Chapter 2
Service Life and Durability of Assemblies

2.1 Theoretical Foundations

The quality and the durability of buildings are an essential dimension for the quality of life, and are critical for the social and economic stability of contemporary societies (Wekesa et al. 2010). In fact, the building stock represents approximately 50 % of the wealth of most European countries (Long et al. 2001). The increased degradation of the built heritage is due to the natural ageing process of materials and components, which begins as soon as buildings are put into use, associated with the scarcity of resources and—in some countries—a yet incipient culture of building's maintenance. According to Haagenrud (2004), when adopted, an attitude of "build and let it stay" leads to an accelerated loss of building's performance. This loss of performance, which manifests itself in ever higher levels over time, expressed by the presence of defects, leads to the inability of the buildings to fulfil the requirements for which they were designed (Chai et al. 2014). Therefore, the knowledge concerning the service life of buildings and their components assumes a very important role, allowing understanding how to manage a vast—and often aged—built park.

The service life prediction is a field that leads to more rational and sustainable solutions. In the last decades, the possibility of using data on the service life of materials and components during the design and construction phase has been thoroughly analysed (Frohnsdorff and Martin 1996; Soronis 1996). This interest arose due to two main factors: (i) environmental factors, since the energy crisis led to a scarcity of resources and an increased awareness of the notion of sustainability (witnessing a growing concern in terms of the environmental impact of the construction sector); (ii) economic factors, since the management and maintenance of the built stock is a very significant dimension of the economy of societies (Hovde 2002). Moreover, the changes in construction methods, the onset of durability

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problems and the need to understand the performance of new building materials also contribute to the pursuit of knowledge regarding the durability of buildings and their components.

This chapter aims to establish the first approach to the service life prediction methods applied to the façades claddings, with three main objectives: (i) perform an extensive survey regarding the concepts related with the service life and durability of building components, the methodologies and standardization related to this matter; (ii) define the information collected during the fieldwork, which allows the physical and visual characterization and further quantification of the degradation condition of the claddings analysed; iii) the characterization of the samples collected during the fieldwork.

2.2 Service Life of Buildings

Making an analogy with living beings, it can be said that all buildings have a life cycle during which they "are born", "get older" and "die" (Gaspar 2009). Often does this analysis appear in the literature on the subject, namely regarding life cycle assessment analysis, referred to as "cradle to grave". The building's life cycle comprises all stages of its life, i.e. the time elapsing since it is placed in use, after construction (birth—corresponding to the stages of design and construction) and ending at the instant from which it is unable to meet the acceptable minimum performance requirements (ISO 15686: 2011). The concept of service life is relatively simple, although different definitions can be found in the literature, sharing common ideas

- According to ISO 15686: 2011 (Service life planning), service life can be defined as the period of time after installation in which the buildings or their parts meet or exceed the minimum performance requirements;
- ASTM (1990) shares the same definition of ISO 15686: 2011 and also mentions that during this period of time the building and its elements must be subjected to periodic maintenance;
- The Canadian standard CSA S478-95 (Guideline on Durability in Buildings) refers that the service life can be described as the period of time during which the building or its components fulfil the requirements for which they were designed, without unexpected costs or maintenance and repair actions;
- EOTA, in the document Assumption of Working Life of Construction Products in Guideline for European Technical Approvals and Harmonized Standards (EOTA 1999), characterizes service life as the period of time during which the performance of the product is maintained at a level compatible with the fulfilment of the essential requirements.

The concept of service life is often confused with that of durability, leading to the misuse of the terms. Contrary to the concept of service life, durability is not related to a period of time but instead corresponds to the building's ability and that of their components to show an adequate performance during their life cycle. According to the Canadian standard (CSA S478-95: 2001), the concept of durability refers to the ability of a building or its components to achieve the best performance in a given environment or location, without having to be subjected to significant corrective measures or to the repair or replacement of its elements. In turn, the New Zealand Building Code includes a functional requirement, referring that the elements and construction materials as well as construction methods should be sufficiently durable, thereby ensuring that the building meets all the performance requirements during the building's service life, without having to be subjected to significant rehabilitation works (Lee et al. 2008). In reality, durability cannot be seen only as an intrinsic quality of a material; simple changes in the construction details may promote a higher protection of a building element against the degradation agents, contributing to the increase of its service life (John et al. 2002). The service life prediction methodologies gain therefore an increasingly important role in the implementation of durable buildings, which should be designed based on: (i) the knowledge of the performance of the materials over time; (ii) the knowledge regarding the capacity of the material withstanding the degradation mechanisms it will be subjected to, under a given set of environment exposure conditions; (iii) the characteristics of the construction and its context (Wyatt 2005). In the end, although being different concepts, the service life and durability of constructions are closely related and necessary to understand the life of buildings; they are therefore relevant concepts in the construction process, either at the design stage or in the use phase, thus allowing reducing the maintenance costs, increasing the comfort of users and the sustainability of the solutions adopted (Moreno 2012).

A study performed by Bordeau (1999) for the CIB W82 commission reveals that in some languages (Dutch, Finnish, Romanian, among others), the word "sustainable" can be translated by "durable". This "overlapping" between the two concepts seems logical, since the increase in the durability and service life of the constructions is an acting vector in the search for sustainability, in order to decrease the environmental impact of buildings, because it directly contributes to a more rational management of resources, reducing the production and disposal of waste (DeSimone and Poppof 1998). In recent decades, the concept of sustainable development has even led to a reassessment of the contribution of the construction industry in the quality of life (Pearce 2003). The sustainable development of the construction sector can be analysed in three dimensions: (i) environmental; (ii) social; (iii) and economic (Mateus et al. 2008). A sustainable development can only be achieved in these three levels if measures to reach sustainability are adopted during all the phases of the buildings' life cycle. In particular, during the use phase, it is extremely important to carry out detailed planning of the maintenance needs (Daniotti et al. 2008). Inversely, various authors (Takata et al. 2004; Donca et al. 2007) refer that maintenance actions, if properly implemented and planned in a rational and technically informed manner, allow increasing the buildings' service life (thereby contributing to improved durability and sustainability of buildings). In practice, one of the most effective ways of optimizing maintenance actions in buildings is through the knowledge how the building and their components deteriorate over time, estimating the instant after which it is necessary to intervene (Talon et al. 2005). Generally, without this information, maintenance actions may generate high costs associated with unnecessary interventions or urgent repairs, which could be avoided. According to Vanier (1999), before implementing any maintenance policy, a set of questions should be answered, in which it is necessary to evaluate the condition of the element in question and its remaining service life, so as to define the extent of the intervention that should be performed.

2.2.1 Criteria that Influence the End of the Service Life of Buildings

During its life cycle, a building should meet a set of performance requirements, e.g. safety, watertightness, compatibility to the substrate, visual comfort, durability, among others. However, in some situations, the building's components fail to fulfil these requirements after some time. Obsolescence is also a concern for all owners and users, for even if the building may fulfil the initial requirements, it may fail to respond to new expectations or requirements especially when compared to (often newer) available alternatives. Sarja (2005) defines obsolescence as the inability of the building or its parts to adapt over time to the functional, economic and cultural requirements. The usefulness of the buildings may also be compromised by their inability to accommodate changes over time (Slaughter 2001); in fact, throughout their life cycle, all the buildings experience changes, e.g. changes in its occupants or their needs and expectations, renovations and/or extensions, the ageing and replacement of components and systems (Cowan 1963; Brand 1997; Augenbroe and Park 2002).

Construction assets suffer various types of depreciation throughout their life cycle, in a process that begins as soon as the building is put into use (Rikey and Cotgrave 2005), eventually leads to the end of the building service life. This process is due to several factors: (i) physical deterioration; (ii) economic obsolescence; (iii) functional obsolescence; (iv) technological obsolescence; (v) changes in the social context; (vi) obsolescence due to the building envelope; (vii) legal obsolescence; (viii) aesthetic obsolescence; and (ix) environmental obsolescence (Flanagan et al. 1989; Flores-Colen and de Brito 2010). Hovde (2002) refers as the main reasons to establish the end of the service life of a building: (i) technical aspects; (ii) economic aspects; (iii) environmental reasons; (iv) planning reasons—e.g. when the demolition of a building or a structure leads to the construction of a railway or other construction for public service; (iv) society requirements or technological development. On the other hand, Moser (2004) proposes a more strict range of reasons, suggesting three main reasons to establish the end of the service life of a building: (i) safety; (ii) functionality; and (iii) aesthetics. Gaspar (2009) refers that despite the relative simplicity of the service life concept, the service life is extremely difficult to predict or simulate through models, since it "depends on the definition of acceptance criteria, which varies to the time, place and the stakeholder and even with the social, economic, political, aesthetic, environmental context of the building under analysis". Generally, new performance requirements (usually more demanding) are enforced all the time, leading to a constant investment to keep up with them and to delay the degradation trend affecting the building elements. Aikivuori (1999) states that, even if the building maintains its original properties (not showing visible degradation), the end of its service life is inevitable due to the evolution of the acceptance criteria, for example by comparing the existing situation and a new available constructive solutions. In the definition of the service life prediction methods it is therefore necessary to understand and incorporate the maximum acceptable degradation level for the element under analysis—i.e. the minimum acceptable level of performance—after which the element has reached the end of its service life. This theoretical limit is not generally easy to specify (Moser 2004); in fact, as mentioned by Iselin and Lerner (1993), there are no rational criteria to guide the decision to intervene, but rather subjective and programmatic criteria. A study performed by Aikivuori (1999) shows that in only 17 % of the situations, the decision to intervene is taken based on the building's deterioration and in 44 % of cases maintenance actions are performed based on subjective criteria. This study also concludes that, when the decision to intervene is based on technical criteria only, depending on the building's degradation condition, the rehabilitation action takes place later than it would if the criteria were subjective (e.g. due to the aesthetic criteria). Sarja (2005) drew similar conclusions, referring that the most prevailing reasons for heavy refurbishments or demolitions of buildings are (i) obsolescence under changing use, (ii) demands of users and (iii) general requirements of the society; and indeed not the buildings' degradation as we are led to believe.

Regardless of the variability of the acceptance criteria, the service life of buildings can be distinguished into three main categories: (i) physical service life; (ii) functional service life; and (iii) economic service life (Marteinsson 2003). The physical or technical service life is related with the deterioration of the materials and building elements. The deterioration of the construction elements occurs systematically, which implies that its failure rate increases over time (Zhang and Gao 2011). The physical deterioration of buildings is mainly due to the action of the degradation agents (whether physical, chemical or mechanical) and the natural ageing process. In several situations, design and construction errors, or the application of inadequate materials, can contribute to the reduction of the physical service life of buildings. The functional service life is directly related with the expectations and demands of the users; Davies and Szigeti (1999) refer that, as is the case of computer applications or the motor industry, the functional obsolescence of buildings occurs when they are unable to follow the users' requirements. In the real word, the service life of buildings is often conditioned by economic reasons; Brand (1997) states that the economic service life can be defined as the time elapsing since the construction is placed into use until the instant that it is replaced by a more profitable solution. The author also refers that buildings do not reach the end of their economic service life while the cost/benefits ratio is more attractive than the alternatives. In this case, the end of the economic service life is reached when the cost of replacing an element by another is lower than that of maintaining the existing one. Naturally, over time, and with the emergence of new constructive solutions (more economical, more durable and requiring less maintenance), buildings became economically obsolete.

This book addresses the physical service life of façade claddings, evaluating the physical and visual degradation of the claddings analysed, as described ahead in Sect. 2.5. In this study, the end of the service life is reached when the façade shows a degradation condition considered inadmissible, i.e. when the maximum acceptable degradation level is reached. This level is a theoretical limit that seems realistic considering the local context of the study (the Portuguese context) but, as referred before, this limit is subjective and difficult to define, since it varies according to the users' demands, changing over time.

2.3 Methodologies for Service Life Prediction

In the last decades, different methodologies for service life prediction and different tools to support the decision-making process regarding the maintenance of construction have been put forward. Nevertheless, these models have several shortcomings, essentially due to: the complexity of the degradation phenomena; the lack of understanding of the degradation mechanisms and how these affect the construction elements; the scarcity of reliable methods to quantify the durability and service life of buildings (Lounis et al. 1998). In fact, the service life prediction of buildings and their components can be a complex and time-consuming process that is associated with many factors (Hovde 2004), such as the quality of materials, the design and execution level, the indoor and outdoor environment conditions, as well the use and maintenance conditions (ISO 15686-1: 2011). The researcher must choose the best approach to the problem that he/she wants to model, considering the advantages and limitations of each methodology (Freitas et al. 2013). Generally, in the literature, the service life prediction methods have been grouped into deterministic, stochastic and engineering models (symbiosis between the other two methodologies) (Moser 2004; Lacasse and Sjöström 2004). This classification is also used in the next sections to describe the existing methodologies for service life prediction.

2.3.1 Deterministic Models

The deterministic models are based on the study of the degradation factors affecting the elements under analysis, on the understanding of the degradation mechanisms and, finally, on their quantification translated into degradation functions. These degradation factors are then translated into formulas that express their action over time until the maximum acceptable degradation level of the element analysed is reached. These methods have significant advantages: are easy to understand and apply; can be easily implemented; and maintain their operability even when all the variables related with the modelled phenomena are unknown. However, these approaches have been subjected to several criticisms, essentially due to the simplistic way with which they deal with complex phenomenon such as the service life of building's components. According to Paulo et al. (2014), the deterministic models are unable to capture the random nature of the degradation phenomena. Various authors (Hovde 2000; Mc Duling et al. 2008) state that in the deterministic models, the service life is given by an absolute value that does not provide any information regarding the degradation process or related to the probability of transition from one degradation condition to another. Nevertheless, these methods have produced practical solutions to the problem and are widely used; they have also provided the basis for the international standard for the durability of buildings (ISO 15686: 2011).

Within the deterministic methods, empirical methods have been developed in order to evaluate the durability (or loss of performance) of a building or its components under real conditions of service, at different stages of its service life, based on data collected during field work (Shohet and Paciuk 2004; Gaspar and de Brito 2008). In these methods, the characterization of the buildings' degradation condition is performed through the definition of a classification system for defects and degradation ratings in order to express the physical and functional degradation of the elements under analysis, which can be converted into quantitative information. Based on this information, the loss of the material's capacity to answer the requisites demanded can be expressed by degradation functions (Bordalo et al. 2011). In practice, after collecting the fieldwork information regarding the degradation condition of the façades—which needs to be converted to quantitative, numerical data—service life can be estimated using a graphical procedure and a statistical analysis of the evolution of degradation over time. The evolution of degradation is thus represented graphically by degradation curves that can be associated with specific degradation mechanisms (Shohet et al. 1999; Florentzou et al. 1999). This methodology is implemented and described in Part 3A of this book.

2.3.2 Stochastic Models

Due to the uncertainty associated with the building's performance, it is often necessary to use probabilistic models to predict the service life of the construction elements (Ross 1996). In the probabilistic methods, the degradation of construction is regarded as a stochastic process, which is described by a set of random variables that define probabilistic parameters affecting the average degradation curve (Moser 2003).

These methods are usually quite complex and require an extensive data collection to obtain sufficiently representative samples, which is not always possible, due to time and cost constraints (Re Cecconi 2002). According to this author, the translation of these models into real situations can be complex, which implies that these methods are only profitable on large-scale projects. In fact, these methods are often beyond the reach of a common designer, due to the impossibility of this acquiring all the necessary knowledge in the time required for the application of the methodology (Moser and Edvardsen 2002). Stochastic models are usually associated with three main drawbacks, which can restrict their application: (i) the high complexity of the mathematical expressions used; (ii) the large amount of data required necessary to validate the model, which should preferably be collected over a long period of time; (iii) the great dependence of the fieldwork.

In the literature, there are several studies addressing the application of probabilistic methods for service life prediction

- Markov chains are a probabilistic method widely used in the study of the deterioration of buildings. This method is based on the assumption that a deterioration model can be defined based on a limited number of conditions, evaluating the probability of transition between a degradation level to the next one (Frangopol et al. 2004);
- Using a development of the Markovian transition matrix, Mc Duling et al. (2008) suggest a hybrid model between artificial intelligence and fuzzy logic (neuro-fuzzy artificial intelligence) that allows translating the rate of changes between degradation states, incorporating the effects of maintenance actions in the buildings service life prediction;
- Liang et al. (2001) suggest a model based on fuzzy logic to evaluate the service life of bridges, in which the end of service life is defined based on a minimum security index, by assessing the state of degradation of the existing elements;
- Leira et al. (1999) propose the Trend plots method, which is a simple statistical tool for forecasting rehabilitation needs, requiring a large amount of information regarding the durability of a given element to be applied;
- The European project Energy Performance Indoor Environment Quality Retrofit (EPIQR) proposes a tool for diagnosis and support of decision-making regarding the maintenance actions, based on the classification of the buildings' degradation condition in four states, ranging from "a" (best condition) and "d" (worse state condition, requiring an immediate intervention) (Balaras et al. 2000);

- The MEDIC method (*Méthode d'Évaluation de scénarios de Dégradation probables d'Investissements Correspondants*), proposed by Flourentzou et al. (1999), is based on the EPIQR tool and uses the theory of conditional probabilities (Bayes' theorem) to evaluate the transition between degradation states over time, allowing evaluating the residual service life of the buildings, thus predicting the investments necessary to the buildings' rehabilitation;
- Some probabilistic methods are based on the concept of fault and decision trees, assessing the durability of structures based on the definition of deterioration levels and the conditional probability of transition until their failure (Faber and Gehlen 2002).

Despite these approaches, the majority of the probabilistic models proposed in the literature focus one type of material only—usually reinforced concrete—subjected only to a degradation agent (usually chloride attack) (Lounis et al. 1998; Abraham 2002; Siemes and Edvardsen 1999; Edvardsen and Mohr 2000).

2.3.3 Engineering Models

The engineering "design" methods are a symbiosis between the two previous methods. These models are as easy to learn, understand and implement as the deterministic methods, but allow describing the degradation process in a stochastic way (Re Cecconi 2002). Usually, engineering models possess an acceptable level of complexity and are implemented using probabilistic data, leading to simple deterministic equations. According to Daniotti and Spagnolo (2008), engineering methods can be used to identify in a more analytical way the degradation phenomena, thus allowing the implementation of this information in the design stage or establishing a methodical planning of maintenance actions. Some of the best known engineering methods are

- The Failure Modes and Effects Analysis (FMEA) method, which was initially developed by the aerospace industry and later used in mechanical and electrical engineering; it has rarely been used in the construction sector (Lair 2003). Nevertheless, when applied to the construction sector, this method can be used for the certification of construction products, allowing obtaining an as complete as possible list of the degradation agents and failure mechanisms that can act in building elements during their use phase (Talon et al. 2005);
- The Performance Limits method, whose aims are to evaluate the durability of building components by simulating their performance over time, until their physical or performance limit has been reached. In this method, the degradation phenomena is evaluated by a chain of events: agents → actions → effects → deterioration (Daniotti and Spangolo 2008);
- Besides these methods, the probabilistic approach of the factorial method can also be seen as an engineering model. In this approach, the quantification of the

durability factors is performed based on probability density functions instead of absolute values, (Moser 1999; Aarseth and Hovde 1999; Moser 2004). Therefore, this model combines the simplicity of the factorial method and the probabilistic analysis of the degradation factors.

2.4 Normative Framework for the Service Life Prediction of Buildings

Currently there are numerous standards and guidelines that intend to establish standardized methodologies to evaluate the durability and service life of buildings and their components. In 1979, the Architectural Institute of Japan decided to organize a technical commission in order to systematize the concept of durability of constructions. This study led to the creation of the first normative document addressing the durability and service of life of buildings and their components: the Japanese guide developed in 1989, later translated to English under the title "(Japanese principal) guide for service life planning of buildings" (AIJ 1993). The Japanese guide establishes a set of recommendations for the service life prediction of buildings, their components or equipments, assuming that the end of their service life is determined by physical deterioration or obsolescence (Rudbeck 2002). This methodology is the basis of the factorial models, leading to a number of studies and standards currently published. Also, in Japan, with the approval of the Housing Quality Assurance Law (HQAL 2000), a series of measures were imposed in order to monitor the degradation of buildings and their components (Nireki 1996). Other guiding documents for the rehabilitation of buildings were put forward, such as the Guide to Condition Assessment for Refurbishment (1993) and Design Guide Refurbishment (1999).

In 1992, the British Standards Institute published standard 7543 for durability "British guide to durability of building elements, products and components" (BS 7543: 1992) that lists various methods to estimate the service life of construction products: (a) through past experience, using similar buildings, subjected to similar use and climatic conditions; (b) by evaluating the degradation level of the elements in a short period of use or exposure, estimating the value for which the durability limit is reached; (c) through accelerated ageing tests, which is a complex approach, due to the need to simulate real situations that have many variables to be considered. BS 7543 proposes defining the service life of buildings as a function of the type of use; buildings are classified into five categories: temporary buildings, with a service life of less than 10 years; short-lived buildings, such as storehouses, with a service life of at least 10 years; average buildings, such as industrial buildings, with a service life of at least 30 years; current buildings, such as new housing, hospitals and schools, with a service life of at least 60 years; long-living buildings, such as public buildings, with a service life of at least 120 years. The standard also prescribes that façade claddings must guarantee a service life similar to that of the building, with proper periodic maintenance.

Inspired by the Japanese guide, the International Organization for Standardization (ISO) proposed an international standard for the service life prediction of buildings, based on a recommendation of RILEM (International Union of Testing and Research Laboratories for Materials and Structures) (Frohnsdorff et al. 1996). Currently, the ISO 15686 "Building Service Life Planning" standard has eleven parts that define the general principles, framework and procedures of the proposed service life prediction methodology. Moreover, this standard defines the functional performance criteria to be fulfilled in the design phase and throughout the buildings' life cycle, which ultimately contribute to the definition of the end of the service life of the elements under analysis (Hed 1999). The ISO 15686 standard is one of the most relevant information sources regarding service life prediction and is composed of the following parts (Sjöström and Davies 2005; Haapio 2008): (i) ISO 15686-1: 2011, which defines the general principles to be adopted in the design phase, in order to ensure the buildings' durability; (ii) ISO 15686-2: 2012 (Service life prediction procedures); (iii) ISO 15686-3: 2002 (Performance audits and reviews); (iv) ISO 15686-4 (Data requirements/data formats); (v) ISO 15686-5: 2008 (Life cycle costing); (vi) ISO 15686-6: 2004 (Procedure for considering environmental impacts); (vii) ISO 15686-7:2006 (Performance evaluation for feedback of service life data from practice); (viii) ISO 15686-8: 2008 (Reference service life and service life estimation); (ix) ISO 15686-9: 2008 (Service life declarations); (x) ISO 15686-10: 2010 (Using requirements for functionality and ratings of serviceability during the service life); (xi) ISO 15686-11 (Terminology).

Other documents and guidelines have been developed within the service life prediction of buildings (Rudbeck 2002; Lacasse and Sjöström 2004; Kooymans and Abbott 2006), in countries like: (i) **Nordic countries**, which established a joint committee in 1976 to develop a Nordic model for the creation of standards based on the performance of buildings; (ii) **Norway**, which established a standard that specifies the performance criteria, as recommendations for maintenance and rehabilitation of buildings (NS 3422: 1994); (iii) **Denmark**, through the Danish Building Defects Fund committee that, since 1986, promotes projects (such as Quality-Assurance Danish and Liability Reform) that intend to reduce the defects in buildings, improving their performance (e.g. through the knowledge of the behaviour of building materials in service); (iv) the **Netherlands**, where the first standards based on performance requirements were defined, which subsequently formed the basis for the development of the European Directive on Construction Products; (v) **New Zealand Building Code**, which establishes the service life of buildings, depending on the easiness of the access to the component under analysis, the easiness of repair and the defects detection; (vi) **USA**, through the Partnership for Advancing Technology in Housing (PATH) and the American Society for Testing and Materials (ASTM); (vii) **Canada**, with the Standard S478: Guideline on durability in buildings, which describes the main methodologies for service life prediction.

In addition to the normative documents, a set of reference documents has been published that propose estimated service lives (average, standard values) for construction elements: (i) the HAPM (Housing Association Performance Management), which establishes a range of estimated service life values for a wide range of building components, depending on the materials' characteristics and their exposure conditions; (ii) the NAHB (National Association of Home Builders) that provides an estimated service life for the construction elements based on the opinion of experts and manufacturers.

Internationally, some I&D companies developed studies in the service life prediction area, namely: (i) TNO (Netherlands Organisation for applied scientific research), which applies the knowledge on the service life of current buildings in order to reduce the maintenance costs of these elements; (ii) Building Research Establishment (BRE), which provides expertise services in the detection and correction of defects and the context of life cycle analysis (economic and environmental) of the construction elements. Other organizations have developed studies concerning the durability and service life of structures, such as the International Association for Building Materials and Structures (RILEM) and the International Council for Research and Innovation in Building and Construction (CIB). Within CIB, some commissions address the durability and maintenance of buildings, such as the committees: (i) W60—Performance concept in building; (ii) W70—Management maintenance and modernization of buildings facilities; (iii) W086—Building Pathology; and (iv) W094—Design for durability. On this subject, the W080 commission—Prediction of service life of building materials and components—with the cooperation of the Committee TC59 Technical of RILEM, has been actively working within the service life prediction of constructions.

2.5 Degradation Phenomena of Façade Claddings

Buildings are composed by different components that reach the end of their service life in different stages of the buildings' life cycle. Various authors (Brand 1997; Slaughter 2001; Gaspar 2009) subdivide the building in durability layers, i.e. in construction subsystems whose degradation occurs at different rates, among which are the "structure", the "skin", the "systems" and the "interior lay-out and finishes". The façade can be seen as the "skin" of the building, contributing to increase the durability of the structure, protecting it from the environmental agents. Since the cladding is the most exterior layer of the building, and therefore more exposed to agents causing degradation, it is also more prone to defects. In fact, a research carried out by the BRE concluded that façades are the building component most affected by pathological manifestations, representing 20 % of the defects detected in current buildings (Watt 1999). Façades also present a very important aesthetic function since they represent the public image of the building. Their visual degradation not only affects the quality of urban space and impact on the perception of buildings and—indirectly—of their owners, but is also a major concern for the latter, since in the majority of the cases, maintenance and rehabilitation actions are performed based on the appearance of the building only (Balaras et al. 2005).

2.5.1 Data Acquisition Methods to Establish Service Life Prediction Models

Service life prediction is a multidisciplinary research field, which should be based on the knowledge acquired from materials' science, laboratory testing and from the behaviour of building elements in service conditions (Sjöström 1985). An efficient evaluation of the service life of construction elements must take into account various random factors, such as the natural ageing of materials and the environmental exposure conditions.

The data related with the durability of building components can be obtained through various methods. Clifton (1993) states that the methodologies for the service life prediction of structures can be based on: (i) previous experience; (ii) the performance of the materials analysed under similar conditions; (iii) laboratory tests, e.g. accelerate ageing tests; (iv) mathematical models to describe the physical and mechanical degradation processes; and (v) through the application of reliable stochastic models. Gaspar and de Brito (2008) refer that in the definition of models to simulate the degradation of façades claddings over time two approaches can be used: (i) laboratory testing; and (ii) the evaluation of the condition of the elements under analysis, in real situations, based on in situ surveying work. Laboratory testing presents an important role in assessing and understanding the performance of materials and construction elements, for which they employ a single arbitrary set of stringent conditions (say, the combined effects of temperature and moisture variations). Norvaišienė et al. (2003) refer that this approach has as main advantage, the speed with which they can obtain results, regardless of the relevance of the experimental conditions, compared with the study of degradation of materials in real service conditions. Rimestad (1998) and Augenbroe and Park (2002) state that the field data on the performance of buildings should be used whenever possible, which can also be applied to guide the definition of the accelerated ageing tests. However, according to Frohnsdorff and Martin (1996), such artificial reduction of the degradation effects fails to simulate the holistic effect of the environmental actions that together contribute to the degradation of the building elements. A number of authors further indicate that the relationship between the exposure conditions in the laboratory and real life in-use situations is not generally known or easy to establish, even in the case of natural ageing tests in monitored conditions (Kus and Carlsson 2003). In fact, after installation, a building is exposed to a number of environmental agents whose combined actions are not easily modelled and reproduced.

To assess the durability of buildings through the analysis of their behaviour in service, various techniques can be used ranging from destructive tests carried out in situ to visual inspections. Destructive testing provides accurate information on the performance and characteristics of materials and building components, but they are often expensive and require repair work afterwards. On the contrary, non-destructive assessment methods—most notably, visual inspections of building elements—are generally less expensive, faster to carry out and may be very useful in providing relevant information regarding the degradation process of materials (Meola et al. 2005). Often do they also provide relevant enough early warnings of problems that may occur that can be avoided by repair work or further investigated by on site destructive testing.

In this study, the description of the degradation condition of the façades analysed is based on visual inspections. Visual inspections are an easily grasped method but present some limitations since their accuracy depends significantly on the experience/background and classification criteria of the surveyor. This method also depends on the atmospheric conditions at the time of the inspection (e.g. the difficulty of detecting defects in smooth and dark claddings when under direct solar exposure). On the other hand, this method does not usually require costly equipment, and it is often perfectly adequate to determine the degradation condition of the elements under analysis. Usually, a straightforward visual inspection is considered sufficient to evaluate the degradation state of the façades claddings, and it is sufficient for the surveyor to collect in situ the data regarding the defect type, its intensity and extension (Straub 2003).

2.5.2 Systemic Analysis of the Façades Degradation Condition

In this study, four most current types of claddings are analysed, based on their use in Portugal

- Natural stone claddings—this type of claddings has a large variability concerning its construction technology; it can comprise various types of stone, different thicknesses and different types of finishing. Additionally, there are several fastening technologies, e.g. it can be directly adhered to the substrate or it can be applied indirectly with the application of metallic elements. Stone claddings correspond to 14.6 % of the claddings existing in Portugal (Census 2001). The sample analysed comprises 203 stone claddings; the oldest building was built in 1891 and later rehabilitated in 1948, and the newest building dates from 2008. In this study, a comprehensive sample is analysed, representative of the type of natural stone found in Portuguese claddings;
- Rendered façades—these claddings are traditionally composed of a binder (cement, lime or both), sand, water and other minor constituents; the composition of the mortar (content of the various constituents) depends on their function. Generally, traditional renderings are applied in three distinct layers (spatterdash, base coat and finishing layer), with a small thickness to facilitate

their drying and a gradual decrease of the binder's content from the inside to the outside layer, thus minimizing occurrence of cracking in the cladding (Kus 2002). In Portugal and in most European countries, rendered façades are the most common type of cladding (Flores-Colen et al. 2010). In this study, 100 rendered façades are analysed with different typologies and ages under 60 years;
- Painted surfaces—Portuguese standard NP 41 (1982) defines paint as a liquid, in paste or solid material, with a pigmented composition, which is converted after a period of time into a solid film, coloured and opaque, when applied in a thin layer on a suitable surface in the state in which it is provided or after fusion, dilution or dispersion in volatile products. Generally speaking, paints are constituted by pigments, fillers, binder or vehicle (fixed and volatile) and additives. Painted surfaces, like rendered façades, are a very common cladding solution adopted in Portugal. In this study, 220 painted surfaces are analysed; these paintings were applied on rendered façades or over existing paintings belonging to the building stock of Lisbon, with a range of ages of 18 years;
- Ceramic tiling systems—this cladding system comprises the ceramic tile, the substrate, the adhesive material needed to ensure the bond between the tile and the substrate, and the filling material for the joints (Chew 1999). Ceramic claddings represent a small percentage of façade claddings in Portugal (5.5 % in buildings built between 1946 and 2001) (Flores-Colen et al. 2008) and their use is often associated with fashion trends (Bordalo et al. 2011). For this reason, the sample analysed (195 case studies) comprises a wide range of construction dates, with an historical peak for the use of this cladding in the period 1920–1949, due to socio-economic reasons.

This study is intrinsically related to various studies performed at Instituto Superior Técnico of the University of Lisbon (as mentioned in Part 1), already published in a number of ISI-indexed journals that address the service life of construction elements. Therefore, this study applies fieldwork data gathered and analysed in previous studies, namely: (a) the 203 stone claddings are composed by a comprehensive sample collected by Silva et al. (2011) and Emídio et al. (2014); (b) the 100 rendered façades analysed are initially analysed by Gaspar and de Brito (2008); (c) the 220 painted surfaces are inspected by Chai et al. (2014); and (d) the ceramic tiling systems are collected by Bordalo et al. (2011) and Galbusera et al. (2014).

All these studies apply the same methodology in the systemic analysis of the degradation condition of the façades analysed (Fig. 2.1). The first step for the application of this methodology is the characterization of each case study; for that, complementary information (location, drawings, documentation from the Municipalities and other relevant data) was collected for each case study. Furthermore, an inspection and diagnosis file is created, where the gathered data can be grouped into two categories: façade condition and durability related data. Concerning the data related with the façade's condition, the following information is collected (Silva et al. 2013b): (i) a detailed survey of the façade's dimensions; (ii) the list and description of the defects detected, their extent within the façade and their location; (iii) an indication of the probable causes; (iv) a list of the diagnosis means and inspection techniques adopted in data collection; (v) the definition of the severity of the defects detected to be used later on the definition of the degradation models. The durability related data include the following information: (i) the identification number of the case study; (ii) the building's location; (iii) date and nature of the last intervention on the façade; (iv) construction size and geometry; (v) material's characteristics (type of material, colour, texture, among other parameters); (vi) design factors; (vii) level of detail and execution; (viii) potential critical points in the façade (e.g. balconies or protruding elements); (ix) environmental exposure conditions (temperature, exposure to damp, wind-rain action); (x) type of use.

The survey of the façades during fieldwork is complemented with photographs, direct measurements and diagrammatic sketches. Subsequently, this information is processed by computer, using image processing applications, computer-aided design and calculus spreadsheets. Additionally, the users and owners of the buildings inspected are also inquired. During fieldwork, the inspector should carefully characterize the building's pathological situation, since defects with accidental causes or due to vandalism cannot be used to feed the degradation models, since they are unpredictable and do not represent the natural degradation process of the elements under analysis. In this methodology, the variable 'age' is given by the period of time elapsing between the last significant intervention in the cladding–e.g. generalized repair, with partial or total replacement of the cladding—and the inspection date. The information concerning the last intervention is obtained through the documentation from the Municipalities or provided by the owners of the buildings surveyed.

2.5.2.1 Definition of Degradation Conditions

Currently, there are various methods to assess the degradation condition—often referred to as degradation level—of building's components. Usually, these methods are established based on the importance rating of the construction elements, the rating of the defects and the definition of the condition parameters associated with the defects (Straub 2003). Several authors have established classification systems for defects and degradation ratings in order to express the visual and functional deterioration of the elements analysed (Balaras et al. 2005; Shohet et al. 1999; Marteinsson and Jónsson 1999; Freitas et al. 1999; Brandt and Rasmussen 2002; Chew 2005). Generally, these classification systems consist of rating the defects according to a scale of discrete variables, which varies from the most favourable condition (no visible degradation) to the most unfavourable condition (generalized degradation or loss of functionality). In more simplified approaches, each degradation condition is established based on a set of reference characteristics analysed in real situations during the fieldwork. Even though they are easy to use and interpret, these classification systems present some limitations since the scales adopted provide qualitative degradation parameters only (instead of quantitative ones). To

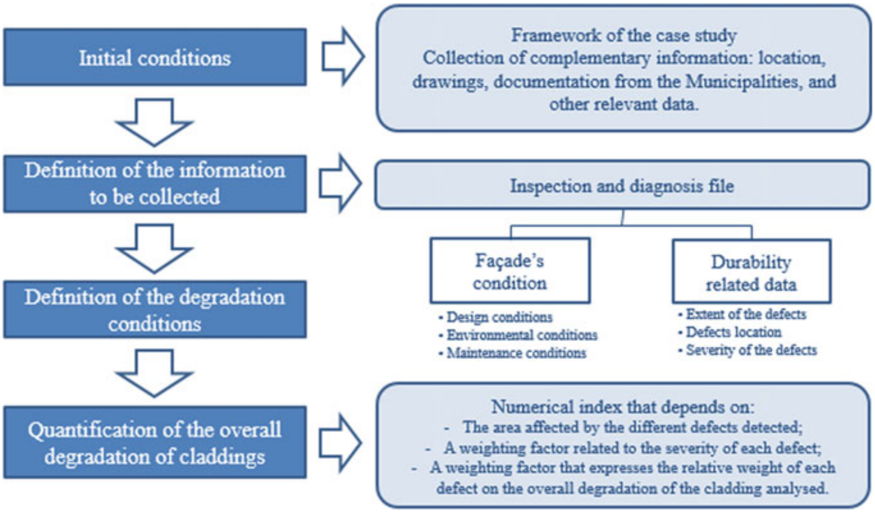


Fig. 2.1 Methodology used in the systemic analysis of the façades degradation condition

overcome these limitations, Shohet and Paciuk (2004) suggest a moderately complex system in which each degradation level is associated with the extent of the defect detected. In these models, the degradation severity is rated based on the defects detected at the inspection only. This method shows some limitations due to the difficulty of knowing with certainty the future consequences of the defects detected; therefore, Florentzou et al. (1999) suggest the implementation of a risk concept in the definition of degradation levels, in which the degradation conditions are defined as a function of the consequences of the problems detected, leading to the definition of risk in probabilistic terms that generally varies from 0 (no probability of occurrence) to 1 (maximum probability of occurrence). Van Winden and Dekker (1998) propose a degradation scale with six levels, where the weight of the proposed degradation levels is not linear; the authors relate each degradation condition to a numerical weight, thus providing an exponential relationship between the degradation levels.

Based on the different degradation scales proposed by various authors, in this study, the degradation conditions of the façade claddings analysed are defined according to the extent of the façade affected by each group of defects and taking into account the importance of the different defects within each group in terms of gravity. The degradation conditions considered vary between A (no visible degradation) and E (generalized degradation); condition D corresponds to the end of the claddings service life, assuming that a cladding with a degradation condition above this level is no longer capable of performing the function for which it was designed and requires comprehensive rehabilitation actions in order to restore its essential properties. In the next sections, the various degradation scales adopted for the different claddings analysed are proposed. These scales were previously defined in different studies performed in this area. Although this information is essential for the definition of the service life prediction models, the detailed discussion of the scales adopted is outside the scope of this book, since these scales were previously presented and discussed by several authors duly referenced.

Natural Stone Claddings

The degradation of natural stone claddings is influenced by several factors, such as the incidence of wind and rain, considered as one of the main physical agents of deterioration of natural stone (Camuffo 1995; Barberousse et al. 2007). However, the degradation of stone claddings is often due to the poor quality and unsuitability for use of the type of the stone applied, due to its high porosity associated with a low mechanical strength, which promote the presence of defects (Shohet et al. 1999). This study focuses on stone directly adhered to the substrate—often glued to the wall—and does not address cladding systems in which the stone is held by fasteners. The defects in stone claddings studied are arranged into four groups (Silva et al. 2011):

- **Visual or surface degradation** (Fig. 2.2)—these defects generally affect the cladding, not contributing to the failure of the cladding system, and do not represent a risk to its integrity. These are the most common defects, appearing prematurely in some cases due to design or execution errors;
- **Joint defects** (Fig. 2.3)—which include situations in which the cladding's joints do not function adequately and may even lead to the occurrence of new defects;
- **Loss of bond to the substrate** (Fig. 2.4)—which characterize the situations when stone material is lost either in small proportions (scaling) or significant proportions (loss of adhesion); these defects usually compromise the integrity of the cladding, jeopardizing the safety demands of the cladding and sometimes constitute a risk for people and property;
- **Loss of integrity** (Fig. 2.5)—which affects irremediably the stone, due to the alteration of the physical and chemical properties of the natural stone, also leading to the visual deterioration of the cladding.

Fig. 2.2 Visual or surface degradation defects in natural stone claddings (from *left* to the *right*): efflorescence, localized stains (rising dump), parasitic vegetation, biological growth and flatness deficiencies

Fig. 2.3 Joint defects (from *left* to the *right*): lack of linearity between the joints of stone plates, material loss—open joint and scaling of stone near the joints

Fig. 2.4 Bond-to-substrate defects in natural stone claddings (from *left* to the *right*): loss of an element in the stone cladding and partial loss of stone material

Fig. 2.5 Loss-of-integrity defects in natural stone claddings (from *left* to the *right*): fracture, cracking, erosion, exfoliation and alveolarization of stone plate

Table 2.1 shows the degradation conditions for natural stone claddings.

The degradation levels for the defects in joints and those related to loss of bond to the substrate leap directly from condition A to condition C, because it was considered that conditions below condition B did not represent the gravity of these defects from the moment they are detected.

Table 2.1 Proposed degradation levels for natural stone claddings (data sourced from Silva et al. 2011)

Degradation level	Defects		Area of cladding affected (%)	Illustrative example
Level A ($S_{w,rp} \leq 1\ \%$)	No visible degradation		–	–
Level B *Good* ($1\ \% < S_{w,rp} \leq 8\ \%$)	Visual or surface degradation defects	Surface dirt	>10	
		Moisture stains	≤15	
		Localized stains		
		Colour change		
		Flatness deficiencies	≤10	
	Loss-of-integrity defects	Material degradation[a] ≤ 1 % plate thickness	–	
		Material degradation[a] ≤ 10 % plate thickness	≤20	
		Cracking width ≤ 1 mm		
Level C *Slight degradation* ($8\ \% < S_{w,rp} \leq 20\ \%$)	Visual or surface degradation defects	Moisture stains	>15	
		Localized stains		
		Colour change		
		Moss, lichen, algae growth	≤30	
		Parasitic vegetation		
		Efflorescence		
		Flatness deficiencies	>10 and ≤50	
	Joint anomalies	Joint material degradation	≤30	
		Material loss—open joint	≤10	
	Bond-to-substrate defects	Scaling of stone near the edges Partial loss of stone material	≤20	

(continued)

Table 2.1 (continued)

Degradation level	Defects		Area of cladding affected (%)	Illustrative example
	Loss-of-integrity defects	Material degradation[a] $\leq$ 10 % plate thickness	≤ 20	
		Material degradation[a] > 10 % and $\leq$ 30 % plate thickness	>20	
		Cracking width ≤ 1 mm	≤ 20	
		Cracking width >1 mm and ≤ 5 mm	≤ 20	
		Fracture	≤ 5	
Level D *Moderate degradation* (20 % < $S_{w,rp} \leq$ 45 %)	Visual or surface degradation defects	Moss, lichen algae growth	>30	
		Parasitic vegetation		
		Efflorescence		
		Flatness deficiencies	>50	
	Joint defects	Joint material degradation	>30	
		Material loss—open joint	>10	
	Bond-to-substrate defects	Scaling of stone near the edges Partial loss of stone material	>20	
		Loss of adherence	≤ 10	
	Loss-of-integrity defects	Material degradation[a] > 10 % e $\leq$ 30 % plate thickness	>20	
		Material degradation[a] > 30 % plate thickness	≤ 20	
		Cracking width > 1 mm and $\leq$ 5 mm	>20	
		Cracking width $\geq$ 5 mm	≤ 20	
		Fracture	>5 and $\leq$ 10	

(continued)

Table 2.1 (continued)

Degradation level	Defects		Area of cladding affected (%)	Illustrative example
Level E *Generalized degradation* ($S_{w,rp} \geq 45$ %)	Bond-to-substrate defects	Loss of adherence	>10	
	Loss-of-integrity defects	Material degradation[a] > 30 % plate thickness	>20	
		Cracking width > 5 mm		
		Fracture	>10	

[a]Material degradation is meant to be every anomaly that involves loss of volume of the stone material

Rendered Façades

According to Gaspar and de Brito (2005), the extensive application of renderings as exterior claddings is essentially due to their low cost and the low technology required to their execution when compared to the other types of cladding systems. However, the low investment in this type of cladding often leads to high levels of degradation in the façades (Freitas et al. 1999). The diagnosis of the degradation in rendered façades is not easy, given the variability of causes that can contribute to a given defect. Nevertheless, during their life cycle, rendered façades present a relatively clear degradation pattern, which starts with the presence of surface dirt, soot, stains, and in some situations small cracks, which evolve over time, until the loss of adhesion of the renderings (Gaspar and de Brito 2008). The defects present in rendered façades can be grouped in three main categories

- **Visual or surface degradation defects** (Fig. 2.6)—essentially characterized by the presence of stains, often associated with the presence of damp (Chew and Ping 2003); these defects are the less severe, not compromising the claddings' service life;
- **Cracking** (Fig. 2.7)—these defects are more severe than staining, however, they do not usually jeopardize the claddings' safety and are a natural consequence of the claddings behaviour (Bone et al. 1989; Bonshor and Bonshor 2001);

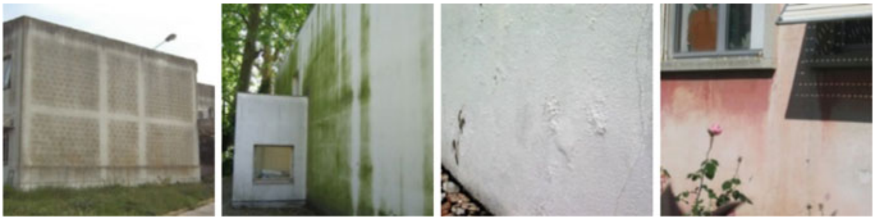


Fig. 2.6 Visual or surface degradation defects in rendered façades (from *left* to the *right*): thermophoresis, biological growth, efflorescence, colour change (data sourced from Gaspar 2009)

Fig. 2.7 Cracking defects: mapped cracking in rendered façades (*left*) and oriented cracking (*right*) (data sourced from Gaspar 2009)

Fig. 2.8 Loss of adhesion or cohesion in rendered façades (from the *left* to the *right*): detachment, pulverulence, arenization, erosion (data sourced from Gaspar 2009)

- **Loss of adhesion or cohesion** (Fig. 2.8)—this group of defects corresponds to the most serious situations and are caused by different factors, such as the combination of cracking with the presence of water (Hansen et al. 1999), often leading to the end of the service life of the renderings.

Based on this classification of the defects, five degradation conditions are established for rendered façades, where condition A corresponds to the most favourable situation and condition E to the most serious one (generalized degradation). Table 2.2 shows the proposed degradation conditions for rendered façades.

Painted Surfaces

In painted surfaces, there are several factors that promote the presence of defects, such as the design and application conditions, the drying circumstances and the environmental exposure conditions, among others. The degradation of painted surfaces not only leads to the loss of their aesthetic performance but may also jeopardize their protective function. For painted surfaces, the degradation levels are defined in terms of the intensity and type of defect, regardless of the extent of the pathological manifestation. The extent is taken into account at a later stage, when the overall level of degradation of the façade coating is defined. In this case, this assumption is adopted since there are several Portuguese standards currently enforced (NP EN ISO 4628-1: 2005; NP EN ISO 462———8-2: 2005; NP EN ISO 4628-4: 2005; NP EN ISO 4628-5: 2005; NP EN ISO 4628-7: 2005) that allow establishing the criteria to evaluate the degradation conditions of painted surfaces. Based on these standards, four main defects that affect paint coatings are considered (Chai et al. 2014)

- **Staining/colour change** (Table 2.3 and Fig. 2.9)—which mainly affect the aesthetic appearance of paintings, usually occurring at the early stages of the paintings service life;
- **Chalking** (Table 2.4)—it generally occurs after loss of gloss and causes wear, detachment and loss of material. Given the difference (in terms of the coating's durability) between small and moderate/high scale chalking, it was decided to adopt a nonlinear degradation scale, considering very low degradation levels

Table 2.2 Proposed degradation levels for rendered façades (data sourced from Silva et al. 2014a)

Condition levels	Severity of degradation (%)	Physical and visual assessment	Illustrative example
Level A	<1	Complete mortar surface with no deterioration. Surface even and uniform. No visible cracking or cracking $\leq$ 0.1 mm. Uniform colour and no dirt. No detachment of elements	
Level B	1–5	Non-uniform mortar surface with likelihood of hollow localized areas determined by percussion, but no signs of detachment. Small cracking (0.25–1.0 mm) in localized areas. Changes in the general colour of the surface. Eventual presence of microorganisms	
Level C	5–15	Localized detachments or perforations of the mortar. Hollow sound when tapped. Detachments only in the socle. Easily visible cracking (1.0–2.0 mm). Dark patches of damp and dirt, often with microorganisms and algae	
Level D	15–30	Incomplete mortar surface due to detachments and falling of mortar patches. Wide or extensive cracking ($\geq$2 mm). Very dark patches with probable presence of algae	
Level E	>30	Incomplete mortar surface due to detachments and falling of mortar patches. Wide or extensive cracking ($\geq$2 mm). Very dark patches with probable presence of algae	

(conditions A and B) and moderate or high levels (levels D and E) of the defect; finally, in advanced degradation situations, very pronounced chalking may cause total or local obliteration of the paint pellicle, leaving the rendering bare; this is considered to signal the end of the cladding's service life (level E);

- **Cracking** (Table 2.5 and Fig. 2.10)—the ranking by degradation level of this defect is based on visual patterns, in terms of cracking frequency. Contrary to

Table 2.3 Definition of degradation levels for stains/colour change defects in painted surfaces (data sourced from Chai et al. 2014)

Level A			
Intensity of the change	No degradation visible		
Defects characterization	Without visible defects		
Examples			
Description	No perceptible changes		
Level B			
Intensity of the change	Slight or little perceptible changes		
Defects characterization	Uniform surface dirt; Change in colour or brightness		
Examples			
Description	Little perceptible uniform surface dirt	Little perceptible change in colour	
Level C			
Intensity of the change	Moderate or quite perceptible changes		
Defects characterization	Uniform surface dirt; Change in colour or brightness		
Examples			
Description	Quite perceptible uniform surface dirt	Quite perceptible change in colour	
Intensity of the change	Slight or little perceptible changes		
Defects characterization	Localized surface dirt; Humidity stains; Efflorescence		
Examples			
Description	Light humidity stains		
Level D			
Intensity of the change	Moderate or quite perceptible changes		
Defects characterization	Humidity stains; Efflorescence; Biological growth; Localized surface dirt		
Examples			
Description	Quite perceptible humidity stains	Quite perceptible biological growth	
Examples			
Description	Quite perceptible localized surface dirt		Quite perceptible efflorescence
Intensity of the change	High or very perceptible changes		
Defects characterization	Uniform surface dirt; Change in colour or brightness		
Examples			
Description	Very perceptible uniform surface dirt and change in colour	Very perceptible Localized surface dirt	Very perceptible change in colour (discoloration)
Level E			
Intensity of the change	High or very perceptible changes		
Defects characterization	Biological growth		
Examples			
Description	Very perceptible biological growth		

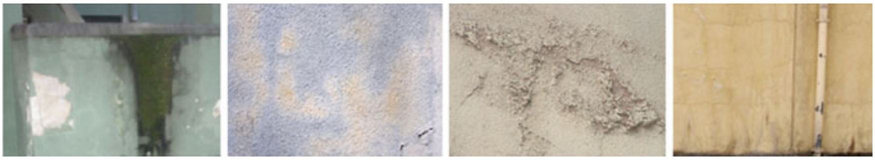


Fig. 2.9 Visual or surface degradation defects in painted surfaces (from *left* to the *right*): biological growth, colour change, efflorescence and damp stains (data sourced from Chai 2011)

Table 2.4 Definition of degradation levels for chalking defects (data sourced from Chai et al. 2014)

Degradation level	Quantity
Level A	No degradation visible
Level B—Good	Clearly perceptible
Level D—Moderate degradation	Quite perceptible
Level E—Generalized degradation	Very perceptible

other materials, in paintings, cracking is usually less than 1 mm wide, which makes it difficult to distinguish the size without magnifying equipment (Table 2.6);

- **Loss of adherence** (Table 2.7 and Fig. 2.11)—these defects usually arise from the combination of various other defects and degradation mechanisms. Therefore, two situations are considered: (i) blistering and (ii) peeling. Due to the severity of these defects, every blistering occurrence has a severity degree of C or higher and every peeling occurrence is condition D;

Ceramic Tiling Systems

Ceramic tiles present a huge variety of sizes, colours, textures, among other characteristics, thus being considered in Mediterranean countries as one of the noblest materials for cladding (Silvestre and de Brito 2009; Bovea et al. 2010). Although there are very old buildings that testify the durability of this type of cladding (e.g. buildings more than a hundred years old with their ceramic cladding intact), in recent decades there has been a significant decrease in the use of this type of cladding. Various authors (Mansur et al. 2008; Wetzel et al. 2010) refer as the main reason for the decline in the use of ceramic tiling system the high incidence of defects throughout their life cycle. Shohet and Laufer (1996) refer that adherent ceramic tiles are extremely susceptible to design and execution errors, as well as to the choice of materials applied. Bordalo et al. (2011) also mention other causes for the premature failure of these claddings, such as the growing demands of the construction market, which implies the reduction of the construction delivery times and the poor education of technicians involved at design and execution phases.

Table 2.5 Definition of degradation levels for peeling and blistering defects in painted surfaces (data sourced from Chai et al. 2014)

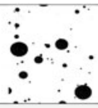
Level A			
Defect characterization	No degradation visible		
Level C			
Defect characterization	Blistering		
Quantity and size of the areas affected (greatest size)	Small amount and size up to 3 cm		
Visual scale [NP EN ISO 4628-2, 2005 e NP EN ISO 4628-5, 2005]			
Level D			
Defect characterization	Blistering		
Quantity and size of the areas affected (greatest size)	Small amount and size between 3 and 5 cm	Moderate amount and smaller than 3 cm	
Visual scale [NP EN ISO 4628-2, 2005 e NP EN ISO 4628-5, 2005]			
Defect characterization	Peeling		
Quantity and size of the areas affected (greatest size)	Small amount (area affected up to 1%) e size up to 3 cm		
Visual scale [NP EN ISO 4628-2, 2005 e NP EN ISO 4628-5, 2005]			
Level E			
Defect characterization	Blistering		
Quantity and size of the areas affected (greatest size)	Larger than 5 cm, regardless of the amount	Dense pattern regardless of the size	Moderate amount e and dimension between 3 and 5 cm
Visual scale [NP EN ISO 4628-2, 2005 e NP EN ISO 4628-5, 2005]			
Defect characterization	Peeling		
Quantity and size of the areas affected (greatest size)	Dense and moderate pattern (affected area higher than 1%) regardless of the size	Small amount and larger than 5 cm	
Visual scale [NP EN ISO 4628-2, 2005 e NP EN ISO 4628-5, 2005]			

Fig. 2.10 Cracking defects in painted surfaces (data sourced from Chai 2011)

Table 2.6 Definition of degradation levels for cracking defects in painted surfaces (data sourced from Chai et al. 2014)

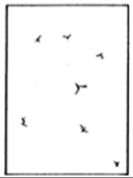
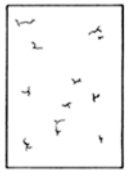
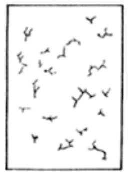
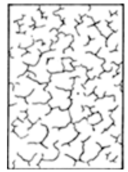
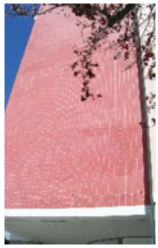
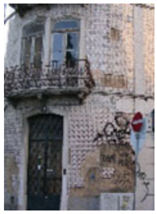
Degradation level	Level A	Level B Good condition	Level C Slight degradation	Level D Moderate degradation	Level E Generalized degradation
Quantity	No visible degradation	Small number of cracks	Moderate width or number of cracks	Considerable number of cracks	High number or density of cracks
Visual scale [NP EN ISSO 4628-4, 2005]					

Table 2.7 Proposed degradation levels for ceramic tiling systems (data sourced from Bordalo et al. 2011)

Condition level	Defects		Area of cladding affected (%)	Illustrative example
Level A ($S_{w,rp} \leq 1$ %)	No visible degradation		–	–
Level B *Good* (1 % < $S_{w,rp} \leq 6$ %)	Visual or surface degradation defects	Surface dirt	–	
		Small surface craters	≤ 10	
		Wear or scratches		
		Crushing or scaling of the borders		
		Change of shine and/or colour		
		Damp stains		
	Cracking	Cracked glazing[a]	–	
		Markedly orientated cracking (<0.2 mm)[(1)] without leakage[a]		
	Joint deterioration	Staining or change in colour	–	
Level C *Slight deterioration* (6 % < $S_{w,rp} \leq 20$ %)	Visual or surface degradation defects	Small superficial craters	>10 and ≤ 50	
		Wear or scratches		
		Crushing or scaling of the borders		
		Change of shine and/or colour		
		Damp stains		
		Biological growth	≤ 30	
		Graffiti		
		Efflorescence		
	Cracking	Cracking with no predominant direction[a]	≤ 30	
		Markedly orientated cracking (>0.2 mm)[(2)] without leakage[a]		
	Joint deterioration	Without loss of filling material[a]	≤ 30	
		With loss of filling material[a]	≤ 10	
	Detachment	Loss of adherence	≤ 20	
		Swelling		

(continued)

Table 2.7 (continued)

Condition level	Defects		Area of cladding affected (%)	Illustrative example
Level D *Moderate degradation* (20 % < $S_{w,rp}$ ≤ 50 %)	Visual or surface degradation defects	Small superficial craters	>50	
		Wear or scratches		
		Crushing or scaling of the borders		
		Change of shine and/or colour		
		Damp stains		
		Biological growth	>30	
		Graffiti		
		Efflorescence		
	Cracking	Cracking with no predominant direction[a]	>30 and ≤50	
		Markedly orientated cracking (>1 mm)[(3)] without leakage[a]		
	Joint deterioration	Without loss of filling material[a]	>30 and ≤50	
		With loss of filling material[a]	>10 and ≤ 30	
	Detachment	Loss of adherence	>20	
		Swelling		
		Localized detachment	≤10	
Level E *Generalized degradation* ($S_{w,rp}$ ≥ 50 %)	Cracking	Cracking with no predominant direction[a]	>50	
		Markedly orientated cracking (>5 mm)[(4)]		
	Joint deterioration	Without loss of filling material	>50	
		With loss of filling material	>30	
	Detachment	Generalized detachment	>10	

[a]With leakage—the degradation level is increased by one
[(1)]Cracking, detectable at a distance greater than 5 m only if binoculars are used
[(2)]Tenuous cracking line, easily detectable at a distance greater than 5 m, using binoculars
[(3)]Well defined cracking visible from a distance of more than 5 m, without using binoculars
[(4)]Cracking characterized by a thick line in which a clear separation of the borders can be seen, from a distance of more than 5 m, with the aid of binoculars

According to Campante and Paschoal (2002), the main defects observed in ceramic claddings are efflorescence, detachment and cracking. In turn, Silvestre and de Brito (2009) classify the defects in four groups: (i) adhesion failure and/or detachment of ceramic claddings; (ii) cracking; (iii) deterioration of the cladding

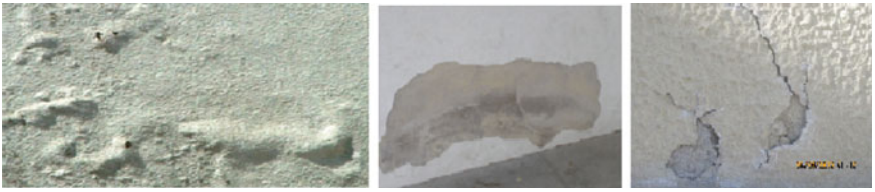


Fig. 2.11 Loss of adhesion or cohesion: debonding (*left*) and detachment in painted surfaces (*right*) (data sourced from Chai 2011)

tiling system, with direct consequences in its performance; (iv) defects of a strictly aesthetic nature. Besides these defects, Timellini and Palmonari (1989) mention the relevance of joints defects in the overall performance of this cladding system. Silvestre and de Brito (2007) also refer that there is a high incidence of defects in the material used to fill the joints, since this material is highly susceptible to the aggressive deterioration agents. Considering the literature, the defects observed in ceramic tiling systems are classified into four categories (Bordalo et al. 2011)

- **Visual defects** (Fig. 2.12)—which affect the visual appearance of the cladding, although they do not usually determine the end of the service life of ceramic claddings;
- **Cracking** (Fig. 2.13)—which is divided in three subcategories, taking into account the characteristics of each type of cracking:

Fig. 2.12 Visual or surface degradation defects in ceramic tiling systems (from *left* to the *right*): localized colour change, parasitic vegetation, efflorescence, crushing or scaling of the borders and small superficial craters (data sourced from Bordalo 2008)

Fig. 2.13 Cracking defects in ceramic tiling systems (from *left* to the *right*): cracked glazing, markedly orientated cracking and with no predominant direction (data sourced from Bordalo 2008)

Fig. 2.14 Joint deterioration defects in ceramic tiling systems (from *left* to the *right*): cracking of the filling material, cracking between the filling material and the edges of the ceramic tile and loss of filling material (data sourced from Bordalo 2008)

Fig. 2.15 Detachment defects in ceramic tiling systems: debonding (*left*) and detachment of ceramic tiles (data sourced from Bordalo 2008)

  – Glazing cracking, looking like a spider's web, which is a surface problem being usually caused by the ageing of the tiles or by the difference between the thermal expansion coefficients of the glazing and of the inner body of the tile;
  – Cracking with no predominant direction, which is usually more superficial and affects large portions of the cladding surface;
  – Markedly orientated cracking, which is usually local, deep and wide;

- **Joint deterioration defects** (Fig. 2.14)—which are usually related with the deterioration of the filling material; they compromise the overall performance of ceramic tiles, since joints are responsible for the system's tightness and ability to absorb deformations;
- **Detachment** (Fig. 2.15)—this is the most serious defect on ceramic tiling due to the hazardous consequences that may occur if ceramic elements fall from the façade and the cost of repairs (Lo 2002). Loss of adherence, swelling and detachment are the main defects present in this group.

Table 2.7 presents the proposed degradation levels defined for ceramic tiling systems, according to the defects previously described, their extent in the façade and the severity of their appearance.

2.5.3 Degradation of Façade Claddings

Sjöström (1985) states that service life prediction should include the definition of a mathematical model to quantify the degradation actually observed. Gaspar (2009) refers that it is possible to assess the overall level of degradation of any construction using a quantitative index that reflects the overall performance of the element under analysis. Therefore, Gaspar (2009) and Gaspar and de Brito (2008, 2011) proposed the definition of a numerical index, called as severity of degradation (S_w), to quantify the overall degradation of the façades claddings.

The severity of degradation is given by the ratio between the weighted degraded area and a reference area, equivalent to the total cladding area having the highest possible level of degradation as shown in Eq. (2.1). The weighted degraded area is given by the product of the façade area affected by different groups of defects, by a weighting factor related to the severity of each detected defect—k_n, and a weighting factor that reflects the relative weight of each defect on the overall degradation of the façade—$k_{a,n}$,. This method, originally developed for rendered façades, established a general framework model, allowing its subsequent adaptation to the specific case of stone claddings (Silva et al. 2011), ceramic cladding systems (Bordalo et al. 2011), painted surfaces (Chai et al. 2014) and ETICS (Ximenes et al. 2015).

$$S_w = \frac{\Sigma\left(A_n \times k_n \times k_{a,n}\right)}{A \times \Sigma\left(k_{\max}\right)} \tag{2.1}$$

where S_w represents the severity of degradation of the façade, as a percentage, A_n the area of the cladding affected by a defect n, in m^2, k_n the defects' "n" multiplying factor, as a function of its condition (between 1 and 4), $k_{a,n}$ the weighting coefficient corresponding to the relative importance of each defect obtained through cost of repair or risk ($k_{a,n} \in R^+$) (if no instructions are provided, it is assumed $k_{a,n}$ = 1), k the weighting factor equal to the highest condition level, and A the total area of the cladding, in m^2.

2.5.3.1 Relative Weighting of Defects

Different defects that appear in the façade claddings during their life cycle have different levels of severity. Indeed, although two defects can affect the same extent of cladding, e.g. localized staining and detachment, they represent different damage types, with distinct levels of risk and type of repair work required. The application of weighting coefficients depending on the severity of the defects allows obtaining an indicator of the overall degradation of façades more appropriate to the actual state of decay of the inspected facades. Therefore, in this study the defects are weighted based on the fulfilment of performance criteria or minimum requirements (safety and watertightness), their susceptibility to generate new defects and essentially based on their repair cost. The latter variable seems to be a preponderant parameter in the perspective of decision-makers. According to Rudbeck (2002), the cost is a fundamental aspect, indeed even more relevant than durability, to guide decision-making process throughout the different phases of the construction life cycle.

In the next sections, the weighting factors are established based on the cost of repair of the different defects, using present-day values, at the moment when repair is needed. The cost of repair is calculated as the ratio between the sum of the costs of each operation within the required intervention and the cost of replacing the cladding. Repair costs are estimated based on available literature, expert opinion and cost simulators, in order to adjust the model to the Portuguese market.

Natural Stone Claddings

Table 2.8 presents the weighting coefficients for natural stone claddings. The replacement of stone plates entails costs that easily equal or surpass the cost of a new cladding due to the need to remove of the old cladding.

However, a cladding's replacement is not a consensual decision; in fact, in some cases, owners choose to fasten the stone plates detached from the support or to change the fastening system, rather than replace the entire cladding. Also regarding loss of integrity of the stone elements, in some cases, owners opt for clogging the degraded stone with epoxy resins, instead of replacing them. Therefore, the costs of maintenance/repair present some subjectivity, since they depend on the acceptance criteria of users and owners.

Rendered Façades

Regarding rendered façades, the distinction between the three groups of defects is based on the cost of repair, ranging from simple cleaning, to remove stains and soot, repair of cracks or, in more serious situations, to repair and substitute areas affected by the loss of cohesion of mortar or detached. Table 2.9 presents the weighting coefficients adopted for rendered façades, revealing, as expected, a correlation between the cost of repair of the different defects and the severity of these defects empirically perceived.

Painted Surfaces

For painted surfaces, the quantification of the weighting coefficients is made iteratively, based on the analysis of different scenarios; the scenario with the best results is selected regarding its ability to translate the physical reality observed during the fieldwork. In this case, more qualitative criteria are adopted based on the study performed by Chai et al. (2014). A growing hierarchy of the defects "staining and colour changes", "cracking", "chalking" and "loss of adhesion" is adopted as shown in Table 2.10. When comparing this scenario with a neutral scenario

Table 2.8 Weighting coefficients ($k_{a,n}$) for natural stone claddings (data sourced from Silva et al. 2011)

Defect	Performance criteria Requirements		Possibility of generating new anomalies	Repair operation (cost in €/m^2)	Ratio between repair cost and replacement cost[a] (%)	Weighting coefficient $k_{a,n}$
	Safety	Watertightness				
Visual or surface degradation	○○	●○	●○	Cleaning (11.7 €/m^2)	13	0.13
Joints						
Degradation of filling material	●○	●○	●●	Joint repair (23.4 €/m^2)	25	0.25
Loss of filling material				Replacement of the joint material in cladding directly adhered to the substrate involves some risks, and may damage the natural stone	100	1.0
Bond-to-substrate	●●	●●	●●	Replacement of stone plates always costs at least as much as executing a new cladding, and may cost more because of having to remove the degraded original cladding	120	1.2
Loss of integrity	●●	●●	●●	Repairing loss-of-integrity anomalies may involve only surface repair (epoxy resins or equivalent) or replacement of the stone plate	100	1.0

○○—No correlation; ●○—probable correlation; ●●—high correlation

[a]The cost of building a vertical granite cladding façade with a cementitious adhesive is around 93 €/m^2

Table 2.9 Weighting coefficients ($k_{a,n}$) for rendered façades (data sourced from Gaspar and de Brito 2011)

Degradation condition	Stains		Cracking		Loss of adhesion	
B	$k_{a,n}$ = 0.12	2.50 €/m^2	$k_{a,n}$ = 0.95	20.50 €/m^2	$k_{a,n}$ = 1.53	33.00 €/m^2
C	$k_{a,n}$ = 0.53	11.50 €/m^2	$k_{a,n}$ = 0.95	20.50 €/m^2	$k_{a,n}$ = 1.53	33.00 €/m^2
D	$k_{a,n}$ = 0.53	11.50 €/m^2	$k_{a,n}$ = 1.12	24.00 €/m^2	$k_{a,n}$ = 1.53	33.00 €/m^2
E	$k_{a,n}$ = 0.53	11.50 €/m^2	$k_{a,n}$ = 1.53	33.00 €/m^2	$k_{a,n}$ = 1.53	33.00 €/m^2

Table 2.10 Weighting coefficients ($k_{a,n}$) for painted surfaces (data sourced from Chai et al. 2014)

Defect	Stains/colour change	Cracking	Chalking	Loss of adherence
$k_{a,n}$	0.25	1.00	1.00	1.50

(corresponding to the same severity for all defects—$k_{a,n}$ = 1), the following conclusions can be drawn: (i) without weighting, the values of the severity of degradation of painted surfaces present a high scatter; (ii) the values of the severity of degradation without weighting are generally higher than the values with weighting, confirming the hypothesis that the model without weighting portrays a pessimistic view of the physical reality; (iii) the degradation model with weighting varies between 0 and 100 %, thus producing results easier to interpret.

Ceramic Claddings

Concerning adherent ceramic claddings, the same criteria applied to stone claddings is adopted, giving particular relevance to the repair cost associated to the different defects that affect the ceramic tiling systems (Table 2.11).

2.5.3.2 Definition of the End of Service Life of Façade Claddings

As already referred, the definition of the end of service life is not an easy task, depending on often subjective and context dependent acceptance criteria, which are not easily established by "pure" scientific methods. In this study, the maximum acceptable degradation level is established based on the careful analysis of the degradation condition of the claddings analysed, so that coherent values can be obtained for the Portuguese context.

From the analysis of each case study analysed (considering the four claddings under analysis, a sample of 718 case studies is evaluated), a critical degradation value was adopted equal to a severity of degradation of 20 %, beyond which the probability of no longer fulfilling the essential requirements is too high. In fact, in the analysis performed, the adoption of a maximum degradation level of 10 % seems too conservative to establish the end of the service life of the claddings

Table 2.11 Weighting coefficients ($k_{a,n}$) for painted surfaces (data sourced from Bordalo et al. 2011)

Defect	Performance criteria Requirements		Possibility of generating new anomalies	Repair operation (cost in €/m^2)	Ratio between repair cost and replacement cost[a]	Weighting coefficient $k_{a,n}$
	Safety	Watertightness				
Visual or surface degradation	○○	●○	●○	Cleaning (13.09 €/m^2)	18	0.18
Cracking	●●	●●	●●	The repair of cracking in ceramic tiles may involve different types of intervention, ranging from superficial clogging of the affected material to replacement of the degraded tiles.	100	1.0
Joints						
Degradation of filling material	●○	●○	●●	Joint repair (23.4 €/m^2)	32	0.32
Loss of filling material				Replacement of the joint material in cladding directly adhered to the substrate involves some risks, and may damage the natural stone	100	1.0
Loss of adhesion	●●	●●	●●	Replacement of ceramic tiles always costs at least as much as executing a new cladding, and may cost more because of having to remove the degraded original cladding	120	1.2

○○—No correlation; ●○—probable correlation; ●●—high correlation

[a]The cost of building a ceramic tiling system substantially varies according to the cost of the tile chosen. Assuming a cladding constituted by stoneware tiles with 40 × 40 cm, with a cost of 19 €/m^2, an execution cost around 75.57 €/m^2 is estimated

Fig. 2.16 Case study that illustrates the end of the service life of stone claddings (with a severity of degradation around 20 %) (data sourced from Silva 2009)

Fig. 2.17 Case study that illustrates the end of the service life of rendered façades (with a severity of degradation around 20 %) (data sourced from Gaspar 2009)

analysed. In turn, the adoption of a maximum degradation level of 30 or 40 % seems too high, revealing a generalized degradation state. Nevertheless, the maximum degradation level adopted in this study may vary according to the level of demand of the owners or users or even the social context of the building. Figures 2.16, 2.17, 2.18 and 2.19 illustrate the degradation condition that corresponds to the end of the service life of stone claddings, rendered façades, painted surfaces and ceramic claddings, respectively.

Fig. 2.18 Case study that illustrates the end of the service life of painted surfaces (with a severity of degradation around 20 %) (data sourced from Chai et al. 2014)

Fig. 2.19 Case study that illustrates the end of the service life of ceramic claddings (with a severity of degradation around 20 %) (data sourced from Bordalo 2008)

2.6 Characterization of the Samples Analysed

In this study, the samples analysed are as homogeneous as possible regarding the age of the claddings, their characteristics and the degradation agents to which they are subjected. All the case studies that present high degradation levels at an early stage, apparently caused by gross design or execution errors or due to vandalism were excluded, since their degradation is caused by discrete phenomena, which are not possible to predict or model. Concerning the age of the claddings, the sample covers a large range of ages, homogeneously distributed. Figure 2.20 shows the distribution of the samples according to the age of the façades analysed.

For rendered façades, the age of the case studies (meaning the time since the last major repair or maintenance intervention) ranges between 0 and 57 years. 31 % of the sample present ages lower than 5 years and are therefore within the warranty period of buildings in Portugal (this information is relevant since some early defects are corrected during the warranty period). The majority of the rendered façades (77 % of the sample) has less than 20 years. Between years 20 and 60, the sample is distributed with relative uniformity, with around four buildings in each year (however, there are intervals of less than 5 years, without any façade inspected). For painted surfaces, the claddings analysed present ages between 0 and 18 years,

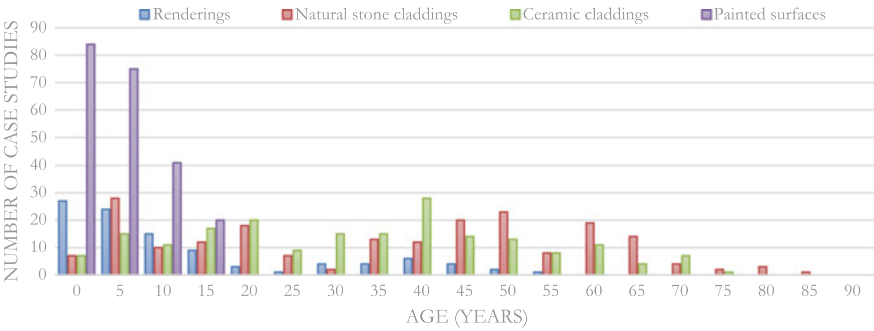


Fig. 2.20 Distribution of the samples according to the age of the façades analysed

with a high incidence of cases with less than 5 years (55 % of the sample). Regarding natural stone claddings, the sample analysed presents ages between 1 and 89 years. Ceramic tiling systems present ages between 1 and 77 years. In these two types of claddings, the majority of the sample has ages between 20 and 60 years (52 % of the sample for stone claddings and 61 % for ceramic claddings), and only 8 % of the sample has ages below 5 years. These data provide some indications regarding the durability of the types of cladding analysed. The samples corresponding to rendered façades and painted surfaces present a smaller range of ages, i.e. these samples have a lower average age when compared with stone or ceramic claddings. Since this study does not contemplate maintenance actions, it is not easy to obtain case studies of renderings or paintings with advanced ages that have not yet been subjected to any intervention.

Figure 2.21 shows the distribution of the severity of degradation of the samples analysed according to their age. Rendered façades are those that have higher degradation indexes, however, for this type of cladding, it has been considered the possibility of overlapping of the defects, which implies that the severity of degradation can be higher than 100 %. For the other types of claddings, the overlapping of defects was not considered, thus normalizing the severity of degradation index, assuming that in the worst case scenario the severity of degradation does not exceed 100 %. This methodological distinction is inherent to the fact that the samples analysed have been collected in previous studies; in fact, this book is the result of an extensive work, in constant progression, whose methodology, concerning the collection of data and the quantification of the degradation, has been evolving over time. By the analysis of the results of natural stone claddings, ceramic claddings and painted surfaces, the following conclusions can be drawn: (i) painted surfaces are those that have higher degradation indexes in earlier ages, with an average severity of degradation of 14.8 % and a maximum value 72 %; (ii) adherent ceramic claddings present an average severity of degradation of 13.1 %, with a maximum value of 61 %; (iii) finally, natural stone claddings present the lowest degradation indexes, with an average severity of degradation of 8.5 % and a maximum value of 43 %. A brief characterization of the samples analysed is presented in the next sections.

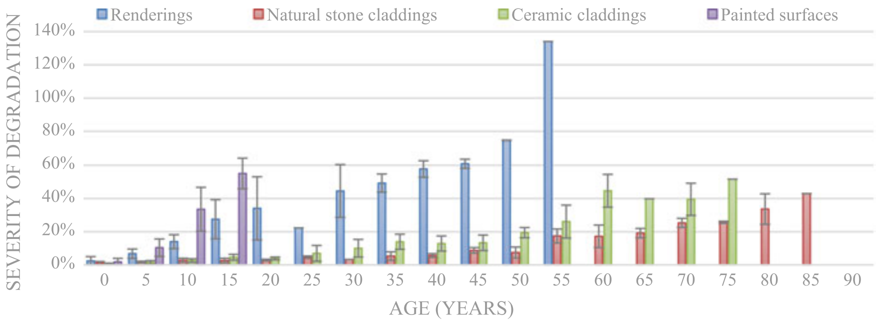


Fig. 2.21 Distribution of the severity of degradation obtained for the claddings analysed according to their age

2.6.1 Natural Stone Claddings

Table 2.12 presents the characterization of the sample analysed for natural stone claddings. During the collection of the sample, case studies were selected randomly and then filtered in order to obtain a representative sample of the types of natural stone found in Portuguese claddings. According to a study performed by Esteves

Table 2.12 Characterization of the sample analysed for natural stone claddings

Characteristics of natural stone claddings		% of case studies (number of cases)	Average ages (standard deviation), in years	Average S_w (minimum/maximum)
Type of stone	Limestone	35 % (72)	41.8 (25.5)	9.7 % (0 %/37 %)
	Granite	27 % (54)	23.9 (13.3)	3.3 % (0 %/12 %)
	Marble	38 % (77)	43.8 (20.9)	11.0 % (0 %/43 %)
Colour	Light	66 % (134)	42.0 (23.9)	10.0 % (0 %/43 %)
	Dark	34 % (69)	29.7 (17.1)	5.6 % (0 %/37 %)
Type of finishing	Smooth	47 % (96)	29.9 (19.5)	5.7 % (0 %/30 %)
	Rough	53 % (107)	44.9 (22.9)	11.1 % (0 %/43 %)
Dimension of stone plates	Medium sizes	64 % (129)	31.7 (21.6)	6.1 % (0 %/28 %)
	Large sizes	36 % (74)	48.5 (20.2)	12.7 % (0 %/43 %)
Thickness of stone plates	Less than 2.5 cm	76 % (154)	35.4 (19.7)	7.2 % (0 %/43 %)
	≥ 2.5 cm	24 % (49)	45.2 (28.9)	12.5 % (0.1 %/29 %)
Type of cladding	Integral/partial	30 % (61)	21.0 (21.8)	5.0 % (0 %/25 %)
	Bottom wall	70 % (142)	45.0 (18.9)	10.0 % (0 %/43 %)
Façade orientation	North	14 % (29)	29.3 (21.4)	6.6 % (1 %/37 %)
	NE/E/SE	43 % (88)	39.1 (21.5)	8.0 % (0 %/30 %)
	W/NW	25 % (51)	35.5 (21.9)	8.9 % (0 %/40 %
	S/SW	17 % (35)	44.8 (25.3)	10.9 % (0 %/43 %)
Distance from the sea	Less than 5 km	38 % (77)	38.4 (28.5)	11.1 % (0 %/43 %)
	More than 5 km	62 % (126)	37.4 (18.2)	7.0 % (0 %/40 %)
Wind-rain action	Moderate	84 % (170)	39.3 (23.2)	9.2 % (0 %/43 %)
	Severe	16 % (33)	30.1 (17.7)	5.0 % (1 %/14 %)
Exposure to damp	Low	59 % (119)	44.1 (19.7)	9.2 % (0 %/43 %)
	High	41 % (84)	28.8 (23.5)	7.6 % (0 %/37 %)
Type of use	Commerce and services	49 % (99)	35.6 (20.6)	7.6 % (0 %/28 %)
	Housing	51 % (104)	39.9 (24.3)	9.4 % (0 %/43 %)
Ease of inspection	Current	54 % (110)	44.2 (24.6)	11.1 % (0 %/43 %)
	Unfavourable	46 % (93)	30.3 (17.2)	5.4 % (1 %/37 %)

(2007), the overall consumption (production minus exportation plus importation) of natural stone in the Portuguese market in 2003 comprised 22.6 % marble and similar, 13.9 % granite and similar and 63.5 % pavement stone. By analysing only data common to both studies, i.e. admitting that the sample comprises only granite and marble, the study by Esteves (2007) leads to 62 and 38 % of marbles and granites, respectively. In this study, the sample analysed comprises a 59 % of marbles and 41 % of granites which was considered representative of the local context. The majority of the cases analysed has medium-sized stone plates (64 %) and thicknesses lower than 2.5 cm (76 %).

Regarding the orientation of façades, there is a predominance of case studies facing East, Southeast, and Northeast (43 %); the remaining cases are equally distributed by the other categories. Considering the environmental exposure conditions, the following conclusions can be drawn: (i) the majority of the case studies are located at more than 5 km from the sea (62 %); (ii) 84 % of the sample present a moderate exposure to wind-rain action. The sample analysed displays an almost uniform distribution in terms of exposure to damp, type of use and ease of inspection.

2.6.2 Rendered Façades

The characterization of the sample analysed for rendered façades is shown in Table 2.13. The sample analysed mainly consists of current cement renderings (60 %), followed by lime–cement renderings (21 %), single-layer renderings (13 %) and renderings with crushed marble (6 %). Lime–cement renderings correspond to older buildings (with a higher average age), thus presenting the highest values of the severity of degradation (48.6 %). The majority of the sample analysed correspond to housing buildings. Regarding the colour of the façade, white renderings represent 19 % of the sample; light colours are the most common (48 %). Concerning building geometry, the sample is well distributed between compact buildings (without protruding and exceptional construction elements) and irregular buildings.

The majority of rendered façades is located in buildings with eave's and ground floor protection, and without platbands or balconies copings. The majority of the rendered façades analysed presents medium design level (65 %) and only a small percentage of façades (6 %) presents a superior design level (corresponding to more recent buildings, with small average degradation indexes). The sample is relatively well distributed in terms of façades' orientation. The majority of the façades analysed are located at more than 5 km of the sea (77 %), in urban areas, close to traffic routes, thus presenting normal or unfavourable exposure conditions to the pollution sources. The majority of the case studies present favourable conditions of exposure to damp (66 %). Finally, the sample is distributed with relative uniformity for the variables façade protection level and ease of inspection.

Table 2.13 Characterization of the sample analysed for rendered façades

Characteristics of rendered façades		% of case studies (number of cases)	Average ages (standard deviation), in years	Average S_w (minimum/maximum)
Render type	Lime-cement renderings	21 % (21)	32.0 (17.0)	48.6 % (1 %/134 %)
	Current cement renderings	60 % (60)	11.6 (11.3)	13.9 % (0 %/58 %)
	Renderings with crushed marble	6 % (6)	9.1 (10.6)	8.5 % (1 %/32 %)
	Single-layer renderings	13 % (13)	7.0 (4.5)	7.9 % (0 %/23 %)
Colour	White	19 % (19)	8.7 (5.5)	12.5 % (0 %/49 %)
	Light colours	48 % (48)	18.5 (17.0)	25.4 % (0 %/134 %)
	Dark colours	33 % (33)	14.0 (14.3)	16.9 % (0 %/63 %)
Building geometry	Compact	41 % (41)	14.7 (14.4)	18.0 % (0 %/62 %)
	Irregular	59 % (59)	15.4 (15.3)	21.6 % (0 %/134 %)
Eaves' protection	Without protection	47 % (47)	12.3 (13.6)	17.0 % (0 %/134 %)
	With protection	53 % (53)	17.6 (15.7)	22.8 % (0 %/83 %)
Platbands copings	Without copings	79 % (79)	16.2 (15.4)	22.2 % (0 %/134 %)
	With copings	21 % (21)	11.1 (12.1)	12.1 % (0 %/67 %)
Balcony copings	Without copings	66 % (66)	16.5 (16.3)	23.4 % (0 %/134 %)
	With copings	34 % (34)	12.6 (11.4)	13.8 % (0 %/52 %)
Ground floor protection (socle)	Without protection	17 % (17)	10.7 (13.0)	14.6 % (0 %/67 %)
	With protection	83 % (83)	16.1 (15.2)	21.2 % (0 %/134 %)
Detailing/design level	Inferior	29 % (29)	14.3 (13.0)	20.2 % (0 %/63 %)
	Medium	65 % (65)	15.9 (16.1)	21.1 % (0 %/134 %)
	Superior	6 % (6)	10.5 (9.8)	9.2 % (1 %/32 %)
Façade orientation	E/SE	25 % (25)	13.5 (13.9)	17.2 % (0 %/64 %)
	N/NE	34 % (34)	17.8 (16.2)	26.1 % (0 %/134 %)
	W/NW	18 % (18)	14.2 (15.1)	19.2 % (0 %/83 %)
	S/SW	23 % (23)	13.8 (14.1)	15.1 % (0 %/63 %)
Distance from the sea	Less than 5 km	23 % (23)	18.1 (14.1)	26.4 % (0 %/83 %)
	More than 5 km	77 % (77)	14.3 (15.1)	18.2 % (0 %/134 %)

(continued)

Table 2.13 (continued)

Characteristics of rendered façades		% of case studies (number of cases)	Average ages (standard deviation), in years	Average S_w (minimum/maximum)
Exposure to damp	Unfavourable	11 % (11)	12.3 (5.2)	19.2 % (5 %/49 %)
	Normal	23 % (23)	22.5 (17.8)	34.0 % (0 %/134 %)
	Favourable	66 % (66)	13.1 (14.2)	15.4 % (0 %/64 %)
Distance from pollution sources	Unfavourable	24 % (24)	14.4 (13.2)	19.8 % (0 %/61 %)
	Normal	70 % (70)	16.1 (15.8)	21.3 % (0 %/134 %)
	Favourable	6 % (6)	6.7 (5.4)	7.8 % (0 %/20 %)
Façade protection level	Without protection	46 % (46)	15.8 (15.4)	22.7 % (0 %/64 %)
	Normal situation	24 % (24)	14.2 (15.8)	18.1 % (0 %/134 %)
	With protection	30 % (30)	14.9 (13.8)	17.7 % (0 %/67 %)
Type of property	Private	82 % (82)	15.1 (15.5)	19.8 % (0 %/134 %)
	Public sector	14 % (14)	18.4 (12.2)	26.4 % (5 %/63 %)
	Commerce and services	4 % (4)	7.0 (0.8)	5.3 % (1 %/9 %)
Ease of inspection	Normal	59 % (59)	19.6 (16.4)	26.5 % (0 %/134 %)
	Unfavourable	41 % (41)	8.9 (9.1)	11.0 % (0 %/58 %)

2.6.3 *Painted Surfaces*

Table 2.14 shows the characteristics of the sample analysed for painted surfaces. Plain paints and elastic membranes are the most common type of paint, representing three-fourth of the sample. Silicate and silicone paints are the less common type of paint (only 4 % of the sample). In the sample analysed, only 4 % of paintings present dark colours.

Most of the buildings analysed present a compact volume (81 %), heights below 15 m (73 %) and are home to services or commerce (67 %). The sample is relatively homogeneous according to façades' orientation, distance from the sea and exposure to damp. Finally, in the sample analysed there is a prevalence of case studies with current exposure to pollution sources.

2.6.4 *Ceramic Tiling Systems*

The characterization of the sample of adherent ceramic claddings is presented in Table 2.15. In this sample, there is a predominance of glazed tiles (86 %) with light colours (59 %), with sizes of less than 20 cm (83 %). In most cases, the cladding is

Table 2.14 Characterization of the sample analysed for painted surfaces

Characteristics of painted surfaces		% of case studies (number of cases)	Average ages (standard deviation), in years	Average S_w (minimum/maximum)
Type of paint	Plain paints	37 % (81)	6.6 (4.0)	12.5 % (0 %/60 %)
	Elastic membranes	38 % (83)	5.5 (3.9)	10.3 % (0 %/69 %)
	Silicate and silicone paints	4 % (9)	8.1 (5.8)	25.8 % (2 %/72 %)
	Textured paint	21 % (47)	10.1 (4.8)	24.6 % (0 %/68 %)
Colour	White	30 % (66)	6.5 (3.7)	11.9 % (0 %/69 %)
	Light	66 % (144)	7.1 (4.7)	15.3 % (0 %/72 %)
	Dark	4 % (10)	8.5 (6.9)	25.8 % (0 %/63 %)
Type of finishing	Smooth	56 % (124)	6.3 (4.1)	12.9 % (0 %/72 %)
	Rough	44 % (96)	7.8 (5.0)	17.3 % (0 %/69 %)
Building geometry	Compacta	81 % (179)	7.4 (4.5)	15.7 % (0 %/72 %)
	Irregular	19 % (41)	5.2 (4.4)	10.7 % (0 %/69 %)
Façade orientation	E/SE	29 % (65)	8.1 (4.4)	17.3 % (0 %/72 %)
	N/NE	19 % (41)	6.9 (4.1)	12.5 % (0 %/63 %)
	W/NW	31 % (68)	6.3 (4.7)	13.5 % (0 %/68 %)
	S/SW	21 % (46)	6.4 (4.6)	15.1 % (0 %/69 %)
Wind-rain action	Severe	33 % (72)	6.2 (3.8)	12.1 % (0 %/63 %)
	Moderate	45 % (99)	5.5 (4.1)	10.4 % (0 %/72 %)
	Low	22 % (49)	11.2 (3.9)	27.5 % (2 %/68 %)
Distance from the sea	Less than 5 km	52 % (114)	5.4 (3.8)	10.1 % (0 %/69 %)
	More than 5 km	48 % (106)	8.7 (4.7)	19.8 % (0 %/72 %)
Exposure to damp	High	53 % (116)	5.4 (3.7)	10.1 % (0 %/69 %)
	Low	47 % (104)	8.7 (4.7)	20.0 % (0 %/72 %)
Distance from pollution sources	Current	79 % (174)	6.6 (4.2)	13.2 % (0 %/69 %)
	Unfavourable	21 % (46)	8.5 (5.4)	20.7 % (0 %/72 %)
Type of use	Commerce and services	67 % (72)	6.7 (3.5)	13.0 % (0 %/68 %)
	Housing	33 % (148)	7.1 (5.0)	15.6 % (0 %/72 %)
Ease of inspection	Current	73 % (161)	7.2 (4.8)	15.8 % (0 %/72 %)
	Unfavourable	27 % (59)	6.3 (3.6)	12.0 % (0 %/63 %)

applied over a masonry support (54 %), not presenting peripheral joints (85 %) but with peripheral protection (52 %). Regarding the façades orientation, the number of case studies analysed for each category is evenly distributed. Finally, most of the

Table 2.15 Characterization of the sample analysed for ceramic tiling systems

Characteristics of ceramic claddings		% of case studies (number of cases)	Average ages (standard deviation), in years	Average S_w (minimum/maximum)
Type of surface	Glazed	86 % (167)	36.3 (18.8)	14.2 % (0 %/61 %)
	Not glazed	14 % (28)	24.0 (15.6)	6.5 % (1 %/19 %)
Colour	Light	59 % (115)	38.2 (18.7)	15.5 % (0 %/61 %)
	Dark	41 % (80)	29.3 (18.0)	9.6 % (0 %/52 %)
Tiles size	L $\leq$ 20 cm	83 % (162)	37.9 (17.9)	14.7 % (0 %/61 %)
	L > 20 cm	17 % (33)	18.0 (14.2)	5.4 % (0 %/21 %)
Substrate	Masonry	54 % (106)	43.1 (17.3)	19.2 % (1 %/61 %)
	Concrete	46 % (89)	24.3 (15.3)	5.8 % (0 %/32 %)
Peripheral joints	No	85 % (166)	34.6 (18.2)	13.0 % (0 %/61 %)
	Yes	15 % (29)	34.1 (22.6)	14.1 % (0 %/48 %)
Peripheral protection	No	48 % (94)	32.8 (19.7)	12.4 % (0 %/61 %)
	Yes	52 % (101)	36.2 (18.0)	13.8 % (0 %/52 %)
Façade orientation	E/SE	25 % (48)	34.4 (18.3)	12.1 % (0 %/48 %)
	N/NE	30 % (59)	36.2 (19.1)	14.2 % (0 %/58 %)
	W/NW	24 % (46)	29.9 (16.6)	9.4 % (0 %/50 %)
	S/SW	22 % (42)	37.3 (21.2)	16.9 % (0 %/61 %)
Distance from the sea	Less than 5 km	71 % (139)	38.1 (19.7)	16.1 % (0 %/61 %)
	More than 5 km	29 % (56)	25.6 (13.0)	5.7 % (0 %/26 %)
Wind-rain action	Severe	27 % (53)	41.3 (20.3)	19.3 % (0 %/61 %)
	Moderate	50 % (97)	29.8 (18.1)	10.2 % (0 %/50 %)
	Low	23 % (45)	36.7 (16.3)	12.2 % (1 %/44 %)
Exposure to damp	High	43 % (84)	37.3 (20.1)	17.4 % (0 %/61 %)
	Low	57 % (111)	32.4 (17.7)	9.9 % (0 %/45 %)
Ease of inspection	Current	65 % (127)	38.6 (16.9)	14.9 % (0 %/61 %)
	Unfavourable	35 % (68)	26.9 (20.0)	9.8 % (0 %/48 %)

case studies are located at less than 5 km from the sea (71 %), with moderate exposure to wind-rain action (50 %) and low exposure to damp (57 %).

2.7 Conclusion

The degradation of buildings is a complex phenomenon that depends on many factors and severely affects the built heritage. Degradation begins as soon as constructions are put into use, due to ageing and the effect of environmental agents; it is also directly affected by an incipient culture of maintenance of the building somewhat prevalent in many countries—in which repair actions are only taken after the occurrence of defects—which leads to the buildings' premature loss of performance. The service life prediction of buildings and their components has paramount importance for the concept of a sustainable environment, enabling a more rational use of resources. In particular, buildings may present a better performance during their life cycle, thus reducing their financial and environmental costs. The knowledge of durability and service life of building components is also crucial for maintenance policies—for it allows planning in a technically informed manner the timely occurrence of maintenance investments—which are indispensable in the context of the present huge demand to rehabilitate.

In recent decades, several international standards and studies have been put forward, which intend to establish methodologies to assess the durability of buildings as well as predict their service life. The main approaches to the problem can be divided in deterministic, probabilistic and engineering methods. These methods are useful to stakeholders in the construction sector, who should decide on the best approach to the problem, taking into account the available data, the desired result, the complexity of each approach and the advantages/disadvantages inherent of each one of the service life prediction methods. Generally speaking, more complex approaches (stochastic or computational models) lead to more rigorous models; however, often does it seem appropriate to sacrifice some accuracy in exchange for a greater applicability and simplicity of the model—and especially in the case of exterior façades claddings.

In the definition of service life prediction models, one of the main factors to be taken into consideration is the maximum acceptable degradation level, which establishes the end of service life of the construction elements. However, as referred to in this chapter, this theoretical limit is somewhat subjective and may vary according to owners and users demands; and these depend on several factors such as the social and economic context of societies. Additionally, the requirements of users and owners permanently change over time, thus requiring continual (re)investment in buildings.

In this chapter, a model is proposed to quantify the overall degradation of existing façades claddings in real life exposure conditions. This model is based on the determination of a numerical index (referred to as severity of degradation), based on the extent of the façades degradation, the severity of the defects detected and their cost of repair. The proposed methodology is based on the fieldwork study of claddings degradation condition, analysed in service conditions, based on an extensive survey, using visual inspections only. This model was successfully applied to the identification and quantification of the degradation of various types of claddings (renderings, ETICs, natural stone claddings, adherent ceramic tiles and painted surfaces). This index (S_w) is used as a reference value (observed on field) that may benchmark and validate the results from the models proposed in the following chapters. In spite of its limitations, this approach presents some advantages, since: (i) it can be easily complemented, at any time, with new data; and (ii) it is easy to apply, even for other types of non-structural elements, allowing their adjustment to other realities (e.g. it can be applied in other countries and building contexts, by simply changing the weighting coefficients and making them meet the costs practiced or the conditions observed in those countries or contexts).

References

Aarseth LI, Hovde PJ (1999) A stochastic approach to the factor method for estimating service life. In: 8th DBMC international conference on durability of building materials and components; Vancouver, Canada, pp 1247–1256

Abraham TH (2002) (Physio)logical circuits: the intellectual origins of the McCulloch-Pitts neural networks. J Hist Behav Sci 38(1):3–25

AIJ (1993) The English edition of the principal guide for service life planning of buildings. Architectural Institute of Japan, Tokyo

Aikivuori AM (1999) Critical loss of performance—what fails before durability. In: 8th International conference on durability of buildings materials and components, Vancouver, Canada, pp 1369–1376

ASTM E632 (1990) Standard practice for developing accelerated tests to aid prediction of the service life of building components and materials. In: Annual book of ASTM standards, section 4: construction, vol 04.07. Building seals and sealants; fire standards; building constructions. Easton, USA. American Society for Testing and Materials, p 1078

Augenbroe GLM, Park C-S (2002) Towards a maintenance performance toolkit for GSA, interim report submitted to GSA, Georgia Institute of Technology, Atlanta, USA

Balaras A, Droutsa K, Argiriou AA, Asimakopoulos DN (2000) EPIQR surveys of apartment buildings in Europe. Energy Build 31(2):111–128

Balaras A, Droutsa K, Dascalaki E, Kontoyiannidis S (2005) Deterioration of European apartment buildings. Energy Build 37(5):515–527

Barberousse H, Ruot B, Yéprémian C, Boulon G (2007) An assessment of façade coatings against colonisation by aerial algae and cyanobacteria. Build Environ 42(7):2555–2561

Bone S, Heard H, Horsfall D (1989) Defects in buildings. Department of Environment, PSA Directorate of Building Development, HMSO, London

Bonshor R, Bonshor L (2001) Cracking in buildings. BRE, London

Bordalo R (2008) Service life prediction of adherent ceramic tiling systems. Master thesis in Civil Engineering, Instituto Superior Técnico, University of Lisbon, Lisbon (in Portuguese)

Bordalo R, de Brito Jorge, Gaspar P, Silva A (2011) Service life prediction modelling of adhesive ceramic tiling systems. Build Res Inf 39(1):66–78

Bourdeau L (1999) Sustainable development and the future of construction: a comparison of visions from various countries. Build Res Inf 27(6):355–367

Bovea MD, Díaz-Albo E, Gallardo A, Colomer FJ, Serrano J (2010) Environmental performance of ceramic tiles: improvement proposals. Mater Des 31(1):35–41

Brand S (1997) How buildings learn: what happens after they're built?, 1st edn. Phoenix Illustrated, London

Brandt E, Rasmussen M (2002) Assessment of building conditions. Energy Build 34(2):121–125

BSI (1992) Guide to durability of buildings and building elements, products and components, BS 7543. British Standards Institution, London

Campante E, Paschoal J (2002) Durability of facades with ceramic coverings—Why they fail'. In: 9th International conference on durability on building materials and components, 2002, Brisbane, Australia, pp 17–21

Camuffo D (1995) Physical weathering of stones. Sci Environ 167(1–3):1–14

Chai C (2011) Service life prediction of painted surfaces on exterior walls. Master thesis in Civil Engineering, Instituto Superior Técnico, University of Lisbon, Lisbon (in Portuguese)

Chai C, de Brito J, Gaspar P, Silva A (2014) Predicting the service life of exterior wall painting: techno-economic analysis of alternative maintenance strategies. J Constr Eng Manage 140 (3):04013057
Chew MYL (1999) Factors affecting ceramic tile adhesion for external cladding. Constr Build Mater 13(5):293–296
Chew MYL, Ping TP (2003) Staining of facades. World Scientific Publishing, Singapore, p. 160
Chew M (2005) Defect analysis in wet areas of buildings. Constr Build Mater 19(3):165–173
Clifton JR (1993) Predicting the service life of concrete. ACI Mater J 90(6):611–617
Cowan P (1963) Studies in the growth, change and ageing of buildings. Trans Bartlett Soc 1:55–84
CSA S478-95 (2001) (Canadian Standards Association) Guideline on durability in buildings. CSA, Canada, pp 9–17
Daniotti B, Spagnolo SL (2008) Service life prediction tools for buildings' design and management. In: 11th DBMC, International conference on durability of building materials and components, Istanbul, Turkey, 2008, T72
Daniotti B, Spagnolo SL, Paolini R (2008) Factor method application using factors' grid. In: 11th International conference on durability of building materials and components, Istanbul, Turkey, 2008, T41
Davies G, Szigeti F (1999) Are facilities measuring up? Matching building capacities and functional needs. In: CIB W078 workshop on information technology in construction 1999, Vancouver, Canada, pp 1856–1866
Design guide to refurbishment (1999) Building Maintenance and Management Centre, Tokyo, Japan (in Japanese)
DeSimone LD, Popoff F (1998) Eco-efficiency. In: The business link to sustainable development, 2nd edn. MIT Press, USA, p 280
Donca G, Mihăilă I, Ganea M, Hirłe D, Nica M (2007) Maintenance role in life cycle management. Ann Oradea Univ Fascicle Manage Technol Eng 6(16):2158–2163
Edvardsen C, Mohr L (2000) Designing and rehabilitating concrete structures: probabilistic approach (DuraCrete). In: 5th CANMET/ACI, international conference on durability of concrete, 2000, pp 1192–1208
Emídio F, de Brito J, Gaspar P, Silva A (2014) Application of the factor method to the estimation of the service life of natural stone cladding. Constr Build Mater 66:484–493
Esteves LAR (2007) Portuguese natural stone. The future is paved today. Master thesis in Management and Industrial Strategy, Instituto Superior de Economia e Gestão, University of Lisbon, Lisbon (in Portuguese)
European Organisation for Technical Approvals (EOTA) (1999) Assumption of working life of construction products in guideline for European Technical Approvals and Harmonized Standards. December 1999. Guidance Document 002
Faber MH, Gehlen C (2002) Probabilistischer Ansatz zur Beurteilung der Dauerhaftigkeit von bestehenden Stahlbetonbauten. Beton und Stahlbetonbau 97(8):421–429
Flanagan R, Norman G, Meadows J, Robinson G (1989) Life cycle costing: theory and practice. BSP Professional Books, Oxford
Flores-Colen I, de Brito J (2010) A systematic approach for maintenance budgeting of buildings façades based on predictive and preventive strategies. Constr Build Mater 24(9):1718–1729
Flores-Colen I, de Brito J, Freitas VP (2008) Condition assessment of facade rendering though in situ testing. In: 11th DBMC international conference on durability on building materials and components 2008, Istanbul, Turkey, Paper T71
Flourentzou F, Brandt E, Wetzel C (1999) MEDIC—A method for predicting residual service life and refurbishment investments budgets. In: 8th International conference on durability of buildings materials and components, Vancouver, Canada, pp 1280–1288
Frangopol DM, Kallen M-J, Noortwijk JM (2004) Probabilistic models for life-cycle performance of deteriorating structures: review and future directions. Prog Struct Mat Eng 6(4):197–212
Freitas VP, Sousa M, Abrantes V (1999) Survey of the durability of facades of 4000 dwellings in northern Portugal. In: 8th International conference on the durability of building materials and components, Ottawa, Canada, pp 1040–1050

Freitas VP, Corvacho H, Quintela M, Delgado JMPQ (2013) Durability assessment of adhesive systems for bonding ceramic tiles on façades: the research and the practice. In: Durability of building materials and components, building pathology and rehabilitation, vol 3. Springer, Berlin, pp 173–205

Frohnsdorff GJ, Martin JW (1996) Towards prediction of building service life: the standards imperative. In: 7th International conference on durability of building materials and components. Stockholm, Sweden, pp 1417–1428

Galbusera MM, de Brito J, Silva A (2014) Application of the factor method to the prediction of the service life of ceramic external wall claddings. J Build Perform Constr Facil, pp 19–29. doi:10.1016/j.conbuildmat.2014.05.045

Gaspar P (2009) Service life of constructions: development of a method to estimate the durability of construction elements. Application to renderings of current buildings. Doctor thesis in sciences of engineering, Instituto Superior Técnico, Technical University of Lisbon, Portugal (in Portuguese)

Gaspar P, de Brito J (2005) Mapping defect sensitivity in external mortar renders. Constr Build Mater 19(8):571–578

Gaspar PL, de Brito J (2008) Quantifying environmental effects on cement-rendered facades: A comparison between different degradation indicators. Build Environ 43(11):1818–1828

Gaspar PL, de Brito J (2011) Limit states and service life of cement renders on façades. Mater Civil Eng 23(10):1393–1404

Guide to Condition Assessment for Refurbishment (1993). Building Maintenance & Management Centre, Tokyo, Japan, 1993 (in Japanese)

Haagenrud SE (2004) Factors causing degradation. Guide and bibliography to service life and durability research for buildings and components. In: Joint CIB W80/RILEM TC 140—Prediction of service life of building materials and components, pp 2.1–2.105

Haapio A, Viitaniemi P (2008) How workmanship should be taken into account in service life planning. In: 11th International conference on durability of building materials and components, Istanbul, Turkey, T45

Hansen EJP, Ekman T, Hansen KK (1999) Durability of cracked fibre reinforced concrete structures exposed to chlorides. In: 8th International conference on the durability of building materials and components, Ottawa, Canada, pp 280–289

Hed G (1999) Service life planning of building components. In: 8th International conference on durability of building materials and components, Vancouver, Canada, pp 1543–1551

Ho DCW, Lo SM, Yiu CY, Yau LM (2004) A survey of materials used in external wall finishes in Hong Kong. Hong Kong Surveyor 15(2):7–11

Hovde PJ (2000) Factor methods for service life prediction: a state-of-the-art. Draft Report, Norwegian University of Science and Technology, Trondheim, Norway

Hovde PJ (2002) The factor method for service life prediction from theoretical evaluation to practical implementation. In: 9th International conference on durability of buildings materials and components, Brisbane, Australia, Paper 232

Hovde P (2004) Factor methods for service life prediction. In: CIB W080/RILEM 175 SLM: Service life methodologies prediction of service life for buildings and components, task group: performance based methods of service life prediction 2004, Trondheim, Norway, pp 1–51

HQAL (2000) Housing quality assurance law. Centre for better living, Tokyo, Japan (in Japanese)

Iselin DG, Lemer AC (eds) (1993) The fourth dimension in building: strategies for minimizing obsolescence. National Research Council, Building Research Board, National Academy Press, Washington, DC

ISO 15686-1 (2011) Buildings and constructed assets—service life planning—Part 1: general principles and framework. International Organization for Standardization, Switzerland

John VM, Sjöström C, Agopyan V (2002) Durability in the built environment and sustainability in developing countries. In: 9th International conference on durability of building materials and components, Brisbane, Australia, Paper 11

Kooymans R, Abbott J (2006) Developing an effective service life asset management and valuation model. J Corp Real Estate 8(4):198–212

Kus H (2002) Service life of external renders. In: XXX IAHS world congress on housing, vol III. Coimbra, pp 1875–1882
Kus H, Carlsson T (2003) Microstructural investigations of naturally and artificially weathered autoclaved aerated concrete. Cem Concr Res 33(9):1423–1432
Lacasse MA, Sjöström C (2004) Recent advances in methods for service life prediction of buildings materials and components—an overview. In: CIB World Building Congress, Canada, pp 1–10
Lair J (2003) Failure modes and effect analysis and service life prediction. Intermediary report (D4-C2-jl-01 draft 2), IEA task 27 (project C2: failure mode analysis); CSTB, France, pp 166–212
Lee N, Bennett J, Jones M, Marston N, Kear G (2008) A durability assessment tool for the new zealand building code. In: 11th International conference on durability of building material and components, Istanbul, Turkey, T45
Leira B, Lindgård J, Nesje A, Sund E, Sægrov S (1999) Degradation analysis by statistical methods. In: 8th International conference on durability of building materials and components, Vancouver, Canada, pp 1436–1446
Liang MT, Wu JH, Liang CH (2001) Multiple layer fuzzy evaluation for existing reinforced concrete bridges. J Infrastruct Syst 7(4):144–159
Lo Y (2002) Delamination of external wall finishes of housing. In: XXX IAHS world congress on housing—housing construction—an interdisciplinary task. Coimbra, Portugal, pp 1571–1576
Long AE, Henderson GD, Montgomery FR (2001) Why assess the properties of near-surface concrete? Constr Build Mater 15(2–3):65–79
Lounis Z, Lacasse MA, Vanier DJ, Kyle BR (1998) Towards standardization of service life prediction of roofing membranes. In: Wallace TJ, Rossiter Jr WJ (eds) Roofing research and standards development, vol 4. American Society for Testing and Materials (ASTM STP 1349)
Mansur AAP, Nascimento OL, Vasconcelos WL, Mansur HS (2008) Chemical functionalization of ceramic tile surfaces by silane coupling agents: polymer modified mortar adhesion mechanism implications. Mater Res 11(3):293–302
Marteinsson B (2003) Assessment of service lives in the design of buildings—development of the factor method. Licentiate thesis, KTH's Research School—HiG, Centre of Built Environment, University of Gävle, Sweden
Marteinsson B, Jónsson B (1999) Overall survey of buildings—performance and maintenance. In: 8th International conference on the durability of building materials and components, Vancouver, Canada, pp 1634–1654
Mateus R, Bragança L, Koukkari H (2008) Sustainability assessment and rating of Portuguese buildings. In: World sustainable conference (SB08), Melbourne, Australia, pp 959–966
Mc Duling J, Horak E, Cloete C (2008) Service life prediction beyond the 'factor method'. In: 11th International conference on durability of building materials and components, Istanbul, Turkey, T42
Meola C, Maio RD, Roberti N, Carlomagno GM (2005) Application of infrared thermography and geophysical methods for defect detection in architectural structures. Eng Fail Anal 12 (6):875–892
Moreno SH (2012) The method by factors to estimate service life in buildings projects according to norm ISO 15686. Manage Res Pract 4(4):5–11
Moser K (1999) Towards the practical evaluation of service life—illustrative application of the probabilistic approach. In: 8th International conference on durability of buildings materials and components, Vancouver, Canada, pp 1319–1329
Moser K (2003) Engineering design methods for service life planning—state of the art. In: International workshop on management of durability in the building process (WMDBP 2003). Politecnico di Milano, Milan, Paper 40
Moser K (2004) Engineering design methods for service life prediction. In: CIB W080/RILEM 175 SLM: Service life methodologies prediction of service life for buildings and components, task group: performance based methods of service life prediction, Trondheim, Norway, pp 52–95
Moser K, Edvardsen C (2002) Engineering design method for service life prediction. In: 9th International conference on the durability of building materials and components 2002, Brisbane, Australia, Paper 222

National Statistics Institute (INE) (2001) National statistics—census. http://www.ine.pt/prodserv/quadro/mostraquadro (in Portuguese)
Nireki T (1996) Service life design. Constr Build Mater 10(5):403–406
Norvaišienė R, Miniotaitė R, Stankevičius V (2003) Climatic and air pollution effects on building facades. Mater Sci 9(1):102–105
NP EN ISO 4628-1 (2005) Paints and varnishes—evaluation of degradation of coatings—designation of quantity and size of defects, and of intensity of uniform changes in appearance—Part 1: General introduction and designation system, Portuguese Quality Institute, Lisbon, Portugal, p 8
NP EN ISO 4628-2 (2005) Paints and varnishes—evaluation of degradation of paint coatings—designation of intensity, quantity and size of common types of defect—Part 2: Designation of degree of blistering, Portuguese Quality Institute, Lisbon, Portugal, p 16
NP EN ISO 4628-4 (2005) Paints and varnishes—evaluation of degradation of coatings—designation of quantity and size of defects, and of intensity of uniform changes in appearance—Part 4: Assessment of degree of cracking, Portuguese Quality Institute, Lisbon, Portugal, p 20
NP EN ISO 4628-5 (2005) Paints and varnishes—evaluation of degradation of coatings—designation of quantity and size of defects, and of intensity of uniform changes in appearance—Part 5: Assessment of degree of flaking, Portuguese Quality Institute, Lisbon, Portugal, p 11
NP EN ISO 4628-7 (2005) Paints and varnishes—evaluation of degradation of coatings—designation of quantity and size of defects, and of intensity of uniform changes in appearance—Part 7: Assessment of degree of chalking by velvet method, Portuguese Quality Institute, Lisbon, Portugal, p 8
NS 3422 (1994) Specification texts for operation, maintenance and renewal of buildings and civil engineering works. Norges Standardiseringsforbund, Oslo, Norway
Paulo PV, Branco F, de Brito J (2014) Buildings life: a building management system. Struct Infrastruct Eng Maintenance Manage Life Cycle Des Perform 10(3):388–397
Pearce D (2003) The social and economic value of construction. In: The construction industry's contribution to sustainable development. NCRISP, Davis Langdon Consultancy, London
Re Cecconi F (2002) Performance leads the way to service life prediction. In: 9th International conference on durability of buildings materials and components, Brisbane, Australia, Paper 213
Rikey M, Cotgrave A (2005) The context of maintenance. In: Construction technology. The technology of refurbishment and maintenance, vol. 3. Macmillan Palgrave, New York, pp 50–56
Rimestad L (1998) The use of field failure data in accelerated testing. In: Safety and reliability, Hansen GK, Sandtorv HA (eds) Balkema, Rotterdam, pp 1209–1216
Ross SM (1996) Stochastic processes, 2nd edn. John Wiley & Sons, New York
Rudbeck C (2002) Service life of building envelope components: making it operational in economical assessment. Constr Build Mater 16(2):83–89
Sarja A (2005) Generic limit state design of structures. In: 10th International conference on durability of building materials and components, Lyon, France, TT3-161
Shohet I, Laufer A (1996) Exterior cladding methods: a technoeconomic analysis. J Constr Eng Manage 122(3):242–247
Shohet IM, Paciuk M (2004) Service life prediction of exterior cladding components under standard conditions. Constr Manage Econ 22(10):1081–1090
Shohet I, Rosenfeld Y, Puterman M, Gilboa E (1999) Deterioration patterns for maintenance management—a methodological approach. In: 8th International conference on durability of buildings materials and components, Vancouver, Canada, pp 1666–1678
Siemes T, Edvardsen C (1999) Duracrete: service life design for concrete structures. In: 8th International conference on durability of buildings materials and components, Vancouver, Canada, pp 1343–1356

Silva A (2009) Service life prediction of natural stone walls cladding, Master thesis (in Portuguese). Instituto Superior Técnico, Lisbon, Portugal

Silva A, de Brito Jorge, Gaspar P (2011) Service life prediction model applied to natural stone wall claddings (directly adhered to the substrate). Constr Build Mater 25(9):3674–3684

Silva A, Dias JLR, Gaspar PL, de Brito J (2013) Statistical models applied to service life prediction of rendered façades. Autom Constr 30:151–160

Silva A, Gaspar PL, de Brito J (2014) Durability of current renderings: a probabilistic analysis. Autom Constr 44:92–102

Silvestre J, de Brito J (2007) Statistical analysis of defects of tiles' joints. Análisis estadístico de los defectos de juntas cerámicas. Materiales de Construcción, Instituto de Ciencias de la Construcción Eduardo Torroja, Madrid, Spain 57(285):85–92

Silvestre J, de Brito Jorge (2009) Ceramic tiling inspection system. Constr Build Mater 23 (2):653–668

Sjöström C (1985) Overview of methodologies for prediction of service life. In: Problems in service life prediction of building and construction materials NATO ASI series, vol 95, pp 3–20

Sjöström C, Davies H (2005) Built to last: service life planning. ISO Focus 2(11):13–15

Slaughter ES (2001) Design strategies to increase building flexibility. Build Res Inf 29(3):208–217

Soronis G (1996) Standards for design life of buildings: utilization in the design process. Constr Build Mater 10(7):487–490

Straub A (2003) Using a condition-dependent approach to maintenance to control costs and performances. Facil Manage 1(4):380–395

Takata S, Kimura F, Van Houten F, Westkamper E, Shpitalni M, Ceglarek D, Lee J (2004) Maintenance: changing role in life cycle management. CIRP Ann 53(2):643–655

Talon A, Boissier D, Chevalier J-L, Hans J (2005) Temporal quantification method of degradation scenarios based on FMEA. In: 10th International conference on durability of building materials and components, Lyon, France, TT4-139

Timellini G, Palmonari C (1989) Ceramic floor and wall tile performance and controversies. EdiCer, Sassuolo

Van Winden C, Dekker R (1998) Rationalization of building maintenance by Markov decision models: a pilot case study. J Oper Res Soc 49(9):928–935

Vanier DJ (1999) Why industry needs asset management tools. In: Innovations in urban infrastructure seminar of the APWA international public works congress, Denver, USA, pp 11–25

Watt DS (1999) Building pathology—principles and practice, 1st edn. Blackwell Science Ltd., Blackwell Publishing Company, London

Wekesa BW, Steyn GS, Otieno FAO (2010) The response of common building construction technologies to the urban poor and their environment. Build Environ 45(10):2327–2335

Wetzel A, Zurbriggen R, Herwegh M (2010) Spatially resolved evolution of adhesion properties of large porcelain tiles. Cement Concr Compos 32(5):327–338

Wyatt D (2005) The contribution of FMEA and FTA to the performance review and auditing of service life design of constructed assets. In: 10th International conference on durability of building materials and components, Lyon, France, TT4-206

Ximenes S, de Brito J, Gaspar PL, Silva A (2015) Modelling the degradation and service life of ETICS in external walls. Mater Struct 48:2235–2249

Zhang X, Gao H (2011) Determining an optimal maintenance period for infrastructure systems. Comput Aided Civil Infrastruct Eng 27(7):543–554

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