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Changing Needs, Adaptive Buildings, Smart Cities

Volume 1

- Analytical, Experimental Research Results.
- Building Design Analytical Behaviour Presentations.
- Critical Reviews.
- Methods, Methodologies.
- Product-Oriented, Process-Oriented Design and Applications.

Edited by

Oktay URAL
Emilio PIZZI
Sergio CROCE

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CONTENTS

EVOLVED FACTOR METHOD FOR SERVICE LIFE PREDICTION OF BUILDING COMPONENTS

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Keywords: Factor Method; Durability; Service Life; Log-Normal Function; Probability Distribution Function.

Abstract

Key issues in the production processes associated with construction are the implementation of quality and sustainability principles. Indeed, it is increasingly important for the maintenance of quality levels provided by materials, components and building structures, especially after the recent Regulation (EU) No.305/2011. This document introduced the seventh requirement for the sustainable use of natural resources, guaranteeing the durability of construction products, thus it has to be planned. The international standard for the assessment of durability of building materials and components is the ISO 15686 – Buildings and Constructed Assets – Service Life Planning, Providing the definition of the Reference Service Life (RSL) and identifying the procedures for the estimation of the Estimated Service Life (ESL), by means of three possible approaches: factor method, engineering methods and stochastic methods. The factor method (ISO 15686-8:2008) is the easiest to implement, but it lacks of subjectivity, possibly limited by the use of suitable performance grids, specific for each building component. This research work suggests an evolution of the method in semi-probabilistic way, well-known as 'evolved factor method', based on the substitution of each deterministic value of the factor, proposed by the ISO, with a probability distribution function, in order to obtain a probability distribution function of the ESL. In particular, it is proposed to replace the multiplicity of functions with the use of the log-normal distribution function, as appropriate to model the phenomena where the random variables are multiplied with each other, simplifying the calculation of the ESL. The proposed solution was validated by the application to the example in the ISO 15686-1:2000, leading to consistent results with those of the standard and of other similar reported studies, based on modifying solutions of the evolved factor method.

1. Introduction

The current environment's needs and the growing competition in the productive sector impose a rational use of resources in the construction process and the implementation of quality and sustainability principles[1]. In this context, where the demand for raw materials and energy is growing, it is paramount to maintain over time the expected high levels of quality for materials, components, building elements and structures. The international reference standard for the evaluation of the durability of materials and building components is the ISO 15686 standard, introducing the Reference Service Life (RSL) and identifying the procedures to evaluate the Estimated Service Life (ESL). The RSL defines the service life of a building component in a certain set of in-use conditions, by artificial and natural aging tests and/or statistical analysis and data given by manufacturers. The ESL is referred to the real context of use and stress with three proposed approaches: factor method, stochastic method and engineering method. In the factor method, the ESL is calculated as the value of the RSL

1 The EU Regulation No.305/2011 introduced the seventh requirement on the sustainable use of natural resources and the durability in construction.

multiplied by seven factors, considering the specific context of use. To support to the factor method and to reduce high subjectivity, performance grids are used to calculate the values of the different factors. Calculating the ESL, according to ISO 15686 and the UNI 11156:2006[2] standards, requires the availability of RSL data collection. An international database of RSL is being defined, in collaboration between the DBCG (Durability of Building Components Group) of the Politecnico di Milano and the CSTB (Centre Scientifique et Technique du Batiment) of Grenoble [3], where useful data for the evaluation of the service life are collected, selected and formatted (ISO 15686-8). In the evaluation of the durability of building components, in Italy, the Durability Network [7] carries out intense research activities[3], allowing the establishment of the UNI 11156.

2. The ISO 15686-8:2008 Standard and the Factor Method

The ISO 15686-8:2008 provides guidelines for the RSL recruitment, selection, data formatting and their use in the calculation of ESL by the factor method. The application of the factor method is based on the evaluation of the degradation effects by means of multiplication factors that may be expressed by functions representing probability distributions. Thus, the ESL will be described by a probability distribution function, expressing years, plus/minus a confidence interval, representing the uncertainty in the determination of the ESL. The ESL, being the middle value, is calculated by the following expression:

$$ESL = RSL * A * B * C * D * E * F * G \quad [1]$$

The several correction factors, considering the quality of in-use and stress conditions of the building component, are generally variable between 0.8 and 1.2 (1 for standard conditions) and refer to (Table 1):

- Degradation agents related to the intrinsic quality of the component (A, B, C).
- Environment (D, E).
- Use (F, G).

Table 1: The multiplicative factors (ISO 15686:2008 and UNI 11156:3).

Agents			Example of relevant conditions
Intrinsic quality	A	Quality of components	Performance characteristics, fabrication, storage, transportation, etc.
	B	Design level	Protection degree, materials' characteristics, physical-chemical compatibility, etc.
	C	Work execution level	Quality of manpower, weather conditions during installation, etc.
Environment	D	Indoor environment	Environment aggressiveness, ventilation, condensation, etc.
	E	Outdoor environment	Building height, micro-climate, etc.
Use	F	In-use conditions	Mechanical impacts, type of user, etc.
	G	Maintenance level	Maintenance quality and frequency, accessibility, inspection, cleanability, etc.

2 This standard was implemented by the Italian commission UNI-GL15 'Assessment of the durability of building components', basing on the previous experience of the ISO commission

3 The research was coordinated by prof. Pietro Natale Maggi and prof. Bruno Daniotti, Politecnico di Milano, with the contribution of the Politecnico di Milano and Politecnico di Torino and the Universities of Palermo, Naples, Catania and Brescia, being funded by the Ministry of University in 2003.

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Higher or lower values can be assigned, based on specific situations, as well as each factor can weigh differently based on the significance of the phenomenon expressed by the factor itself. However, the factor method, quite simple in its application, provides values characterized by strong subjectivity in the scoring of each corrective factor, leading to significant variations in the estimation of duration [4]. In order to limit this subjectivity and make it more suitable to express the complexity of the aging phenomena of the building components, several studies proposed the evolution in terms of semi-probabilistic method, defining the 'evolved factor method'. This is based on replacing the deterministic value of the factors, proposed by the ISO procedure, by probability distribution functions to obtain a probability distribution of the ESL. In the last decade, some authors proposed performance grids or factors' grids, as simple tools to help designers to the correct allocation of the values to the factors.

3. The Factors' Grids and the Reference Service Life Database

This branch of research studies the subdivision of each factor in sub-factors, as defining performance grids, constituting a useful support for the designers to estimate the value of the factor. This approach involves the use of reference standards or widespread design procedures to assign the values to the sub-factors. The methodology to define the guide-grids of a building component, by the identification of sub-factors, is based on the identification of factors affecting the service life, by the agent-action-effect analysis [2]. The identification of the degradation agents to which the technical component will be presumably subjected during its service life, is based on the ISO 6241:1984. It follows the identification of the actions induced by these agents and finally the definition of potential effects, not mentioning those agents characterized by low intensity, but with a cycle and/or duration producing critical effects in time. These effects will result into measurable parameters by standardized methods, leading to the definition of each sub-factor and then the assignment of the related values by performance analysis of the technical component. These issues can be translated into factors' grids for the evaluation of the sub-factors, each representing a function or performance class, by which it is possible to obtain the value of the sub-factor to be applied. This procedure is difficult to follow, and therefore should be performed by experts and producers of the technical component under evaluation.
All the factors' grids are characterized by:

- The Zero Value is Generally Assigned to the Reference Class of Performance.
- Monotone Functions (Increasing or Decreasing).
- The Confidence Interval, Conventionally, Varies Between -5 And +5.
- Once defined the 'n' sub-factors, the assignment of the weight of each sub-factor follows, based on considerations accounting for the environment, conditions of use, users, etc. In order to relate each sub-factor to the other, the method provides the use of pair-wise comparison matrices, allowing the determination of the equivalence between the factors and/or the priority of one on the others. By the sum of the scores obtained by each sub-factor, the ranking of the sub-factors is obtained, and then translated into a scale from 0 to 1.

4. The Evolved Factor Method

Recent studies provided substantial contributions to the development of the factor method [5]. In accordance with the ISO 15686 standard, the assessment of the service life of the building component can be based on two different approaches:

- Deterministic approach, assuming fixed values preferably in the range of 0.8÷1.2 (ISO 15686-8).

- Probabilistic or stochastic approach, providing the factors being expressed by probability functions.

The evolved factor method proposes, for each factor, an estimate by defining a probability distribution of values, allowing a better description of the uncertainty of the input data, while maintaining the ease of application of the factor method and a greater adherence to the description of the real phenomena. In 1999, Aarseth and Hovde [1] proposed to adopt a statistical approach to the calculation of the individual factors. The principle of 'step-by-step' is introduced into the factor method, as a systematic approach to the design, based on the contributions from various experts (designers, sociologists, psychologists, pedagogues, etc.) coordinated by a moderator (Delphi method). In the first instance, the value of each multiplication factor is identified by a triple estimate, by determining the minimum value, l, the maximum value, h, and the expected value, m, not necessarily coinciding with the statistical expected value, f. The function of Erlang, with k = 10, is chosen as density function, to give a reasonably valid statistical representation of the triple estimate (Figure 1).

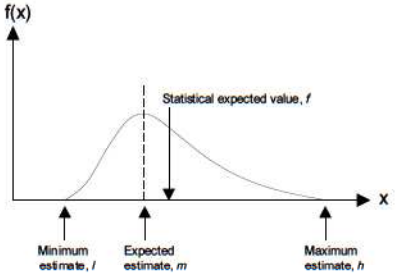

Figure 1. The function of Erlang describing the value distribution of each factor [1].

The statistical expected value, *f*, and the standard deviation, σ, are calculated by the formulas:

$$f = (l + 2.95m + h)/4.95 \quad [2]$$

$$ó = (h - l)/4.6 \quad [3]$$

The first coefficient, *f*, is multiplied to the given RSL, thus giving the value of ESL plus/minus the confidence interval, σ. The sum of the probability density functions is, thus, a normal distribution, in accordance with the central limit theorem, stating that the standardized sum of independent random variables tends to be distributed as a standard normal random variable. This method, based on the conversion of the value of the factors into years, is better suited to evaluate the changes induced by each factor on the ESL. Moser and Edvardsen [8] almost simultaneously emphasized the importance of a multidisciplinary approach to the estimation of the factors and in accordance with Aarseth and Hovde, proposed to submit to a group of experts, based on their professionalism, the choice for each factor of the most suitable density distribution function (normal, log-normal, Gumbel, etc.). For each function taken into account, instead of the minimum, maximum and expected values, they defined the minimum fractile (5% or 10%), the medium fractile (50%) and the maximum fractile (90% or 95%). Each factor is associated with the more representative function and a Monte Carlo simulation is performed. The result is a density function of the estimated service life. Re Cecconi [9] proposes the use of triangular probability distribution functions characterized by the most probable value and by a confidence interval identified by a minimum value and a maximum value. The calculation equation is then carried out automatically with the aid of the 'Service Life Planning Tool' (SLPT) software, elaborating on a probabilistic base, by means of Mon-

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te Carlo simulation, the input data in order to obtain a probability distribution of the ESL. The possibility of using specific software for the calculation of the service life constitutes a further advantage of using this method. Listerud et al. [6] proposed the use of a simplified method based on the β distribution function, obtaining the same results of the Monte Carlo simulation, in the particular application, for the evaluation of the ESL, of oak heartwood cladding panels. On the basis of these studies, the ISO/PDTS 15686-4[4] draft document was drawn up, dealing with the evaluation of the data needed to determining the ESL, related to the whole or part of the building, through various methods including the factor one. The procedure is based, according to the evolved factor method, on distribution functions of density. Each factor is expressed by a triple estimate based on *l* = the lower limit (eg the fractile of 5%); *h* = the upper limit (eg the 95% fractile); *m* = the most expected value. For each factor the expected statistical value, f, and the standard deviation, σ, are calculated by the equation of Erlang, obtaining an elaboration of the two functions, f and σ, slightly different from the previously analysed:

$f = (l + 4m + h)/6$ [4]
$ó = (h - l)/6$ [5]

The product of the triple estimates is calculated using the Monte Carlo simulation, giving as final output a probability distribution curve, from which deriving the average value and the standard deviation, leaving the choice of the best distribution function to the involved experts (Delphi method). The final formula is:

ESL = RSL x (average value ± the standard deviation of the simulation SDS) [6]

5. The Methodological Proposal

This study was geared towards:

- The identification of distribution functions to be assigned to different multiplication factors, being effective to general building components;
- The identification of the functions for calculating the statistical expected value, *f*, and the standard deviation, σ ;
- The possibility of simplifying the calculation of the factorial equation, including a change in the traditional formula and also avoiding the use of monte carlo simulation.

For this purpose, the proposal consists of the using the function of log-normal distribution for all the multiplying factors (already used by Moser, but only for the modelling of factors D and E and the result of the product of the distribution functions) as:

- Suitable to model phenomena in which the random variables are multiplicative factors each other independent, according to the central limit theorem.
- The linearization of the phenomena linked to the factors making the expected statistical value tends to the centre of the confidence interval, thus giving relatively more weight to the estimated fractiles.
- This choice simplifies the solution of the equation;
- The use of the Monte Carlo method can be avoided by simplifying the application, although this is independent from the choice of the log-normal function.

Furthermore, the choice of fractiles, simplified with the aid of the factors' grids, is not limited

4 Buildings and constructed assets – Service life planning. Part 4: Data requirements, in phase of discussion in the ISO TC 59, SC 14 e WG 3 commissions by 2003 and not yet a standard.

only to a range of values (5% -95%), but varies for each single factor (10%-90% or 20-80%), as a function of its uncertainty in the calculation of the ESL. The Estimated Service Life becomes a random variable, calculated by the sum of several random variables, comprising the multiplication factors of the equation of the factor method, transformed by log-normal function. Once established the distribution function, modelling the random variables (log-normal function), the 'linearization' is applied, through the introduction of the expected statistical value, *f*, and the standard deviation, σ. This function transforms each random variable in units of time, as to make possible the sum of random variables, having different distributions. The result of the calculation is the expected statistical value, *f*, representing the service life (average) and the standard deviation, σ, representing the dispersion index of the random variable. Therefore, the distribution curve (Figure 2) identifies the average service life of the analysed component. The log-normal transformation linearizes the phenomena represented by the factors and causes a (modest) 'shift' of the expected statistical value, describing the input data to the centre of the confidence interval, giving more weight to the estimated fractiles, making the random variables homogeneous and also able to be summed. The variable Y can be modelled as log-normal function, being the product of many independent random variables and positive:

$Y = X_1 * X_2 * X_3 * X_4 * X_5 * X_6 * X_7$ [7]
$\log Y = \log X_1 + \log X_2 + \log X_3 + \log X_4 + \log X_5 + \log X_6 + \log X_7$ [8]

There will be substantially three expert judgments for each factor and relative to the average value (*c*), the minimum value (*l*) and the maximum value (*u*). The average value transformed ($\mu = \log c$) and the standard deviation (σ), through the log-normal transformation, will be calculated.

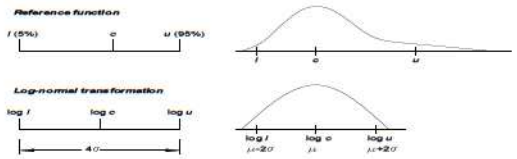

Figure 2. The representation of the reference and the log-normal transformation functions.

The equation of the factor method becomes:

$\log ESL = \log RSL + \Sigma_{i=1\text{-}7} \log c_i$ [9]
$\mu_i = \log U_i + 2\log C_i + \log L_i$ [10]
$(\log ESL)_{l,u} = \log RSL + \Sigma_{i=1\text{-}7}\, \mu_i \pm 2\sqrt{\Sigma_{i=1\text{-}7}\, \sigma_i^2}$ [11]
σi = (logUi - logLi)/4 [12]

The statistical expected value is:

$\mu_i = (\log U_i + 2\log C_i + \log L_i)/4$ [13]

taking into account the maximum and minimum values:

$\mu_i = (\log U_i + \log L_i)/2$ [14]

resulting in the center of the confidence interval, and the coefficient:

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$\mu_i = logc_i/2$ [15]

taking into account the average value, c_i, thus considering the influence of the estimated fractiles and the average value.

6. The Validation of the Proposed Method

The method described was applied to the example within the ISO 15686 standard, particularly relating to the South façade, and the results obtained were compared with those of the proposals of Moser & Edvardsen and Re Cecconi, obtaining comparable values (Table 2).

Table 2: The calculation of ESL according to the ISO 15686 and the three proposals of evolved factor method.

	Moser Proposal		Re Cecconi Proposal	ISO DIS 15686-4 Method	Proposed Method
Factor	Distribution function	m and s values	min/mean/max	f and s values	μ and σ values
A	Normal	1.5/0.185	1.2/1.5/1.8	1.5/0.1	0.1717/0.0440
B	Deterministic	1.20	1.20	1.20	0.0792/0
C	Gumbel	1.25/0.10	1.0/1.2/1.5	1.2167/0.0833	0.0836/0.0440
D	Log-normal	1.05/0.10	0.9/1.0/1.2	1.0167/0.050	0.0084/0.0312
E	Log-normal	1.05/0.20	0.8/1.0/1.3	1.0167/0.0833	0.0043/0.0527
F	Normal	1.0/0.12	0.8/1.0/1.2	1/0.0667	-0.0044/0.0440
G	Normal	1.0/0.06	0.9/1,0/1.1	0.9833/0.0500	-0.0011/0.0218
ESL	Log-normal	62.00 ± 20.40	59.28 ±11.40[5]	55.61 ± 8.91[5]	54.89
ESL+ SDS					87.08
ESL - SDS					34.60

Figure 3 shows, in logarithmic scale, the curve5 representing the distribution function and the obtained results.

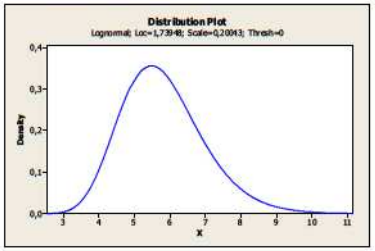

Figure 3: The distribution function of ESL in logarithmic scale.

$log\ ESL = logRSL + \Sigma_{i=1-7}\ logc_i = 1.74$ [16]

$2\sqrt{\Sigma_{i=1-7}\ \sigma_i^2} = 0.2$ [17]

Varying the fractiles according to different range of values, the ESL was recalculated (Table 3).

5 Implementations were made by software Minitab 15®.

Table 3: The values of ESL modifying the range of the fractiles.

Fractiles (5% - 95%)	Fractiles (10% - 90%)	Fractiles (15% - 85%)	Fractiles (20% - 80%)
ESL = 54.8	ESL = 55.5	ESL = 56.1	ESL = 56.5
ESL+SDS = 87.1	ESL+SDS = 83.6	ESL+SDS = 80.1	ESL+SDS = 76.7
ESL-SDS = 34.6	ESL-SDS = 36.9	ESL-SDS = 39.2	ESL-SDS = 41.6

7. Conclusion

The results obtained provide an average value for the ESL of 55 years, but a wider value of standard deviation than the other methods tested, although the average value of ESL remains significantly close to the others. The increased width of the range of values expressed by the standard deviation is due to the use of the log-normal function, giving more weight to the intervals of the input data compared to the other hypotheses. The final results show the possibility to vary the confidence intervals, taking into account the different levels of uncertainty associated with each multiplication factor, without a substantial loss of precision of the data output, in fact, the value of ESL remains close to those obtained in previous literature. The use of the factors' grids, helping the choice of the values of the triple estimates, before the calculation of ESL, and the choice of a simplified function, essentially requiring the use of a spread sheet, do not substantially modify the average value of ESL. Finally, the proposal may represent a contribution to the simplification, in the direction of the initial formulation of the factor method, both in the identification of the input data, as in the actual calculation of the ESL values.

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