Chapter 6

Use and Maintenance

6.1. FUNDAMENTALS OF BUILDING USE AND MAINTENANCE

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This chapter includes six parts:

1) Fundamentals of building use and maintenance;
2) Use of digital technologies in real estate management;
3) Data base for management purposes;
4) Maintenance management plan;
5) Maintenance and repair work;
6) Failure analysis.

The first part gives the insight on fundamentals of building use and maintenance. "Digital solutions" shows how to use digital technologies for collecting geometrical information, climate information, researching of wood constructions and managing the collected data. "Data base for management purposes" shows what is database and how to start using the database for building maintenance to use attribute and geospatial information. "Maintenance management plan" gives general information on maintenance of wooden public buildings in three main views: climate, fire treatment and researching for pests and construction stability.

Every building and structure, including public wooden buildings, must be provided with its **management**, **maintenance** and **administration** in order to achieve the following **goals**:

1) to ensure the operation and maintenance of buildings and structures (physical preservation throughout their life cycle) in accordance with the requirements of the regulatory enactments of each country;
2) to promote the improvement of buildings and structures throughout their operation;
3) to ensure the continuity of the management process of each building and structure;
4) to preserve and develop the aesthetic values of buildings and structures as environmental objects and, consequently, also the aesthetic values of the respective environment;
5) to prevent risks related to public and environmental safety during the operation of buildings and structures;
6) to improve the qualification of persons involved in the management of buildings and structures in order to improve the organisation and efficiency of management work.

The handbook sets out principles for the management of buildings and structures, interrelationships, rights, obligations and responsibilities of those involved in the management of buildings and structures, as well as the competences of countries and municipalities in this area. The issues addressed in the handbook apply to the management of all buildings and structures, regardless of who owns the building and structure, except for the individual cases described in the book.

The **management principles** of buildings and structures are as follows:

1) continuity of management process ensures the preservation of the use properties (quality) of buildings and structures throughout their life cycle;
2) selection of the most optimal possible management work methods, including the formation of optimal management expenses of buildings and structures, comparing them with the solvency of the owner of the building and structure;
3) the content and quality of the provided services ensure the preservation of the use characteristics (quality) of the managed buildings and structures throughout their operation;
4) inadmissibility of an infringement of the safety or health of an individual in the management process;
5) ensuring the preservation and improvement of the quality of the environment in the management process.

Management of buildings and structures includes:

1) mandatory management activities;
2) other management activities.

The mandatory management activities are as follows:

1) maintenance (physical preservation) of buildings and structures in accordance with the requirements of regulatory enactments specified in each country, which includes:
    a) sanitation of buildings and structures;
    b) supply of heat, including natural gas, provision of water and sewerage services, disposal of municipal waste by concluding an appropriate agreement with the service provider;
    c) supply of electricity to the part of the buildings and structures jointly owned (including the operation of the jointly owned facilities);
    d) inspection, maintenance and repair of buildings and structures, as well as their equipment and engineering facilities;
    e) ensuring the fulfilment of the requirements set for buildings and structures as an environmental object;
    f) ensuring compliance with minimum energy performance requirements for buildings and structures;
2) planning, organisation and supervision of management work, including:
    a) drawing up a management work plan which includes a plan of maintenance measures;
    b) drawing up the draft budget for the year in question;
    c) organisation of financial accounting;
3) management of building and structure cases;
4) conclusion of an agreement regarding the use of the attached land plot with the owner of the land plot (in accordance with the legislation of the relevant country);
5) provision of information to state and municipal institutions.

Maintenance of buildings and structures: sanitary maintenance of buildings and structures

The manager of buildings and structures must ensure compliance with the sanitary maintenance requirements at the site in order to prevent the occurrence of danger.

Maintenance of the territory of buildings and structures (land belonging to buildings and structures or the attached land plot)

Territory cleaning shall be performed in accordance with the procedures specified in the binding regulations of the relevant municipality of each country.

Regular cleaning works of the territory:

1) cleaning of sidewalks, paths and driveways;
2) mowing of the grass growing in the territory;
3) collection of fallen leaves, dead plants and branches;
4) care of greenery.

During the winter period additional regular cleaning works of the territory should be done:

1) cleaning of sidewalks, paths and driveways, if necessary, cleaning also other parts of the territory from snow and ice, spreading anti-slip materials on sidewalks, paths and driveways;
2) removal of snow and ice (including icicles) from the facade and roof of the building in order to prevent ice and snow from falling from the roof of the building, cornices, water drains, loggias and balconies;
3) demarcation of dangerous places for the safety of pedestrians and vehicles; measures to prevent the risk must be taken in good time, using all possible safety measures.

In the territory of buildings and structures, including the common areas of the facility, various environmental pollutants, waste and construction debris that pose a risk of poisoning, injuries and infectious diseases or are related to the spread of odours shall be removed in a timely manner. Other necessary measures must be taken in good time to prevent the reproduction and spread of rodents and insects.

Waste management shall be performed in accordance with the regulatory enactments of each country regulating the field of waste management. Waste containers must not be placed under the outdoor air intakes of the ventilation system. It is recommended to place waste containers not closer than 10 metres from the windows of buildings.

If there is a dry toilet, a sewage storage tank or an individual sewage treatment plant in the building, the manager of the residential building is obliged to monitor their condition, ensuring the maintenance of structures in appropriate technical condition and timely removal of necessary tanks to sewage treatment plants.

Rainwater gutters, drainpipes and drainage wells must be cleaned regularly.

The cleaning equipment of buildings and structures as well as disinfectants shall be stored in a specially designed closed place. The manager of buildings and structures shall provide a person who performs sanitary maintenance in a residential building with a water intake.

Maintenance of common areas of buildings

The stairwell must be cleaned at least once a week. In bad weather conditions (for example increased rainfall) wet cleaning should be performed more often within the deadlines set by the manager of the building.

Windows should be cleaned at least once a year.

If the manager of the building finds that it is necessary to disinfect, disinsect or deratise the common areas of the building, she/he must inform the owners of the residential building and other persons in the building in writing at least five working days in advance about the relevant actions to be taken to eliminate the detected danger.

Sanitary maintenance of the building water supply system

The manager of the building is obliged to constantly ensure the hot water temperature at the outlet of the heat exchanger not lower than +55 °C.

The manager of the building is obliged to distribute at least quarterly to the building owners and other persons in the building the informative material available at the website of the national authority responsible for disease prevention and control on individual preventive measures in individual properties.

Maintenance of buildings and structures: supply of heat energy, natural gas

Heating and hot water supply in buildings and structures shall be provided and payment for these services shall be made on the basis of an agreement entered into by the owner of the facility or a person authorised by him or her with the heat energy supplier.

Tenants of non-residential premises in residential buildings shall enter into direct contracts for heating and hot water supply by mutual agreement with the heat energy supplier, if the owner of the building does not wish to enter into such contracts. However, the legal requirements of each country must be observed.

For example, in Latvia a heat supplier who has supplied the building with heat in the previous heating season is not entitled to refuse to enter into an agreement if the building owner has paid in full for the heat received or agreed with the supplier on debt repayment terms and fulfils the agreement, as well as if the owner of the building agrees to pay the supplier for the supplied heat energy within the specified time and according to the previously determined tariff. The heat supply agreement must stipulate that the heat received in the previous month must be paid for no later than by the twentieth day of the following month. If for some reason it is not possible to pay within this term, the owner of the building must agree with the heat supplier on the settlement of debts and the further heat supply regime by the twenty-fifth day of the current month. Heat producers must buy fuel under conditions of competition – as cheaply as possible, thus ensuring the production of the cheapest possible heat.

In turn, the supply of natural gas takes place automatically, only for consumption purposes it is necessary to set the heating mode depending on the time of day, outdoor air temperature and the desired level of comfort. The natural gas heating system is compact and does not require space for fuel storage. Natural gas can also be used for water heating, cooking, fireplace heating and other purposes. By adjusting the tariffs according to the real calorific value of natural gas the customer does not remain a loser comparing, for example, with the risks of firewood quality. When paying for the used natural gas on an equalized basis, the same monthly fee is ensured throughout the year. For the convenience of consumption, it is desirable to use the possibilities of electronic services, but for security – the emergency service. Although natural gas is not a renewable energy resource, it produces the lowest emissions of CO_2, ash, soot, odour sources and other elements, among fuels.

Maintenance of buildings and structures: provision of water supply and sewerage services

The aim of providing water supply and sewerage services is to promote the availability of high-quality and environmentally sound water management services in order to provide service users with continuous and safe services, balancing environmental protection, sustainable use of natural resources and economic interests of society.

The provision of water supply and sewerage services must comply with the requirements of each country's legislation which stipulates:

1) the competence of public institutions in ensuring the availability of water management services;
2) general requirements and procedures for the provision and use of water management services;
3) the rights and obligations of the service provider and the service user.

Maintenance of buildings and structures: municipal waste removal

In each country, requirements are set for the collection, transportation, transshipment and storage of municipal waste in the administrative territory of the municipality. There must be a regulated procedure for the management of sorted municipal waste, certain requirements for waste containers and waste container disposal sites as well as a certain waste generation and management control system. There must be a certain procedure prescribed for determining fees and making payments for municipal waste management as well as liability stipulated for non-compliance with waste management requirements.

Maintenance of buildings and structures: supply of electricity

Energy is one of the most important elements in the development of society which directly contributes to economic growth. The energy sector in the region, as well as around the world, is currently undergoing changes due to ever-evolving technologies and user requirements. As a result, energy companies are expanding and revising their frontiers, offering new approaches and services. Thus, managers of buildings and structures have a wide range of opportunities in cooperation with energy companies to ensure high-quality, safe and environmentally-friendly energy supply in maintenance of buildings and structures.

Maintenance of buildings and structures: inspection, maintenance and routine repair of buildings and structures, equipment and engineering facilities

Inspection, maintenance and routine repairs of buildings and structures, equipment and engineering facilities therein shall be performed in order to ensure the maintenance (physical preservation) of the objects under consideration throughout their operation and to prevent the occurrence of danger.

The technical condition of buildings and structures, their construction as well as the equipment and engineering networks therein shall be determined by visual inspection. Visual inspection of building structures as well as parts of equipment and engineering networks which cannot be accessed due to the technical construction solution of the building shall not be visually inspected. The fact of the visual inspection shall be recorded in the building inspection registration log which is part of the building maintenance file (documentation).

Construction of buildings and structures, common equipment and parts of engineering networks located in groups of residential and non-residential premises shall be visually inspected once a year on a random basis, if the owner of the building has provided such an opportunity. If the owner of the building does not provide the manager with the opportunity to perform visual inspection, the said fact shall be recorded in the building inspection registration log.

Repairs are carried out to ensure the continued operation of the building, its equipment and engineering networks. Types of repairs:

1) extraordinary repairs – timely prevention of the above-mentioned damage;
2) planned repairs – prevention of damage within the term specified by the manager of the building.

The boundary of ownership of a building, its equipment and engineering networks is determined by regulatory enactments or agreements entered into by the manager of building and the respective service provider.

Maintenance intervals and inspections of buildings and structures, their equipment and engineering networks

The manager of the building maintains the maintenance, visual inspection, technical inspection and damage prevention of the building, its equipment and engineering networks.

If the building contains equipment and engineering networks belonging to other persons, the manager of the building may not prevent the owner of the relevant engineering network from providing its maintenance, visual inspection and technical inspection.

The maintenance intervals and maintenance activities of the building, its equipment and engineering networks shall be determined by the manufacturer or regulatory enactments. If the manufacturer's instructions are not available or the said intervals and actions are not specified by regulatory enactments, they shall be determined by the manager of the building.

In order to use heat more efficiently, as well as to facilitate payments, the manager of the building must monitor and regulate the heat regime depending on the time of day and the summer or winter period.

Maintenance of buildings and structures: ensuring compliance with the requirements for buildings and structures as environmental objects

The goal of ensuring the fulfilment of the requirements set for the building and structure as an environmental object is to ensure the preservation and restoration of the quality of the environment as well as the sustainable use of natural resources. For example, in Latvia the preservation and restoration of environmental quality is determined by the country's location on the continental shelf and the existence of exclusive economic zones.

The conditions for the preservation and restoration of the environmental quality of a building and structure as environmental objects are determined in accordance with international law applicable to the discharge of hazardous and other harmful substances:

1) in the internal waters of the country;
2) in the territorial waters of the country;
3) in the exclusive economic zone of the country or in an equivalent zone established in accordance with international law;
4) in straits used for international navigation, observing the transit regime, in accordance with Chapter 2 of Part III of the United Nations Convention on the Law of the Sea as of 10 December 1982, insofar as the relevant strait is under the jurisdiction of a Member State of the European Union;
5) on the high seas;
6) from ships flying the national flag – at any place where the ship is located.

Principles of environmental protection

Environmental policy in the country is developed and decisions that may affect the environment or human health are made in compliance with the following environmental protection principles:

1) the 'polluter pays' principle – a person shall cover the expenses related to the assessment, prevention, limitation and elimination of the consequences of pollution caused by his or her activities;
2) the precautionary principle – it is permissible to restrict or prohibit an activity or measure which may affect the environment or human health but the effects of which have not been sufficiently assessed or scientifically proven if the prohibition is a proportionate means to protect the environment or human health. The principle does not apply to urgent measures taken to prevent the threat of injury or irreparable damage;
3) the principle of prevention – a person shall, as far as possible, prevent the occurrence of pollution and other effects harmful to the environment or human health, but if this is not possible, shall prevent the spread thereof and the negative consequences thereof;
4) the principle of evaluation – the consequences of any such activity or measure which may have a significant effect on the environment or human health must be evaluated prior to the authorisation or commencement of the relevant activity or measure. An action or measure which may adversely affect the environment or human health, even if all environmental protection requirements are complied with, shall be permissible only

if the expected positive result for society as a whole exceeds the damage caused to the environment and society by the action or measure.

The basic principles of regional development must also be observed when formulating environmental policy and taking decisions.

Environmental policy planning

When developing draft policy planning documents and regulatory enactments, the developer must evaluate their impact on sustainable development and the environment in the abstract of the draft planning documents or regulatory enactments. Draft policy planning documents (including buildings and structures) must be subject to a strategic environmental assessment, if this is specified in the regulatory enactments regulating environmental impact assessment.

General public environmental rights

Every individual, associations, organisations and groups of persons have the following rights:

1) to require that state institutions and municipalities, officials or private entities terminate such an activity or inactivity which deteriorates the quality of the environment, harms human health or endangers their life, legal interests or property;
2) to support environmental protection measures and cooperate with state institutions and municipalities in order to prevent the performance of such activities, including the adoption of such decisions which may worsen the quality of the environment or are in conflict with the requirements of environmental regulatory enactments;
3) to provide information to state institutions and municipalities regarding activities and measures that affect or may affect the quality of the environment as well as information regarding the negative changes observed in the environment that have arisen due to such activities or measures;
4) to submit proposals to state institutions and municipalities regarding the legal framework and the developed draft documents in the field of environment.

Public right to environmental information

The society has the right to receive environmental information from state and municipal institutions in writing, audio recording, visual, electronic or other form. In addition, the public shall have the right to receive information, where available, on measurement procedures, including methods of analysis, sampling and pre-treatment methods, or on any other standardised procedure used to compile information on environmental factors.

The applicant for environmental information does not have to justify the purpose for which this information is required.

Public participation in environmental decision-making

The public has the right to participate in the decision-making and drawing up the planning documents, including drawing up the amendments to those documents that may affect the environment. The public has the right to make proposals or express an opinion before taking the relevant decision or drawing up the final version of the document.

Maintenance of buildings and structures: ensuring compliance with the minimum requirements for the energy performance of buildings and structures

Requirements for ensuring energy efficiency of buildings and structures

The manager of buildings and structures shall organise the installation of a meter for the accounting of the amount of heat consumed, if such is not already installed in the facility, to which the heat is supplied by a person who is not an energy supply merchant.

The manager of buildings and structures shall plan energy efficiency improvement measures, including replacement of worn-out elements or structures, if the average heat consumption of the building where the heat is used for heating and hot water production exceeds 200 kWh/m^2 per year or 150 kWh/m^2 per year, if the heat energy is used only for heating the building. When calculating the average heat consumption over the last three calendar years, the useful floor area of the building must be taken into account.

If the building has been energy certified or inspected for a heating or air conditioning system, the manager shall take into account the recommendations of the independent expert specified in the energy certificate or inspection report for the heating or air conditioning system when planning energy efficiency improvement measures.

When planning the renovation of the building, the manager must take energy efficiency measures that:

1) ensure such a reduction in the heat energy consumption of the building that the heat energy consumption is less than the above-mentioned level of heat energy consumption;
2) ensure the highest heat energy savings in relation to the funds necessary for the implementation of the measure.

If conditions are found that contribute to the release of heat into the environment, the manager must take the following measures to increase energy efficiency:

1) the external door must be equipped with a closing mechanism;
2) heating system pipes and hot water pipes located in unheated premises shall be provided with thermal insulation;
3) windows and doors must be sealed or replaced.

For the planning of energy efficiency improvement measures, the manager may decide to perform energy certification of the building.

Other management activities are activities related to the management of buildings and structures and are performed in accordance with the will and solvency of the owner of the buildings and structures. These include activities related to the improvement and development of buildings and structures as well as drawing up a long-term plan of measures necessary for this purpose.

Maintenance file (documentation) of buildings and structures

The information to be included in the maintenance file (documentation) of buildings and structures shall be summarised in the following sections:

1) basic documents of buildings and structures – a document certifying real estate rights, a cadastral survey file of buildings and structures, a boundary

plan of the attached land plot and an agreement regarding the use of the attached land plot;
2) the owner (owners) of buildings and structures, the possessor of state buildings and structures (list);
3) technical documentation – technical passport of buildings and structures (plans, schemes), project documentation, energy passport and energy plan, opinions of technical survey of buildings and structures, etc.;
4) documents related to the maintenance and management of buildings and structures – the management agreement of buildings and structures, decisions taken by the owner (owners) of buildings and structures, including decisions adopted at general meetings of owners of buildings and structures, agreements applicable to management activities, management work plans, budget reports, etc.

The maintenance file (documentation) of buildings and structures shall be kept by the owner, but if the object has several owners – by the manager, unless otherwise provided in the management agreement.

Liability of the owner of buildings and structures

The owner of buildings and structures shall be liable for the management of buildings and structures, including non-performance or improper performance of mandatory management activities, in accordance with the procedures specified in the legislation of each country.

Responsibility of the manager of the building

The manager is responsible to the owner of buildings and structures for the performance of the management task given to him/her in accordance with the requirements specified in the legislation of each country and in accordance with the provisions of the concluded management agreement. The manager shall be liable for non-compliance with the requirements of law when performing the management task in accordance with the procedures prescribed by the law of the respective country. The liability of the manager of buildings and structures shall take effect from the moment specified in the management agreement.

6.2. USE OF DIGITAL TECHNOLOGIES IN REAL ESTATE MANAGEMENT

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Digital technologies in Real Estate Management are one of the tools for analysing the quality of the lifecycle of buildings. With the quality we are not thinking only visual design of the view but also see full management of the property, like the climate, ergonomic, design, environmental, building construction, construction properties, analysis, etc. Digital technologies help to understand the real situation to collect regular information with several tools and put it in databases and give the results of analysis. Wooden public buildings use very specific construction elements and environmental materials for protecting the wood from climate and also are visually aesthetic. Wood in construction is a natural material requiring monitoring. The main requirements are humidity, ventilation, presence of pests, ecosystem and fire treatment. Fire safety is an important factor that makes us particularly think about maintaining a wooden building. Wooden structures can contain various pests, which is a major disadvantage of timber frame houses. The wood should be treated regularly with a special bioservice solution that will protect the wood from both pests and fire (Kolaitis et al., 2014).

Wooden buildings have a high degree of durability, but any artificially constructed building may require replacement of structural elements, interior or exterior modifications. It is necessary to understand and analyse what constructive solutions have been or will be used. To understand the processes for repairing, reconstruction or renovation, BIM is a very good help.

In the control problematics in buildings we need to consider the four main factors that affect life quality inside of them (Novák et al., 2016):

- thermal comfort;
- indoor air quality;
- visual comfort;
- aural comfort.

The goal is to improve those factors with the least amount of building's operating costs possible, ideally, even reducing them. Therefore, in summary, the control objective is:

- to provide a good comfort level – learn the comfort zone from the user's preferences if possible; ensure satisfactory comfort level (thermal, air quality and illuminance) with good dynamic performance;
- to increase energy savings – combine the comfort conditions control with an energy saving strategy;
- to improve air quality control – provide enough ventilation to keep CO_2 levels low, possible use of controlled ventilation (DCV) systems.

A good control system ought to have many benefits such as minimizing the energy consumption, reducing the pollution caused by energy usage, improving the comfort, preventing out of hours operation of the equipment, reducing the maintenance cost and limiting the excessive wear and tear associated with the building systems (Perera et al.,2014):

- thermal comfort can be measured by the predictive mean vote (PMV) and predicted percentage of dissatisfied (PPD), presented in ISO 7730:2005;
- visual comfort is about having enough luminance level either by solar radiation or by lighting based on EN 12464-1 and EN 12464-2 standards;
- aural comfort is related to the acoustical environment inside a building, which means speech intelligibility and privacy;
- CO_2 concentration inside a building characterizes the level of indoor air quality (IAQ).

There are a many other standards (Novák et al., 2016):

- EN15251 specifies indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics;

- ANSI/ASHRAE Standard 55 defines the range of indoor thermal environmental conditions acceptable to a majority of occupants but accommodates an ever-increasing variety of design solutions intended both to provide comfort and to respect today's imperative for sustainable buildings;
- ISO 7730.

This chapter shows how to use digital instruments for controlling the air conditions, humidity, temperature and for inspections of the wooden building constructions. The chapter describes the principle of the building management systems, digital sensors and digital inspection.

6.2.1. Digital Inspection Tools

Visual inspection is one of the oldest and most widely used tools for inspecting and monitoring buildings. Visual inspection provides only part of the information that the human eye can see. Thus, we obtain only information that can be interpreted in RGB colours or visually understand whether the wood material is intact or damaged. Visual inspection also allows to touch the material and understand its internal structure from the touch. Digital tools allow to look deeper into the building elements by identifying the key parameters needed for a wooden building to last for a long time. The parameters to be determined are the internal climate data of the environment and the building element, geometric information, optical-visual information, and the resistance of the protective layers to the effects of the environment. This sub-chapter provides an in-depth look at tools that help inspect wooden buildings using digital visual inspection and climate control tools to obtain geometric information.

Visual and geometrical digital inspection tools

The use of digital tools to collect visual and geometric information from buildings is one way to gather information that is available long after the fieldwork has been completed.

There are many ways to get and save data. Photogrammetry and laser scanning tools are widely used to obtain data. These tools complement each other to produce both high-precision geometric information and high-resolution visual information. Digital tools that can be used are both simple for everyday use: a camera, a laser rangefinder, as well as high-end - laser scanners and unmanned aerial vehicles. This section discusses the use of laser scanners, drones, and simple rangefinders or cameras for digital survey of buildings.

3D Laser scanning

Laser scanning is the measurement of the distance to the surface and back using a visible or invisible laser. This method for surveying buildings has been widely used since the 21st century. With the development of technology and data processing software, laser scanning is becoming one of the leading methods for collecting geometric information data about terrain – buildings, structures, vegetation, surfaces, soil, etc., combining laser scanning data with photogrammetry data results in a high photorealistic set of 3D points. By supplementing the data with photogrammetric data, it is possible to obtain information in places where secure access is not possible. Laser scanning is a surveying technology that allows to obtain high-precision 3D data about the geometry of the object and the environment in a short time. The survey results in a 3D point cloud consisting of several million points, where each point has its own XYZ coordinate. Figure 6.1 shows a point cloud of the wooden

Fig. 6.1. Wood building in 3D point cloud after renovation (developed by authors).

building. At the same time, depending on the scanner parameters, it is also possible to obtain RGB colour and intensity with 3D laser scanning. Laser scanning became more widely used in construction in the late 1990s, when one of the first laser scanning systems was developed. When performing a survey with a laser scanner, high-precision and high-resolution 3D data about the surveyed object are obtained in a short time. Laser scanning data consists not only of XYZ coordinates, but also of high-resolution photographs, which give each measured point its own RGB colour, and the point cloud resulting from the scan can be linked to a construction site or national coordinate system. The data and products obtained as a result of laser scanning are used both in the supervision of buildings and in the renovation and reconstruction of buildings.

A laser scanner is a device that analyses real-world objects and the environment by obtaining data about their geometric shapes, textures, and colours.

The beginning of laser scanning can be tracked back to the 1960s. The first scanners used a combination of light, camera, and projector to accomplish the intended tasks, but due to limited equipment and the complexity of scanning, it often took a long time to accurately measure objects. After 1985, the first scanners were replaced with scanners that used white light, lasers, and shading to obtain the desired surface image. It was also the beginning of 3D laser scanning technology as it is today (Abdel, 2011). However, it was not until the late 1990s that laser scanning entered also the engineering industry.

One of the first 3D laser scanning systems, the Cyrax prototype, was developed in 1997 by Cyra Technologies. The prototype was huge. It was built into an old Volkswagen car and had a measuring speed of 30 dots per second (see Fig. 6.2).


a)


b)

Fig. 6.2. *Cyrax* laser scanning system: a) prototype, b) model *Alpha* (Cheves, 2014).

The most important software for laser scanning data is the one that is designed to process laser scanning data and create a point cloud. Most laser scanner manufacturers have developed their own data processing software because each manufacturer has its own file format in which it stores information. However, some manufacturer's software is also designed to process laser scanner data from other manufacturers.

The laser scanner emits a laser beam at the object and measures the distance from the laser scanner to the object by measuring the return time from the emitted to the reflected beam. The data acquisition speed is currently more than 2,000,000 measurements per second.

Laser scanners are also divided by wavelength (see Fig. 6.3):

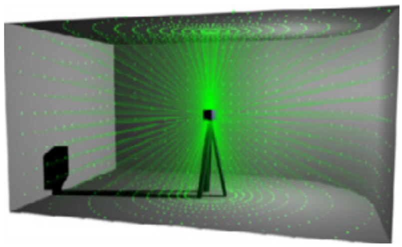
- visible laser scanner (laser beam is usually green): 532 nm;
- near-infrared scanner: 700–1300 nm;
- infrared scanner: 1330–1550 nm.

Table 6.1 shows the main using field and types of the laser scanner. Airborne laser scanning is used for collecting information of the surface from airplanes or unmanned aerial vehicle. The main aim of using this system is to collect information for large area in short time. The main results are a surface model of the area and an orthogonal area image. *Airborne laser scanning* – widely used laser scanners for surveying the geometry of the buildings or infrastructure in short distances – 100 m. The main results are point clouds. Micro Ls are used

Fig. 6.3. Laser scanner with visible laser (LEICA Geosystems, 2020).

for very short distances with high precision. The main field is interior objects. Dynamical-moving scanners are used for very fast data collection to do work in mowing process.

Table 6.1
Laser Scanner Types and Usage (Developed by Authors)

Laser scanner	Usage	Image
ALS – *airborne laser scanning*	Scanners used from aircraft to obtain large areas of 3D data, e.g. in agriculture, forestry, urban areas, etc.	
TLS – *terrestrial laser scanning*	Scanners used for static ground surveying. The scanning distance can range from a few metres to several kilometres.	
Micro LS	Scanners used to scan objects at close range, e.g. in reverse engineering, prototyping, documentation of cultural monuments, etc. The scanning distance is from a few millimetres to a few metres.	
Dynamical-moving scanners	Allow to scan the surroundings while moving. The data is provided with an accuracy of a few centimetres.	

Factors influencing the laser scanning

Laser scanning is a very physical process that is affected by such external conditions as the environment, vibrations, object material, etc. The abovementioned factors determine the quality of the measurement and the result.

Laser scanner measurements are related to the following errors: angular accuracy, distance accuracy, resolution, boundary effects and effect of surface reflectivity.

Angular accuracy: The laser beam in the scanner is curved (refracted) by a mirror or prism and directed at the object. To bend the beam on another surface or perpendicular to the first, the axis of rotation of the instrument or additional optical devices are usually used. Angle reports on a specific surface are used to calculate spatial coordinate points. Any measurement errors of these angles will lead to errors in the direction measurements perpendicular to the propagation of the laser beam line. It is for this reason that errors can occur, which can only be minimized by calibrating the instrument.

Distance accuracy: Laser scanning systems, which are based on distance measurement, measure the distance with time after the output signal or by comparing the phases between the output and incoming beams. Such scanners are designed to work when the object is up to 100 m away, but even over longer distances they are accurate.

Resolution: From the user's point of view, this explanation refers to the ability to find small objects or their components in a set of points. But from a technical point of view, two different technical parameters for laser scanning systems correspond to this explanation. And they are the minimum angle between two adjacent points and the size of the laser print on the object itself.

Boundary effects: When the laser beam falls on the edges or edges of an object, only a portion of the reflected signal will return to the system. The remaining part of the received signal is the reflection from the mixed surface behind the edge or behind a surface that has nothing to do with the object to be scanned. Systematic effects can be observed when cylindrical and spherical objects are scanned from a close distance. In such cases, in the peripheral areas of the objects, their geometric centre may not coincide with the centre of the reflected beam.

Effect of surface reflectivity: White surfaces are able to reflect the signal much more strongly than darker surfaces. When reflected from coloured surfaces, the signal intensity depends on the spectral characteristics of the laser in the green, red and near infrared range. Glossy surfaces make it difficult to register signals. Surfaces with uneven reflectivity have been found to form systematic errors at distances. For some types of materials, these errors can reach a few times the VKK for single-distance measurements. To study the accuracy of measurements, flat objects in white can be used by placing the material to be analysed between them. After determining the approximate surface for this middle part and performing the same operation for the remaining white part of the object, regardless of the average object, a difference can be determined between these two surface types, which will allow to evaluate the effect of the given factor.

Environmental impact

Laser scanning is related to the following environmental impacts: effect of temperature, atmospheric effects, influence of internal radiation sources.

Effect of temperature: Temperature has little effect on the operation of laser scanners because the distances are relatively short. Rather, it is possible to overheat the equipment where the internal temperature differs from the outside temperature.

Atmospheric effects: When measuring short distances, the speed of light propagation due to temperature fluctuations and / or atmospheric pressure will not have a significant effect on the measurement results. When measured in conditions with high concentration of vapor or dust in the air, results equivalent to the same effects as for edge and edge measurements are possible.

Influence of internal radiation sources: Lasers operate in a rather narrow frequency band, so filters should be used at a certain frequency in the signal acquisition module. If the radiation comes from another object (sunlight or artificial lighting) and is quite strong compared to the work signal, then a significant part of this radiation can pass through the filter and affect the accuracy or even the overall result of the work.

Laser scanning workflow

Laser scanning involves a series of steps (Fig. 6.4):

- laser scanning process on field;
- data processing;
- visualization of results.

Fig. 6.4. Laser scanning workflow process (developed by authors).

The laser scanning process begins with a preparatory phase which includes identifying the customer's goals and objectives and desired results, examining existing data, on-site inspection to assess scanning conditions and access to all required locations (roofs, rooms, basements, attics, etc.), work planning so that everything you need can be scanned in the shortest possible time.

The task of data processing is to get a point cloud. In order to create a point cloud from the data obtained during the laser scanning process, which can be fully used for further work such as 3D modelling and BIM modelling, various types of calculations, monitoring or object analysis, the scanned data must first be post-processed, including matching and cleaning. This process can be performed in one of the laser scanning data processing programs, which in most cases is a data processing program developed by each laser scanner manufacturer.

Stages of data processing process are as follows:

- matching scans (automatic and manual);
- attachment to the coordinate system;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103410724
18.12036 0.98179 24.56456 171 61 37 73
18.1667 1.06529 24.55429 168 63 43 80
18.09796 0.9647 24.58594 166 54 34 71
18.12745 0.98659 24.56544 172 62 38 72
18.23223 1.14699 24.64957 172 9 13 104
18.21556 0.94589 24.65992 159 1 11 70
18.17538 0.96645 24.59508 176 53 39 75
18.18456 1.04066 24.58462 170 60 43 85
18.18249 1.0862 24.58713 168 59 41 81
18.07549 0.95044 24.65836 165 29 22 66
18.16118 1.0643 24.55642 168 63 43 80
18.15135 0.95073 24.65052 162 12 7 74
18.18798 1.11787 24.59633 168 59 41 81
18.18266 0.96987 24.59394 166 55 39 78
18.17528 1.05935 24.57103 161 60 42 80
18.22757 1.15763 24.6518 173 0 2 71
18.20385 0.98217 24.64157 133 47 40 74
18.14335 0.98641 24.56905 168 63 37 72
18.11504 0.96121 24.58449 169 54 33 72
18.07836 0.95301 24.6143 164 48 36 76
18.10363 0.96197 24.59377 166 51 34 68
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Fig. 6.5. Point cloud file format (developed by authors).

Fig. 6.6. Point cloud and 360-degree images (developed by authors).

- quality control;
- scan cleaning;
- creating a point cloud.

Once all the scans have been merged and cleared, a cloud of project points can be created and visualized by CAD or modelling software. The processing of laser scanning data results in a point cloud consisting of several million points, in which each point has its own X, Y, Z coordinates and colour. But in order for the point cloud to continue to be used in any CAD or BIM software, it must be exported to the required file format which is supported by the program in use. The most popular point cloud file formats are E57, DXF, XYZ, IGES, PTS and POD. Figure 6.5 shows the point cloud file format in PTS file format containing the point number, x, y, z coordinates, laser beam intensity and RGB colour point.

Laser scanning also produces 360-degree images as a product which can be visualized in combination with a 3D point cloud (Fig. 6.6).

Using these data products, it is possible for the building to perform both a visual virtual survey on a computer as well as to perform geometric measurements in a point cloud to use CAD software or directly in a 360-degree image.

Digital close-range photogrammetry

Photogrammetry is the science of taking measurements from photographs. This method has been used for more than 100 years, but mainly to meet the needs of cartography and architecture. In the last decade, with the development of digital photographic and imaging technologies as well as unmanned aerial vehicles (UAV, drones), the scope of photogrammetry is expanding and becoming one of the leading methods for mass data collection on terrain – buildings, structures, vegetation, surfaces, soil, etc. There is no limit to the distance to an object in photogrammetry – it can be from centimetres to hundreds of kilometres. Unlike laser scanning, this method is more widely available because the shooting does not require expensive equipment and highly professional knowledge, the visual appearance of the result with photorealistic accuracy reflects the measured object or area, but it does not provide such high geometric accuracy. The best results are obtained by combining the laser scanning data with photogrammetry. Figure 6.7 reflects one of the results from photogrammetry – 3D reality model (Borodinecs et al., 2018).

Close-range photogrammetry (CRP) relies on the reconstruction of object simultaneously from several images from different and best possible perspective, to ensure a suitable geometry of intersecting rays. So that, close-

Fig. 6.7. 3D reality model of wooden building complex (developed by authors).

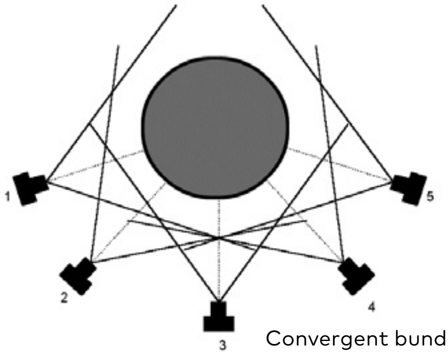

Fig. 6.8. Basic principle for taking the photography (Hanke, 2002).

range photogrammetry is meant to be in that situation when the distance (range) from the camera to the object of interest is somewhere from 1 metre to approximately 100 metres.

Photogrammetric surveying is based on comparing photos that show the same location removed from multiple viewpoints. Therefore, the main requirement is the overlap of areas covered by these images in a sufficient area, usually expressed as a percentage. Since the entire area or object to be surveyed must be covered, the photo must be taken in the same way as a tiled roof – with a partial overlap. Figure 6.8 shows the basic principles for taking the photography from drones or hand cameras.

Photo-take planning is a very important stage to ensure sufficient coverage and informative content of the acquired images in relation to the terrain objects, separate structures, linear corridor objects (roads, railways), high vertical objects (towers, chimneys, masts), interiors. For each type of object the most suitable plan and its parameters must be chosen, the most important of which are:

- distance to the object or flight altitude;
- the size of overlay between adjacent images;
- camera orientation.

The choice of the distance to the subject is determined by the accuracy and / or resolution requirements of the result and depends on the parameters of the camera: the size and resolution of the sensor and the focal length of the lens according to the above relationships. In turn, the choice may be limited by the peculiarities of the area to be measured – narrow approaches, obstacles such as trees, tall structures, air ducts, etc.

The required coverage between adjacent images depends on the type of object, the required product and the characteristics of the area. Coverage must be provided both in the direction of movement of the camera (frontal coating) and between images on the side in that direction (lateral coating).

Survey of a separate building or group of buildings

Pictures are taken by bypassing the building. Admission must be planned in such a way that no parts of the facade are left out and obscuration is controlled. At least 60 % coverage between images must be provided. When bypassing corners of the building or changing the direction of view of the camera, it must be ensured that the viewing angle between adjacent companies does not exceed 15°. When shooting with a drone, the building is flown on several levels vertically, ensuring 60 % coverage between images of adjacent levels. It is also recommended to add ground intake. Such a plan for the reception of a structure ensures the collection of the most detailed information about what allows to reconstruct the geometry of the structure. The obtained data products are further used to determine and document the technical condition of the building and as input data for the development of renovation and reconstruction projects. Figure 6.9 shows the main principle of trajectories using UAV technologies.

Photogrammetric data processing results in the 3D data products are a dense cloud of 3D points, where each point is represented by its X, Y, Z coordinates

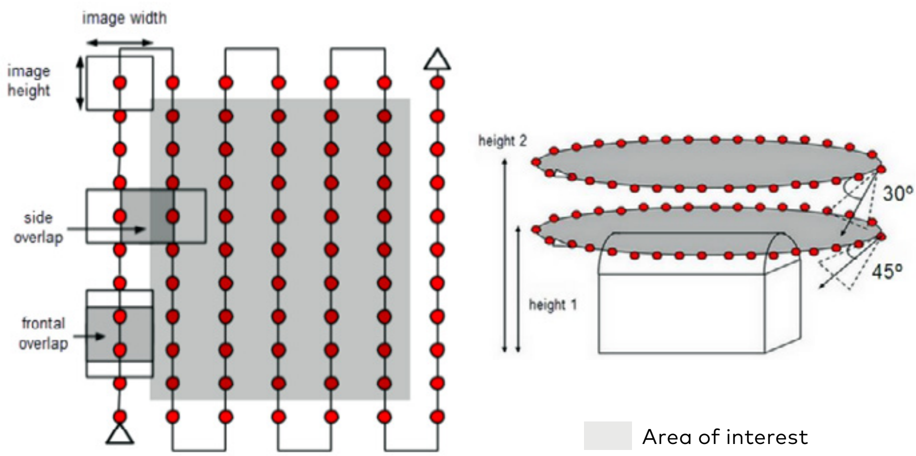

Fig. 6.9. UAV trajectories (Pix4D manuals, 2020).

and its colour in RGB encoding. This type of representation can take up a very large amount of computer memory (several gigabytes and more), as tens to hundreds of millions of points are stored. A 3D grid model is a collection of vertices, edges, and faces that represent the shape of polyhedral objects. Triangular faces are usually used. Faces can be represented with textures to create a photorealistic object model. Such a model significantly saves computer memory compared to the point cloud (by several layers).

The quality and applicability of these data products are characterized by two indicators:

- Geometric accuracy – the correspondence of the spatial position of points (points to the cloud) and vertices (grid model) to the position of the corresponding point in the object to be measured. In the case of photogrammetric surveying, the accuracy is determined by the camera parameters (sensor size, sensor resolution, focal length), shooting distance (height) and image capture according to the photogrammetric requirements as well as the optical properties of the subject.
- Level of detail – point density (point cloud) and number of faces per unit surface area (grid model). The higher the level of detail, the more detailed the details of the object in the point cloud or grid model. The required level of detail is given as an input parameter in the data processing.

Figures 6.10, 6.11 and 6.12 show 3D reality models in different periods: before renovation process, during renovation process and after renovation process.

Fig. 6.10. 3D reality model before renovation process (Jelgavas Vecpilsētas ēku pārbūve, restaurācija, 2020; Tehnoloģiju pieskāriens vēsturei, 2020; Jelgava old city, 2020).

Fig. 6.11. 3D reality model during renovation process (Jelgavas Vecpilsētas ēku pārbūve, restaurācija, 2020; Tehnoloģiju pieskāriens vēsturei, 2020; Jelgava old city, 2020).

Fig. 6.12. 3D reality model after renovation process (Jelgavas Vecpilsētas ēku pārbūve, restaurācija, 2020; Tehnoloģiju pieskāriens vēsturei, 2020; Jelgava old city, 2020).

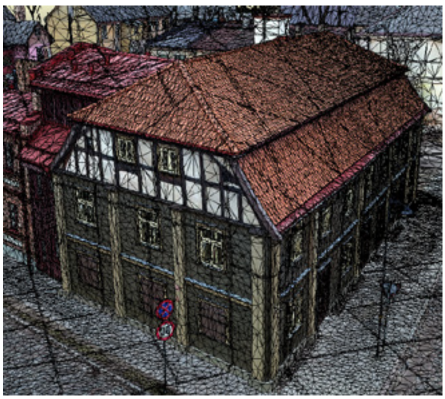

Fig. 6.13. 3D reality model in mesh format (developed by authors).

The reality models and mesh models (Fig. 6.13) give possibilities to understand the building geometry, to measure dimensions or cross sections directly in software.

Visual material gives distance researching from computers. Maintenance process with reality models gives possibility to understand periodical changes.

Laser distance meters

Laser distance meter is a device that measures distance using a laser beam. Such devices are widely supplied in engineering surveying, topographic surveying, navigation, architecture and construction. Laser distance meter is very compact with many features as well as operating in a short time. Figure 6.14 shows a simple laser distance meter to measure the distance angles for calculating the plane and height values between elements.

The 3D laser distance meter is a laser scanner designed for measuring complex architectural structures, rooms with non-standard walls with different angles, as well as rooms with many small details (Fig. 6.15). Laser distance meter with a built-in electronic angle reader can read the distance to the object, horizontal and vertical angles and assign coordinates to a point in the local coordinate system. Using its own software, the tool can instantly create a spatial project by drawing lines, circle and other geometric shapes between points. Using automatic motors, the tool, like the scanner, can scan surfaces and lines. As well as by operating the instrument manually, it is possible to measure only those points that are necessary. They facilitate the post-processing process. When controlling the instrument using the control board, it is possible to

Fig. 6.14. Simple laser distance meter (GPS Partners, 2020).

Fig. 6.15. 3D laser distance meter (GPS Partners, 2020).

take measurements remotely from the instrument because the connection is established with a WiFi signal emitted by the instrument. The whole project remains on the tablet, as well as using the instrument's built-in camera, it is possible to see what the instrument sees, which facilitates measurement and endorsement. The project can be exported in DXF format.

Simple photo measure tools

Measuring images is one of the fastest tools for getting both image and geometry information at the same time. Such tools can be combined with both a photo taking function and a distance detection function between the objects shown in the images. Another tool is 360-degree images providing full around image. Figure 6.16 demonstrates the results from image measurement tools. Use of the tool with functions directly taking image measurements gives possibilities determining the extent of damage immediately at the site.

Fig. 6.16. Photo 3D measurement tool (GPS Partners, 2020).

Conclusion

Digital tools help to understand the building during its maintenance period and make it possible to understand the behaviour of structures, including the most important components such as foundations and the roof. Wooden structures are affected by practically any geometric change that exceeds the limit value and the wood breaks. Ground stability or the movement of structures is mainly influenced by meteorological parameters such as wind, snow, rain and temperature.

6.2.2. Digital Sensors for Climate and Energy Analysis in Buildings

This chapter shows how to use digital sensors for controlling the air conditions, humidity, and temperature. There are various digital sensors in the world for smart building and you can find a lot of possibilities how to control the climate inside for living and for building construction. This section shows only a few types of sensors without mentioning a specific manufacturer or developer. The main task of sensors is to collect and record data and display the real situation in real time or from the database on the situation in advance through applications. Digital climate sensors can be connected to building management systems (BMS) and act as a single element in climate monitoring. The second type of sensors signed in this section are stability sensors for building structures, such as the movement of a building under the influence of wind or ground stability. Deformation limits control for rafters, curved busbars and beams.

Climate control sensors are usually used in conjunction with energy saving resources. This chapter contains parts from The Advanced Controls / Performance Monitoring and Control of Integrated Systems from H2020 project Development and advanced prefabrication of innovative, multifunctional building envelope elements for MOdular REtrofitting and CONNECTions (Novák et al., 2016).

The main factors influencing the longevity of wood are loads, moisture and cracking of wood. All these factors are interdependent. In turn, the mechanisms for controlling the strength limits of wood are selected according to the type of wood construction, which may be different for round wood, glued wood or wood of lumber type. Maintenance and monitoring tools are usually determined at the design stage. They are different for beams, poles, trusses, pavements, etc.

Digital climate control tools

Dry air can cause problems with wooden furniture, stairs, floors, and doors. This is especially true during the heating season when the indoor humidity often drops below 25 %. When it dries strongly, the wood starts to crack. Cracking occurs during the use phase. Cracks appear in the parquet, etc.

Most used control strategies for climate and energy systems are reflected in Table 6.2.

Table 6.2
Control Strategies (Novák et al., 2016)

On/Off control (Thermostat)	Feedback type Availability Generic Well understood Low initial cost Simple structure Fast response	Accepts only binary inputs Often incapable of tracking the setpoint accurately and hence could be inefficient Not versatile and effective in the long run
Feed forward control (Weather compensator)	Availability Increased energy savings Very fast reaction to changes	Open-loop type Negligence of all effects related to unmeasured signals / disturbances Unpredictable changes of the system behaviour Parameter storage requirements to accommodate many operating conditions System performance not measured Possibility of system failure if the relationship between the environmental measurements and system model parameters change
PID control (Feedback)	Feedback type Robustness to disturbances Derivative term combat with sudden load changes in the system	Little measurement and process noise can cause large variations in the output due to derivative term Energy inefficient Tuning is time consuming
MPC	Increased energy savings Cost effective Robustness to disturbances Can involve bounds Control of multiple variables Steady state response improvement Future disturbance prediction Prediction of future control actions Better transient response Handles slow moving processes with time delays	Need to identify a suitable model of the system Installation could be expensive Set-up can be time consuming

ON/OFF technique examples: thermostat, humidistat, and pressure switch. Commonly found in home heating systems and domestic refrigerators. Most used in HVAC systems due to the advantages it offers. However, intensive oscillations during operation and low energy efficiency reflect high cost of both maintenance on actuators and energy.

Advantages:

- simplicity;
- low initial cost.

Disadvantages:

- high maintenance cost;
- low energy efficiency.

Weather-compensated (equithermal) control. A feed-forward type of control, known in the market as equithermal controller for HVAC systems. The disturbances are measured and accounted for before they have time to affect the system. This strategy responds to its control signal in a pre-defined way without a feedback technique (not-error based), which means it is based on the knowledge of the process or measurements of its disturbances.

In heating systems, weather compensation is a communication between the source of hot water (boiler, for example) and an outside temperature sensor. Since the weather has the main influence on the heat demand of a building, the controller adjusts the heat supplied according to the weather conditions and inside temperature setpoint, via pre-defined heating curves, ensuring a more constant temperature in the rooms and better energy savings (15 % according to some system manufacturers).

PID controller continuously calculates the error between the desired setpoint and a measured process variable and adjusts the control signal accordingly. It is also known as feedback control for HVAC systems (Balas et al., 2013).

'Proportional' accounts for present values of the error. For a large and positive error, for example, the control signal will be proportionally large and positive.

'Integral' accounts for past values of the error. For example, if the current control signal is not strong enough, the error will accumulate over time and the controller will respond by applying a stronger action.

'Derivative' predicts the future offsets based on the actual rate of change of the process and suppresses oscillations.

A PID controller is very versatile and can be widely applied because it does not use knowledge / model of the interested system. When correctly tuned, the controller can adjust its output to match the power that is required to keep the process stable at the setpoint. However, it requires the tuning for this purpose, creating some limitations and inconveniences (Ashida et al., 2017).

Model predictive control (MPC). Predictive control applied to building automation systems provides increased energy savings, being often more cost-effective than non-predictive control applications and providing some other benefits too. They can be applied to both single-zone and multi-zone buildings, whether residential, commercial or public buildings. However, the decision of implementing the predictive control for a particular building depends on the payback period. This multivariable control technique is based on a prediction model using past information and future inputs to predict what the future output should be. While controlling the process according to the model, MPC generates a cost function control vector to minimize it over the prediction horizon, disturbances and constraints that might be present. Model identification is the bottleneck of the whole MPC application procedure, and there are no strict requirements on the model structure. It is possible to use any black box, grey box, or white box model.

Main advantages (Novák et al., 2016):

- energy and maintenance cost savings;
- multivariable;
- peak load shifting capability;
- transient response improvement (decrease in rise time, settling time, and peak time);
- steady-state response improvement (decrease in offset error);
- predictions of future disturbances ƒ – future control actions prediction;
- control of variables within bounds ƒ – reduction in fluctuations from a setpoint (better regulation);
- efficiency and coefficient of performance (COP) improvements;
- robustness to disturbances and changes in operating conditions;
- indoor air quality and thermal comfort improvement.

Main disadvantages:

- relies on model accuracy;
- strong dependence on the model;
- need to identify a suitable model of the system;
- installation could be expensive (e.g. use of remote server for calculation);

- a direct implementation to PLC is not possible;
- needs computational time;
- does not account for user controllability, and subjective level of comfort is not adaptive.

Digital sensors for building construction stability control

The main task for the stability of digital sensor structures is to follow the behaviour-deformation of structures under the influence of external processes. Possible external processes can be weather conditions: wind, temperature and precipitation, as well as soil stability. The most popular are tilt meter and joint & crack meter.

Tilt sensor

The main task of the tilt sensor is to follow the vertical or horizontal-spatial deviation of the structure from the design position. Tilt meters are designed to measure tilt on submerged structures either on a vertical, inclined or horizontal surface.

They consist of highly accurate MEMS sensors mounted in robust watertight stainless-steel housing which can be attached to the structure by bolting, bonding or welding.

Each unit is individually calibrated to provide the ultimate in system accuracy and repeatability and can be used in conjunction with a hand-held readout, automatic data acquisition system and Wi-SOS to provide a wireless monitoring solution. Figure 6.17 shows that the MEMS tilt beams are designed for attachment to structures, on either a vertical or horizontal surface, for the measurement of tilt or differential settlement.

Fig. 6.17. Geosense MEMS tilt beam (Geosense, 2020).

Joint & crack meters

Crack meters are designed to measure displacements across cracks and joints typically in buildings, bridges, dams, pipelines and rock formations. They are used for measuring movement in one (1D) or three axes (3D).

Joint meters are ideal for monitoring movement of joints between two structures. Typical applications include abutments, slabs, foundations and retaining walls, tunnels or shaft linings, arch, gravity, and buttress dams. Also, it is possible to use them for wooden construction joints.

Data can be obtained using a portable readout or connected into a data logger for automatic monitoring. Figure 6.18 shows an example of crack meter for controlling distance movements between two constructions.

Building monitoring process is one of the parts in maintenance plan. Combining sensors with geometrical information and bringing raw data to

Fig. 6.18. Geosense joint & crack meter between two constructions (Geosense, 2020).

Fig. 6.19. Public wooden building with wood construction elements (Koka ēku renovācijas centrs "Koka Rīga", 2017).

Management database systems, it will be possible to analyse the building with BIM or GIS systems. Regular analysis of the data forms a monitoring process. Analysis of monitoring results provides an opportunity to regularly improve maintenance tasks for buildings. Figure 6.19 shows a public building with massive wooden structures that perform both the aesthetic function and the structural durability function. This building needs regular visual and geometrical control with sensors.

Digital tilt logger

The digital tilt logger (Fig. 6.20) is a simple, battery-powered data logger and tilt meter in a single compact unit. It measures tilt in either one or two perpendicular axes in the plane of the base. The unit is intended to be permanently installed to provide long-term observation with maximum resolution and sensitivity and is conveniently designed for manual monitoring or remote data acquisition.

The sensor is usually used for observations of vertical structures – for observation of vertical tower supports.

Fig. 6.20. Digital tilt logger (Geosense, 2020).

Conclusion

Digital building surveillance tools help manage a building as a safe place for people to stay and as protection of structures against damage. Using digital sensors, we obtain data in real time or very close to real time by pre-processing it. Sensor indicators and processing results should be published on web services. Digital technical tools help to quickly determine the safety performance of buildings and at the same time monitor the climatic parameters in the building.

6.3. DATA BASE FOR MANAGEMENT PURPOSES

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The main task of the building management database is to ensure the management of the processes related to building management and timely execution of building maintenance tasks. Various database management systems can be used for building management: building information modelling systems, building management systems, facilities management systems, geographical information systems. Guided by the type of database structure, we can divide building management into the following groups: textual or analytical databases, graphical databases, and combined systems of both databases.

Building information modeling (BIM) is a process that begins with the creation of an intelligent 3D model and enables document management, coordination, and simulation during the entire lifecycle of a project (plan, design, build, operation and maintenance) (Autodesk, 2020).

The building management system must provide three main functions: event logging, data storage and process traceability. BMS systems are 'intelligent' microprocessor-based controller networks installed to monitor and control a buildings technical systems and services such as air conditioning, ventilation, lighting and hydraulics.

The term 'facilities management' (FM) has been the subject of much debate since its conceptualization. "Facilities management brings together knowledge from design and knowledge from management in the context of buildings in everyday use" (Finch & Zhang, 2013).

GIS is one of the tools that helps to manage a building through both visualizing and analysing building information. It is a system that helps to identify the scene and display it in space. The key functions of GIS use in facilities management are spatial visualization and geodatabase management functions. It has been used extensively for facilities management in the public sector and has great potential for use in the private sector as well. GIS has been used to assist in the management of building spaces and facilities in recent years (Mwaniki & Odera, 2014). GIS as a building maintenance tool allows to view a building as a spatial object in a real environment by integrating the results of data analysis of building in 3D GIS.

The building database management system must be based on a maintenance plan. All procedures of the maintenance plan must be registered and traced.

6.3.1. Building Information Modeling System

BIM (building information modeling) is the process of creating and managing data over the life cycle of an object. The obtained information model is used as a basis for decision-making, as it includes objective information, from the idea to the conclusion of the operation phase of the building.

Building information modeling process supports the creation of intelligent data that can be gathered throughout the lifecycle of an infrastructure or building project.

BIM life cycle includes the following processes (Autodesk, 2020):

- Planning – reality capture and real-world data are used for project planning to generate context models of the existing built and natural environment.
- Designing – conceptual designing, analysis, detailing, and documentation are carried out. The preconstruction process begins using BIM data to inform scheduling and logistics.
- Building – fabrication begins using BIM specifications. Project construction logistics are shared with trades and contractors to ensure optimal timing and efficiency.

- Operating – BIM data carries over to operations and maintenance of finished assets. BIM data can be used down the road for cost-effective renovation or for efficient deconstruction.

Life cycle of an enterprise in BIM can be seen in Fig. 6.21.

Building information modeling (BIM) has the potential to advance and transform facilities operation and maintenance (O&M) by providing a platform for facility managers to retrieve, analyse, and process building information in a digitalized 3D environment (Gao & Pishdad-Bozorgi, 2019).

In the operation and maintenance (O&M) phase of an existing building frequently different systems are available to manage data about building maintenance. All building structures, material, finishes, and services deteriorate over time through an inevitable process of the effects of climate and usage. This process of decay can be controlled, and the physical life of the buildings can be extended if they are properly maintained (Chew et al., 2004).

BIM can be classified in three types: corrective, preventive, and predictive. The corrective maintenance concerns about a reactive maintenance in response to a cause of failure or breakdown (Motawa & Almarshad, 2013). Preventive maintenance is carried out by periodically undertaking routine tasks necessary to maintain a component or system in a safe and efficient

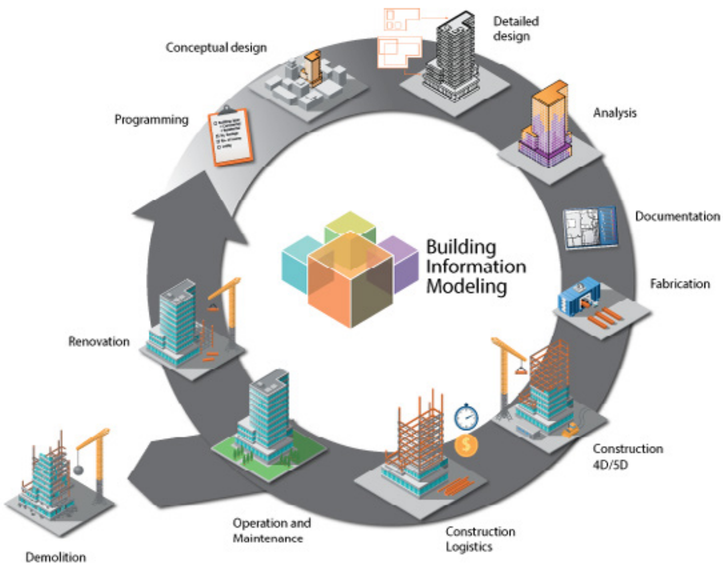


Fig. 6.21. Life cycle of an enterprise in BIM (BIMMDA, 2020).

operating condition on a regularly schedule. More recently, the advance in technology made the development of another maintenance category called predictive maintenance (Yam et al., 2001). This approach detects the system degradation and conduce maintenance on the actual condition of the facility (Bortolini et al., 2016). The BIM model (Fig. 6.22) used in the construction of a building must be refined after the construction of the building, so that the BIM can be fully integrated into the building management systems.

6.3.2. Building Management System (BMS)

Building management system has been introduced to this world in 1970, initially it was started with very limited features but within time a lot of changes and modifications had been made, starting with the controlling of power and lightening to heating and cooling of a building together with the alarm system as a further modification in order to provide maximum security. The main purpose of a BMS is to increase people's comfort by maintaining the building in the desired state every time and reduce energy consumption by avoiding situations in which elements are being overused. For instance, by predicting the time of entrance of a person in a room, it is possible to adjust the temperature in advance, or by detecting that a room is empty, lights can be turned off if they have been left on by mistake. The building management system (BMS) is an overarching control system that

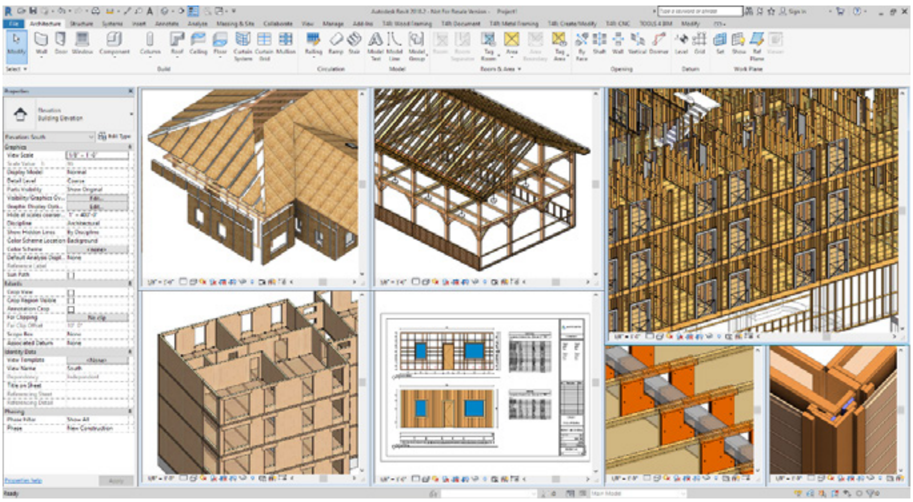


Fig. 6.22. Wood constructions in BIM (Agacad, 2020).

is responsible for the automatic regulation and control of non-GMP facility subsystems maintaining predefined parameters (or set points) and the control of their functionality. The major aim of the BMS is to guarantee the safety of facility operation, while also monitoring and optimizing the use and efficiency of its supervised subsystems to allow more efficient operation.

Examples of the major subsystems controlled by the BMS are (Joseph, 2018):

- HVAC System. The duct temperature, pressure, and humidity, as well as exhaust temperature are connected to the BMS, and if their value exceeds defined limits, an alarm is generated.
- Central fume collection, laminar flow units, dust collection system, central vacuum system, heat blowers. The BMS monitors the performance of these systems allowing for early identification of units requiring maintenance.
- Technical steam system. Should, for instance, the pressure or temperature in the piping system fall below the defined regulatory values for clean steam, the BMS shall trigger an alarm, indicating a threat to product quality.
- Hot water system and central heating. Temperature and pump control monitoring via the BMS allows for a proper functioning of hot water distribution through the facility.
- Chilled water system. Control of the facility chillers could be supervised by BMS to monitor proper behaviour of the system in terms of water / coolant temperature control or pump control to assure proper distribution within the distribution loop.
- Sprinkler system (for fire safety).
- Electrical monitoring system. The BMS may monitor the consumed electrical power and the state of main electrical switches.

Figures 6.23 and 6.24 show the main components of BMS systems. The principle of the BMS system's main unit is to connect all components in one field device, compound all parameters in database and check the data quality for air, temperature, and humidity inside the building. Building management systems (BMS) and facilities management systems (FMS) can work together to use the Internet / Intranet – web-based access (including database integration) and the integration of BMS and FMS. These should be addressed for accessing BMS remotely via Internet, integrating control networks using the Internet protocols and infrastructures, and using Internet / Intranet for building facilities management (Wang & Xie, 2002).

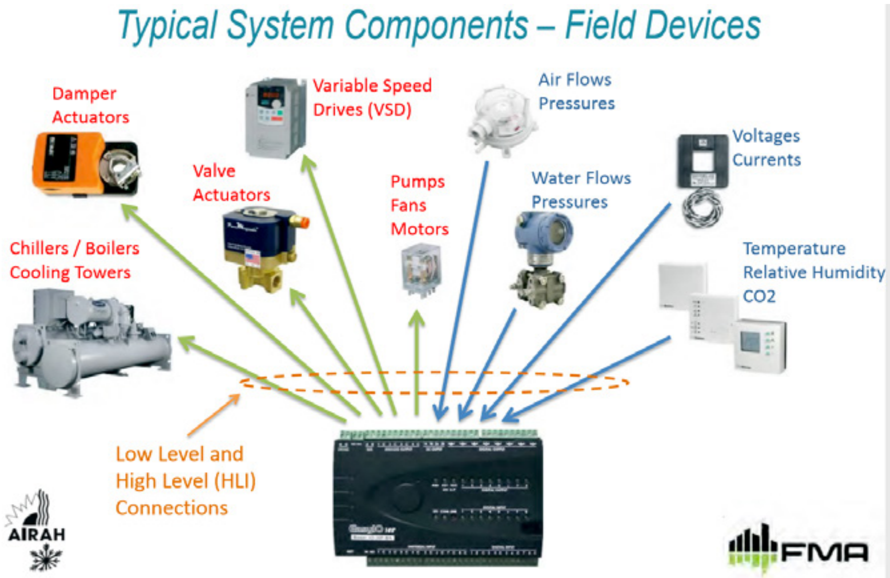


Fig. 6.23. BMS system's components – field device example (City of Melbourne, 2020).

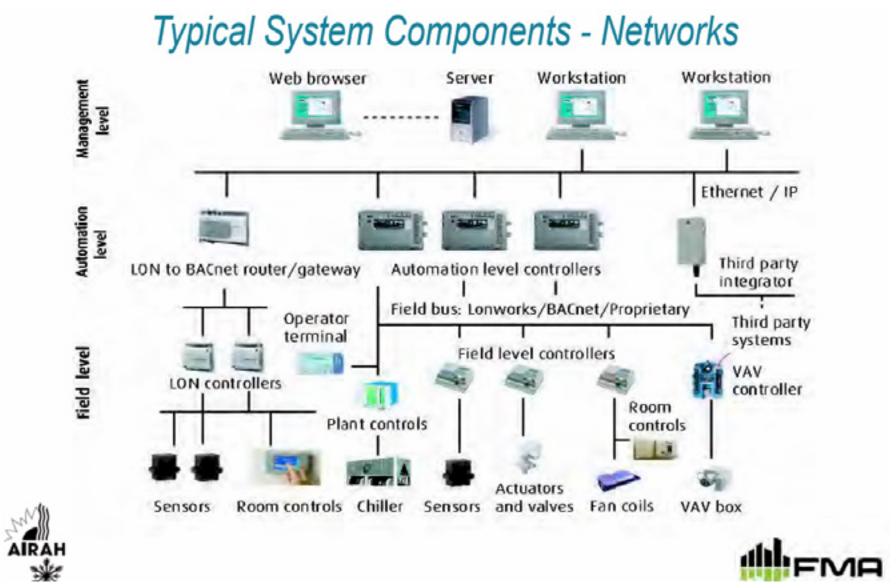


Fig. 6.24. BMS system's components – network example (City of Melbourne, 2020).

How to use BMS systems for public wood buildings?

The main components for controlling the public wooden buildings are temperature, air conditions and humidity. All these components are working together. If a building does not have good ventilation, the humidity will go up and wooden construction will start the process of spoil. If the temperature goes up, the humidity will go down and again wooden construction will start the process of spoil. Wooden buildings need to maintain water and air combination in long term. Wooden construction features have very high fire hazard possibilities in low temperature of the fire. There are several ways to protect wooden surfaces against fire, and using fire retardant products is one of them. Wooden panels and boards treated with fire retardant products are used in residential buildings, nursery homes, schools and other public buildings which are typically occupied by many people simultaneously (Tikkurila, 2020).

All previous building components are possible to control using simple or complicated BMS systems to connect sensors.

6.3.3. GIS Systems as Building Management System

Geographic information system (GIS) technology manages infrastructure both outside and inside of buildings to provide full operational awareness. It is used to optimize existing space, move staff efficiently and map asset conditions. Throughout the facility life cycle, GIS supports you in your mission, from site selection to space planning and maintenance, lease management and usage, safety issues, and continuity planning. GIS gives organizations a look at their facilities across all scales using the same data and software, allowing them to analyse dependencies, decrease costs, make better decisions, and improve performance management. GIS is a robust information system that supports a diverse set of analytic capabilities, workflows, and applications. Figure 6.25 describes the main feature elements of GIS.

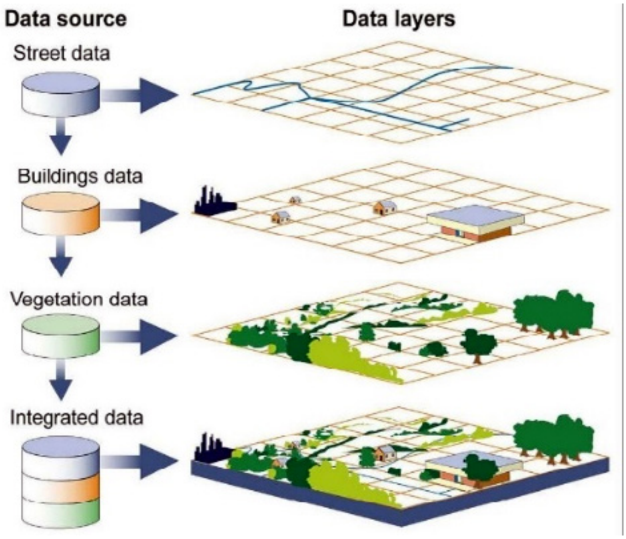


Fig. 6.25. GIS features (National Geographic, 2017).

3D GIS for building management

3D GIS is adding a third dimension by adding height (coordinate z) to two dimensional (coordinates x and y) creating a 3D plane or feature. It is inherited strongly from the 2D (two dimensional) GIS, yet it has its own unique characteristics. It includes terrain visualization, cityscape modeling or virtual reality and analysis of complex spatial data. The main components of 3D GIS are: 3D data capture, 3D visualization and 3D modeling and management (Al-Ansari et al., 2014). Figure 6.28 visualizes the building's volume from 3D GIS systems. 3D GIS system gives possibilities to integrate and show the results from BIM, reality view and maintenance databases in one platform.

BIM and GIS integration

GIS data is one of the ways to connect the maintenance object in the building with maintenance data results.

BIM and GIS integration are the process of blending the BIM model into layers of the geospatial context. Designers can use GIS to get the most accurate information about some areas where construction is to take place. If the area is prone to flooding, designers will learn about it and influence a structure's construction materials, orientation, location, etc. (Andrews, 2019; Bortolini et al., 2016).

BIM data is closely tied to designing and constructing a specific object, structure, or shape. By combining the two, you get the capability to build any structure at an object level.

GIS adding makes the entire picture bigger by adding a smarter and larger environment context, meaning that the object will become a part of the roads, utilities, and land in that environment (Zhang et al., 2009).

Although the main functionality of both BIM and GIS is to create digital representation of the real world, they are different in many ways. They have been developed as solutions to different problems in different domains: the former optimized for the modelling of new, but well-defined objects; the latter for the re-construction of existing objects about which only sparse and incomplete information is available. In comparison, BIM is used at a relatively micro level of the real world, e.g. buildings, and handles mainly 'indoor' data. GIS, on the other hand, is used at a macro level of the real world, e.g. terrain, river, land parcels, and focuses on 'outdoor' data. Therefore, GIS uses geographic coordinate systems and world map projections, while BIM coordinates are relative to the object being modelled and are not usually relative to any place on earth (Zhang et al., 2009).

Traditionally the information in a GIS is paired with two dimensional points, lines and polygons, while in BIM the objects are linked to three dimensional solids and surfaces.

Information about many factors that are related with building asset management has to be brought into consideration to support activities in the process. The factors are not only coming from economic perspective but also social and environmental perspectives. The modelling of these complex systems goes beyond the drawing part of the problem into the simulation, budgeting, environmental impact analysis and decision support. This makes a strong case for a tighter integration of GIS and BIM in a full three-dimensional environment (Zhang et al., 2009).

Integrating GIS and BIM data allows design and construction companies to collect accurate and valuable data that will lead to much more effective and efficient design and project management (Victor, 2020). Figures 6.26 and 6.27

show main integration parts between BIM and GIS. We can migrate BIM features to GIS features and store existing building models and attributes data. GIS systems visualize BIM data together with other spatial layers and give maintenance analysis possibilities to connect attributed data from the building maintenance works.

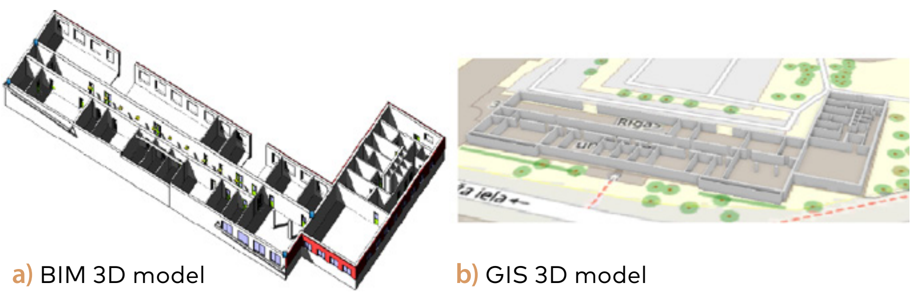
GIS and BIM advantages:

- 3D spatial model;
- attribute data;
- analysis of possibilities;
- dynamical data.

GIS and BIM disadvantages:

- problems related to big data;
- BIM models are very complicated.

Fig. 6.26. BIM-GIS integration (Victor, 2020).



a) BIM 3D model

b) GIS 3D model

Fig. 6.27. BIM and GIS integration example (developed by authors).

6.3.4. Data Management Systems for Buildings

The database system of building management process is one of the ways to store information and data obtained during the implementation of the maintenance plan.

A lot of the data are obtained in building maintenance processes:

- annual building surveys;
- various repair and maintenance works;
- service works;
- other works.

Relational database management systems are used mostly for data collection. A relational database management system (RDBMS or just RDB) is a common type of database whose data is stored in tables. The most used databases in businesses these days are relational databases, as opposed to a flat file or hierarchical database (Bakuya, 1997).

A Relational Database Management System (RDBMS) is a database management system based on the relational model introduced by E. F. Codd. In relational model, data is stored in relations (tables) and is represented in a form of tuples (rows).

RDBMS is used to manage a relational database. Relational database is a collection of organized set of tables related to each other from which data can be accessed easily. Relational database is the most used database these days. Relational database model – a table, is a collection of data elements organized in terms of rows and columns. A table is also considered as a convenient representation of relations. But a table can have duplicate rows of data, while a true relation cannot have duplicate data. Table is the simplest form of data storage.

Benefits of relational databases:

- Manageability: an RDB is easy to manipulate; each table of data can be updated without disrupting others.
- Flexibility: if you need to update your data, you only must do it once – so no more having to change multiple files one at a time.
- Avoid errors: there is no room for mistakes in a relational database because it is easy to check for mistakes against the data in other parts of the records.

The most popular database management systems are SQL database systems. SQL (pronounced 'ess-que-el') stands for structured query language. SQL is used to communicate with a database. According to ANSI (American National Standards Institute), it is the standard language for relational database management systems. SQL statements are used to perform tasks such as update data on a database or retrieve data from a database. Some common relational database management systems that use SQL are: Oracle, Sybase, Microsoft SQL Server, Access, Ingres, etc. Although most database systems use SQL, most of them also have their own additional proprietary extensions that are usually only used on their system. However, the standard SQL commands such as 'Select', 'Insert', 'Update', 'Delete', 'Create', and 'Drop' can be used to accomplish almost everything that one needs to do with a database. Figure 6.28 shows the main working principle of the database management system (Sisense, 2020).

Figure 6.29 reflects the database management system.

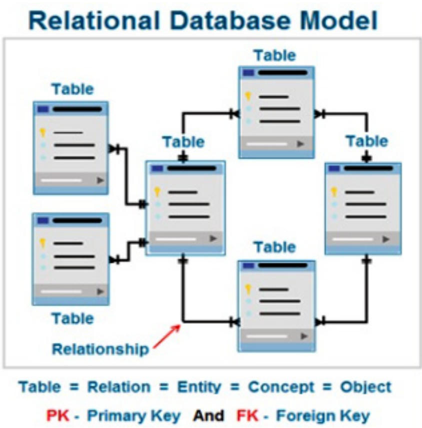


Fig. 6.28. Principle of the relational database model (Learn Computer Science, 2020).

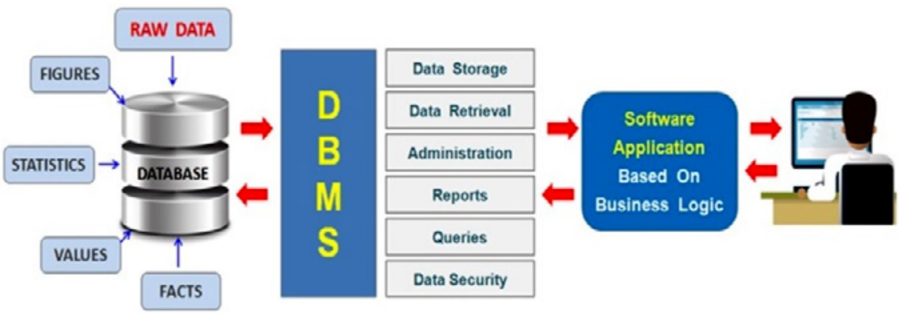


Fig. 6.29. DBMS database management system (Learn Computer Science, 2020).

Content of the database for management purposes

The main tasks of database management are:

- capture data (raw data);
- store data;
- analyse data;
- show results;
- premature decisions.

Figure 6.30 shows the principal schema from data capture to show results.

Databases include all types of data: textual, numerical, file storage, GIS data, BIM data. It is not possible to store all these data in a traditional relational database system or GIS system because we are discussing big data formats. For example, raw data have various file formats: point clouds, image data, pdf files and others. The task of the database is to store the main parameters or results and show the reports on the real situation in building maintenance periods. At the same time database stores evidence of building maintenance events and links to raw data. Cloud storages and SQL servers are very good tools for

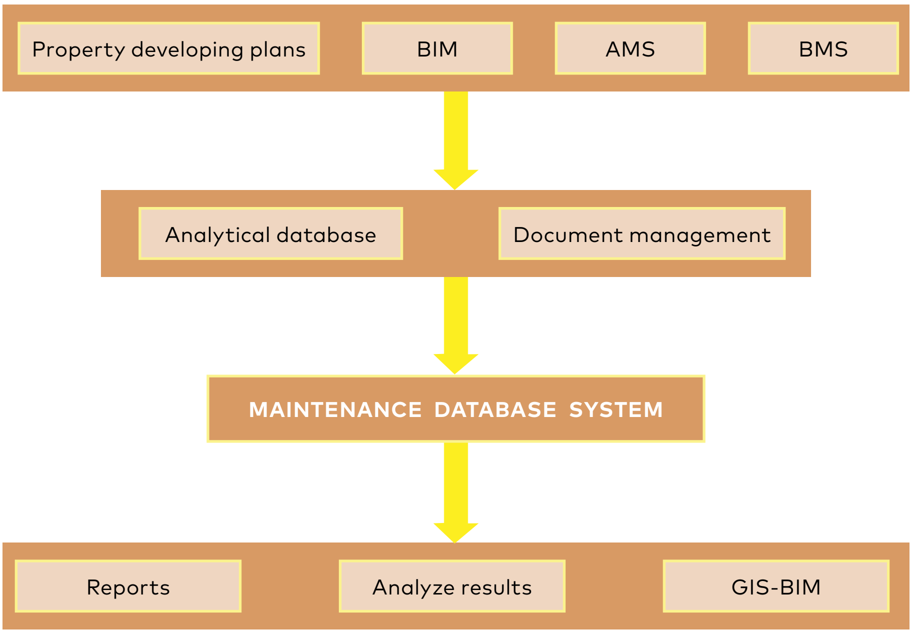


Fig. 6.30. Maintenance database system's principal schema (developed by the authors).

raw data storage. Practically, discussion is about building maintenance system database which includes the results from maintenance works, BMS systems, BIM systems, asset management systems (AMS) and property developing plans (Fig. 6.30).

Conclusion

There are many different types of data storage – from file management systems to high-level SQL systems. In building management, it is important that all events that take place in a building are recorded to track the important stages of building maintenance that are determined by building maintenance processes. The chapter covered – BIM, BMS, GIS and DBMS, which are more widely used platforms to store data from sensors, information from building design solutions and results from building monitoring and their interaction in determining the tasks required for building maintenance.

6.4. MAINTENANCE MANAGEMENT PLAN

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Building maintenance policy is a written document that provides a management framework to the maintenance personnel to determine appropriate maintenance strategy and standard. Building maintenance policy and strategy is one of the main aspects in management of building maintenance operation processes (Lee & Scott, 2009).

Maintenance policy is a tool for maintenance personnel to plan their appropriate maintenance strategies (Donnelly, 2007; Shen, 1997; Al-Zubaidi, 1997). However, before a maintenance plan is prepared, maintenance personnel and top management are required to agree on maintenance policy because it requires strategic directions as well as resources. The maintenance policy consists of five major components and different maintenance strategies which are developed from these components. Without defining this policy, maintenance operation processes will be in a random order. The five major components (RICS, 1990; Chanter & Swallow, 2008) are as follows:

- the length of time for maintaining their present use;
- the life requirements of the buildings and their fittings and services;
- the standard to which the building and its services are to be maintained;
- the reaction time required between a defect occurring and a repair being carried out;
- the legal and statutory requirements shall also be considered.

Maintenance plan is one part of the life cycle which describes how to manage the building. Maintenance plan is different for simple buildings, but it includes three main parts:

- maintenance procedure manuals;
- inspection methods;
- maintenance period.

Figure 6.31 reflects the framework of maintenance plan.

Development of maintenance management plans

While developing the maintenance management plan, experts analyse and determine the type of the public building: museum, office, theatre or other. Maintenance management plan is different for such types of buildings, and it is dependent from the number of visitors.

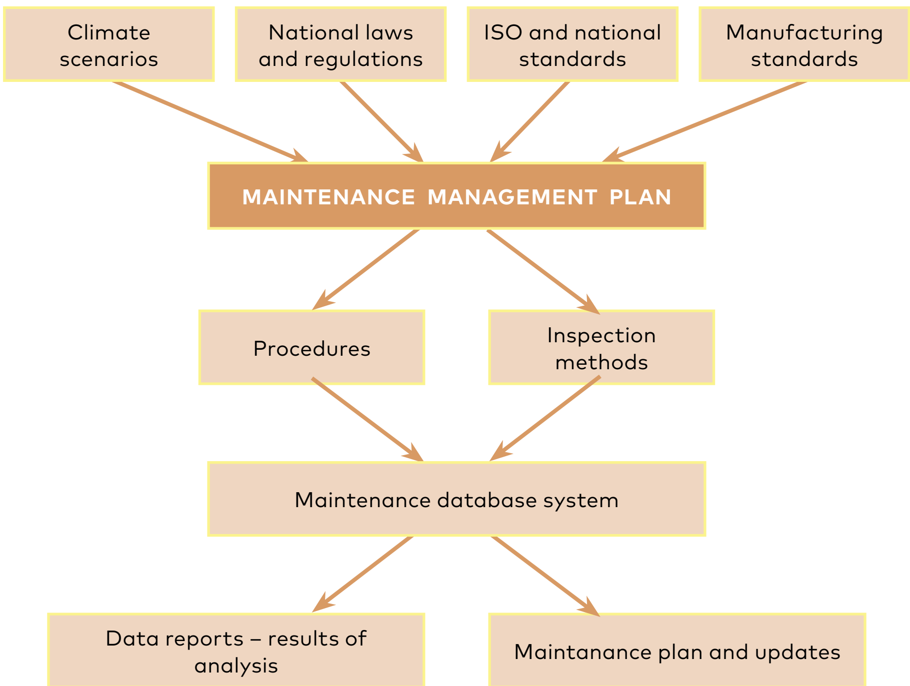

Fig. 6.31. Framework of maintenance plan (developed by authors).

Maintenance workflow

Regular inspection and unplanned control are necessary to assess the condition of a building and report any problems, and decide whether repair or other work is necessary.

There are specific regular tasks, like cleaning of the gutters, to ensure long term service of the building as well as minor repairs, like replacement of broken glass or tile to avoid larger scale damages.

Maintenance differs from repair, which is working to return a building to a good condition on a long-term basis.

Planned and regular maintenance actions must be documented in the maintenance plan. The maintenance plan shall identify each element of the building, like roofs, foundations, walls, etc., demanded maintenance tasks and the frequency. Frequency may depend on the condition of the identified building element and could be:

- **occasional** (after a storm or specifical reasons);
- **regular** (for tasks carried out at least once a year);
- **cyclical** (for tasks carried out less than once a year).

Results and findings of all inspections and tests as well as all maintenance works and materials used must be recorded in Maintenance Log. Experts must enter all results in the building management database system and check deviations from government laws and standards which are related to the procedures for the maintenance of the building. There are also specific standards for wooden buildings to save and exploit wood like eco material.

Content of maintenance procedure manuals for building management

The Maintenance Procedure Manual should stipulate the following (Shen, 1997; Rovers et al., 2018):

- Responsibility of qualified inspection agencies, which are hired by facility owners or authorized persons and which implement inspection to diagnose the results of inspection. The diagnosis should be made for each structure and facility. Qualified inspection agencies should record the information on facility selection, inspection items, inspection methods, inspection results and diagnosis into check sheets or database systems.

- Responsibility of facility owners or authorized persons to preserve maintenance records, including the check sheets, during maintenance periods.
- Responsibility of facility owners and authorized persons to hire qualified agencies and implement detailed surveys to formulate repair work plans when serious defects or deterioration such as degradation in function and capacity is detected.
- Inspection of building construction elements is one of the most important parts for understanding and managing the life cycle of buildings.

Maintenance Procedure Manual must include the principle how and when to adjust reports to wood manufacturing standards and government standards. We must understand what we need to check from time to time and how to fix it, if necessary.

Types of inspection

There are several types of inspection: routine inspection, periodic inspection, and unscheduled inspection, which also includes detailed surveys and monitoring of facilities. Framework of the inspection is briefly described below (Heritage Building Maintenance Manual, 2008).

a. Routine inspection

Routine inspection is a daily inspection to quickly find out any unusual incidents and defects of the building facilities. It generally consists of visual inspections while walking in and around building facilities.

b. Periodic inspection

Periodic inspection is applied in the following cases: to survey damages including deterioration and defects; to diagnose deterioration and defects; to select the suitable repair methods for light damages and deteriorations.

Also, it should make judgment on the need of a further survey on the heavy damages and deterioration. With this, it is carried out at a fixed interval. The periodic inspection provides base information for the planning of maintenance and repair works.

c. Unscheduled inspection

Unscheduled inspection is applied in the following cases: to survey and evaluate the effects of unexpected incidents occurring, such as floods, strong wind, fires, and other natural disasters which have impact on building facilities.

d. Detailed survey

Survey and design are applied in the following cases:

- to further specify causes of structural defects and damages;
- to find out the most suitable repair works for the damages;
- to evaluate the performance of repair works;
- to survey unidentified incidents arising after repair works and the final inspection;
- to ensure structural safety when facilities are to be used with greater loading conditions than the design conditions;
- to evaluate structural safety when facilities are to be used more frequently than design periods.

Inspection methods

Inspection methods can be selected from the list below. However, it should be noted that design consultants can change inspection methods with explanation, taking in account the scales of building facilities (Lee & Scott, 2009):

- visual inspection;
- operation tests;
- check of embedded pressure gauge;
- check by tapping with a test hammer;
- check by touching;
- check with crack scales;
- check with dossiers of drawings and measurement with steel tapes, etc.;
- check with plummet;
- non-destructive equipment, etc.;
- interlocking function test;
- measurement with a voltmeter;
- measurement with steel tapes, 3D laser scanner, drones, etc.;
- visual inspection and check by touching;
- visual inspection with binoculars, etc., as needed.

The inspection methods can be updated periodically and connected to maintenance plan and procedures. It is recommended that the inspection procedures of construction elements include visual and geometrical methods.

Maintenance tasks are very closely connected with climate scenarios in the region. Climate scenarios are dependent from country and geographical deployment. For example, climate scenarios close to the sea have wind periods in location place.

Occasional and regular tasks including 10 main parts:

- area – foliage and large trees close to walls, slope;
- basement – water leakage, air circulation and exchange;
- rainwater disposal – rainwater goods generally, rainwater goods, below ground drainage;
- external walls – external walls generally, external walls, copings and parapets, ventilation, bird screens, window flashings;
- doors – bird screens, window flashings;
- internal structure – internal spaces generally, internal structure and fabric, exposed woodwork, roof and floor voids, wood constructions;
- attic – attic general, ventilation;
- roof coverings – roof areas generally, connections and parapets, slate and tile roofs, sheet metal roofs and cladding, cleaning of the dirt, nails, amount of the snow;
- building services – lightning protection installation, firefighting equipment, burglar alarm system, emergency notification system, sewer system and water supply, outdoor watering system, heating system general, heating system, stoves.

Tables 6.3, 6.4 and 6.5 show the list of main maintenance tasks and frequencies. These maintenance tasks are divided in groups by building elements. Building element groups include indoor elements and environmental objects. Maintenance tasks include general work description. These works can be done by visual and technical inspection methods. Table 6.4 and 6.5 include the periods and periodical frequencies. The building maintenance plan must include regular update of the tasks, periods, and frequencies.

Table 6.3
Maintenance Tasks (developed by authors from the Department for Environment Food & Rural Affairs (2020), JICA Project Team (2020))

Ref	Building element	Maintenance task
1.	**Area**	
1.1.	Foliage and large trees close to walls	Check and report any dead branches and signs of ill health or root damage to the building or below ground drainage.
1.2.	Slope	Check and report the slope of the ground around the building for water flowing off walls.
2.	**Basement**	
2.1.	Water leakage	Check the basement for moisture or leakage.
2.2.	Air circulation and exchange	Check the basement for sufficient air circulation.
		Provide ventilation of cellars by opening ventilation hatches in spring and close the hatches before winter.
3.	**Rainwater disposal**	
3.1.	Rainwater goods generally	Inspect rainwater goods from the ground and accessible high points and report any loss or damage.
3.2.	Rainwater goods I	Clear rainwater goods of debris and ensure that overflows are clear. Rod if necessary. Check that stainless steel guards are secure.
3.4.	Perimeter drainage channel	Clear drainage channel from vegetation and debris.
3.5.	Perimeter drainage channel	Inspect drainage channel for cracks and open joints. Seal with appropriate sealant.
3.6.	Below ground drainage	Open up inspection chambers. Check that all gullies and gratings are free from silt and debris and that water discharges freely to the main sewerage or soakaway.
4.	**External walls**	
4.1.	External walls generally	Inspect external walls from the ground and accessible high points and report any damage, cracks and signs of movement.
4.2.	External walls, copings and parapets	Remove any vegetation, ivy, etc.
4.3.	Ventilation	Ensure that ventilation grilles, air bricks, louvres, etc. are free from obstruction.

Ref	Building element	Maintenance task
4.4.	Bird screens	Check that tower, roofs and windows are bird-proof before nesting starts. Do not disturb bats.
4.5.	Window flashings	Check for leakage and, if necessary, make minor repairs.
5.	**Windows**	
5.1.	Functionality	Check operation of hinges, bolts and locks and lubricate as necessary. Check security of locks.
5.2.	Window glazing	Inspect windows and make essential minor repairs to glazing.
5.3.	Conditions of the frames	Check the wooden frames for signs of moisture damage, insect infestation and / or rot, cracks and opened joints.
5.4.	Painting of frames	Check the paint of the window frames and repaint if necessary.
5.5.	Glazing sealants	Check the glazing sealants for damages (cracks and loses) and make essential minor repairs.
5.6.	Metal furnishing	Check for missing fastenings, parts and any signs of rust. Make essential minor repairs.
5.7.	Leaded light windows	Inspect lead frames, putty, glass and wire ties and report any problems. Clear condensation drainage channels and holes.
6.	**Doors**	
6.1.	Functionality	Check operation of hinges, bolts and locks and lubricate as necessary. Check security of locks.
6.2.	Paint / Varnish	Check the paint / varnish of wooden parts and repaint if necessary.
6.3.	Conditions of the frames and sashes	Check the wooden parts for signs of moisture damage, insect infestation and / or rot, cracks and opened joints.
6.4.	Metal furnishing	Check for missing fastenings, parts and any signs of rust. Make essential minor repairs.
7.	**Internal structure**	
7.1.	Internal spaces generally	Inspect roof voids and internal spaces, particularly below gutters. Report on any evidence of roof or gutter leaks.
7.2.	Internal structure and fabric	Inspect internal structure and fabric, including roof timbers and bell frames, and report on any signs of structural movement or damp, fungal growth and dry rot.

Ref	Building element	Maintenance task
7.3.	Exposed woodwork	Inspect exposed woodwork and surfaces below for signs of active beetle infestation. Report any beetles or fresh wood dust.
7.4.	Roof and floor voids	Check roof and floor voids, inspect for signs of vermin and remove. Avoid using poison when bats are roosting.
7.5.	Internal spaces generally	Ventilate the building.
8.	**Attic**	
8.1.	Attic general	Check the attic and roof ventilation, check for condensation.
8.2.	Ventilation	Provide ventilation of the attic.
8.3.	Wood constructions I	Check the wood construction for signs of moisture damage, insect infestation and / or rot.
8.4.	Wood constructions II	Check the wood construction for cracks, opened joints or pins for pull-out.
9.	**Roof coverings**	
9.1.	Roof areas generally	Inspect roof areas from the ground and accessible high points and report any loss or damage to the roof coverings.
9.2.	Connections and parapets	Check roof joints and chimney connections for damage.
9.3.	Slate and tile roofs	Inspect for cracked, displaced and broken slates and tiles. Replace to match.
9.4.	Sheet metal roofs and cladding	Inspect condition of panels, joints and clips. Make temporary repairs to cracks and splits.
9.5.	Cleaning of the dirt	Cleaning dirt, moss leaves, vegetative matter and mildew.
9.6.	Nails	Checking the nails that attach the shingles to the roof for corrosion and pullout.
9.7.	Amount of snow	Clean the roofs from snow.
10.	**Building Services**	
10.1.	Lightning protection installation	Visually inspect the lightning conductor system, including spikes, tapes, earth rods and all connections and fastenings.
10.2.	Fire-fighting equipment	Service fire extinguishers.
10.3.	Burglar alarm system	Test the system and visually inspect wiring. Qualified engineer to service alarm.
10.4.	Emergency notification system	Test functionality of the system.

Ref	Building element	Maintenance task
10.5.	Sewer system and water supply	Ensure that all exposed water tanks, water pipes and sewer system are protected against frost.
10.6.	Sewer system and water supply	Check that water tanks, pipes and radiators do not flow.
10.7.	Sewer system and water supply	Check for leakage in the sewer system for cleaning of inspection holes.
10.8.	Outdoor watering system	Check if outdoor watering systems are switched off.
10.9.	Heating system general	Service the heating system and update the service schedule.
10.10.	Heating system	Ensure that all heating pipes are protected against frost.
10.11.	Chimneys	Clean the chimneys.
10.12.	Stoves	Check the condition of heating stoves, stoves and chimneys for cracks with soot.
10.13.	Temperature and humidity	Record temperature and humidity in different parts of building.

Table 6.4
Frequency of Maintenance Tasks by Month (developed by authors)

Ref	Building element	Frequency	J	F	M	A	M	J	J	A	S	O	N	D
1.	**Area**													
1.1.	Foliage and large trees close to walls	Annually					x							
1.2.	Slope	Annually			x									
2.	**Basement**													
2.1.	Water leakage	I After stormy weather												
		II Twice per year			x							x		
2.2.	Air circulation and exchange	I Annually							x					
		II Twice per year			x						x			
3.	**Rainwater disposal**													
3.1.	Rainwater goods generally	I during / after stormy weather			x									
		II Annually												
3.2.	Rainwater goods I	Twice per year					x						x	
3.3.	Rainwater goods II	Twice per year					x						x	
3.4.	Perimeter drainage channel	Monthly, spring and summer				x	x	x	x	x	x			
3.5.	Perimeter drainage channel	Twice per year					x						x	
3.6.	Below ground drainage	Twice per year					x						x	
4.	**External walls**													
4.1.	External walls generally	I After stormy weather			x									
		II Annually												
4.2.	External walls, copings, and parapets	Annually											x	
4.3.	Ventilation	Twice per year			x						x			
4.4.	Bird screens	Annually			x									
4.5.	Window flashings	Annually								x				
5.	**Windows**													
5.1.	Functionality	Twice per year			x						x			

Ref	Building element	Frequency	J	F	M	A	M	J	J	A	S	O	N	D
5.2.	Window glazing	Twice per year				x							x	
5.3.	Conditions of the frames	Annually								x				
5.4.	Painting of frames	Once per year				x								
5.5.	Glazing sealants	Once per year				x								
5.6.	Metal furnishing	Annually				x								
5.7.	Leaded light windows	Annually				x								
6.	Doors													
6.1.	Functionality	Twice per year				x					x			
6.2.	Paint / varnish	Once per year									x			
6.3.	Conditions of the frames and sashes	Annually								x				
6.4.	Metal furnishing	Annually				x								
7.	**Internal structure**													
7.1.	Internal spaces generally	I During / after stormy weather					x							
		II Annually												
7.2.	Internal structure and fabric	Annually					x							
7.3.	Exposed woodwork	Annually					x							
7.4.	Roof and floor voids	Annually					x				x			
7.5.	Internal spaces generally	Monthly on dry days					x	x	x	x	x			
8.	**Attic**													
8.1.	Attic general	Twice per year			x							x		
8.2.	Ventilation	Monthly on dry days												
8.3.	Wood constructions I	Annually								x				
8.4.	Wood constructions II	Annually								x				
9.	**Roof coverings**													
9.1.	Roof areas generally	I After stormy weather												
		II Annually			x									

Ref	Building element	Frequency	J	F	M	A	M	J	J	A	S	O	N	D
9.2.	Connections and parapets	I After stormy weather												
		II Annually												
9.3.	Slate and tile roofs	I After stormy weather												
		II twice per year			x								x	
9.4.	Sheet metal roofs and cladding	Twice per year					x						x	
9.5.	Cleaning of the dirt	Annually								x				
9.6.	Nails	Annually								x				
10.	**Building Services**													
10.1.	Lightning protection installation	Annually						x						
10.2.	Fire-fighting equipment	Annually									x			
10.3.	Burglar alarm system	Annually										x		
10.4.	Emergency notification system	Annually					x							
10.5.	Sewer system and water supply	Annually									x			
10.6.	Sewer system and water supply	Annually									x			
10.7.	Sewer system and water supply	Annually									x			
10.8.	Outdoor watering system	Annually									x			
10.9.	Heating system general	Annually					x							
10.10.	Heating system	Annually									x			
10.11.	Chimneys	Annually									x			
10.12.	Stoves	Annually									x			
10.13.	Temperature and humidity	Every day												

Table 6.5
Frequency of Maintenance Tasks (developed by authors)

No.	Building element	Maintenance task	Frequency
1.	Rainwater goods	Repaint	7 years
2.	Timber parts	Repaint	7 years
3.	Doors and window frames	Repaint	7 years
4.	Wiring and electrical installations	Inspect all wiring and electrical installations in accordance with regulations and perform the testing, including all wiring and electrical equipment associated with building and all portable electrical equipment	10 years

Conclusion

Maintenance is a very dynamic process. Maintenance plan must be updated periodically. Periodical updates depend on the lifecycle of the building – renovation process and repairs must be included in maintenance procedures. The whole maintenance process must be reported and analysed. Building maintenance requirements cannot be fixed but are based on the procedures that are based on regulatory requirements, national standards and factory requirements. The procedures need to be regularly reviewed and updated based on survey results. Combining the procedures with the building maintenance database, it is possible to fully trace the physical condition of the building and the stability of the structures. The main tasks of the maintenance are ensuring the safety of people and wooden constructions.

6.5. MAINTENANCE AND REPAIR WORKS

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All elements of a building are subject to deterioration over time. Timber structures can undergo alteration during their service life, which can be caused by mechanical, environmental or biological agents (bacteria, insects and fungi) because of the biological nature of the material (Sandak et al., 2015).

Deterioration due to aging cannot be eliminated, but good design, workmanship and appropriate maintenance can slow the rate of deterioration. Some of the preventive measures, maintenance strategies, repair and replacement works applied in wooden buildings are described in this chapter.

6.5.1. Maintenance

Maintenance needs to be considered at the design stage. When deciding on the quality of elements and fittings that will be specified for a newly designed structure, a designer frequently chooses between items that have relatively high initial costs and low ongoing maintenance requirements and items that are cheaper to purchase but may have more onerous maintenance requirements. In some design briefs, the designer is called upon to devise a maintenance schedule for the completed structure. Table 6.6 gives a list of the items that may need to be considered when drawing up a maintenance schedule (Wood Solutions, n.d.).

Table 6.6
Maintenance and Inspection Periods for Wooden Buildings (adapted from Wood Solutions, n.d.)

Item	Maintenance or inspection period	Remarks
Finishes • internal • external	≈10 to 15 years	
Cleaning	Clean non-confined surfaces as required. Remove build-up of soil against timber near to ground.	Dirt, mould, etc. traps moisture, increases potential for decay.
Cladding • roofing, weatherproofing	≈10-year inspections. Some environments may make inspection of weatherproofing more frequent.	Timber cladding can have design life (5 to 100 years).
Termite protection • physical barriers • chemical barriers	Inspect annually or in accordance with standards. ≈10 years for maintenance of barrier. As required by supplier (≈2 to 20 years).	Any sign of termites / other insects should prompt action.
Ventilation • subfloor, wall, roof	Check that vents are not blocked annually or after any new work. Clean as required in ≈10 years.	Vents are essential to prevent build-up of moisture / condensation.
Vapour barriers • subfloor, roof	Check integrity each ≈15 years or after any new work or other maintenance in the area.	
Metal fasteners • integrity • corrosion	Retighten bolts, screws and repunch nails if required after 6 months and one year if unseasoned timber is used. Check at intervals dependent on type of corrosion protection used. Inject water repellents for bolts.	Replace any suspect fasteners. Hot dipped galvanised fasteners solve many corrosion problems.
Plumbing	Inspect gutters, downpipes, etc. each 10 years. Repair any plumbing if a leak is noticed.	Moisture accelerates decay and deterioration.
Decay	Check at the same time as connections. Repair or replace as soon as any decay is noticed.	
End-grain • sealants / caps	Inspect each 3–5 years. Replenish as required by manufacturer and before repainting.	

All wood is susceptible to decay; however, the rate of deterioration varies depending on the species. Factory applied preservative treatment, as opposed to field applied treatment, provides the most reliable protection. Alkaline copper quat (ACQ), copper azole (CA) and chromated copper arsenate (CCA) type preservatives are suitable for exposed exterior conditions, while borate type preservatives are only suitable for situations protected from continuous exposure to liquid water. Only preservative treated wood that has been incised (small slots created in the sides of the wood so that preservative chemicals can penetrate more deeply) should be used when placed in contact with soil. Field cuts, notches and holes should be treated with preservatives specifically intended for field cuts, as they are formulated to soak into the wood and penetrate well through the end grain (Homeowner Protection Office, n.d.).

Table 6.7 gives guidance on the maintenance of paints and stains for exterior surfaces. There are significant differences in the expected life of the various coating systems, and these can influence the type of coating system selected. Note that clear finishes have a much shorter life than opaque finishes (Wood Solutions, n.d.).

Table 6.7
Maintenance of Paints and Stains for Exterior Surfaces (Wood Solutions, n.d.)

Finish	Appearance of wood	Initial treatment		Maintenance of surface finish		
		Coats	Cost	Procedure	Period	Cost
Paint	Grain and natural colour obscured	Prime and two top coats	Medium to high	Clean and apply top coat or remove and repeat initial treatment if required	7–10 years	Medium
Clear	Grain and natural colour unchanged if adequately maintained	Four coats (minimum)	High	Clean and stain bleached areas and apply two more coats	2 years or when breakdown begins	High
Water repellent	Grain and natural colour – visibility becoming darker and rougher textured	One or two coats of clear material, or preferably dip applied	Low	Clean and apply sufficient material	1–3 years or when preferred	Low to medium
Stains	Grain visible, coloured as desired	One or two brush coats	Low to medium	Clean and apply sufficient material	3–6 years or when preferred	Low to medium
Organic solvents preservatives	Grain visible, coloured as desired	Pressure, steeping, dipping, brushing	Low to medium	Brush down and reapply	2–3 years	Medium
Waterborne preservatives	Grain visible, greenish, fading with age	Pressure	Medium	Brush down to remove surface dirt	None unless stained, painted or varnished	–

Protection against moisture

The key to the durability of timber has already been identified as 'keeping it dry'. Most of the maintenance requirements outlined in Table 6.6 lead to the exclusion of moisture from timber.

Exterior wood elements come in contact with moisture through exposure to rain or ground water. A third possible form of exposure to moisture, ambient exterior humidity, does not cause exposed wood to reach the required high moisture content levels that would allow deterioration to occur.

Whenever possible, it is recommended that exposure to moisture be eliminated or minimized. Many exterior wood elements can be protected from wetting by roofs or metal flashings. Sloping of horizontal wood surfaces for positive drainage and detailing that allows drying are some other ways to limit the time that moisture stays in contact with the wood (Homeowner Protection Office, n.d.).

Exposure to moisture may also be limited by the application of coatings such as paints or stains. However, their use must be carefully considered, as some coatings will also restrict drying of the wood structure in the event that water unintentionally penetrates past the coating at some location. There are almost always breaks in the coating caused by the seasonal expansion and contraction of the wood with changes in humidity levels. If the wood is not coated before assembly, there may also be portions of the structure that have not been reached during coating application, e.g. inaccessible surfaces at connections (Homeowner Protection Office, n.d.). Painting will provide the greatest degree of protection.

Coatings are generally composed of three components: solvent, pigment and binder. The solvent thins the pigment resin mixture to application consistency. Pigment provides the colour and gloss adjustment. The binder, or resin, binds the pigment particles together and adheres the film to a surface, giving the paint durability and adhesion. Coatings are classified according to their binder, typically: alkyd, latex, acrylic, epoxy or urethane. The type of binder plays a large factor in the performance of the coating. However, the type and amount of pigment in a coating will also significantly affect its performance (Homeowner Protection Office, n.d.).

The performance and durability of coatings is dependent on many factors besides the basic paint composition and quality of application. Surface preparation and compatibility between substrate and coating are critical to the durability of the coating (Homeowner Protection Office, n.d.).

There are several factors to consider that can impact a coating recommendation and the final outcome. When determining the appropriate coating and maintenance interval, it is important to look at the wood species / substrate, its expected exposure, and whether it will be used for an interior or exterior application. Based on this starting point, the impact of weathering and biological/physical factors such as UV exposure, humidity, exposure to traffic/human touch or pollutants, and temperature range can be evaluated. Nevertheless, the type of wood and the conditions it will be exposed to in situ are only part of the equation. Coatings must also be properly applied (Bos, 2018).

In factory settings, undercoats and topcoats can be applied under exacting conditions with temperature and humidity controls, and an easier ability to ensure sufficient product is applied to achieve the desired coating thickness. Increasingly, mass timber manufacturers are applying all coats in the factory and delivering the product prefinished for on-site installation (Bos, 2018).

Sometimes, only the undercoat (or primer) will be applied in the factory with subsequent topcoats applied on-site. Selecting the right undercoat to apply to all six sides of a CLT or glulam piece is critical to garner all the benefits of protection and ensure the successful, subsequent topcoat application. Absorption of the undercoat enhances the stability of wood components and increases topcoat performance, so it is imperative that the undercoat allows subsequent topcoats to sink in and penetrate the wood for optimal performance. An effective undercoat also protects the pieces from moisture intrusion in transit and during construction, especially on the all-important end grain. It also helps control finish clarity, colour, and grain definition while offering deep wood protection against UV damage and moisture (Bos, 2018).

Sometimes the design intent is to keep the wood as natural as possible; other times there is a desire to play with colour to make designs come alive. When comparing coatings such as natural, translucent, or opaque, the tint load is an important consideration. With lighter-toned woods, where a natural look is desired, it is often necessary to fine-tune transparency. In general, the stronger the colour system, the greater the UV blockage (Bos, 2018).

According to Bos (2018), designers should take the following things into consideration when selecting a coating product: environmental performance, ability to penetrate wood, ultra-low VOC profile, ability to customize tone, overall performance, and ease of maintenance. Increasingly, specifications also need to consider regulations surrounding fire retardancy.

Protection against insects

Wood-damaging insects are insects that damage wood by tunneling through it to live, nest, or feed. There are a number of insects that cause damage to wood, among the most dangerous are termites (Fig. 6.32).

During construction and maintenance phases the importance of protecting timber buildings or elements against pest infestation should not be underestimated. When used correctly, preservatives offer professional and reliable timber protection, thus helping avoid the potential complications and costs connected with repairing infested timber in future. After all, painting, spraying or dipping is often used (Bochemit, 2020).

Fig. 6.32. Destruction of wood by termites (DC Scientific Pest Control, n.d.).

Protection against fungi

Wood becomes susceptible to fungal infestation under specific environmental conditions, i.e. moisture content above 20 %, oxygen availability and a temperature between 15 and 45 °C. Fungal deterioration affects then mainly outdoor wooden structures, reducing wood mechanical and aesthetical properties, and significantly limits its service life (Zabel & Morrell, 2012).

A broad range of effective synthetic wood preservatives has been applied to prevent this, including copper-based agents (i.e. chromated copper arsenate), triazoles (azaconazole, propiconazole, tebuconazole), pentachlorophenol or boron-based fungicides. Due to environmental and health concerns, however, many of them have been banned from the use, creating the need for developing alternative wood protection agents and methods based on non-toxic natural products (Broda, 2020).

Nowadays, environmentally-friendly wood protection is an object of extensive research. Exposure to fungal spores that develop into fungi cannot be avoided, as the spores are found everywhere. These spores will germinate and grow if the following four requirements are present (Homeowner Protection Office, n.d.):

- oxygen;
- mild temperatures;
- moisture;
- suitable food (the wood).

For exposed wood structures, control over oxygen and temperature is not possible. However, control over the other two requirements is possible. Eliminating either one of these requirements will eliminate the potential for fungal growth and decay (Homeowner Protection Office, n.d.).

Since the growth of wood-degrading fungi depends on water availability, one of the methods is moisture control using natural hydrophobising agents, such as resins and waxes of plant or animal origin, or plant oils (González-Laredo et al., 2015; Broda, 2020). Another approach for extending the service life of wood is the utilisation of natural compounds with biocidal properties and fixing them inside the wood structure (González-Laredo et al., 2015; Broda, 2020). The more innovative method involves using biological control agents, i.e. microorganisms such as other fungi and bacteria which act as antagonists to wood-decaying fungi (González-Laredo et al., 2015; Broda, 2020).

6.5.2. Repair and Replacement

Building owners, maintenance personnel and employees are often in a position to notice certain conditions that can lead to timber repairs. Cracks in ceiling or wall materials, sagging ceilings or floors, and loose ceiling tiles or panels that show enlarged gaps can all be early signs of distress. There are many conditions that can result in the need for the evaluation of a structure (Western Wood Structures, 2020):

- As older structures change ownership or building usage, remodelling can increase loads to the structure which can require upgrading. These loads may result from multiple layers of roofing, roof over-builds, installation of additional mechanical equipment such as HVAC units, suspended ceilings, and attic storage.
- Over time, structural timber elements may experience decay which ultimately requires repair. This can occur due to a penetration of the roof or walls that creates water leaks, or from improper ventilation of an area with increased moisture, including swimming pools or steam-emitting machinery.
- Forklift impacts to wood structural members which can occur in timber structures used as warehouses.
- Deficiencies in the original design.
- Improper connection details to wood structural members.
- Isolated weather events that exceed loading capacity, including ice or rain on top of a snow load, or clogged roof drains that allow water to pond on the roof.
- Repairing failed structural timbers is, of course, not a new practice. For centuries repairs have been fashioned using carpentry methods or with blacksmith-made splints, brackets and ties (Russell, 2020).

In more recent times modern materials were utilised, such as steel, epoxy resins, carbon fibre rods and wire rope, to reinforce structures. Building repairs can also be affected by completely replacing timbers with new timber or, where used appropriately and sympathetically, materials such as steel or reinforced concrete. It may also be possible to reduce the loads through the design of secondary structures and in-fills such as brick panels, or packing-up under partly decayed timbers (Russell, 2020).

The form of repair largely depends on the situation. Although there is no right or wrong method, there is always a solution that is most appropriate to the circumstances presented by the building. In choosing the right approach and repair mechanism one must take all the evidence into account, including the type of failure that has been observed and, by deduction, the reason for it. Often these observations, decisions and design solutions are the realm of specific professional consultants, such as structural engineers or building surveyors (Russell, 2020).

The repair services may include (Russell, 2020):

- replacement of broken members;
- strengthening or stiffening of existing members;
- installing shear dowels in failed structures;
- post tensioning beams and timber trusses.

The complete removal and replacement of a failed timber member should be the last solution. Where the structure is concealed (as in a wall or roof space), a new member can be inserted beside the old one, or the old member can be patched with timber or strengthened by attaching steel bracing. Where members are patched with timber, the strength of the joint is critical. The traditional scarf joint will resist most stresses in rafters, posts or beams, while a simpler halved joint can be used in wall plates. If the joint will be exposed to view, bolts can be concealed behind timber plugs (NSW Heritage Office, 2004).

Steel reinforcement can also be used with timber members. It may consist simply of steel plates either side of a member (or top and bottom), bolted through the timber. A method sometimes used for overstressed beams is to convert them to trussed girders by adding steel struts and tension rods underneath. Where space is not available for this, a variation using side rods is possible (NSW Heritage Office, 2004).

In Denmark, the civil engineering office of Eduard Troelsgård has introduced an approach to the repair of timber structures, where decayed wood is replaced by splicing in new, seasoned wood, and craftsmen work with contemporary tools and techniques. They base their repairs on solutions that resemble old methods; decayed parts are replaced in a way familiar to today's carpenters while still rooted in tradition (Larsen & Marstein, 2016).

A second approach is to introduce new elements for the reinforcement of the old structure. In freely-supported structures, like roofs, various reinforcement techniques using supports and additional elements have been widely used. In many cases, best be fulfilled by reinforcing the weakened structural element using an additional structure, for example made of wood or steel. Replacement, on the other hand, whereby decayed wood is removed, is by nature a non-reversible intervention (Larsen & Marstein, 2016).

Replacement of ceiling joists is particularly difficult and expensive because of the risk of damage to floorboards above and the ceiling below. Repair should, where possible, leave the ceiling joists in place, while reinforcing them with timber or steel. Another option is to insert a new ceiling joist between the damaged ones (Larsen & Marstein, 2016).

The third approach is to re-build the structure replacing damaged parts with new, identical parts – that is, by copying (Larsen & Marstein, 2016).

Where beams or joists are not deep enough for their loading, the result is excessive bending, bouncing floors, and possibly even cracks. One option is to increase the effective depth by fixing additional timber to the top of the component to increase its stiffness. If the depth of a beam only needs to be increased marginally, one very neat solution is to firmly attach the floorboard material to the top of the beam. However, fixing the rest of the floorboards around it can be a head-scratcher (Russell, 2020).

When the ends of beams or joists are decayed, or in cases where either the beam or its support has moved leaving too little bearing, it is essential to increase the junction between the two. Extending the end of the timber can be done with side-planting or splicing-in, but the alternatives are many and varied. The bearing can be extended by introducing steel or timber bolted under the beam; by forming a whole box section steel shoe attached into the beam; by adding a timber, steel or masonry post under the end of the beam, down to the ground; or by creating a timber or steel corbel on the wall beneath

Fig. 6.33. Typical solutions where a beam end has decayed (Russell, 2020).

the end of the timber. Similarly, a beam pulling out of an adjacent beam can be picked up with a fabricated strap like a joist hanger (Fig. 6.33) (Russell, 2020).

Doors and windows typically suffer from rot at the base of the frame and door leaf or window sash, and also from loosening of joints. After any necessary patching of pieces which are beyond repair, the joints should be made tight by replacing wedges and reglueing. On window sashes, minor decay combined with loose joints can often be repaired by removing the decay and repairing with epoxy, and using brass angle brackets let into the surface on the inner face (NSW Heritage Office, 2004).

6.6. FAILURES OF WOODEN BUILDINGS AND PREVENTIVE ACTIONS

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A meaning for failure may be deterioration or decay, especially of vigour, strength, etc. It means that there is an expectation about the structure performance, which is not satisfactory (Palaia, 2007).

Building failures can be categorized into the two broad groups of *physical (structural)* failures (which result in the loss of certain characteristics, e.g. strength) and *performance* failures (which means a reduction in function below an established acceptable limit) (Douglas & Ransom, 2007).

Failures also can be defined as events which directly or indirectly have or could have implied risk for human lives. Examples are direct collapses of structures, local cracking, crushing or degradation which can be expected or suspected to have adverse effects on the safety of the structure (Frühwald et al., 2007).

Mechanical failures can affect the structure at any level: members, units, connections, and whole structural system. The most common types of failures are discussed below.

6.6.1. Common Types of Failures of the Timber Structural Systems

1. Failures of members

Due to the fibrous nature of the wood tissue, the way of breaking of the members is influenced by the kind of stress (Tampone, 2007). The most common types of stress are compression, tension and bending.

Compressive stress is the force that can cause the deformation of the material. High compressive stress leads to failure of the material due to tension.

Some examples of failure types of nonbuckling clear wood in compression parallel to grain are provided in Fig. 6.34.

The longitudinal compression stress mainly occurs in pillars, columns, posts, stakes, in rulers of the lattice girders. The failures are transversal lines which represent the crumpling and buckling of the cells, generally visible to the unaided eye, sometimes to be looked for with optical aids (Tampone, 2007).

The consequences are generally severe on the member and on the whole structural system with regrettable consequences on the construction: the simple deflection of the strut, slender and therefore flexible, is sufficient to reduce the tension and avoid rupture in the member but the rafter experiences a further deformation and at last it breaks (Tampone, 2007).

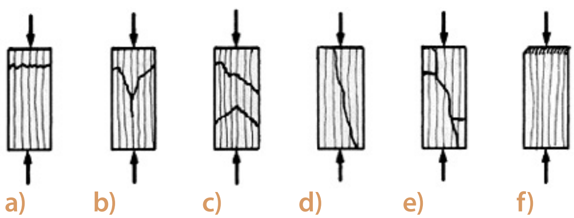

Fig. 6.34. Failure types of nonbuckling clear wood in compression parallel to grain: (a) crushing, (b) wedge splitting, (c) shearing, (d) splitting, (e) crushing and splitting, (f) brooming or end rolling (Bodig & Jayne, 1993).

An example can be seen in Fig. 6.35. Break of the rafter of a truss caused by the instability of the strut, with the complicity of a knot of the rafter and the notch for the joint, both exactly at the connection with the strut; this, too thin, is bent with the concavity towards the tie. The bending of the strut has been most probably preceded by the deformation of the rafter (Tampone, 2007).

A problem which is typical for timber structures is the risk for tension failure due to the low strength of wood in the perpendicular to grain direction (Fig. 6.36).

Fig. 6.35. Church of Mirteto, Italy (Tampone, 2007).

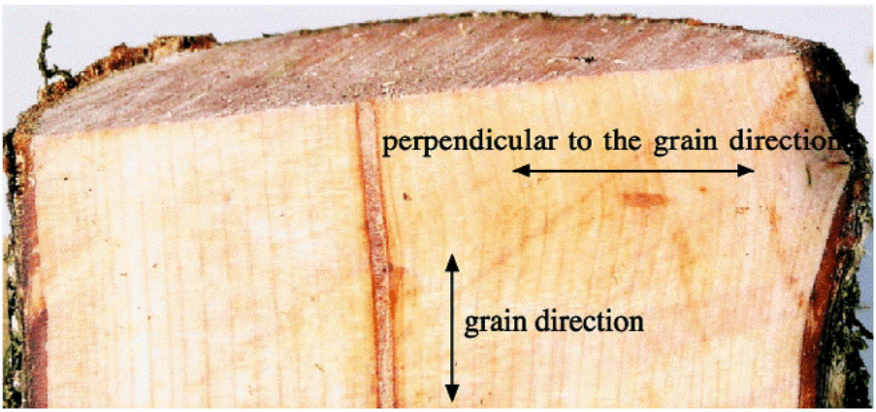

Fig. 6.36. Grain directions on a tree (Aydin et al., 2007).

The value of ultimate tensile stress parallel to the grain is of the order of 45–120 MPa at 12 % moisture content, whereas the tensile stress perpendicular to the grain may only be 2–6 % of the parallel-to-grain value. "Thus, it is difficult to get wood to fail in tension parallel to the grain without having excessive failure in tension perpendicular to the grain" (Encyclopedia of Materials: Science and Technology, 2001).

Because of these low strength values, it is advisable to design timber structures in such a way that tension stresses perpendicular to grain do not occur or are minimized (Woodproducts.fi, 2020).

In practice a break to tensile stress is rare in the ties unless these are damaged by fungal attacks; mostly this kind of failure should be found in the beams (Tampone, 2007).

Predominantly, breaks of the members are caused by bending moments. The strength of the wood is fundamentally affected by the direction in which it is loaded in relation to the grain. In the direction of the grain, the bending strength is directly proportional to the density of the wood. In uniform, flawless wood, the bending strength is as great as the tensile strength (Woodproducts.fi, 2020).

Example of beam failure due to bending is provided in Fig. 6.37.

Fig. 6.37. Beam cracked by bending. The crack extends from the sides to the bottom edge (Tampone, 2007).

2. Failures of connections

Amongst the main causes of disconnection of the joints we ought to remember the effects of swelling and shrinkage produced by the fluctuations of temperature and humidity, the ageing of the adhesives, the defects and the biotic damage of the wood, the corrosion of the metallic fastenings, the inadequacies of the design and occasional factors. At the more general level, the effects are reduction of the abutment surfaces and consequent concentration of the stresses on small areas, eccentricity of the stresses, widening of the encasement with occurrence of clearances (Tampone, 2007).

The most common method to connect timber elements today is by mechanical dowel type joints. Among the failure cases where joints are involved this is also the dominating type. The design of joints in timber structures is a difficult problem. The stress transfer in dowel type joints is very complex and cannot be described in detail in normal design situations. An additional complication is that wood is anisotropic and the risk of creating stresses perpendicular to grain is hard to evaluate. Eccentricities may develop in the joint area leading to much higher stresses in the wood than those found from the global analysis

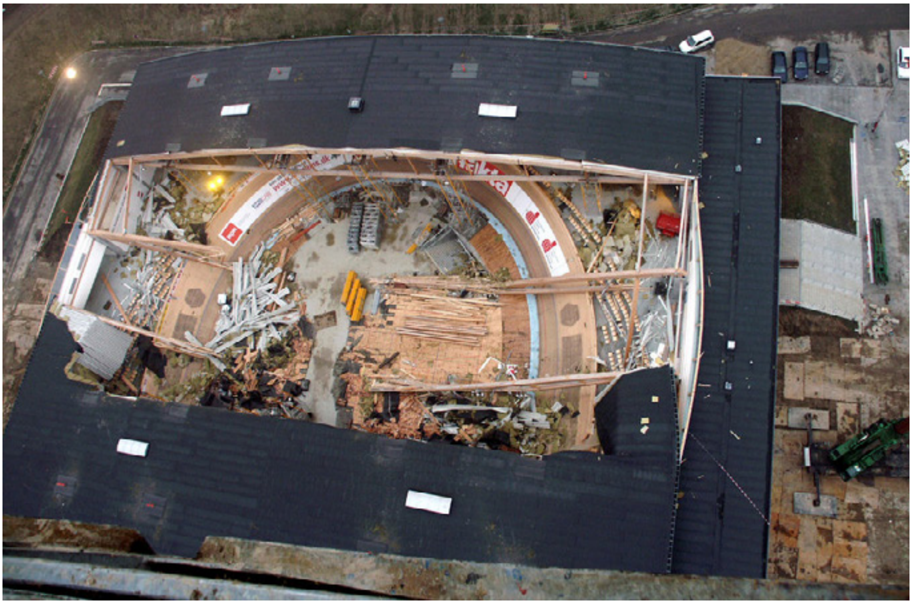

Fig. 6.38. Top view on Siemens Arena Ballerup, Denmark, collapse of 2 out of 12 main trusses (Hansson & Larsen, 2005).

of the structure. In the joint region the dowels may also reduce the wood cross section in a significant way (Frühwald et al., 2007).

A well-known example is the spectacular collapse of two long span roof trusses in the Ballerup arena in Denmark in January 2003. It suffered from gross errors in the structural design, reducing the load-carrying capacity of the heel joint of the fish-shaped truss to 25–30 % of its required strength. Due to this, two of the 72 m long trusses collapsed without warning and under very low variable loads shortly after the opening of the arena (see Fig. 6.38).

3. Failures of units

Structural units fail when the connections lose their efficacy and, obviously, when one or more members lose their integrity (Tampone, 2007).

Geometrical imperfections of the members such as irregularities of the grain or differences in width along the shaft, geometric imperfections of the assembly of the pieces, lack of linearity or not rational position of the loads can have the effect of the unit to twist or, in any case, loose its planarity. For example, trusses of the roofs are supposed to lay in a vertical plane; when they twist or rotate, in general around the chord and on the supports, they lose almost completely their bearing capacity (Tampone, 2007).

Large-span timber structures usually consist of main frames (i.e. columns and girders), secondary elements and bracing elements (Thelandersson & Honfi, 2009). To avoid collapse due to bracing failure, it is recommended to implement moment-resisting joints between columns and horizontal girders (Thelandersson & Honfi, 2009, cit. from Huber et al., 2019).

Bracing can be used temporarily for safety whilst erecting the trusses, for stability on a permanent basis (to keep the trusses in place) or to combat wind where bracing can transmit wind forces to suitable load bearing walls (Minera, n.d.) (Fig. 6.39).

Mistakes are made with respect to temporary bracing during the construction phase, which may lead to instability collapse and accidents at the building site. This type of failure is very typical and can be avoided by planning of the erection sequences to minimise the risks and by giving clear instructions to the construction workers at the site on how to provide temporary bracing. Generally, more careful work preparation is needed at the building site.

Fig. 6.39. Bracing of the roof (Minera, n.d.).

For more complex structures, the designer should be responsible for giving instructions about appropriate methods of bracing also in the construction phase (Frühwald et al., 2007).

4. Failures of systems

Break of the components, units and members, disconnections are not a necessary condition for the failure of the system due to favourable factors as elasticity and deformability of the wooden members, ductility of the joints, solidarity, etc. (Tampone, 2007).

Final failure of the structural systems leads to the collapse of the construction. An example of this mode is the failure of Temple of Pagan-gyi in Mianmar (Fig. 6.40), being about to collapse since years, affected by instability and irreversible, severe deformation which is most probably caused by deficiency of stiffness in the posts at the various levels and lack of bracing of the

Fig. 6.40. Temple of Pagan-gyi in Mianmar (Tampone, 2007).

construction. They are an extraordinary witness of structural behaviour, and the proof of the enormous resources of endurance the wood owns is very strong (Tampone, 2007).

6.6.2. Causes of Failures

The causes of structural failures are numerous. Frühwald et al. (2007) studied and summarized 127 timber structures' failure cases mostly from Scandinavia (Sweden, Finland and Norway) as well as Germany and the United States. For each case in the study, one cause or sometimes several causes of failure were identified. The different types of errors were classified with respect to the following nine categories (Frühwald et al., 2007).

1. Wood material performance: the materials used in the product have been of poor quality in relation to practice. Example: larger knots than permitted in glulam laminations.
2. Manufacturing errors in factory: this relates to manufacturing errors which should have been detected in the production process according to

practice and internal quality control. Example: poor bonding quality of finger joints in glulam.

3. Poor manufacturing principles: this means that the basic principle used for manufacturing the product has been poor. However, the poor principle has been used as intended in the process. Example: use of a wrong glue type.
4. On-site alterations: here, alterations of the structure have been made on site. These alterations have led to the failure. Note that it is often difficult to know whether these alterations were intended from start or made on site for practical reasons.
5. Poor principles during erection: failures which are due to poor handling at the erection of the structure are grouped in this category.
6. Poor design / lack of design with respect to mechanical loading: this means that the failure was due to errors in the strength design of the structure (design method). In this category only mechanical loading is considered.

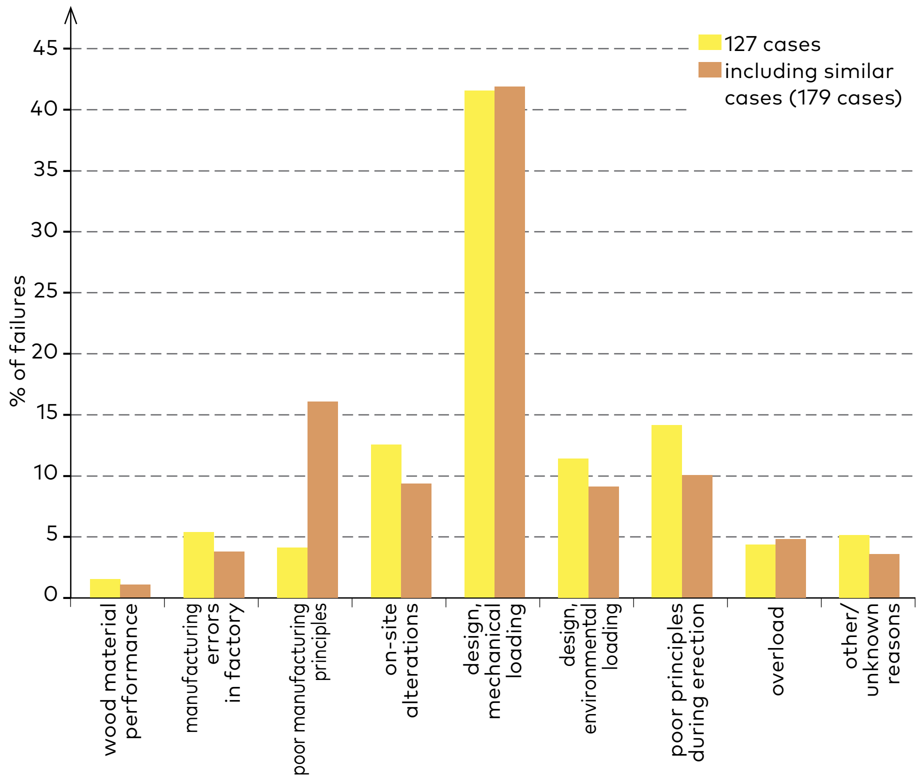

Fig. 6.41. Distribution of error types for the cases in the data base with or without including parallel cases (Frühwald et al., 2007).

7. Poor design / lack of design with respect to environmental actions: this means that the failure was due to errors in strength design, but the failure was caused by mechanical loading in combination with environmental actions. Example: drying cracks, shrinkage effects and durability damage.
8. Overload in relation to building regulations.
9. Other / unknown reasons (e.g. lack of maintenance).

The most common cause of failure found in the investigated cases is poor design or lack of strength design (41 %). Other important failure causes are poor principles during erection (14.1 %), on-site alterations (12.5 %) and insufficient or lacking design with respect to environmental actions (11.4 %). In total, about half of the failures are related to design. About one fourth of the failures are caused at the building site (on-site alterations, poor principles during erection). This means that wood quality, production methods and principles only cause a small part (altogether about 11 %) of the failures. The problem is, therefore, not the wood material but engineers and workers in the building process. This picture is similar to that found from other failure

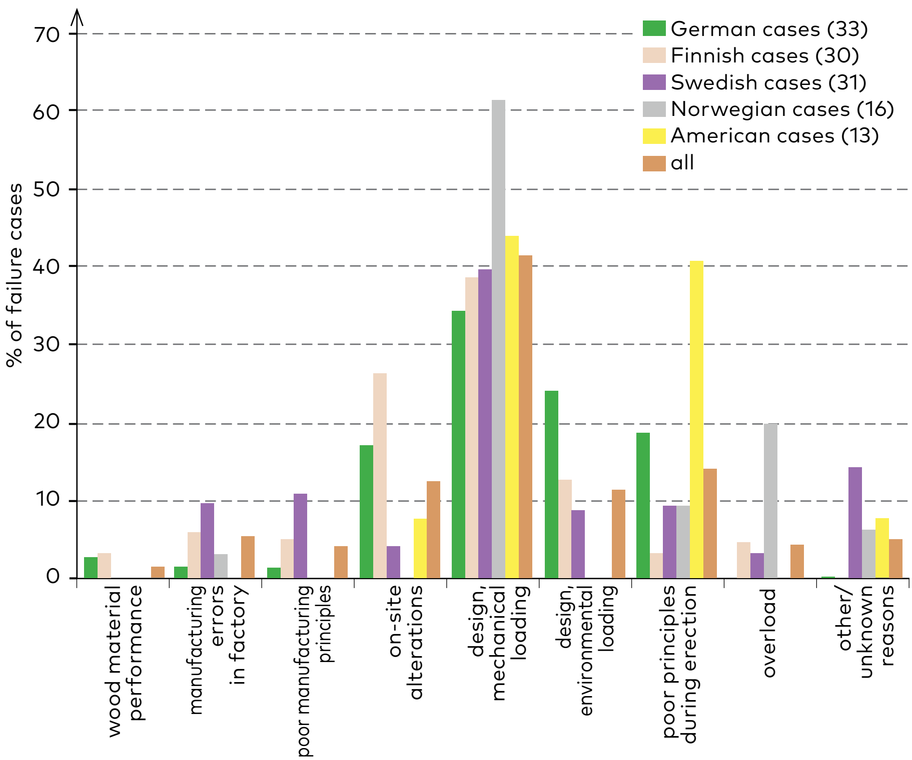

Fig. 6.42. Failure causes depending on country (Frühwald et al., 2007).

investigations for other types of structures (mostly steel and concrete), where human errors were found to be the dominating cause behind failure events. Figure 6.41 shows the distribution of error types in the case studies. It can be seen that the most common cause of failure is related to design and mechanical loading (Frühwald et al., 2007).

The study by Frühwald et al. (2007) also showed that some failure causes are more common in certain countries. For example, overloading (of snow) seems to be particular to Norway, whereas disregard of design for environmental actions is mostly found in the German cases (see Fig. 6.42). Manufacturing errors in factory and poor manufacturing principles are most common in the cases from Sweden. On-site alterations are most common in Finnish cases, and poor principles during erection is frequent in the cases from the United States (Frühwald et al., 2007).

6.6.3. Preventive Actions

The progression of the failures in a wooden healthy structural system is, generally speaking, rather slow; this is also due to the deformability of the wooden members and the ductility of the joints, two factors that prevent the system from immediate breaks. Therefore, a number of symptoms make their appearance since the very beginning of a critical situation (Tampone, 2007).

One more fundamental factor, solidarity of the healthy members towards the failing ones, is to be taken into special account. In fact, in a structural system well designed, the connections at any level are efficacious and if happens, for instance, that a rafter of a truss breaks, the auxiliary beams, i.e. the other beams which connect the trusses and bear the covering, in a roof the purlins, will act as ties and keep the broken rafter even if this will sink considerably. It is a very dangerous, temporary phase but the delay of collapse is sufficient to allow the quick adoption of suitable measures (Tampone, 2007).

Many examples of this complex, surprising mechanism are to be found in the practice. The experienced technician is able, in general, to detect precocious symptoms of failure in occasion of inspections or normal maintenance to the building because the structures, especially the timber ones, are very communicative and express clearly their disease (Tampone, 2007).

Recent studies, however, have revealed that most failures of timber structures are not caused by local defects but by global defects from systematic mistakes such as global weakening of structural elements due to systematic (repetitive) mistakes (Dietsch & Munch-Andersen, 2010).

It can be stated that there is no strategy for the structural designer which ensures robustness in all cases. When deciding on a robustness strategy, one has to consider different scenarios. The major difference is whether the cause of failure is likely to be a systematic (mostly human) error or an unforeseeable (mostly local) incident. This is subsumed in Table 6.8 which lists types of damaging effects and possible robustness approaches according to Dietsch & Munch-Andersen (2010).

Table 6.8
Preferable Robustness Approach Depending on the Type of Damaging Effect (Dietsch & Munch-Andersen, 2010)

Local effects – local failures, e.g.	Global effects, e.g.
• Local deterioration of element from, e.g. local water ingress • Local weakening of element from, e.g. holes • Local overloading from, e.g. local snow accumulation	• Global weakening of structural elements due to systematic mistakes • Global deterioration of elements from, e.g. wrong assumption of ambient climate • Global overloading from, e.g. addition of green roof without structural verification
Robustness approach	**Robustness approach**
• Redistribution of loads to adjacent (undamaged) elements by, e.g. redundant secondary system	• Limiting failure to local level by, e.g. determinate secondary systems with 'weak / flexible' connections • Compartmentalization / segmentation

It is more or less impossible to eliminate the risk of human errors completely, but their frequency can be reduced by improving building process management, where an important element is to assign or commission personnel with adequate experience and education, as well as with the right attitude to the tasks at hand. This is, however, difficult to achieve in many building projects, since the client which should have the incentive for this often lacks the professional competence. This is a general problem in the building sector (Frühwald et al., 2007).

On a generic level, only the first category of human error, lack of knowledge, can be reduced by improved training and education. The second and the third types which have to do with human attitudes are more difficult to take measures against. One way is to implement more efficient Quality Assurance (QA) systems in the building process. Such systems may be developed with special focus on design and construction of timber structures (Frühwald et al., 2007).

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