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UNCERTAINTY MODELLING OF SERVICE LIFE AND ENVIRONMENTAL PERFORMANCE TO REDUCE RISK IN BUILDING DESIGN DECISIONS

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Abstract. Life-cycle assessment (LCA) is increasingly used to quantify the environmental impacts of construction materials. However, the relationship between the durability and LCA of these complex products with long life-cycles must be analysed in detail, namely using stochastic data from service life prediction (SLP) studies. However, SLP uncertainty is not yet considered in LCA, thus resulting in insufficiently sound decisions at the design stage. This paper presents the modelling of the uncertainty of SLP using advanced statistical methods and its application in the estimation of SL and corresponding number of replacements of claddings (renderings and stone claddings). These results are used in an interdisciplinary study of SLP and LCA to apply in the stochastic comparison of the LCA of claddings. This methodology aids in the choice of the option with better environmental performance right at the design stage, via the comparison of their standard, deterministic and stochastic LCA results.

Keywords: building design, claddings, decision-making, life cycle assessment, service life prediction.

Introduction

Concern with the economic and environmental sustainability of the construction sector has been growing over the past 20 years, since it is responsible for using a significant part of the material, energy and electricity resources of Europe (Balaras *et al.* 2005). The construction industry consumes a large quantity of environmental resources and is also one of the largest polluters (Shen *et al.* 2005). Pearce (2003) says that the concept of sustainable development is leading to a fundamental re-evaluation of the contribution the construction industry makes to the quality of life. Life-cycle assessment (LCA) considers the environmental impact over the lifetime of a product by identifying and quantifying the environmental emissions and consumption of energy and materials. Building materials and assemblies are complex products with long life-cycles, and defining a functional unit and the boundary of the assessment for an LCA study is both complex and constraining. This is even more important when the relationship between the durability and LCA of building materials and components is analysed because service life prediction (SLP) is central to achieving a sustainable built environment (Abbott *et al.* 2007). However, SPL is not yet included in LCA studies and a deterministic analysis of the life cycle of building components is normally performed.

ISO 15686-6:2004 (2004) and FprEN 15804:2011 (2011) already establish the interface between LCA and service life planning and describe how to consider the service life of construction materials and buildings in LCA studies. They particularly stress that the use phase should be included and that LCA results will be significantly dependent on scenarios and assumptions about the duration and the processes involved in the use phase. Realistic scenarios require the incorporation of information obtained from the SLP studies. The reference service life of a product can be based on empirical, probabilistic, statistical, deemed to satisfy or research (scientific) data and must always take into account the intended use (description of use) (FprEN 15804:2011 (2011)).

There is already a common understanding that LCA results are uncertain and that several factors contribute to this uncertainty (e.g. parameters of the LCA model or uncertainty in model structure). Despite that, most LCA results present deterministic figures even though this is not the best option when the final aim is to use LCA as a decision-support tool. Providing the results together with uncertainty information permits the assessment of their stability and can sometimes lead to changes in the ranking order of the different solutions being evaluated. Therefore, uncertainty information is of paramount importance to making decisions based on the result of a study, and it has an increasing practical relevance. Uncertainty is always important for decision-makers, regardless of their attitude towards risk, and also to showing the quality of data and to motivating the search for data with better quality (Ciroth 2004).

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There is uncertainty inherent to each SLP method that results from its characteristics of reliability, degree of precision and confidence. The corresponding LCA results are affected by this uncertainty. However, the uncertainty of neither the SLP methods nor the corresponding LCA results has yet been studied in detail with appropriate statistical tools. Therefore, the aim of this paper is to present an interdisciplinary study of the interrelation between SLP and LCA via modelling the uncertainty of SLP methods and applying it in the stochastic comparison of the LCA of building assemblies. In particular, these uncertainty models are applied to the LCA of cladding solutions for external walls.

The results presented in this paper are of paramount importance for designers who need to choose from alternative claddings for external walls of buildings using environmental criteria, especially early in the design stage, where there is an opportunity to decrease the environmental impacts of the project via the selection of adequate materials. The method proposed in this paper would make SLP more accurate by incorporating advanced statistical methods that aid the choice of the solution with the best environmental performance, particularly by calculating the stochastic LCA for each solution.

1. Degradation of external cladding

External claddings play a fundamental role in building performance. The degradation of the exterior face of buildings is one of the major concerns of building owners and maintenance managers since in most cases maintenance actions are based only on the external look of the buildings (i.e. building aesthetics) (Balaras *et al.* 2005). The external claddings increase the structure's durability, protect it from environmental agents and are very important in terms of aesthetics. Besides quality/cost criteria, the selection of the cladding must take into account the conditions it will be subjected to throughout its service life (Ho *et al.* 2004).

In theory claddings are very durable elements. This is demonstrated by many buildings a hundred years old and more that retain all their original cladding elements and still have a satisfactory performance (Ashworth 1996). But it is very often found that these elements have a much shorter service life than the building itself and periodic maintenance of cladding is required over the building's life-cycle; it sometimes even has to be refurbished or replaced.

1.1. Quantification of the global degradation of external claddings

Estimates of the life expectancy of building components result in different outputs depending on what is required of them. In theory, many of the components of buildings are capable of lasting a very long time, as is proved in very old buildings where an original component continues to perform well. However, in practice, the life expectancy of building components is frequently much shorter, for a variety of reasons. The obsolescence that eventually afflicts both design and technology is perhaps the main reason why generally sound components are removed and replaced. Otherwise, components decay, are damaged or misused (Ashworth 1996).

In this study the degradation of external claddings is studied based only on visual inspection. Data on degradation in real in-service conditions is therefore acquired. This method is an alternative to the lab tests that some authors believe represent a simplification of reality and whose results do not have a clear correspondence with the complexity of the phenomena associated with natural degradation under real in-use conditions (Kus *et al.* 2004; Daniotti, Paolini 2005), even if these conditions are known, the mechanisms of deterioration are understood and the causes of deterioration are identified (Norvaišiene *et al.* 2004).

Overall degradation of the claddings analysed was quantified using the method put forward by Gaspar and de Brito (2008) and Gaspar (2009). These authors proposed a numerical "severity of degradation" index which is obtained as the ratio between the extent of the façades degradation, weighted as a function of the degradation level and the severity of the anomalies, and a reference area, equivalent to the maximum theoretical extent of the degradation for the façade under analysis, as in expression (1):

$$S_w = \frac{\sum \left(A_n \times k_n \times k_{a,n} \right)}{A \times k}, \qquad (1)$$

where: S_w – normalised severity of degradation of the façade, in percentage; A_n – area of cladding affected by an anomaly, in m^2; k_n – anomaly's "*n*" multiplying factor, as a function of its condition (between 0 and 4); $k_{a,n}$ – weighting coefficient corresponding to the relative importance of each anomaly ($k_{a,n}$ Є R$^+$) (if no instructions are provided , one should assume $k_{a,n}$ = 1); k – weighting factor equal to the highest degradation level in the façade; A– total area of the cladding, in m^2.

Therefore this indicator takes into account both the degraded area of the cladding, affected by the different types of anomaly, and the severity level of the anomalies, also designated "condition". The anomalies are classified in terms of condition through a weighting factor (k_n) using a discrete scale of values from the most favourable condition (level 0 – absence of visible degradation) to the most unfavourable (level 4 – extensive degradation or loss of function).

1.2. Service life prediction (SLP) of external claddings

ISO 15686-1:2000 (2000) defines the reference service life as the period of time that a building or its parts are expected to last with standard in-use conditions. Predicting the service life of buildings or building elements can be complex and time-consuming. To date, SLP methods have not been developed into an exact science because of the many conditioning factors that make a thorough SLP an interdisciplinary activity.

Many studies have examined service life prediction. Hovde (2004) says that it can be a complex and lengthy process with many associated variables. According to some authors (Daniotti 2003; Moser 2004; Lacasse, Sjöström 2004), the main methods used to estimate service life may be classed as deterministic, probabilistic and engineering (a symbiosis of the previous two).

Deterministic methods are based on an analysis of the factors and degradation mechanisms that affect the elements studied, and quantifying them in terms of degradation. The great impetus for these methods came from Japan, through the "Japanese principal guide for service life planning of buildings" (Gakkai 1993) that proposed the factor method for the first time. More than a method, it is a general framework for service life estimation. Its flexibility and relative ease of application led to the factor method developing into one of the main tools offered, and it became the basis of the international standard for durability, partially published, the ISO 15686:2000 (2000).

Probabilistic methods came along based on the general concept that no two buildings degrade in exactly the same way during their life cycle since degradation depends on a series of random factors. Therefore, these methods look at degradation as a stochastic process that evolves probabilistically over time, where only the initial parameters are known (Moser 1999). These models are generally highly complex since they endeavour to handle different statistics and include the uncertainty resulting from the time periods considered (Kliukas, Kudzys 2004).

Rudbeck (1999) proposes to improve existing methods with the use of statistical tools. Moser (2004) looks at the work of various authors in this area and concludes that more studies are needed to identify the parameters that influence the service life of construction elements and that it is necessary to create viable mathematical formulae to enable these methods to be applied.

1.2.1. SLP – determinist approach

Various studies and standards in the area of service life prediction have mentioned the intention of estimating a reference service life for buildings and their components. The first standard to dwell on the durability and service life prediction issues was the Japanese guide developed in 1989 by the Architectural Institute of Japan and later translated into English (Gakkai 1993). This was pioneering at world level and represented the genesis of the factor methods, where the estimated service life of an element is obtained as the product of a reference service life by a series of factors modified as a function of the specific conditions of the element under analysis. According to this document the end of the service life is determined on the basis of the physical deterioration and the functional obsolescence of the element. The guide prescribes that external claddings should have a service life of at least 10 years.

In 1992 the British Standards Institute published standard 7543 for durability "British guide to durability of building elements, products and components" (BS 7543:1992) (1992) that lists various methods to estimate the service life of construction products, from past experience to accelerated degradation tests (Gaspar 2009). BS 7543 (1992) proposes defining the service life of buildings as a function of the type of use envisaged, and therefore five categories are proposed: 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-lived 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), based on a recommendation of RILEM (International Union of Testing and Research Laboratories for Materials and Structures) suggests a standard for service life prediction (Frohnsdorff *et al.* 1999). This standard, called ISO/DIS 15686-8.2:2006 (2006) "Building Service Life Planning" presently consists of 11 parts that define the general principles, framework and procedures of the method of service life prediction proposed. Furthermore, it defines the functional performance criteria that must be respected at the design stage and throughout the service life of constructions, and this will ultimately contribute to defining the end of the service life of the elements analysed (Hed 1999). ISO 15686:2000 (2000) suggests that façade claddings must have a service life of 25 years in current buildings whose service life is 60 years.

Standards relating to service life prediction have been published in countries that include: New Zealand (New Zealand Building Code 1992), which establishes a service life of 50 years for buildings and allows their components to have different service lives, depending on easy access, repair and anomaly detection; Australia (ABCB 2006); the United States, through the Partnership for Advancing Technology in Housing (PATH) that has funded a series of publications relating to the service life of buildings, and the American Society for Testing and Materials (ASTM); and Canada (Standard S478-95: Guideline on durability in buildings 2007) (Koymans, Abbott 2006).

Besides standards the Institute of Technology of Israel has produced several studies on the degradation of façades and the determination of their service life (Shohet, Paciuk 2004; Shohet *et al.* 1999). They propose a classification of façade degradation through the average of the physical and the visual degradation. Physical degradation includes all aspects related to the degradation mechanisms façades are subjected to while visual degradation takes into account the area of the façade affected by the various anomalies. This analysis is performed using visual inspections. Once the façade's degradation is quantified, the authors propose that degradation patterns are defined that permit the evaluation of loss of performance over time. The end of the service life is reached when, for a given sample, the average degradation curve reaches a minimum admissible level of performance. Shohet and Paciuk (2004) define two minimum performance levels: one for situations when claddings must have a high performance level; the other for a lower performance level, when the building owners want to minimise maintenance actions on the claddings.

Table 1 shows the reference service life proposed by various authors and standards for two types of external claddings under analysis.

All of these studies look at the service life of façade claddings as a deterministic value. This approach has been the target of much criticism because of service life being seen as an absolute value, with no data on the degradation process or on the transition from one degradation state to the next one (Mc Duling *et al.* 2008), therefore it fails to incorporate all the variability associated with degradation processes (Hovde 2000).

1.2.2. SLP – stochastic approach

The studies developed by the Institute of Technology of Israel (Shohet, Paciuk 2004; Shohet *et al.* 1999) led to the development of empirical methods implemented to evaluate the durability (or loss of performance) of a building or its components in real in-service conditions at different stages of the service life, through extensive field work (Gaspar, de Brito 2011). These methods make it possible to represent graphically the degradation patterns of various types of claddings and statistically analyse the performance of the claddings throughout their life cycle, with the aim of estimating their service life as a function of the level of demand.

For this, various cases are analysed in real in-service conditions and different degradation states. Using the model developed by Gaspar and de Brito (Gaspar, de Brito 2008; Gaspar 2009) it is possible to define the global degradation of the façade claddings. Each case corresponds to a coordinate (x, y) where x represents the age of the cladding (age here is the time since the last corrective, at the time of the inspection) and y represents the degradation observed. Once all the coordinates are determined they are represented graphically, leading to a cloud of points that depicts the case studies of the field study. Using a simple regression analysis it is then possible to obtain the function that best fits the cloud of points. This method is usually called the graphic method.

Gaspar (2009) used this method to evaluate the service life and durability of current renderings, based on a study of 100 coatings in the Lisbon region. For a maximum level of degradation of 20% the author obtained a reference service life of 15 years. By analysing the estimated service life of each case of the sample the author determined an average value of 17.5 years, with a standard deviation of 5.35 years and a confidence interval of ±1.05 years.

Based on the same method Silva *et al.* (2011a) analysed 140 stone claddings (directly adhered to the substrate) and found that the reference service life of this type of cladding is 68 years. By performing the same analysis of the estimated service life of each case study the authors found an average value of 66 years, with a standard deviation of 8.54 years and a confidence interval of ±1.40 years.

Another statistical method that can be used to predict the service life of façade claddings is multiple linear regression analysis. This is an extension of simple linear regression analysis in that it is based on the same hypotheses. However, multiple regression involves more than one independent variable (Satapathy *et al.* 2009).

Table 1. Reference service life proposed by different authors and normative documents

Authors	External cladding solution	
	Renderings	Stone claddings
BS 7543:1992 (1992) Recommended design life (years)	>60 (most external claddings for buildings with normal life – new housing)	
AIJ (1993) Recommended planned service life (years)	>10	
Shohet *et al.* (1999) Standard life expectancy (years)	20	40
ISO 15686:2000 (2000) Suggested service life for components (years)	25 (buildings with a design life of 60 years)	
Shohet and Paciuk (2004) For situations in which components are required to perform at high levels		
Standard life expectancy (years)	15	44
Predicted service life interval (years)	12–19	39–50
Shohet and Paciuk (2004) For situations in which owners want to minimise maintenance costs		
Standard life expectancy (years)	23	64
Predicted service life interval (years)	19–27	59–70

Wooldridge (2009) notes that since multiple regression allows the addition of more factors that contribute to explaining the dependent variable it is expected that more efficient models are obtained.

A study by Silva *et al.* (2013) applies multiple linear regression analysis to the prediction of the service life of current renderings. In this study, to perform this regression analysis it was necessary to quantify the qualitative variables. This quantification was based on the relationship between the overall degradation path (from which the reference service life for the whole sample was defined) and the degradation paths associated with each specific characteristic of the façades, from which the estimated service life for each characteristic is obtained. The Stepwise method was used to select and build the regression model, including only the statistically significant predictors. The authors conclude that age, exposure to humidity, the type of render and the level of protection of the façades are conditioning variables that explain a façade's degradation. The authors thus propose a mathematical function that is used to estimate the service life of this type of cladding based on these four variables, which leads to an average estimated service life of 15 years, with a standard deviation of 2.90 years and a confidence interval of ±0.57 years.

In a similar study Silva *et al.* (2012) used the same statistical tool to evaluate the service life of stone cladding. In this case they found that the conditioning variables to explain the degradation of façades are age, distance from the sea, the type of finishing, and the area of the stone plates. Based on the mathematical expression that relates the degradation of the façades with these variables the authors found an average estimated service life of 77 years, with a standard deviation of 11.21 years and a confidence interval of ±1.86 years.

Artificial neural networks are another statistical method employed in service life prediction. This statistical tool is usually an emulation of the human biological system. The networks "learn" from a series of patterns that are provided in relation to a given problem and based on data acquired are capable of predicting the behaviour of new patterns. Silva *et al.* (2013) applied this tool to the prediction of the service life of current renderings. Taking as independent variables those that were considered in the multiple linear regression analysis (age, exposure to humidity, the type of render and the level of protection of the façades) the authors determined a mathematical function produced by the neural networks that permitted the evaluation of the degradation of rendered façades. For a maximum admissible level of degradation of 20% the average estimated service life found was 17.5 years, with a standard deviation of 2.74 years and a confidence interval of ±0.90 years.

In a similar study on stone claddings Silva *et al.* (2011b) evaluated their service life using the same artificial neural networks. Once again they considered the same relevant variables as those in the multiple linear regression analysis (age, distance from the sea, the type of finishing and the area of the stone plates). Based on the mathematical function obtained through the neural networks, the authors found an average estimated service life of 80 years, with a standard deviation of 9.34 years and a confidence interval of ±3.10 years.

Table 2 shows a summary of the service lives estimated by the various statistical methods.

The life cycle of a building or its components is the period of time from when it is put into service until it reaches the end of its service life. In most codes it is considered that a current building reaches the end of its service life at 50 years. Over that period the claddings whose service life is shorter than that of the building, such as current renderings, go through various life cycles. It is assumed that each life cycle is independent of the next one, thus considering degradation as stochastic process; this means that the fact that during the first life cycle the rendering reached the end of its service life at 25 years does not mean that the new, replacement, rendering, even though subjected to the same exposure conditions, will reach the end of its service life after the same period of time.

Table 2. Summary of the service lives estimated by the various statistical methods

Service life prediction methods	External cladding solution	
	Renderings	Stone claddings
Graphical method		
Reference service life (years)	15	68
Average estimated service life (years)	17.5	66
Standard deviation (years)	5.35	8.54
95% C.I. (years)	±1.05	±1.40
Multiple linear regression		
Average estimated service life (years)	15	77
Standard deviation (years)	2.90	11.21
95% C.I. (years)	±0.57	±1.86
Artificial neural networks		
Average estimated service life (years)	17.5	80
Standard deviation (years)	2.74	9.34
95% C.I. (years)	±0.90	±3.10

To proceed to the life cycle assessment (LCA) of the claddings studied in order to evaluate the corresponding environmental impact, the estimated number of replacements over 50 years must be established. To take uncertainty into account when determining the number of replacements needed in 50 years it is assumed that the service life estimated by each method for each life cycle until replacement follows a Normal distribution. This assumption is quite often fundamental in the process of statistical inference. One of the rules used to ascertain whether a variable follows a Normal distribution is the central limit theorem, which states that the distribution of an average will tend to be Normal as the sample size increases (Barnes 1994). The central limit theorem states that the sampling distribution tends to be Normal in big samples – regardless of the shape of the data actually collected (and the sampling distribution will tend to be Normal regardless of the population distribution in samples of 30 or more), which means that the sample studied is normally distributed (Field 2008; Motulsky 1999).

The linear combination theorem shows that the sum of or difference between two or more random independent variables with Normal distribution is also a Normal random variable, thus allowing the average and standard deviation of the sample distributions to be summed. If each life cycle period until replacement follows a Normal distribution and since they are independent, the linear combination theorem is used to show that the set of the various life cycles up to 50 years also follows a Normal distribution.

In this case the sample used to predict the service life of current renderings using the graphic method and multiple linear regression analysis is composed of 100 case studies, a significantly bigger sample than needed by definition to state that the variable has a Normal distribution. For stone claddings the sample consists of 140 case studies. Based on the central limit theorem and on the size of the samples it can be considered that the service life values (SLVs) estimated by these methods follow a Normal distribution (as $n >> 30$ then one can say that SLV ~ N (μ, σ)).

For the artificial neural networks the overall sample is split into two main subsamples: the learning sample, used to learn from a set of patterns fed into the network; and the test sample, which is used to check whether the prediction model defined through the learning sample can safely be generalised. In this study the test sample for estimating the service life of stone claddings consists of only 35 case studies, and 36 case studies for current renderings. In this case it seems less reasonable to assume that the sample size is sufficient to justify adopting the hypothesis that the service life estimated by the neural networks follows a Normal distribution. Therefore, to test whether that is true, two statistical tests were performed: the Kolmogorov-Smirnov (K-S) test (Chakravarti *et al.* 1967) and the Shapiro-Wilk test (Shapiro, Wilk 1965). The K-S test was performed with the Lilliefors correction (Lilliefors 1967). For current renderings the K-S test with the Lilliefors correction yields a p-value of 0.145 and the Shapiro-Wilk test a p-value of 0.408. Conversely, for stone claddings the K-S test with the Lilliefors correction yields a p-value of 0.20 and the Shapiro-Wilk test a p-value of 0.462. This indicates that for a 5% significance level the estimated service life of both claddings follows a Normal distribution (Table 3).

The number of replacements is evaluated based on the ratio between the reference service life of the building (50 years) and the estimated service life of each of the claddings analysed, and this ratio is determined through the various methods used to predict the service life and for each case study. Based on the central limit theorem and on the size of the samples used to predict the service life of external claddings by the graphic method and multiple linear regression analysis (100 case studies of current renderings and 140 case studies of stone claddings), it can be considered that the number of replacements follows a Normal distribution. For neural networks it seems less reasonable to assume that the sample is large enough to justify adopting the hypothesis that the number of replacements follows a Normal distribution and the Kolmogorov-Smirnov (K-S) and the Shapiro-Wilk test were performed to ensure that. For current renderings the K-S test with the Lilliefors correction yields a p-value of 0.199 and the Shapiro-Wilk test a p-value of 0.109. Conversely, for stone claddings e K-S test with the Lilliefors correction yields a p-value of 0.177 and the Shapiro-Wilk test a p-value of 0.069. This indicates that for a 5% significance level the estimated service life of both cladding types follows a Normal distribution (Table 4).

There is an uncertainty associated with the determination of the service life using the statistical methods presented in Table 2. For that reason the estimated service life is presented as an average value, associated with a standard deviation and a 95% confidence interval.

Table 3. Results of the normality tests of the samples used in this study for the artificial neural networks method

Normality tests	External cladding solution	
	Renderings	Stone claddings
n (sample size)	36	35
K-S	0.145	0.20
Shapiro-Wilk	0.408	0.462

Table 4. Results of the normality tests of the samples used in this study for the artificial neural networks method

Normality tests	External cladding solution	
	Renderings	Stone claddings
n (sample size)	36	35
K-S	0.199	0.177
Shapiro-Wilk	0.109	0.069

Consequently this uncertainty will always be present when determining the number of cladding replacements in the period under analysis. Table 5 thus includes a reference value for the average number of replacements (deterministic) as well as a stochastic value that takes uncertainty into account.

2. Environmental performance of external claddings

The envelope of the building is a key element because it strongly influences its comfort, safety and aesthetics. Because it is in close contact with the environment it is constantly affected by the weather and atmospheric pollution, which can speed up the degradation rate, with likely serious implications for safety and user comfort. One of its elements, the external cladding, directly influences the thermal and environmental performance of the building envelope because of its share in the envelope's initial embodied energy and life cycle cost. External cladding is the first and outermost layer that separates the inner space from environmental agents and is therefore particularly prone to failures and defects, with direct consequences for the quality of urban space, user comfort, and repair and maintenance costs. For all these reasons and also because of the relatively long service life of buildings, both the LCA and the SLP of this building assembly are of the utmost importance (Silvestre *et al.* 2011a, b; Silvestre, Lasvaux 2012). This section of the paper explains the application of the LCA method to each cladding solution through an internationally standardised procedure (ISO 14040:2006 (2006); ISO 14044:2006 (2006)), using both the corresponding deterministic and stochastic service life.

2.1. LCA study – scope and functional unit

The LCA method considers the environmental impacts during the life cycle of a product by identifying and quantifying the environmental emissions and consumption of energy and materials (Ortiz *et al.* 2009). LCA implementation is divided into four phases according to ISO standards (ISO 14040:2006 (2006); ISO 14044:2006 (2006)): goal and scope definition, inventory analysis, impact assessment and interpretation. The first phase describes the product to be assessed, the scope of the associated system and the functional unit.

The construction of buildings differs from other industrial processes by yielding a product that: incorporates a high quantity of products and processes; has a long life-cycle; contains components that have different service lives; has a dynamic that differentiates it from other standard industrial products, in particular during the execution, use and end-of-life phases (Blok *et al.* 2007; Chevalier, LeTeno 1996; Kibert 2002). The definition of a functional unit (that is a service and not only a product) and the boundary of the assessment in LCA studies is therefore even more important, in order to lessen the sensitivity and errors of the results (Erlandsson, Borg 2003; Ozik 2006). Previous LCA studies of construction materials and buildings (Silvestre *et al.* 2011a, b; Silvestre, Lasvaux 2012) confirmed the relevance of the definition of a functional unit and of the boundary in this type of study.

Table 5. Reference and stochastic number of replacements over a 50-year period (considering that the number of replacements follows a Normal distribution)

External cladding solution	Service life prediction methods					
	Graphic method (GM)		Multiple linear regression (MLR)		Artificial neural networks (ANN)	
	Average reference number of replacements / Standard deviation	Stochastic number of replacements [μ–σ:μ+σ]	Average reference number of replacements / Standard deviation	Stochastic number of replacements [μ–σ:μ+σ]	Average reference number of replacements / Standard deviation	Stochastic number of replacements [μ–σ:μ+σ]
Renderings	3.10/0.906	[2.20: 4.01]	3.53/0.823	[2.71: 4.35]	2.93/0.476	[2.45: 3.40]
Stone claddings	0.77/0.108	[0.66: 0.88]	0.67/0.111	[0.55: 0.78]	0.64/0.079	[0.56: 0.71]

Table 6. Characteristics of each external wall cladding and the Ecoinvent system processes used in the LCA calculations

External cladding solution		Ecoinvent database system processes
Rendering and paint	Rendering – 3 cm cement mortar	Cover coat, mineral, at plant/CH
	Paint – two coats of water based paint	Alkyd paint, white, 60% in H_2O, at plant/RER
Stone	3 cm stone plate plus cement mortar and joints material	"Natural stone plate, polished, at regional storage/CH" and "cement mortar, at plant/CH" (mortar and joints material)

The characteristics of each external wall cladding compared in this study are summarised in Table 6. The functional unit of the study is "a square meter of cladding applied on the external surface of the external wall of a building during 50 years". This table also includes the Ecoinvent system processes used to model each of these cladding solutions in the LCA calculations.

2.2. Boundaries of the LCA study

The LCA calculations took into account the different stages of the life cycle for each external wall cladding solution. The operations considered in the LCA calculations that occur in each life cycle stage for each external wall cladding are summarised in Table 7.

The construction process (A4-transport to the building site and A5-installation into the building) and use stages (information modules related to the operation of the building) (B6-operational energy use and B7-operational water use) were not included in the LCA calculations because they were considered to be the same for both solutions under analysis. The maintenance actions (B2) were not included in the LCA calculations either, because it was considered that the corresponding environmental impacts are the same for both solutions under analysis (and are also negligible – e.g. cleaning with water, compared with replacement) and a similar approach was used for the B1, B3, B5, C1 and C2 stages.

The LCA from the production of each construction material ("cradle to gate" approach – stages A1–A3 in Table 7) was calculated using appropriate software (SimaPro) and available "Life cycle Inventory" (LCI) databases, in particular the "Ecoinvent database system processes" mentioned in Table 6, taking into account the European reference case and previous research works (Silvestre *et al.* 2011a, b; Silvestre, Lasvaux 2012). This database was also used to model each cladding replacement (stage B4) during the service life of the building (50 years). But each rendering and stone cladding replacement generates demolition waste. Therefore,

Table 7. Life cycle stages (taken from European standards) considered in LCA calculations for the two external wall claddings (FprEN 15804:2011 (2011))

Modules	Life-cycle stage name and description		External cladding (EC) solution	
			Rendering and paint	Stone
Product stage	A1	Raw material extraction and processing, processing of secondary material input	X	X
	A2	Transport to the manufacturer		
	A3	manufacturing		
Use stage - information modules related to the building fabric	B1	Use or application of the installed product	–	
	B2	Maintenance	Total cleaning every 5 years (but not included in LCA calculations)	
	B3	Repair	–	
	B4	Replacement	Repainting every 10 years and rendering replacement when it reaches the end of its service life	Stone cladding replacement when it reaches the end of its service life
	B5	Refurbishment	–	
End-of-life stage	C1	Deconstruction, demolition		
	C2	Transport to waste processing		
	C3	Waste processing for reuse, recovery and/or recycling		Stone (from replacement operations) crushing for reuse
	C4	Disposal	Cement plaster (from replacement operations and contaminated by paint) to landfill	
Benefits and loads beyond the system boundary	D	Reuse, recovery and/or recycling potential		Reuse of stone (from replacement operations) crushing avoids the use of natural aggregates

the environmental impacts of the "End-of-life stage" (C) and the "Benefits and loads beyond the system boundary" (stage D) were considered only for the demolition waste from the replacement operations. It was assumed for comparison purposes that in the 50th year the state of conservation of the claddings would be the same as when they were applied and the LCA of the demolition of the claddings in that year was therefore not considered (the service life of the building assumed in the design phase is 50 years but it was considered that the building does not actually reach the end of its service life in that year). This is the only approach that allows a balanced comparison of the solutions and the consideration of partial rates of replacement. In fact, using the reference number of replacements presented in Table 5 – e.g. 3.53, the parcel of 0.53 replacements is considered to mean that 53% of total sample of claddings will reach the end of their service life before or at 50 years and have to be totally replaced in order to restore the initial state of repair.

For the "End-of-life stage" (C) it was considered that the cement mortar and any paint are mixed after demolition and therefore have to be considered as undifferentiated CDW (waste code 17 09 04 – mixed construction and demolition waste (EC 2000)) and sent to landfill. The mixture of stone plates and mortars (waste code 17 01 07 – mixtures of concrete, bricks, tiles and ceramics (EC 2000)) yielded by demolishing stone cladding can be sent for "rock crushing" (with an output of 80%) to reduce the use of natural aggregates, thus generate "Benefits and loads beyond the system boundary" (stage D), which highlights that the end-of-life phase can make a positive contribution to the environmental performance of construction materials (Silvestre *et al.* 2011b).

The reference study period was set at 50 years because this is the service life considered for a building at the design stage.

2.3. LCA results using standard SLP

LCA is a procedure that aims at studying the environmental aspects and potential impacts of a product, starting with the raw materials' extraction and going on to product manufacturing, until the use and final disposal stages. In the inventory phase, all the relevant inputs and outputs of the system are identified and quantified, which requires data collection and calculation procedures. These inputs and outputs are "use of resources" (raw materials and energy) and "emissions to air, water and soil". In the impact assessment stage the results of the inventory analysis are assigned to environmental impact categories in order to provide an environmental performance of the product through an internationally standardised procedure (ISO 14040:2006 (2006); ISO 14044:2006 (2006)).

The environmental performance of the external wall solutions was compared following the LCA method (based on ISO 14040:2006 (2006) and ISO 14044:2006 (2006) international standards). This procedure allows LCA results from different studies to be compared and used to make meaningful choices (Ekvall 2005; Krigsvoll *et al.* 2007). This assessment also followed most of the principles already included in the draft standards *FprEN 15643-2:2010 Sustainability of construction works –Assessment of buildings – Part 2: Framework for the assessment of environmental performance* (2010) and *FprEN 15978:2010 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation methods* (2010), such as:

- The assessment of the environmental performance shall apply the LCA approach in accordance with the guidelines and requirements of ISO 14044:2006 (2006);
- The results of the assessments shall be organised into three main groups: impacts specific to building fabric and site (results from the product stage and from the construction process stage); impacts and aspects specific to building in operation (maintenance, repair, replacement, water and energy use and all activities with an environmental impact), and results from the end-of-life stage of the building;
- The impacts and aspects related to benefits and loads beyond the building life cycle, e.g. those that result from further reuse, recycling potential and energy recovery and other recovery operations, may be included as supplementary information. They are essential to promoting and allowing a cradle-to-cradle (C2) approach in the life-cycle of the buildings and their assemblies;
- The default value for the reference study period shall be the required service life of the building and the estimated service life of the assemblies shall take into account rules and guidance contained in the ISO standards ISO 15686-1:2000 (2000), ISO 15686-2: 2001 (2001), ISO 15686-7: 2006 (2006) and ISO 15686-8:2006 (2006).

The LCA results in six of the environmental categories defined in the European Standards specified (using an EIAM with a mid-point approach – CML 2001 version 2.05) for the cladding solutions being evaluated, and using a standard SLP, these are presented in Table 8 for cumulative stages "A1–A3 and B4" and "A1–A3, B4, C3–C4, and D". The reference value used for the service life of the two solutions was 25 years because it is the period suggested for building components in the International Standard (Table 1), which is a reference that can be, and often is, used by building designers in this area of knowledge if they want to take into account in a very simplified way the durability for both solutions (despite this not being a realistic assumption).

The results presented in Table 8 show that the consideration of standard SLP (two replacements of each solution within 50 years) leads to the choice of the rendering solution. In fact, the higher environmental impacts of the application (stages A1–A3 plus the same number of replacements – B4 stage – for both solutions) of the stone cladding (between 4.3 and 8.4 times higher than the rendering) prevent it from being an alternative, even taking the replacement operations and end-of-life of

Table 8. LCA results of each alternative using standard SLP

Environmental category	Rendering and paint		Stone	
	A1–A3 and B4	A1–A3, B4, C3–C4, and D	A1–A3 and B4/% of difference from rendering and paint	A1–A3, B4, C3–C4, and D/% of difference from rendering and paint
ADP – Abiotic Depletion Potential (kg Sb eq.)	1.27E–01	1.38E–01	6.69E–01/429%	6.63E–01/380%
AP – Acidification Potential (kg SO_2 eq.)	7.02E–02	9.27E–02	5.92E–01/743%	5.80E–01/525%
EP – Eutrophication Potential (kg PO_4^{-3} eq.)	2.20E–02	2.22E–01	2.06E–01/837%	2.06E–01/–7%
GWP – Global Warming Potential (kg CO_2 eq.)	1.59E+01	5.16E+01	1.01E+02/531%	9.93E+01/92%
ODP – Ozone layer Depletion Potential (kg CFC-11 eq.)	2.11E–06	2.37E–06	1.25E–05/491%	1.22E–05/413%
POCP – Photochemical oxidation (kg C_2H_4)	3.39E–03	1.39E–02	1.86E–02/449%	1.81E–02/30%

demolition waste into account (stages A1–A3, B4, C3–C4, and D). In fact, only in one environmental category (Eutrophication) does the rendering perform slightly worse, due to the impact of landfilling the demolition waste.

The LCA results presented in this section comply with the common approach used in building design. Therefore, it is important to analyse its consequences on the decision process and to find which other decisions and questions arise from the use of stochastic SLP instead of this approach. The next section of this paper aims to shed some light on this issue.

2.4. LCA results using stochastic SLP

The technical service life (hypothetically correct use/maintenance/replacement conditions) is normative in most LCA studies of buildings (Lassandro *et al.* 2007) and its use has a positive effect on the outcome of the LCA, because components in the calculation are in general supposed to have a longer service life than the real situation (Hendriks *et al.* 2004). Nevertheless, a more realistic forecast of the maintenance and its effect on the global and local environmental impacts of a building must also be made.

The LCA results in six environmental categories (Table 8) for the cladding solutions being evaluated and using the stochastic SLP reference value (Table 5) are presented in Figures 1 and 2 for cumulative stages "A1–A3 and B4" and "A1–A3, B4, C3–C4, and D". Each service life prediction method is identified by an acronym (GM for graphic method, MLR for multiple linear regression and ANN for artificial neural networks).

Figure 1 presents results that are similar to the ones in Table 8 for cumulative stages "A1–A3 and B4", even though the difference between the environmental performance of the rendering and stone cladding solutions decreases because a higher reference value of stochastic service life was assumed for the last solution.

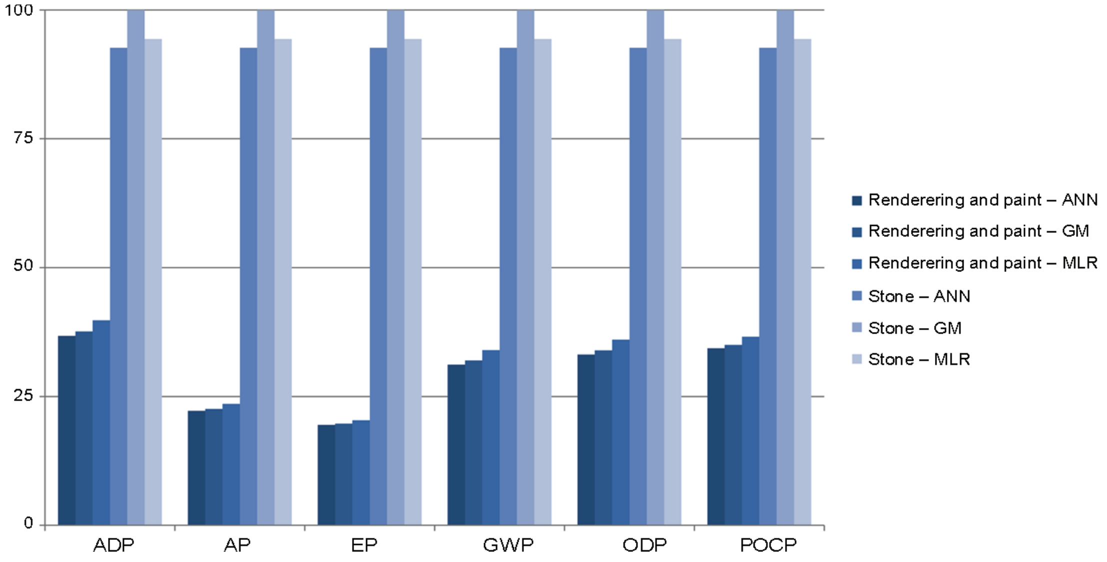

Fig. 1. LCA results (in relative percentage in each environmental category) of each alternative for cumulative stages "A1–A3 and B4" using the reference value of stochastic SLP

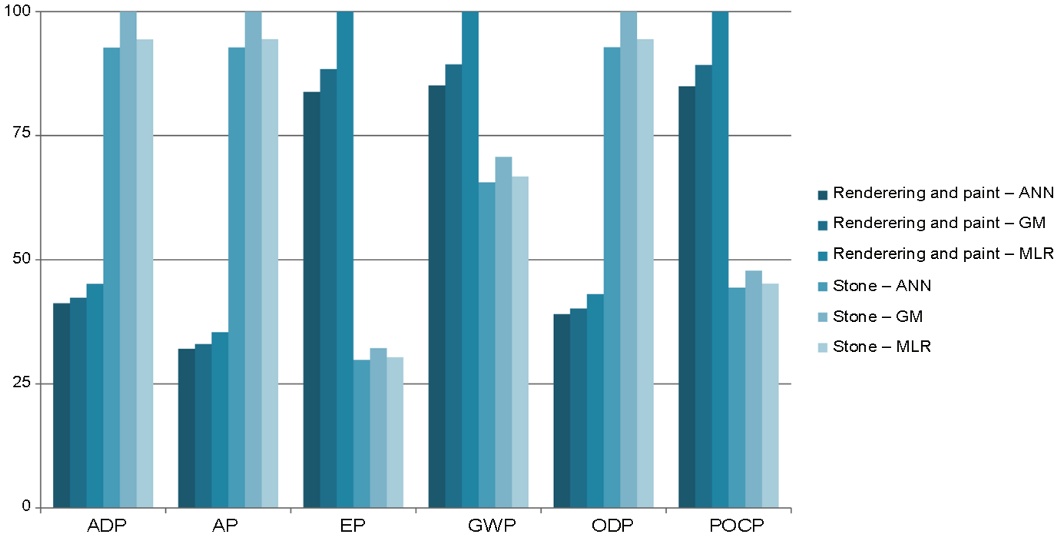

Fig. 2. LCA results (in relative percentage in each environmental category) of each alternative for cumulative stages "A1–A3, B4, C3–C4, and D" using the reference value of stochastic SLP

The LCA results presented in Figure 2 consider not only the replacement operations (B4 stage) but also the corresponding end-of-life of demolition waste (stages C3–C4, and D). Therefore, this approach led to an inversion in the preferred solution in three out of six environmental categories: EP, GWP and POCP. This is caused by the impact of landfilling the demolition waste from a greater number of rendering replacements and also by the benefits of reusing stone demolition waste as aggregate.

Figure 2 raises some questions. Maintenance operations (B4 and the corresponding end-of-life of demolition waste – C3–C4, and D) during service life are often very uncertain. But their frequency depends directly on the service life of the cladding solutions. Since this paper has already characterised the uncertainty inherent to each of the three SLP methods (and probed the possibility of using Normal distribution to model the number of replacements of each solution over a 50-year life cycle – see Section 1.2.2), these data can be used to evaluate the uncertainty of LCA calculations. In fact, it is possible to apply Monte Carlo analysis in SimaPro software (and only using "system processes" from Ecoinvent to avoid including uncertainty in parameters other than SLP), which is a statistical approach that incorporates parameter uncertainty to compare solutions that are not correlated (Jolliet *et al.* 2010). This approach can be completed in five steps (Heijungs *et al.* 2008):

1. Define the number of replacements as a stochastic variable with a specified probability distribution – Normal – and corresponding parameters (average values and standard deviations presented in Table 5 for each SLP method and cladding solution);
2. Build the LCA-model with one specific realisation of every stochastic parameter;
3. Determine the LCA-results with this particular realisation;
4. Repeat this for a large number of realisations – e.g. N (number of runs) = 1000;
5. Investigate statistical properties of the sample of LCA-results – e.g. the mean, the standard deviation, the confidence interval, or the distribution.

In each iteration of the Monte Carlo analysis, the number of replacements of each cladding solution is randomly selected according to the corresponding distribution. Then the LCA is recalculated for each cladding solution and the difference between one result and the other is stored. After 1000 runs the distribution of results is plotted. Conclusions can be drawn from this plot but if there are more than 10% of contradictory runs the results are considered too uncertain to draw conclusions.

It is important to highlight that, in each iteration, the solutions are held to be mutually independent because they are considered to be exposed to the same average conditions (which are reflected in the expected service life and standard deviation). However, the causes related to the application or quality of materials can lead to a longer or shorter service life of each solution in each iteration, but those are inherent to each solution and therefore not intercorrelated.

A Monte-Carlo analysis was used to evaluate the uncertainty of the LCA results presented in Figure 2 and the results are in Table 9. In at least one environmental category (GWP, which is one of the most-often used internationally) this approach can provide an improved understanding of the differences between alternatives. It can also test their similarity because the analysis of the results achieved using the reference value of stochastic SLP is not sufficiently clear, because it does not consider the uncertainty of this parameter.

The results presented in Table 9 provide a better understanding of the relative environmental performance in every category of the solutions under analy-

Table 9. Monte-Carlo analysis of the LCA results (for each environmental category) for cumulative stages "A1–A3, B4, C3–C4, and D" using stochastic SLP

Environmental categories	ADP			AP			EP			GWP			ODP			POCP		
SLP methods	ANN	GM	MLR	ANN	GM	MLR	ANN	GM	MLR	ANN	GM	MLR	ANN	GM	MLR	ANN	GM	MLR
Percentage of the 1000 runs when stone claddings have a better performance	0	0	0	0	0	0	100	98.7	99.7	93.8	*79.9*	92.1	0	0	0	99.9	96	99.5

Table 10. Overview of the increasing level of complexity in the combined use of statistical models for SLP and LCA of building assemblies, the external cladding solution that offers the better environmental performance and the design choice

Increasing level of complexity	SLP method	Type of SLP method	Life cycle stages considered (Table 7)	LCA method	Best environmental performance	Design choice
1	ISO 15686-2:2001 (Table 1)	Standard	A1–A3	Deterministic (Table 8)	Render and paint	Render and paint
2			A1–A3, B4			
3			A1–A3, B4, C3–C4, D			
4	Reference value of stochastic SLP (Table 5)	ANN GM MLR	A1–A3	Deterministic (Figs 1 and 2)		
5			A1–A3, B4			
6			A1–A3, B4, C3–C4, D		Depends on the environmental category	Depends on weighting factor or BEAS
7	Stochastic SLP with probabilistic distribution (Table 5)			Stochastic using Monte-Carlo analysis (Table 9)		Depends on weighting factor or BEAS or design stage

sis. In fact, the difference between the environmental impacts of stone claddings and renderings is negative in more than 90% of the runs for EP and POCP (using any SLP method) and is always positive for ADP, AP and ODP. Therefore, it can be concluded that stone claddings have a worst environmental performance than renderings in these three last categories but have a better one in EP and POCP. But a Monte-Carlo analysis does not definitively identify the solution that performs better environmentally in the GWP category. The answer obtained by the Normal distribution defined according to the GM method is similar to the one given by the other two SLP methods, but it yields more than 10% of contradictory runs (20%). Therefore, the results for GWP using the GM method are considered too uncertain to enable conclusions to be drawn, while the results achieved using the ANN or MLR methods indicate a better environmental performance of stone claddings in this category but with a number of contradictory runs near 10%. From these results it can be taken that stone claddings also perform better in the GWP environmental category (the only result below 90% was achieved using the GM method, for which the number of replacements is maximum for stone claddings and the standard deviation is maximum for renderings, within the different SLP methods – see Table 5), and therefore each cladding solution is preferred in three out of six environmental categories. This conclusion can only lead to a final decision by the designer if weighting factors are associated with each environmental category, especially under a national regulation or a voluntary building environmental assessment system (BEAS). In fact, weighting factors and the specific assessment method are of the utmost importance for LCA results because a different method may lead to a different outcome.

Table 10 provides an overview of the different levels of complexity that characterise the combined use of statistical models in the SLP and LCA of building assemblies and it shows the external cladding solution that offers the better environmental performance according to the results of each approach and the relevant design choice.

According to Table 10, the choice of wall cladding can also depend on the design stage, when the decision process is quite uncertain. At the final design stage, for instance, there is less uncertainty about the type of material to be used (it has indeed already been chosen), the maintenance procedures that will be put into practice during the building's service life and the level of demand of the building owner/users (they are already known and are also interrelated). A higher level of demand, for example, can lead the designer to use a higher reference value for the number of replacements in LCA calculations than the values presented in Table 5.

Conclusions

Modelling the uncertainty associated with each of the SLP methods selected allowed the uncertainty associated with the service life of each cladding solution to be estimated. Therefore, an SLP method (with uncertainty modelled) for building assemblies is proposed in this paper.

The service life considered for each element of buildings can have a bigger influence on LCA results than the characteristics of their components. In fact, the question of a building's service lifespan is critical in LCA studies where just a few grams of material may cause an enormous environmental burden (Hendriks *et al.* 2004). Construction, disposal and deconstruction are processes that can be generally traced and described to calculate environmental impacts, whereas the building's use, maintenance and management are characterised by the utmost variability. These stages involve other variables that are totally unpredictable and hard to define because they depend on decisions about building operation and maintenance scheduling, thus creating limitations to the actual reliability of LCA studies. Therefore, only a thorough interdisciplinary study of the interrelation between the service life prediction (SLP) and LCA of buildings or building elements permits the characterisation of the dependence between their durability and environmental impacts along the entire life cycle. The importance of this interrelation is increasing, largely because of several research studies that compare different options based on their service life or environmental performance (Nunen 2010).

The results of the LCA study presented in this paper include a standard, a deterministic and a stochastic evaluation of the environmental performance of each cladding solution for external wall. These results are compared, including a thorough analysis of their consequences for the choice made by the designer at an early stage of the building project and a forecast of the changes that can be made to the decision later in design stage. The deterministic and stochastic environmental performances of the wall cladding solutions under analysis were also compared to ascertain the relative advantages and disadvantages of these approaches and the influence of the uncertainty modelling in the environmental ranking of the solutions studied. This ranking provides a basis for decision-making under (modelled) uncertainty while reducing the risk of the decisions made at the design stage.

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