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BUILDING PATHOLOGY

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1. Introduction

CIB was established in 1953 as an Association whose objectives were to stimulate and facilitate international cooperation and information exchange between governmental research institutes in the building and construction sector, with an emphasis on those institutes engaged in technical fields of research. CIB has since developed into a worldwide network of over 5.000 experts from about 500 member organisations with a research, university, industry or government background, who collectively are active in all aspects of research and innovation for building and construction.

CIB W086 Commission's main objective is to use the inspection and diagnosis of building pathology as the stepping-stone to better manage the welfare of the built environment and namely base all decisions concerning its maintenance/rehabilitation on rational technical-based criteria. It is envisaged that access to research on Building Pathology will be offered through the web. As well, guidelines are to be prepared in regards to the use of different inspection and diagnosis techniques, including the most recent ones. The link between these areas and those of maintenance/rehabilitation will be clearly established. A closer bond with the professional community, namely using forensic engineering approaches, will also be a goal of the works of the Commission.

The study of building pathology has been performed practically since constructions have been erected by Mankind. Learning was acquired mostly on a trial and error basis with great losses of human and material resources. Nowadays, this learning procedure cannot be accepted anymore and a scientific stance must be adopted. W086 has contributed to this progress with two state-of-the-art reports:

- “Building Pathology. A State-of-the-Art Report”, Publication 155, CIB, 1993;

- “A State-of-the-Art Report on Building Pathology”, ISBN 978-90-6363-082-9, CIB, 2013.

Now the time has come to analyse how building pathology diagnosis is going to move forward in its never-ending quest to improve the quality of the built environment. This report has three main goals: i) Understanding the point of view of all professionals involved in the process of buildings and make scientific developments, namely in terms of advanced diagnosis methods, in the area of building pathology more accessible and easier-to-apply in practice; ii) Strongly linking the tasks of inspection and diagnosis of building pathology with all subsequent maintenance/rehabilitation activities. This will be discussed in terms of the uncertainty and risk analysis in diagnosis and the decision criteria used to implement those actions; iii) Linking building pathology inspection and diagnosis with forensic engineering approaches (See: Table of Contents). In order to bridge the gaps identified, a systemized glossary of terms used in pathology, diagnosis and maintenance/rehabilitation of buildings will be appended to the project’s report.

CIB W86 intends to publish this report to boost the use of the building pathology inspection and diagnosis by practitioners, with the following objectives:

- Establish a closer bond between the professional actors involved in building pathology and the scientific community;
- Review the new advanced diagnosis methods available in the market;
- Establish a clear connection between inspection and diagnosis activities and maintenance/rehabilitation actions and create a glossary of corresponding terms;
- Apply forensic engineering approaches to building pathology.

2. The vision of building pathology professionals

This section should be cited as:
Freitas, V. P. "The vision of building pathology professionals", in New Trends on Building Pathology, CIB W86 Report, 2021.

2.1. CIB W086 - Building Pathology and Practice

2.1.1. Introduction

CIB was established in 1953 in order to stimulate and facilitate international cooperation and information exchange between government research institutes in the building and construction sector, with an emphasis on those engaged in technical fields of research. CIB has since evolved into a worldwide network of a large number of experts from organizations with research, university, industrial or governmental background, who collectively are active in all aspects of research and innovation for building and construction. The W086 commission is concerned with learning from past and current building defects and encouraging the systematic application of that knowledge to the design, construction and management of buildings. One of the objectives of W086 is to produce information that will assist the practitioner's and establish a strong link between the scientific knowledge and practice.

According to Bill Porteous, in his text in the CIB publication 393 [1], Building Pathology is arguably as useful to the science and practice of buildings as medical pathology is to the science and practice of medicine. The main benefits of the practice of building pathology are as follows:

a) Building pathology provides a systematic scientific approach to discovering what has gone wrong in a failed building. The building pathologist is concerned with what has happened and how it came to happen, rather than with attributing blame;

b) Building pathology investigations carried out on a large enough sample of buildings will reveal patterns of building failure by identifying the common features of buildings that have failed;

c) Building pathology provides convincing evidence because it involves buildings that have actually been constructed and are being tested in use in a real-world environment.

There are other desirable consequences of applying the practices of building pathology to the investigation of building failures. Some of these can be described as follows: i) avoid superficial judgment; ii) better design to avoid failures and development of better materials.

Building pathology is as important to the science of building as medical pathology is important to the science of medicine and provides the opportunity to dispassionately observe in detail what has gone wrong with a building and to provide guidance to prevent as well as to repair.

The systematic and repeatable application of building pathology principles makes its use very valuable in practice.

2.1.2. Building pathology related costs

The costs of building pathology are very important for companies and designers. In order to accurately access building pathology related costs, countries must commit and make an added effort to establish guidelines for data collecting systems, as well as observatories for monitoring the evolution of building defects. To collate the reports made by experts and insurance companies, in different countries, is essential in order to understand the most common building defects and their causes and estimate the annual repair costs. This was not done in many countries because the mandatory insurance systems are not implemented.

Building pathology is vital to assess causes, which will allow the acquired knowledge to be available in the future, hopefully contributing to the reduction or elimination of those defects. By doing so, we are able to enhance the quality of construction of our built stock while drastically reducing the considerable amounts spent each year in repair interventions, which can amount to millions of euros.

2.1.3. Building Pathology: Dissemination of knowledge

Building Pathology can be described as the scientific study of the causes, processes, development, consequences and nature of building failure. Defects may compromise the building in several ways, such as structural performance, hygrothermal performance or indoor air quality, and require expensive interventions to return the building to its original state. Therefore, building failure is a quality indicator of the utmost importance for the construction industry. Even though each building is unique, and presents different types of failure, it is possible to identify certain patterns of failure when investigating a significant sample of buildings. Through the systematic analysis of the data collected during these investigations, it is possible to establish a reliable database that provides guidance to prevent and repair.

At a time when the building process is evolving at the speed of light, assimilating new technologies, techniques and materials, the number of problems affecting buildings is bound to increase at a similar rate. Insufficient knowledge of materials and techniques, the stress of deadlines and the non-multidisciplinary character of the design process all contribute to the appearance of defects. The dissemination of pathology catalogues or a database would provide an invaluable contribution to preventing most problems observed in buildings and construction nowadays: by learning from past mistakes we are able to grow and evolve, assuring the defects become less frequent.

By integrating that knowledge into the process of designing new buildings, construction professionals may be encouraged to develop better materials and better building design, whilst incorporating innovative techniques and focusing on performance besides aesthetics.

As mentioned above, the continuous process of evolution and learning from past mistakes must be supported by a vast and reliable database. Therefore, various countries have created their own database based on data collected throughout the years, organizing them into pathology catalogues. These can be found either in printed form or online.

Some of the most relevant information available are:

a) Between May 1982 and March 1990, several pathology records entitled the “Defect Action Sheet - DAS”, were prepared and published by the Housing Defects Prevention Unit of the Building Research Establishment (BRE), a British organization specialising in buildings.

The files are structured as follows: Description of the pathology and its causes, using diagrams and photographs wherever possible; Identification of main prevention measures, presented diagrammatically; List of bibliographic references and related bibliography.

The Building Research Establishment (BRE) has not published pathology records in the DAS series since 1990. However, it periodically issues a vast list of publications in the area of construction in the form of files or guides known as “Digests”, “Information Papers”, “Good Building Guides” and “Good Repair Guides”.

b) The records entitled “Pathologie du bâtiment” were prepared and published by the “Agence Qualité Construction” (AQC), a French organisation responsible for the inspection and implementation of quality in construction, in association with the “Fondation Excellence SMA”, of the SMABTP Group, a leading insurance company operating in the field of construction in France.

c) PATORREB has created a website www.patorreb.com coordinated by the Faculty of Engineering - Porto University, where a Pathology Catalogue has been running since June 2004.

After careful consideration and analysis of all collected data, some recommendations are available today to treat or prevent future problems.

2.1.4. Final remarks

It can be seen that there is a growing concern about the quality of construction, explained by the introduction of specific regulations but it can be also be observed that the buildings constructed in recent years do not have the expected quality and durability. The growing complexity of constructions, the lack of knowledge systematization, the absence, in many countries, of an effective system of insurance and guarantees, the speed required to the construction process, the new architectural concerns, the new materials’ application, the absence of a project team of specialists in building physics and technology are fundamental causes of buildings’ non-quality. Building Pathology intends to be a contribution to the systematization of information and knowledge.

3. Advanced diagnosis methods

3.1. Drones

This section should be cited as:
Falorca, J.; Lanzinha, J.: "A brief reflexion on the use of drones for technical inspection and diagnosis of building envelope anomalies", in New Trends on Building Pathology, CIB W86 Report, 2021.

3.1.1. The context

It is quite common that building inspectors face situations of buildings and structures with peculiar characteristics, which may at times hinder their work or even endanger their lives. Constraints arise particularly when sites are hard to access, safety risks may exist for the inspector(s) especially in tall buildings, scaffolding assembly is expensive and/or economically unviable, etc. This situation may even occur under urgent or reactive circumstances, thus requiring a quick inspection action. In all cases, it could be important to rely on alternative methodologies to support technical inspection, aimed at overcoming such setbacks and from which substantial benefits can still result. It is in this context that relevant potential may derive from the use of drones. Nowadays, great focus has been put on this kind of small aircraft as an emerging technology in the Construction Industry (CI).

In this reflexion, the adaptability and versatility of using drones are discussed, since it may be a promising alternative methodology to support the technical inspection in the process of condition monitoring of building envelopes and other kind of structures (e.g. bridges, viaducts, dams, communications towers, chimneys). In fact, drones seem to be a worthwhile tool for supporting some civil engineering activities - particularly when displaying a multirotor configuration, loading high-definition (HD) cameras, for both photography and video.

3.1.2. Drones - A new technology trend

Drone evolution is mainly characterized by its post-9/11 expansion. In fact, the conflicts in Afghanistan and Iraq, coupled with the broader "Global War on Terror", led to the expanded use of drones on an unprecedented scale. Simultaneously with the development of technology in different areas, it has helped to adapt their use to many non-military fields [1]. Since around 2010, the falling prices and the increasing ease of operation have changed the scenery. The miniaturisation of components such as gyros and GPS units made the machines smaller and cheaper and the advances in programming and autopilot systems also made them easier to fly [2].

Presently, these machines have a high level of popularity, and its technology has got a maturity level that makes it both user-friendly and less expensive ([3] mentioned by [4]). Drone technologies are upsetting business models and reshaping industry landscapes, ranging from agriculture to filmmaking [5] and the continuous growth of a wide range of applications is remarkable. Through the analysis of some sources, an exercise can be made in order to position drones in the context of contemporary technologies. For instance, in the *Gartner Top 10 Strategic Technology Trends for 2019* [6], drones fall within the first trend, as one of the five types of *Autonomous Things*, using *Artificial Intelligence* (AI) to perform tasks traditionally done by humans.

3.1.3. Drones - The aircraft

In this text, the term "drone" is most frequently employed, since it is considered as more widely used and understood than other terminology. In the literature, particularly concerning the drone definition, some cases can be found. For instance, according to [7], "*Drones are more formally known as unmanned aerial vehicles (UAV). Essentially, a drone is a flying robot aircraft that may be remotely controlled or can fly autonomously through software-controlled flight plans in their embedded systems working in conjunction with GPS*."

About the markets for drones' use, some studies [8] divide it into five groups considering the theoretical segmentation background: toys, hobby, professional, commercial and military. In the context of building inspection, it may be accepted that the range of drones to be used can be framed mainly in the hobby/professional/commercial group and may vary a lot depending on the rigor wanted for the work to be executed and on the costs that can be supported to that end.

Concerning the configurations, the classification of drone systems and other technical intrinsic aspects can already be found with higher detail in many prominent publications [9-13]. Generally, the entire drone system includes the aircraft (and its components), the control stations (ground support equipment) and data and communication links [9]. The equipment for data treatment and results (mainly computers) can also be included. In the scope of this text, the extension of the entire drone system is limited mainly to: (i) a ground operator who manoeuvres the flying device through the instructions given from (ii) a manual remote controller connected to a smartphone containing a pre-installed app, using (iii) a set of radio and satellite communication mechanisms, and (iv) the aircraft itself, consisting of some type of platform and a payload.

Making an overview using some sources from the literature [9-11, 13-17], it is possible to understand the main characteristics and technological aspects related with the whole drone system, including the drone's platform and the payloads (aircraft), and to distinguish the categories (ranging from micro to large combat devices), their weight, the normal operating altitude, radius of mission or range, endurance or autonomy and some typical operation uses. It was decided to restrict the presentation so as not to include minute details, as it would make this discussion more extensive.

In the domain of operation in the CI, it is more suitable to use a drone with the vertical take-off and landing (VTOL) capabilities. It is also preferable to opt for a multicopter, since it can be more affordable and easier to set up at location and it has very good handling capabilities, sufficient range and large accessibility of components on the market. Although there are many alternatives of commercially useable multicopters, the basic components and operating principles are generally quite similar for the most available versions [18].

Drones are also built with intelligent stabilisation systems to keep them flying and can carry sensors to perform more dedicated functions. Cameras mounted on gimbals to obtain high-quality videos and still photography are one of the most common devices. Likewise, depending on their lifting capacity and payload specifications, drones may also carry various sensors that allow extracting a wide range of information, increasing the number of possible applications and the business value of their outcomes [19]. The main physical parts of more usual drones are represented schematically in Figure 3.1.1. In the case of the smaller drones, manufacturers have tended to increasingly produce aircrafts with integrated camera, in the detriment of a gimbal.

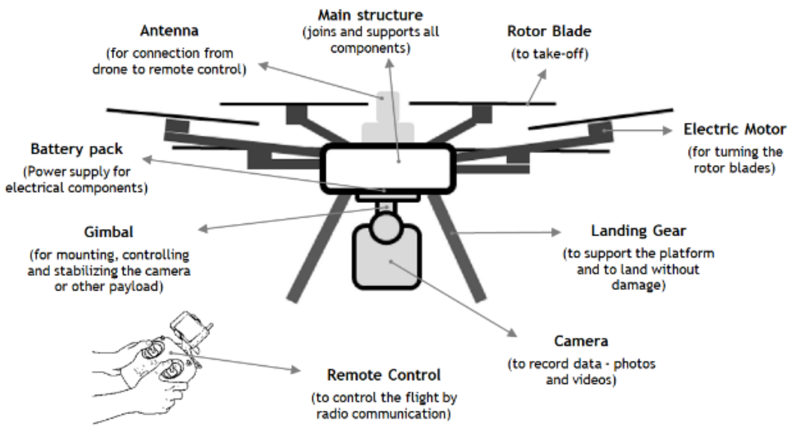


Figure 3.1.1 - Schematic representation of the main physical parts of common drones (based on [20]).

3.1.4. Drones - The regulatory field

According to [21], regulating the use of drones for civil purposes is being widely discussed around the world, but advances are still small in many countries. Three major reasons explain why drone regulation is a delicate matter [22]: i) congested airspace - in some regions and around major cities, airspace is already congested, so an out-of-control drone is a threat; ii) inherent risks - drones can move anywhere and everywhere, as they are airborne, any failure can cause them to fall from the sky; iii) public concern - it is mainly related with privacy issues, since cameras and other sensors attached on drones could be used for constant surveillance of everything. In this text, there will be no detailed analysis of existing regulatory content in a number of countries as this would be an exhaustive exercise and it would be running the risk of not being updated, since different countries are still in a phase of rules' adjustment. Nevertheless, some recent publications already address this subject very effectively [23, 24]. Other detailed information can be also taken by consulting some known sources providing links to national drone regulations (mainly through its Internet presence). One example is: https://droneregulations.info/index.html [25].

One of the shortcomings currently present in the world of drones is the question of not having a global consensus on what characteristics should be taken into account for their classification, so that they can be regulated and operated safely at an international level. For instance, in Europe, countries do not yet have harmonized legislation, although from about the beginning of 2019 we are one step closer to aligning rules for safe drone operation. According to the European Union Aviation Safety Agency - EASA [26], to ensure the free circulation of drones and a level playing field within the European Union, it has developed common rules. The EASA Committee voted unanimously to approve the European Commission's proposal for an Implementing Act [27] to regulate the operations of Unmanned Aircraft Systems (UAS) in Europe and the registration of drone operators and of certified drones. This document is accompanied by a Delegated Act [28], which defines the technical requirements for drones. By 2022, the transitional period will be completed, the regulation will be fully applicable and the operations of UAS in Europe will be classified in three main categories: i) the 'open' category; ii) the 'specific' category; and iii) the 'certified' category (further details can be seen in [26]).

3.1.5. General remarks on the potential of using drones in the Construction Industry (CI)

Drones are now demonstrating numerous possibilities to add business value, because they are no longer limited to commercial activities. Potential business applications are wide ranging and drones offer disruptive opportunities for companies in the engineering and construction industries. They can broaden the human operations by enabling remote sensoring and the actuation and predictive capabilities [19]. In a 2018 international report for technology trends in Construction [29], drones were already emerging as the main trend in the use of advanced tools. Another study [30] also indicated that drones appear at the top of the preferences among the new robotic technologies of Construction. *Goldman Sachs* estimates that the Construction sector will adopt the use of drones faster than any other sector [31]. In fact, construction is already on the third wave of the drone industry [32].

Still according to [33], the use of these devices can contribute to reduce the time of tasks, increase the quality of work, improve safety standards and reduce costs. The use of drones in the CI is thus a relatively new concept and industry stakeholders are still discovering their applications that, according to the literature, can go through monitoring of construction activities, surveying, photography and surveillance, visual inspection in hard-to-reach places, on-site safety inspection, budgeting, detection of anomalies and defects in construction and interaction with workers, etc. In addition, numerous studies have recently been published on the subject of drone applications in areas of construction. Some examples are focused on: i) a look at current and projected uses of drones in the CI [4]; ii) an highlight of the existing and future issues and opportunities for using drones in Construction [17]; iii) some applications and issues of drones in the CI [33]; iv) masonry construction with drones [34]; v) an analysis of the potential applications of drones along the Construction's value chain also suggesting a drone BIM (Building Information Modelling) framework [35]; vi) the drone technology in monitoring the progress on construction site through visualization approach [36]; vii) a proposal for an inspection planning concept for highly automated inspections in BIM projects [37]; and viii) a review about drones in the CI [38]; among others.

3.1.6. A case in particular: Inspection of buildings (and structures) using drones

In recent years, greater attention has been given to the active development of different systems for building monitoring and inspection, which, when carried out in a timely manner, can make a significant contribute to reduce repair costs - especially in major civil engineering structures, such as towers, bridges, dams, buildings (and tall buildings), monuments, etc. Traditional methods of inspection are primarily based on visual inspection of constructions, which are often time-consuming, expensive and technically difficult. In many cases, because of difficulties of site accessing, it is necessary to use special equipment as scaffolding, different types of cranes, lifting platforms, boom lifts, etc., thereby increasing the related costs. With the development of drones, some innovation can be introduced in the inspection techniques. Thus, the potential of drones is above all in non-destructive testing (NDT), mainly for pathology detection, damage examination and condition monitoring. On the other hand, more from a theoretical point of view, the utilisation of drones can bring other advantages, particularly when: (i) presuming the necessity of building (or elements) rehabilitation, the preliminary inspections results are used - this can be taken into account in the scope of some methodologies already developed to rate the condition status (e.g. [39, 40]); (ii) or using the inspection results within the framework of building maintenance management, in order to accomplish the characterisation of the state of reference of the elements - this could be made by filling the inspection event sheets, aiding thus later maintenance plans preparation (e.g. [41]).

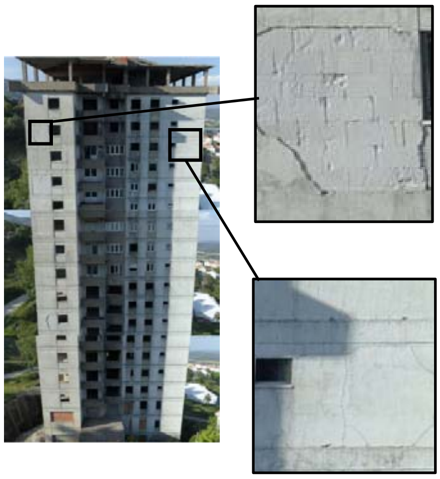
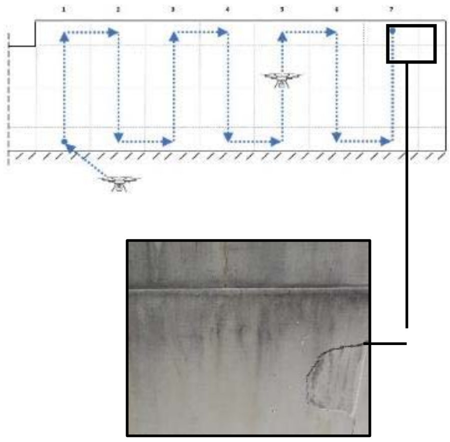
Under some circumstances, building pathology detection and diagnosis with drones can be done at a lower cost, faster than traditional methods, and more safely. In general, drone studies have shown good results [42-46], and some researchers have focused on the use of coupled cameras to capture HD images and videos and sensors or infrared cameras (and 3D scanners), as well as the use of digital photogrammetry used for large-scale mapping applications, etc. Some authors offer a concise review about these questions [47].

Worldwide, great importance has started to be given to this specific issue, e.g. the American Society for Testing and Materials (ASTM International) is already developing a standard - ASTM WK58243 - *New Guide for Visual Inspection of Building Facade using Drone* [48].

3.1.7. Presentation and analysis of some exploratory study cases

Three exploratory field cases are briefly described in this section to exemplify the potential of the use of drones, as shown in Table 3.1.1.

Table 3.1.1 - Exemplification of three exploratory study cases of visual inspection with drones

Case 1 (Tall building)	**Case 2** (Blind façade of a building)	**Case 3** (High bearing wall)
 (Adapted from [49])		(Flight 

In addition, in correspondence with each case, Table 3.1.2 presents, in summary, several intrinsic aspects and the results treatment, including a characterisation of the state of reference, since this was considered, theoretically, the first inspection carried out on each element.

3.1.8. Discussion and final remarks

In general, the literature analysis allowed perceiving that the advantages of using drones in the building envelope inspection and in other kind of structures can be wide. For example, it is possible to rely on the great manoeuvrability of these devices, the possibility of optimizing maintenance costs, the mitigation of operational risks, a substantial improvement in the quality of results, as well as a fast scanning of the general condition, etc. In addition, the visual clarity allowed by HD or thermal cameras, may reveal problems, often undetectable by human eye. However, on the other hand, the quality of the photos and videos obtained can be strongly influenced by several parameters, such as lighting conditions, inspection distance to elements and vehicle movement induced by environmental effects. Other important technological setbacks of drones yet persisting are the limitations of batteries, some risks which may arise from possible electromagnetic interferences and from physical obstacles.

Also, some challenges are associated to the utilisation of drones for visual inspection of building pathology, which at this moment are: the evolution of national regulations, the costs of the equipment’s, the operation range, the technology to detect and to avoid collisions, the load limitations, the meteorological conditions, the local physical limitations (e.g. trees near the façades), etc. Despite their pros and cons, it appears that drones are indeed an emerging technological tool with great potential for conducting inspections on buildings and structures - even though the first steps in this direction are still being given, in particular with the interest focused on the use of photography and digital video, thermography and 3D scanner. Stakeholders are awaking to the economic advantages that this technology can bring, especially when it allows access to areas difficult to inspect. In addition, at an academic level, it is realized that the interest for the development of studies, particularly focused in this field, already begins to show some dynamism.

Table 3.1.2 - Exploratory study cases with drone – description, objectives, methodological approach and results registration and analysis

		Case 1	Case 2	Case 3
Brief description	**Type of construction**	Tall housing building, with 18 floors and over 54 metres.	Blind façade of a building for services, approximately 9 metres high.	High bearing wall of a public space, 6 metres high.
Brief description	**Age** (Years - approx.)	40	10	16
Main objectives:		Quick check of the general condition of inaccessible façade areas without the installation of auxiliary means.	Quick scanning of the general condition of the higher points of the façade (mainly on the platband). Highlighting the representation of a predefined flight path. (Cases 2 and 3)	Quick scanning of the general condition of the higher points of the wall.
Methods/ approach	**Drone type used**	DJI Phantom 4 [50]	Parrot Bebop 2 [51] (Cases 2 and 3)	
Methods/ approach	**Pre-flight checklist** (main points)	Knowledge of the surrounding environment (obstacles or interferences of any order); Predefined flight path establishment; Verification of suitable meteorological conditions (fair weather, good visibility and low wind speed); The flight: on daylight / in line of sight; In general: compliance with regulations and safety rules.		
Inspection event sheet (in accordance with the methodology of [41])	**Brief description of the inspection**	On-site visual inspection, using drone, equipped with high resolution camera (video and photography).		
Inspection event sheet – **Diagnosis**	**Type of diagnosis**	General or preliminary inspection; Type of evaluation obtained: qualitative.		
Inspection event sheet – **Diagnosis**	**Brief anomalies' description**	Loss of adhesion of the external coating mortar and subsequent detachment; Existence of large coating cracked areas.	In surface painting: □ Wrinkled and cracking zones; • Some areas with blistering; ⌗ Cracking in the transition areas of structural elements-masonry.	❖ Water runoff discoloration; Coating detachment areas.
Inspection event sheet – **Diagnosis**	**Cause** (eventual)	The main one: lack of maintenance measures since it is a long-time empty building (never had significant human habitation).	□ Layer too thick; □ Application of a second coat with the first coat still wet, due non-observance of drying times. • Application after incomplete drying of the support materials; • Environmental conditions unfavourable to application, namely excessive moisture (on the substrate surface) and too low temperatures; ⌗ Shrinkage and expansion phenomena of support components.	❖ Action of atmospheric agents. ➢ Some effect of runoff from localized drainage leaks; ➢ Vandalism in accessible areas; ➢ Shrinkage and expansion phenomena of support component.
Inspection event sheet – **Diagnosis**	**Effect**	With immediate direct effects (in the elements under analysis) and nearby (in adjacent elements)	For now, only with immediate direct effects. (Cases 2 and 3)	
Critical analysis	Severity level	Moderate	Small	Low
Critical analysis	Occurrence level	High	Moderate	Moderate
Critical analysis	Detectability level	Moderately High	High	Moderately high
Critical analysis	**Global evaluation**	Within a tolerable risk	Acceptable risk	Acceptable to tolerable risk
	Recommended actions and prioritisation	Need for total rehabilitation (repair and adaptation to current requirements).	There are localized anomalies, which can be easily corrected. Possible slight repairs, depending on the owner maintenance policies.	There are symptoms of propagation of anomalies, with potential although moderate progression; in this case, the evolution of these symptoms must be monitored to decide when to intervene.

In order to make an empirical verification of this reality, some exploratory field tests were carried out with drones. It was thus allowed to check its great utility and a set of intrinsic advantages, particularly when it is possible to make quick technical inspections in hard-to-access sites, in which resource to the use of other auxiliary means would be certainly much more expensive and greater security risks to inspector could exist. In addition, it has also been possible to have a notion of the basic logistics necessary for the inspection's achievement, thus facilitating progress in future studies.

3.2. Infrared thermography

This section should be cited as:
Edis, E.: "Infrared thermography use in building pathology - Where we are?", in New Trends on Building Pathology, CIB W86 Report, 2021.

3.2.1. Introduction

There are various kinds of anomalies in buildings, such as cracks, detachment, mould growth, etc., and each of these may be a result of various phenomena (*e.g. thermal movement, uneven foundation settlement, excessive loading, etc., in the case of cracks*). Even sometimes, these anomalies occur because of the coupled effect of phenomena (*e.g. coupled effect of temperature and moisture in mould growth*). Non-destructive examination techniques are valuable tools to investigate the underlying causes of some of these anomalies, and Infrared Thermography (IRT) that allows imaging of the object by sensing the infrared radiation emitted is one of them.

In buildings, the visible pathological signs do not always show up immediately, such as in the case of complete detachment of an adhered cladding occurred due to gradual increase of delamination underneath. Sometimes, a visible sign might not even show up, as in the case of a moist thermal insulation in a stud wall where surface mould growth as a visible sign is not possible due to other reasons. Once the presence of a subsurface or hidden anomaly is suspected, various techniques are employed to investigate it, and IRT is among them as well as for some other anomalies.

The use of IRT in building inspections for these purposes, i.e. to detect subsurface/hidden defects and to determine the root causes, is a still evolving field. In some areas of its application, standards stipulating specific procedures are already present, while scientific research studies are still done on these and some others, either to improve the methods, or to extend their field of application. Concerning these, the objective of this section is to briefly present the current situation on IRT's use in building pathology with some in-situ inspection examples from the literature, and explore recent trends. A thorough state-of-the-art review within this context is not intended, and reviews of this kind are referred where relevant. In this respect, a general review considering all fields of application, as well as its brief history, can be found in [1].

3.2.2. Underlying principles and types of thermographic procedures

All objects in the environment emit infrared radiation, and *infrared imaging systems* are used to convert spatial variations of emitted and/or reflected radiation into a *thermogram* of the same scene presenting variations in radiation power with corresponding grey tones or colours [2, 3] (Figure 3.2.1). The radiation from a surface depends mainly on its *temperature,* and its *emissivity* and *reflectivity* characteristics [2], and surface temperature differences occurring because of an anomaly are employed in inspections using IRT. In other words, if an anomaly changes the thermal behaviour of that part of the object inspected in comparison to that of its surrounding, it can be detected by IRT.

(a) (b)

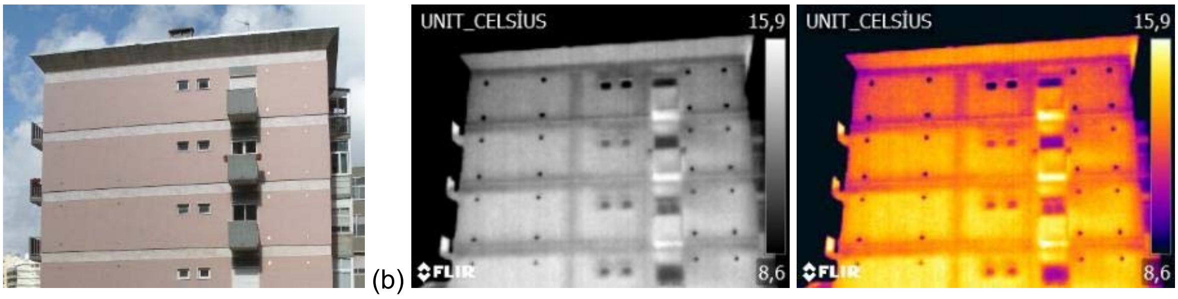


Figure 3.2.1 - (a) Daytime photograph, and (b) grey tone and coloured night-time thermograms of a facade showing structural variations behind the surface with the help of differences in their thermal behaviour.

In IRT inspections, heat flow at or through the anomaly, which in turn produces surface temperature variations, can be excited passively or actively, and two different types of IRT are defined accordingly as; passive and active thermography (Table 3.2.1). However, there is no consensus on their boundaries regarding some energy resources. In the ISO 10880 standard [4], for instance, *passive thermography* is defined as being performed without using any additional energy source for thermal stimulation, while an additional thermal stimulation is necessary in *active thermography*, and thermal loading by solar radiation is explicitly mentioned as passive thermography. In the EN 16714 standard [5], on the other hand, *passive thermography* is defined as using heat flow due to the intrinsic heat of the object under test, while a non-stationary heat flow is necessary in *active thermography* provided by natural or additional energy sources only for the purpose of thermographic test, and solar radiation is listed explicitly under energy sources of active thermography. Still, independent from the present differences in their classification of energy sources, they both imply the necessity of a thermal excitation, which is vital for performing an IRT inspection.

Table 3.2.1: Types of thermographic procedures [5]

Evaluation	Excitation	
	Active	**Passive**
Qualitative	Examination of thermal patterns/radiation distribution	
Comparative	Differential quantities	Differential quantities
Quantitative	Absolute quantities	Absolute quantities

The data gathered through IRT inspections can be used differently in the evaluations, and three types of IRT are defined accordingly as: qualitative, comparative and quantitative thermography (Table 3.2.1). In *qualitative thermography*, patterns in radiation density or apparent temperature distribution are analysed just to reveal the existence of anomalies and locate their positions [3, 5]. In *quantitative thermography*, on the other hand, absolute quantities, such as temperature, are determined and evaluated from the measured radiation values to determine seriousness and classify or characterise the flaw [3, 5]. In *comparative* *thermography*, differential quantities, such as temperature differences, are evaluated. To do this, either the same test object is observed at different times under conditions that are as similar as possible, or different objects are observed under an identical test with the same conditions [5].

In active thermography, as used in EN 16714 [5] and EN 17119 [6], different types of applications are also defined depending on how unsteady heat flow is excited. These types are: pulse thermography, step thermography and lock-in thermography. Both in *pulse* and *step thermography*, the external energy source is activated in intervals. However, the duration of the pulse is significantly less than the time needed to record a thermal signature of the defect in the case of the former, while the signature appears during excitation in the case of the latter [6]. In *lock-in thermography*, on the other hand, the intensity of external energy source is periodically modulated for temporal excitation [6].

3.2.3. International standards on the use of IRT in building pathology applications

International standards that provide detailed explanations on the use of IRT for building diagnosis within pathological context are currently limited in number (Table 3.2.2). There are also some others that address IRT as one of the techniques that can be used to detect a given problem or to inspect a given building element. However, they do not detail IRT use much. Additionally, standards that refer to IRT as a supportive tool in determining thermal characteristics/behaviour of building elements are also present (e.g. ASTM C1046 [7]), but their relation with building pathology field is relatively indirect.

In the first group of aforementioned standards, IRT use is explained generally for the purpose of detecting a hidden/subsurface defect, rather than determining the root causes of a defect. The building element under consideration is building envelop in all, and they explain procedures to detect and evaluate thermal irregularities, air leaks and/or moist components *qualitatively*. The main intention is to locate relevant ‘abnormal’ surface temperature distributions, and then to assess the type and extent of the defect causing it (e.g. missing/damaged insulation). Among these standards, the use of reference thermograms is suggested in the ISO 6781 [8], ASTM C1060 [9] and EN 13187 [10] standards either to decide the abnormality of a temperature distribution or to assess the type of defect. However, they cannot be defined as comparative thermography applications, since a procedure to use differential quantities as explained in [5] is not indicated.

Regarding the excitation, in the detection of thermal irregularities, a nearly steady-state heat flow through the envelope is requested [8-10], where use of space-conditioning systems of building might sometimes be necessary. In the detection of air leaks, in addition to temperature difference between interior and exterior environment, a given air pressure difference is requested [10, 11, 12], where use of the ventilation systems of building might be necessary when available. In the detection of wet insulation in a roof system, solar heat gain and/or exterior-interior air temperature difference are suggested for stimulation purposes. When the passive thermography definition given in [4] is considered in a broad sense, all of these can be classified as *passive thermography* applications. The necessary stimulation can be obtained by using already available systems of the building, which is similar to the case using solar heat gain.

There is also another international standard, ASTM D4788 [13], which is actually not on diagnosis of buildings but bridge decks. It is a resource utilised in research studies regarding the inspection of delamination in buildings. In this standard, solar exposure is employed for thermal stimulation just to locate areas with delamination by assessing surface temperature distribution anomalies. Thus, it can also be defined as *qualitative* and *passive thermography* according to [4].

Table 3.2.2: International standards on the use of IRT in diagnosis of buildings and other structures

Standard No.	First published in	Evaluation	Excitation [a]	Main subject of concern	Building element / structure inspected
ISO 6781 [8]	1983	Qualitative	Passive [b] ΔT_{e-i}	Thermal irregularity	Building envelop (General)
ASTM C1060 [9]	1990	Qualitative	Passive [b] ΔT_{e-i}	Thermal irregularity	Building envelop (Framed building)
ASTM E1186 [11][c]	1998	Qualitative	Passive [b] ΔP_{e-i}, ΔT_{e-i}	Air leakage	Building envelop Air barrier systems
ASTM C1153 [12]	1997	Qualitative	Passive SG, ΔT_{e-i}	Moist/wet component	Roof system (Classical flat roof)
EN 13187 [10]	1999	Qualitative	Passive [b] ΔT_{e-i}, ΔP_{e-i}	Thermal irregularity Air leakage	Building envelop (General)
ASTM D4788 [13]	1988	Qualitative	Passive SG	Delamination	Concrete bridge deck

Notes - [a]: *According to definitions given in ISO 10880 standard* [4]
[b]: *Excitation with ordinary services systems of building as energy sources*
[c]: *Methods other than IRT are also explained*

Symbols and abbreviations - ΔT_{e-i}: Exterior - interior air/surface temperature difference
ΔP_{e-i}: Exterior - interior air pressure difference
SG: Solar heat gain

3.2.4. Evolving uses of IRT in building pathology applications

In detecting a particular building pathology problem by IRT, usually the primary determinants regarding the appropriate procedures are: (i) the characteristics of the element to be inspected – *e.g. its assembly, materials used*, (ii) the excitation method in general and in particular, and (iii) the evaluation method in general and in particular. Although there are standards on the use of IRT for some pathological problems, they either concern a particular construction type (*e.g. framed building, concrete deck*) or employ a particular excitation and evaluation method (*e.g. qualitative evaluation employing exterior-interior air or surface temperature difference* - ΔT_{e-i}) as given in Table 3.2.2. Therefore, scientific research studies on detecting these anomalies are still made concerning different assemblies and materials, and employing different excitation and evaluation methods. This is also in line with the letter and spirit of these standards, since in the ones that are not on a distinct construction type, the effects of the design characteristics of the object inspected and of the environmental conditions during inspection are highlighted both when performing the inspections and assessing the observations. In the following subsections, examples of the evolving uses of IRT in terms of the aforementioned determinants are given briefly for moisture and delamination detection. Examples of the use of IRT in air leak detection are also given as a separate subsection, while examples of crack detection are considered under detection of delamination. In this respect, detailed reviews of IRT studies in literature considering the excitation/evaluation type used, and the anomaly and construction type inspected, can be found in [14] and [15].

3.2.4.1. Detection of moisture

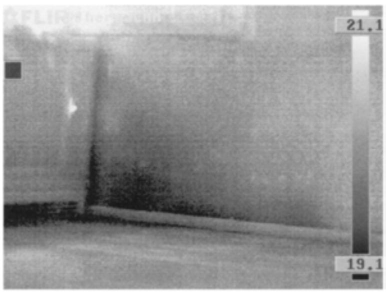
Sources of undesired moisture in buildings are various (*e.g. rising damp, condensation, leaking joints*), and IRT can be used to detect local moisture content increases occurring because of these. Concerning the moisture problems in walls, the standards given in Table 3.2.2 suggest employing $\Delta T_{e\text{-}I}$ for thermal excitation taking *increased thermal conductivity* of moist material into account. Thermal patterns that can be observed due to this characteristic change are briefly given either for walls in general or particularly for moist insulation within a stud wall [3, 9, 10]. In the scientific studies on the other hand, different phenomenon or other material characteristics that vary with moistening are taken into account as well.

Evaporative cooling is one of these, which is usually employed in the inspection of porous materials. Evaporation intensified by air movement obtained either naturally or artificially can create temperature variations in moist areas, and this usually allows a qualitative detection [16]. In porous materials, *increased (specific) heat capacity* of moist material is also employed, especially in time-dependant examinations [17]. In the cases where evaporation is restricted, *increased heat storage capacity* of the moist material is employed in creating temperature differences at deficient areas [18]. The ASTM C1153 standard on roof detection takes also the increased heat storage capacity of the moist material into account, as it is proposed for detecting problems underneath waterproofing membrane [12]. Some examples of in-situ research studies employing these phenomena/characteristic changes as stimulant are given in Table 3.2.3. Laboratory research studies using these are made as well either to assess the success, precision and limits of IRT or to improve and develop procedures followed in its use (*e.g.* [19] *and* [20] *employ evaporative cooling in porous materials,* [21] *discusses the effect of evaporation and increased specific heat capacity in moist wood).*

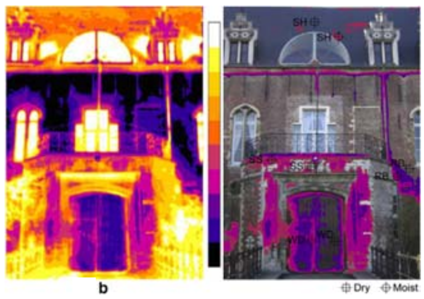
Methods to enhance the thermograms to improve the visibility of moist areas are also investigated in the scientific studies, and Principal Component Analysis (PCA) is one of them with increasing use. In the enhancement with PCA, briefly, thermograms of the object taken in regular intervals during and/or after excitation are processed to highlight the defect. Some examples of its use in in-situ inspections are given in Table 3.2.3 as well.

Table 3.2.3: Examples of IRT methods used in moisture detection in buildings and of in-situ research studies.

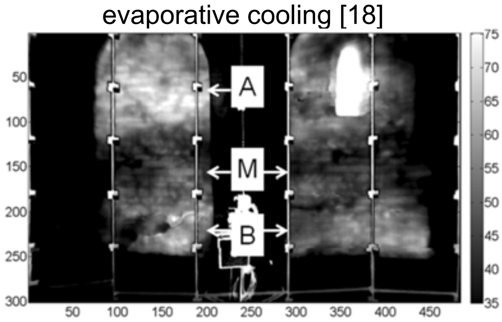
Construction characteristic	Excitation*	Stimulant / Phenomenon	Evaluation	In-situ research study example
Stud wall	Passive *Solar gain*	Evaporative cooling	Qualitative	[18] (Figure 3.2.2 a)
Masonry wall -Porous surface	Passive *Strong draught*	Evaporative cooling	Qualitative	[16]
	Passive *Solar gain*	Evaporative cooling	Qualitative	[22]
	Passive	Increased specific heat capacity and heat retaining period	Qualitative + enhancement with PCA	[23] (Figure 3.2.2 b)
	Passive *Solar gain*	Increased heat capacity mainly	Quantitative *Amplitude and phase analysis*	[17] (Figure 3.2.2 c)
	Active *Draught by fan*	Evaporative cooling	Quantitative + *enhancement with PCA*	[24] (Figure 3.2.2 d, e)
Masonry wall - Impervious surface	Passive *Solar gain*	Increased heat storage capacity	Qualitative	[25] (Figure 3.2.2 f)
			Qualitative + enhancement with PCA	[26]
*: *According to definitions given in ISO 10880 standard* [4]. PCA: Principal Component Analysis				



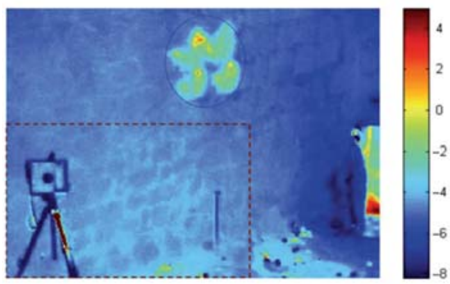
a - Thermogram of a stud wall employing evaporative cooling [18]



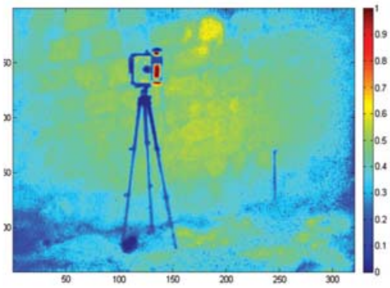
b - PCA image of a masonry wall (left) and superimposition to RGB image (right) [23]



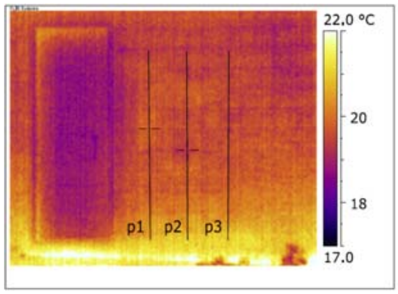
c - Amplitude image of a masonry wall with fresco presenting wetter areas (M) [17]



d - Enhanced thermogram by PCA [24]



e - Saturation Thermal Index (i.e. quantitative evaluation) of red dotted area in (d) [24]



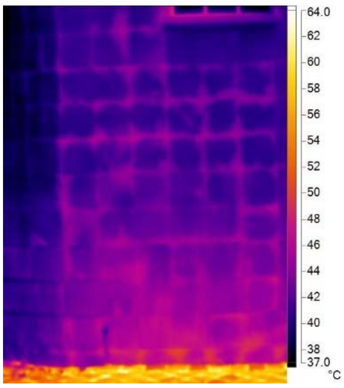
f - Thermogram of a masonry wall with impervious surface employing increased heat storage capacity [25]

Figure 3.2.2 - Thermograms/images from in-situ moisture detection examples.

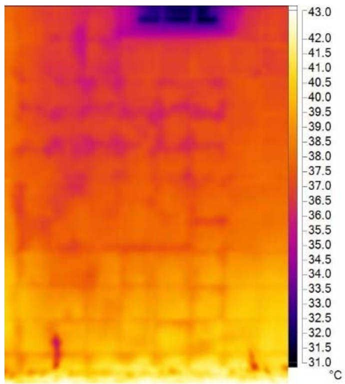
3.2.4.2. Detection of delamination and voids

In detection of a delamination within a building element or a void within a building component, insulating performance of the entrapped air allows generating surface temperature variations at the deficient area. Once there is heat flow within the object inspected, warmer or colder areas on the surface, depending on the direction of heat flow within the object and on the position of the observer, are induced by entrapped air (Figure 3.2.3), and it allows making a qualitative evaluation, such as the one explained in ASTM D4788 [13].

Picture of an adhered ceramic cladding with delamination



Its thermogram during solar heat gain (12:00h) - *delamination shows up with increased temperature*



Its thermogram during heat loss (19:00h) - *delamination shows up with decreased temperature*

Figure 3.2.3 - Thermal behaviour of areas with delamination at different times of a day.

In the scientific research studies, rather than investigations performed at a single moment, periodic/time-dependant investigations are usually preferred. Time-dependent investigations, either with passive or active excitation, may allow quantitative evaluations (e.g. [27]), while still being used in qualitative evaluations as well (e.g. [28]. Laboratory research studies on specimens with artificial delamination also confirm that, once appropriate excitation is provided, characteristics of the delamination such as its distance from the surface can be predicted by comparative or quantitative analysis of time-dependant IRT data with post-processing techniques available such as thermal contrast [29, 30]. The relation between the depth of the delamination from the surface and the necessary excitation time or energy to create detectable indications allow this prediction. As reported in laboratory research studies, the necessary time or energy increases as the delamination depth increases [30, 31]. Similarly, the size of the delamination; i.e. its width, length and thickness are reported to have effects on surface temperature variations generated [29-32], which can allow its characterisation likewise. Regarding the assembly/material of the element inspected, successful applications on different assemblies and materials are present, and some examples of in-situ inspection studies are given in Table 3.2.3. Studies performed on test walls exposed to exterior environmental conditions are included into this table as well, in order to give information on the size and depth of the delamination that can be detected.

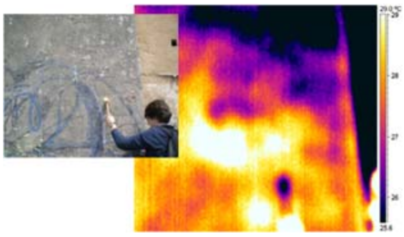
Similar to the case in moisture detection, studies on methods to improve the visibility of area with defect on the thermograms are also made regarding delamination detection. PCA is one of these methods with applications on materials such as concrete [30], ceramic tile [40], reinforced concrete component strengthened with CFRP [41]. Pulsed Phase Thermography (PPT), which allows also the characterisation of delamination, is another method that is reported to help supressing the effects of non-uniform heating [29, 30, 42].

Table 3.2.3 - Examples of IRT methods used in detecting delamination at different materials and of in-situ research studies.

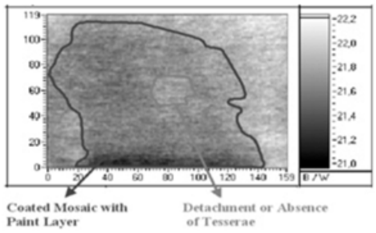
Material	Excitation [a]	Evaluation	In-situ research study example
Render/plastered mosaic	Passive *Solar gain*	Qualitative	[33] (Figure 3.2.4-a) [34] (Figure 3.2.4-b)
	Passive *Solar gain*	Quantitative (*thermal tomography*) *amplitude analysis*	[27] [b] – *the deepest defect's depth is ca. 2 cm, and has a thickness of 5 mm and a diameter of 20 cm*
	Active *Optical lamp*	Qualitative	[35] (Figure 3.2.4-c)
Limestone (masonry wall)	Active *Fan heater*	Qualitative	[28] (Figure 3.2.4-d)
Sandstone (column)	Active *Halogen lamp*	Qualitative and comparative	[36] (Figure 3.2.4-e)
Ceramic tile/mosaic	Passive *Solar gain*	Qualitative	- On ETICS and render [37][b] (Figure 3.2.4-f) - *the depth of delamination is ca. 8 mm with a thickness of 2-3 mm*; - On render [32]; - Substrate not defined [38] (Figure 3.2.4-g), [39]
		Qualitative + *enhancement with PCA*	- On render [40] (Figure 3.2.4-h)

[a]: *According to definitions given in ISO 10880 standard* [4].
[b]: Inspection performed on test wall

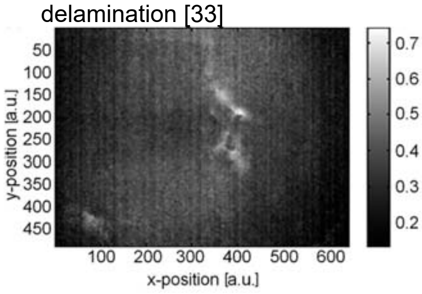
a - Thermogram of a render with delamination [33]



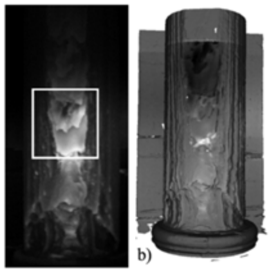
b - Thermogram of a render with delamination [34]



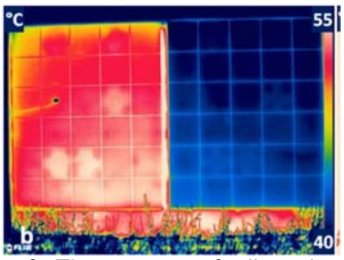
c - Thermogram of a plastered mosaic with delamination [35]



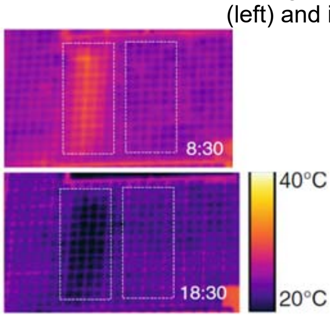
d - Thermogram of crack-like void within stone masonry [28]



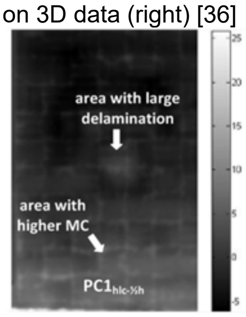
e – Thermogram of sandstone column with delamination (left) and image fused on 3D data (right) [36]



f - Thermogram of adhered ceramic tiles on ETICS with delamination [37]



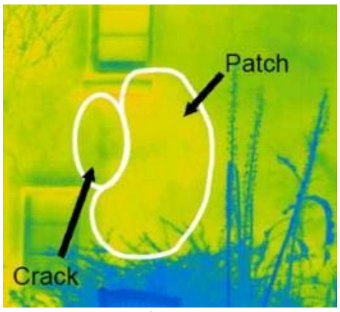
g – Thermograms of adhered ceramic cladding with delamination [38]



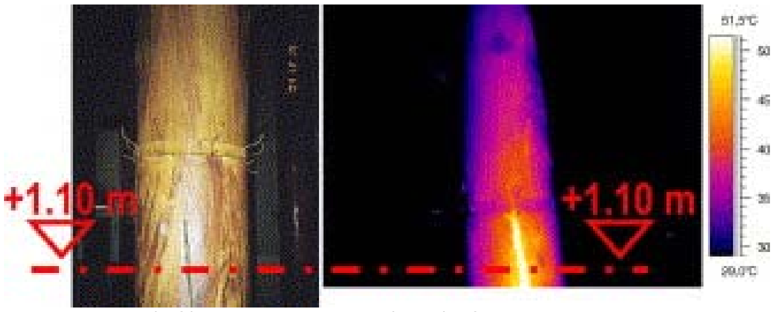
h –PCA of an adhered ceramic cladding with delamination [40]

Figure 3.2.4 - Thermograms/images from in-situ delamination detection examples.

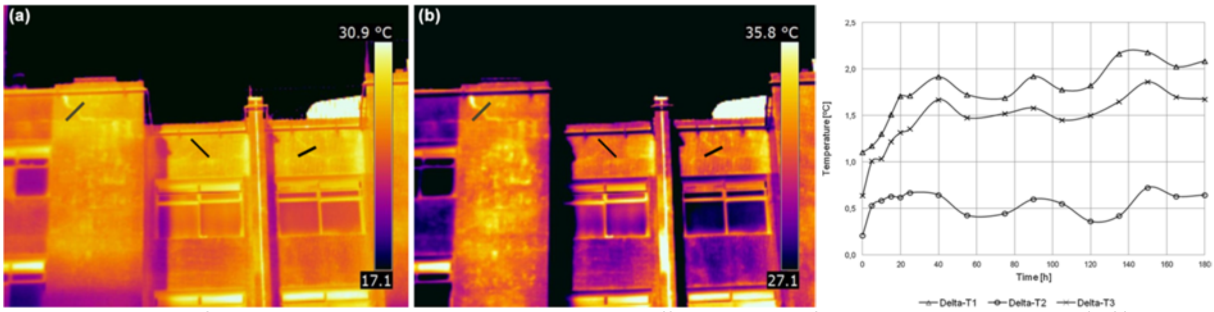
Cracks can also be detected by IRT using the thermal behaviour difference of air within the crack, like in the case of delamination. However, in the case of cracks that are not visible on the surface, there may be some difficulties in detection that arise because of their small width, as discussed in a laboratory research study on reinforced concrete [43]. Yet, they also report that a crack as small as 1.5 mm wide could be identified on the thermograms accurately by proper excitation and using an IR camera with high thermal sensitivity. In the case of cracks that are visible on the surface, presence of surface temperature variations at the area with crack is reported in various studies, and thermograms from some of these studies are given in Figure 3.2.5 as examples. Regarding this temperature variation, as well as being a tool that will assist visual inspection of surfaces, research studies on predicting the damage degree (e.g. its depth) are made considering the time-dependant response to the excitation. In an in-situ inspection study on ceramic claddings for instance, the depth of the cracks relative to each other are discussed considering the evolution of temperate differences observed at cracks over time and numerical simulation results jointly (Figure 3.2.5 -c) [44].



a - Thermogram of render with crack and delamination (i.e. patch) [45]



b - Picture (left) and thermogram (right) of a timber pillar with crack (hottest trace on the thermogram) during heating of the space [46]

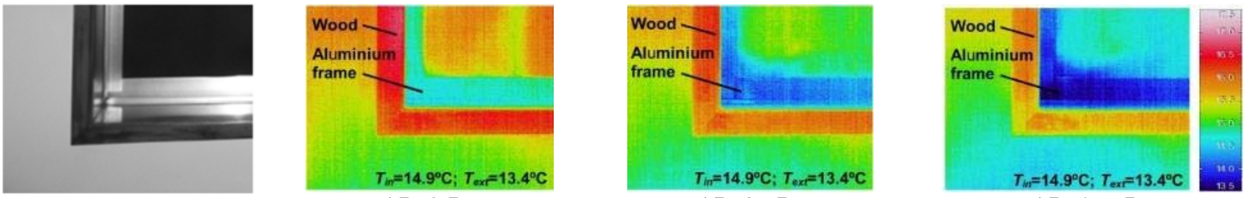


c - Thermograms of a ceramic cladding with cracks taken at different times of heat gain period - 0 min (left), 20 min (centre), and ΔT graph over time (right) [44]

Figure 3.2.5 - Thermograms and images from in-situ crack detection examples.

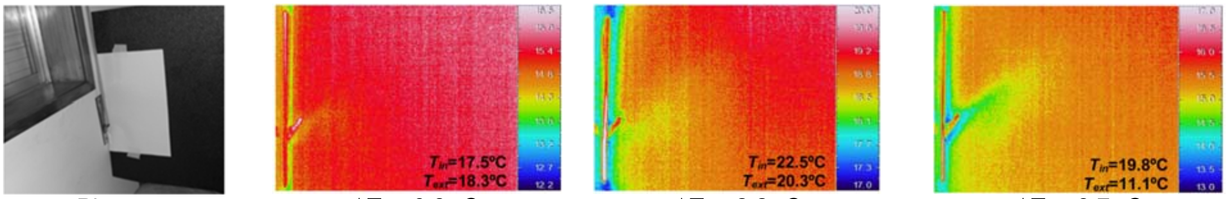
3.2.4.3. Detection of air leaks

To detect air leakage points, present within an element, mainly within buildings' envelope, infiltration of either warmer or colder air than that of the spaces in which the inspection is performed allows creating surface temperature variations around these leaking points. To provoke infiltration, air pressure difference between the spaces (ΔP), separated by the element inspected, is also needed as stated before. In standards, the ΔP and ΔT_{e-i} values recommended for a qualitative assessment of this problem vary. In EN 13187 standard [10] a minimum of 5 Pa ΔP is recommended without any suggestion on ΔT_{e-i}. In ASTM E1186 [11], a greater ΔP, between 10 and 50 Pa, is said to be adequate to perform inspections, while a minimum of 5 ºC ΔT_{e-i} is implied. In the literature, as well as studies directly on the use of IRT for air leak detection, studies on the evaluation of buildings' air tightness by IRT are present. In both types of studies, detections generally rely on ΔT_{e-I} and ΔP. Although the underlying principles used in these studies for exciting surface temperature variations are the same as the ones used in standards, they also provide information on the effects of values selected for them, and on other affecting conditions. A study on detecting leaks at window frame and roller shutter handle exemplifies for instance how the visibility of leakages on the thermograms increases as ΔP increases (Figure 3.2.6-a), and a ΔT_{e-I} as small as 0.8 ºC can produce surface temperature variations allowing detection (Figure 3.2.6-b) [47]. The relative influence of these variables on the visibility of leaking points, a numerical simulation study reports that the effect of ΔT_{e-I} on the surface temperature variation observed is greater than that of ΔP [48]. The duration of the depressurisation is another factor that is reported to have effects on surface temperature variations observed, and this also helps ruling out other anomalies like thermal bridges [48]. Thermograms given in Figure 3.2.6-c exemplify this, where the size and magnitude of the surface temperature variation change with the change in duration. Similarly, in two other studies on the assessment of airtightness of buildings, they explain that they took thermograms at natural state and after 30 minutes of depressurisation to determine places with air leak [49-50]. The thermograms from these studies also present how actual points with leak show up with depressurisation (Figure 3.2.6-d and e).



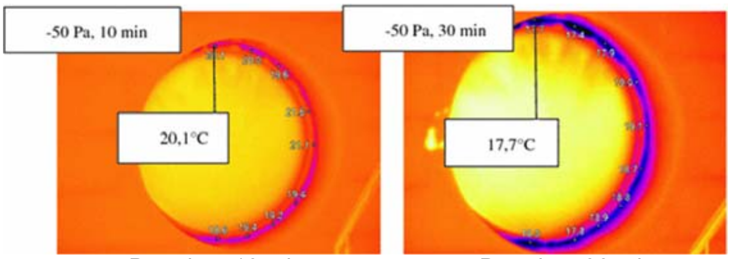
Picture | ΔP: 0 Pa | ΔP: 25 Pa | ΔP: 175 Pa

a - Window frame inspection [47] **-** *ΔT_{e-i}: 1.5 °C, ΔP: As given under thermograms*



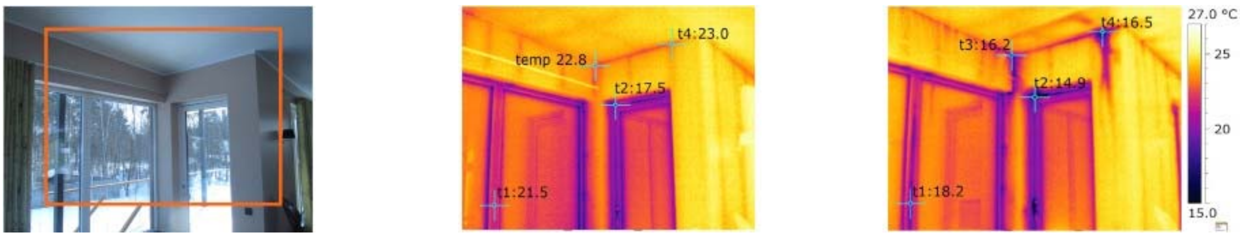
Picture | ΔT_{e-i}: 0.8 °C | ΔT_{e-i}: 2.2 °C | ΔT_{e-i}: 8.7 °C

b - Roller shutter handle inspection [47] **-** *ΔT_{e-i}: As given under thermograms, ΔP: 175 Pa*



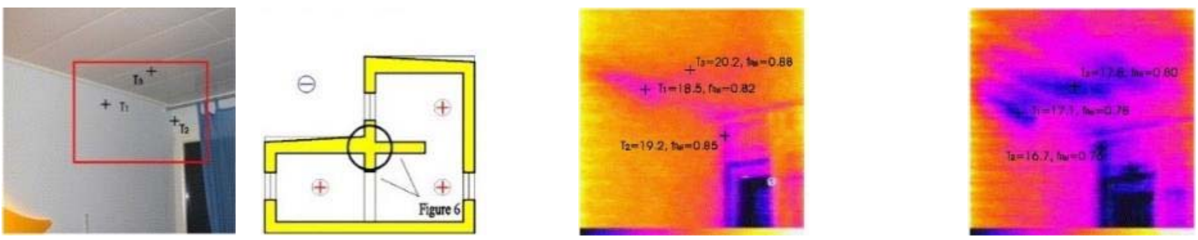
Duration: 10 min | Duration: 30 min

c - External wall - window interface inspection [48] - *ΔT_{e-i}: not mentioned, ΔP: 50 Pa*



Picture | ΔP: 0 Pa (*i.e. without additional depressurisation*) | ΔP: 50 Pa - Duration: ~30 min

d - External wall-floor joint inspection [50] - *ΔT_{e-i}: ≥ 20 K, ΔP: As given under thermograms*



Picture | Schematic drawing | No additional pressure difference | ΔP: 50 Pa - Duration: 30 min

e - External wall - ceiling- roof joints inspection [49] - *ΔT_{e-i}: ≥ 20 °C, ΔP: As given under thermograms*

Figure 3.2.6 - Thermograms and images from in-situ air leak detection studies.

3.2.5. Society and technology pull in building-related IRT studies

Energy use performance of buildings is one of the widely studied subjects in the last decades due to economic and environmental impacts. Thermal performances of existing buildings are also under investigation within this context to improve their energy use performances. IRT, as aforementioned, is one of the tools that can be used in determining thermal behaviour and characteristics of building elements. Therefore, its use in thermal assessment of existing buildings is one of the commonly studied topics in recent years, and a review on these studies can be found in [51].

Methods of and developments in other fields, as well as their trends, influence and inspire IRT studies too. In this respect, methods of automatic detection of problems in IRT applications is one the topics studied in relation with building diagnosis (*e.g. by adapting visible image processing techniques to detect moisture problems* [52] *or by using supervised learning procedures of machine learning to detect voids* [53]). Similarly, use of unmanned aerial vehicles (i.e. drones) is attracting attention in various fields, and its use in IRT inspection of buildings is being investigated too, where a brief review on these studies together with a case application can be found in [54]. Likewise, use of Building Information Modelling (BIM) is becoming a standard practice in the construction industry, and integration of IRT data into as-is BIM models is being studied as well, generally for energy-related purposes. A review on this subject and an application example can be found in [55] and [56] respectively.

3.2.6. Final remarks

IRT finds place in building pathology field in relation with the detection of moisture, delamination and air leak problems mainly. IRT methodology continues to evolve regarding these problems, as well as others, as exemplified throughout the paper. The standards on its use in building inspections usually suggest employing particular excitation approaches that are passive in nature, and IRT data is evaluated qualitatively. Scientific research studies investigating the use of alternative excitation approaches, evaluation procedures and thermogram enhancement techniques widen its fields of use regarding the assembly and materials of the element inspected, improve the accuracy in detecting aforementioned problems, and take a step forward in characterisation of the flaws. Additionally, new forms of use, which are led and inspired by societal concerns such as sustainability and industrial interests such as BIM and drone-use, are providing opportunities to widen its area of use in building pathology field.

3.3. New methods

3.3.1. Infrared thermography

This section should be cited as:
Madruga, F. J.; Lombillo, I.: "Infrared thermography in building thermal envelope: A qualitative and quantitative example", in New Trends on Building Pathology, CIB W86 Report, 2021.

3.3.1.1. Introduction

Thermal transmittance (U-value) is one of the most important parameters of a construction element for the analysis of energy efficiency in building envelopes. It depends on the thermal conductivity and geometry of the materials, as well as on the thermal radiation and convection on the surfaces of the element. It is used, among other applications, to determine the heat losses of a building through the elements that make up its envelope.

The precise determination of the thermal transmittance of an envelope should be a crucial aspect when deciding to carry out an intervention to improve the energy efficiency of a building. Investigations carried out to evaluate the thermal transmittance of the building elements (facades, gaps and roofs), before and after the addition of insulation, indicate that the disposition of insulation material, regardless of the location and the method used, leads to an improved transmittance and reduced CO_2 emissions from the building [1].

Studies carried out conclude that, in the comparisons between the U-values measured experimentally and those calculated analytically, differences are observed, but they do not identify the reasons associated with them. Likewise, the literature has studied how the costs of experimental transmittance measurements based on the quantification of heat flux could be reduced [2]. However, Infrared Thermography (IRT), a non-destructive technique that has recently been widely applied in different fields of knowledge, has hardly been used for providing experimental measurements of the U-value. IRT provides images, in the form of maps of temperature, from which specific areas of the sample can be identified where the evaluation of thermal conductivity and/or additional analyses can be carried out with different techniques [3].

Considering that in Europe buildings are responsible for more than 40% of energy consumption and 36% of total CO_2 emissions, it is evident that, currently, building has become one of the sectors with the greatest potential for energy savings. For this reason, the European Commission published Directive 2002/91/EC on the Energy Performance of Buildings (EPBD, in Spain DEEE), recast in Directive 2010/31/EU, which forces the countries of the European Union to comply with a series of minimum energy efficiency requirements in buildings and their facilities [4].

Therefore, in the present work, the values obtained for the thermal transmittance will be contrasted by the analytical method proposed by the Spanish Technical Building Code

(CTE) and by the use of the IRT, in order to assess the potential use of this non-destructive technique for the experimental measurement of this important thermal parameter of building envelopes, fundamental for the subsequent analysis and selection of the most appropriate therapeutic measures for the energy rehabilitation of existing buildings.

3.3.1.2. Methodological background

The main objective of the study was to evaluate the thermal transmittance of the envelope of a traditional building, to provide an accurate, agile and versatile methodology for evaluating energy performance and implementing energy efficiency measures in these buildings.

The thermal transmittance (U-value), together with the air permeability of the openings, are parameters that intervene in the energy efficiency of the thermal envelope of the building, and must not exceed the values established by the Spanish Technical Building Code (CTE) in its Basic Document HE1, which defines the U-value of an envelope as the heat flow, in steady state, for an area and difference of unit temperatures of the media located on each side of the element under consideration [5].

For this purpose, measurements of the interior temperature were made, using a digital thermometer installed on the internal surface; and collecting data on the ambient temperature outside by means of sensors installed near the building under study, performing the arithmetic mean of each of the measurement points of the referred sensors. The U-value can be estimated using a simple averaging procedure. The disadvantage of the averaging method is that, during short monitoring periods, the thermal capacity of the wall is not taken into account; therefore, the difference in surface temperature across the wall must be used to determine its thermal resistance and add the standard internal and external surface resistors, respectively [6].

On the other hand, it is often said that thermal imaging is an easy to use and interpret inspection tool in building applications that mainly include three specific areas:

- Quality control of new buildings, with the associated problems that there are no visible symptoms of failures;
- Estimation of the conditions of existing buildings where, given their high artistic-historical-cultural value, other quasi-non-destructive methods cannot be applied;
- Energy audits of buildings, taking advantage of their ability to detect heat or energy leaks.

A building is made of different parts from different materials, and infrared thermography is very effective at non-destructive and non-contact inspecting underlying problems. With thermography, it is possible to identify air leaks in the homogeneous part of the envelope or around the gaps (windows, doors, skylights), humidity in facades and roofs, capillary humidity, thermal bridges (for example, facade-structure, facade-window or facade joints-forged), the lack of insulation, the insulation on the facade that creates cold pockets and quality of the carpentry.

This identification is based on three heat transfer mechanisms that are commonly used in building inspection: conductivity differences, change of state (evaporation) and the phenomenon of mass transport. Figure 3.3.1 graphically describes the three mechanisms. The conductivity difference is used to identify both thermal bridges and humidity since they have a higher thermal conductivity than the isolated façade. Trapped water makes evaporation waste energy and the walls feel colder. And the transport of air mass through cracks leaks generates a convection heating or cooling process.

These mechanisms require a temperature gradient between the two sides of the wall. If the gradient can be achieved naturally, either by the effect of solar heating or by the effect of the habitual use of heating in the building, it is called passive thermography. If, on the other hand, the gradient is achieved by forced effects such as heating with infrared or halogen sources, blower-door, etc., it is called active thermography. Active thermography is not subject to external effects or dependencies that limit the use of passive thermography to specific weather situations. But in building, a large amount of energy is necessary to obtain the necessary differences, so its application is limited to study construction materials in laboratory.

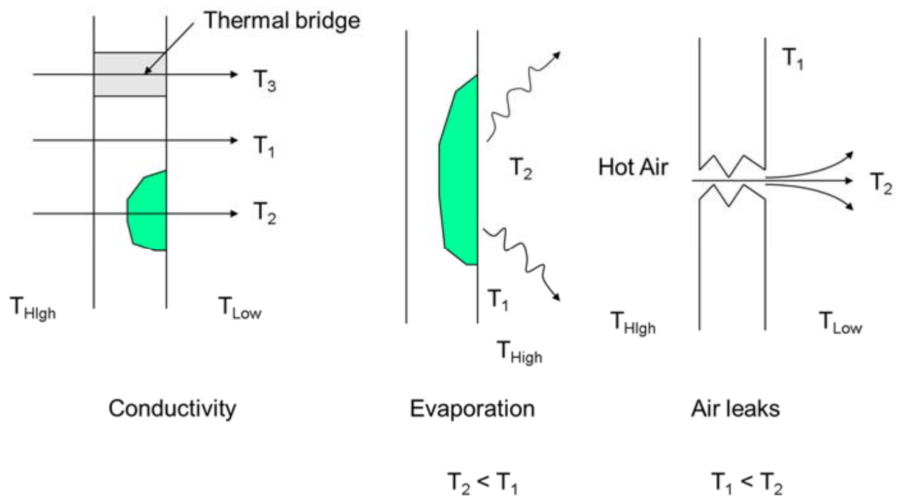


Figure 3.3.1 - Heat transfer mechanisms useful in building inspection: a) conductivity differences; b) evaporation and c) mass transport.

3.3.1.3. Methodology applied to a case study

One of the most important parameters for calculating the energy needs of a building undergoing renovation is the loss of heat due to its construction elements (U-Value [W/m^{2}K]). In most cases, the difference between the theoretical thermal transmittance (obtained by theoretical calculation based on the CTE DB-HE1) and the actual one (measured with instrumentation) can be wide. Therefore, it is important to define some simple but efficient methods for estimating the true U-value in buildings already built.

After presenting the physical or thermodynamic foundations to be used to understand infrared thermography and its applicability, at least one question arises: when is the right time to do thermography in buildings? The moment of greatest thermal gradient between the environment and the object to be measured, i.e. the moment in which the thermal transfer will be maximum between building and environment, should always be sought.

On the other hand, one must consider how to proceed to inspect. Typically, the inspection of a building can be done from both the outside and the inside. According to the climatic conditions, a decision is made to obtain the best results. In energy audits, it is normal to perform them from the inside since heat rarely escapes in a straight line through the envelope and, therefore, the detection point from the outside may differ from where it was originally produced. In addition, wind, rain and sunlight can interfere with the measurement by disturbing the maximum thermal transfer gradient between the building and the environment. Outdoor inspections are only recommended in summer days, if possible, very hot and cloudless nights.

Thermography can also be complemented with other techniques such as infiltrometer to detect air leaks and achieve the tightness of a building. It is based on generating a pressure difference continuously between the interior and the exterior so that a cooler area is observed by means of a thermal imager due to the air flow that passes through that filtration since energy is transferred from that area to the air by the convection phenomenon.

3.3.1.3.1. Building Description

The case study is a building consisting of 18 dwellings on Antonio López Street, Nº. 24, in the city of Santander, Spain. The plot is located in an Urban Intensive Zone, corresponding to a composition in height of a ground floor and nine floors. The building was designed in May 1965 and built in 1967 under the building code M.V. 101 - 1962. The designed facade is illustrated in Figure 3.3.2.

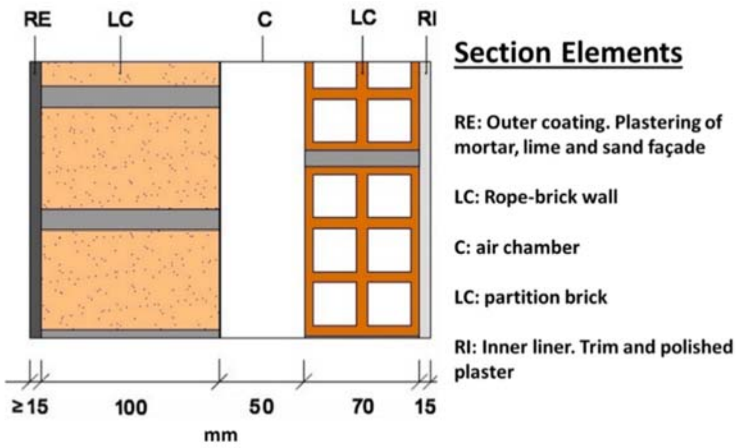


Figure 3.3.2 - Designed facade cross-section.

3.3.1.3.2. Calculation of theoretical transmittance

The theoretical calculation was made based on the CTE DB-HE1, taking into account the data of the materials existing in the original project and, failing that, on approximations based on the tables in Appendix E of said document. To calculate the thermal transmittance in enclosures in contact with the outside air, as is the case study, equation (3.3.1) applies.

$$U = \frac{1}{R_T} = \frac{1}{R_{si} + \sum \frac{e_i}{\lambda_i} + R_{se}} \tag{3.3.1}$$

Where: R_{si} and R_{se} are the surface thermal resistances corresponding to indoor and outdoor air, which take into account the convective and radiative component of the flow; e_i

the thickness of each layer of the enclosure; and λ_i is the thermal conductivity of the material formed in each layer.

Table 3.3.1 lists the thickness, thermal conductivity (according to different references) and thermal resistance of each layer, R_i, as well as the surface thermal resistances. The value obtained for the total thermal resistance (R_T) and for the thermal transmittance of the enclosure (U-value) is also presented.

Table 3.3.1 Technical characteristics of the components of the wall cross-section.

Section elements		***Thickness [m]***	***Thermal conductivity [W/(m·K)]***		***Thermal Resistance [m²·K/W]***	
			NBE-CT79 [7]	AIPEX [8]	NBE-CT79	AIPEX
Outdoor surface thermal resistance	R_{se}	-	-	-	0.04	0.04
Outer Cladding	RE	0,015	0.870	0.875	0.02	0.02
Ceramic brick	LC_{ext}	0,100	0.490	0.625	0.20	0.16
Air chamber	C	0,050	0.024	0.026	2.08	1.92
Ceramic brick (e=70 mm)	LC_{int}	0,070	0.490	0.625	0.14	0.11
Inner lining	RI	0,015	0.300	0.280	0.05	0.05
Indoor surface thermal resistance	R_{si}	-	-	-	0.13	0.13
				R_T [m²·K/W]	2.67	2.44
				U [W/(m²·K)]	**0.37**	**0.41**

3.3.1.4. Experimental campaigns for measurement of UTIR

The monitoring should be carried out during the dates in which there is the highest possible temperature contrast between interiors and exteriors. Starting from the fact that the building's heating was not used, the summer period was chosen as the one that offers better monitoring conditions on the selected days, with different weather conditions, in the months of June and July.

The campaigns have been carried out with a duration of at least 24 hours to take into account the thermal capacity of the wall. In this case, measurements have been taken every 20 minutes for both indoor and outdoor temperatures on June 16 (24 hours), and July 18-20 (48 hours). The weather present in those days was characterized by:

- - June 16: High temperatures and dry environment;
- - July 18: Decrease in temperatures and abundant rains (humid environment);
- - July 19: Slight increase in temperatures, without rain and a humid environment.

A methodology was developed to conveniently calculate thermal transmittance. For this purpose, the studies carried out, for real cases in other works of determination of the transmittance in envelopes [9] [10], were used. These walls have the characteristic that the solar rays do not affect them and therefore there is no natural thermal differentiation between rooms, so it was forced, requiring an active thermography.

The global heat transfer coefficient is calculated from equation (3.3.2).

$$\dot{Q} = UA(T_{IN} - T_{OUT}) \quad (3.3.2)$$

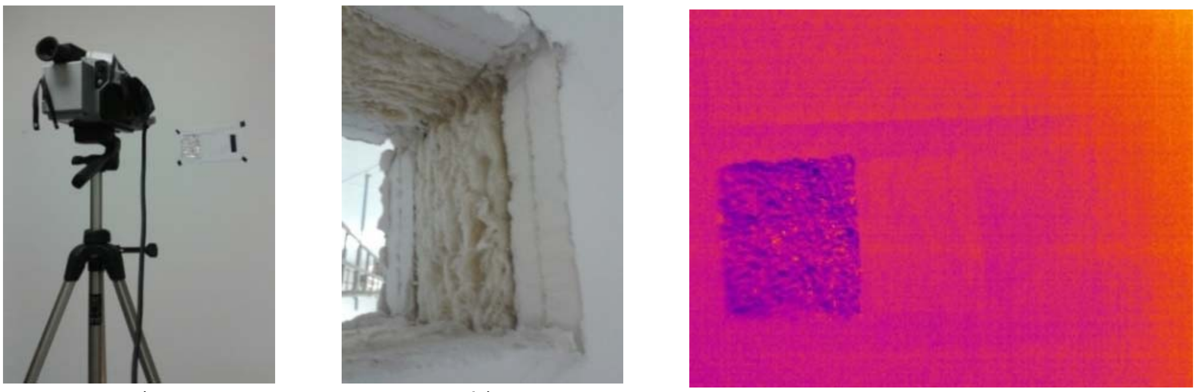
Where $\dot{Q}$ [W] is the heat flux, U [W / m^{2}K] is the global heat transfer coefficient, A [m^2] is the area, T_{IN} [K] is the temperature within the room and T_{OUT} [K] is the temperature outside the room. As stated in other works [9], the U-value can be calculated using the equation (3.3.3).

$$U = \frac{4\varepsilon\sigma T_W^3(T_W - T_{REF}) + h_{IN}(T_W - T_{IN})}{T_{OUT} - T_{IN}} \quad (3.3.3)$$

Where ε is the emissivity of wall surface, σ =5.67 x 10^{-8} W/m^{2}K^4 is Stefan-Bolzmann's constant, h_{IN} [W/m^{2}K] is the convection coefficient, T_W is the temperature of the wall surface and T_{REF} is the ambient reflection temperature in Kelvin.

A necessary condition for the calculation to be correct is that the temperature difference between both spaces (indoor and outdoor) is greater than 10K. The ambient temperature of reflection is calculated by placing crumpled aluminium foil and glued to the wall, to calculate the temperature as an average of that obtained in the area of the paper and using the conversion of radiation to temperature with ε equal to 1. ε is calculated using a black tape of known emissivity, for example, with ε = 0.95, and knowing that the tape and the surface of the wall have the same temperature.

The reliability of this equation has been previously tested in the laboratory with an intramural wall with temperature control of both rooms. The theoretical calculation of thermal transmittance gave U=0.53 m^{2}K/W, while a thermal transmittance value of U_{TIR}=0.46 m^{2}K/W was determined through the presented method. An error of 12.3% with respect to the theoretical value occurred and it influenced largely the union between the different elements of the partition, with the presence of spaces filled with air. Figure 3.3.3 shows images of the experiment reported in the laboratory on the wall studied with temperature control of both rooms.



a) b) c)

Figure 3.3.3 - a) Obtaining thermograms, b) Constituent elements of the partition, c) Thermogram of the test area and aluminium foil to obtain the ambient temperature of reflection.

3.3.1.5. Discussion of the results

The methodology followed in the laboratory was applied to a real facade in a building near the sea in the city of Santander, Spain. In section 3.3.1.3.2, the approximate theoretical calculation of the thermal transmittance has been made, setting it between the values of 0.37 and 0.41. Figure 3.3.4 shows the evolution of the temperature of the wall according to the hours of the day, allowing the cycle of heating, heat maintenance and cooling it undergoes to be observed.

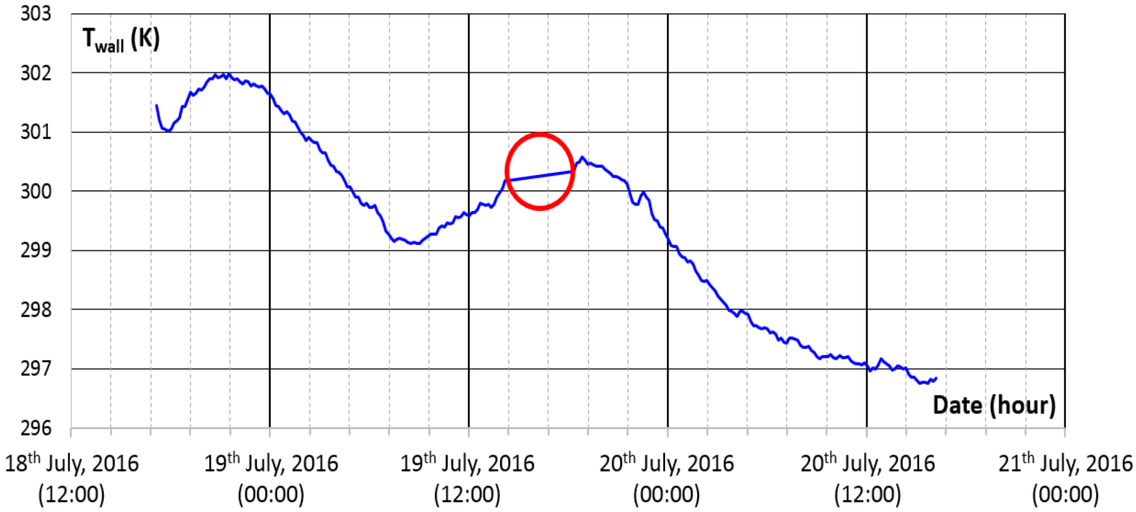


Figure 3.3.4 - Evolution of the wall temperature during the experiment from 18th July at 16:30 to 20th July at 15:30. On 19th July the measurements suffered a cut between 14:30 and 18:15 (red circle).

Applying equation (3.3.3), the results obtained are presented in Table 3.3.2, where the value of U calculated from the measurements of July 18, 2016 is shown, attending to the day and time of the measurement. According to the data obtained from the sensors of the Smart Santander platform, the Maximum Temperature on July 18 was 28.9 ºC at 23:16 and the minimum 19.3 ºC at 06:14 on July 19 was 28.8 ºC at 2:23 and the minimum 21.3 ºC at 23:59 and on July 20 it was 21.2 ºC at 00:03 and the minimum 19.4 ºC at 10:54. These data have been used to determine the outside temperature.

Averaging the measurement yields, a value of U_{TIR} = 0.477, which compared to that theoretically calculated between 0.37 and 0.41 is higher and has an error of 16%. The variance of the results is estimated at 0.005, which is demonstrated by the method. It is perfectly in tune with the uncertainty of the Manning method here exposed that is estimated at 12% for controlled conditions [11]. It is quite accurate and given the parameters used in its calculation, it is highly dependent on the external climatic conditions, which vary the most, comparing the results of the last night and also some point value see 18th July at 5:20 p.m. that distort the average value, since internally the values are very stable and expected.

Table 3.3.2. U_{TIR} calculation and data obtained from the measurement (temperature in K, other data in U.I.)

U_{TIR}	Emissivity	T_W	T_{ref}	h_{IN}	T_{out}	T_{IN}	Date (hour)
0.502	0.949	301.233	300.935	5	307.4	300.935	18/07/2016 17:00
0.490	0.949	300.961	300.619	5	308.2	300.619	18/07/2016 17:10
0.646	0.949	301.012	300.507	5	309.0	300.507	18/07/2016 17:20
0.449	0.948	301.735	300.957	10	328.5	300.957	18/07/2016 21:40
0.431	0.948	301.909	301.238	10	326.0	301.238	18/07/2016 21:50
0.418	0.949	301.901	301.319	10	323.5	301.319	18/07/2016 22:00
0.324	0.950	300.875	300.710	10	308.8	300.710	19/07/2016 1:40
0.521	0.949	300.747	300.531	10	307.1	300.531	19/07/2016 1:50
0.580	0.949	300.791	300.616	10	305.4	300.616	19/07/2016 2:00
0.468	0.950	299.675	300.001	10	289.0	300.001	19/07/2016 5:50
0.442	0.950	299.746	300.070	10	288.5	300.070	19/07/2016 6:00
0.572	0.951	299.790	300.233	10	288.0	300.233	19/07/2016 6:10
0.472	0.950	299.849	299.912	10	297.8	299.912	19/07/2016 13:00
0.451	0.950	299.771	299.823	10	298.0	299.823	19/07/2016 13:10
0.568	0.950	299.809	299.869	10	298.2	299.869	19/07/2016 13:20
0.429	0.950	300.180	300.302	10	295.8	300.302	19/07/2016 20:51
0.416	0.949	300.165	300.283	10	295.8	300.283	19/07/2016 21:01
0.442	0.950	300.152	300.277	10	295.8	300.277	19/07/2016 21:11
0.443	0.951	298.977	299.601	10	277.4	299.601	20/07/2016 0:51
0.467	0.951	298.762	299.415	10	277.4	299.415	20/07/2016 1:01
0.487	0.951	298.802	299.485	10	277.4	299.485	20/07/2016 1:11
0.477	0.950	300.326	300.319	9.286	300.143	300.319	**Mean-Value**
0.005	0.000	0.851	0.279	3.061	209.267	0.279	**Typical deviation**

3.3.1.6. Final remarks and future works

In this communication, the application of infrared thermography for calculating thermal transmittance in facades has been presented. A method used on walls within closed rooms has been used, having verified and established the viability of its use on facades.

The results presented here are the first in which this methodology, based on infrared thermography, has been used to calculate the thermal transmittance, U-value, applied to a real building without forcing thermal conditions either inside or outside.

The results are, as expected, very dependent on these conditions, although the results are quite adjusted, considering that the conditions are not controlled, that the wall under measurement is unprotected against the sea and that the conditions of external winds. It can be concluded that, in the absence of further experimentation, the results are successful.

Measures have been made in periods of 24-48 hours for statistical calculations to avoid the dependencies described previously.

However, as future work, the effect of external wind (speed and direction) could be considered in the model in order to optimize the calculation, or other alternative ways of calculating U-value using thermography could be used [11], although the latter have been demonstrated less precise, through controlled experiments, it would be interesting to check its results in real buildings.

3.3.2. X-ray Computed Tomography

This section should be cited as:
Pinto, R.T.; Flores-Colen, I.; Francisco, M.; Maurício, A.; Torres, I.: "Potential of X-Ray microtomography (Micro-CT) applied to the performance and degradation of mortars", in New Trends on Building Pathology, CIB W86 Report, 2021.

3.3.2.1. Introduction

Since the discovery of X-ray Computed Tomography in the medical field, several studies have been published giving birth to several applications in the industrial field. It has become an important method for studying materials like wood, polymer and it has allowed increasing its application in other materials with greater attenuation characteristics such as concrete, mortars, steel, and metals, among others. X-ray technology enables the development of faster, non-destructive, and three-dimensional testing methods for material 3D microscopy studies inside the object [1, 2].

This non-destructive technique has been applied to cement-based materials and internal visualization becomes possible without damaging the samples under study (Mendes, 2010). An ever increasing interest in new formulations of more sustainable cement-based materials has led to a more in-depth knowledge of microstructure characterization, including a more complete 3D microscopy studies of the physical, structural, mechanical, chemical and mineralogical properties [3-6]. The main anomalies that can be found in cement-based mortars are cracking, crushing, bulging, loss of cohesion, loss of adhesion, efflorescence, blistering, staining, amongst others. The investigation of the microstructure is essential to complement the diagnosis of the pathologic phenomena, since it is possible to have a volumetric bulk analysis of the sample.

Micro-CT (X-ray Computed Microtomography) together with other advanced laboratory techniques such as XRD, FTIR and SEM were considered for the purpose of this study. These techniques in combination with other observations allow the collection of detailed information about the solid and/or voids (pores, cracks,...) structure of the mortars and the results obtained within the framework of this study provide the better studying of their behaviour. As each technique has a given range of applicability and some limitations, it is necessary to combine different techniques to describe the microstructure in detail.

3.3.2.2. X-ray Computed Microtomography

Micro-CT is a non-destructive test technique that allows seeing the internal structure of solid objects. The micro prefix indicates that the resolution is in the range of micrometres. This technique has a wide application in the study of cement-based materials, because it very often enables valid enough geometrical characterization of its internal components, its porosity and evaluation of the development of cracks [4, 5, 7-12]. This technique is based on the interaction of X-rays with the sample. When an X-ray beam passes through the material, it undergoes an attenuation. The intensity of X-ray depends on the compactness and composition of the material. A mathematical algorithm is used not only to compose a three-dimensional image but also to make the study of the sample possible. Some of the potentialities associated with the computerized X-ray microtomography technique are the ability to analyse the three-dimensional spatial distribution of components at microscopic scales; the possibility of repetition of sequential tests; possible detection of internal defects; and evaluation of the voids spectrum (morphologic and/or topologic) of materials. However, this technique cannot be applied to materials opaque to the x-rays and it/or requires big samples. The image resolution is limited due to the equipment manufacture constraints (camera resolution and pixel size); and complementary techniques for investigating of chemical and mineral composition are needed.

The 3D visualization of the samples by means of Micro-CT also allows: i) qualitative and/or quantitative investigating the volumetric content of voids in samples, obtaining a better understanding of fractures and mechanisms of failure in the meso-scale voids spectrum (morphologic and/or topologic); ii) the quantification of damage by the variation of the fraction of volume of cracks and voids; iii) the distinction of the constituents by compactness and measuring the amount of binder [4, 5, 6-10, 12].

3.3.2.3. Examples of microstructural study of mortars

The advanced technique of characterization by means of Micro-CT can become an important method for the comprehension of morphological pathologies. Macrostructure is a familiar concept, but the study of the microstructure can explain the origin and effect of such pathological phenomena, increasing the performance and durability of mortars. Some studies concerned with the microstructure have been conducted and it is sought here to present a small review of what is currently being researched. Micro-CT has become an important technique for visualizing porosity, distribution and pore size, pore connectivity and porous structure density [13]. With the use of this advanced characterization technique, it is possible not only to quantify the volume of pores and their distribution but also to simulate the permeability of the cementitious matrix [14]. Reference was also given to the phenomenon of carbonation at a microstructural level, its evolution over time and the creation of models that can predict this evolution [15,16]. The internal analysis of the pore structure of the mortar can be carried out as a function of the voids spectra in relation to the aggregate grain size and cement used [17]. Gastaldi *et al*. [18] used Micro-CT to evaluate the microstructural early hydration behaviour of cement systems.

3.3.2.4. Conducted and ongoing studies at Instituto Superior Técnico (IST)

Research on the microstructure of mortars has been underway since 2011 and the following studies deserve special mention: Fontes [19] studied the carbonation process and used Micro-CT to observe the pores of lime mortars in detail (Figure 3.3.5). Custódio *et al*. [20] carried out a study that involved test techniques for the determination of open porosity and from this research the interest to use microstructural analysis techniques arose (Mercury intrusion; Micro-CT; SEM) in order to use other scales of observation. Mauricio *et* *al*. [21] state that Micro-CT is a valid technique for compositional and microstructural characterization of mortars, encompassing aspects of production and in-service behaviour (Figure 3.3.6).

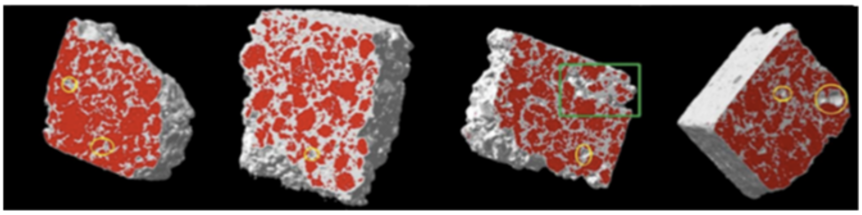


Figure 3.3.5 - Reconstruction of images in a 3D model, for lime mortars, at different ages of curing

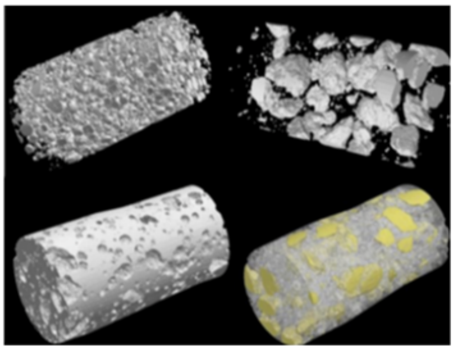


Figure 3.3.6 - Perspectives of 3D models (resolution 10µm). Above, pores and light aggregates (left) and coarse aggregate: marble (right). Below, fine matrix: sand + fine pores (left) and overall model with transparency in the fine matrix (right)

Gominho *et al*. [22] summarised the microstructure of thermal mortars, and an evaluation methodology, which can be applied to any microstructural investigation, was proposed and consists of aggregate analysis; binder analysis (thickness and percentage); aggregate/binder ratio; analysis of the porous structure (quantity estimation); and portlandite/calcite ratio. With the study of the microstructural characteristics, it was possible to characterize different mortars' microstructures, as shown in Figure 3.3.7.

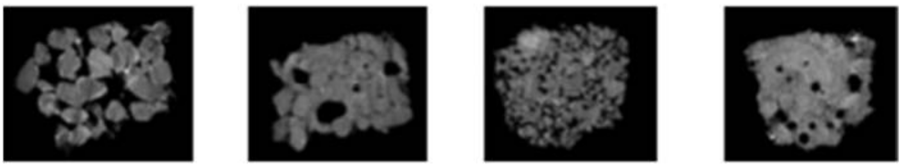


Figure 3.3.7 - Tomographic sections of different types of mortars

Pereira *et al*. [23] used Micro-CT (Figure 3.3.8) to evaluate the curing conditions of mortars in order to complement results obtained in open porosity tests. At present, the purpose of the ongoing IFMortar Project, a joint research project between ITECONS (Coimbra) and IST, is to investigate relationship between the mortar and the support and to investigate the microstructure of the interface. It is expected that Micro-CT contributes to a better understanding of the performance at interface mortar-support and of the relevant degradation mechanisms (e.g. loss of adhesion).

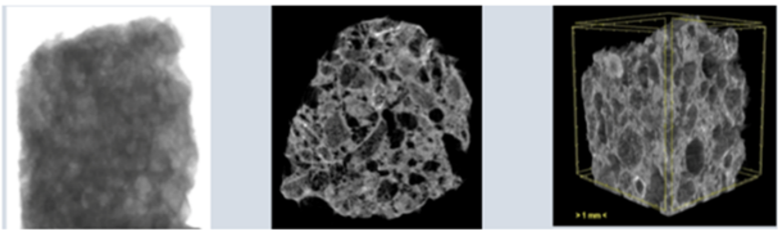


Figure 3.3.8 - Radiography, reconstructed section, and 3D visualization

For this purpose, experimental campaigns are being conducted combining complementary techniques such as Micro-CT, XRD and SEM to microscopically analyse the evolution of the interface during the curing process of the mortars (7, 14 and 28 days, in the first experimental program) (Figure 3.3.9).

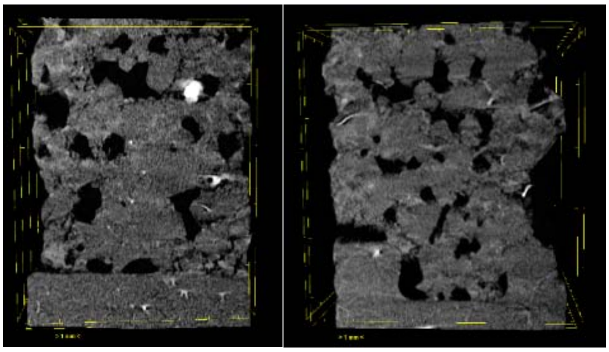


Figure 3.3.9 - Tomographic sections scales of mortar applied on the brick substrate (7 and 14 days, respectively)

3.3.2.5. Final remarks

In general, the microstructural characterization of mortars is very useful in optimizing the properties/performance of mortars in the hardened state. The knowledge of the microstructure is also very important for the study of the pathology of mortars because it allows a bulk comparative analysis of the internal properties of sound and non-sound mortars. The Micro-CT is especially adequate to support mortar studies under accelerated or natural ageing tests. Some limitations of Micro-CT can be easily overcome by making an integrated combination of analytical methodologies. Typically, compositional and chemical analyses (XDR and FTIR) and scanning electron microscopy are integrated in the study of mortars, when there is a need for greater descriptive detail.

Acknowledgements

The authors acknowledge FEDER, for the ongoing research project - IF MORTAR project (POCI-01-0145-FEDER-032223), and the support of Instituto Superior Técnico, University of Lisbon, CERIS and CERENA.

3.3.3. Stress measurement in walls

This section should be cited as:
Blanco, H.; Boffill, Y.; Lombillo, I.; Villegas, L.: “A novel device for continuous assessment of stresses of masonry structures”, in New Trends on Building Pathology, CIB W86 Report, 2021.

3.3.3.1. Introduction

Of the different existing constructive systems, masonry structures represent a high percentage of historic construction [1, 2]. Knowledge of the mechanical characteristics of the materials and the behaviour of the structure play an important role on the process of intervention in ancient buildings. Their characterization requires the evaluation of the properties of the constituent materials, units, and mortar [3]. However, this aspect in masonry structures is not easy to deal with given their considerable heterogeneity, with rigid materials (bricks, stones, etc.) along with more deformable ones (mortar). Moreover, the necessity to know how effective a reinforcement will be, among other aspects, make it necessary to propose new devices and/or techniques that enable the characterization and evaluation of the associated masonry structures.

Being non-destructive techniques, Structural Health Monitoring (SHM) systems are particularly recommendable for the monitoring and verification of the structural behaviour [4, 5]. Through a combination of sensors, the structure under study can be monitored in real time over long periods, providing guidance for making decisions about safety and enabling the adoption of the most reasonable strategies for intervention/maintenance from the technical-economic viewpoint.

In this context, structural monitoring systems enable information to be obtained about the movements undergone by the structure, the effects of atmospheric conditions as well as the magnitude and configuration of the applied loads. For the latter, pressure cells and load cells, fundamentally applied to civil infrastructures, should be highlighted; however, their use in the building sector, and specifically in historic buildings, is very limited.

Moreover, non-minor destructive assessment methods provide valuable information about the mechanical properties and the behaviour of masonry structures with or without minimal damage. In the particular case of techniques based on stress-related aspects, with the aim of estimating the stress level in structural elements, the simple flat-jack [6, 7], hole-drilling [8] and tube-jack [9, 10] tests can be highlighted. However, despite the advantages of these tools, tests of these types only provide a value associated with a specific instant in time, but not continuous monitoring of the stress state.

Consequently, this article presents a device, based on the flat jack technique, applied to continuous stress monitoring over time. It also focuses the onsite determination of service stresses and its continuous monitoring in several masonry buttresses of a historic building, as well as the assessment of the structural safety before, during, and after an intervention process. A brief analysis of the research is performed, and the motivation and methodology adopted are described.

3.3.3.2. Stress device. Laboratory calibration

The device developed enables the determination of the existing stress state, and its continuous monitoring over time. Moreover, in combination with other devices, it is possible to monitor the loading of a structural strengthening applied to a construction. It is composed of a pressure pad (flat jack), a pressure transducer and a system of hydraulic connections designed to monitor the pressure of the fluid inside the pressure pad (Figure 3.3.10).

Figure 3.3.10. Device for continuously monitoring stress level variation.

The device was calibrated in laboratory in order to evaluate the sensor performance under real conditions [11]. For this propose, it was investigated how temperature affects the device's behaviour and, in consequence, different variables were monitored in relation to the ambient temperature, among others: stress variations, internal fluid of the pad temperature, stress device surface temperature, and structural element surface temperature. The deformations of the wall in the zone where the sensor was installed were also monitored with 16 pairs of control points.

Figure 3.3.11 shows a general view of the experimental set-up developed in laboratory. The flat jack used in the experimental campaign was semi-circular with dimensions of 350 × 260 × 3.5 mm, geometry to which the cut was adapted. The oil pressure inside the flat jack was measured and monitored continuously with an A-10 model pressure transducer recording the electrical signal with a portable acquisition and registration system. The variation of the distances between the pairs of points was monitored with a DEMEC deformation meter with a measurement range of 200 mm and a precision of 1 μm.

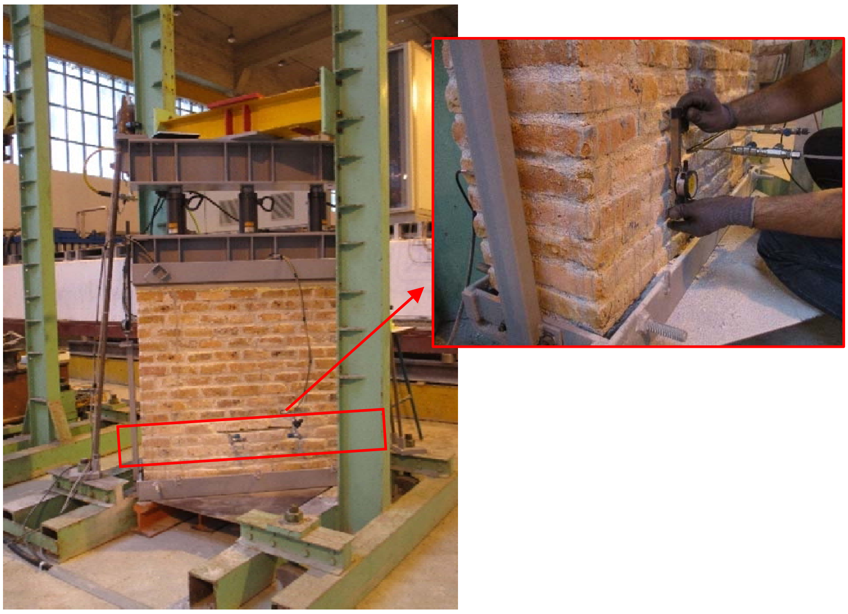


Figure 3.3.11 - General view of the experimental set-up.

The calibration test was carried out on a brick masonry wall built with low-strength bricks and lime mortars (during 10 months) under various cycles of loading. The wall had been built two years before the beginning of the calibration test to favour the carbonation of lime mortars. A wall had a header bond brickwork configuration and dimensions 1050 × 1170 × 275 mm (height × width × thickness).

Before the calibration test of the stress-monitoring device, it was necessary to introduce a preload on the brick wall with the aim of guaranteeing the stability of the deformations that can be produced, thus avoiding possible deformations during the calibration phase. The preload was introduced through three loading cycles of 0.33, 0.41, and 0.51 MPa over a period of 40 days. For the increment of one loading cycle to the next, a stabilisation criterion was established whereby during several consecutive days of monitoring, there would be no deformational increments on the walls of more than 0.015‰ with respect to that recorded the previous day.

The device's response was analysed in each load cycle, and a good relationship between the stress variations applied in the masonry wall and the stresses measured by the device was obtained. A notable influence of the thermal variations on the sensor registers was found, and a correction for temperature was carried out [11].

3.3.3.3. Implementation in a case study

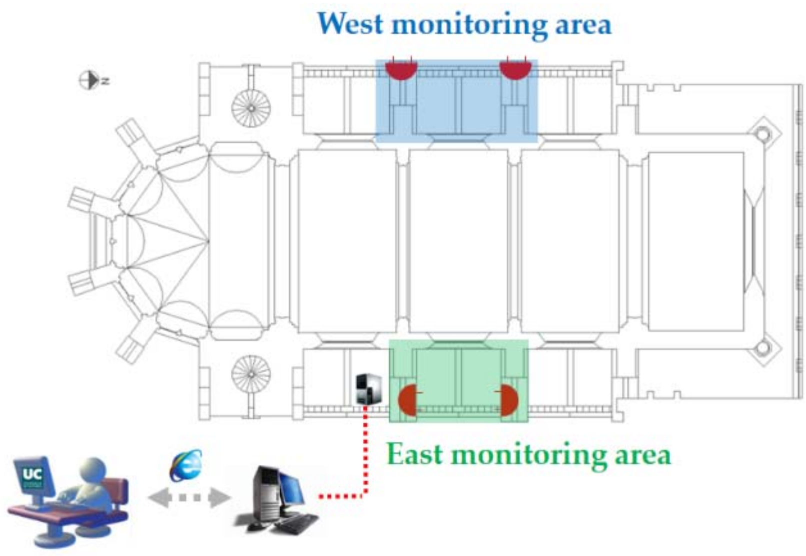
The device was implemented in a 19th century church (Figure 3.3.12) listed as a Historic-Artistic Monument [12]. The building, of more than 100 years old, was built with mixed masonry of low-strength solid ceramic bricks and limestone pieces, with poor bonding. The presence of several rows of bricks with low-strength lime mortar at the lower part of the buttresses and walls of the building was also detected.

Figure 3.3.12 - The building monitored: Church of the “Seminario Mayor de Comillas”, Spain.

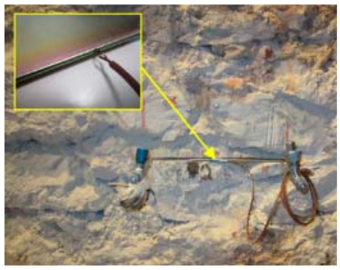
The building, which was in a relatively good state until the eighties, suffered a progressive deterioration process since it became derelict. Consequentially, and as the years passed, several pathological processes were undergone [13], leading to a problem with the stability of the construction. Additionally, during the rehabilitation actuations on the east cloister, some areas were opened between this building and the church, which led to a redistribution of the loads on the building.

Bearing in mind the existing pathological processes, as well as the intervention process to carry out on the building, it was necessary to check the structural safety of the load-bearing elements with the aim of not increasing the serviceability stress levels existing in the masonry structure. For these reasons, four stress sensors were installed in four buttress of the building (Figure 3.3.13a). These were included in an integrated structural health monitoring system developed and applied to the building [13].

Two of stresses devices were included to monitor the effectiveness of a passive strengthening consisting of a framework of reinforced concrete connected to the buttresses, with the idea of favouring the transmission of loads between these and the framework. The other two devices were installed to monitor the intervention devised in the west load-bearing wall. It consisted of the opening of gaps on the ground floor to facilitate the communication between the west cloister and the church and then, the construction of some reinforced concrete columns, which along with an upper lintel and a lower continuous footing guaranteed a uniform transmission of loads. In both cases, the behaviour of these elements were monitored, before, during and after the intervention.



(b)



(a) (c)

Figure 3.3.13 - Monitoring areas and examples of sensors installed.

Additionally, sensors to monitor displacements, manually and continuously, in the zone of the location of the stress sensors were included (Figure 3.3.13b). The monitored displacements were vertical, parallel to the direction of the stresses. This was done to evaluate the relationship between the stress variations and the displacements. This control was done through two procedures, one discrete manual measurement and another with continuous registration. The first was done in both monitoring areas (east and west) making use of the Demountable Mechanical (DEMEC) strain gauge, with a measurement range of 200 mm and a precision of 1 µm. The continuous monitoring was done using four potentiometric transducers installed in the east monitoring area. The use of the systems considered (manual and continuous) enabled the contrast of the results obtained with the two methodologies. The thermal variations around the stress sensors and ambient temperature in the test areas (Figure 3.3.13c) were also monitored, with the aim of monitoring the temperature around the fluid contained in the inside of the sensors, to analyse the possible influence of the ambient temperature on the registers of the stress sensors.

In order to illustrate the potential of the designed system, next the evolution of the registers related to the stresses, displacements (obtained through discrete *in situ* monitoring and by continuous remote monitoring), and the correlation between the two parameters (stress and displacement) and the influence of the thermal gradients on the stress measurements, were analysed.

As an example, Figure 3.3.14 shows the evolution of stresses in the east buttresses of the building during 19 months of monitoring (SS-Buttr02E and SS-Buttr03E). During this period, passive strengthening interventions took place in the east load-bearing wall and the monitoring of this area before, during, and after these. In addition, by means of a discontinuous constant reference, the stress value determined in the masonry (SS-Buttr02E-I and SS-Buttr03E-I) is included.

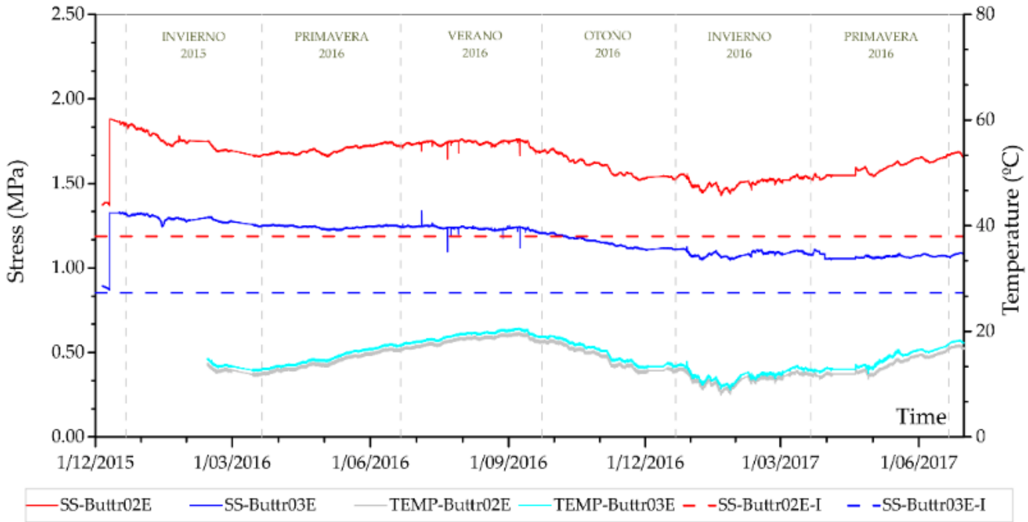
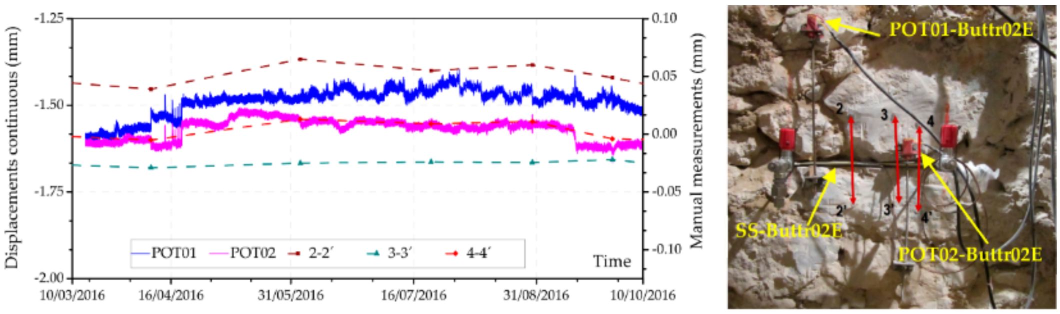


Figure 3.3.14 - Stress evolution in the monitored areas of the building's east buttresses (SS-Buttr02E and SS-Buttr03E). In addition, the temperature was recorded with the aim of assessing the influence of temperature variations on the measurements.

In relation to the evolution of the pressures during the monitored period, it should be indicated that the variations registered were not significant and were influenced, largely, by the thermal environmental changes undergone by the building. Figure 3.3.14 illustrates, in addition to the evolution of the stresses, the values recorded by the thermocouples installed in the sensors (TEMP-Buttr02E and TEMP-Buttr03E). The behaviour related to the seasonal variations can be observed, decreasing values of the stresses as temperatures decreases, and vice-versa. These variations were related to the influence that the ambient temperature exerts on the internal density of the liquid in the pressure pad, which in turn influences the pressure of the system.

In addition to the continuous stress monitoring points, the evolution of the displacements in the monitored areas was monitored by two methodologies (manual and continuous). The aim of these registers was to check the evolution of the stresses in the masonry, while checking the appropriate adjustment between them. In relation to the last aspect, the displacements in the buttresses were monitored through the manual reference points (D-Buttr02E and D-Buttr03E), composed of four pairs of reference points each; and displacement transducers (POT01-Buttr02E and POT02-Buttr02E installed on Buttress 2, whereas POT03-Buttr03E and POT04-Buttr03E were installed on Buttress 3).

In relation to the correlation between the displacements registered by the two methodologies, the evolution of the movements between the manual monitoring point of area D-Buttr02E and the displacement transducers POT01- Buttr02E and POT02-Buttr02E can be seen in Figure 3.3.15. It can be seen that in this period (7 months), the fit of the measurements is very good.



(a) (b)

Figure 3.3.15 - Evolution graphs registered by the continuous displacement sensors and comparison with the manually obtained measures.

The good correlation between the measurements of the manual and continuous displacements makes it possible to contrast the evolution of the stresses in the buttresses of both sides of the church. In this sense, an analogous behavior was obtained in the registers of the two parameters.

3.3.3.4. Final remarks

This research developed a new SHM system that was applied to a historical masonry building under rehabilitation. The novel methodology implemented in several buttresses of the church for continuously monitoring the stress variation was very useful, as it enabled the interventions carried out on the building to be monitored without the occurrence of any significant irregular incidence. The serviceability stresses were at all times maintained below the characteristic strength of the masonry.

Analysis of the long-term measurement results demonstrates the proposed device is capable of automatic and real-time monitoring and can be applied and utilized for safety evaluation of ancient buildings. In relation to the evolution of the stress sensors, their good response during the work actuations should be highlighted, being shown in the registers of the incidences occurring.

Regarding the behaviour of the displacement and stress sensors, it should be indicated that their registers are generally influenced by the thermal changes in the building.

It was found that the displacements registered by manual and continuous electronic monitoring showed good fit. Hence, it is recommended to combine both types of control, not only to increase the number of monitoring points at a reduced cost but also to provide contrast measurements.

A good correlation was also obtained between the variations of the stresses and the displacements. Consequently, the latter make it possible to provide an additional control element for continuous monitoring of the stresses.

Finally, the application of the proposed methodology constitutes a useful tool for monitoring and evaluating the stress state of masonry structural elements over time, and it can be used in monitoring rehabilitation work, including the evaluation of the effectiveness of structural reinforcements, monitoring of increments in load because of changes in use, and/or substitution of structural elements.

3.3.4. Identification and assessment of biological growth on building façades

This section should be cited as:
Borsoi, G., Viegas, C.A., Moreira, L.M., Flores-Colen, I., Cooman, Q. De; Van Den Bossche, N.: "Identification and Assessment of biological growth on building façades", in New Trends on Building Pathology, CIB W86 Report, 2021.

3.3.4.1. The bioreceptivity of the built façades

Building façades (composed of mortars, concrete, paints, composite systems, etc.) are commonly exposed to weathering, and, in urban areas, to environmental pollutants or vandalism, which can lead to physical-mechanical (e.g. microcracks, material detachment, cohesion and material loss, etc.) and aesthetical anomalies, such as stains [1, 2].

Stains generally different show a significant variation in origin and morphology, and their origin is often associated to several factors (e.g. water run-off and leaching of the façade, accumulation of dirtiness or pollutants, oxidation of metallic elements, crystallization of soluble salts or calcium carbonate, erosion, etc.). Furthermore, stains are also frequently associated to biological growth [3,4].

The susceptibility to biological colonization is among the most widely known anomaly on building façades, and often identified in Portugal [3, 5]. (Fig. 3.3.16). Among composite materials, External Thermal Insulation Composite Systems (ETICS) are generally prone to biocolonization, due to their peculiar hygrothermal conditions and also to the degradation of the finishing coat (mostly polymeric-based, and thus with abundance of carbon, which favours biocolonization) [6].

Biological growth is a complex phenomenon, linked to the combination of biotic (e.g. organic nutrients, presence of other microorganisms, etc.) and abiotic (temperature, relative humidity - RH%, pH, etc.). Material bioreceptivity is also linked with its physical-chemical characterization (e.g. porosity, roughness, chemical composition, hygroscopicity, pH, etc.) [7].

Biofilm formation can start from phototrophic organisms (microalgae and cyanobacteria), which use light as energy source and CO_2 as carbon source [8] and resist to the lack of organic material or to drying process. Successively, heterotrophic organisms (which need organic nutrient as carbon source) generally develop, such as fungi and bacteria. Filamentous fungi (molds) are among the most deleterious microorganisms for construction materials, due to their diversified and intense enzymatic activity. Furthermore, lichens and mosses can develop [7]. Further details on these microorganisms (e.g. ideal growth conditions, visual identification and location and possible biodeterioration) can be found on Table 3.3.3.

Biodeterioration can be induced by microorganisms, with chemical, mechanical or aesthetical alterations of the surface. As an example, finishing coats or paints based on organic (polymers, pigments) and inorganic (binders, aggregates, fillers) materials are substrates potentially suitable for biological growth. Metabolic activity can produce and excrete hydrolytic enzymes and organic acids, which can chemically attack the substrate and induce material loss and the formation of microcracks and/or stains.

The inclusion of biocides (algaecides and fungicides) is a commonly adopted solution in protective coatings to prevent biological growth. Nevertheless, the efficiency and durability of biocides is generally not declared by producers. Additionally, biocides often have environmental detrimental effects, and for this reason its use and commercialization are normalised [9].

It is worth noting that a protocol for the identification and evaluation of microorganisms was not yet systematically defined. A discussion on the methods available is thus proposed.

As described in the next sections, presumable signs of biocolonization are initially identified by visual analysis, fulfilling inspection sheets. However, the *in situ* sample collection and relative laboratorial analysis, is also a common practice. Analysis by scanning electron microscopy can provide useful hints on the possible presence of biological colonization on the samples. Isolation and identification of culturable microorganisms, as well as phylogenetic analysis based on metagenomic DNA sequencing, can also be carried out for the characterization of the diversity of microbial communities, which sometimes synergically coexist on the building material.

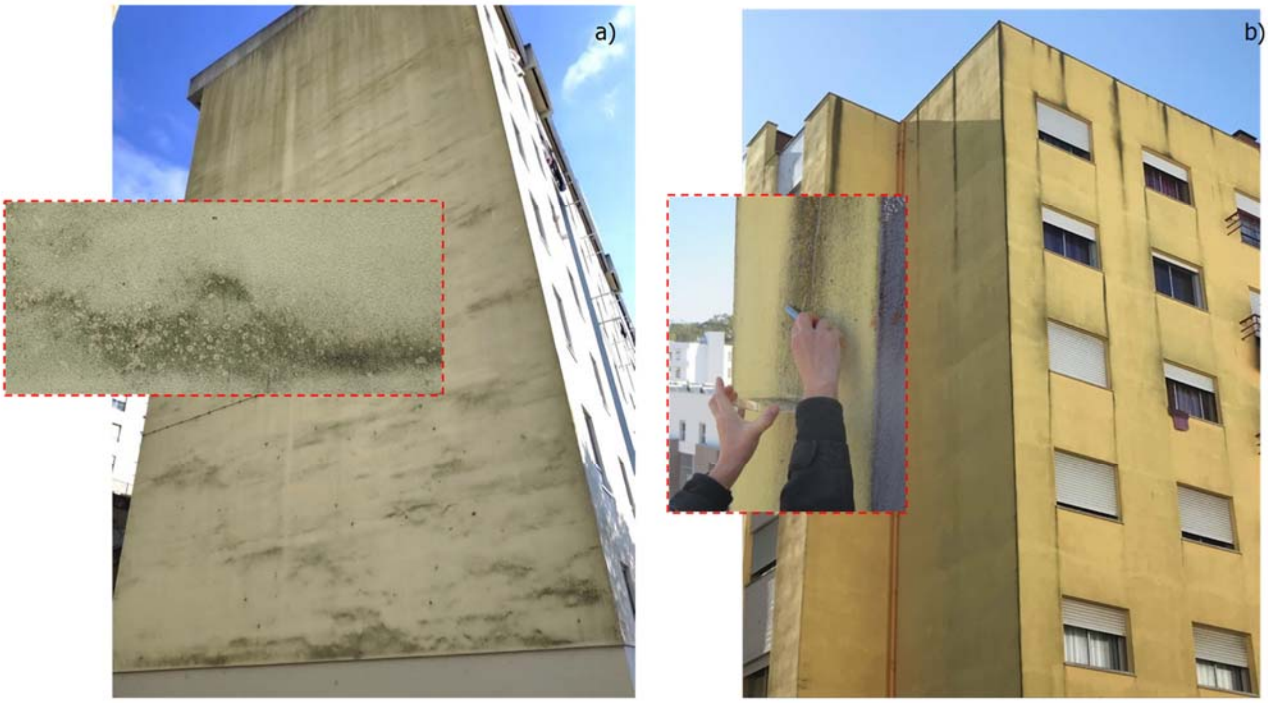


Fig. 3.3.16 - a) Biofilm formation and b) collection of samples of biological colonization on a North-oriented ETICS façades in Lisbon, Portugal.

Table 3.3.3 - Types of (micro)organisms commonly found on ETICS [7,8 10, 11].

Microorganisms	Ideal growth conditions	Visual analysis	Location and possible biodeterioration
Algae (green, red) and *cyanobacteria – phototrophic*	Minerals salts, light, high RH%	Powdery or filamentous deposits, with several colours (green, red, orange, brownish, and greyish for algae; green-blue, and dark for cyanobacteria), often viscous with high RH% conditions	Commonly found in luminous and moist places, even highly resistant to drying-rehydration processes. Growth is favoured on highly absorbent, porous or rough substrates. They frequently lead to chromatic alteration (due to their pigmentation), and can also be substrate for other microorganisms (e.g. fungi, bacteria, etc.)
Filamentous fungi (mold)	Organic matter, water, not phototropic	Stains or spots with powdery surface, with green, greyish, black or brownish colour. They can also form on coatings, with pink to purple stains.	Commonly identified as mold and found on rough and porous surfaces, with accumulation of dirtiness or pollutants. They can easily proliferate on surfaces with high RH% and with algae, and lead to chromatic alterations. Hyphae can deeply eradicate within the surface, inducing mechanical micro-tensions. They can excrete organic acids and produce hydrolytic enzymes, which can induce surface discoloration, biodeterioration, micro-cracks, etc.
Lichens	Minerals salts, light	Formed by coriaceous inlays, deeply eradicated in the substrate, with orange, green, greyish, black colour	Symbiotic organisms, formed by the combination of filamentous fungi with algae (green algae, in most cases) or cyanobacteria. The latter produce organic nutrients for the fungi. They can survive at high T and low RH% conditions.
Moss	Minerals salts, light, low T	Greenish pillow, with prickly or flat proliferation, turn brownish when dried	Commonly found on wet and shadowy areas, with abundance of nutrients and dirtiness. They can incorporate dirtiness over time, and generally form on algae-rich substrate. Although they can be a fertile substrate for plants, they generally do not induce mechanical tensions.
Heterotrophic bacteria	Sulphates, CO_2, organic compounds, etc. Not phototropic	Not visible at naked eye	They might induce substrate deterioration (chemical alteration, biodegradation due to their metabolism) and survive also with low concentration of nutrients. Biodegradation is associated to the complex interaction between the surface and the metabolic activity of the bacterial cells (e.g. enzymatic activity, acid metabolites).

3.3.4.2. Methods

A specific identification of the most prevalent microorganisms can also help in the identification of a proper maintenance strategy, as well as for the development of more bioselective and sustainable biocides for building façades.

3.3.4.2.1. Visual analysis and in-situ inspection

Physical-mechanical surface anomalies (e.g. microcracks, blistering, etc.), as well as stains and possible hints of biological colonization, are generally identified by visual analysis, in accordance with ASTM D3274-95 (2002) [12].

The presence of biological colonization is often associated to other anomalies, such as cracking, formation of other type of stains (e.g. efflorescence, $CaCO_3$ dissolution-reprecipitation, accumulation of pollutants etc.). Uniform or differential stains, often related to superficial condensation [13] and poor construction details or poor-quality materials, respectively, are commonly associated to biological colonization, which is normally found in proximity of water runoff, windows-sills and parapets.

In the case of Lisbon, it is also worth noting that the most dominant yearly wind directions are north and northwest. Therefore, façades with these orientations, being also less exposed to sunlight, have generally higher susceptibility to microbial colonization (Fig. 3.3.16) [14].

In situ visual analysis can be corroborated adopting high-resolution cameras, or magnifying objective lenses, compatible with most of smartphones. These tools allow an in situ initial analysis of micro-constructive details or hints of biological colonization (Fig. 3.3.17).

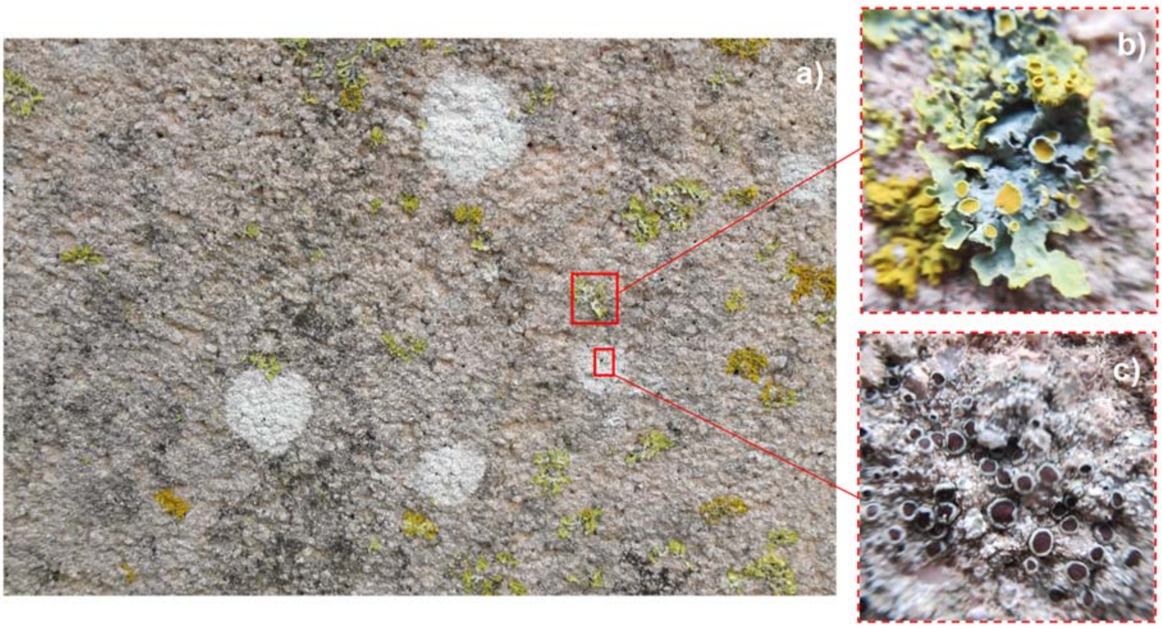


Fig. 3.3.17 - a) Hints of biological growth on ETICS façades: probable presence of b) lichens and c) possibly fungi, observed using a magnifying objective lenses for smartphone.

3.3.4.2.2. Sampling

Samples can be collected using different methods, such as scraping the surface with a sterile spatula and collecting the samples within polyethylene containers (Fig. 3.3.16b); the surface can be also wiped in a $10cm^2$ area with Zaragatoa Critical Swabs, previously saturated with a sterile isotonic solution. Prior to analysis, samples are generally placed in a fridge (4°C) for 16h (prior to microscopy analysis and isolation of culturable microorganisms) or within a freezer at -20°C (for microbiological analysis based on metagenomic DNA).

3.3.4.2.3. Scanning electron microscopy

Laboratorial analysis of samples collected *in situ* can be carried out by scanning electron microscopy (SEM), which can give hints on the morphology and presumable presence of cells and microbial structures (for instance, fungal hyphae, spores, etc.) (Fig. 3.3.18). Furthermore, this analytical technique allows better understand the possible interface interaction among the biological growth and the building material, and thus its biodeterioration [15,16].

However, the morphology or specific features (e.g. dimension, colour) of most of microorganisms is often not completely exhaustive for its full identification. Furthermore, microbial cells can be damaged and/or mixed in the samples with particles of organic and inorganic material with variable shapes.

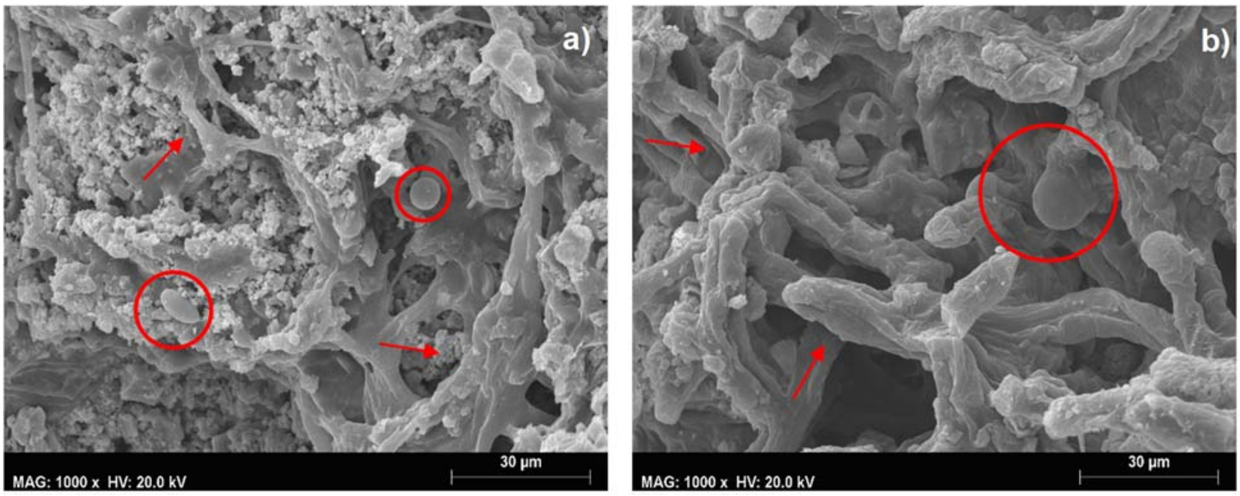


Fig. 3.3.18 - SEM microphotograph of circular (red circles) and filamentous (red arrows) microstructures, which might indicate the presence of round microbial cells and hyphae.

3.3.4.2.4. Culturable microorganism detection and identification

Culturable microorganisms, capable of forming colonies within culture media at laboratorial conditions, can be studied with the aim of detecting heterotrophic microorganisms, i.e. fungi and bacteria.

In this method, a small amount of sample (0.1 g) is diluted in a saline solution and then spread-plated onto the surface of selective culture media (containing e.g. glucose, peptides, amino acids, carbohydrates, etc.), used for the isolation of fungi or heterotrophic bacteria. The formed colonies are then observed, photographed and counted after 5-9 days of incubation at room temperature (Fig. 3.3.19). The preliminary observation of cellular morphology of selected colonies can be performed using an optical compound microscope (Fig. 3.3.19).

Specific colonies (for instance, of the most prevalent and morphologically different filamentous fungi) can be selected for further phylogenetic identification at the level of the genus (please see legend of Fig. 3.3.19). Fungal genus identification can be achieved based on the analysis of partial sequences of the Internal Transcribed Spacer (ITS) variable regions flanking the 5.8S RNA gene of the ribosomal RNA (rRNA) operon, and further homology search using bioinformatics algorithms (e.g. BLASTN) in specific databases (e.g. the National Center for Biotechnology Information -NCBI, or the User-friendly Nordic ITS Ectomycorrhiza - UNITE) [17].

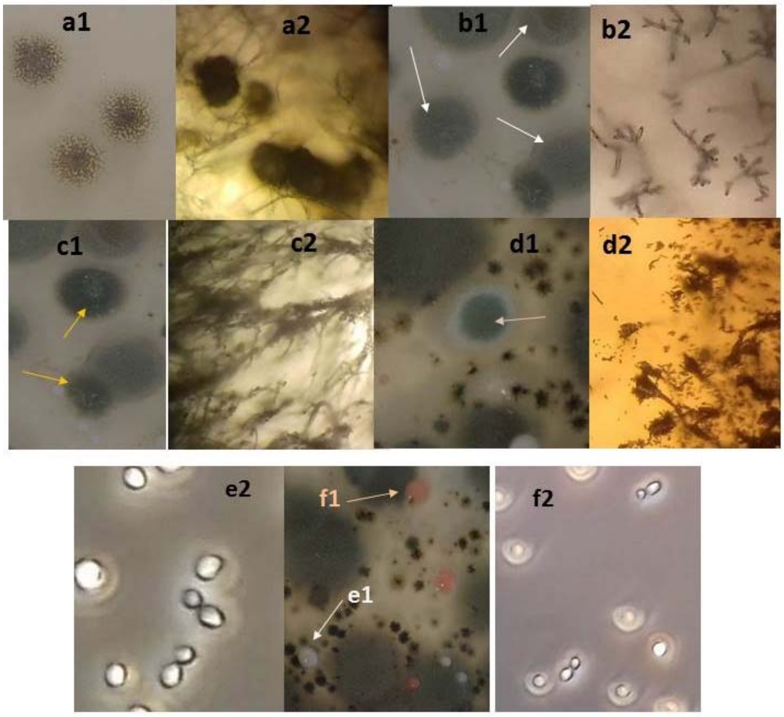


Fig. 3.3.19 - Micropictures of the most prevalent culturable filamentous fungi (colonies type a, b, c and d) and unicellular fungi (yeast; colonies type e and f), isolated from the samples collected from ETICs façades (e.g., as in Fig. 3.3.16.b). Filamentous fungi a (phylogenetic identification: *Didymella* spp.): (a1) colonies and (a2) optical micrograph at 100x amplification; Filamentous fungi b (phylogenetic identification: *Cladosporium* spp.): (b1) colonies (white arrows) and (b2) optical micrograph at 100x; Filamentous fungi c (phylogenetic identification: *Cladosporium* spp.): (c1) colonies (yellow arrows) and (c2) optical micrograph at 100x; Filamentous fungi d (morphological and phylogenetic identification: *Penicillium* spp.): (d1) colonies (pink arrow); (d2) detail at 100x (100x). Micropictures of the two yeast isolates, yeast e (non-identified): (e1) white colonies and (e2) optical micrograph at 400x; yeast f (non-identified): (f1) pink colonies and (f2) optical micrograph at 400x.

3.3.4.2.5. Microbiological analysis based on metagenomic DNA

The culture-independent phylogenetic analysis based on metagenomic DNA allows identifying culturable and unculturable microorganisms, thus providing a more complete description of the microbial community [18]. This analysis is based on the direct DNA extraction from the pool of microbial cells present in the sample (for instance, a specific commercial kit for genomic DNA extraction from soil can be used). Then, variable regions of the marker genes corresponding to relevant small subunit rRNA molecules (e.g., 16S rRNA for prokaryotes and algae and plant plastids, 18S rRNA for most eukaryotes, and specific ITS regions for fungi), are amplified using the Polymerase Chain Reaction (PCR) technique with specifically designed primers. The generated amplification products are then sequenced with the aim of identifying the microbial phylogenetic taxonomic groups in the sample. The obtained gene sequences can be clustered into Operational Taxonomic Units (O) based on a percentage identity with known taxa within specific databases using bioinformatic platforms such as the Quantitative Insights into Microbial Ecology – QIIME. An example of the type of results obtained is shown in Fig. 3.3.20 for a case study in ETICS façades in Lisbon [14].

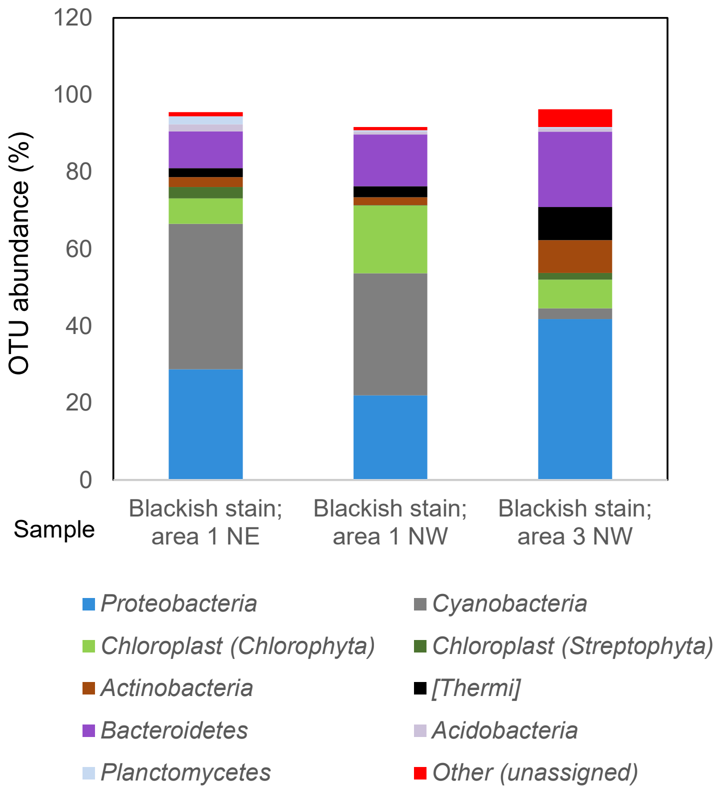


Fig. 3.3.20 - Abundance (%) of operational taxonomic units (OTU) at phylum level within prokaryotic communities and presumable microalgae plastids (chloroplasts), obtained by 16S rRNA gene sequencing analysis based on the metagenomic DNA extracted from samples collected in ETICS façades (as in Fig. 3.3.16 b).

3.3.4.2.6. Final remarks

A proper identification of the most prevalent microorganisms can help in the identification of a suitable maintenance strategy, as well as for the development of more bioselective and sustainable biocides for building façades.

Visual analysis can be a useful tool for the initial detection of the façade anomalies, including biological colonization. In this case, several parameters (e.g. façade orientation, physical-chemical properties of the material, macroscopically visible constructive anomalies) are important for the comprehension of the in-service state of the façade.

Additionally, the collection of sample allows a laboratorial analysis, which include scanning electron microscopy, can provide further hints on the presence of biological species.

However, more in-depth microbiological analysis is fundamental for a comprehensive description of the biological colonization, usually combining different types and affecting in-service diagnosis and repair strategies. In the referred case-study [14], culture-dependent microbiological analysis showed that 6 different type of culturable fungi (2 yeasts and 4 filamentous fungi) and numerous heterotrophic bacteria were predominantly detected in the ETICS façades. In addition, the culture-independent phylogenetic analysis with basis on the metagenomic DNA of the same biocolonization samples provided further evidences of the presence of diverse microbial colonizers, including heterotrophic bacteria, cyanobacteria, fungi as well as photosymbiotic microalgae.

A specific identification of the most prevalent microorganisms can also help in the identification of a proper maintenance strategy, as well as for the development of more bioselective and sustainable biocides for building façades.

Acknowledgements

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4. Uncertainty and risk analysis

4.1. Inspection and diagnosis

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4.1.1. Introduction

Uncertainty and risk are inherent to all activities related to the inspection and diagnosis of the degradation condition of buildings and their components. Even if neither is quantified, surveyors, designers, engineers and prescribers know that every diagnosis has some level of subjectivity, while recommendations and decisions have degrees of vulnerability and unpredictability. Furthermore, the levels of uncertainty or risk are not constant or similar for all events.

Uncertainty during inspection and diagnosis procedures may arise from different steps of the process, namely: while observing, understanding and analysing a degradation phenomenon; while performing a diagnosis that includes a clear identification of a defect, its causes and the best course of action to reinstate the fulfilment of the functional requirements of the element where it was detected.

Risk derives from uncertainty and may be more worrying when the latter is not acknowledged. If the recommendations of the diagnosis are considered as set on stone, the risk is high, since unexpected events may occur. On the other hand, if the recommendations of the diagnosis are not followed nor considered, the risk is even higher, since interventions will be carried out disregarding the existing knowledge, probably assuming that the easiest solution is the right one.

4.1.2. Sources of uncertainty and risk

Considering the methodology of building inspection and diagnosis, uncertainty may be associated with several procedures, namely:

1. Observation of building elements, related to: the professional experience and knowledge of the surveyor; observation circumstances, such as means of access and weather conditions; the expeditious means of observation available and effectively used; the planning of inspection procedures, referring to data search and availability before the procedures;

2. Decision-making during the diagnosis, at different levels:

    a. First level: determining whether additional *in situ* diagnosis methods are needed;

    b. Second level: if *in situ* diagnosis methods are fundamental for an accurate diagnosis, determining which are more adequate considering their potential usefulness, intrusiveness, ease of use, cost, and estimated time for obtaining results;

c. Third level: with the results of *in situ* diagnosis methods, deciding whether they are conclusive and sufficient to continue with the diagnosis;

d. Fourth level: determining whether additional laboratory tests are needed;

e. Fifth level: if laboratory tests are fundamental for a more precise diagnosis, determining those that are more adequate considering their potential usefulness, intrusiveness, cost, accuracy, and estimated time for obtaining results;

f. Sixth level: identifying the defect and its causes based on all the available information (building information, visual inspection and any additional test);

g. Seventh level: developing recommendations based on the diagnosis;

3. Communication of recommendations in a clear and informative way, allowing stakeholders to weigh various factors that influence their judgement and conclusions.

While uncertainty refers to unpredictable and uncontrollable outcomes, risk assesses danger, the possibility and severity of the negative effects of an undesirable event, or, in economic terms, risk represents the difference between the expected financial feedback and that effectively obtained. Despite the uncertainty, when action must be taken, risk is a measurable consequence accounting for the possibility of losing valuable assets.

In the context of building inspection and diagnosis, some examples of loss of value resulting from uncertainty may be outlined:

- Incorrect diagnosis: resources are allocated to tasks whose result does not increase durability, requiring another set of resources to put adequate means and works in place;
- Applying inadequate repair techniques: although having a correct diagnosis and clear recommendations, repair measures may be disproportionate, compromising, for instance, (1) the good functioning conditions of building elements that did not show any defects, or (2) the future dismantling of building elements/materials to be reused or recycled, at the end of the building's service life;
- Decontextualised analysis of the built object: building elements with a relevant historical value may be obliterated;
- Imprudent safety assessment of the building: personal and material damage may occur.

4.1.3. Formulations of uncertainty

4.1.3.1. Bayes' theorem

Decision-making in the context of building diagnosis may be compared to that in the medical context. Wolf *et al*. [1] referred to the competing-hypotheses heuristic and Bayesian probability as complementary strategies to face uncertainty in differential diagnosis. This study acknowledges the presence of uncertainty associated with: (i) clinical information, which is comparable to data on the building and its components; (ii) interpretation of laboratory data, which is comparable to data from *in situ* and laboratory tests performed on building elements; (iii) the relationship between clinical findings and diseases, which is similar to the relationship between defects and causes of defects; and (iv) the effects of various therapies, which are comparable to those of repair techniques on building elements.

The mathematical form of Bayes' theorem may be used when estimates of likelihood of a disease (cause of defect) for relevant groups of individuals (building elements/materials) are available. However, Bayes' theorem can help clinicians (surveyors) manage diagnoses assisting in deciding the relevance of additional data, even without calculations [1].

The use of the Bayes' theorem may be debatable [1], due to: requiring large amounts of data; inconstant availability of probability estimates; difficulty to state hypotheses based on anomalous manifestations; and difficulty to compute probabilities manipulation from memory. Additionally, Bayes' theorem does not conveniently accommodate the hypothesis of multiple causes of defects in the same element, or of non-independence of defects associated with a single cause. However, the theorem's underlying logic may still be useful and valid, in spite of incomplete information and obstacles. It may help to improve systematic problem-solving while performing diagnosis.

Bayes' theorem simplest form is as follows (Equation 1):

$$P(\text{cause}|\text{defects}) = [P(\text{defects}|\text{cause}) \times P(\text{cause})]/P(\text{defects}) \qquad (1)$$

which represents the probability P of a building element/material having a cause of defect given the observation of a set of particular defects. In the calculation, the numerator refers to the product of the probability of having the particular set of defects given the presence of the cause being considered and the probability of having the cause in the relevant building elements/materials population. The numerator is divided by the probability of occurrence of the defects.

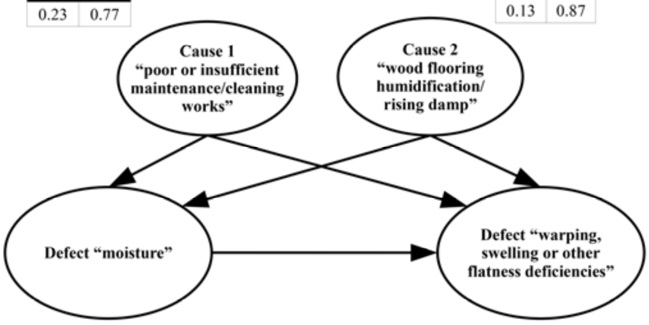
Using data on building pathology in wood floorings [2,3], and considering the competing causes "poor or insufficient maintenance/cleaning works" and "humidification/rising damp", the probability of occurrence of defect "moisture" when "poor or insufficient maintenance/cleaning works" are identified may be computed. The probability of identification of the cause "poor or insufficient maintenance/cleaning works" given the occurrence of "moisture" is 0.33, while the probability of identification of "poor or insufficient maintenance/cleaning works" is 0.23. The probability of occurrence of defect "moisture" given the identification of "humidification/rising damp" is 0.39, while the probability of identification of "humidification/rising damp" is 0.13. Given these data, and applying Bayes' theorem, the probability of occurrence of "moisture" given the identification of "poor or insufficient maintenance/cleaning works" is 0.11. The application of Bayes' theorem in the diagnosis of building defects thus provides a quantification of uncertainty through probabilities.

4.1.3.2. Bayesian networks

The components of complex systems can be reduced to two states, formulating binary hypotheses, in order to simplify the analysis of intricate problems. Bayesian networks provide a framework to represent events using discrete random variables, thus framing probabilistic events. Relationships between events are represented by conditional probabilities [4]. Uncertainty in building diagnosis may be represented in a Bayesian network. In Figure 4.1.1, a simple Bayesian network illustrates the diagnosis of defect “warping, swelling or other flatness deficiencies” in wood flooring considering its relationship with causes “poor or insufficient maintenance/cleaning works” and “humidification/rising damp”, and with defect “moisture” [2].

Cause 1	
T	F
0.23	0.77

Cause 2	
T	F
0.13	0.87



		Moisture	
Cause 1	Cause 2	T	F
F	F	0	1
F	T	0.43	0.57
T	F	0	1
T	T	0.3	0.70

			Warping, swelling or other flatness deficiencies	
Cause 1	Cause 2	Moisture	T	F
F	F	F	0.14	0.86
F	F	T	0.50	0.50
F	T	F	0.83	0.17
F	T	T	0	1
T	T	T	0.40	0.60
T	T	F	0	1
T	F	F	0	1
T	F	T	0.50	0.50

Figure 4.1.1 - Simple Bayesian network with conditional probability tables: occurrence of warping, swelling or other flatness deficiencies in wood floorings [2,3]

A framework for the use of Bayesian networks in the field of building performance has been developed to predict the condition of buildings [5-7]. However, it deals with the uncertainty of progression of degradation instead of the uncertainty of degradation diagnosis.

Performing calculations based on Bayes’ theorem or representing Bayesian networks for degradation mechanisms requires significant sets of useful data and automated systems, which, nevertheless, would only provide probabilities, while it is not impossible for the least likely option to be the correct one. However, uncertainty would be somehow quantified.

4.1.3.3. Possibility theory and fuzzy sets

Another method of dealing with uncertainty was applied in a satellite fault diagnosis application, combining possibility theory with fuzzy sets in a causal relational method in the framework of “fault modes effect and criticality analyses” (FMECA) [8]. In the context of the space industry, real time monitoring provides incomplete symptoms due to: (i) the limited observability of satellites; (ii) additional symptoms being often discovered through a finer analysis of the past telemetry flow; and (iii) the inexistence of effects of the fault at a given moment, as satellite dynamics are not instantaneous. Although the space industry has a sophistication level that does not resemble the characteristics of many buildings, inspection and diagnosis issues may be comparable. In buildings, symptoms are also incomplete because: (i) visual observation does not provide complete data about the building; (ii) building failure's symptoms may be better ana-lysed with chronological data on the building's design, construction and maintenance and operation events; and (iii) some degradation mechanisms may already be in place although no symptoms are observed at a given moment.

Cayrac *et al*. [8] consider a qualitative approach that is more consistent to capture un-certainty, as knowledge is considered incomplete. Therefore, symptoms are distinguished according to being more or less surely observed or possible. Possibility theory [9] uses fuzzy sets to represent gradual aspects of vague concepts (e.g. "large") and incomplete knowledge affected by imprecision and uncertainty. Cayrac *et al*. [8] formulate a possibility measure Π, valued on [0, 1], generally in an ordered scale, ruled by axioms. Additionally, a necessity measure *N* is formulated, stating that the available knowledge *p* is more certain as *-p* is impossible (Equation 2):

$$\forall p, N(p) = 1 - \Pi(-p) \quad (2)$$

Possibility theory requires a set of conventions summarised in Figure 4.1.2 [8]. Then, possibility measure Π is associated with possibility distribution π, representing the available knowledge. Possibility theory contrasts with probability theory since, in the former, stating *N*(*p*)=0 is not equivalent to stating *N*(-*p*)=1.

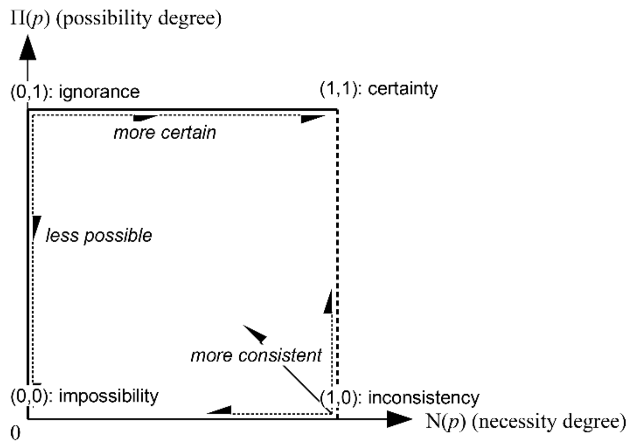


Figure 4.1.2 - Conventions of possibility theory [8]

Causal knowledge considers that no manifestation of fault (defect) can simultaneously be a somewhat certain and somewhat impossible result of a disorder (cause of defects) [8]. Additionally, the sets containing more or less certain consequences of a cause, and more or less impossible consequences of the same cause, do not fully define the population of defects, as the knowledge about the effects of causes is considered incomplete (Figure 4.1.3).

A consistent diagnosis requires finding the set of causes that are coherent with the observations, *i.e.* “defects observed present and “defects observed absent” (Figure 4.1.3) [8]. Additionally, causes are relevant if (i) some of its (more or less) certain resulting defects are indeed present, or if (ii) some of its (more or less) impossible resulting defects are indeed absent. When multiple faults occur, relevant causes can be used as basic units to construct multiple-fault explanations.

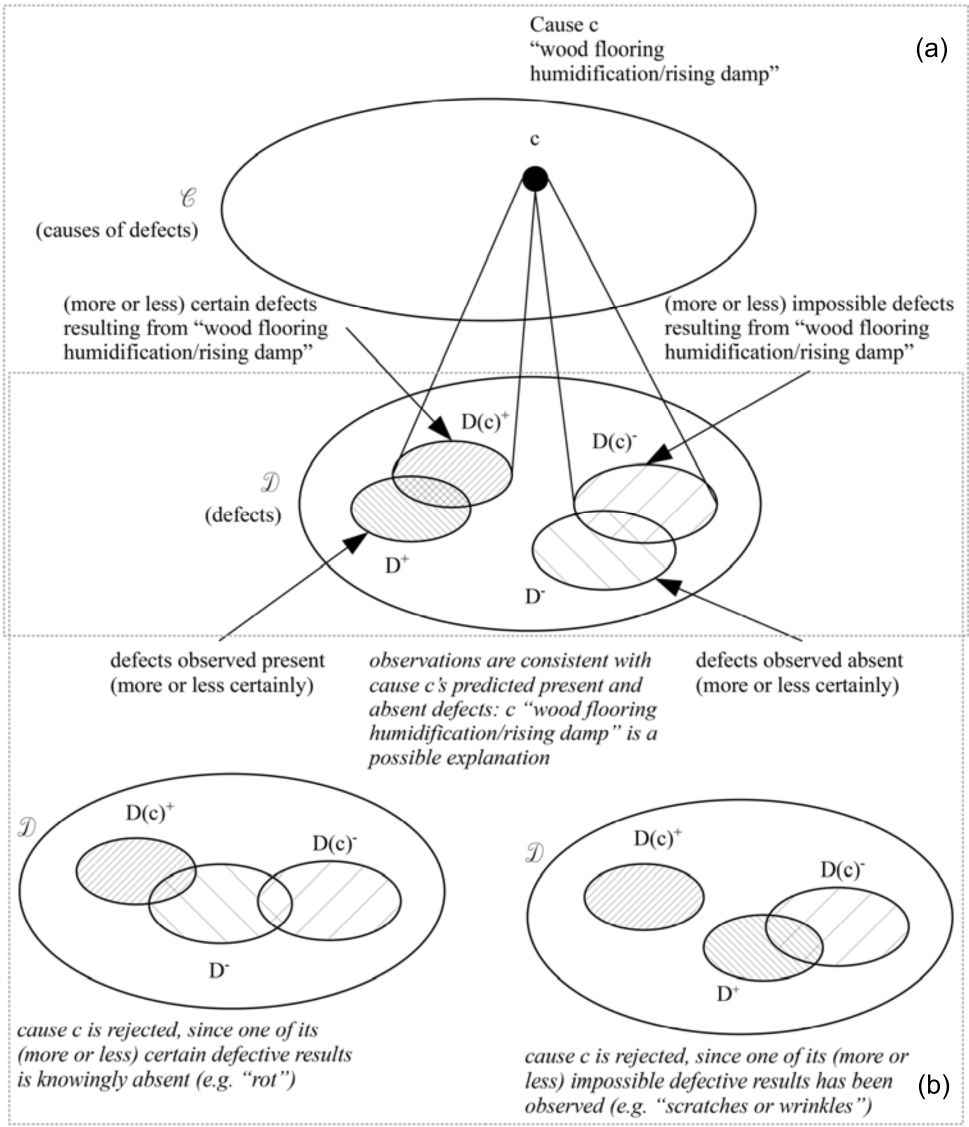


Figure 4.1.3 - Representation of the incomplete causal knowledge (a) and consistent explanations showing no conflict between predictions and observations (b) (adapted from [8])

Moreover, assuming the iterative characteristics of the diagnosis process, measures of utility of testing a given occurrence should be considered [8]. Such a measure would help to maximise the impact of testing on the evolution of the diagnosis process.

4.1.4. Risk-based inspection and maintenance

Studies about infrastructures have already proposed methodologies for risk-based inspection and maintenance, namely concerning offshore and onshore oil and gas installations and operations [10,11]. These methodologies are comparable to those adopted for buildings.

In offshore installations, it is important to document personnel, environmental and economic risk requirements [10]. Moreover, all components and systems should be assessed consistently, uniformly quantifying risk. Considering that operation under “no-risk” is unreasonable, risk-based inspection is supported by overall facility risk acceptance criteria, from which individual risk acceptance criteria are derived for components [10,11].

Deterioration processes must be controlled so that the acceptance criteria are fulfilled throughout the service life of a facility. For offshore installations, four inspection objectives guarantee that [10]: (i) the risks to personnel are “as low as reasonably practicable”; (ii) the risks to the environment are maintained below given limits; (iii) the physical condition of the infrastructure remains within design parameters; and (iv) the target production availability is maintained or exceeded.

The effectiveness of inspection as a means of controlling degradation should be confronted with its impact on the operation of the infrastructure and corresponding costs. Thus, planning inspections should reach a balance between benefits and economic consequences. The minimisation of the infrastructure’s overall service life cost under reliability conditions constitutes an optimisation problem whose parameters are [10]: the number of inspections; the time of each inspection; their qualities; and the mitigation strategy (if necessary).

A risk-based inspection project starts by identifying the acceptance criteria. Then, basic information on the facility is collected and organised in a database system. A qualitative and semi quantitative risk analysis follows, constituting a preliminary analysis of all influential components. This screening process groups components into: (i) those needing regular maintenance and monitoring activities; and (ii) those requiring further detailed quantitative assessments. Risk screening is based on some essential principles [10]: if the probability and consequences of failure of a component are both low, minimum observation is recommended; if the probability of failure is low but the consequences are high, preventive maintenance is recommended; if the probability of failure is high but consequences are low, corrective maintenance is recommended; and if both probability and consequences of failure are high, detailed inspection is recommended. Detailed inspections are then planned and, finally, all components are ranked according to risks and different degradation mechanisms are assessed [10].

The optimisation of inspection plans may be simplified considering constant intervals between inspections and establishing a limit for the annual probability of failure (controlled by the number and moment of inspections). Inspection plans are built assuming that no failures are detected. Thus, every detection requires updating the plans. Moreover, practical limitations will have to be considered when scheduling inspections, such as: availability and capacity of surveyors; and impact of inspection on the operation of the infrastructure.

Additionally, data about one component may influence the known risk of others, which may result in short-notice adjustments in inspection planning [10].

Even though the risk-based inspection framework of Goyet *et al*. [10] helps to control the risk of failure, Khan *et al*. [11] developed a more detailed methodology to avoid considerable assessment variations due to subjectivity. Such a methodology is based on a hierarchical risk structure, complemented by a weighting scheme using an analytic hierarchy process (AHP), fuzzy logic and aggregative risk. The method proposed by Khan *et al*. [11]: addresses both quantitative and qualitative data; considers uncertainty throughout the hierarchical structure; is modular and scalable, thus flexible to incorporate new information; enables cost-benefit analyses; and may be computerised.

4.1.5. Future works

Uncertainty and risk assessment methods have been developed in several areas of knowledge, like medical diagnosis, structural design, infrastructures and equipment diagnosis and inspection or even financial services, just to mention a few. A methodological course of action to analyse un-certainty and risk in inspection and diagnosis is to try to transpose an existing uncertainty and risk assessment model to this field of knowledge. The reasoning associated with either Bayes' theorem, Bayesian networks, and possibility theory and fuzzy sets may be used to represent un-certainty through probabilities or possibilities. The inspection and diagnosis processes may be represented in one of those ways, despite the more intuitive and unsystematised procedures that may be carried out by surveyors. The development of automated systems would benefit from one of the presented representations, useful to develop artificial intelligence systems, but decision-making could also be justified and explained using depictions of the applied logic.

4.2. Maintenance / rehabilitation

This section should be cited as:
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4.2.1. Introduction

Planning of the maintenance and rehabilitation (M&R) actions for buildings and their components, without associated uncertainty and risk, is a difficult goal. Risk is strictly associated with the uncertainty inherent to the real world, but also with limitations of the models used to describe the degradation processes. Moreover, risk can be considerably increased by errors, defects or neglected events [1]. The only way to reduce uncertainty and risk in these planning methodologies is by knowing and considering errors and defects from the earliest stages.

Several decision-making models do not consider uncertainty in the definition of M&R activities. In these approaches, the choices are made by neglecting the future behaviour of the components and there is a tendency to choose low initial cost alternatives. The implementation of M&R planning methodologies that consider uncertainty allows to systematically compute the costs and benefits of each alternative and use this information to aid the decision-maker to select the more rational and economical alternative over a given time horizon, allowing increasing the performance with a reasonable investment. These methodologies, however, require the consideration of mathematical tools to model the processes involved in the deterioration mechanisms and maintenance and rehabilitation activities.

Moreover, the present paradigm has shifted in the construction sector (increase of M&R activities and decrease of new construction), and the consideration of this type of tools gains more relevance. The current codes and standards provide little guidance regarding the appropriate assessment of existing buildings during the service life [2]. These guides are mainly focused on safety, without directly addressing the serviceability and durability of buildings and their components. Therefore, decisions related to whether to continue using a building or their components should be supported by quantitative evidence showing that ageing has not significantly decreased its capacity to withstand or mitigate demands from operation, environment and/or accidents [3].

4.2.2. Uncertainty in maintenance and rehabilitation activities

In decision-making models, M&R decisions are based on several types of information, such as the available budget, cost and effectiveness of different M&R activities, impact on users, environmental exposure, current and future use conditions, among others [4]. However, in these models, many uncertainties are involved [5]. Part of these uncertainties are associated with the ability to predict future events, and the remaining uncertainties are related to the intrinsic randomness of the natural phenomena [5].

The degradation condition of buildings and their components is perhaps the most important piece of data required [4,6] since, directly or indirectly, the definition of the degradation condition is related with most of the information needed to build a decision-making model. For example, the impact of different M&R activities on the degradation condition is important to evaluate the benefits of repair.

The degradation condition can be obtained mainly in two ways: i) based on condition measurements, and ii) forecasting [4]. Condition measurements are provided by *in situ* inspections and allow gathering information on the current condition of buildings, while forecasting uses performance models to predict the future condition of building elements. However, these two methodologies are closely linked. In Figure 4.2.1, the causal effects between these two methodologies and the M&R decision-making models are identified.

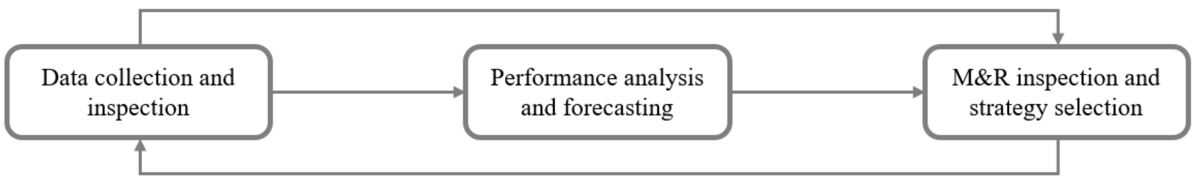


Figure 4.2.1 - Causal effects between the measurement and forecasting of the degradation condition and M&R decision-making model [4]

First, the degradation condition based on condition measurement can be used in two different ways, in the prediction of performance models and in the selection of M&R strategies for the current period. Most of the performance models developed to predict the degradation condition of a given component are mathematical relationships between condition and other variables, such as: age, environment, M&R activities, among others. Therefore, the degradation conditions are used to fit these performance models to predict the future condition of building elements. After that, the performance models can be employed to select M&R activities for the current period and/or plan future M&R activities. Finally, the M&R decision-making model, in addition to selecting M&R activities, allows defining inspection strategies on which future degradation conditions will be collected [4].

Figure 4.2.1 shows that degradation conditions are the base and an important step in any M&R decision-making model. However, these data also have the greatest variability [3]. Both methodologies (condition measurement and forecasting) are characterized by the presence of significant uncertainties, which have substantial life-cycle cost implications. For example, in on-site inspections, the errors can derive from: i) technological limitations; ii) data processing errors; iii) errors due to the nature of the buildings' components surface inspected; iv) errors due to environmental effects; and v) difficult access conditions. On the other hand, in performance models, the error sources are associated with: i) errors in the variables used; ii) inherent randomness; iii) inability to model the true process of deterioration; and vi) lack of in-service measurements and records [3-5].

In this type of models, uncertainties can be classified in two different ways [7]: random and epistemic. The random uncertainty results from the variability associated with the physical processes and environmental degradation agents, caused by the random nature of the data [6,8]. While the epistemic uncertainty is related to the lack of knowledge regarding the phenomenon to be modelled [6,8]. The former type of uncertainty cannot be corrected [4,8], but the latter can be reduced through the acquisition of more and better data [6,8]. Therefore, an appropriate solution to reduce uncertainty over time is through the scheduling of regular inspections. This will allow reducing the epistemic uncertainty and achieve more accurate and reliable models.

4.2.3. Risk in maintenance and rehabilitation activities

The analysis of risks and failures in buildings and their components is a complex task, due to a large range of materials involved, and their varying performance, involving different probabilities of failure [9,10]. Furthermore, the safety of building components is directly related with their performance against loading and weathering conditions, and a poor building performance presents risks towards the safety and health of its users [11]. Several basic risk factors affect the life-cycle costs and maintainability, which should be considered at the design stage for construction, maintenance operations, and any required rehabilitation throughout the life cycle [9].

According to Chew *et al*. [12], a systematic approach to risk management consists of four major steps: risk identification; risk analysis; risk monitoring; and a response process. In the first step, a clear identification of risk factors and their sources applicable to the component in question should be performed [12]. For example, in the construction sector, the main risk factors can be associated with [9,13,14]:

- Accessibility for maintenance;
- Characteristics of building materials and components;
- Design detailing;
- Environmental conditions;
- Requirements for future maintenance;
- Constructability and construction quality;
- Maintenance management process.

In risk analysis, the significant risk factors that had been identified in step 1 [12], are analysed more deeply, by assessing the consequences associated with each risk and its impacts [15]. After that, to mitigate hazards, the risks are monitored through inspections or other monitoring methods [16] and how to manage and respond to such risks should be considered [12,15]. According to Flanagan and Norman [15] and Chew *et al*. [12], the risk response can be classified as i) risk retention: produce individually small, repetitive losses, ii) risk reduction: share risks with other parties, iii) risk transfer: assignment the risks to another party, and/or iv) risk avoidance: refusal to accept risks [15].

Therefore, the first step to avoid and minimize the risks involved with buildings or their components is through the acknowledgement of failure risks [9], and being aware of vulnerabilities and consequences [17]. For example, the detachment of a natural stone tile from the cladding of a tall building in an urban environment has greater consequences than façades with cracking that causes water seepage or other serviceability failures [17].

4.2.4. Conceptualization

An approach based on Petri Nets (PN) is proposed to evaluate the consequences of different M&R strategies to maintain and improve the performance of building components. This model can be described as a full life-cycle model that includes not only the degradation process but also the inspection and maintenance processes. Figure 4.2.2 illustrates the Petri net scheme of the maintenance model.

This maintenance model is considered a condition-based model. First, before any maintenance action being carried out, the condition of the building component is assessed through an inspection. Based on the real degradation condition, the decision to intervene is made. In this maintenance model, four types of intervention are considered: inspection; cleaning operations; minor intervention; and total replacement. In a simplified way, the maintenance model is divided into three main parts (Figure 4.2.2):

i) Degradation process: allows predicting the degradation of the building components over time. This process is described by a linear sequence of five places (p1 to p5) and four timed transitions (t1 to t4). Each place represents a degradation condition, defined in the classification system adopted [18]. Places p1 and p5 represent the best and worst degradation condition, respectively. The transition times between degradation condition are sampled from probabilistic distributions that are fit-ted through inspection records;

ii) Inspection process: allows managing the moments in which inspections are per-formed. The degradation condition of the building components is not continuously known (the condition is considered as unobserved until an inspection occurs, when the condition is revealed). An inspection enables the adoption of the most appropriate maintenance works for tackling existing anomalies with the appropriate priority. This process is represented through the cycle defined by nodes: p6 - t6 - p7 - t5 - p6. A token in place p6 means that an inspection is not required at this time and enables transition t6 that manages the time intervals between inspections. A token in place p7 indicates that is time to perform an inspection. First, one of the transitions t7 to t11 is enabled, revealing the true degradation condition. After that, transition t5 is enabled, allowing the return of the token to place p6;

iii) Maintenance process: identifies the M&R activities to be performed on the building components, considering the constraints imposed on the maintenance strategy and the results from the degradation process. This process is illustrated by places p13 to p32 and transitions t12 to t40. According to the observed degradation condition, the intervention that should be performed is selected. Here, three types of M&R activities are considered: cleaning operations, minor interventions, and total replacement. This information is introduced through places p13 to p27. Tokens in places p13 to p17 mean that cleaning operations must be done, in p18 to p22 that a minor intervention is needed, and in p23 to p27 that a total replacement is required. If there is no token in these places, no interventions should be performed. A token in places p28, p29, p30 or p31 indicates, respectively, that no intervention, cleaning operations, minor intervention or total replacement is required. After that, the token returns to the degradation process by place p32 and transitions t36 to t40. The impact of the M&R activities is modelled through transitions t17 to t31. In this model, M&R activities, when applied, have the effect of improving or maintaining the degradation condition of the component. The impact is quantified based on the historical *in situ* inspection records and is dependent on the type of M&R activity and degradation condition.

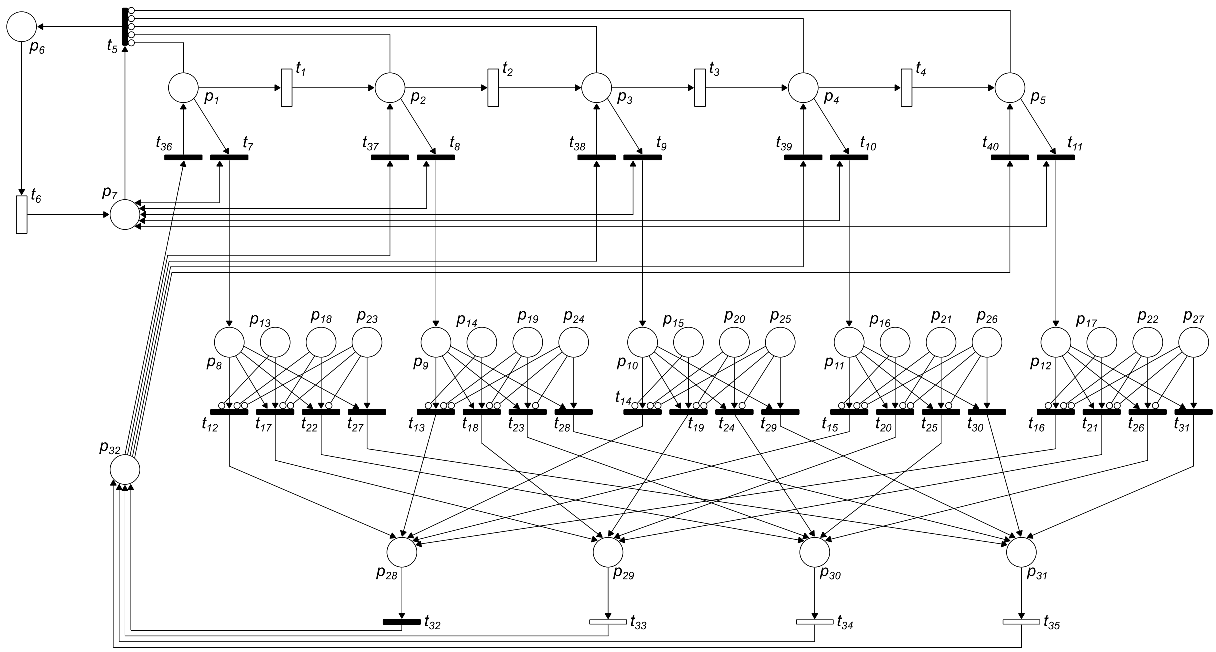


Figure 4.2.2 - Petri net scheme of the maintenance model

This description is a simplification of the maintenance model fully described by Ferreira *et al*. [19].

In engineering, decisions are mostly made in the presence of uncertainties. Therefore, the different types of uncertainty that can occur while modelling M&R activities should be acknowledged and differentiated according to their type and origin [1]. As mentioned, uncertainties can be classified in random or epistemic.

In a few words, the maintenance model, illustrated in this case study, allows analysing the degradation process and the impact of maintenance strategies on the durability of building components. For that purpose, the future degradation conditions and costs are predicted based on historical *in situ* inspection records. Consequently, for this case study, the random uncertainty would be the uncertainty associated with the historical *in situ* inspection records. These records present a high level of uncertainty due to the subjectivity of the inspection procedure [20]. Moreover, uncertainty also arises from the natural variability of the degradation process, which depends on a large set of factors that act simultaneously, such as: materials' quality; design and execution levels; structural typology; environmental exposure conditions; traffic and pollution levels; use and maintenance conditions; among others. On the other hand, the models chosen to describe the degradation process and quantify the impact of maintenance actions will inevitably introduce epistemic uncertainties, mainly due to the limited number of inspection records. Finally, the extrapolation for long periods may also introduce additional epistemic uncertainties. Therefore, considering the different types of uncertainties, the decision on the optimum M&R strategy can be made based on a cost-benefit analysis. Figure 4.2.3 illustrates the presence of the two types of uncertainty in the different layers of the maintenance model.

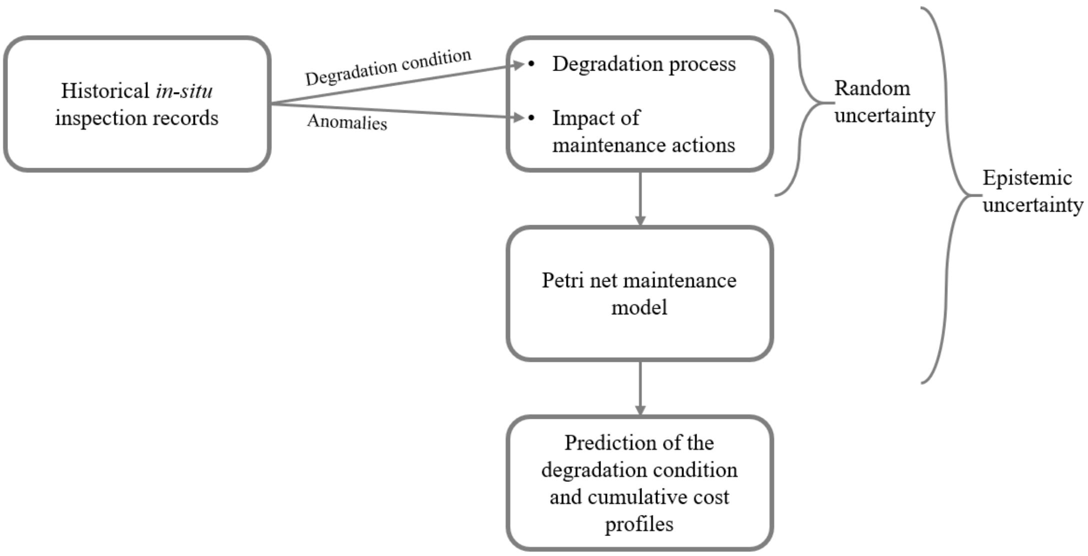


Figure 4.2.3 - Illustration of the presence of the two types of uncertainty in the different layers of the maintenance model

According to Faber [1], the uncertainty associated with the state of knowledge is time-dependent. Figure 4.2.4 shows the observation of an uncertain event when it has occurred. If the observation is perfect, without errors, the knowledge about the event is perfect. However, the future is uncertain and modelling it involves random and epistemic uncertainty. The models available tend to lose accuracy over time. Faber [1] refers that the uncertainty (random and epistemic) associated with a prediction model is transformed into a purely epistemic uncertainty when the event is observed. In other words, epistemic uncertainty can be reduced through the acquisition of more and better data.

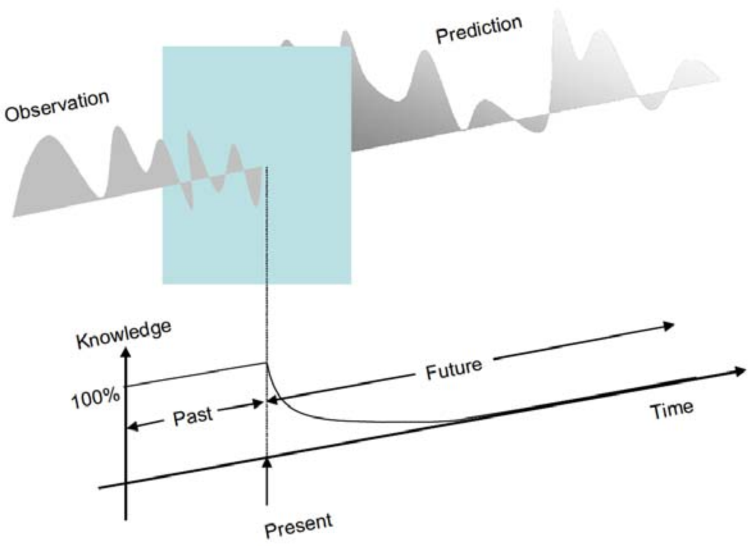


Figure 4.2.4 - Illustration of the time dependence of knowledge (adapted from [1])

4.2.5. Future developments

First, almost more crucial than reducing the risks and uncertainty related to M&R activities, it is fundamental to acknowledge their existence. After that, it is necessary to develop methodologies and strategies to attempt introducing and quantifying uncertainty in the different parts of the decision-making models.

Since a substantial part of the uncertainty arises from lack of information, with the acquisition of more and better data, more accurate and reliable models can be achieved [1,21]. Furthermore, the implementation of approaches based on probabilistic theory will allow quantifying uncertainty through standard errors and, consequently, define acceptable uncertainty levels for the M&R activities.

Moreover, a building is not composed of individual components. When the goal is changed from an individual building component to the entire building, the complexity and the amount of uncertainty increases further, due to the interactions and correlations between the different components and materials, to the variability of performance, and difference in the risk of failures associated with different components and materials.

5. Decision criteria for maintenance/rehabilitation based on anomalies assessment

This section should be cited as:
Flores-Colen, I.; de Brito, J.; Freitas, V. P.: "Decision criteria for maintenance of renders based on anomalies' experimental assessment", in New Trends on Building Pathology, CIB W86 Report, 2021.

5.1. Introduction

Performance-related characteristics defined at the design stage for each building's element must be checked in-service over time, comparing the characteristics with the requirements and identifying the maintenance needs during the life cycle [1]. In this section, decision criteria based on experimental data for renders are discussed.

Decision criteria should be based on: testing results; ratio of testing areas/area of the façade; the acceptable criteria for performance; correlations between in-service parameters; reliability indicators of testing techniques; Example for rendering facades: surface condition (CS); interface assessment (INT); mechanical performance (CM) and physical performance (CFQ).

Figure 5.1 summarizes the relevant factors to in-service performance of rendered façades in view of their use suitability (durability and maintainability). For example, an inadequate render specification can give rise to three types of anomalies with serious consequences, namely cracking/detachment; premature rupture accelerated by water, chemical agents and extreme temperature values; capillary moisture and development of biological colonization. The other relevant factors include location on the façade and interfaces, specific in-service conditions, maintenance policy, agents and mechanisms of degradation, classes of anomalies and performance properties. The combination of those factors influence the reliability of in-situ diagnosis, and therefore, the decision criteria for maintenance.

5.2. Proposal of reliability indicators

An experimental program in Portugal at different times, and in various buildings was carried out for four years and analysed 98 rendered façades [1]. It was possible to prove the useful-ness of the information collected in-situ with the used techniques.

The combined analysis of multiple parameters increased the knowledge on in-service physical (moisture resistance, water permeability resistance, and hygrothermal resistance), chemical (chemical resistance, biological resistance) and mechanical (adhesion to the wall support, cohesive strength, surface resistance, and deformation capacity) properties of rendered walls. In this section, only in-service physical and chemical parameters are discussed. The mechanical parameters were presented in another publication [2].

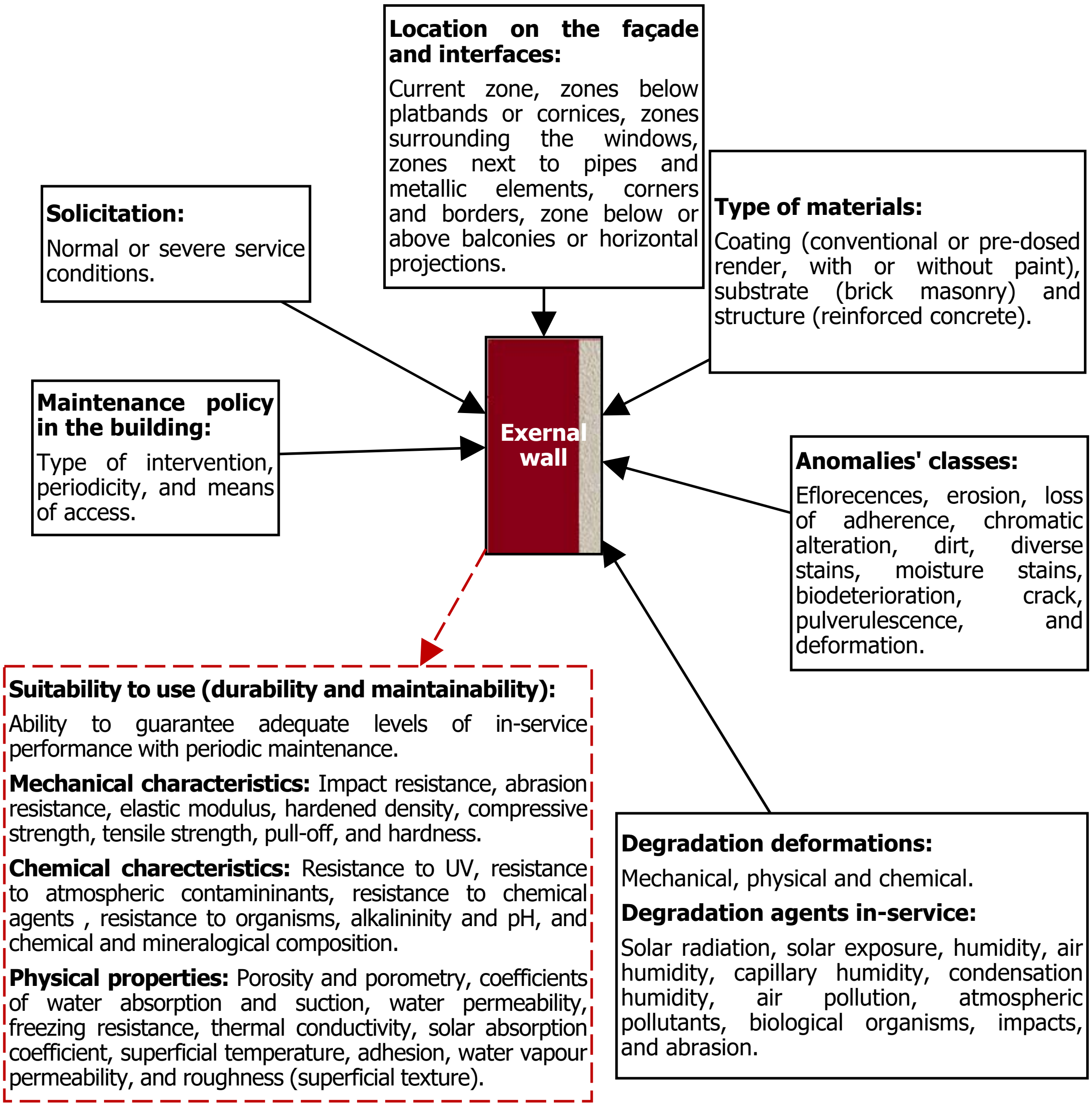


Figure 5.1 - Factors that influence in-service performance of rendered façades

Therefore, three partial reliability indicators were proposed to better interpret the results of multiple in-situ testing techniques, as described below:

- Reference reliability indicator (RRI) - uncertainty (expressed as a percentage) associated with the proposed mean value for the reference, from the laboratory tests or from the relationships between parameters;

- Verification method reliability indicator (VMRI) - includes four indexes that contribute to the classification: If2 - accuracy of the verification method (quantitative, qualitative or a range of values); If3 - contribution of the method to the identification of the two pre-dosed or conventional mortar groups; If4 - sensitivity of the method to in-situ factors (surface moisture, type of finishing and support, among others); If5 - contribution of the method to the characterization of anomalies related to the mechanical behaviour (cracking, loss of cohesion and detachments);

- Reliability indicator of results obtained in-service (RIRS) - it characterizes the greater or lesser variability of the results obtained in the case studies analysed, through two indexes: If6 - variation coefficient of the results and If7 - number of measurements; in these two indexes, the analysis can be done in one or all the surfaces of each case study.

The classification of the global reliability indicator (RI) for each measurement parameter ranges from 1 to 5 and is calculated by Equation 1 (arithmetic mean of the previous indicators).

$$RI = (BRI + VMRI + RIRS)/3 \qquad (1)$$

Where:

RRI = I_{f1} = reliability of the reference parameter (1 ≤ RRI ≤ 5);

VMRI = $(I_{f2} * I_{f3} * I_{f4} * I_{f5})^{1/4}$ = reliability of the verification method (1 ≤ VMRI ≤ 5);

RIRS = $(I_{f6} * I_{f7})^{1/2}$ = reliability of the results obtained in-service (1 ≤ RIRS ≤ 5).

5.3. Laboratory and in-situ measurements

The analysis of the relations between the physical-chemical parameters and the respective coefficients of variation for renders was carried out. The relationships between the physical-chemical parameters led to good correlation coefficients ($R^2 > 0.6$), and some examples are high-lighted: i) the relation of surface moisture with the height of the measurement relative to the ground. This relation is important to characterize the capillary rise, which often reaches heights above the average height of common protective cladding on the bottom part of the wall (0.60 m); ii) the relationship between the moisture to the salt content, in particular chlorides and nitrates, which are the most hygroscopic. The salts' content of 4000 mg per kg of mortar correspond to a surface moisture of more than 60%; iii) The linear relationship between drying index and apparent porosity. This linear relationship, as with laboratory results, was identified using the in-situ results, with a high linear correlation coefficient. In other words, it is confirmed that the apparent porosity is an important parameter in the vapour diffusion process, in which more porous products have greater water vapour diffusion.

According to the results obtained in the analysed case studies, the reference parameters for each physical-chemical testing technique were also made, as shown in Table 5.1. From the manufacturer analysis, only the capillary coefficient is declared for monolayer mortars and mortars of general use, with a maximum limit of 0.4 kg/m^2.min0.5. In this case, the mean values are 0.19 kg/m^2.min0.5 for the former and 0.38 kg/m^2.min0.5 for the latter, and the coefficients of variations varied from 22% to 52%).

Table 5.1 - Synthesis of the physical-chemical parameters and proposal of respective lower and upper limits for pre-dosed and conventional cement-based renders

Measurement parameters	Lower limit	Reference parameter	Upper limit	Reference parameter uncertainty *	Testing technique	Verification method type
H_{sur} (%)	-	-	≤ 11[a]	≥ 50%**	Moisture meter	quantitative
			I[b] II			
$(T_{sur}-T_a)$ (ºC)	-	-	(0.7 *R) / h_e	≥ 50%***	Radiation pyrometer or infrared thermometer + thermo-hygrometer	quantitative
T_{sur} (ºC)	-	-	psychometric diagram (H_r)			
ΔE_{max}	-	n/d	< 2	30%	Colorimeter	quantitative
$C_{ab(60)min}^{kt}$ ($kg/m^2.min^{0.5}$)	-	0.2	c	≥ 50%	Karsten tube	quantitative
	I		II			
$P_{(48)h}^{kt}$ ($ml/cm^2.48h$)	-	1	-	0[d]		
	I		II			
C_d^a ($kg/m^2.min^{0.5}$)		0.4	c	≥ 50%	Capillary absorption	quantitative
	I		II			
W_c^{48h} (%)	-	6	-	33%		
	I		II			
I_d	-	0.31	-	16%	Evaporation	quantitative
	I		II			
m_3 ($kg/m^2.min^{0.5}$)	-	-	-	-		
	I, II		-			
$[Cl^-]$ (mg/kg)	-	-	300[e]	≥ 50%	Field kit or colorimetric tapes	quantitative or interval
			I, II			
$[NO_3^-]$ (mg/kg)	-	-	500[e]	≥ 50%		
			I, II			
$[SO_4^{2-}]$ (mg/kg)	-	-	5000[e]	≥ 50%		
			I, II			
$\Sigma_{salts}^{(C+N+S)}$ (mg/kg)	-	-	5800[e]	≥ 50%		
			I, II			
pH	-	11	-	9%	pH meter,	quantitative
		I, II			conductivity and TDS	
Cond.	-	-	-			quantitative

Legend: * uncertainty which translates into twice the standard deviation obtained in laboratory tests for reference parameter determination (where applicable) or through other considerations resulting from in-service campaigns; [a] = mean value obtained in field results for areas with no visible degradation, excluding recent paintings; [b] = reading difficulty in water-repellent products; R = global solar radiation (W/m^2); h_e = external surface thermal conductance (W

/m^2 °C); ** = uncertainty calculated from field results in 10 zones with no visible degradation; *** = these parameters depend on climatic conditions that may not be the most burdensome during the time of inspection, and an analysis is advisable for a minimum period of 24 hours. c = depends on the requirements associated with the exposure conditions and the type of coating; [d] = parameter established in the technical documentation; [e] = maximum limit corresponding to the unfavourable conditions of salts already characterized; n/d = not determined; I = group that integrates pre-dosed mortars; II = group that integrates conventional mortars and some pre-dosed ones (depending on the manufacturer's composition); H_{sur} = surface humidity; T_{sur} = surface temperature; T_a = ambient temperature; $\Sigma_{salts}^{(C+N+S)}$ = content of chlorides, nitrates and sulphates; ΔE = total colour variation in coordinates L.a.b .; $C_{ab(60)min}^{kt}$ = water absorption coefficient at low pressure in the Karsten tube test for 60 minutes; C_d^a = capillary water absorption coefficient determined by the first slope in the capillary absorption test; m_3 = initial slope in the evaporation phase of the capillary test; [Cl^-] = concentration of chloride ions; [$N03^-$] = concentration of nitrate ions; [$S04^{2-}$] = concentration of the sulphate ions; pH = pH value; Cond. = conductivity; I_d = drying rate of samples collected after capillary absorption test; Wc^{48h} = water content at 48 hours (percentage of initial mass); $P_{(48)h}^{kt}$ = water permeability under pressure determined at 48 hours in the Karsten tube test; TDS = total dissolved solids.

From Table 5.1, it is clear that the H_{sur} measurement parameter (obtained from the moisture meter) has a maximum limit of 11% for the two groups of mortar (I and II), with an associated uncertainty of 50% or more. In addition, the measurement parameter C_d^a (obtained from the capillary absorption test) has a reference parameter of 0.4 kg/m^2.min$^{0.5}$, with an associated uncertainty of 50% or more. This parameter divides the two groups of mortar as follows: the pre-dosed renders have values lower or equal to this value, while conventional renders have higher values. It was not possible to assign maximum limits to conventional renders, because the capillary absorption depends on the binders' percentage, although they are cement-based.

Some thresholds were allocated to on-site campaigns, such as surface moisture limited to 11% (after this percentage significant anomalies occurred) and sulphate content at 5800 mg/kg of mortar (equivalent to 232 mg/l). It was not possible to assign some reference parameters, for ex-ample, for the conductivity (a parameter that depends on the several existing salts) that serves only as a qualitative parameter. The relationship of this parameter with the pH found in the laboratory was not found in-situ. However, by joining all the results obtained in the laboratory with those obtained in-situ, it was possible to confirm a trend of in-service results, with conductivity values below 500 µS/cm and pH below 11.

Despite the carried out experiments, some reference parameters were not established directly, such as the surface temperature. In this sense, only indirect forms of finding the solar ab-sorption coefficient (< 0.7) and the occurrence of surface condensation were indicated. The interpretation of their results depends on the hygrothermal balance between the surface and environ-mental conditions, which may not be the most burdensome at the inspection time. Other considered indirect forms were the heterogeneity factor of the surface temperature and the extension due to the thermal variation.

Similarly, the reference parameter of the drying index was adapted, taking into account the in-situ values and the relationships between this parameter and the apparent porosity measured in samples collected in the field and produced in the laboratory.

In general, most of the reference physicochemical parameters present uncertainty greater than or equal to 50%, translating a greater sensitivity of these parameters to the in-service conditions, when compared with the uncertainty of the reference mechanical parameters. In addition, many of the physical-chemical measurement parameters do not allow dividing the two main groups of cementitious mortars (pre-dosed and conventional). Nevertheless, the verification methods are mostly quantitative (where it is possible to compare with reference values), with some cases of qualitative (allowing comparative results between them) and an interval (results are given in the form of intervals or scales).

5.4. Physical chemical performance evaluation on case studies

The physical-chemical parameters serve as reference for the analysis obtained from the results of various case studies. Table 5.2 presents a synthesis with the analysed parameters' classification for each case (green, yellow, orange and red).

Table 5.2 - Distribution of physical-chemical parameters measured in the case studies, according to the reference parameters, proposed limits and maximum values

Case studies (Renders)	Classification of the results obtained in each measurement parameter				Total of parameters
	green	yellow	orange	red	
CS1 (MR)	H_{sur}; $C_{ab(60)min}^{tk}$; C_d^a; W_c^{48h}; $\Sigma_{salts}^{(C+N+S)}$; I_d	-	pH	-	8
CS2 (PRP)	$C_{ab(60)min}^{tk}$	-	-	H_{sur}; $C_{ab(60)min}^{tk}$	2
CS2 (DSC/DLC)	$C_{ab(60)min}^{tk}$; W_c^{48h}; I_d; pH	$C_{ab(60)min}^{tk}$; C_d^a	$\Sigma_{salts}^{(C+N+S)}$	H_{sur}; $\Sigma_{salts}^{(C+N+S)}$	7
CS3 (MR)	H_{sur}; $C_{ab(60)min}^{tk}$	-	-	-	1
CS4 (MR)	$\Sigma_{salts}^{(C+N+S)}$	-	C_d^a; W_c^{48h}; pH	-	1
CS5 (MR)	H_{sur}; $C_{ab(60)min}^{tk}$; C_d^a; W_c^{48h}	-	$\Sigma_{salts}^{(C+N+S)}$	I_d	4
CS6 (DSC)	H_{sur}; $C_{ab(60)min}^{tk}$; I_d	C_d^a; W_c^{48h}	$\Sigma_{salts}^{(C+N+S)}$	H_{sur}	2
CS9 (PHR)	C_d^a; W_c^{48h}	-	-	-	1
CS10 (DSC)	C_d^a; W_c^{48h}	-	-	-	1
CS30 (DSC)	-	-	-	H_{sur}; $\Sigma_{salts}^{(C+N+S)*}$	1
CS41 (MR)	C_d^a; W_c^{48h}	-	-	-	1

Legend: MR = Monolayer render with pigment; PRP = Pre-dosed render covered with paint; PHR = Pre-dosed heavy render (for tiles and stones); DSC = Dosed on site render (cement render); DLC = Dosed on site render (lime and cement render); H_{sur} = surface humidity; $\Sigma_{salts}^{(C+N+S)}$ = content of chlorides, nitrates and sulphates; $C_{ab(60)min}^{kt}$ = water absorption coefficient at low pressure in the Karsten tube test for 60 minutes; C_d^a = capillary water absorption coefficient determined by the first slope in the capillary absorption test; pH = pH value; I_d = drying rate of samples collected after capillary absorption test; Wc^{48h} = water content at 48 hours (percentage of initial mass); * = determined by colorimetric strips (interval method); - no value.

Regarding the meaning of the used colours, CS6 can be used as an example: i) Green - the result conforms to the reference parameter, in terms of upper and lower limits (where applicable). For example, in CS6, the surface moisture, H_{sur}, is 11.1% for zones with no visible anomalies; ii) Yellow - the result differs from what would be expected, being favourable at first, but requires investigation. For example, the capillary coefficient in CS6, Cd, is lower (0.02 $kg/m^2.min^{0.5}$) than would be expected for a conventional cementitious product (values greater than 0.4 $kg/m^2.min^{0.5}$), which is favourable in the first analysis. However, this reduced absorption may reflect the influence of other factors; iii) Orange - the result is near (above or below) the reference limit. In the case of salts, the moderate conditions previously established in orange are considered, i.e. chloride ion concentrations between 50 and 300 mg Cl^-/kg of mortar; concentrations of nitrate ion between 75 and 500 mg NO^{3-}/kg of mortar; sulphate ion concentrations between 1000 and 5000 mg SO_4^{2-}/kg of mortar; and total salts of those three salts between 1125 and 5800 mg of salts/kg of mortar; and iv) Red - the result does not comply with the proposed lower or upper limits. For example, CS6 shows surface moisture values, H_{sur}, between 26% and 29%, values higher than 11% (considered as a reference for the appearance of anomalies). In other cases, it was not possible to compare the results with the reference parameters or no tests were performed.

5.5. Performance based on reliability indicators

In general, the results show that the combined analysis of different parameters leads to improving the knowledge about physical, chemical, and mechanical properties of rendered walls. Nevertheless, the results also conclude that the in-service diagnosis have several limitations. For example, the techniques are only applicable for accessible zones on the façade, the recommended testing numbers could not be controlled only by the façade' surface area, and most of the testing techniques spoil the render' aesthetic appearance, even those named non-destructive tests (e.g. Karsten tube).

The characterization of physical-chemical reliability indicators (RRI, VMRI, and RIRS) are presented in Figure 5.2. The general classification (RI) varied between 1 and 3, being lower than that for mechanical parameters (where this classification was between 2 and 4 [2]). In other words, the usefulness of the information collected in-service with the analysis of physicochemical parameters is conditioned by the high uncertainty associated with the reference parameters and the verification methods, including the limitations inherent to the results obtained in-service (the coefficient of variation normally higher than 50% and limited number of determinations for a given parameter).

The drying index (I_d) is a parameter that can contribute to a better characterization of the render behaviour than the water vapour diffusion. This characteristic is not currently measured in-service. Although the results of this index differ for the campaigns in the laboratory and in-service, it was possible to establish relations based on the apparent porosity measured in samples collected in-service. However, a number of aspects should be examined in further detail in order to assess the proposed relationships and reduce the variability of the reference, including factors inherent in testing and sampling techniques.

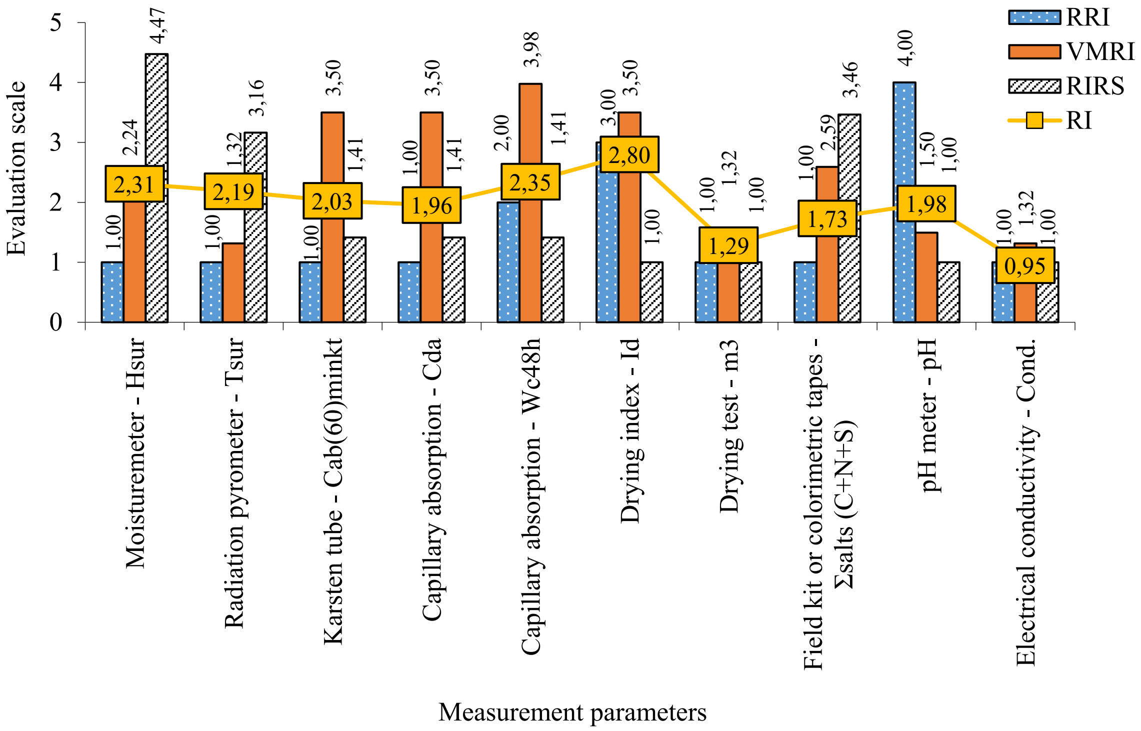


Figure 5.2 - Partial reliability indicators (RRI - reference reliability indicator, VMRI - verification method reliability indicator, RIRS - reliability indicator of in-service results) for each physical-chemical in-service measurement

The water content at 48 hours (W_c^{48h}) is a useful parameter to characterize the water behaviour of the applied renders, efficiently complementing the information obtained with the analysis of the capillary coefficient (whose values depend on the calculation methods). The disadvantage is the duration of the test and the need for periodic recording of mass variation over time.

Despite some uncertainty in the reference parameter and the verification method, surface moisture (H_{sur}) can be useful in-service, since it is determined by a non-destructive technique, allowing the realization of several mappings. The relationship of this parameter with various types of anomalies contributes to a first quantification of the severity of moisture-related anomalies in rendered walls.

Similarly, to H_{sur}, the surface temperature (T_{sur}) has some uncertainty in the reference parameter and the verification method. Nevertheless, the information obtained in-service can be qualitatively improved with the mapping. Although the information obtained is limited to the environmental conditions that exist during the inspection, the analysis of this parameter for periods of 24 hours will contribute to a better understanding of the hygrothermal performance of the rendered wall (particularly in regard to the possible surface condensation occurrence).

The coefficient of absorption under low pressure ($Cab_{(60)min}^{tk}$) allowed complementing the information obtained with the capillary coefficient, differentiating the hygienic behaviour of the pre-dosed renders (mostly water-repellent) from the conventional renders' behaviour. The poor score of the results obtained is due to the reduced number of valid tests and the respective coefficients of variation. In fact, this technique requires some recording time (periodic readings for 60 min) and the placement of the tubes is conditioned by the access to the sites and the degradation state of the surfaces (excluding the cracked areas where this test was not applied.

The pH value is easily determined and requires some stabilization period to read the apparatus. However, the data obtained is not by itself a performance characteristic. In practice, knowledge of the pH value may only contribute to the characterization of some physical and chemical changes occurring in-service in applied renders (e.g. formation of products associated with carbonation, acid rainfall, favourable conditions for development of a particular type of bio-logical organism.

The capillary coefficient ($C_d{}^a$) is a very useful parameter for evaluation of the render behaviour against water. The reference parameter presented some uncertainty associated with the different aggressiveness of the environment/area of the façade where the render is applied. In addition, the obtained results had variability associated with factors inherent to the samples). Furthermore, the number of determinations were limited. It is noted that the capillary coefficient calculation by the slope leads to better results, but requires a greater number of readings up to 90 min in order to identify the different families of pores responsible for capillary absorption. It was also possible to relate this parameter to the existence of several types of anomalies (white stains/efflorescence and other measurement parameters such as surface humidity).

For the content of soluble salts ($\Sigma_{salts\ (C + N + S)}$), there is significant uncertainty associated with the reference parameters and the verification method, in particular in the case of sulphates. The high uncertainty in the reference parameters is due to the scarcity of requirements in standards and technical documents. In spite of this, it was possible to verify that this parameter can justify high values of surface humidity due to the presence of more hygroscopic salts (chlorides and nitrates).

In terms of the initial drying rate (m^3), the results obtained for the reference parameter and verification method (contribution to the identification of the applied renders type) were not conclusive after the campaigns was carried out.

The conductivity (Cond.) parameter only served to make a qualitative analysis that significantly depends on the various salts identification that exist in solution and not only the chlorides, nitrates and sulphates analysed by the field kit or the colorimetric tapes. However, it was possible to detect a trend between this parameter and the pH value.

5.6. Decision criteria for maintenance

A number of measurement parameters have been identified for the available verification methods, which in most cases do not establish a direct and unambiguous relationship with each of the mentioned performance characteristics. In other words, two situations may occur: (1) a parameter can be an indirect measure of one or more performance characteristics, such as apparent density or apparent porosity; or (2) a performance characteristic may not have a sufficient relation with the measurement parameters studied. Despite the mentioned limitations, a selection matrix is proposed that qualitatively identifies the set of parameters that contribute to indirectly analyse the four characteristics and performance relevant to the physic-chemical behaviour of the renders applied on façades (Table 5.3).

Table 5.3 - Measurement parameters relevant to the physical-chemical behaviour of applied renders

Verification method	In-service measurement parameters	Reliability indicator	In-service physical-chemical performance			
			CP5	CP6	CP7	CP8
Moisture meter	H_{sur} (%)	2.31	○	●	●	●
Radiation pyrometer	T_{sur} (ºC)	219	-	-	●	-
Karsten tube	$C_{ab(60)min}^{kt}$ ($kg/m^2.min^{0.5}$)	2.03	●	-	-	○
	$P_{(48)h}^{kt}$ ($ml/cm^2.48h$)	n/d	●	-	-	-
Capillary absorption	C_d^a or C_d^{ad} ($kg/m^2.min^{0.5}$)	1.96	●	●	-	○
	W_c^{48h} (%)	2.35	○	●	-	○
Drying test	I_d	2.80	-	○	●	-
	m_3 ($kg/m^2.min^{0.5}$)	1.29	-	○	●	-
Field kit or colorimetric tapes	[Cl^-] (mg/kg)	n/d	-	●	○	●
	[NO_3^-] (mg/kg)		-	●	○	●
	[SO_4^{2-}] (mg/kg)		-	●	○	●
	$\Sigma_{salts}^{(C+N+S)}$ (mg/kg)	1.73	-	●	○	●
Portable meter	pH	1.98	○	○	○	●
	Cond. (µS/cm)	0.95	-	○	○	●

Legend: CP5 = resistance to penetration of liquid water (in an uncracked zone); CP6 = resistance to rising humidity; CP7 = hygrothermal resistance; CP8 = biochemical resistance; ● = high correlation; ○ = mean correlation; - = without correlation or low correlation; H_{sur} = surface humidity; T_{sur} = surface temperature; $\Sigma_{salts}^{(C+N+S)}$ = content of chlorides, nitrates and sulphates; $C_{ab(60)min}^{kt}$ = water absorption coefficient at low pressure in the Karsten tube test for 60 minutes; C_d^a or C_d^{ad} = capillary water absorption coefficient determined by the first slope in the capillary absorption test on samples taken directly from the coatings or resulting from the adhesion test; m_3 = initial slope in the evaporation phase of the capillary test; [Cl^-] = concentration of chloride ions; [$N03^-$] = concentration of nitrate ions; [$S04^{2-}$] = concentration of the sulphate ions; pH = pH value; Cond. = conductivity; I_d = drying rate of samples collected after capillary absorption test; Wc^{48h} = water content at 48 hours (percentage of initial mass); $P_{(48)h}^{kt}$ = water permeability under pressure determined at 48 hours in the Karsten tube test.

From the several case studies, it was concluded that the analysis of more than one parameter significantly complemented the diagnosis, minimizing other constraints inherent to an in-situ evaluation, such as uncertainty of verification methods or constraints associated with sampling. The analysis of the performance shall account for the measurement parameters determined for zones without anomalies. The conformity of these parameters can be made in two ways: 1) there are elements in the collected information that identify and characterize the applied render; 2) there is no information available, and it is necessary to identify to which group the render belongs (measure, for example, the apparent porosity).

The measurement parameters contribute to the knowledge of more than one characteristic, which is the reason why the study of the set of parameters improves the diagnosis. The relation between these parameters and in-service performance of renders (CP5, CP6, CP7 and CP8) will help in maintenance decision. For example, a low CP5 (resistance to liquid water penetration) can justify a maintenance strategy with an application of a protective hydrophobic layer

5.7. Final remarks

It is concluded that in-situ techniques are useful, because of their application simplicity and the reduced costs of equipment, presenting the following limitations, in addition to those existing in terms of means of access:

- Some methods are not suitable for all types of renders. For example, the moisture meter did not provide readings in water repellent renders;
- The degradation state (type of anomalies) may lead to some tests being carried out: for example, the fixing of the Karsten tubes on dusty surfaces.

The combined analysis of several parameters obtained with the same verification method (e.g. capillary coefficient and water content at 48 hours in the absorption test) or with different methods (capillary coefficient in the capillary absorption test and the coefficient of absorption, by pressure gradient, in the pipe method) allowed a better interpretation of the results.

In spite of the advantage in the analysis of more than one parameter, there were some discrepancies in some cases. Thus, three uncertainty factors were identified as relevant for these differences: i) uncertainty in the reference parameter; ii) uncertainty in the verification method; and iii) uncertainty in the obtained results (in terms of coefficient of variation and number of tests). In this regard, an overall reliability indicator has been proposed that includes criteria related to the previous factors and that supports the inspector in choosing the most reliable parameters for an inspection.

From the application of the overall reliability indicator to the measurement parameters, it was found that the apparent porosity led to a higher score. In this context, it is important to high-light that the apparent porosity allows the identification of the different mortars types (a relevant aspect when the applied renders' characteristics are not known), as well as establishing relations with other measurement parameters.

The measurement parameters do not establish a univocal relation with each of the performance characteristics, given their interrelationship. However, a degree of contribution of each parameter was put forward for each of the performance characteristics. This facilitated the conformity assessment by performance characteristics (resistance to penetration of liquid water; resistance to rising humidity; hygrothermal resistance; biochemical resistance), providing a basis to establish maintenance criteria based on experimental data.

6. Forensic engineering approaches

This section should be cited as:
Pivato, A.; Gwinett, C.; Varghese, G.; Pereira, C.; Flores-Colen, I.; de Brito, J.: “Forensic engineering approaches”, in New Trends on Building Pathology, CIB W86 Report, 2021.

6.1. Introduction

Forensic engineering is a multidisciplinary science that intends to apply scientific methods and knowledge to the diverse sectors of engineering in the context of a regulatory and legal framework. In this context, forensic engineering assumes a fundamental and distinct role from legal sciences. However, continuous and effective dialogue with legal sciences is fundamental to ensure acceptance of the technical forensic procedures and methods in courtrooms.

More specific definitions derive from the different sectors of applications. For example, in the field of civil engineering, the American Society of Civil Engineers [1] defines this discipline as “the application of engineering principles to the investigation of failures or other performance problems. Forensic engineering also involves testimony on the findings of these investigations before a court of law or other judicial forum, when required”. In the field of environmental forensic science, Rusk [2] presented environmental forensics as a mechanism for technical support to complex, controversial and high stakes environmental litigation.

One of the most important purposes of forensic engineering is providing a technical framework for allocating the responsibility of a technical failure or an incident, using scientific methods, in support of a legal regime (*a posteriori* purpose). Here, ‘failure’ can mean fundamental failures that demand complete abandoning/dismantling of the system, functional failures that limit the performance of the system or aesthetic defects, affecting only the acceptance, not the functionality of the system. By incident, here it is meant any particular failure that implies direct or indirect adverse outcomes such as property damage or compromises on human health and safety.

Typical failures or incidents include, in different fields: for civil engineering, building and bridge collapse, facilities or parts of facilities that do not perform as intended by the owner, design professional, or constructor; for environmental forensics, the cases of pollution of different spaces (air, water, soil, biota, sediments); for transportation engineering, road traffic crashes; for fire safety engineering, cases of fires.

An incident that may justify a forensic engineering analysis is not necessarily sudden and/or disastrous. It may be a statistical deviation over time, for example: in a manufacturing process, the acknowledgement of a latent phenomenon such as an explosive mixture, a design option, an alleged civil tort or criminal act, a human error or administrative violation, or a sequence or collection of such occurrences [3].

In addition, forensic engineering can perform a useful proactive function (*a priori* purpose) for the technician, as it provides the knowledge to eliminate, or at least mitigate, the premises of potential involvement in legal processes, a situation that unfortunately has a high probability of occurring in the technical profession and usually is time and cost consuming.

6.2. Forensic methodology

Regarding the forensic methodology, it is worth mentioning the parallelism between the scientific approach and the forensic approach graphically represented in Figure 6.1. They involve a common abductive reasoning that is a form of logical inference that starts with an observation and then seeks to find the simplest and most likely explanation [4]. This is an important aspect because it implies that the Forensic Engineering Expert Report should identify alternative or contrary explanations for the incident, stating the rationale for their acceptance or dismissal [3].

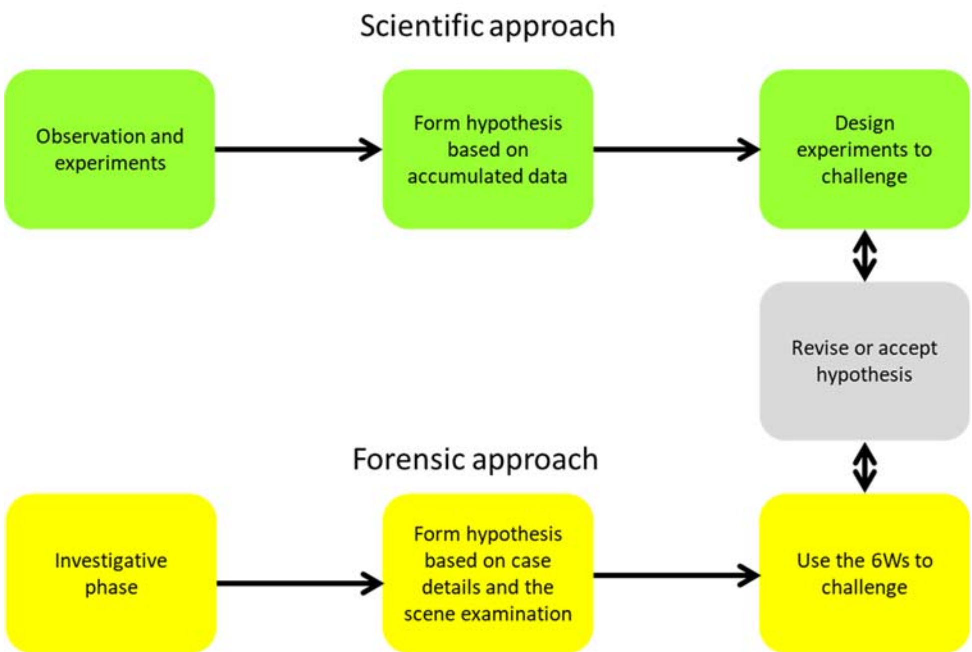


Figure 6.1. - A comparison between the scientific and the forensic approach (based on the work of Pivato *et al*. [5])

In the forensic approach, the phase of the experiment design is replaced by the use of the well-known ‘Six W’s of Investigation’ (what, where, who, when, why and how). Taking ‘building collapse’ as an example which is closely related to Building Pathology, one can apply the forensic investigation approach and attempt to answer the ‘Six W’s’. Considering general research and investigation in building pathology, the “Six Ws” methodology can be compared to a surveyor’s diagnosis methodology, although the purposes are different. Table 6.1 shows that comparison.

Table 6.1. - Comparison between the forensic and the building pathology approaches

Six Ws (forensic approach)	Research on building pathology [6]	Example: detachment of natural stone slabs from a façade
What: What is the technical failure or the incident one has to analyse? Can one identify a conceptual model of the event including the fundamental elements that characterize it?	Problem definition: identification of the problem—symptom.	A stone cladded façade is missing four stone slabs.
Where: Can one identify the building in terms of its configuration, architectural characteristics, building details and material nature? Does one have a geographic location (including street address and latitude and longitude coordinates if appropriate)?	Observation/data collection: checking the conditions in which the problem occurs and its characteristics.	Type of stone: limestone. Cladding bonded to the substrate. Height of the missing slabs: 2 m. Size of the stone slabs: 20 x 40 cm, 3 cm thick. North-oriented façade. Building next to the shore.
Who: Can one identify the main cause of the collapse and the person(s) responsible (designer, contractor, occupants or others)?	Survey of possible causes: sensory or organoleptic analysis; measurements, tests and trials; inference; logical thinking; imagination; broad and multifocal knowledge; auxiliary tools. Narrowing down of probable causes: identifying the causes that have a higher probability of starting the problem. Confirmation of probable causes: further observation/data collection according to the hypotheses to confirm or reject them.	Probable causes due to design, construction or usage errors: - Incorrect specification or use of inadequate materials; - Incorrect prescription or execution of the fastening system; - Deformation of the substrate; - Stress concentration within the substrate; - Temperature. Further tests: - Thermography; - Percussion; - Pull-off test.
When: Can one narrate the chronology of the technical failure or the incident? What preceded the failure? Was there evidence of defects in the structure before the collapse? Can one reconstruct events before, during and after the failure and incident?	Historical survey (interview with those involved; document analysis; database query; multimedia records): to obtain information about the building's characteristics and its historical data—date of emergence of symptoms, seasonality of symptoms, possible interventions, non-visible symptoms, changes in the environment.	Building from 1998 without regular maintenance of the façades. No maintenance plan. Surveys/interviews with users can help the diagnosis.
Why: This is a matter for the judiciary to decide.	-	In some relevant cases, for example stone detachment, the process may include a judiciary process, for example between the user and the builder.
How: How do processes and mechanisms influence the unwanted event?	Deeper analysis of the degradation processes gathering all the data. Use of mathematical models to: - Analyse the problem risk: classification of the problem to guide and prioritise corrective actions; - Estimate the evolution of the problem—prognosis: based on the causes and risk of the problem, the progression of the problem if anything is done may be estimated.	The problem requires immediate intervention, as it is dangerous for passers-by. The problem may evolve to the detachment of other stone slabs, compromising the substrate and the watertightness of the façade.

6.3. Final remarks and further development

Forensic engineering represents an emerging science where several topics are still debated in the scientific community. Among these, the following ones can be considered “hot topics” for Building Pathology:

- Cognitive bias - pattern of deviation in judgement whereby inferences about people and situations may be drawn in an illogical fashion. Newman [7] emphasizes 27 tendencies with the potential of compromising cognition by individuals, including scientists and risk assessors. Cognitive bias is now well documented in wider forensic disciplines, such as fingerprint analysis, but has not yet been fully explored in forensic engineering and further research is needed [8].

- Representativeness of experimental data with respect to the objective of the study - the measure of the degree to which data accurately and precisely represents a characteristic of a population, parameter variations at a sampling point, a process condition, or an environmental condition [9]. The sampling design specifies the number, type, and location (spatial and/or temporal) of sampling units to be selected for measurement [10]. If evidence for representativeness is not presented, the data cannot be characterized as robust for project decision-making [11];

- The correct interpretation of the meaning of association, correlation and causation - there has been great ambiguity in the definitions of these concepts that assume a fundamental role in civil or criminal litigations (in particular the causation principle). When two variables (A and B) are found to be correlated, it is tempting to assume that this shows that one variable causes the other. That "correlation proves causation" is considered a questionable cause logical fallacy. Citing Altman and Krzywinski [12], “correlation implies association, but not causation. Conversely, causation implies association, but not correlation”.

The “Six Ws” methodology can be a good strategy to apply forensic methodology to building pathology, with the necessary adaptations.

7. Atlas of defects within an inspection system

This section should be cited as:
Pereira, C.; de Brito, J.; Flores-Colen, I.; Silvestre, J.D.: "Atlas of defects within Inspection Systems", in New Trends on Building Pathology, CIB W86 Report, 2021.

7.1. Introduction

The built environment is key to achieve sustainable development [1]. Several issues may be crucial in this context, like urban and spatial planning, energy use, greening, material selection, design strategies, thermal comfort and indoor air quality. Building maintenance also has a relevant role. Well-planned maintenance strategies extend the service life of buildings, hence contributing to their continuous use, reducing the need for new buildings, and lowering construction and demolition waste. Therefore, effective building maintenance leads to a decrease in resources' consumption.

Building maintenance planning combines proactive (preventive or predictive) and reactive strategies [2], all benefitting from the results of building inspections [3, 4], which are used to determine repair actions. To make inspection procedures as unbiased as possible, they have to be systematised, in order to increase objectivity and improve diagnosis results, becoming more reliable. That is the role of building inspection systems.

The structure of building inspection systems benefits from including methods to rate the degradation of defects and urgency of repair of building elements to enable maintenance optimisation [5, 6]. The quantification of the level of deterioration of building elements allows prioritising interventions [7], to comply with functional requirements at a minimal cost [8].

While systematising the knowledge on building pathology, a research team from Instituto Superior Técnico (IST), University of Lisbon (UL), developed a set of expert inspection systems, each one dealing with a specific type of building element/material. These systems include classification lists of defects, their causes, diagnosis methods and repair techniques, along with correlation matrices between defects and the other items. However, building inspections do not usually focus on a single type of building element/material, considering the building as a whole instead. Therefore, surveyors would have to employ various inspection systems to evaluate the real condition of different types of building elements/materials. To pragmatically tackle this issue, a global building inspection system is under development at IST-UL, based on the individual inspection systems [9–20]. The harmonised classification lists of the global system, referring to defects, their causes, diagnosis methods and repair techniques, have already been published [21–24]. Additionally, each type of defect, in each type of building element/material, is given specific conditions to determine its urgency of repair [24]. Within this context, how can an expeditious tool to identify defects and their urgency of repair be achieved?

The objective of this section is to propose an atlas of defects appropriate for several types of building elements/materials, simplifying issues associated with the identification and characterisation of building defects. This research is based on the elements of the global building inspection system already developed, namely the harmonised classification list of defects and the criteria to determine the urgency of repair [24]. The proposed atlas is expected to aid building surveyors during technical inspections, whether occasional or periodic.

7.2. Expeditious tools to assess building pathology

Analysing building pathology is a complex process concerning the observation of anomalous occurrences, deciding whether they are defects, determining their causes and origin. It may com-prise elaborate assessment procedures, involving several *in situ* non-destructive and destructive tests or even laboratory tests on collected samples.

Centred on observing building elements to detect defects, inspections may be assisted by some simple tools. Some of these, like binoculars, help to have a closer look at building components and decide whether an occurrence is worth registering or just a temporary observation interference (e.g. an obstacle). Other tools provide basic information on building elements and detected defects, like a tape measure, which adds dimensional information to observations, or a spirit level, which assesses the orthogonality of edges and surfaces. Additionally, portable and light comparison tools for inspection procedures are quick tests that can be easily carried out any-where, not requiring advanced knowledge or sophisticated apparatuses [25]. Crack width rulers [26–28] and colour systems' samples [29–31] illustrate that concept and are widely used.

Crack width rulers provide a small transparent rectangle with a group of printed organised lines with different thicknesses [27]. Each thickness is identified, easily allowing determining the width of a crack. In other words, graphical data are complemented with quantitative data, providing a user-friendly instrument [26, 28].

Colour system's samples are a set of cards, manufactured in a resistant paper, printed with solid colours to be compared with those of building surfaces. Each solid colour is identified with a code, according to the predetermined colour system, such as the natural colour system [30] or Munsell's [29, 31]. The use of colour samples allows comparing (i) the initial colour (from design) with the observed colour, and (ii) different observed colours in various areas. Once more, graphical information, complemented with coded information, allows a more accurate diagnosis methodology.

Additionally, standards EN ISO 4628-4:2016 [32] and EN ISO 4628-2:2016 [33] propose comparison methods to assess the degradation of paint and varnish coatings, namely to assess the degree of cracking and blistering, respectively. These standards provide pictorial criteria to be matched with the visual characteristics of detected defects, referring to the size, number and density of cracking and blistering. In these situations, the diagnosis is also strengthened by the use of graphical in-formation.

The advantages of the mentioned easy-to-use, graphical and informative tools to assist inspection procedures raise interest in a similar tool to aid the observation of defects and the systematisation of their diagnosis. Such tool, proposed in this section as "atlas of defects", would be an image-based scale to identify the type of detected defect and evaluate its urgency of repair, complemented with essential written parameters difficult to represent in photographs.

The set of individual expert inspection systems developed by the authors' research team at IST-UL includes, in each detailed file of a defect, the classification parameters to ascertain the severity/repair urgency level of each defect. These parameters are applied to rate defects from levels 0 to 2. Level 0 corresponds to the need of immediate intervention, level 1 to the need of intervention in the medium-term, and level 2 to the need of monitoring the progression of the defect. Using the set of individual inspection systems to develop the global inspection system led to adapting the three levels to a five levels' scale, considering implicit gravity differences between different building elements/materials. Furthermore, the global inspection system complements service life prediction methodologies for the same scope of building elements/materials [34]. Those methodologies already determined the severity of degradation of building elements. For this reason, in the global building inspection system, defect rating was limited to the urgency of repair [24].

Ruiz *et al*. [7] studied the optimal metric for condition rating scales. This research tested a representative sample of experts on how they would grade 33 cases of pathology in building elements through direct assignment, according to a scale with 11 levels of severity. The statistical analysis of the answers detected the need of improving the proposed scale since the research only achieved a 32.07% probability of correct classification of the defects. Using a clustering algorithm, it was concluded that a five levels' scale provided the lowest standard deviation of the global error. IST-UL's global inspection system proposes five levels of urgency of repair too. Additionally, Ruiz *et al*. [7] identified that a catalogue of images of deteriorated building elements with reference values of severity would be an asset to classify building pathology, increasing the rating accuracy. The proposed atlas of defects is the realisation of such a catalogue.

7.3. Materials and methods

With the purpose of creating a catalogue to ease correlating building failures with defects in a classification list and to levels of urgency of repair, a reference database was devised for fieldwork. Components of the global building inspection system were used, namely the classification list of defects [24] and the detailed files of defects, where the urgency of repair was characterised.

First, the structure of such a database was designed. The atlas of defects has several pages, each corresponding to a defect classified in the list of defects of the global inspection system. Each page is organised as a table, with columns of types of building elements/materials and rows of levels of urgency of repair. The number of columns changes according to the field of application defined in the detailed file of the defect. Again, the levels of urgency of repair are specified in the files of defects, varying from 0 to 4 (level 0 is the most urgent and level 4 the least). Therefore, the table has five rows. In each cell of each page's table, an illustrative photograph and a short description are available, establishing the parameters to identify a defect in a building element/material with a given level of urgency of repair.

The levels of urgency of repair are defined as follows [24]:

- 0: imminent danger, contingency measures needed;

- 1: need of immediate intervention;
- 2: need of intervention in the short-term;
- 3: need of intervention in the long-term;
- 4: no urgent need, assess in the next inspection.

During fieldwork, a level of urgency of repair is attributed to each defect based on the application of algorithms. In other words, each degree of urgency of repair corresponds to a set of requisites determined for each type of defect according to the type of building element/material.

After determining the structure of the atlas of defects (Figure 7.1), all the pages were filled with the contents. The photographs of the atlas of defects were collected from the authors' research team, mainly from inspection campaigns, or taken specifically for the atlas of defects.

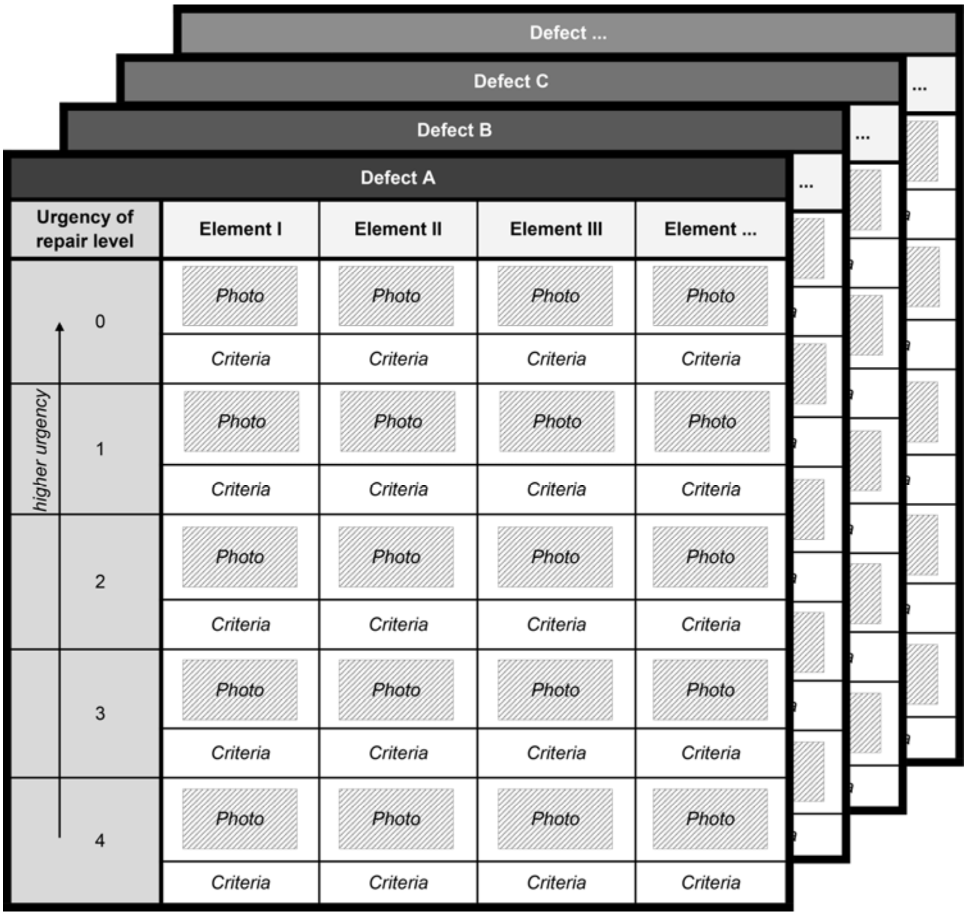


Figure 7.1 - Structure of the atlas of defects

7.4. Illustration of the concept

Figures 7.2 and 7.3 show excerpts of the atlas of defects of the global building inspection system. Figure 7.2 partially shows the page of defect "A-A3 Dirt and accumulation of debris" with columns referring to external claddings of pitched roofs, adhesive ceramic tiling, and architectural concrete surfaces. Figure 7.3 shows a portion of the page of defect "A-C1 Mapped cracking", presenting the columns for adhesive ceramic tiling, natural stone claddings and wall renders.

A-A3 Dirt and accumulation of debris			
Urgency of repair level	**External claddings of pitched roofs**	**Adhesive ceramic tiling**	**Architectural concrete surfaces**
0			
1			 - Affected areas of high aesthetical value; - Or phenomenon with conditions to progress and affected area larger than 30%.
2	 - Leakage occurs; - Or phenomenon with conditions to progress.	 Affected areas of high aesthetical value.	 Affected area larger than 15%.
3	 Affected areas of high aesthetical value.	 Remaining situations.	 Remaining situations.
4	 Remaining situations.		

Figure 7.2 - Excerpt of the atlas of defects: page of defect "A-A3 Dirt and accumulation of debris" with columns corresponding to three different types of building elements/materials

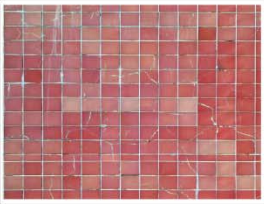
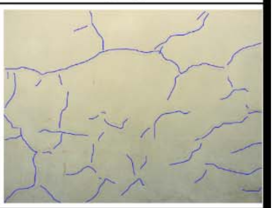
A-C1 Mapped cracking			
Urgency of repair level	Adhesive ceramic tiling	Natural stone claddings	Wall renders
0		 Safety of users compromised by the detachment of stone tiles from the façade.	
1		 - Simultaneous occurrence of leakage; - Or average crack width of 0.5 mm or larger.	
2	 - Simultaneous occurrence of leakage; - Or average crack width of 0.5 mm or wider.	 Remaining situations.	 - Affected area larger than 50%; - Or affected areas of high aesthetical value, larger than 20% and phenomenon with conditions to progress.
3	 Remaining situations.		 Remaining situations.
4			

Figure 7.3 - Excerpt of the atlas of defects: page of defect “A-C1 Mapped cracking” with columns corresponding to three different types of building elements/materials

Figures 7.2 and 7.3 show that not all levels of urgency of repair apply in all instances. For ex-ample, in Figure 7.2, for external claddings of pitched roofs, only levels 2, 3 and 4 are defined. In the same figure, for adhesive ceramic tiling, only levels 2 and 3 are considered. This is related to the severity of the consequences of a defect in different building components. In these cases, the most urgent situations of “dirt and accumulation of debris”

(A A3) on claddings of pitched roofs or on adhesive ceramic tiling are considered to lead only to interventions in the short-term (level 2), as this defect does not usually raise safety concerns. Furthermore, in pitched roofs, lighter cases of A-A3 may only require monitoring in posterior inspections (level 4).

But, in the case of “mapped cracking” (A C1) on natural stone claddings, defects range from levels 0 to 2 of urgency of repair (Figure 7.3), as, in severe situations, the occurrence of cracking on stone claddings may endanger users and passers-by, requiring contingency measures (level 0).

Considering the number of types of defects (38) included in the respective classification list and the (varying) number of building elements/materials that each one applies to, the atlas of defects totals 179 columns (combination defect–building element/material). Of the latter, 94% are filled in the row of level 2 of urgency of repair, while only 1% are filled in the row of level 4. Level 0’s row is also seldom filled, with only 13% of columns completed. Defect–building element/material combinations are more often defined for levels 1, 2 and 3 (rows filled in more than 50% of columns).

Additionally, most of level 0 definitions (61%) refer to defects occurring in natural stone claddings. The prospect of a stone slab falling from a façade is seen as a threat to safety due to its weight, thus increasing the likely level of urgency of repair of defects on natural stone claddings.

Observing the descriptive contents of Figures 7.2 and 7.3, different types of criteria may be distinguished. Some refer to the concomitant occurrence of other defects (e.g. leakage), some to the context of the defect (e.g. the aesthetical value of affected areas), some to the characteristics of the defect (e.g. extent), and others to the defect’s effects (e.g. safety issues). Many criteria are not identifiable through exemplificative photographs. It is the case of the conditions of a phenome-non to progress, aesthetical value of the affected areas, some safety risks, and percentage quantification of the affected area.

Analysing a phenomenon’s conditions to progress requires on-site assessment. Data like temperature, relative humidity, aggressiveness of the environment and maintenance means should be taken into account. They may be recorded for off-site evaluation, but at least a visit to the site under inspection is required. In photographs, some indication of this type of facts may be identified (e.g. signs of rainwater runoff), but they generally surpass the visual information (e.g. a sunny photograph may not correspond to high temperatures). Therefore, information impossible/difficult to register in photographs is a factor to be taken into account while using the atlas of defects (e.g. Figure 7.2, level 2 of “A-A3 Dirt and accumulation of debris” in external claddings of pitched roofs).

Generally, the aesthetical value of the affected areas is defined by the contextual importance of the façade, roof or flooring. Typically, in current buildings, the front façade has high aesthetical value, as it is adjacent to a public street and encompasses the main entrance to the building, while side and rear façades usually have medium and low aesthetical value, respectively. Since the photographs of the atlas of defects tend to centre on the defects, the aesthetical value of the building elements is not obvious. It is the case of the pictures in the column of architectural concrete surfaces in Figure 7.2. If the exemplificative case of level 3 of "dirt and accumulation of debris" (A A3) in architectural concrete occurred on the front façade of the building, it would be immediately considered of level 1, thus requiring immediate intervention, instead of intervention in the long-term.

As for safety risks, the criteria establishing the urgency of repair may refer to slippery floorings, risk of stumbling, or to the possibility of fall of cladding elements from façades. These occurrences are not usually evident in photographs. For instance, the possibility of a natural stone tile falling from a façade is related to different safety assessments depending on the height of the defect: risks are lower next to the floor than at a 10 m height. Still, that height may not be understandable in defect-centred photographs. So, the indefinite representation of safety risks affects the atlas of defects. It is the case of the picture representing level 0 of "mapped cracking" (A C1) on a natural stone cladding in Figure 7.3.

The percentage quantification of the affected area depends both on the extent of the defect and on the extent of the whole surface. Although it is viable to estimate the absolute area affected by the defect, whether using on-site measurements or reference elements in the photograph (like tiles with known size), the whole affected surface is not usually visible in defect-centred photo-graphs. For that reason, pictures like those illustrating architectural concrete surfaces in Figure 7.2 do not provide all the data needed to assess the urgency of repair of cases of "dirt and accumulation of debris" (A A3).

In short, the utility of the atlas of defects relies on the close combination of exemplificative photographs with descriptive criteria. Moreover, it should be highlighted that the same defect may manifest in different ways, even in the same type of building component (e.g. different fungi). In its current state, the atlas of defects is not an all-inclusive catalogue of all possible forms of defects.

7.5. Final remarks

Taking the research question into account (how can an expeditious tool to identify defects and their urgency of repair be achieved?), this section has shown that it is possible to develop a compendium of defects for the building envelope considering: (i) a well-defined classification of defects; (ii) a predetermined scope of building elements/materials; and (iii) a scale of urgency of repair levels, whose classification is determined by specific criteria. The atlas of defects combines graphical and descriptive contents, aiming at a simple identification approach, easy to use during fieldwork.

Such an atlas of defects may be useful to surveyors during inspections. Furthermore, occasional surveyors, like architects and engineers, may also use the proposed tool when performing building assessments. Technical building inspections are used in several situations, like with-in maintenance plans, before deciding on retrofitting or rebuilding options, at the design stage (retrofitting), and to assess insurance claims. Additionally, researchers may also use the proposed tool.

The proposed atlas of defects was developed within a global building inspection system, but, with the presented methodology, other atlases may be developed within different systems, given the basic materials and, most importantly, a well-defined scope and classification systems (of defects and urgency of repair or others).

To the best of the authors' knowledge, there is no such catalogue, combining building defects and their urgency of repair, in the literature. Furthermore, the need for the proposed atlas of defects had been previously identified [7].

In the future, the atlas of defects may be enhanced with better and more varied photographs. Moreover, the whole building inspection system will be computerised, including the atlas of defects. That step will be advantageous for developing a building pathology database, which may be useful for devising maintenance plans and new research. The visual assistance of the atlas of defects is valuable for faster analyses. Moreover, the parameters that define the urgency of repair may be included in automated algorithms, simplifying the rating process for the user of the computerised inspection system.

8. Glossary of pathology, diagnosis and maintenance/rehabilitation terms

Term	Designation/references (examples)
Active thermography	Infrared thermographic examination of materials and objects that requires additional thermal stimulation (ISO 10878). Thermographic procedure in which an artificial or natural source of energy is used to produce a nonstationary heat flux for the purpose of testing (EN16714-3)
Ageing	Degradation due to long-term influence of agents related to use (ISO 15686-1)
Anomaly	An indication of a possible defect or problem, which is directly visible or measurable (CIB W86 1993)
Building pathology	The systematic study of building defects, their causes, their consequences and their remedies (CIB W86 1993) The systematic and the more complete possible study (Treatise), regarding all possible types of study object´s "Diseases/Anomalies" . In this case regarding Built Heritage objects and/or its significant parts.
Comparative thermography	Thermographic procedure that evaluates temperature differences or phase differences or differences of secondary parameters (EN16714-3)
Computed tomography (CT)	X Ray scanning technique that uses a number of CT projections (1D or 2D radiographic image) of an object at different angles in order to allow calculation of a CT image (2D or 3D image of the CT grey values obtained by reconstruction) (ISO 15708-1)
Condition	Level of critical properties of a building or its parts, determining its ability to perform (ISO 15686-1)
Defect	Fault or deviation from the intended level of performance of a building or its parts (ISO 15686-1, 2011) A situation where on or more elements do not perform its/their intended functions (CIB W86 1993)
Degradation (deprecated)	Changes over time in the composition, microstructure and properties of a component or material that reduce its performance (ISO 15686-1)
Degradation agent	Whatever acts on a building or its parts to adversely affect its performance (ISO 15686-1)

Degradation process	Chemical, mechanical or physical path of reaction that leads to adverse changes in a critical property of a building product (ISO 15686-1)
Diagnostic	Pertaining to the detection, analysis or description of faults, failures or mistakes (ISO/IEC 2382-14)
Drone	Unmanned system that is remotely or autonomously operated (ISO 21384-4)
Façade inspection report	A detailed documentation of qualified professional's findings, observations, discussions, conclusions, and recommendations about the subject building facades (ASTM E 2270)
Failure	Loss of the ability of a building or its parts to perform a specified function (ISO 15686-1). The termination of the ability of a functional unit to perform a required function (ISO/IEC 2382-14)
Fault	An abnormal condition that may cause a reduction in, or loss of, the capability of a functional unit to perform a required function (ISO/IEC 2382-14)
Flat jack	A flat jack is a thin envelope-like bladder with inlet and outlet ports that may be pressurized with hydraulic oil. Flat jacks may be of any shape in plan, and are designed to be compatible with the masonry being tested. For determining load-deformation properties of masonry, flat jacks are typically rectangular or semi-rectangular (…) (ASTM C 1197).
Forensic engineering	Forensic engineering is the application of engineering principles to the investigation of failures or other performance problems. Forensic engineering also involves testimony on the findings of these investigations before a court of law. (ASCE Forensic Engineering Division)
Incompatibility	Detrimental chemical and/or physical interactions between materials and/or components that lead to premature degradation (ISO 15686-1)
Infrared thermography	The process of displaying variations of apparent temperature (variations of temperature or emissivity, or both) over the surface of an object or a scene by measuring variations in infrared radiance (ASTM E1316 – 19). Technique allowing imaging of objects by sensing their emitted infrared (thermal) radiation (ISO 10878)

Inspection	Close and careful scrutiny of an item carried out either without dismantling or with partial dismantling as required, supplemented by means such as measurement, in order to arrive at a reliable conclusion as to the condition of an item (AS 4349.0)
Inspection-detailed inspection	Visual observation from less than 6 ft (1.8 m) and tactile evaluation of façade components, including probing and non-destructive testing to observe concealed conditions of wall construction (ASTM E 2270)
Inspection-general inspection	Visual observation of façade components from distances equal to or greater than 6 ft (1.8 m) with or without magnification or remote optical devices (ASTM E 2270)
Maintainability	The ability of a functional unit, under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function when maintenance is performed under given conditions and using stated procedures and resources (ISO/IEC 2382-14)
Maintenance	Combination of all technical and associated administrative actions during the service life to retain a building or its parts in a state in which it can perform its required functions (ISO 15686-1)
Non-destructive testing (NDT)	A test that causes no significant structural damage to buildings components (ASTM E2270)
Passive thermography	Thermographic technique for inspecting objects or installations by measuring their emitted thermal radiation, without using any additional energy source for thermal stimulation (ISO 10878). Thermographic procedure in which no external heating source is used for the purpose of testing, only heat flow due to intrinsic heat of the object under test is used (EN16714-3)
Pathology	Something abnormal occurs within the individual; this may be present at birth or acquired later. A chain of causal circumstances, the "etiology", gives rise to changes in the structure or functioning of the body, the "pathology". Pathological changes may or may not make themselves evident; when they do they are described as "manifestations", which, in medical parlance, are usually distinguished as "symptoms and signs". (…) Someone becomes aware of such an occurrence; in other words, the pathological state is exteriorized. (…) (a) Not infrequently, symptoms may develop that cannot currently be linked to any underlying disease process. Something is certainly being exteriorized, even if it cannot be accounted for. Most health professionals would attribute such symptoms to a disturbance—

	as yet unidentified—of some essential structure or process within the body. (b) In contrast, some deviation may be identified of which the "patient" himself is unaware. Such pathology without symptoms sometimes constitutes subclinical disease, which is encountered with increasing frequency as screening programmes are extended. (…) (WHO 1980)
Pulsed phase thermography (PPT)	Processing technique used in pulsed thermography and in which data are analysed in the frequency domain rather than in the time domain (ISO 10878)
Pulsed thermography	Active infrared thermographic inspection technique, in which a test sample is stimulated with a pulse of energy and recorded infrared image sequences are analysed to enhance defect "visibility" and to characterize defect parameters (ISO 10878). [*Infrared thermographic inspection technique where*] energy is introduced by means of a short pulse that can be considered as a Dirac pulse (EN 17119)
Qualified inspector	A qualified professional or person working under the direct supervision of a qualified professional (ASTM E2270)
Qualitative infrared examination/ qualitative thermography	Technique that relies on the analysis of thermal patterns to reveal the existence and locate the position of anomalies (ISO 10878). Thermography in which the radiation flux or the temperature or the phase angle or secondary parameters derived there from are not determined (EN16714-3)
Quantitative infrared examination/ quantitative thermography	Technique that uses quantitative temperature measurement to determine the seriousness of an anomaly, in order to establish repair priorities (ISO 10878). Thermography in which the radiation flux, the temperature, the phase angle or secondary parameters derived there from are determined (EN16714-3)
Refurbishment, rehabilitation, renovation	Modification and improvements to an existing building or its parts to bring it up to an acceptable condition (ISO 15686-1)
Step thermography	[*Infrared thermographic inspection technique where*] energy source is switched on or/and off for a defined time during which thermal diffusion can occur (EN 17119)
Thermal tomography	Processing technique used in pulsed thermography and in which data are analysed by reference to a particular instant of interest such as the time of maximum thermal contrast (ISO 10878)

Thermogram	Thermal map or image of a target where the grey tones or colour hues represent the distribution of infrared thermal radiant energy over the surface of the target (ISO 10878)
Thermography	Determination and representation of surface temperature distribution by measuring the infrared radiation density from a surface, including interpretation of thermal images (ISO 6781) Contact-free detection, processing and visual display of the distribution of the thermal radiation originating from an object and recordable with an IR detector system (EN16714-3)
Unsafe condition	A condition identifies at the time of inspection of a component or system that presents an imminent threat of harm, injury, damage or loss to persons or property (ASTM E2270)
Vibrothermography	Thermographic technique for examining an object where temperature differences are produced by mechanical vibrations (ISO 10878)

9. References

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