social (public) housing estates in Nigeria. J. US-China Public Admin. **10**(9), 901–913 (2013)
29. Radović, N., Šešlija, M., Peško, I.: Expert project analyses in the process of road maintenance management. Građevinar **65**(7), 641–652 (2013)
30. Marenjak, S., El-Haram, M.A., Horner, R.M.W.: Analysis of overall project costs for the building industry. Građevinar **54**(7), 393–401 (2002)
31. EU criteria for green public procurement for the design and construction of office buildings and their management. EU Commission staff working document, Bruxelles (2016)
32. Road Law, Official Gazette 84, Croatia (2011). (in HR)
33. Fang, T., Zhao, Y., Gong, J., Wang, F., Yang, J.: Investigation on maintenance technology of large-scale public. Sustainability **13**, 1–18 (2021)
34. Perhavec, D., Vidaković, D.: Is it time for new approach on historical building preservation or conservation project? In: Proceedings of the REHABEND 2016 Euro-American Congress on Construction Pathology, Rehabilitation Technology and Heritage Management, pp. 1411–1418, University of Cantabria, Burgos (2016)
35. Building facade maintenance – Legal liability and damage limitation. A guide for building owners and occupiers. www.bre.co.uk/pdf./facademaintenance.pdf. Accessed 10 Oct 2016
36. Li, Y., Vrouwenvelder, T., Wijnants, G.H.: Deterioration and maintenance of concrete bridges based on spatial variability of structural properties. In: Proceedings Risk-Based Maintenance of Civil Structures, pp. 86–93, Serie Workshop Proceedings no. 8, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft (2004)
37. Gaspar, P.L., de Brito, J.: Assessment of the overall degradation level of an element, based on field data. In: Proceedings of the 10th International Conférence on Durability of Building Materials and Components on Proceedings, TT8-68, Lyon (2005)

38. Yacob, S., Shah Ali, A., Cheong Peng, A.: Building condition assessment: lesson learnt from pilot projects. In: Proceedings of the 4th International Building Control Conference. MATEC Web of Conferences. Vol. 66, 00072, pp. 1–7 (2016)
39. Hećimović, D., Vidaković, D.: Analyses cost effectiveness energy reconstruction family houses in Osijek-Baranya county. In: Proceedings of the 27th International and Scientific Professional Conference 'Organization and Maintenance Technology' – OTO 2018, pp. 97–104, Faculty of Electrical Engineering, Computing and Information Technology, Osijek (2018)
40. Law on Protection and Preservation of Cultural Heritage, Official Gazette 69 (1999). (in HR)
41. Cerić, A., Katavić, M.: Building maintenance management. Građevinar **53**(2), 83–89 (2001)
42. Petrović, B., Zhang, X., Eriksson, O., Wallhagen, M.: Life cycle cost analysis of a single-family house in Sweden. Buildings **11**(2015), 1–20 (2021)
43. Boussabaine, A., Kirkham, R.: Whole Life-Cycle Costing Risk and Risk Responses. Blackwell Publishing Ltd., Oxford (2004)