CIB W080

Prediction of Service Life of Building Materials & Components

Publication 421

International Council
for Research and Innovation
in Building and Construction

CIB W080

Report prepared by CIB W080 - Prediction of Service Life of Building Materials & Components

Edited by:

Jorge de Brito and Ana Silva

Instituto Superior Técnico, University of Lisbon

Task Group

The factor method as a general framework for service life prediction

Past and future trends

July 2021

The factor method as a general framework for service life prediction: Past and future trends

CIB W080 - Prediction of Service Life of Building Materials & Components

Acknowledgements

This report was developed over the course of the 2017-2021 work programme of the CIB W080 Commission - *Prediction of Service Life of Building Materials and Components*. The editors of this report would like to acknowledge the valuable contribution of the colleagues within the Task Group who made contributions. The report had the collaboration of several members, from various universities and research centres, namely from the University of Lisbon (Portugal), the University College London and Whole Life Ltd. London (UK), Tampere University (Finland), BRANZ (New Zealand), Austral University of Chile, University of Brasília (Brazil), Politecnico di Milano (Italy) and McDuling Consulting Pty Ltd. (Australia). The editors are also grateful to the colleagues that offered suggestions, assisted in the review of the documents, and as well to those who helped prepare the final version of this report.

The factor method as a general framework for service life prediction: Past and future trends

CIB W080 - Prediction of Service Life of Building Materials & Components

Table of contents

1. Introduction

***Jorge de Brito and Ana Silva; University of Lisbon* ……………………………………………… 3**

2. The origin of the factor method

***Kathryn Bourke; University College London and Whole Life Ltd. London*……………………… 5**

3. Methodology for modelling the service life prediction using the factor method

3.1. The factor method in Finnish concrete codes

***Arto Köliö; Tampere University*………………………………………………………………. 16**

3.2. Materials testing in the estimation of a reference service life

***Catherine L. Nicholson; BRANZ*……………………………………………………………….. 22**

3.3.Application of factor method, encompassing the real degradation condition of the building component under analysis

***Ana Silva, Jorge de Brito and Pedro Lima Gaspar; University of Lisbon* ………………………… 27**

4. Current applications of the factor method

4.1. Service life prediction of buildings' envelope in Portugal

***Ana Silva, Jorge de Brito and Pedro Lima Gaspar; University of Lisbon* ………………………… 34**

4.2.Service life prediction of claddings in South America

***Ana Silva, Andrés J. Prieto and Jéssica Souza; University of Lisbon, Pontificia Universidad Católica de Chile, and University of Brasília*…………………………………………………………………… 44**

4.3.Service life prediction of existing concrete structures: feedback from practice

***Arto Köliö, Tampere University*………………………………………………………………. 52**

5. New trends for the factor method

5.1. Enhancing the factor method - suggestions to avoid subjectivity

***Fulvio Re Cecconi; Politecnico di Milano*…………………………………………………..... 58**

5.2.Artificial intelligence models for the quantification of the durability factors

***Johann McDuling; McDuling Consulting Pty Ltd.*………………………………………………… 69**

5.3.Stochastic approach to the factor method

***Ana Silva, Jorge de Brito and Pedro Lima Gaspar; University of Lisbon*………………………… 78**

The factor method as a general framework for service life prediction: Past and future trends

CIB W080 - Prediction of Service Life of Building Materials & Components

1. Introduction

The mission of the CIB W080 commission is to help to develop the necessary guides, methods, and techniques for the service life prediction of building materials and components. The commission encourages the international cooperation and information exchange in building and construction research and innovation. CIB is engaged in the scientific, technical, economic, and social domains related to the durability of construction, enabling practitioners with relevant information and tools for an adequate service life prediction, supporting improvements in the building process and the performance of the built environment.

Considerable work has been developed in the service life prediction of building and components. This report addresses the application of the factor method as a general framework for service life prediction. This method has been initially suggested by the Architectural Institute of Japan, in 1993, and later adopted in the ISO 15686: 2011, as a standard tool for the service life prediction of components.

The factor method is a simple and practical tool, easily applicable by practitioners in real-world situations. Despite being subjected to criticism, due to the simplistic way in which it addresses the degradation and service life of buildings, the factor method is seen as a methodology that provides relevant information, when more accurate scientific methods are not available.

The report discusses the application of the factor method as a general framework for service life prediction, analysing the past and future trends. It is divided in four parts:

I. First, the origin of the factor method is analysed, describing the first steps and key source documents developed for the creation of the factor method as a general framework for service life prediction;

II. The second part addresses the methodology for modelling the service life prediction using the factor method, discussing three relevant steps:
   a. The importance of an adequate quantification of the modifying factors;
   b. The relevance of the estimation of the reference service life, and the adoption of material testing or real life data; and
   c. The development of tools to consider the real degradation condition of the building component under analysis, in the estimations of the factor method, in order to provide more reliable results;

III. The third part describes current application of the factor method, namely in Portugal, in South America and in Finland, showing different approaches to different components in different climatic contexts;

IV. The fourth part presents the new trends for the application of the factor method. This part essentially discusses the application of probabilistic tools and artificial intelligent methods to enhancing the factor method, intending to avoid the subjectivity in the quantification of the durability factors and in the estimated service life of buildings and components.

The factor method as a general framework for service life prediction: Past and future trends

CIB W080 - Prediction of Service Life of Building Materials & Components

Each chapter provides a literature review and an assessment of the current state-of-the-art related with the application of the factor method as a tool for service life prediction. Different examples are provided related to the application of the factor method, using input data related with the actual degradation of different building components.

This report is a compendium of technical and practical information on service life prediction. It provides a helpful background information on the origin and utility of the factor method, offering a guide and practical approaches for the application of the factor method for the service life prediction of buildings and components.

Chair/Co-coordinator of CIB W080,
Jorge de Brito

Secretary of CIB W080,
Ana Silva

The factor method as a general framework for service life prediction: Past and future trends

CIB W080 - Prediction of Service Life of Building Materials & Components

2. The origin of the factor method

Kathryn Bourke; University College London and Whole Life Ltd. London

2.1. Introduction to the Factor Method and its data sources

ISO 15686-1: 2000 - the General Principles part of the ISO series of standards was published in September 2000 and included within it in Section 9 the Factor Method for Estimating Service Life. Its purpose was described as being to 'allow an estimate of a service life to be made for a particular component or assembly in specific conditions'. It was distinguished from service life prediction based on exposure and performance evaluation in Section 8 of the standard, but both were methods of undertaking a service life forecast - described in Section 5.2 as the primary objective of service life planning. A forecast was intended to assure, so far as possible, that the estimated service life of the building or component would meet or exceed the design life.

The Bibliography at the end of ISO 15686-1: 2000 made it clear that service life planning generally was grounded in RILEM Technical Recommendation 64, its forerunners including the Systematic Methodology for service life prediction of buildings materials and components (Masters and Brandt, 1989), and the associated work of CIB W080 / RILEM TSL 175 on Service Life Methodologies. The Factor Method contributed to the papers produced by CIB W080 in the period between the creation of the joint committee in 1996 and the publication of the State-of-the-Art Reports on Service Life Methodologies in 2004 (CIB report 294). One objective of the joint committee was to facilitate and develop the pre-standardisation activities in support of the work within the ISO 15686 series of standards, and work was underway across various countries, which fed into the formal outputs of the joint committee. These papers were collated in the proceedings of the 7th Durability of Building Materials and Components conference in 1996 (Sjöström, 1996).

The Factor Method was first published in a Building Research Establishment Laboratory Report in 1997 (Bourke and Davies, 1997). The introduction by Dr Roger Browne, who chaired the Ad Hoc Group of TC59 and subsequently ISO TC9/SC3/WG9 indicated that the purpose of the discussion paper, and its contribution to Part 1 of the ISO Standard then in preparation, was that it should 'enable the designer to handle performance data on products and components in this process for his particular structure'. It reflected work done in 1995, but only published later so that it could be made available to the international experts working on the range of durability related standards, symposia, and workshops.

So, what were the key data sources, the particular circumstances and varied efforts internationally and particularly within the United Kingdom that gave rise to the Factor Method, and how did they influence it and its future role as one of the main approaches used within the construction industry for service life estimation?

The discussion presented in the next sections will not deal with the various commentaries and critiques of the Factor Method, or its academic evolution and challenge, but confine itself to the industry applications.

2.1.1. Key Source Documents

The Factor Method of ISO 15686 drew upon three main sources or originating documents - each of which was based on experiential approaches to estimating durability. These were:

- The Architectural Institute of Japan (AIJ, 1993) Principal Guide for Service Life Planning of Buildings 1993 -herein referred to as the AIJ Principal Guide;
- The HAPM Component Life Manual (1992) - referred to in this paper as the HAPM Manual;
- BCIS 1st edition of Life Expectations of Building Components: Preliminary Results from a Survey of Building Surveyors Views (RICS, 1992) - referred to in this paper as the RICS Survey as BCIS is a trading company within the Royal Institution of Chartered Surveyors.

It is important to note that though these data sources were the originating documents, they all rested on experiential assessments of performance and durability by experienced practitioners in each domain.

2.1.2. Overview of the AIJ Principal Guide

The AIJ Principal Guide was perhaps the strongest source for the Factor Method approach, as it included numerous examples of calculations which broadly followed the approach advocated by the Factor Method. The Introduction gives the background to this document. The AIJ Durability sub-committee revised the Building Code in 1983 to assign new duties for preparing a building maintenance plan to the owners or managers of theatres, hospitals and department buildings. The AIJ Principal Guide was published in Japan in 1989 after extensive discussion and debate sponsored by the Ministry of Construction. The English edition was developed by Dr Takashi Nireki under the chairmanship of Dr K. Shirayama, the Chairman of the Durability Sub-Committee of AIJ. Dr Nireki was a long-standing member of CIB W080, and also the principal delegate to ISO TC 59/SC14, the committee responsible for developing ISO 15686. Dr Nireki presented copies of the AIJ Guide to members of the Ad Hoc Group, which was the forerunner of TC 59 SC14 at Omiya at the 6th DBMC conference.

It is summarised and evaluated in some detail in the Bourke and Davies (1999). A few points to note though include that it was intended for use on new buildings, with the aim to ‘systematise the concept of durability in the field of building engineering. This Principal Guide is intended to show the fundamental concept of durability within each stage of the life cycle of buildings, such as planning, design, contract, construction, utilisation, maintenance and modernisation and demolition.

2.1.3. Review of HAPM Component Life Manual and subsequent development

The HAPM Manual by Construction Audit Ltd, who provided the audit function to a novel UK system of latent defects insurance for social housing over a 35-year period. Housing Association Property Mutual (HAPM), the insurer, indemnified housing associations against premature failure of components within this time period as part of the insurance cover. HAPM therefore needed to identify what was premature, and by extension, what was normal durability of components. They also needed to communicate these expectations (and associated limitation to the insurance cover) to the housing associations who sought their insurance cover, and the decision was taken to publish the HAPM Manual. The methodology was explained in a HAPM Technical Note which was included as an annex to the BRE Factor Method discussion paper (Bourke and Davies 1997). It was prepared after extensive research into existing industry sources of lifespan data including the preliminary version of the RICS paper (RICS, 1992).

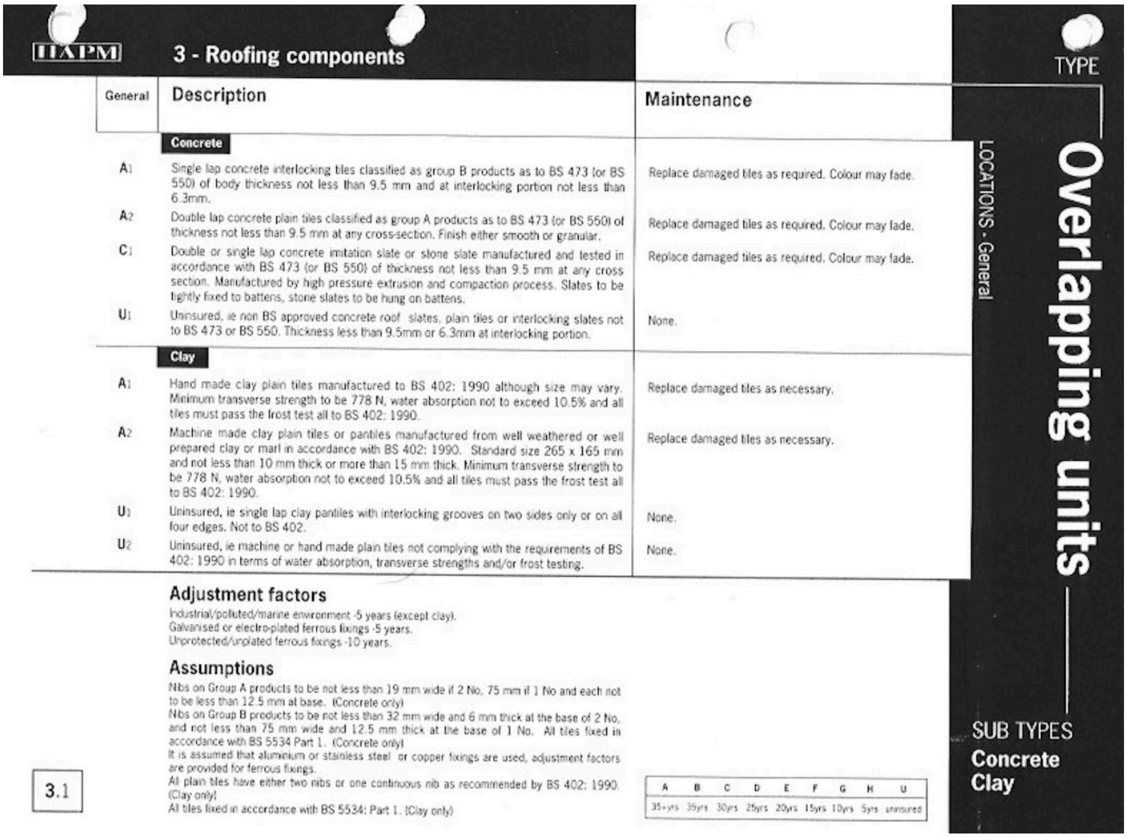
The HAPM Manual was published in 1992 in hard copy and was updated every 6 months via a loose-leaf supplement that ceased some years later. However, the coverage was expanded prior to the cessation of publication of the HAPM Manual, via several commissioned pieces of work from Construction Audit Ltd., Building Performance Group and HAPM's successor Building Life Plans. The HAPM methodology was further detailed in a series of papers, by Bourke (1996) and through her unpublished M. Phil research (Bourke, -), by Mayer and Wornell (1999), by Bourke and Davies (1999), and by Mayer and Bourke (2005). The building fabric components coverage was extended to cover additional building services components in more detail in 2001, and the whole pack of information was reissued in 2003 as the HAPM Component Life Service Pack (HAPM, 2003).

Following a further commission by the Housing Corporation (funders of social housing investments at the time) Building LifePlans provided the data in an online format for some years from 2005 onwards, known as the Construction Durability Database (which used to be available at www.componentlife.com but which is no longer updated or available for subscriptions). This last version also included further survey data and use of failure mode effect and criticality analysis more explicitly. It also extended the maximum period of the reference service lives to 60 years, allowing the data to be used more immediately than where the 35-year period of insurance cover was the maximum service life available.

Figure 2.1 below shows an example of the HAPM Component Life Manual information on overlapping roof coverings, and Figure 2.2 shows the equivalent data from the Construction Durability Database.

The similarities and differences provide an overview of the development during the 10-year period in which the data was expanded and amended. The standards change, further refinements are added, some of the lower rated options disappear, the failure mode, effect and criticality (FMECA) assessment are added, and the maximum potential default service life is increased to 60 years, rather than the 35-year cap associated with HAPM insurance.

The RICS Survey (RICS, 1992) and successive iterations of the survey have also moved from a hard copy basis to an online basis, but these are on a subscription basis only now. Originally the survey was framed as 'opinions' by surveyors on the lifetime of building elements, and the results were subject to statistical analysis, giving maximum and minimum values and standard deviations for a wide range of components. The methodology for the survey was not explained in detail, and the ranges reported were wide. For example, softwood windows were described as lasting between 20 and 55 years, with a mean value of 35 years, while natural slate roof coverings were described as lasting between 45 and 110 years, with an average of 75. The general format has been maintained but more consistency has been introduced in analysis.



HAPM

3 - Roofing components

TYPE

Overlapping units

LOCATIONS - General

General	Description	Maintenance
	Concrete	
A_1	Single lap concrete interlocking tiles classified as group B products as to BS 473 (or BS 550) of body thickness not less than 9.5 mm and at interlocking portion not less than 6.3mm.	Replace damaged tiles as required. Colour may fade.
A_2	Double lap concrete plain tiles classified as group A products as to BS 473 (or BS 550) of thickness not less than 9.5 mm at any cross-section. Finish either smooth or granular.	Replace damaged tiles as required. Colour may fade.
C_1	Double or single lap concrete imitation slate or stone slate manufactured and tested in accordance with BS 473 (or BS 550) of thickness not less than 9.5 mm at any cross section. Manufactured by high pressure extrusion and compaction process. Slates to be tightly fixed to battens, stone slates to be hung on battens.	Replace damaged tiles as required. Colour may fade.
U_1	Uninsured, ie non BS approved concrete roof slates, plain tiles or interlocking slates not to BS 473 or BS 550. Thickness less than 9.5mm or 6.3mm at interlocking portion.	None.
	Clay	
A_1	Hand made clay plain tiles manufactured to BS 402: 1990 although size may vary. Minimum transverse strength to be 778 N, water absorption not to exceed 10.5% and all tiles must pass the frost test all to BS 402: 1990.	Replace damaged tiles as necessary.
A_2	Machine made clay plain tiles or pantiles manufactured from well weathered or well prepared clay or marl in accordance with BS 402: 1990. Standard size 265 x 165 mm and not less than 10 mm thick or more than 15 mm thick. Minimum transverse strength to be 778 N, water absorption not to exceed 10.5% and all tiles must pass the frost test all to BS 402: 1990.	Replace damaged tiles as necessary.
U_1	Uninsured, ie single lap clay pantiles with interlocking grooves on two sides only or on all four edges. Not to BS 402.	None.
U_2	Uninsured, ie machine or hand made plain tiles not complying with the requirements of BS 402: 1990 in terms of water absorption, transverse strengths and/or frost testing.	None.

Adjustment factors

Industrial/polluted/marine environment -5 years (except clay).
Galvanised or electro-plated ferrous fixings -5 years.
Unprotected/unplated ferrous fixings -10 years.

Assumptions

Nibs on Group A products to be not less than 19 mm wide if 2 No, 75 mm if 1 No and each not to be less than 12.5 mm at base. (Concrete only)
Nibs on Group B products to be not less than 32 mm wide and 6 mm thick at the base of 2 No, and not less than 75 mm wide and 12.5 mm thick at the base of 1 No. All tiles fixed in accordance with BS 5534 Part 1. (Concrete only)
It is assumed that aluminium or stainless steel or copper fixings are used, adjustment factors are provided for ferrous fixings.
All plain tiles have either two nibs or one continuous nib as recommended by BS 402: 1990. (Clay only)
All tiles fixed in accordance with BS 5534: Part 1. (Clay only)

3.1

A	B	C	D	E	F	G	H	U
35+yrs	35yrs	30yrs	25yrs	20yrs	15yrs	10yrs	5yrs	uninsured

SUB TYPES
Concrete
Clay

Figure 2.1. - Typical page from HAPM Component Life Manual 1992

2.1.4. Review of the RICS Survey and subsequent developments

The format of these data has some problems other than the range of values though - in particular, it does not explain what assumptions were in the minds of those returning the survey questionnaire about design, installation, maintenance or environment - but some of these must be behind some of the variation of opinions. For example, cast iron drainage pipes have the following reported results in Figure 2.3.

This disguises the more detailed information, which indicates that some correspondents considered the minimum, mean and maximum life cycle would exceed 95 years - as shown on the detailed graphs (Figures 2.4). It is reasonable to assume that in addition to the limitations of analysis by mean, median and mode averages there is also a different application assumed between those respondents who considered 20-25 years was a reasonable minimum life cycle estimate, and those who considered 95-100 years a reasonable minimum. Indeed, generally the maximum and minimum results do not differ widely, so the range is less informative than it might seem. Some of these aspects were assessed in more detail in Bourke unpublished thesis (Bourke, n.d.).

2C-Roof
Coverings - overlapping units **Concrete**

Concrete

Life	Durability descriptions
60	Double lap concrete plain tiles classified as group A products as to BS 473/BS 550 (or BS EN 490) of thickness not less than 9.5mm at any cross-section. Finish either smooth or granular.
60	Single lap concrete interlocking tiles classified as group B products as to BS 473/BS 550 (or BS EN 490) of body thickness not less than 9.5mm and at interlocking portion not less than 6.3 mm.
30	Double or single lap concrete imitation slate or stone slate manufactured and tested in accordance with BS 473/BS 550 (or BS EN 494) of thickness not less than 9.5mm at any cross section. Manufactured by high pressure extrusion and compaction process. Slates to be tightly fixed to battens, stone slates to be hung on battens.

Adjustment factors	**Adjustment yeai**
Galvanized or electro-plated ferrous fixings	-5
Industrial, polluted or marine environment (except clay)	-5
Unprotected or unplated ferrous fixings	-10

Maintenance requirements	**Period**
Replace damaged or slipped tiles	As necessary
Replace damaged tiles as required. Colour may fade.	Not applicable

Inspection Requirements	**Period**
Inspect condition and for damage	Annually

Design assumptions

Nibs on Group A products to be not less than 19 mm wide if 2 No, 75 mm if 1 No and each not to be less than 12.5 mm at base. (Concrete only) Nibs on Group B products to be not less than 32 mm wide and 6 mm thick at the base of 2 No, and not less than 75 mm wide and 12.5 mm thick at the base of 1 No. All tiles fixed to BS 5534 Part 1. (Concrete only) It is assumed that aluminium or stainless steel or copper fixings are used, adjustment factors are provided for ferrous fixings.
All plain tiles have either two nibs or one continuous nib as recommended by BS 402: 1990.
(Clay only) All tiles fixed to BS 5534: Part 1. (Clay only)

Installation, commissioning and inspection assumptions

None

Key failure modes

Cracking; Spalling; Detatchment; Chemical attack, for example water and acid rain, carbonation, sulfate attack, chlorides

Key durability issues

Cement content; Thickness; Compressive strength; Fixings, non-corrosive, pull-out strength

Notes

None.

References

BS 473, 550:1990 Specification for concrete roofing tiles and fittings (Withdrawn, superseded by BS EN 490 and BS EN 491)

BS 5534-1:1997 Code of practice for slating and tiling - Design. Replaced by BS 5534-1:2003.

BS EN 490:1994 Concrete roofing tiles and fittings. Product specifications.

05/04/2006 G:\DATA\1706 Component Life Manual\4 Database\Reports\QryAll06.rpt Page 265 of 2807

Figure 2.2. - Typical page from BLP Componentlife.com (2006)

Median typical life	Range	Median minimum life	Median maximum life
50 years	10 to over 100 years	30 years	75 years

Figure 2.3. - Summary results for cast iron drainage pipes from RICS Survey - online results (see RICS database)

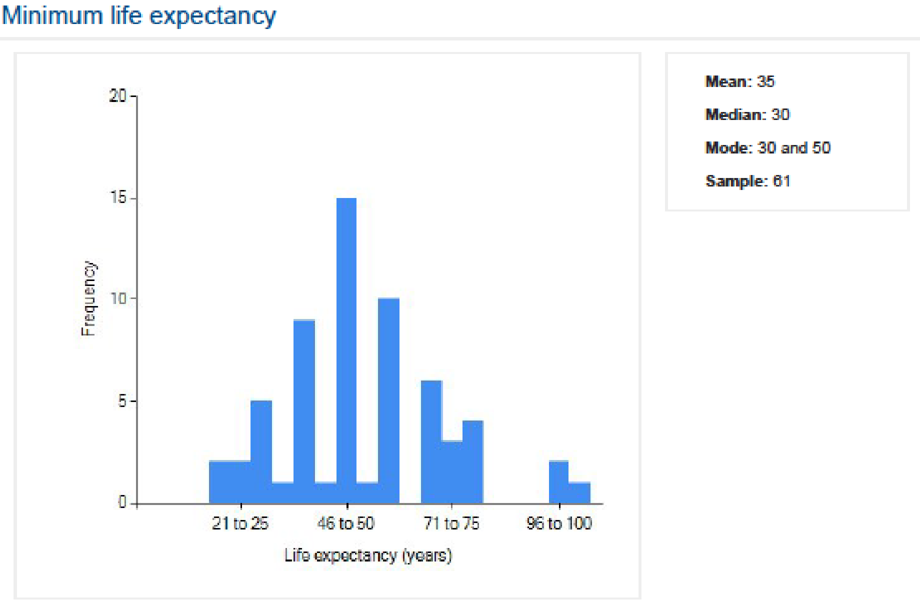


Figure 2.4. - Detailed minimum results for cast iron drainage from RICS Survey - online results (see RICS database)

There is also some interesting analysis of anchoring and adjustment bias included in a paper by Kempton et al. (2002). However, the RICS Survey now informs BCIS subscription software for running costs analysis (see RICS database) so is not readily available as a data source, although some information on the survey and other data sources used by RICS has been published. There are various analyses available to subscribers that provide life cycle cost benchmark rates, but it is also possible for subscribers to access the component life database.

2.2. *Brief overview of industry application of the Factor Method in the UK*

The HAPM Manual and the RICS Survey both originated in the United Kingdom at approximately the same time, but wholly separate from each other in origin and methodology. It is worthy of note that the UK data sources have remained relevant and continue to be updated and refined. The latest amendment to the RICS Survey took place in 2018 (RICS, 2018) although the data is now embedded within a paid subscription service for estimating life cycle costs. Similarly, although HAPM itself no longer provides insurance, its successor BLP Insurance exists and still provides latent defect cover to building owners and also provides durability assessments as a consultancy service.

Both publications were influenced by the level of focus of the construction industry in the United Kingdom at the time on Private Finance Initiative (PFI and later PF2), a mixed public/private partnership form of procurement that had become the dominant procurement route for major public sector construction procurement following its introduction in 1992. It remained a significant form of procurement in the UK until 2012, before finally being dropped formally in 2018, following long-standing concerns about value for money, effectiveness of risk transfer and public accountability. A detailed evaluation of PFI is outside the scope of this document.

The ongoing influence of both PFI and PPP contractual procurement routes in the UK should be recognised. According to HM Treasury and Infrastructure and Projects Authority (2018), there were 704 central government PFI or PF2 projects, with a nominal capital value of £57 billion. The numbers, originating government departments and dates of major PFI projects are shown in Figures 2.5 and 2.6.

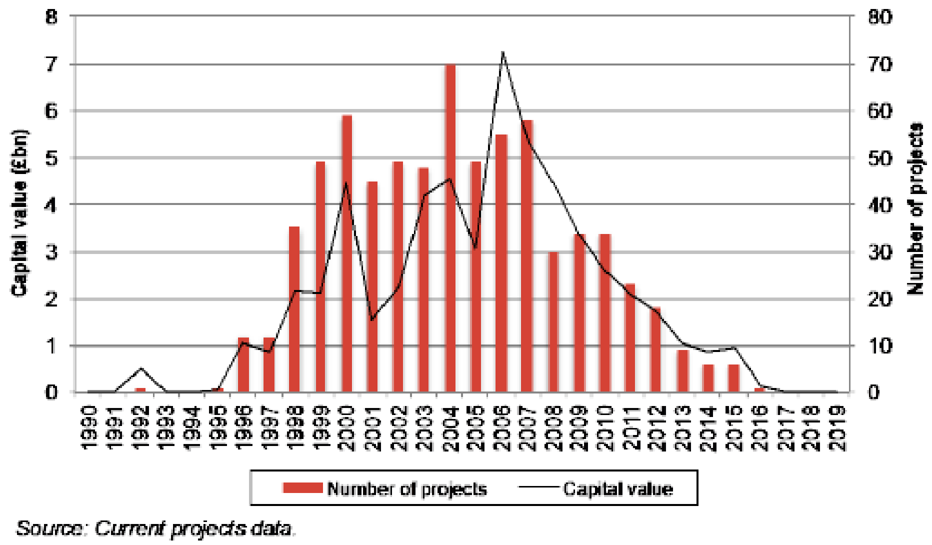


Figure 2.5. - Current UK PFI and PF2 projects in 2018 - number and capital value by year of financial close

From the point of view of this report, the critical issue is that PFI and subsequent PPP procurement methods in the UK (and beyond) share the characteristic that they require operation of the facilities beyond the period of construction to be included in the contract bid and subsequent management, and therefore they introduce life cycle costing as a requirement for bidding. The main reason why the factor method remains influential in the UK is the need for inputs to life cycle costing from an early stage of design, alongside life cycle assessment of environmental impacts, which also requires numerical assessment of service life of components, alongside at least assumptions about maintenance tasks and frequency required to attain that service life.

For example, in addition to the Standardised Method for Life Cycle Costing (PD156865: 2008), which provided supplementary UK guidance to practitioners and cited the factor method (and the HAPM Component Life Manual) from 2008, additional guidance on life cycle costing within the UK which references the Factor Method indirectly has included BS 8544 (2013) on life cycle costing of maintenance, guidance by RICS on life cycle costing in 2016 (RICS, 2016) and the publication of the 2nd edition of the International Construction Measurement Standards (RICS, 2020; ICMS, 2020).

As a result of its ongoing development, the HAPM Component Life Manual also provided a published source of reference service lives for components over a long period of time. It was updated and widely used in the UK (where the assumptions and standards were most directly applicable) and beyond as a starting point for default service lives. It was a data source which was referenced in the highly influential BRE Green Guide to

Specification (Anderson, 2002) (and subsequent editions) having previously influenced the associated BRE Methodology for Environmental Profiles (Howard et al., 1999) and BSRIA's guidance within the Carbon and Cost Analysis Set (BSRIA, 2016).

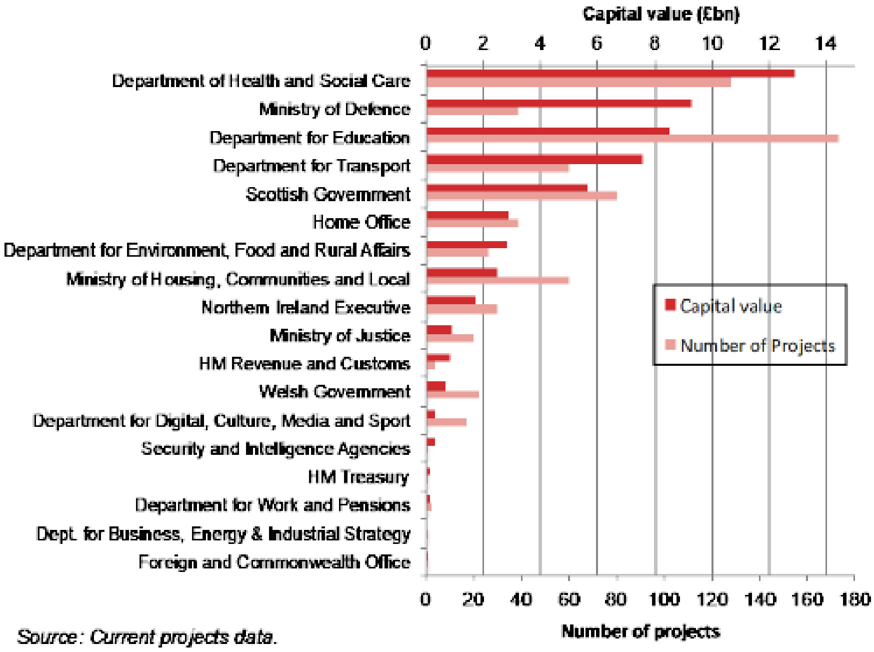


Figure 2.6. - UK Portfolio of current PFI and PF2 projects - number and capital value by department in 2018

These led to citation of ISO 15686-1 and the associated Factor Method in the BREEAM Environmental Assessment Methodology (BREEAM) as one basis on which component durability could be based. All major public sector new build construction projects were required to have a BREEAM or similar rating under UK government Common Minimum Standards (see https://www.gov.uk/government/publications/common-minimum-standards). Therefore, a substantial number of projects invoked either life cycle assessment of environmental impacts or life cycle cost assessment as part of their BREEAM submissions. This strand of influence of the factor method remains within the UK, and has influenced subsequent software tools and publications in the UK (e.g. the IMPACT software by IES Ltd. (available on https://www.iesve.com/research/design/impact and https://www.bregroup.com/impact/impact-compliant-tools/) with BRE, AEC3 and Willmott Dixon Group which has now influenced three further software tools) and the current BREEAM Methodology and Green Guide (BRE, 2020). Similarly, publications on embodied carbon (RICS, 2017), for example, typically cite the same data sources for service life as those originally reviewed for the Factor Method.

Another fairly direct influence was on the modelling of whole life costs associated with benchmark funding envelopes for social housing described in a Housing Corporation publication (BCIS, 2003) concerning the costing associated with standard housing archetypes. This was followed by a software tool developed through a collaborative research project between BLP, University of Cambridge, University College London and Willmott Dixon Construction curiously named Butterfly (see https://www.blpinsurance.com/latest-news/news/blp-unveils-sustainability-software-2259/) in the same grouping and timescale as the IMPACT software described above. These tools were also influenced by the Factor Method.

New UK publications since the original publication of the Factor Method of relevance include CIBSE'S Guide M (2014), with its associated economic life expectancy tables (last updated in 2019), as well as the RICS New Rules of Measurement Part 3 (RICS, 2014), which recommends the RICS Survey and the CIBSE Guide M. Finally, BESA have produced their SFG20 (see https://www.sfg20.co.uk/what-is-sfg20/) maintenance task schedules which align the data structures from RICS NRM3 with the economic lives from CIBSE Guide M.

The ongoing development of what would be termed reference service life datasets in the UK is now being stimulated by Building Information Modelling, where the availability of a value for the service life and the potential to vary that default value via a factor is very welcome, but is bound to place more scrutiny on the origin and evidence for the values reported.

2.3. *Concluding remarks*

The overarching impression from the review of the industry application of the Factor Method (and the ongoing revisions and amendments to the key data sources associated with it) is that the need for a means of estimating and adjusting numerically a reference service life is clearly demonstrated. Despite any criticisms there are (and it is acknowledged that the critiques and challenges have been powerful and evidenced) the original concept laid out in the paper by Bourke and Davies (1997) was justified and has proved useful and influential. Their conclusion was that "ease and speed to learn, use and amend are critical, together with the adaptability of the system to use with existing databases and design methods. A very simple system is most likely to be acceptable. A more complex and accurate system may then result following additional research'. Many of the further research needs identified in the original paper are being or have been addressed, yet the need to expand and improve the dataset remains and may increase as a consequence of increasing focus on Building Information Modelling, life cycle costing and analysis as a means of improving sustainability.

Others have reviewed the validity, limitations, and alternatives to the factor method, but its great strength remains that it is a structured assessment that builds on whatever data is already available and can be used by construction practitioners in real time on construction projects.

References

AIJ - Architectural Institute of Japan (1993). *The English edition of principal guide for service life planning of buildings*. Published by the Architectural Institute of Japan.

Anderson J., Shiers D., Sinclair M. (2002). *The Green Guide to Specification*. 3rd Edition. Blackwells, Available from CRC Ltd (EP 57), Oxford, UK.

BCIS (2003). *Whole Life Costing of Social Housing - Housing Corporation Innovation and Good Practice Project 098/2002*. Stage 1 Final Report July, BCIS, London, UK.

Bourke, K.P. (1996). *Model for Insuring Durability of Building Components, Durability of Buildings Materials and Components*. Proceedings of the Seventh International Conference in Stockholm, Sweden, E&FN Spon, London, UK.

Bourke, K.P. Davies, H. (1997). *BR 320:1997 Factors affecting service life prediction of buildings: A discussion paper*. Construction Audit Ltd., BRE Press, UK.

Bourke, K., Davies, H. (1999). *Estimating service lives using the Factor Method for use in whole life costing*. 8th International Conference on Durability of Building Materials and Components; Vancouver, Canada, pp. 1518-1526.

Bourke, K.P. (n.d.) Estimating building component durability for the purpose of risk management. Unpublished Master of Philosophy thesis.

BS 8544 (2013). *Guide for life cycle costing of maintenance during the in use phases of buildings*. British Standard Institution, UK.

BSRIA (2016). *Cost and Carbon Analysis Set includes BG 67/2016 on LCA, BG 67/2016 on LCC and BG10/2011 on inventory of carbon and energy*. BSRIA. Authors Churcher, D., Jones, C. and editors Lowrie, F., TSE, P and Hammond, G. Available at: https://www.bsria.com/uk/product/enp5mD/carbon_and_cost_analysis_set_cc1_a15d25e1/.

Building Performance Group Limited (2001). *Building Services Component Manual*. Blackwell Science, Oxford, UK.

BRE Group (2020) Green Guide to Specification. Available at: https://www.bregroup.com/greenguide/podpage.jsp?id=2126

CIB Report 294 (2004). *CIB W080/RILEM 175-SLM Service Life Methodologies - Prediction of Service Life for Buildings and Components*. CIB W080 / RILEM 175 SLM: Service Life Methodologies Prediction of Service Life for Buildings and Components, Task Group: Performance Based Methods for Service Life Prediction. ISBN 90-6363-040-9.

CIBSE Guide M (2014). Maintenance, Engineering and Management. CIBSE 2014 and updated schedule are available online at: https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q20000008I7oZAAS

HAPM (1992). *Component Life Manual*. E&FN Spon, London., UK.

HAPM (2003). *HAPM Component Life Service Pack*. Taylor & Francis, London, UK.

HM Treasury and Infrastructure and Projects Authority (2018) *Private Finance Initiative and Private Finance 2 projects*; 2018 summary data. Crown Copyright 2019. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/805117/PFI_and_PF2_FINAL_PDF1.pdf

Howard, N., Edwards, S., Anderson, J. (1999). *BRE methodology for environmental profiles of construction materials, components and buildings (BR 370)*. Garston, CRC Ltd., UK.

ICMS: International Construction Measurement Standards (2019). Available online at: https://www.rics.org/uk/upholding-professional-standards/sector-standards/construction/icms-international-construction-measurement-standards/

ISO 15686-1 (2000) Buildings and constructed assets - service life planning - part 1: general principles and framework. International Organization for Standardization, Switzerland.

Kempton, J., Chapman, K., Alani, A. M. (2002) Surveyor element lifetime predictions and the anchoring and adjustment heuristic. In: Greenwood, D (Ed.), 18th Annual ARCOM Conference, University of Northumbria. Association of Researchers in Construction Management, Vol. 1, 145-54.

Masters, L.W., Brandt, E. (1989). Systematic Methodology for service life prediction of building materials and components. *Materials & Structures*, V. 22, pp. 385-392.

Mayer, P. D., Wornell, P. (1999). Assessing the remaining service life of existing building components for insurance. 8th International Conference on Durability of Building Materials and Components; Vancouver, Canada, pp. 1447-1456.

Mayer, P.D., Bourke, K. P. (2005). Durability Rankings for building component service life prediction. 10th International Conference on the Durability of Building Materials and Components, Lyon, France, TT4-118.

PD156865:2008 *Standardized method of life cycle costing for construction procurement*. A supplement to BS ISO 15686-5 Buildings and constructed assets. Service life planning. Life cycle costing, BCIS/BSI, UK.

RICS (1992) *Life Expectations of Building Components: Preliminary Results from a Survey of Building Surveyors Views*. Royal Institution of Chartered Surveyors, London, UK.

RICS (2014) RICS new rules of measurement. NRM 3: Order of cost estimating and cost planning for building maintenance works. 1st Edition. Royal Institution of Chartered Surveyors, London, UK.

RICS (2016) Lifecycle Costing. 1st Edition. Royal Institution of Chartered Surveyors, London, UK.

RICS (2017) Whole Life carbon assessment for the building environment. 1st edition, Royal Institution of Chartered Surveyors, London, UK.

RICS (2018) BCIS component life expectancy update for 2018. Available online at: https://www.rics.org/uk/news-insight/latest-news/news-opinion/bcis-component-life-expectancy-update-for-2018/

RICS (2020) ICMS 2 will impact life-cycle cost analysis for constructed assets Available online at: https://www.rics.org/uk/news-insight/latest-news/news-opinion/icm-2-will-have-a-significant-impact-on-life-cycle-cost-analysis-for-constructed-assets/

RICS database - *Building Running Costs Online*. https://www.rics.org/uk/products/data-products/facilities-management/building-running-costs-online/

Sjöström, C. (1996). Durability of building materials and components: Proceedings of the 7th International Conference on Durability of Building Materials and Components, 7DBMC: Stockholm, Sweden, Edited by Christer Sjöström, Spon, London, UK.

3. Methodology for modelling the service life prediction using the factor method

3.1. The factor method in Finnish concrete codes

Arto Köliö, Tampere University

3.1.1. The context

The durability of concrete structures has traditionally been pursued by choosing the structure and material properties according to environmental loads. However, the effect of specific design choices on durability has not been clear or quantified but been based more on tradition or workmanship. In Finland, more attention has been paid to the durability of structures since the late 1970s by increasing the quality requirements for structures and materials in contact with outdoor climate. Nevertheless, the approach then and since has been prescriptive. The development of service life models for service life design has started in the 1980s (Vesikari 1988, 1998). Finnish concrete codes have required service life design of concrete structures based on calculated service life in new construction since 2005. This calculation-based design is based on the factor approach defined in ISO 15686 standards where the target service life set by the client, usually 50 to 200 years, is achieved by optimizing material and structural properties with mathematical models. These properties are then used in the design and construction of the structure (by 50 Concrete Code, 2004).

The service life of a structure is defined as the period of time for which the performance of a structure remains, with a given probability, above an acceptable level. It is derived from this definition that the service life of a structure ends when its performance falls under the acceptable level. Only when the criteria for performance and for the demand are set, there is a possibility to calculate or define a numerical service life. These are the key concepts on which the service life design of structures methodology is based on.

It is assumed that presently the most common method for the estimation of the service life of a structure or a component is the factor method. The impact of different material properties and structural dimensions, workmanship, environment and maintenance are in this method represented as factors that either improve/maintain (factor ≥ 1) or shorten (factor < 1) an experimentally or empirically determined reference service life (*RSL*) to produce a specific estimated service life (*ESL*) for each case under analysis (ISO 15686-1:2011). Finnish service life design of concrete structures is also based on the factor method. Although the method itself is very simple, the difficulty lies in defining the factors correctly and producing reliable *RSL* data for different structures (Corvacho et al., 2011).

The degradation of concrete structures is caused by the simultaneous influence of environmental, structural and material factors. A common denominator in every mechanism is water in varying forms. It can either work as a passage for harmful substances, cause damage due to its phase changes (e.g. freeze-thaw) or cause dissolution of substances in concrete (Nilsson, 2003). Degradation eventually results in cracking or spalling of concrete that reduces the bearing capacity or bonding reliability of the structures. Harsh climate increases the design requirements for durable materials. The major mechanisms in Finnish climate are corrosion of facade reinforcement due to carbonation and freeze-thaw weathering of concrete (Pentti et al., 1998). The presence of chlorides in facade structures is very rare. From this point of view, the factorial approach to service life design in the Finnish concrete code has been developed to describe the durability of concrete under a) freeze-thaw and b) carbonation induced corrosion. The service life of a concrete structure is calculated with a factor approach designed for each of the two degradation mechanisms separately and then, finally, the minimum of the two is chosen as the definitive service life.

3.1.2. Definitions of the factor method

The standard ISO 15686-8 (2008) defines the reference service life (*RSL*) as a service life of a building component in standardized conditions, while the estimated service life (*ESL*) is defined as a case-specific service life of that component, which has been modified to match the case-specific environmental conditions and material properties. The *ESL* is produced from *RSL* data by multiplying it by different factors from *A* to *G*, considering different properties and environmental conditions. The formula for *ESL* is (ISO 15686-8:2008) presented in equation (3.2.1.).

$$t_{ESL} = t_{RSL} \cdot A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G \qquad \textbf{(3.2.1)}$$

Where t_{ESL} is the estimated service life of a component in use, t_{RSL} is the reference service life of a component in standard conditions, and *A* to *G* are the factors taking into account different properties of the component analysed. The factor definitions are compiled in Table 3.2.1 (ISO 15686-8: 2008).

Table 3.2.1. - Definition of the factors considering different properties of the component analysed (ISO 15686-8: 2008)

Factor	Factor category	Description
A	Inherent performance level	Grade of the component in the time on delivery. Durability properties of the material.
B	Design level	Reflects the component's installation in the building. The design choices made can provide shelter and protection from degradation agents.
C	Work execution level	Considers the level of skill and control in site work. Storage, protection during installation, ease of installation, manufacturer's recommendations, etc.
D	Indoor environment	Considers the exposure of component to indoor degradation agents.
E	Outdoor environment	Considers the exposure of component to outdoor degradation agents. The effect of weather conditions and microclimate surrounding the component should be taken into account.
F	Usage conditions	Takes into account the wear that occurs during the use of the building.
G	Maintenance level	Represents the level of maintenance of the component. Includes cleaning, maintenance, repair, replacement, among other activities and how accessible the component is for maintenance.

ISO 15686-8 (2008) refers that the factor method is not entirely precise but merely an estimate based on available reference information. Properties can cause also over cautious estimated service lives, if adverse conditions are accidentally double counted in more than one factor, e.g. on-site mixing of concrete.

The standard is mainly based on the work of the Architectural Institute of Japan, the British Standard Institution and the Canadian Standards Association (AIJ 1993; BSI 1992; CSA 1995). The factor method is introduced in the standards for service life planning purposes. It is widely recognized as an essential tool, but it has to be kept in mind that it is not a degradation model but a means of transforming service life data to case-specific needs (Lacasse and Sjöström, 2004). The estimation of service life of a structure is a vital part of assessing the profitability of a building project or the rationality and timing of renovation of existing structures.

3.1.3. Application of the factor method

The factor method has in current Finnish practice been implemented only in the design of structures made of concrete and it is represented in the national concrete code (by 50 Concrete Code, 2004). The estimated service life is calculated separately for freeze-thaw and corrosion of reinforcement and the shorter of these two is regarded as the end of service life. Equation (3.2.1.) is used for calculating the service life. Commonly, the Finnish application of the factor method includes the following factors proposed in ISO 15686 standards:

i. Material properties;
ii. Detailing and design of structures (regarding coatings and how massive the structure is);
iii. Curing of concrete;
iv. Environmental exposure class, facing and geographical location of the structure, and;
v. Maintenance schedule

The impact of indoor environment and usage conditions are not currently taken into account in the Finnish code and their factor is set to 1. The value ranges of the relevant factors for freeze-thaw and for corrosion are shown in Figures 3.2.1 and 3.2.2. The reference service life for structures is 50 years to which the factors have been validated with service life models (by 50 Concrete Code, 2004).

The quantification of the material factor *A*, related to freeze-thaw, can vary from 0.90 to 4.00 and from 0.54 to 6.23 regarding corrosion. The factor related with freeze-thaw considers the following properties: w/c ratio; maximum aggregate size; and air content of fresh concrete. The factor is based on a number used nationally to describe the freeze-thaw resistance of a concrete mix (by 50 Concrete Code, 2004). Naturally, these properties are closely related to the strength and pore structure of hardened concrete. The material properties associated with the corrosion of reinforcement are the strength and type of cement or binder of concrete and the air content of fresh concrete (by 50 Concrete Code, 2004). No other factor related to freeze-thaw can have as high scale of impact on the estimated service life as material factors. Based on the factors, it can also be concluded that corrosion has been regarded as higher service life risk than freeze-thaw damage. These material properties associated with service life design are such that are not easily nor explicitly measured from concrete samples from hardened concrete, which lowers the usefulness of this practice on the estimation of residual service life of existing structures.

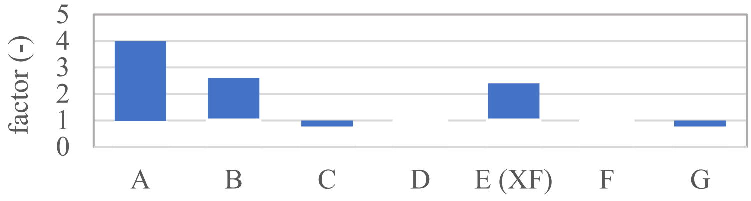


Figure 3.2.1. - Service life factors and their value ranges associated with freeze-thaw

Figure 3.2.2. - Service life factors and their value ranges associated with carbonation induced corrosion

Factors associated with the design level (factor B) of construction hold within separate factors that depict the proportions of the structure, surface coating and, regarding corrosion, the concrete cover of reinforcement. The combined effect of these factors ranges, for freeze-thaw, between 1.00 and 2.60, while for corrosion it ranges between 0.04 and 11.52. These factors represent concrete cover of 5 to 60 mm, which has on its own a decisive impact on the estimated service life.

The work execution level (factor C) is taken into account by assessing the quality of curing. If the curing of concrete is done according to the instructions in the concrete code, the factor is 1.00. If this is not the case, the factor is 0.70. The handling of work execution could be taken into account in more detail regarding, for instance, the detailing of rainwater flashings and scatter in material and structural properties, which is always in connection with the building process.

Factor D, related to the indoor environment, is constant, and equal to 1.00. On the other hand, outdoor environment is currently taken into account with three properties, encompassing the microclimate surrounding the structure: environment exposure classes; the facing direction of the structure; and harmfulness of the environmental agents due to the geographical location. For assessing the durability against freeze-thaw weathering, different factors have been assigned to the facing and geographical location: 1.00 to 2.00 depending on the structures' orientation (north is assigned with the value 2.0, while south and southeast are assigned with the value 1.0), and 1.00 to 1.20 depending on the geographical location (from coast to north, respectfully). The environment exposure class (XF1 or XF3) decides whether only one or both factors are taken into account. For carbonation induced corrosion, the exposure class has its own factor, ranging from 1.00 to 4.00. If the exposure class is XC4 (structures that are subjected to rain), factors are also assigned for the facing (0.80 to 1.40), geographical location (1.00 to 1.30), in the same way than with freeze-thaw damage, and the combined effect of freeze-thaw damage (0.20

to 1.00) (by 50 Concrete Code, 2004). The factors are based on computer simulations. Future research is needed to analyse whether the impact of scatter and alterations of prevailing weather is actually sufficiently taken into account.

The use conditions (factor *F*), regarding wear induced by everyday use, is considered to have low relevance and to be neutral (equal to 1.00). For facades, the effect of wear can be assumed to be minor, but it should be kept in mind that it can be relevant for more exposed structures.

Factor *G* represents the maintenance level of the structure and it is defined by the maintenance and inspection schedule. For an inspection interval of one to two years, a factor of 1.00 is considered, while for less frequent inspections a factor of 0.70 is assigned, thus slightly decreasing the estimated service life of the structure analysed. For the carbonation induced corrosion, the factor for less frequent inspection intervals is 0.85. For some reason, the maintenance of a structure is thereby regarded less crucial from the carbonation point of view than for freeze-thaw damage.

3.1.4. Concluding remarks

The material properties and design level (factors *A* and *B*), namely concrete cover, are in the described methodology given more weight than the other factors (Figures 3.2.1. and 3.2.2.). Additionally, in the same magnitude, the factor *E* (used to describe the environment exposure conditions) is also extremely relevant. Another general conclusion is that the defined factors have more tendency to lengthen the *RSL* rather than shorten it. This is visible in the numerical values which are weighed more often above 1 than below (Figures 3.2.1. and 3.2.2.).

The issues related to in-use conditions, for instance wear resulting from everyday use, can be regarded as having a minor influence on facade structures, considering that the in-use wear occurs mainly due to the erosive effect of the environment. For more exposed concrete structures, e.g. industry facilities or concrete floor slabs, the influence of in-use conditions may be of higher significance than presumed by the current factors.

The factors related to the design level (factor *B*) can be, possibly, analysed in more detail. Especially regarding carbonation induced corrosion, the impact of factor *B* is decisive mainly because it is affected by the cover depth of reinforcement. Further development of factor B might be possible by also taking more precisely into consideration the micro climate surrounding the structure and the restrictions and requirements that it sets on the design of the structure, usually related to the design of details e.g. window flashings, drainpipes etc. (in facades), material interfaces and discontinuities in the structure. The importance of detailing is acknowledged in practice, but it has not been included in the calculation-based method (by 50 Concrete Code, 2004).

It has to be also noted that the effect of outside environment can, according to current knowledge (Lahdensivu 2012, Köliö 2016, Pakkala 2020), have dramatic impact on the service life of concrete, either positive or adverse. As mentioned above, the design of details together with rough changes in the surrounding climate should be taken into consideration as a high risk for shorter service life. The current method that is based on factors cannot react efficiently to the dynamic changes in weather conditions that can vary greatly even between consecutive years.

References

AIJ - Architectural Institute of Japan (1993). *The English edition of principal guide for service life planning of buildings*. In ISO 15686-1: 2011. Buildings and constructed assets, Service life planning part 1: General principles and framework.

by 50, *Betoninormit 2004* (Concrete code 2004). Jyvaskyla, Finland, Suomen Betonitielo Oy (Concrete Association of Finland).

BS British Standard Institution (1992). Guide to durability of buildings and building elements, products and components, BS 7543-1992 In ISO 15686-1: 2011. Buildings and constructed assets, Service life planning part 1: General principles and framework.

Corvacho, H., Quintela, M. (2011). *Establishing specific criteria for the application of ISO15686 Factor Method for service life estimation*. 12nd International Conference on Durability of Building Materials and Components. Vol. 3, Porto, Portugal.

CSA Canadian Standards Association (1995). Guideline on durability in buildings. CSA S478-1995 In ISO 15686-1: 2011. Buildings and constructed assets, Service life planning part 1: General principles and framework.

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

ISO 15686-8. 2008. Buildings and constructed assets, Service life planning - part 8: reference service life and service life estimation. International Organization for Standardization, Switzerland.

Köliö, A. (2016). *Propagation of carbonation induced reinforcement corrosion in existing concrete facades exposed to the Finnish climate*. Doctoral dissertation, Tampere University of Technology, Tampere, Finland.

Lacasse, M., Sjöström, C. (2004). *Recent advances in methods for service life prediction of building materials and components - an overview*. CIB World Building Congress. Toronto, Canada.

Lahdensivu, J. (2012). *Durability properties and actual deterioration of Finnish concrete facades and balconies*. Doctoral dissertation, Tampere University of Technology, Tampere, Finland.

Nilsson, L-O. (2003). *Durability concept; pore structure and transport processes*, Advanced Concrete Technology, pp. 3-29. DOI: 10.1016/B978-075065686-3/50255-X

Pakkala, T. (2020). *Assessment of the climate change effects on Finnish concrete facades and balconies*. Doctoral dissertation, Tampere University, Tampere, Finland.

Pentti, M., Mattila, J., Wahlman, J. (1998). *Repair of concrete facades and balconies, part I: structures, degradation and condition investigation*. Tampere, Tampere University of Technology, Structural Engineering, Tampere, Finland (In Finnish)

Vesikari, E. (1988). *Service life of concrete structures in regard to corrosion of reinforcement*. VTT, Technical Research Centre of Finland, research report 553.

Vesikari, E. (1998). *Prediction of service life of concrete structures by computer simulation*. Licentiate's thesis. Helsinki University of Technology, Espoo, Finland.

3.2. Materials durability and service life prediction for the New Zealand building industry

***Catherine L. Nicholson; BRANZ*[1]**

3.2.1. The context

Although the New Zealand Building Code (NZBC) is performance-based, it is unique in its requirement for all building elements to demonstrate a minimum service life (NZ Government, 2014). The stipulated minimum service life is contained within Clause B2 Durability of the NZBC and depends on whether the component performs a structural function, how difficult it is to replace and how easily its failure would be detected during normal building use and maintenance (Table 3.2.1.).

Table 3.2.1. - Summary of New Zealand Building Code durability requirements specified in Clause B2

Nature of component	Default requirement	Typical examples
i. Provides structural stability, *or* ii. Difficult to replace, *or* iii. Failure undetectable through normal maintenance regimes	50 years	▶ Loadbearing walls ▶ DPC under loadbearing walls ▶ Buried pipework ▶ Ties behind masonry veneer walls
i. Moderately difficult to replace, *or* ii. Failure undetectable during everyday occupancy of building	15 years	▶ Building envelope claddings ▶ Sealants and flashings
i. Easily replaced, *and* ii. Failure readily apparent	5 years	▶ Linings ▶ Architectural coatings ▶ External gutters

There are two main issues with demonstrating durability and estimating service life:

i. Long term durability data supplied by product manufacturers is rarely available. There has been little uptake of the general principles of service life planning or statements of reference service life as per ISO 15686-1:2011 (ISO 2011);

ii. There are no generic methods currently available to verify that materials will comply with minimum durability requirements of 5, 15 or 50 years.

There is, therefore, a pressing and ongoing need to develop standardised test methods for predicting the expected service life of materials. Without these, it is difficult to introduce new materials onto the market, or to use existing materials in new applications. To address this, BRANZ (Building Research Association of New Zealand) has undertaken a number of projects, described in the following sections.

[1] BRANZ is an independent research organisation that uses an impartial evidence-based approach to improving the performance of the New Zealand building systems. BRANZ's mission is to transform insightful research into trusted, accessible, and actionable knowledge.

3.2.2. BRANZ Durability Assessment Tool

The BRANZ Durability Assessment Tool was envisaged as providing a database of verified knowledge around the durability of building materials and components commonly used in New Zealand construction (Lee et al., 2008). The concept was to deliver it as an interactive web-based tool with the potential to generate an audit trail for verification of compliance with NZBC service life requirements.

The objectives for developing this tool were to provide a living repository of new durability information obtained from BRANZ and elsewhere, as well as a roadmap to existing NZBC Acceptable Solutions, i.e. prescriptive methods for a very limited range of situations that are deemed to comply when carried out to the letter, e.g. light timber-framed construction.

The expected outcomes from the tool were to provide:

- A database of existing durability information.
- Information to inform the development of new testing and compliance methodologies.
- A knowledge gap analysis for materials durability to focus future research needs.
- A potential methodology to demonstrate compliance with B2 Durability.

The tool was structured as three modules and designed to distinguish between normative (i.e. NZBC requirements) and informative (i.e. advice) material:

1. ***Performance requirements*** - the user-defined building element determines the required service life;
2. ***Verification methods*** - the user-defined building element composition and in-service environment returns an existing Acceptable Solution, BRANZ verification method or a statement that no service life prediction method currently exists;
3. ***Specialist advice*** - the rationale for the first two modules is presented, along with all relevant durability information.

A working prototype of the tool was developed for testing and feedback from potential users. The expectation was that this tool would provide the New Zealand building industry with enhanced knowledge and confidence to at least meet, and preferably exceed, durability expectations.

BRANZ is currently using this tool as a valuable in-house durability resource that can be accessed by our technical experts to assist industry.

3.2.3. BRANZ Residual Service Life Assessment Tool

The BRANZ Residual Service Life Assessment Tool was seen as providing a simple deterministic estimate of residual service life based on visual correlation of the condition of a building element with an atlas of case study photographs (Marston et al., 2011).

The concept was to estimate the residual service life of building components in situ using photographs illustrating degradation condition scales. A particular advantage of this tool was its ease of use and the ability it gave to less experienced practitioners to identify common defects or material degradation mechanisms. This contrasts with models such as EPIQR (Genre et al., 1998), MEDIC (Flourentzou et al., 1998) and the Factor Method described in ISO 15686 (ISO 15686: 2011) which require significant expertise to use and interpret correctly.

The expected outcomes from the tool were to provide:

- A web-based tool that could be downloaded or accessed via a smartphone;
- A database of existing residual service life information;
- On-site condition assessments using photographs;
- Condition scales developed for the most commonly used building components;
- A knowledge gap analysis to focus future research needs.

The tool was structured to present reference images using the Wordpress publishing platform and consisted of:

1. ***Entry screen*** - the user selects the relevant material from a list of possible choices. Images are then displayed to show typical defect types;
2. ***Material refinement*** - the entry can be further refined by selection of multiple material types, e.g. painted timber;
3. ***Content management interface*** - a dashboard allows images to be tagged with applicable material types.

3.2.4. BRANZ Evaluation Method development

While not providing durability data or an estimation of service life directly, BRANZ has developed a number of Evaluation Methods that can contribute to both.

The most recent example is BRANZ Evaluation Method 7 - Performance of mid-rise cladding systems (BRANZ Ltd. version 2, May 2019). This represents a series of tests from AS/NZS 4284:2008 Testing of building facades (Standards Australia / Standards New Zealand 2008) and it provides a means of assessing weather tightness. It is also a means of testing and demonstrating via a recognised Verification Method, E2/VM2 (NZ Government 2019), that a wall cladding system will prevent water penetration to the extent required by the NZBC.

Mould growth occurs in the presence of moisture which may arise from both internal (e.g. condensation within a wall) and external (e.g. rain penetration) sources. The risk of mould developing on timber building elements has important implications for durability.

3.2.5. Durability assessment of specific materials

Research at BRANZ has also been directed at specific building materials and/or components where an issue is deemed to be sufficiently important to merit an in-depth study. A recent example of this is a project investigating polyurethane (PUR) based structural adhesives used in engineered wood products (EWPs) such as glulam, CLT and LVL.

Conventional structural adhesives based on resorcinol have a long history of use in New Zealand, providing evidence of their ability to meet the minimum NZBC durability requirement of 50 years (Table 1). Adhesives based on polyurethanes (PURs) are used extensively in other parts of the world, but with a lack of data around their performance in the preservative-treated pine EWPs typically manufactured in New Zealand, it is difficult to provide evidence-based long-term durability predictions.

In this research project, attenuated total reflectance Fourier transform infrared (ATR FTIR) spectroscopy in conjunction with multi-component analysis (chemometrics) was used to understand the changes that accelerated ageing cause in the chemistry of polyurethane adhesives (Nicholson et al., 2017; Nicholson, 2020). FTIR spectroscopy has shown that some PUR formulations are susceptible to hydrolysis under elevated temperature and moisture conditions (Dubelley et al., 2018), as may potentially be found intermittently during in-service conditions in the temperate maritime climate of New Zealand. The effect of hygrothermal stress was investigated through exposure of samples to various accelerated ageing cycles at temperatures between -20 ºC and 80 ºC and RH of < 15% to 100% for up to 3 years.

Different samples were affected to different extents by each cycle, with some appearing to be highly resistant to hygrothermal degradation whereas others showed evidence of significant hydrolytic degradation (Fig. 3.2.1.).

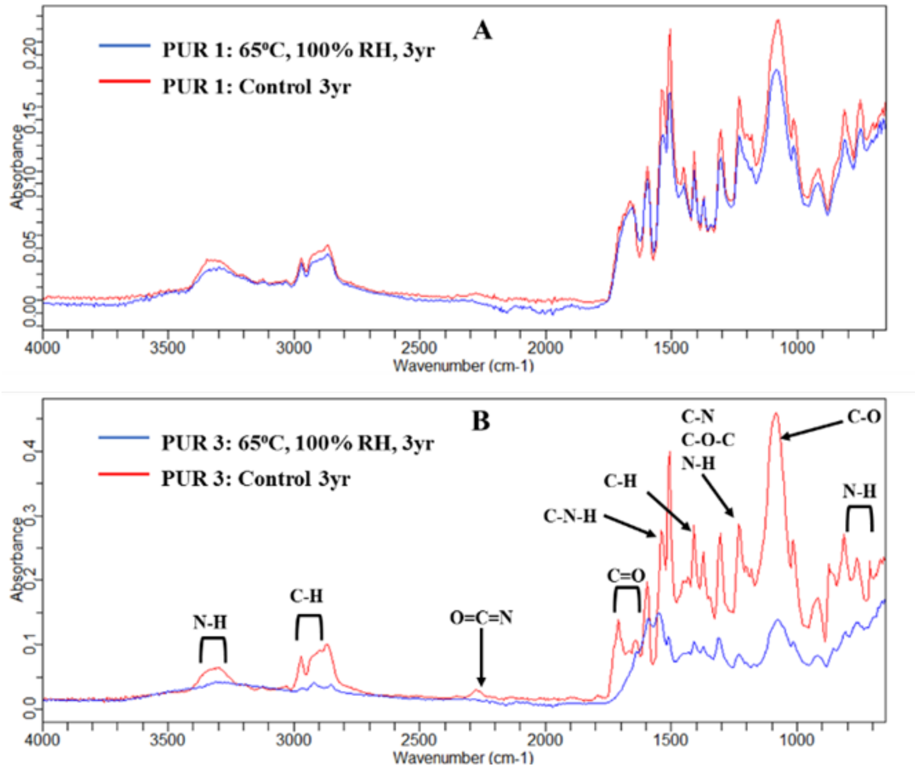


Figure 3.2.1. - ATR FTIR spectra of (A) sample PUR 1, showing excellent resistance to hygrothermal degradation and (B) sample PUR 3, showing significant hydrolytic degradation after 3 years of constant exposure to 65ºC and 100% RH. Regions associated with changes in PUR chemistry over time are indicated by arrows

Spectroscopic data were also used to build predictive models which have the potential to be used in long-term durability assessment. These models will be tested using laboratory-fabricated EWP samples that are undergoing natural outdoor ageing in order to measure the reliability of the correlation between natural weathering and accelerated ageing.

3.2.6. Conclusions

Despite the undisputed importance of materials durability and service life estimation, their prediction remains an inexact science. Over the years, BRANZ has undertaken a number of different projects with the aim of improving existing predictive methods or developing new methods of durability evaluation. While many of the difficulties are technical in nature, other potential durability assessment tools have not been deemed feasible based on potential unintentional misuse by non-expert end-users and subsequent legal liability. Many challenges remain to improve the tools that we have at our disposal. This is set to become ever more important in the future as life cycle analysis (LCA) and the circular economy become central to our thinking around how we construct, use and dispose of our built environment assets.

References

BRANZ Ltd. (2019). *Performance of mid-rise cladding systems* (version 2, May 2019). BRANZ Evaluation Method EM7, Judgeford, New Zealand.

Dubelley, F., Bas, C., Planes, E., Pons, E., Yrieix, B., Flandin, L. (2018). Durability of polymer metal multilayer: focus on the adhesive chemical degradation. *Frontiers in Chemistry*, 6, Article 459.

Flourentzou, F., Genre, J.-L., Faist, A. (1998). *MEDIC: prediction method of probable deterioration scenarios and refurbishment investment budgets*. 2nd European Conference: Energy Performance and Indoor Climate in Buildings (EPIC), Lyon, France.

Genre, J.-L., Flourentzou, F., Faist, A. (1998). *EPIQR: a new refurbishment concept*. 2nd European Conference: Energy Performance and Indoor Climate in Buildings (EPIC), Lyon, France.

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

Lee, N.P., Bennett, J.M., Jones, M.S., Marston, N.J., Kear, G. (2008). *A durability assessment tool for the New Zealand Building Code*. 11th International Conference on Durability of Building Materials and Components, Istanbul, Turkey.

Marston, N.J., Vohora, S., Jones, M. (2011). *A residual service life assessment tool for New Zealand*. 12th International Conference on Durability of Building Materials and Components, Porto, Portugal.

Nicholson, C.L., Shaw, P., Marston, N.J. (2017). *Preliminary investigation of the durability of structural adhesives using FTIR spectroscopy and chemometrics*. XIV International Conference on Durability of Building Materials and Components, Ghent, Belgium.

Nicholson, C.L. (2020). *Durability studies of polyurethane-based structural adhesives used in engineered wood products in New Zealand*. XV International Conference on Durability of Building Materials and Components, Barcelona, Spain.

NZ Government, Ministry of Business, Innovation and Employment. (2014). Acceptable solutions and verification methods for New Zealand Building Code Clause B2 Durability. 2nd Edition, amendment 8.

NZ Government, Ministry of Business, Innovation and Employment. (2019). Verification Method E2/VM2: Cladding systems for buildings up to 25 m in height - including junctions with windows, door and other penetrations.

Standards Australia / Standards New Zealand. (2008). AS/NZS 4284:2008 Testing of building facades.

3.3. Application of factor method, encompassing the real degradation condition of the building component under analysis

Ana Silva, Jorge de Brito and Pedro Lima Gaspar; University of Lisbon

3.3.1. The context

As discussed in previous sections, in the last decade, the factor method has been seen as a general methodology for service life prediction of buildings and components. The main advantage of this method relies on its simplicity, which made it a perfect tool to be applied in practice, in the construction and maintenance sector. The method proved to provide reasonably reliable results, especially in the absence of more precise tools, or even 'scientific' data (Davies and Wyatt, 2004).

Nevertheless, this method may be overly simplistic, especially when applied as a purely deterministic tool. Due to its characteristics, and since the estimated service life is obtained by the multiplication of a reference service life by several factors (Equation 3.3.1.), small variations in the quantification of the model's parameters may result in significant estimation errors.

$$ESL = RSL \cdot A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G \qquad \textbf{(3.3.1)}$$

Where (ISO 15686: 2011) *ESL* is the estimated service life, *RSL* the reference service life, *A* is related to the quality of the materials, *B* is related to the design level, *C* is related to the execution level, *D* is related to the interior environmental conditions, *E* is related to the external environmental conditions, *F* is related to the in-use conditions, and *G* is related to the level of maintenance.

Moreover, one of the main shortcomings of the factor method is related to the fact that the model usually neglects the degradation condition of the building component under analysis (Shohet et al., 2002), and is unable to encompass the variability of the degradation phenomenon, which occurs at different paces over the components' service life (Hovde, 2000; Moser and Edvardsen, 2002; Mc Duling et al., 2008).

In this sense, Gaspar and de Brito (2008) suggested a methodology, later applied in several studies (Magos et al., 2016; Silva et al., 2016; Marques et al., 2018; Jardim et al., 2019; Maia et al., 2020), which intends to take into account the real degradation condition of the element under analysis, in the quantification of the reference service life and in the quantification of the durability factors. This section of this report intends to describe this methodology, which takes into account the state of degradation of the construction elements when estimating their service life, using the factorial method.

This approach comprises the following steps, described in detail in the next sections: i) Assessment of the estimated service life for each element within the sample analysed; ii) Identification and quantification of the durability factors that influence the service life of the element under analysis; iii) Determination of the reference service life; iv) Definition of the equation that enables the practical application of the factor method to the service life prediction of the element analysed; and v) Fine-tuning of the durability factors and model's validation.

3.3.2. Assessment of the estimated service life for each point within the sample

The method proposed by Gaspar and de Brito (2008) is based on an empirical method, initially described by Shohet el al. (1999) and Shohet and Paciuk (2004), in which the degradation of a given component over time can be described by a degradation pattern, which graphically correlates the deterioration index of different examples of the element analysed and the ages of these case studies. In this method, the overall estimated service life of the element is obtained through the intersection between the overall degradation curve and the maximum admissible degradation condition (which establishes the end of service life of the component under analysis).

The same methodology can be adopted to estimate the service life of each case study within the sample analysed. In this sense, an individual curve, correlated with the average degradation curve of the building component, is made to pass through each of the case study points within the sample (Silva et al., 2016). For that purpose, the overall degradation curve (function *f*, which is usually a third-degree polynomial function) is converted into an individual curve (function *f*′, related to *f*), which passes through each of the sample's points (Emídio et al., 2014). A factor *k* is adopted to correlate the ordinates of a given point *B*, with coordinates (*x*′; *y*′), and another *A*, with coordinates (*x*′; *y*); hence, *k* is the ratio between the ordinates (*y*'/*y*) and it is applied to the function *f*, to determine the function *f*′ that passes through point *B* - Equation (3.3.2.).

$$f' = k(f) \Leftrightarrow f' = k \cdot a \cdot x^n + k \cdot b \cdot x^{n-1} + \ldots + k \cdot c \cdot x \quad \textbf{(3.3.2.)}$$

Where *f* is the function of the average degradation curve of the element, *k* the conversion factor equal to the ratio between the ordinates of points *A* (any) and *B* (belonging to *f*) with the same abscissa as *A*.

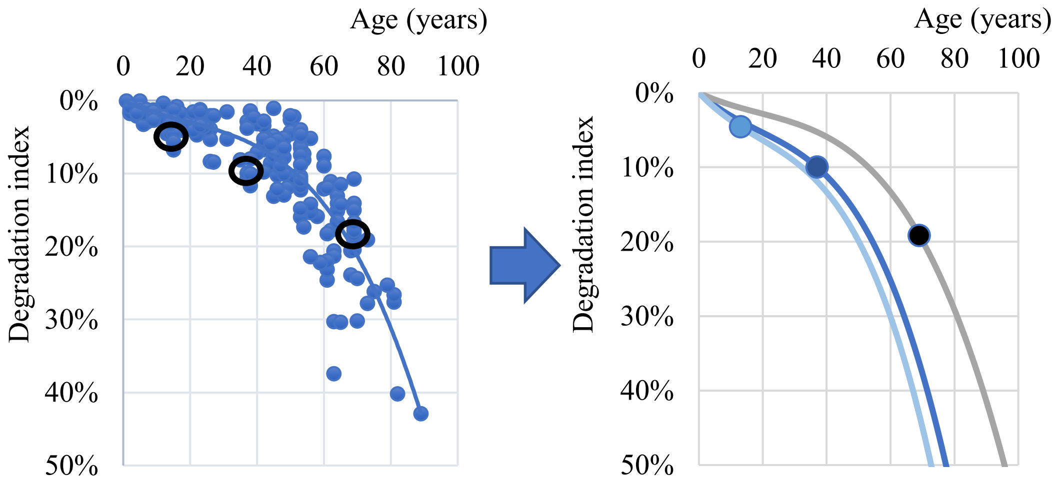


Figure 3.3.1 - Theoretical example of a degradation curve (left) and individual curves for three case studies analysed (right)

3.3.3. Identification and quantification of the durability factors

The durability factors vary according to the building component analysed. Nevertheless, ISO 15686: 2011 proposes to group the different sub-factors into seven main categories (Silva et al., 2016):

I. Quality of the materials (factor *A*), which encompasses the materials' properties, related to their performance and durability in service conditions. This factor can be evaluated through *in situ* inspections, analysing the impact of the different degradation agents on the component analysed, or though laboratory tests;
II. Design level (factor *B*), which considers the characteristics of the element that can either allow mitigating the occurrence of anomalies or promote their appearance;
III. Execution level (factor *C*), which considers the adoption of good practices and the fulfilment of the techniques prescribed during the design stage;
IV. Interior environmental conditions (factor *D*), which concerns the action of the degradation agents in the interior of buildings (e.g. exposure to moisture, in kitchens and sanitary facilities);
V. Exterior environmental conditions (factor *E*), which considers the action of the degradation agents in the exterior of buildings (e.g. exposure to pollutants, sea salts, damp, wind-rain action, among others);
VI. In-use conditions (factor *F*), which takes into account the type of use of the building, since an intensive use can promote a higher incidence of defects;
VII. Maintenance conditions (factor *G*), which encompasses the maintenance strategies and plans adopted for the building component under analysis.

Once the durability factors are identified, they must be quantified in order to estimate the service life of a given component. In ISO 15686 (2011), three standard values are recommended: 0.8 for unfavourable conditions; 1.0 for current conditions; and 1.2 for favourable conditions. This approach for quantification of the durability factors can be too simplistic, being unable to capture the random nature of the degradation phenomena. Marteinsson (2003) suggested that the durability factors may have any value, i.e. vary continuously and not be limited to discrete values, as long as these values are adjusted to the specific conditions of the element under analysis, in relation to what would be the reference conditions.

In this sense, Gaspar and de Brito (2008) established a different approach for the quantification of the sub-factors, considering the impact of the different sub-factors in the degradation condition of a specific building component under analysis. In other words, two methods have been developed and adopted in several studies (Magos et al., 2016; Galbusera et al., 2014; Silva et al., 2016; Marques et al., 2018; Jardim et al., 2019; Maia et al., 2020), in order to determine the influence of the characteristics of the component in its estimated service life. In the first method, entitled degradation curves (DC), an average degradation curve is plotted, in order to estimate an average service life for the building component; then, different degradation curves are defined for the different sub-factors, in order to estimate an expected service life for the building component according to each one of the sub-factors considered. In the second method, named graphical method (GM), the method described in section 3.3.2 is adopted, to estimate the service life of each point within the sample (which represent the degradation behaviour of the component under analysis); based on that, an average estimated service life is obtained for each sub-factor, by calculating the average estimated service lives of all points that consider a given sub-factor. Both methods intend to identify durability patterns for each sub-factor analysed, in comparison with the average service life obtained for the whole sample.

3.3.4. Determination of a reference service life

According to ISO 15686: 2011, the reference service life is the period of time that a building or its elements are expected to last in a given set (reference set) of in-use conditions. Nevertheless, the reference service life could be difficult to quantify. Various authors (Hovde, 1998; Teplý, 1999; Nireki, 2002) suggested that the reference service life can be obtained based on: i) the opinion of experts in the field, based on previous experience; ii) technical information from manufacturers; iii) the results of laboratory tests or aging tests; iv) scientific research; and v) construction regulations and standards.

In the methodology described in this section, the reference service life is estimated based on the knowledge of the behaviour of components in real conditions of use. For that purpose, a comprehensive fieldwork survey must be performed, analysing a representative sample, collected through *in situ* inspections, followed by a detailed statistical analysis. Three methodologies are thus adopted for the estimation of a reference service life for the component analysed (Silva et al., 2016).

In the first method, the reference service life is obtained through the degradation curve for the whole sample, as described before. I.e., the reference service life is obtained, in a simplified manner, through the intersection between the average degradation curve and the maximum theoretical limit that establishes the end of service life of the building component under analysis.

In the second method, the average exposure conditions for a single component are considered to obtain the reference service life. For that purpose, a preliminary quantification of the durability factors is performed, according to the values proposed in ISO 15686: 2011, Mc Duling (2006) and Silva et al. (2016): 0.8 for components exposed to very aggressive conditions; 0.9 for aggressive conditions; 0.95 for averagely aggressive conditions; 1.0 for current conditions; 1.1 for slightly favourable conditions; and 1.2 for favourable conditions. Then, the case studies within the sample, exposed to a current average condition, i.e. those for which all the sub-factors are equal to 1.0, are considered in the determination of the reference service life (*RSL*), as described in Equation (3.3.3.).

$$\mathrm{ESL} = RSL \cdot A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G \Leftrightarrow RSL = \frac{\mathrm{ESL}}{A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G} \Leftrightarrow RSL = \frac{\mathrm{ESL}}{(0.8^{v} \cdot 0.9^{w} \cdot 0.95^{x} \cdot 1.1^{y} \cdot 1.2^{z})} \quad \textbf{(3.3.3.)}$$

in which exponents v, w, x, y and z correspond to the number of times that each k value is present in the case study in question.

In the third method, the average conditions for the whole sample are analysed. A preliminary quantification of the sub-factors is also performed, and the ratio between the estimated service life (*ESL*) of each case study obtained by the graphical method (described in section 3.3.2) and the *ESL* obtained by the factor method is calculated. Afterwards, the reference service life is given by the average of the values of the *ESL* for the case studies in which this ratio is lower than 3%.

Finally, the reference service life used in the factor method corresponds to an average of the three values obtained through the three methods described.

3.3.5. Application of the factor method, fine-tuning of the durability factors and model's validation

The generic expression of the factor method (Equation 3.3.1) should be adapted to the specific context of the component under analysis. The equation should include all the relevant sub-factors that influence the service life of the component, as long as these factors can be quantified with a known accuracy. Therefore, a multiplicity of equations of the factor method can be found, when applied to different components and even the same component, in different contexts, can lead to different formulas.

After defining the equation of the factor method that allows estimating the service life of the component under analysis, the durability factors included in the equation should be quantified. In the methodology described in this section, the durability factors are fine-tuned based on the knowledge obtained through the fieldwork survey, related to the degradation path of the component over time and according to its characteristics. For that purpose, the durability factors are obtained through an iterative process, intended to minimize the differences between the *ESL* obtained by the factor method and the *ESL* obtained through the graphical method. In the various studies (Silva et al., 2016; Marques et al., 2018; Jardim et al., 2019; Maia et al., 2020) in which this approach to the factor method was applied, other scenarios were tested for the quantification of the factor method, namely: a neutral scenario, where all the sub-factors are equal to 1.0, which is only used to prove the impact of the factors; and a scenario where the durability factors are quantified based on ISO 15686: 2011, which is used in the comparison with the optimised or fine-tuned scenario. The comparison between the different scenarios allows proving that the fine-tuned scenario is more reliable, leading to more realistic *ESL*, since it encompass the real degradation phenomena of the component under analysis.

Finally, the model is validated, considering that the graphical method is more accurate in the description of the degradation phenomena of the component analysed, since it is based on the actual degradation condition observed for different components in real use conditions. The model's validation is based on statistical indicators, as follows (Gaspar and de Brito, 2008; Emídio et al., 2014; Galbusera et al., 2015, Silva et al., 2016):

- The average of the ratio between the *ESL* obtained through the factor method (*FM*) and the graphical method (*GM*) should not differ from 1 by more than 5%, i.e. its maximum range is [0.95; 1.05];
- The amplitude of values obtained through the *FM* (i.e., the variation between the highest and the lowest values) should be lower than the amplitude of values obtained through the *GM*;
- The results obtained through the *FM* must have physical meaning, i.e. excessively high or low *ESL* usually correspond to outliers or case studies that have not been adequately modelled by the *FM*;
- At least, 50% of the sample analysed should present a *FM*/*GM* ratio of 0.85 or greater, i.e. the *ESL* predicted by the *FM* and by the *GM* should be similar, adopting a conservative approach in the estimation of the service life of the

component under analysis;

- The cumulative number of *FM*/*GM* ratios of 1.50 or greater (that is, failed estimations) should be lower than 10% of the sample;
- The iterations come to an end when the maximum number of *FM*/*GM* ratios falling in the range [0.85; 1.15] is reached.

Once the optimum quantification of the durability subfactors is defined, considering the observed degradation condition of an extensive and representative sample, through the fulfilment of the model's validation criteria, it is assumed that the proposed model is adequate for predicting the service life of the component under analysis. Nevertheless, the approach described in this section, allows a continuous analysis of new case studies, which can be easily implemented in the proposed model, in order to calibrate it.

3.3.6. Concluding remarks

The factor method is seen as a general framework for service life prediction, mainly due to its simplicity, which enabled its practical application in the sector of construction and maintenance of buildings. Nonetheless, the method can be too simplistic, mainly because does not take into account the degradation phenomena associated to the component under analysis, which can lead to biased service life estimations. In this sense, a more detailed approach was proposed, in order to encompass the evolution of the degradation condition of the component analysed (over time and considering its characteristics), in order to obtain more realistic estimations. The methodology proposed in this section allows overcoming some of the limitations of the factor method, without significantly increasing its complexity, which could compromise its applicability in practice. This methodology was already successfully applied to several components of the building's envelope (e.g. renderings, paintings, natural stone, ceramic claddings, ETICS, architectural concrete surfaces, window framing and wooden walls). The practical implementation of this methodology is shown in section 4.1 of this report.

References

Davies, H. and Wyatt, D. (2004). Appropriate use of the ISO 15686-1 factor method for durability and service life prediction. *Building Research and Information*, V. 32(6), pp. 552-553.

Emídio, F., de Brito, J., Gaspar, P. and Silva, A. (2014). Application of the factor method to the estimation of the service life of natural stone cladding. *Construction and Building Materials*, V. 66, pp. 481-493.

Galbusera, M. M., de Brito. J. and Silva, A. (2014). Application of the factor method to the prediction of the service life of ceramic external wall cladding. *Journal of Performance of Constructed Facilities*, V. 29(3), pp. 04014086.

Gaspar, P. L. and de Brito, J. (2008). Service life estimation of cement-rendered facades. *Building Research & Information*, V. 36(1), pp. 44-55.

Hovde, P.J. (1998). *Evaluation of the Factor Method to estimate the service life of building components*. CIB World Building Congress, Gaevle, Sweden, pp. 223-232.

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

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

Jardim, A., Silva, A., de Brito, J. (2019). Application of the factor method to the service life prediction of architectural concrete. *Canadian Journal of Civil Engineering*, V. 46(11), pp. 1054-1062.

Magos, M., de Brito, J., Gaspar, P. L. and Silva, A. (2016). Application of the factor method to the prediction of the service life of external paint finishes on facades. *Materials and Structures*, V. 49, 12, pp. 5209-5225.

Maia, M., Morais, R., Silva, A. (2020). Application of the factor method to the service life prediction of window frames. *Engineering Failure Analysis*, V. 109, 104245. DOI: https://doi.org/10.1016/j.engfailanal.2019.104245.

Marques, C., de Brito, J., Silva, A. (2018). Application of the factor method to the service life prediction of ETICS. *International Journal of Strategic Property Management*, V. 22(3), pp. 204-222.

Mc Duling, J. J. (2006). *Towards the development of transition probability matrices in the Markovian model for the predicted service life of buildings*. PhD Thesis in Civil Engineering, Faculty of Engineering, Built Environment and Information Technology, University of Pretoria, Pretoria.

Mc Duling, J., Horak, E. and Cloete, C. (2008). *Service life prediction beyond the 'Factor Method'*. 11th International Conference on Durability of Building Materials and Components; Istanbul, Turkey, T42.

Moser, K., Edvardsen, C. (2002). *Engineering design method for service life prediction*. 9th International Conference on the Durability of Building Materials and Components, Brisbane, Australia, paper 222.

Nireki, T., Inukai, T., Motohashi, K. (2002). *Toward practical application of factor method for estimating service life of building*. 9th International Conference on the Durability of Building Materials and Components, Brisbane, Australia, paper 218.

Silva, A., de Brito, J. and Gaspar, P. (2016) *Methodologies for service life prediction of buildings: with a focus on façade claddings*. Springer International Publishing, Switzerland.

Shohet, I., Rosenfeld, Y., Puterman, M. and Gilboa, E. (1999). *Deterioration patterns for maintenance management - a methodological approach*. 8th International Conference on Durability of Building Materials and Components; Vancouver, Canada, pp. 1666-1678.

Shohet, I.M., Puterman, M., Gilboa, E. (2002). Deterioration patterns of building cladding components for maintenance management. *Construction Management and Economics*, V. 20(4), pp. 305-314.

Shohet, I. M., Paciuk, M. (2004). Service life prediction of exterior cladding components under standard conditions. *Construction Management and Economics*, V. 22(10), pp. 1081-1090.

Teplý, B. (1999). Service life prediction of structures - factor method. Structural Horizon, Vol. 8, pp. 137-141. [in Czech]

4. Current applications of the factor method

4.1. Service life prediction of buildings' envelope in Portugal

Ana Silva, Jorge de Brito and Pedro Lima Gaspar; University of Lisbon

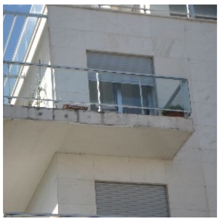
4.1.1. The context

Among the existing methodologies for service life prediction, the factor method stands out as a general framework that establishes the principles for the estimation of the service life of buildings and their components (Silva et al., 2016). The factor method is a simple tool that can be easily implemented in practice, allowing different procedures for the quantification of the durability factors. Although the simplicity of the method can be seen as its main advantage, when the estimation of the durability factors and the reference service life is performed in a too simplistic manner, large errors can be obtained. In this sense, Gaspar and de Brito (2008) suggested a methodology to encompass the impact of the degradation phenomena in the application of the factor method, as described in section 3.3 of this report. This approach allows obtaining more reliable results, since it considers the real degradation condition of the component under analysis.

4.1.2. Application of the factor method to the elements of the building's envelope in Portugal

The methodology proposed by Gaspar and de Brito (2008) has been applied to several elements of the building's envelope in Portugal. For that purpose, a comprehensive sample was collected over the years for each element, in order to identify a degradation pattern for the element analysed (Figure 4.1.1.).

85 rendered façades
Silva et al. (2016)



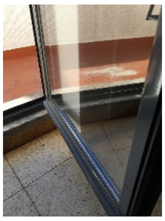
203 natural stone claddings
Silva et al. (2016)

186 Ceramic claddings
Silva et al. (2016)

177 Painted surfaces
Silva et al. (2016)

263 ETICS
Marques et al. (2018)

239 architectural concrete surfaces
Jardim et al. (2019)



126 window framing (aluminium)
Maia et al. (2020)

41 Window framing (wooden)
Maia et al. (2020)

Figure 4.1.1. - Samples analysed in the application of the factor method to the elements of the building's envelope in Portugal

Based on the sample collected, and adopting the methodology proposed by Gaspar and de Brito (2008) (described in detail in section 3.3 of this report), the various authors established mathematical equations for the determination of an estimated service life of the different elements of the buildings' envelope, as shown in Table 4.1.1.

Table 4.1.2. - Mathematical equations for the application of the factor method to the elements of the buildings' envelope

Element of the buildings' envelope	Mathematical equation for the application of the factor method
Renderings *Silva et al. (2016)*	$ESL = RSL \cdot A1 \cdot B1 \cdot B2 \cdot B3 \cdot B4 \cdot B5 \cdot E1 \cdot E2 \cdot E3 \cdot E4 \cdot E5 \cdot F1 \cdot G1$ Where *ESL* represents the estimated service life, *RSL* the reference service life (equal to 16.1 years), *A*1 the render type, *B*1 façade colour, *B*2 building geometry, *B*3 eaves' protection, *B*4 protection of parapets in roofs and terraces, *B*5 protection of balcony parapets, *B*6 ground floor protection (socle), *B*7 detailing/design level, *E*1 façade orientation, *E*2 distance from the sea, *E*3 exposure to damp, *E*4 distance from pollution sources, *E*5 façade protection level, *F*1 in-use conditions, and *G*1 ease of inspection of the façade
Natural stone claddings *Silva et al. (2016)*	$ESL = RSL \cdot A1 \cdot B1 \cdot B2 \cdot B3 \cdot B4 \cdot B5 \cdot E1 \cdot E2 \cdot E3 \cdot E4 \cdot F1 \cdot G1$ Where *ESL* represents the estimated service life, *RSL* the reference service life (equal to 68.3 years), *A*1 the type of stone, *B*1 the colour, *B*2 the type of finishing, *B*3 the size of stone plates, *B*4 the thickness of stone plates, B5 the location of the cladding, *E*1 the façades orientation, *E*2 the distance from the sea, *E*3 the exposure to wind-rain action, *E*4 the exposure to damp, *F*1 the type of property, and *G*1 the ease of inspection
Ceramic claddings *Silva et al. (2016)*	$ESL = RSL \cdot A1 \cdot B1 \cdot B2 \cdot B3 \cdot B4 \cdot B5 \cdot E1 \cdot E2 \cdot E3 \cdot E4 \cdot G1$ Where *ESL* represents the estimated service life, *RSL* the reference service life (equal to 51 years), *A* the type of surface, *B*1 façade colour, *B*2 tiles size, *B*3 the substrate, *B*4 presence of peripheral joints, *B*5 presence of peripheral protection, *E*1 façade orientation, *E*2 distance to the sea, *E*3 wind-rain action, *E*4 exposure to damp, and *G*1 ease of inspection of the façade
Painted surfaces *Silva et al. (2016)*	$ESL = RSL \cdot A1 \cdot B1 \cdot B2 \cdot B3 \cdot E1 \cdot E2 \cdot E3 \cdot E4 \cdot E5 \cdot F1 \cdot G1$ Where *ESL* represents the estimated service life, *RSL* the reference service life (equal to 9.7 years), *A* the type of paint, *B*1 façade colour, *B*2 type of finishing, *B*3 building geometry, *E*1 façade orientation, *E*2 wind-rain action, *E*3 distance to the sea, *E*4 exposure to damp, *E*5 distance to pollution sources, *F*1 in-use conditions, and *G*1 ease of inspection of the façade
ETICS *Marques et al. (2018)*	$ESL=RSL \cdot A1 \cdot Bl \cdot B2 \cdot B3 \cdot C1 \cdot E1 \cdot E2 \cdot E3 \cdot E4 \cdot E5 \cdot G1$ Where *ESL* represents the estimated service life, *RSL* the reference service life (equal to 21 years), *A*1 the type of cladding system, *B1* the colour; *B*2 the type of finishing, *B*3 the protection level, *C*1 the execution level, *E*1 the façades orientation, *E*2 the distance from the sea, *E*3 the exposure to damp, *E*4 the wind/rain action, *E*5 the exposure to pollution sources, and *G*1 the ease of inspection
Architectural concrete surfaces *Jardim et al. (2019)*	$ESL = RSL \cdot A1 \cdot A2 \cdot B1 \cdot E1 \cdot E2 \cdot E3 \cdot E4 \cdot E5 \cdot G1$ Where *ESL* represents the estimated service life, *RSL* the reference service life (equal to 43.8 years), *A*1 the colour of the surface, *A*2 the type of the surface treatment, *B*1 is the type of finishing, *E*1 the surfaces orientation, *E*2 the distance from the sea, *E*3 the exposure to damp, *E*4 the surfaces level of protection, *E*5 the exposure to wind-rain action, and *G*1 the ease of inspection
Window framing *Maia et al. (2020)*	$ESL = RSL \cdot A1 \cdot B1 \cdot B2 \cdot D1 \cdot E1 \cdot E2 \cdot E3 \cdot E4 \cdot G1$ Where *ESL* represents the estimated service life, *RSL* the reference service life (equal to 37.7 and 27.6 years, for aluminium and wooden frames, respectively), *A*1 the type of coating, *B*1 the window glazing, *B*2 the shading conditions, *D*1 the exposure to water vapour, *E*1 the facade orientation, *E*2 the exposure to wind/rain action, *E*3 the distance from the sea, *E*4 the exposure to pollutants and G1 the existence of regular maintenance and cleaning actions

The number and combination of the durability factors considered in the factor method should vary according to the building component under analysis (Re Cecconi and Iacono, 2005). In this sense, even though the methodology adopted for the application of the factor method was the same in all mentioned studies, each author defined different durability factors, depending on the specific characteristics of the element analysed, as shown in the various mathematical equations proposed in Table 4.1.1.

4.1.2.1. Quantification of the durability factors

Various authors (Emídio et al., 2014; Galbusera et al., 2014; Magos et al., 2016; Silva et al., 2016; Marques et al., 2019; Jardim et al., 2019; Maia et al., 2020) adopted the same methodology for the quantification of the durability factors, i.e. the data collected *in situ*, regarding the degradation condition of several case studies (with different ages and characteristics), were used to define degradation curves that allow quantifying the impact of the different sub-factors on the overall estimated service life of the element analysed.

Table 4.1.2 presents the sub-factors considered in factor *A*, related to the quality of the materials used, for each element analysed. In architectural concrete surfaces, the factor *A* was not evaluated, since the surfaces were inspected several years after installation, and the characteristics related to the composition of concrete are difficult to obtain. For all the elements analysed, the most favourable conditions are assigned higher values, which increase the estimated service life of these elements, and, on the contrary, the less favourable conditions lead to lower values of the sub-factors.

Table 4.1.3. - Quantification of factor *A* (quality of materials) for the elements of the buildings' envelope analysed

Element of the buildings' envelope	Factor *A* - quality of the materials used
Renderings	***A*1 - type of render:** Lime-cement renderings = 0.875 Current cement renderings = 1.025 Renderings with crushed marble = 1.325 Single-layer renderings = 1.425
Natural stone claddings	***A*1 - type of stone:** Marble = 0.95; Limestone = 1.00; Granite = 1.10
Ceramic claddings	***A*1 - type of surface:** Not glazed = 0.95; Glazed = 1.00;
Painted surfaces	***A*1 - type of paint:** Silicate and silicone paints = 1.00; Elastic membranes = 1.015; Plain paints = 1.025; Textured paint = 1.025
ETICS	***A*1 - type of system:** Traditional = 1.00; Strengthened = 1.10; Ceramic = 1.25
Architectural concrete surfaces	-
Window framing (aluminium)	***A*1 - type of coating:** Without protection = 0.90; Lacquering = 0.95; Anodic treatment = 1.10
Window framing (wooden)	***A*1 - type of coating:** Varnish = 1.00; Paint = 1.10

Table 4.1.3 shows the quantification of factor *B* (quality of design) for the elements of the buildings' envelope analysed.

In the analysis of factor *B*, the quantification of the colour of the elements may appear to reveal some incongruence, i.e. for some elements, dark colours (e.g. natural stone claddings) are assigned with most favourable values, while for other elements (e.g. painted surfaces) darker colours represent more unfavourable conditions. This choice is conditioned by the results obtained during the extensive fieldwork surveys, which revealed different patterns of degradation according to the type of colour of the elements analysed. In natural stone claddings, darker colours were associated with more durable stones, and, in these claddings, the identification of the anomalies is more difficult. On the other hand, in painted surfaces, darker colours lead to higher thermal variations, which can promote the incidence of anomalies.

Table 4.1.4. - Quantification of factor *B* (quality of design) for the elements of the buildings' envelope analysed

Element of the buildings' envelope	Factor B - quality of design
Renderings	***B*1 - Colour:** White = 0.70; Light colours = 1.025; Dark colours = 1.125 ***B*2 - Building geometry:** Irregular = 0.975; Compact = 1.025 ***B*3 - Eaves' protection:** Without protection = 1.00; With protection = 1.125 ***B*4 - Platbands copings:** Without copings = 0.85; With copings = 1.20 ***B*5 - Balcony copings:** Without copings = 1.00; With copings = 1.20 ***B*6 - Ground floor protection (socle):** Without protection = 1.00; With protection = 1.05 ***B*7 - Detail / design level:** Inferior = 0.80; Medium = 1.0; Superior = 1.15
Natural stone claddings	***B*1 - Colour:** Dark colours = 1.00; Light colours = 1.025 ***B*2 - Type of finishing:** Rough = 1.00; Smooth = 1.10 ***B*3 - Size of stone plates:** Large = 0.90; Medium = 1.00 ***B*4 - Thickness of stone plates:** Less than 2.5 cm = 1.00; ≥ 2.5 cm = 1.10 ***B*5 - Location of the cladding:** Partial and integral elevated cladding = 0.95; Bottom wall cladding = 1.00
Ceramic claddings	***B*1 - Colour:** Light colours = 1.00; Dark colours = 1.05 ***B*2 - Size tiles:** L > 20 cm = 0.825; L ≤ 20 cm = 1.00 ***B3* - Type of substrate:** Masonry = 1.00; Concrete = 1.05 ***B*4 - Peripheral joints:** Without = 1.00; With = 1.15 ***B5* - Peripheral protection:** Without = 1.00; With = 1.125
Painted surfaces	***B*1 - Colour:** Dark colours = 0.975; Light colours = 1.00; White = 1.075 ***B*2 - Type of finishing:** Smooth = 1.00; Rough = 1.15 ***B*3 - Building geometry:** Irregular = 0.975; Compact = 1.00
ETICS	***B*1 - Colour:** White = 1.10; Light colours = 1.00; Dark colours = 1.40; Other (associated with the colour of the ceramic tiles) = 1.40 ***B*2 - Type of finishing:** Rough = 0.90; Smooth = 1.00; Other (ceramic tiles) = 1.10 ***B*3 - Protection level:** Other = 0.775; Wainscot = 1.10; Peripheral profile = 1.15
Architectural concrete surfaces	***B*1 - Colour:** Dark colours = 0.90; Light colours = 1.20 ***B*2 - Surface treatment:** Without protection = 0.80; Varnish = 0.90; Paint = 1.10; Water repellent = 1.025; Paint + water repellent = 1.20 ***B*3 - Type of finishing:** Flat = 0.80; Textured = 1.20
Window framing (aluminium)	***B*1 - Window glazing:** Opaque lamina = 0.80; Single-glazed = 0.975; Double-glazed = 1.00 ***B*2 - Shading conditions:** No = 0.975; Yes = 1.00
Window framing (wooden)	***B*1 - Window glazing:** Opaque lamina = 0.85; Single-glazed = 1.00; (None of the wooden frames under analysis present a doubled-glazed framing) ***B*2 - Shading conditions:** No = 1.00; Yes = 1.10

Usually, factor C is not considered in these studies, since the degradation of the elements is evaluated several years after installation, and the information related with the execution conditions is difficult or even impossible to obtain. Nevertheless, Marques et al. (2018) considered factor C in the equation proposed for the application of the factor method. The authors considered two categories: adequate execution conditions, assigned with the value 1.0, for current situations; and inadequate execution conditions, assigned with the value 0.8, for situations in which execution errors were identified, or for case studies with lack of protection in accessible areas, among other deficiencies observed, related with the execution stage. This is one area in which further studies are essential.

Factor *D*, related with the inner environmental conditions, is only considered in the service life prediction of window frames. Maia et al. (2020) considered the influence of the exposure to water vapour on the durability of aluminium and wooden frames, as shown in Table 4.1.4. In the remaining elements analysed, this factor was not considered since the inner environmental conditions do not affect the durability of the external claddings.

Table 4.1.5. - Quantification of factor *D* (inner environment) for window frames

Element of the buildings' envelope	Factor *D* - internal environmental conditions
Window framing (aluminium)	***D*1 - Exposure to water vapour:** Yes = 1.00; No = 1.10
Window framing (wooden)	***D*1 - Exposure to water vapour:** Yes = 1.00; No = 1.015

Table 4.1.5 presents the quantification of the external environmental conditions (factor *F*) for the elements analysed. This factor presents the higher number of sub-factors, mainly due to the easiness of obtaining reliable information on the environmental exposure conditions to which the elements are subjected, and moreover, due to the significant impact of the environmental deterioration agents in the estimated service life of the elements of the buildings' envelope. The factors considered are almost the same for all the elements, with small differences between studies. The quantification of the distance from the sea, exposure to damp, the combined effect to wind and rain, and to pollutants, presents a similar trend in all studies, i.e. a higher exposure to these agents has harmful consequences on the elements, and decreases their estimated service life. However, in the quantification of the elements' exposure, some variations are observed in the impact of the different orientations on the estimated service life of the elements. In most of the elements, north and west are the most unfavourable conditions, due to a high exposure to rain and damp. Nevertheless, for other materials, south is the most unfavourable orientation, due to a higher incidence to UV radiation, which promotes the incidence of some anomalies, such as cracking.

The quantification of factor *F*, related with the use conditions, is presented in Table 4.1.6. Most of the studies do not consider this factor in the analysis. Moreover, in the three studies in which this factor is evaluated, the values proposed were almost neutral, i.e. both housing or commerce are assigned with the value 1.0, or near that value, which revealed the lack of significance of this factor to the estimation of the service life of the elements of the buildings' envelope. This conclusion is perhaps related with the characteristics of these models, which do not consider the maintenance actions in the evaluation of the degradation condition of the elements; in other words, the age of the elements is given by the time between the construction or the last intervention or maintenance action and the inspection time, and therefore assuming that during this period (the age of the element), no maintenance actions were performed. Consequently, the type of property and the way in which it promotes a greater number of interventions or a more adequate level of maintenance, is not relevant to the study, given the characteristics of the models described here.

Table 4.1.6. - Quantification of factor *E* (external environmental conditions) for the elements of the buildings' envelope analysed

Element of the buildings' envelope	Factor *E* - external environmental conditions
Renderings	***E*1 - façades orientation:** N/NE = 0.825; West/NW = 1.05; E/SE = 1.05; S/SW = 1.25 ***E*2 - distance from the sea:** Less than 5 km = 0.95; More than 5 km = 1.05 ***E*3 - exposure to damp:** Unfavourable = 1.00; Normal = 1.10; Favourable = 1.125 ***E*4 - exposure to pollution sources** Unfavourable = 0.80; Normal = 0.80; Favourable = 1.50 ***E*4 - façade protection level (wind-rain action)** Without protection = 1.00; Normal situation = 1.00; With protection = 1.00
Natural stone claddings	***E*1 - façades orientation:** North = 0.90; West/NW = 0.90; NE/E/SE = 0.95; S/SW = 1.00 ***E*2 - distance from the sea:** Less than 5 km = 1.00; More than 5 km = 1.15 ***E*3 - exposure to wind-rain action:** Severe = 1.00; Moderate = 1.00 ***E*4 - exposure to damp:** High = 0.90; Low = 1.00
Ceramic claddings	***E*1 - façades orientation:** West/NW = 0.945; S/SW = 1.045; E/SE = 1.125; N/NE = 1.125 ***E*2 - distance from the sea:** Less than 5 km = 0.85; More than 5 km = 1.00 ***E*3 - exposure to wind-rain action:** Severe = 0.90; Moderate = 0.995; Low = 1.00 ***E*4 - exposure to damp:** High = 0.90; Low = 1.00
Painted surfaces	***E*1 - façades orientation:** S/SW = 0.925; West/NW = 0.95; E/SE = 1.00; N/NE = 1.05 ***E*2 - exposure to wind-rain action:** Severe = 0.95; Moderate = 0.975; Low = 1.00 ***E*3 - distance from the sea:** Less than 5 km = 0.975; More than 5 km = 1.00 ***E*4 - exposure to damp:** High = 1.00; Low = 1.05 ***E*4 - exposure to pollution sources** Unfavourable = 0.95; Normal = 1.00
ETICS	***E*1 - façades orientation:** North = 0.80; South =1.00; East = 1.00; West = 1.00 ***E*2 - distance from the sea:** Less than 1 km = 0.80; Between 1 and 5 km = 1.00; More than 5 km = 1.10 ***E*3 - exposure to damp:** High = 1.00; Low = 1.15 ***E*4 - exposure to wind/rain action:** Severe = 0.80; Moderate = 0.90; Low = 0.95 ***E*5 - exposure to pollution sources** High = 0.95; Low = 1.10
Architectural concrete surfaces	***E*1 - façades orientation:** S/SW = 0.85; West/NW = 1.00; NE/E/SE = 1.00; North = 1.10 ***E*2 - distance from the sea:** Less than 1 km = 0.80; Between 1 and 5 km = 0.95; More than 5 km = 1.10 ***E*3 - exposure to damp:** High = 0.875; Low = 1.00 ***E*4 - surfaces level of protection (surrounding conditions, such as vegetation and adjacent buildings):** Without protection = 1.00; With protection = 1.05 ***E*5 - exposure to wind/rain action:** High = 1.00; Low = 1.25

Table 4.1.5. - Quantification of factor *E* (external environmental conditions) for the elements of the buildings' envelope analysed (continued)

Element of the buildings' envelope	Factor *E* - external environmental conditions
Window framing (aluminium)	***E*1 - façades orientation:** North = 0.975; West = 0.995; South =1.00; East = 1.05 ***E*2 - exposure to wind/rain action:** High = 0.975; Low = 1.00 ***E*3 - distance from the sea:** Less than 5 km = 0.975; More than 5 km = 1.00 ***E*4 - exposure to pollution sources** High = 1.00; Low = 1.10
Window framing (wooden)	***E*1 - façades orientation:** North = 0.90; West = 0.995; South =0.90; East = 1.00 ***E*2 - exposure to wind/rain action:** High = 0.95; Low = 1.00 ***E*3 - distance from the sea:** Less than 5 km = 0.90; More than 5 km = 1.00 ***E*4 - exposure to pollution sources** High = 1.00; Low = 1.05

Table 4.1.7. - Quantification of factor *F* (in-use conditions) for the elements of the buildings' envelope analysed

Element of the buildings' envelope	Factor *F* - in-use conditions
Renderings	***F*1 - type of property:** Private = 0.80; Public sector = 1.075; Commerce and services = 1.075
Natural stone claddings	***F*1 - type of property:** Housing = 1.00; Commerce and services = 1.00
Ceramic claddings	-
Painted surfaces	***F*1 - type of property:** Housing = 1.00; Commerce and services = 1.00
ETICS	-
Architectural concrete surfaces	-
Window framing (aluminium)	-
Window framing (wooden)	-

Table 4.1.7 shows the quantification of factor *G*, related with the maintenance conditions of the elements of the buildings' envelope.

Table 4.1.8. - Quantification of factor *G* (maintenance conditions) for the elements of the buildings' envelope analysed

Element of the buildings' envelope	Factor *G* - maintenance conditions
Renderings	***G*1 - ease of inspection:** Unfavourable = 1.00; Current = 1.225
Natural stone claddings	***G*1 - ease of inspection:** Unfavourable = 0.925; Current = 1.05
Ceramic claddings	***G*1 - ease of inspection:** Unfavourable = 0.985; Current = 1.00
Painted surfaces	***G*1 - ease of inspection:** Unfavourable = 0.985; Current = 1.00
ETICS	***G*1 - ease of inspection:** Unfavourable = 1.00; Current = 1.10
Architectural concrete surfaces	***G*1 - ease of inspection:** Unfavourable = 1.00; Current = 1.05
Window framing (aluminium)	***G*1 - regular maintenance:** Non-existent = 0.90; Monthly or higher = 0.975; Weekly / Bimonthly = 1.10
Window framing (wooden)	***G*1 - regular maintenance:** Non-existent = 0.85; Monthly or higher = 0.95; Weekly / Bimonthly = 1.10

In external claddings, only the ease of inspection is considered, since the maintenance conditions of these claddings cannot be evaluated with precision during the fieldwork survey, since this information is not always available in Municipalities, and the owners do not always know when a maintenance action was performed. On the other hand, for window frames, this information is more easily obtained, since the inspection is performed on each individual dwelling, and all the respective owners were consulted, which were able to provide reliable information regarding the maintenance actions performed. This is another area in which further studies are essential.

4.1.3. Estimated service life of the elements of the building's envelope

The application of the factor method to the different samples analysed, was evaluated based on a set of statistical indicators (explained in detail in section 3.3. of this report). The three more relevant parameters to consider are the average of *FM*/*GM*, the number of failed estimations (*FM/GM* ≥ 1.50) and the maximum number of *FM*/*GM* ratios falling in the range [0.85; 1.15]. The results presented in Table 4.1.8 reveal that, for all the elements analysed, the factor method proposed led to adequate results (an average of *FM*/*GM* near 1.0), i.e. the estimated service life (*ESL*) obtained through the application of the factor method is similar to the *ESL* obtained by the graphical method, based on the degradation condition of the elements observed in fieldwork.

Table 4.1.9. - Statistical indicators used to evaluate the model's validation

		Element of the buildings' envelope							
		Renderings	Natural stone claddings	Ceramic claddings	Painted surfaces	ETICS	Architectural concrete surfaces	Window framing	
								Aluminium	Wooden
Average of *FM/GM*		**0.97**	**0.99**	**1.00**	**1.03**	**1.03**	**1.02**	**1.01**	**1.04**
Standard deviation *FM/GM*		0.40	0.25	0.33	0.27	0.34	0.37	0.24	0.20
Range of results	***FM* (years)**	26.2	52.6	42.9	4.7	28.0	65.6	29.4	13.7
	***GM* (years)**	39.1	125.4	95.4	21.5	32.5	85.3	40.1	17.4
Extreme values of *FM*	**Maximum (years)**	33.1	97.4	70.8	7.9	40.0	89.9	55.0	33.8
	Minimum (years)	7.0	44.8	27.9	4.7	12.0	24.3	25.7	20.1
***FM/GM* ≥ 0.85**		71.8%	76.4%	69.9%	83.6%	74.1%	70.71%	75.6%	87.8%
***FM/GM* ≥ 0.70**		77.6%	90.6%	82.3%	89.3%	85.6%	83.3%	89.4%	100%
***FM/GM* ≥ 1.50**		**8.2%**	**4.4%**	**5.9%**	**5.1%**	**8.4%**	**8.79%**	**3.3%**	**2.4%**
0.85 ≤ *FM/GM* ≤ 1.15		**50.6%**	**60.1%**	**50.0%**	**59.9%**	**52.9%**	**45.19%**	**54.5%**	**63.4%**

In almost all elements, the maximum number of *FM*/*GM* ratios falling in the range [0.85; 1.15] is higher to 50%. The only exception is architectural concrete surfaces. The service life of this cladding solution is highly dependent of the characteristics of the concrete applied (e.g. concrete composition, the exposure class, among other parameters). Nevertheless, Jardim et al. (2019) were unable to obtain this information, since the surfaces were evaluated through visual inspections, several years after construction and the Municipalities do not have information about the construction processes. The fact that concrete characteristics are not considered in the surfaces' service life may justify the results obtained. This is yet another area in which further studies are essential, not only for concrete but also for other materials.

Table 4.1.9 presents the average estimated service life obtained for the elements of the buildings' envelope under analysis. In the different studies, the authors compared the results obtained with the literature related with the durability of the different element analysed, concluding that the results obtained are coherent and make sense from an empirical point of view. The discussion of the results obtained in the different studies, demonstrated the validity of the proposed models for the service life prediction of the element under analysis through the application of the factor method.

Table 4.1.10. - Statistical indicators regarding the *ESL* obtained for the elements of the buildings' envelope

	Element of the buildings' envelope															
	Renderings		**Natural stone claddings**		**Ceramic claddings**		**Painted surfaces**		**ETICS**		**Architectural concrete surfaces**		**Window framing**			
													Aluminium		**Wooden**	
	FM	*GM*	*FM*	*GM*	*FM*	*GM*	*FM*	*GM*	*FM*	*GM*	*FM*	*GM*	*FM*	*GM*	*FM*	*GM*
Average *ESL*	**16.2**	**18.8**	**66.9**	**70.5**	**49.8**	**54.5**	**10.4**	**10.0**	**21.0**	**21.9**	**43.9**	**48.0**	**39.5**	**40.5**	**28.5**	**27.8**
Median *ESL*	15.2	15.7	66.3	68.1	48.9	50.1	9.7	9.9	20.3	21.3	42.0	44.1	38.9	38.7	28.9	27.6
Standard deviation *ESL*	5.9	9.0	10.2	17.1	9.0	18.1	3.3	1.1	4.5	6.2	11.8	19.0	5.4	8.3	3.7	4.0
Confidence interval of 95%	± 1.2	± 1.8	± 2.0	± 3.4	± 1.3	± 2.6	± 0.5	± 0.2	± 0.6	± 0.8	± 1.5	± 2.4	± 1.7	± 2.5	± 1.1	± 1.2

4.1.4. Concluding remarks

Gaspar and de Brito (2008) proposed a new approach to the factor method, which intended to take into account in the determination of the reference service life and of the durability factors the real deterioration pattern of the building component under analysis. This approach has been applied to several elements of the buildings' envelope, leading to coherent results. Therefore, this approach to the factor method allows allying the simplicity and flexibility of the factor method as service life prediction tool, to a more reliable and realistic manner of quantifying the degradation phenomena of the element under analysis. The proposed methodology can be applied to other components (or other types of the same components) and in different geographic contexts, although, to do this, reliable information about the degradation of the element under analysis should be collected, through fieldwork surveys, which allows characterising the real degradation condition of the element in in-service conditions.

References

Emídio, F., de Brito, J., Gaspar, P. and Silva, A. (2014). Application of the factor method to the estimation of the service life of natural stone cladding. *Construction and Building Materials*, V. 66, pp. 481-493.

Galbusera, M. M., de Brito. J. and Silva, A. (2014). Application of the factor method to the prediction of the service life of ceramic external wall cladding. *Journal of Performance of Constructed Facilities*, V. 29(3), pp. 04014086.

Gaspar, P. L. and de Brito, J. (2008). Service life estimation of cement-rendered facades. *Building Research & Information*, V. 36(1), pp. 44-55.

Jardim, A., Silva, A., de Brito, J. (2019) Application of the factor method to the service life prediction of architectural concrete. *Canadian Journal of Civil Engineering*, V. 46(11), pp. 1054-1062.

Magos, M., de Brito, J., Gaspar, P. L. and Silva, A. (2016). Application of the factor method to the prediction of the service life of external paint finishes on facades. *Materials and Structures*, V. 49, 12, pp. 5209-5225.

The factor method as a general framework for service life prediction: Past and future trends

Maia, M., Morais, R., Silva, A. (2020). *Application of the factor method to the service life prediction of window frames*. Engineering Failure Analysis, V. 109, 104245. DOI: https://doi.org/10.1016/j.engfailanal.2019.104245.

Marques, C., de Brito, J., Silva, A. (2018). Application of the factor method to the service life prediction of ETICS. *International Journal of Strategic Property Management*, V. 22(3), pp. 204-222.

Re Cecconi, F., Iacono, P. (2005) *Enhancing the factor method - suggestions to avoid subjectivity*. 10th International Conference on Durability of Building Materials and Components 2005, Lyon, France, TT4-172.

Silva, A., de Brito, J. and Gaspar, P. (2016) *Methodologies for service life prediction of buildings: with a focus on façade claddings*. Springer International Publishing, Switzerland.

4.2. Service life prediction of claddings in South America

Ana Silva, Andrés J. Prieto and Jéssica Souza
University of Lisbon, Austral University of Chile, and University of Brasília

4.2.1. The context

The factor method has been used by practitioners in the last decades, mainly due to its simplicity, which makes it extremely easy to use in practice, allowing obtaining a more or less accurate estimation of the service life of the component analysed. The accuracy of the estimation depends on the existing knowledge regarding the behaviour of the component analysed. Nevertheless, over the years, the method proved to offer trustworthy results and it is a relatively reliable solution for service life prediction of buildings and components.

However, various authors (Hovde, 2000; Shohet et al., 2002; Moser and Edvardsen, 2002; Mc Duling et al., 2008) discussed the limitations of this method, essentially criticising it for neglecting the degradation state of the component in the moment of the service life prediction analysis, thus ignoring the variability of the degradation phenomenon, as well as the degradation pattern of the component analysed.

To overcome this limitation of the factor method, Gaspar and de Brito (2008) suggested a methodology to encompass the real degradation condition of the component under analysis, as described in detail in section 3.3. of this report. In this approach, the degradation condition of a large sample is assessed, and the knowledge regarding the progression of the degradation phenomena over time in the component analysed is used to quantify the reference service life and the durability factors encompassed in the service life estimation using the factor method.

The methodology of Gaspar and de Brito (2008) has been adopted by various authors (Galbusera et al., 2014; Magos et al., 2016; Silva et al., 2016; Marques et al., 2018; Jardim et al., 2019; Maia et al., 2020), as described in the previous sections of this report, and has been applied to different components of the buildings' envelope. All these studies mentioned that the local context of the studies influence the durability factors considered. Most of these studies analysed claddings or building components located in Lisbon or in other shoreline regions of Portugal, and in this sense, for example, the influence of freeze/thaw cycles is virtually non-existent, and it was not encompassed in these studies. These studies thus proposed the hypothesis of adopting the same methodology for other regions of the globe, with different climatic conditions. Moreover, the authors (Galbusera et al., 2014; Silva et al., 2016; Marques et al., 2018) argued that the proposed approach to the factor method could be easily adapted to other regions and to other building components, calibrating the degradation rate to specific intrinsic and indigenous characteristics of the component analysed.

The studies of Souza et al. (2018b) and Prieto and Silva (2019) proved that, in fact, the methodological approach established by Gaspar and de Brito (2008) could be applied to other geographical contexts, namely in South America. Souza et al. (2018b) adopted this methodology for the service life estimation of ceramic claddings in Brasília, Brazil, while Prieto and Silva (2019) applied the methodology to the service life prediction of timber claddings in South Chile. In the next sections, the two applications are described in detail.

4.2.2. Application of the factor method, based on the degradation condition of the claddings to ceramic tiling systems in Brasília-Brazil

In the study of Souza et al. (2018b), the factor method was applied to 96 ceramic tiling systems in Brasília-Brazil, collected by researchers of the University of Brasília (UnB), through *in-situ* inspections complemented by other diagnosis techniques (e.g. thermographic analysis, percussion tests, pull-off tests).

The authors identified nine durability factors that should be considered in the factor method, when applied to the service life prediction of ceramic tiling systems in Brasília-Brazil, as shown in Equation (4.2.1). The reference service life was obtained through the three methodologies described in section 3.3. of this report, and the average of the values obtained by the three methodologies is 44 years.

$$ESL = RSL \cdot A1 \cdot A2 \cdot A3 \cdot B1 \cdot B2 \cdot B3 \cdot E1 \cdot E2 \cdot E3 \qquad \textbf{(4.2.1)}$$

Where *ESL* is the estimated service life, *RSL* the reference service life (equal to 44 years), *A*1 the ceramic claddings colour, *A*2 the variety of ceramic tiles applied, *A*3 the ceramic tiles size, *B*1 the claddings' area, *B*2 the presence of joints, *B*3 the construction elements, *E*1 the exposure to pollutant sources, *E*2 the exposure to wind action and *E*3 the claddings orientation. For the application of the factor method to ceramic tiling systems in Brasília, the durability factors should be quantified as described in Table 4.2.1.

Table 4.2.1. - Weighting of the durability factors adopted in the factor method applied to ceramic tiling systems in Brasília (data sourced from Souza et al., 2018b)

Characteristics		***ESL***		**Quantification of the durability factor**
		DC	***GM***	
Colour (*A*1)	Light	43	46	1.000
	Dark	38	50	0.925
Variety (*A*2)	One type	52	54	1.150
	Various types	42	47	1.000
Size (*A*3)	Small	46	45	1.000
	Large	-	50	0.975
Area (*B*1)	Current	44	48	1.100
	Extensive	43	48	1.000
Joints (*B*2)	With joints	-	53	1.175
	Without joints	43	45	1.000
Element (*B*3)	Facade	43	46	1.000
	Gable	43	51	1.000
	Staircase	69	48	1.025
Pollution (*E*1)	Current	43	47	1.000
	Unfavourable	37	49	0.975
Wind (*E*2)	Current	43	52	1.150
	Unfavourable	42	46	1.000
Orientation (*E*3)	North	41	46	0.950
	South	-	48	1.000
	East	52	49	0.975
	West	-	48	0.975

These factors were optimised, adopting the methodology proposed by Gaspar and de Brito (2008), in order to minimise the deviation between the values predicted by the factor method (*FM*) and the values observed during fieldwork (*GM*).

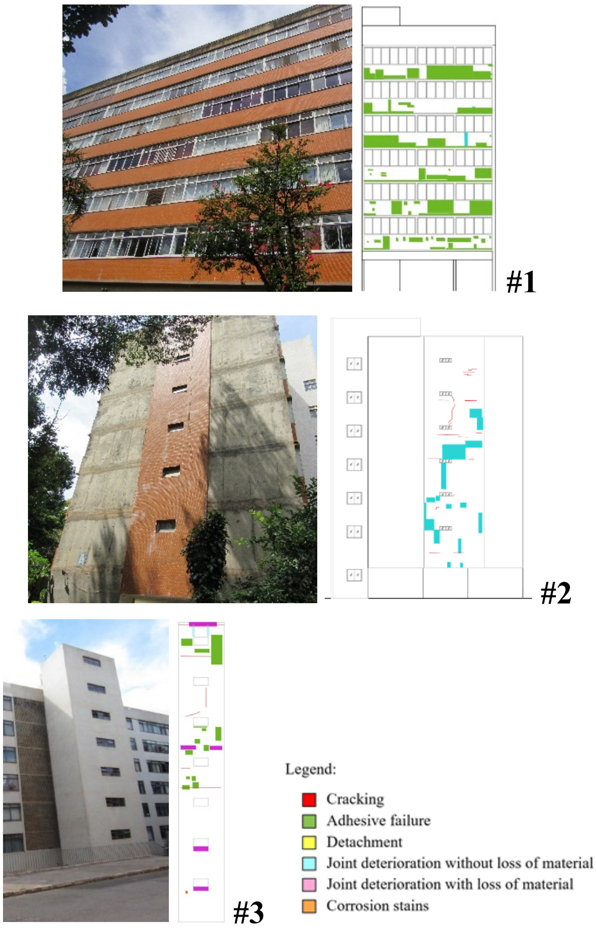
Souza et al. (2018b) adapted the initial proposal of Silva et al. (2016), for the application of the factor method to the service life prediction of ceramic claddings, to the Brazilian context. Some factors included in the model of Silva et al. (2016) were not encompassed in the model of Souza et al. (2018b), for example, the distance from the sea and the exposure to damp, since in Brasília all the buildings analysed have the same exposure conditions to these two factors. Concerning the façades orientation, in Portugal, ceramic claddings facing South tend to show higher levels of degradation due to a longer exposure to UV radiation and, therefore, this orientation was considered the most unfavourable, while in Brasília (south hemisphere) the North orientation was considered the most unfavourable. Moreover, in Brasília, the factors related with the design characteristics (factor *B*), are different from the factors analysed in the Portuguese context. These factors are related to the specificity of the Pilot Plan and the regional plans adopted in the construction of Brasília.

The validation of the proposed model was performed through the evaluation of a series of statistical indicators (mentioned in section 3.3.5. of this report), and the following results were obtained: i) the average of the ratio between the estimated service life (*ESL*) from the *FM* and the *GM* is equal to 1.04, which reveals that this ratio does not vary from 1 by more than 5%; ii) the number of failed estimations is below 10% (8.6%); and iii) 55.9% of the sample present a ratio between the values of the *FM* and the *GM* within the range 0.85-1.15, thus revealing a lower percentage of errors between the predicted (*FM*) and the observed (*GM*) estimated service life of the sample.

In the study of Souza et al. (2018b), a deterministic and a stochastic approach for modelling the service life of ceramic tiling systems through the adoption of the factor method were adopted. For both approaches, a reference service life (*RSL*) of 44 years was obtained. Adopting a deterministic approach, an average estimated service life (*ESL*) around 47 years was obtained, while through the adoption of the stochastic approach, an average estimated service life (*ESL*) around 56 years was achieved. The stochastic approach leads to a higher variation of results, since it allows encompassing the variability of the degradation phenomena and the specific conditions of each case study analysed. The results obtained are in accordance with the *ESL* obtained with the *GM*, which was around 48 years, which describes the real degradation of ceramic claddings, observed during the fieldwork. Moreover, the values obtained are also in accordance with the expected service life of these claddings according to the literature (Galbusera et al., 2014; Silva et al., 2016; Gaspar, 2017).

In Figure 4.2.1., three illustrative examples are presented, to describe the application of the methodology to ceramic tiling systems in the context of Brazil. The comparison between the values of the *ESL* predicted by the *FM* and the values obtained by the *GM*, for the three case studies shown, reveal that the proposed model is able to accurately estimate the service life of ceramic tilling systems. The difference between case studies #2 and #3 lies only on the colour of the ceramic claddings applied. This apparent small difference in the characteristics of the two case studies leads to a difference of 5 years in the estimated service life of the ceramic tiling systems. Souza et al. (2018a) refer that ceramic claddings with “light colours” are more prone to reflecting solar radiation, which reduces the extent of thermal variations in the ceramic cladding system and, consequently, reduces the tendency of the cladding to suffer anomalies due to this phenomenon. This proves once again that small variations in the quantification of just one factor can lead to significant variations in the estimated service life of the component analysed.

Illustrative example



Characteristics of the case study and application of the factor method

Ceramic cladding with 35 years and with a degradation severity index equal to 5.4%;

Ceramic cladding with dark colours (0.925), with one type (1.150) and small-sized tiles (1.000), with a current area (1.100), without joints (1.000), the cladding is in a façade (1.000) facing North (0.950), and with unfavourable exposure to pollutants (0.975) and current exposure to wind (1.100).

$ESL_{FM} = 44 \cdot 0.925 \cdot 1.15 \cdot 1 \cdot 1.1 \cdot 1 \cdot 1 \cdot 0.95 \cdot 0.975 \cdot 1.1 \approx 52$ years

$ESL_{GM} \approx 46$ years

Ceramic cladding with 35 years and with a degradation severity index equal to 3.1%;

Ceramic cladding with dark colours (0.925), with one type (1.150) and small-sized tiles (1.000), with a current area (1.100), without joints (1.000), the cladding is in a gable (1.000) facing West (0.975), and with current exposure to pollutants (1.100) and to wind (1.100).

$ESL_{FM} = 44 \cdot 0.925 \cdot 1.15 \cdot 1 \cdot 1.1 \cdot 1 \cdot 1 \cdot 0.975 \cdot 1.1 \cdot 1.1 \approx 61$ years

$ESL_{GM} \approx 60$ years

Ceramic cladding with 38 years and with a degradation severity index equal to 3.3%;

Ceramic cladding with light colours (1.000), with one type (1.150) and small-sized tiles (1.000), with a current area (1.100), without joints (1.000), the cladding is in a staircase (1.025) facing South (1.000), and with current exposure to pollutants (1.100) and to wind (1.100).

$ESL_{FM} = 44 \cdot 1 \cdot 1.15 \cdot 1 \cdot 1.1 \cdot 1 \cdot 1.025 \cdot 1 \cdot 1.1 \cdot 1.1 \approx 69$ years

$ESL_{GM} \approx 63$ years

Figure 4.2.1. - Illustrative examples of the application of the factor method to ceramic tilling systems in Brasília, Brazil

4.2.3. Application of the factor method, based on the degradation condition of the claddings to timber claddings in South Chile

The condition-based approach to the factor method, proposed by Gaspar and de Brito (2008), was also applied by Silva and Prieto (2019) to the service life prediction of external timber claddings in South Chile. This is a new application of the methodology, to a new material and in a different geographical context.

This methodology relies on the evaluation of the degradation condition of 102 timber claddings located in the Valdivia area, Los Ríos region. Silva and Prieto (2019) thus proposed a new application of the factor method, adapting the mathematical equation to the specific regional or local surrounding environmental conditions and to the intrinsic characteristics of the material under analysis.

The authors identified 11 durability factors, considering previous knowledge about the influence of these factors in the degradation pattern of external timber claddings (Prieto and Silva, 2018, 2020). The authors adapted the three methodologies exhaustively described previously, and a reference service life of 36.9 years was determined. Therefore, Equation (4.2.2) shows the proposal of the authors (Silva and Prieto, 2019) for the application of the factor method to the service life prediction of external timber claddings in the Chilean context.

$$ESL = RSL \times A1 \times B1 \times B2 \times B3 \times E1 \times E2 \times E3 \times E4 \times E5 \times F1 \times G1 \qquad \textbf{(4.2.2)}$$

Where *ESL* represents the estimated service life, *RSL* is the reference service life (equal to 36.9 years), *A*1 is the type of wood, *B*1 is the colour of the finishing layer, *B*2 is the location of the cladding, *B*3 is the direction of the wood elements in the cladding, *E*1 is the claddings orientation, *E*2 is the distance from the sea, *E*3 is the exposure to damp, *E*4 is the exposure to wind-rain action, *E*5 is the exposure to pollutants, *F*1 is the type of use, and *G*1 is the ease of inspection. Table 4.2.2 shows the quantification of the durability factors for the application of the factor method to external timber claddings in South Chile.

Table 4.2.2. - Weighting of the durability factors adopted in the factor method applied to timber claddings in Valdivia (data sourced from Silva and Prieto, 2020)

Surfaces' characteristics		***ESL***		**Quantification of the durability factor**
		DC	***GM***	
Type of wood (*A*1)	Pinus radiata/Eucalyptus globulus	35.6	40.8	0.950
	Nothofagus obliqua/Nothofagus alpina	25.0	41.4	1.000
Colour (*B*1)	White	33.9	42.9	1.000
	Light	36.0	37.1	0.975
	Dark	34.4	41.2	0.950
Location of the cladding (*B*2)	Partial elevated	38.1	41.3	1.000
	Bottom wall	35.5	43.1	0.950
Direction of the cladding (*B*3)	Horizontal	34.3	36.4	1.000
	Vertical	33.3	37.6	0.900
Orientation (*E*1)	N/NE/NW	35.6	45.3	1.000
	W	37.5	42.9	1.075
	E/	34.6	39.6	1.075
	S/SE/SW	33.3	36.2	1.050
Distance from the sea (*E*2)	< 5 km	35.3	42.9	0.995
	> 5 km	35.3	42.9	1.050
Exposure to damp (*E*3)	Low	33.3	36.2	1.025
	High	36.1	42.3	1.000
Wind/rain action (*E*4)	Low	34.4	40.1	1.150
	High	36.1	42.3	1.000
Exposure to pollutants (*E*5)	Low	34.4	40.1	1.000
	High	35.9	40.4	0.975
Type of use (*F*1)	Housing	22.4	51.4	0.900
	Commerce	36.1	42.3	1.000
Ease of inspection (*G*1)	Current	34.4	40.1	1.150
	Unfavourable	35.6	40.8	1.000

Following the same approach described previously, the durability factors were optimised, in order to minimise the differences between the *ESL* predicted by the *FM* and the *ESL* obtained through the *GM*, which depicts the real degradation path of the timber claddings observed during the fieldwork survey.

The proposed model was validated considering the statistical indicators mentioned in section 3.4.5. of this report, and the following results were obtained (Silva and Prieto, 2020): i) 61.74% of the sample presents a cumulative frequency of *FM*/*GM* greater than or equal to 0.85; ii) the number of failed estimations is 8.8% (below 10%); iii) 37.25% of the sample shows a variation of less than 15% compared to the perfect situation (i.e. the values of the *ESL* obtained by the *FM* are equal to the values of the *GM*), while 50.0% of the sample presents a variation of less than 20% compared to the perfect situation, in which *FM*/*GM* ratio is equal to 1.

The application of the factor method to the service life prediction of timber claddings leads to an average ESL of 37 years, which is in accordance with previous studies that proposed an estimated service life between 30 to 35 years for wood materials in outdoor exposure environments (Thelandersson et al., 2011). Silva and Prieto (2019) refer that the *ESL* of timber claddings varies significantly with the type of wood and with other cladding's characteristics, especially, those related with the environmental exposure conditions, as can be checked in the three illustrative examples presented in Figure 4.2.2.

Illustrative example	Characteristics of the case study and application of the factor method
 #1	**Timber cladding with 45 years and with a degradation severity index equal to 27.8%;** Timber cladding in Pinus radiata/Eucalyptus globulus (0.950), with dark colours (0.950), in a bottom wall cladding (0.950), with horizontal direction of the timber elements (1.000), facing West (1.075), at more than 5km from the Pacific ocean (1.05), with low exposure to damp (1.025), high exposure to wind-rain action (1.00), with high exposure to pollutants (0.975), housing (0.900), with unfavourable inspection conditions (1.000). $ESL_{FM} = 36.9 \cdot 0.95 \cdot 0.95 \cdot 0.95 \cdot 1 \cdot 1.075 \cdot 1.05 \cdot 1.025 \cdot 1 \cdot 0.975 \cdot 0.9 \cdot 1 \approx 32$ years $ESL_{GM} \approx 37$ years
 #2	**Timber cladding with 30 years and with a degradation severity index equal to 13.0%;** Timber cladding in Pinus radiata/Eucalyptus globulus (0.950), with dark colours (0.950), in a partial elevated cladding (1.000), with vertical direction of the timber elements (0.900), facing West (1.075), at less than 5km from the Pacific ocean (0.995), with high exposure to damp (1.000), low exposure to wind-rain action (1.15), with high exposure to pollutants (0.975), housing (0.900), with current inspection conditions (1.150). $ESL_{FM} = 36.9 \cdot 0.95 \cdot 0.95 \cdot 1 \cdot 0.9 \cdot 1.075 \cdot 0.995 \cdot 1 \cdot 1.15 \cdot 0.975 \cdot 0.9 \cdot 1.15 \approx 37$ years $ESL_{GM} \approx 39$ years
 #3	**Timber cladding with 19 years and with a degradation severity index equal to 5.0%;** Timber cladding in Pinus radiata/Eucalyptus globulus (0.950), with dark colours (0.950), in a bottom wall cladding (0.950), with horizontal direction of the timber elements (1.000), facing West (1.075), at more than 5km from the Pacific ocean (1.05), with low exposure to damp (1.025) and to wind-rain action (1.15), with high exposure to pollutants (0.975), housing (0.900), with current inspection conditions (1.150). $ESL_{FM} = 36.9 \cdot 0.95 \cdot 0.95 \cdot 0.95 \cdot 1 \cdot 1.075 \cdot 1.05 \cdot 1.025 \cdot 1.15 \cdot 0.975 \cdot 0.9 \cdot 1.15 \approx 42$ years $ESL_{GM} \approx 46$ years

Figure 4.2.1. - Illustrative examples of the application of the factor method to timber claddings in Valdivia, Chile

These examples prove the applicability of the model, showing that, despite the natural deviations between the predicted and observed values, resulting from the complexity of the modelled phenomenon and the high number of durability factors considered, the results obtained by the *FM* are similar to those observed in fieldwork (*GM*).

4.2.4. Concluding remarks

Modelling and prediction the service life of external claddings can be a complex and time-consuming task, mainly due to the complexity of the degradation phenomenon, and the large number of factors that simultaneously influence this phenomenon. Nevertheless, the factor method proves to be a reliable and simple tool, to be adopted in practice, to provide some information regarding the estimated service life of external claddings. The approach proposed by Gaspar and de Brito (2008), based on the condition of the component analysed, allows obtaining more realistic estimations of its expected service life, since it takes into account its real deterioration path. The different studies mentioned (Galbusera et al., 2014; Magos et al., 2016; Silva et al., 2016; Marques et al., 2018; Jardim et al., 2019; Maia et al., 2020) refer that the this methodology can be adopted in other geographical contexts and to other building components, and the proof of concept of these proposals is these two studies, which applied the same methodology to geographic locations so different from Lisbon, and to a new cladding material, showing that consistent and reliable results are obtained. Considering the complexity of the phenomena under analysis, the similarity between the results obtained through the factor method and those observed during the fieldwork survey (*GM*) allows validating the proposed methodology, revealing that, with the necessary adaptations, this general approach to the factor method could, in fact, be applied in other regions, to other buildings components, with other constructive characteristics.

References

Emídio, F., de Brito, J., Gaspar, P. and Silva, A. (2014). Application of the factor method to the estimation of the service life of natural stone cladding. *Construction and Building Materials*, V. 66, pp. 481-493.

Galbusera, M. M., de Brito. J. and Silva, A. (2014). Application of the factor method to the prediction of the service life of ceramic external wall cladding. *Journal of Performance of Constructed Facilities*, V. 29(3), pp. 04014086.

Gaspar, P. L. and de Brito, J. (2008). Service life estimation of cement-rendered facades. *Building Research & Information*, V. 36(1), pp. 44-55.

Gaspar, P. L. (2017) End of the service life of ceramic cladding: Lessons from the Girasol building in Madrid. *Journal of Performance of Constructed Facilities*, V. 31(2), pp. 04016088.

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

Jardim, A., Silva, A., de Brito, J. (2019) Application of the factor method to the service life prediction of architectural concrete. *Canadian Journal of Civil Engineering*, V. 46(11), pp. 1054-1062.

Magos, M., de Brito, J., Gaspar, P. L. and Silva, A. (2016). Application of the factor method to the prediction of the service life of external paint finishes on facades. *Materials and Structures*, V. 49, 12, pp. 5209-5225.

Maia, M., Morais, R., Silva, A. (2020). *Application of the factor method to the service* *life prediction of window frames*. Engineering Failure Analysis, V. 109, 104245. DOI: https://doi.org/10.1016/j.engfailanal.2019.104245.

Marques, C., de Brito, J., Silva, A. (2018). Application of the factor method to the service life prediction of ETICS. *International Journal of Strategic Property Management*, V. 22(3), pp. 204-222.

Mc Duling, J., Horak, E. and Cloete, C. (2008). *Service life prediction beyond the 'Factor Method'*. 11th International Conference on Durability of Building Materials and Components; Istanbul, Turkey, T42.

Moser, K., and Edvardsen, C. (2002). *Engineering design method for service life prediction*. 9th International Conference on the Durability of Building Materials and Components, Brisbane, Australia, paper 222.

Prieto, A. J., Silva, A. (2018). Service life prediction and environmental exposure conditions of timber claddings in South Chile. *Building Research & Information* 2020, 48(2), pp. 191-206.

Shohet, I.M., Puterman, M., Gilboa, E. (2002). Deterioration patterns of building cladding components for maintenance management. *Construction Management and Economics*, V. 20(4), pp. 305-314.

Silva, A., de Brito, J. and Gaspar, P. (2016) *Methodologies for service life prediction of buildings: with a focus on façade claddings*. Springer International Publishing, Switzerland.

Silva, A., Prieto, A. (2019) *Application of the Factor Method to the service life prediction of external timber claddings*. CIB World Building Congress 2019 - Constructing Smart Cities, Hong Kong, China.

Silva, A., Prieto, A. (2021) Modelling the service life of timber claddings using the factor method. *Journal of Building Engineering*, 37, 102137.

Souza, J., Silva, A., de Brito, J., Bauer, E. (2018a). Application of a graphical method to predict the service life of adhesive ceramic external wall claddings in the city of Brasília, Brazil. *Journal of Building Engineering*, 19, pp. 1-13.

Souza, J., Silva, A., de Brito, J., Bauer, E. (2018b) Service life prediction of ceramic tiling systems in Brasília-Brazil using the factor method. *Construction and Building Materials*, 192, pp. 38-49.

Thelandersson, S., Isaksson, T., Suttie, E., Frühwald Hansson, E., Toratti, T., Grüll, G., Vittanen, H., Jermer, J. (2011). Quantitative design guideline for wood in outdoor above ground applications. Document IRG/WP, 11-20465.

4.3. Service life prediction of existing concrete structures - Feedback from practice

Arto Köliö, Tampere University

4.3.1. The context

The calculational estimation of the service life of concrete structures has been available in the Finnish concrete codes since 2004. The code is based on the factor method prescribed in ISO-15686 (2011) standards. Some practical applications of this method are described in the following chapters (cases 1 to 5). All the described cases are focused on renovation or existing structures. The cases do not consider new construction. Practical experiences derived from these cases are discussed in this section.

4.3.2. Case study #1, Precast concrete facades

In the Finnish construction, especially in some eras (approximately 1965 to 1980), concrete buildings have had poor durability resulting from both bad execution and inadequate description of the durability demands in the concrete code (Lahdensivu, 2012). The concrete codes prior to 2004 have been prescriptive in nature, where criteria of acceptable concrete have been given. The primary concrete properties that were regulated have been the concrete grade (compressive strength) and cover depth of reinforcement. The calculational design of service life has been considered from 2004 onwards shifting concrete design more to a performance-based approach.

Even though the calculational design of service life has not been available before 2004, it was tested with the specification in earlier concrete codes. The motivation for this study was the known poor durability of these concrete structures of the earlier era.

The specification for outdoor exposed structures was especially studied, and a facade surface and a balcony frame panel both facing either north or south (4 different cases) were chosen in the calculations. The concrete properties were taken from the concrete codes from 1965…2004 (and from a technical durability specification from 1976) when applicable. The concrete grade and cover depth were available in all codes. Later codes also specified other parameters, e.g. the minimum applicable w/c ratio. When the specification was not available in the code, the following constant values were used: w/c ratio = 0.8, max. aggregate size = 12 mm, cement type = CEM I (all precast panels). The effect of curing or maintenance was not taken into account in this comparative study (factors C and G are set to 1.0).

According to the calculation results (Table 4.3.1.) the durability prescription of outdoor exposed structures was greatly increased in the technical durability specification in 1976 and the following concrete codes. From 2004 onwards the durability specification against corrosion increased notably (also to a level where the calculated service life is more regarded as "theoretical", as in the case of the service life against corrosion: 410 years). The more aggressive environmental action in south facing surfaces is consistently visible also in the calculated service life estimates.

Table 4.3.1. - Service lives calculated by the factor method (concrete codes 2004) for facade and balcony structures with durability properties prescribed in earlier concrete specification (1965 - 2004). The service life is calculated separately for freeze-thaw (f-t) and reinforcement corrosion (c) for both north and south facing concrete surfaces

	Concrete codes 1965	Concrete codes 1967	Durability specification 1976	Concrete codes 1978	Concrete codes 1981	Concrete codes 2004	
						Target SL 50 years	Target SL 100 years
facade facing north	f-t: 64 c: 32	f-t: 64 c: 32	f-t: 136 c: 103	f-t: 136 c: 52	f-t: 136 c: 52	f-t: 97 c: 175	f-t: 190 c: 410
facade facing south	f-t: 32 c: 32	f-t: 32 c: 32	f-t: 68 c: 59	f-t: 68 c: 52	f-t: 68 c: 52	f-t: 48 c: 166	f-t: 95 c: 410
balcony frame panel facing north	f-t: 21 c: 24	f-t: 21 c: 24	f-t: 46 c: 44	f-t: 46 c: 52	f-t: 46 c: 52	f-t: 32 c: 175	f-t: 63 c: 410
balcony frame panel facing south	f-t: 21 c: 13	f-t: 21 c: 13	f-t: 46 c: 39	f-t: 46 c: 46	f-t: 46 c: 46	f-t: 32 c: 111	f-t: 63 c: 410

4.3.3. Case study #2, The concrete cover of underground piles

The service life of newly installed concrete piles with a diameter of 300 mm was assessed by the factor method. The application of this calculation was to assess the effect of the deviation of the concrete cover of reinforcement (observed in standard quality control procedures) to the achieved service life of the installed piles.

The design service life of the piles was 100 years in the exposure class XC2. The concrete grade was C40/50. The reinforcement with diameter 20 mm had the nominal concrete cover of 25 mm. The diameter of the stirrups was 5 mm. The installation depth of the piles was 30…40 m underground.

The factor method was applied to determine the minimum acceptable concrete cover to achieve the design service life. Due to the environment of the piles (underground) the assessed case in the factor method was corrosion. Harmful chloride content was not present in soil samples from the site. The assessment was carried out by setting all parameters constant except the concrete cover.

The reference service life used was 50 years and the constant factors were A = 3.245, C = 1, D = 1.4, E = 1 and G = 0,85. The factor F was neglected from the analysis. Factor B was given values according to the cover depth 0.058–3.240. The effect of the concrete cover to the calculational service life is shown in Figure 1.

The design service life of 100 years was in the calculation achieved with the minimum concrete cover of 18 mm which allows the deviation of -7 mm from the concrete cover specified in the design documents.

The factor method results were then contrasted to the bare concrete carbonation analysis based on the square root relationship (Tuutti, 1982) and the corresponding carbonation coefficient was 3.24 mm/√a. This coefficient value is typically found in fast carbonating concrete surfaces such as facades and balconies in exposure classes XC3 and XC4. In the case of concrete with relative high strength class and situated conditions that are unfavourable to carbonation (XC2), the resulting carbonation coefficient should be much lower. A value below 1.0 is expected (Grantham, 2011). Therefore, it was also concluded that the factor method approach overestimates the exposure of the structure.

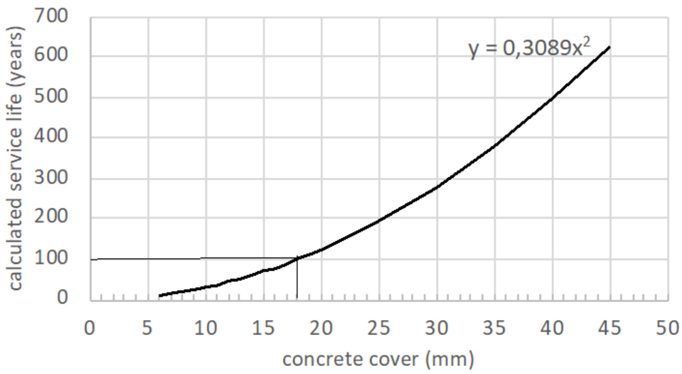


Figure 4.3.1. - Calculated service life of a concrete pile as a function of the concrete cover of the reinforcement

4.3.4. Case 3, The concrete frame of a sports hall

One motivation for the calculational analysis of the service life of a structure is to justify refurbishment. The residual service life of a concrete frame of a sports hall was analysed by the factor method (by 65 Concrete Code 2016). The frame of the sports hall was built in 1983 and consisted of in-situ cast cellar walls, pool structures and supporting columns made of reinforced concrete, in-situ cast post-tensioned large supporting beam and precast pre-tensioned supporting concrete beams. The motivation was to analyse the feasibility of refurbishment that would prolong the use of the building 30 more years. The study question was whether the frame of the building was able to provide the extension.

The analysis of the service life required quite thorough initial condition investigation to be made since initial data for the calculation was scarce. The initial surveys included a) determination of the exposure class with indoor air data collection, b) determination of the material properties by concrete sample analyses and c) determination of the structure properties by field measurements.

Finally, the service life of the structure was calculated with a reference service life of 50 years and with the following factors (an example of concrete columns), as shown in Table 4.3.2.

The resulted service life of the structure was 68,9 years. Taking into account the current age of the structure (37 years) at the time of the analysis, the residual calculational service life was +32 years.

The estimate of service life considers the carbonation of concrete (initiation phase) and a rough inclusion of active corrosion (propagation phase). It was observed here that the service life estimate is greatly affected by the concrete cover parameter (factor B). On the other hand, the estimate does not consider whether the structure is sheltered from rain or excess moisture, which suggests that the actual residual service life will be longer than the calculated estimate. Possible chloride penetration and its influence are not included in the analysis.

The calculated estimate is based on an assumption that the environment in which the structures are located does not change during the residual time. This assumption must be made but it is usually contrary to real conditions. Local excess moisture loads (drainpipes, leaks, condensation) or the capillary moisture from the soil may accelerate active corrosion in structures where the carbonation front has already reached the level of reinforcement. Fast carbonation is usually expected in indoor concrete structures.

Even though the calculated estimate implied that one refurbishment interval of 30 years may be achieved by the concrete frame, localized damage and renovation need may arise especially in locations with excess moisture loads.

Table 4.3.2. - Quantification of the durability factors to estimate the service life of the structure

A1	0.95	The experimentally determined concrete grade of C25/30 resulted in a factor of 0.95
A2	0.92	The cement type (CEM II) determined from the petrographic analysis of a thin section sample resulted in a factor of 0.92
A3	1.16	The air content (4 %) approximated from the petrographic analysis of a thin section sample resulted in a factor of 1.16
B1	1.00	The average of the measured concrete cover (25 mm) resulted in a factor of 1.00
B2	1.36	The use of cement-based grout/coating resulted in a factor of 1.36
C	1.00	The application of curing was unknown. Therefore, a factor of 1 was chosen (it does not increase/decrease the calculational service life)
E1	1.00	The exposure class XC3 resulted in a factor of 1.00
E2	1.00	The facing direction of the structure has no effect on the exposure class XC3.
E3	1.00	The geographical location does not influence the concrete frame
E4	1.00	The combined action of freeze-thaw was not considered (frame is located indoors).
G	1.00	The service and maintenance of the facilities was active. Therefore, a reduction in service life was not needed.

4.3.5. Case study #4, The supporting structures of a car deck

The supporting concrete structures of a car deck were subjected to calculational service life estimation in order to decide between heavy or light renovation actions. The concrete deck belonged to a housing corporation that consisted of two multi-storey apartment buildings built in 1955. The deck formed the inner courtyard for the two buildings and functions as the ceiling of an underground car park. The supporting structure was formed by primary and secondary beams made of reinforced concrete. Typical of the construction practice of that age, the material consumption for both concrete and steel was highly optimized.

Regarding the renovation actions, the heavy renovation included the renewal of the whole deck including the supporting structures while the light renovation included only the renewal of surface structures and waterproofing. The decision was affected by whether the expected service life of the existing supporting structures would allow one more renovation cycle of the overlaying structures.

The residual service life was analysed by the factor approach (by 65 Concrete Code 2016) and input data was determined by initial condition investigation. The initial surveys included a) determination of the exposure class with expert assessment, b) determination of the material properties by concrete sample analyses and c) determination of structure properties by field measurements. The properties were observed to fulfil the prescribed requirements set by the exposure class (XC1). The exposure had however changed over time towards class XC3 making the structures more vulnerable.

The age of the supporting structure was 64 years. The structure was expected to maintain its current condition well in exposure class XC1. However, the calculated service life in the altered conditions (exposure class XC3) gave an estimated service life of 37 years. The tricky part was that the precise point of time when leakage, which altered the environmental exposure of the structure, had emerged was unknown. The leakage was observed in an inspection done 7 years before the service life analysis. Finally, a residual service life of 20 to 25 years was assured for the structure applying a “safety factor” way of thinking. The most decisive factor for the relatively short residual service life was shallow reinforcement cover depths (average 18 mm) in the primary supporting concrete beams.

4.3.6. Case study #5, Industry reservoir tanks/pools

Concrete reservoir tanks were subjected to service life analysis to allow the long-term maintenance planning of an industry facility. The tanks were massive in-situ cast concrete structures built in 1982. The dimension of the main wall structures was approximately 500…1000 mm thick. The main function of the walls was water tightness (low porosity, high density, avoidance of cracks) to avoid leakages but also a large load-bearing capacity was inherent from the structure dimensions.

The residual service life was analysed by the factor approach (by 65 Concrete Code 2016) and the condition and material properties of the structures were surveyed to provide input data for the analysis. The initial survey showed that the overall condition of the pools was good, and no signs of damage/degradation/harmful cracking were found. Microcracking of the concrete matrix, which may occur in massive in-situ structures, was observed in the petrographic studies of concrete samples alongside with variable concrete quality. The structures were located so that they were sheltered from freeze-thaw action. This guided the analysis to study primarily the service life regarding reinforcement corrosion. The w/c ratio was found to be rather low (0.45…0.50). The concrete compressive strength was found to exceed the specified concrete grade (30 MPa), in some locations considerably (+70 % up to even +150 %).

The age of the structure during the analysis was 37 years. The calculated service life of the structure, taking into account structure properties including a mild increase in concrete grade (35 MPa), was 319 years. This accounts for 282 years of residual service life from the present. This calculated residual service life is very long. Therefore, it should also be carefully considered. Even though the calculation suggests it, any concrete structure should not be guaranteed such a long service life maintenance-free. The analysis is also based on an assumption that the structure is affected by a certain constant environment during the whole residual service life - which cannot be reliably foreseen. Finally, the structure was given an estimate of 100 years residual service life and a regular inspection/maintenance procedure was defined for the structures.

4.3.7. Concluding remarks

The calculative approach in Finnish concrete codes from 2004 onwards to assess the service live of concrete structures is a versatile tool. As an application in renovation its main focuses are on i) assessing the residual service life of a structure, ii) setting up maintenance strategies or iii) proving the fulfilment of durability requirements.

As shown by the case studies, the calculative model operates on input data which may be difficult to define for new construction, let alone obtain from existing structures. An initial survey and some specific material tests are required for a reliable analysis. The essential tests include e.g. the concrete grade, assessment of w/c ratio and measurement of the reinforcement cover depth. Since the determination of these properties relies on material samples, the number of samples has a direct link to the reliability of the values. A sufficient sampling volume should therefore be assured.

Even though a statistically sufficient number of samples was taken, the measured result may differ remarkably from a presumed or prescribed property (e.g. strength up +150 %). The scatter of these empirically determined properties is also typically quite large. The variability of data requires the application of a "safety factor" way of thinking in both determining the input data and in the analysis of the calculated service life. A maintenance-free service life should never be guaranteed.

Even though it is a useful tool, the calculation is highly theoretical and takes into account only few very "isolated" environmental actions. This limits the usefulness of the calculative model. Engineers applying this method should be aware of the limitations of the analysis and their impact on the final conclusions that can be drawn from it. Overestimation may occur in some cases, e.g. with very focused environmental actions. The degradation of structures in practice is usually more complicated than in theory and are for example a result of the simultaneous effect of multiple degradation mechanisms (chemical-, mechanical- or physical actions).

The calculated estimate is based on an assumption that the environment in which the structures are located does not change during the residual time. In the calculation it was thereby assumed that the exposure to environmental action and harmful agents will remain constant during the assessed period. This assumption needed to be made but it is usually contrary to real conditions.

References

Concrete Association of Finland. 2004. by 50, Betoninormit 2004 (Concrete Code 2004).

Concrete Association of Finland. 2016. By 65 Betoninormit 2016 (Concrete Code 2016).

Grantham, M. (2011). Concrete Repair - A practical guide. Taylor & Francis. 302 p.

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

Lahdensivu, J. (2012). Durability properties and actual deterioration of Finnish concrete facades and balconies. Doctoral dissertation, Tampere University of Technology, Tampere, Finland.

Tuutti, K. (1982). Corrosion of steel in concrete. Stockholm. Swedish Cement and Concrete Research Institute. CBI Research 4:82. 304 p.

5. New trends for the factor method

5.1 Uncertainty in building components service life prediction

Fulvio Re Cecconi; Politecnico di Milano

5.1.1 The context

Service life is defined by the ISO 15686-1 (2011) standards as the period of time after installation during which a facility or its component parts meet or exceed the performance requirements. A schematic representation often used to illustrate this definition is shown in Figure 5.1.1. The blue line represents the performance trend over time. It starts from an initial value, which corresponds to the component's performance when it is installed, and it is characterised by a slow degradation process, i.e. a decrease in performance; maintenance operations performed at an initial stage, and almost instantaneous increase the component's performance, bringing it back nearly to the initial value. The light blue band around the blue line represents the uncertainty in estimating performance over time and the dashed grey line represents the minimum performance required. As can be observed, the service life of the component, i.e. the abscissa corresponding to the intersection between the line of performance provided and that of the required performance, may vary greatly due to the uncertainty. Thus, dealing with uncertainty in service life prediction is very important.

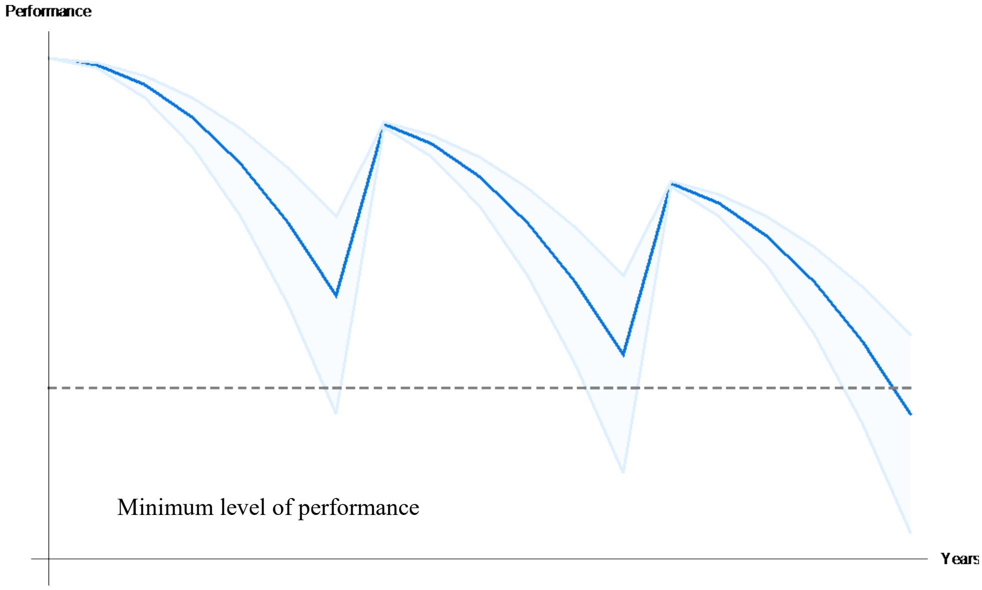


Figure 5.1.1. - A schematic representation of the definition of service life given in the ISO 15686-1 standard and of its uncertainty

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 (Silva et al., 2016b). Over time, a great amount of work has been carried out in the area of service life prediction as requisite tools for helping assess long-term environmental effects, for maintenance management of infrastructure systems, such as roads, bridges, waterways, water distribution and wastewater removal systems, or indeed for maintenance of building envelope systems, envelope components and related materials (Hovde, 2004).

One of the biggest concerns about the use of service life data is that they can lead to inconsistencies when performing building related assessment such as environmental Life Cycle Assessment (LCA) or Life Cycle Costs (LCC) computations (Lasvaux et al., 2018). As Ristimäki et al. (2013) pointed out that these analyses require a significant amount of data whose outcome depends on the accessibility, quality and accuracy of the input data. The data considered to have the highest uncertainty are future operational costs and life cycle performance information. Evaluating the service life of a building is a complex and uncertain process (Ristimäki et al., 2013) and many authors have dealt with service life predictions' reliability. A bibliometric analysis may help to understand how the problem of uncertainty in service life predictions is dealt with in the scientific literature.

5.1.2 Bibliometric analysis

Bibliometric analysis (BA) is a statistical evaluation of published scientific articles, books, or the chapters of a book. It is an effectual way to measure the influence of publication in the scientific community (Schubert et al., 1989; de Moya-Anegón et al., 2007; Iftikhar et al., 2019; Dias Morales et al., 2020). The indicators obtained from a BA constitute a way to assess the current state of science, which can help shed light on its structure (Okubo, 1997). The aim of this brief BA is to understand how the uncertainty in estimates of the service life of building components has been dealt with by scientists through the years. To this end, the two best-known databases of scientific articles were used: SCOPUS and Web of Science (WoS). The two queries were made with the same search string:

Building* AND ((service AND (life OR lives)) OR Durability) AND (uncertainty OR reliability) (5.1.1.)

Moreover, both queries were limited to English documents. The two DB have slightly different structures, documents in SCOPUS are categorized in few "subject areas" while in WoS they are catalogued in many more "categories". Thus, SCOPUS query was limited to the "Engineering" area while the WOS one was narrowed to the following categories: a) Engineering, civil; b) Construction building technology; c) Materials science multidisciplinary; d) Green sustainable science technology; e) Materials science characterization testing; f) Materials science composites; g) Engineering multidisciplinary.

These two queries led to 908 documents in SCOPUS and 319 publications in WoS. The former results were further refined limiting the publication so to consider only the latest 870 and make the two results comparable. Figure 5.1.2. shows the number of documents recorded each year in the two databases. The queries were made in the first day of June 2020 so the lower number of documents in 2020 is not to be taken as a decrease tendency in the last year. In the first five months of year 2020, 40 documents have been recorded in SCOPUS, amounting to 48% of the previous year and 15, 40% of the previous year, in WoS.

Figure 5.1.2. clearly shows that interest in the subject has grown over the years. In fact, the number of publications is constantly rising, regardless of the absolute value that is different in the two DBs due to different inclusion policies.

Further bibliometric analyses can be done using Bibliometrix (Aria and Cuccurullo, 2017), an open-source tool for quantitative research in scientometrics and bibliometrics. Among the analyses that this tool allows, one of the most interesting is the keywords co-occurrence. Bibliometrix counts how many times a word appears among keywords and links it to other keywords depending on how they are structured. This analysis, although conducted by the tool in a slightly different way in the two DBs, allows observing how the main concepts are linked together in the articles. Two figures produced by Bibliometrix clearly show a trend, more pronounced in SCOPUS (Figure .) than in WoS (Figure 5.1.3.), uncertainty is frequently associated with the design of reinforced concrete structures and their reliability. In Figure , the cluster of "concrete construction", "concrete buildings", "reinforced concrete" and "concretes" is the biggest, i.e. these are the most used keywords. Likewise, in WoS (Figure 5.1.3.) the structural cluster (violet) is very important. This first result is not unexpected, since the evaluation of structural safety has long been based on the concept of probability and uncertainty, especially in the evaluation of the strength of structures, has always been of great importance (CEN, 2002).

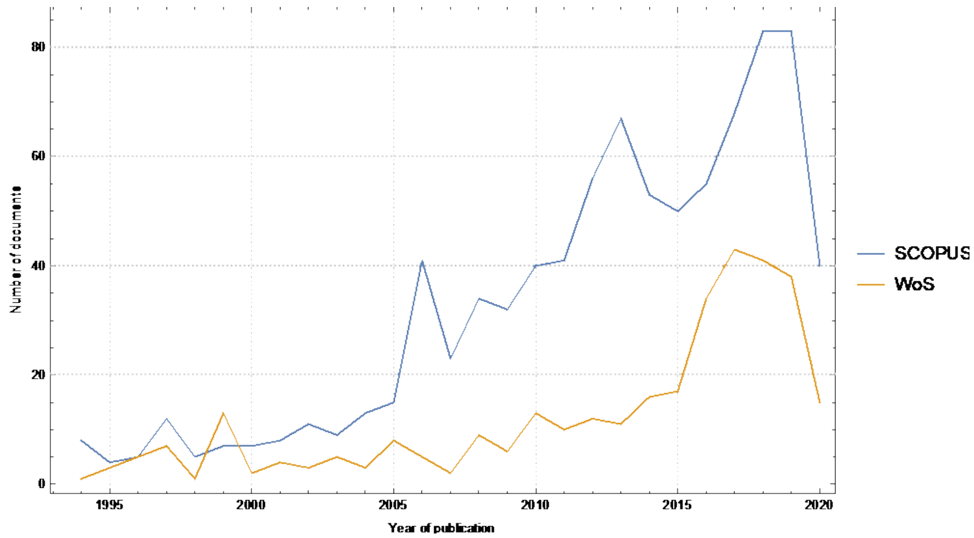


Figure 5.1.2. - Number of documents recorded each year in the two bibliographic databases

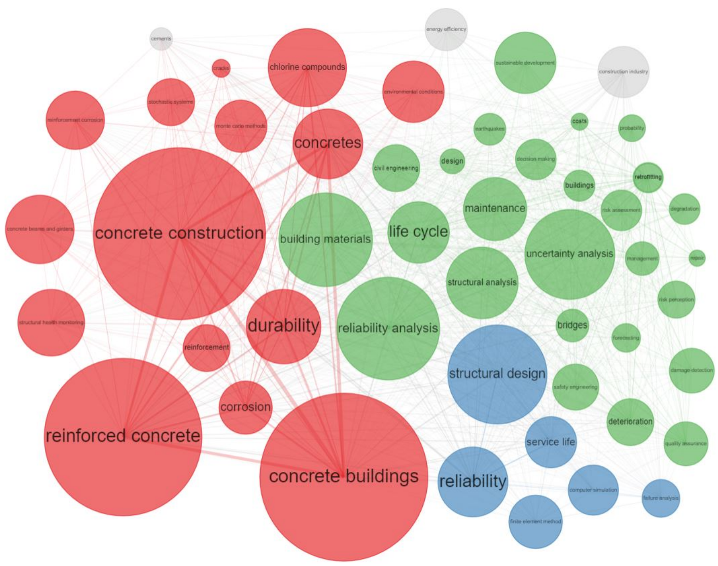


Figure 5.1.3. - Co-Occurrence keyword graph. Data from Scopus

Another field where the concept of uncertainty is very present, as can be easily seen from Figure 5.1.3., is the one of environmental impact measured using Life Cycle Assessment (LCA) techniques. In environmental impact assessments, service life plays a decisive role as the impacts related to the replacement of building components are generally high. Thus, the issue of uncertainty in LCA is often dealt with in association with LCA.

Eventually, Bibliometrix also provides an interesting analysis of the origin of the documents, or rather of the institutions to which the authors belong and their links. The institutions where the authors who have contributed most to the body of knowledge on the subject work are in the United States, China and Australia (Figure 4.1.5). The strong links between the work of North American and Chinese authors are also highlighted.

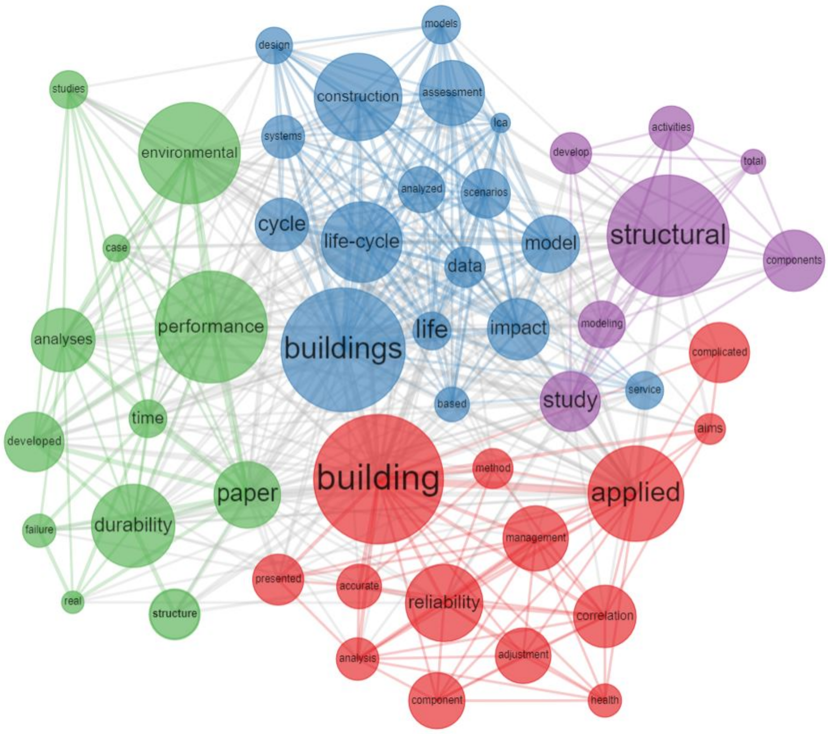


Figure 5.1.3. - Co-occurrence keywords graph. Data from WoS DB

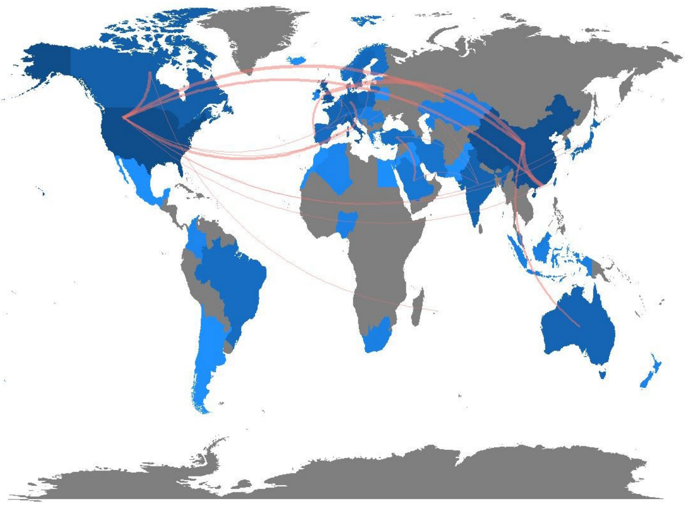


Figure 4.1.5. - World map collaboration. Data from Scopus DB

5.1.3 Uncertainty in the factor method for service life prediction

One of the most recognised methodologies to estimate the service life of construction components is the Factor Method (FM), which is widely accepted in the scientific community and is characterised by its systematic approach, easy applicability and operability in real projects. The FM firstly appeared in the Principal Guide for Service Life Planning of Buildings, a normative document proposed by the Architectural Institute of Japan (AIJ, 1993). Since the publication of the Japanese guide, the FM, thanks among other contributions to the work of CIB working commission W080 “Prediction of Service Life of Building Materials and Components”, has become the basis of the ISO 15686: 2011 standard. In its most recent version, this standard describes the FM as the modification of Reference Service Life (RSL) by factors to take into account specific in-use conditions and the RSL as the service life of a product, component, assembly or system that is known to be expected under a particular set, i.e. a reference set, of in-use conditions. The FM can be applied at different level of sophistication, from working as a checklist to complex calculation (ISO 15686-8: 2008). Maybe the best-known level of sophistication is the multiplication level. On this level, the estimation of the actual service life of a component, the Estimated Service Life (ESL), is carried out by multiplying the RSL value by seven numerical factors as in Equation (5.1.2.).

$$ESL = RSL \times A \times B \times C \times D \times E \times F \times G \qquad (5.1.2.)$$

The FM is affected by a substantial uncertainty (ISO 15686-8: 2008), hiding a great sensitivity to errors in input factors that can lead unaware users to large errors in the ESL, an example of how significant this sensitivity is can be found in Table 5.1.2., where changing by 10% every factor leads to a prediction that differs from -52% up to almost 95%. The difference would be even greater if the RSL is affected by uncertainty too.

Table 5.1.2. - Errors in ESL due to 10% uncertainty in each factor

ESL		RSL	A	B	C	D	E	F	G
-52.17%	11.957	25	0.9	0.9	0.9	0.9	0.9	0.9	0.9
0.00%	25	25	1	1	1	1	1	1	1
94.87%	48.717	25	1.1	1.1	1.1	1.1	1.1	1.1	1.1

Noteworthy, researchers found that the factors estimating service life with a given confidence limit are shown to have a wide range in values that give considerable uncertainty to the practical use of the standardized methodology (Marteinsson, 2003).

Many authors have proposed methods that deal with the problem of accuracy in service life prediction in different ways, a summary is given in Table 5.1.3. The articles selected in the table are a subset of those obtained with the Scopus and WoS database queries. To select the relevant articles, the two queries have been refined by selecting only those articles containing the string "Factor Method*". Among the results, all the articles related to the application of the partial factors method (CEN, 2002) for structural safety assessments of reinforced concrete works have been eliminated.

Among the many examples of research that deal with uncertainty in the factor method, some (Moser, 1999; Re Cecconi, 2004) use probability distribution functions instead of numeric values for the seven factors and other use guidelines in form of tables (Hovde, 2005) or grids (Re Cecconi and Iacono, 2005) that, driving the user over a specific path for assessing each factor, minimise the probability of error.

Table 5.1.3. - List of references that deal with accuracy in service life prediction

Reference	Methods to deal with accuracy in service life prediction
Ianchenko et al., 2020 0	This research models the lifespan of American residential housing stock as a probabilistic survival distribution based on available data from the American Housing Survey (AHS). The log-normal, gamma, and Weibull distributions are used.
Diamantidis et al., 2019	The article explores the obsolescence of buildings and in particular the definitions of obsolescence, the related influencing factors and the associated uncertainties. It is focused on the service life of the structure.
Silva et al., 2018	This study compares different service life prediction models applied to renderings. It concludes that: a) simpler methods can be highly accurate but are only capable of analysing the degradation phenomena in one dimension; b) more complex models, are more demanding and more accurate, allowing encompassing the relevant variables for the explanation of the degradation of rendered façades and c) stochastic models lead to the most relevant results, providing the risk of failure of the renderings according to their age and characteristics.
Silva et al., 2016a	In this study, a stochastic approach to the factor method is proposed to predict the service life of rendered façades. The factors that affect the durability of this type of coating are identified and translated into probability distributions. The model proposed is based on a survey of the degradation state of 85 rendered façades located in Portugal.
Silvestre et al., 2015	This article 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).
van Nunen and Mooiman, 2012	This paper shows the influence of the applied life span and service lives on these environmental calculations. Important parameters influencing the service life and solutions for improving service life predictions for buildings and building elements are presented in order to optimize the reliability of the environmental assessments.
Boussabaine and Kirkham, 2008	In the context of whole life costing, the book suggests a method for the estimation of the service life of new structures and of the remaining service life for existing structures.
Shohet and Paciuk, 2006	The article proposes a method for service life prediction that addresses two issues raised in ISO-15686 in order to improve the precision and reliability of service life forecasting: (a) modifying factors for quantifying the effect of failure mechanisms are estimated within 80% confidence limits and (b) the prediction models yield high degrees of fit to the data

5.1.4 Possibilistic uncertainty in the factor method

Nowadays, even the standards (ISO 15686-8: 2008) state that, when using the FM at multiplication level, the factors may be applied in the form of a probability distribution or probability function, in which case the resulting quantity ESL also describes a probability distribution.

This approach, so far one of the few “engineering methods” for service life prediction known, may lead to unexpected results if used without attention to the assumption (maybe unconsciously) made when selecting distribution functions. Noteworthy, in risk analysis uncertainty is typically considered of two different types: randomness due to inherent variability in the system behaviour and imprecision due to lack of knowledge and information on the system. The former type of uncertainty is often referred to as objective, random, stochastic, whereas the latter is often referred to as subjective, epistemic state of knowledge (Apostolakis, 1990) and often referred as partial ignorance. In current service life estimation practice (Moser, 1999; Re Cecconi, 2004), both types of uncertainty are represented by means of probability distributions and the uncertainty propagation is often carried out by a Monte Carlo simulation. In the case of partial ignorance, the use of a single probability measure introduces information that is in fact not available. This may seriously bias the outcome of service life estimation in a non-conservative manner. In fact, while it is commonly accepted that the random uncertainty is appropriately represented by probability distributions, there has been some scientific disputes about the potential limitations associated to a probabilistic representation of epistemic uncertainty under limited information. (Re Cecconi, 2011) shows how to deal with uncertainty propagation in the FM especially when the uncertainty is "epistemic", i.e. due to a lack of knowledge, and not random, i.e. arising due to randomness, and it does so using a method based on the possibility theory, first introduced by Prof. L. Zadeh in 1978 as an extension of his theory of fuzzy sets and fuzzy logic. Mixing both the uncertainties means that one cannot see how much of the total uncertainty comes from epistemic and random uncertainties. If one knows that a large part of the total uncertainty is due to epistemic uncertainty, then by collecting further information and thereby reducing total uncertainty one would be able to improve the estimate of the future. On the other hand, if the total uncertainty was nearly all due to variability, it is a waste of time to collect more information and the only way to reduce the total uncertainty would be to change the factor method, i.e. avoid the multiplication level.

One way to deal with epistemic uncertainty is using possibility distributions. Possibility theory is the simplest uncertainty theory devoted to the modelling of incomplete information. It is characterized by the use of two basic dual set functions that respectively grade the possibility and the necessity of events (Dubois and Prade, 2009). If it is assumed that some of the seven factors are random variables and are represented by probability distributions while other are epistemic variable represented by possibility distributions then ESL can be computed combining the two uncertainty in the following way: Monte Carlo sampling of the random variables is repeatedly performed to process the random behaviour of some factors while possibilistic distribution analysis is carried out at each sampling to process the epistemic uncertainty in the remaining factors. This method leads to the computation of a possibilistic random distribution representing the ESL for each considered realization of the random variables. Finally, the obtained possibilistic random distributions are combined into a set of limiting cumulative distributions characterized by different degrees of confidence (Cooper et al., 1996; Baraldi and Zio, 2008).

The results of uncertainty propagation in the four different examples are shown in Figure 5.1.5. where the case of pure probabilistic uncertainty propagation is the central dashed green line representing the cumulative distribution function (CDF) of the estimated service life when errors in the input factors are all due to inherent variability of the component behaviour. In the same figure, the two blue and orange solid lines represent the Plausibility and Belief measure of the set $A=(-\infty,x]$ when a) one; b) two; c) three and d) four of the seven factor are described by possibility distributions.

Belief measures and plausibility measures are two common types of semi continuous fuzzy measures used for modelling uncertainty (Zhenyuan et al., 1998); in a very simplified expression, the larger is the distance between the two measures, the bigger the uncertainty is. In the example shown in Figure 5.1.5, the distance increases by more than 280% when going from one possibilistic distribution to four possibilistic distributions (Figure 5.1.6).

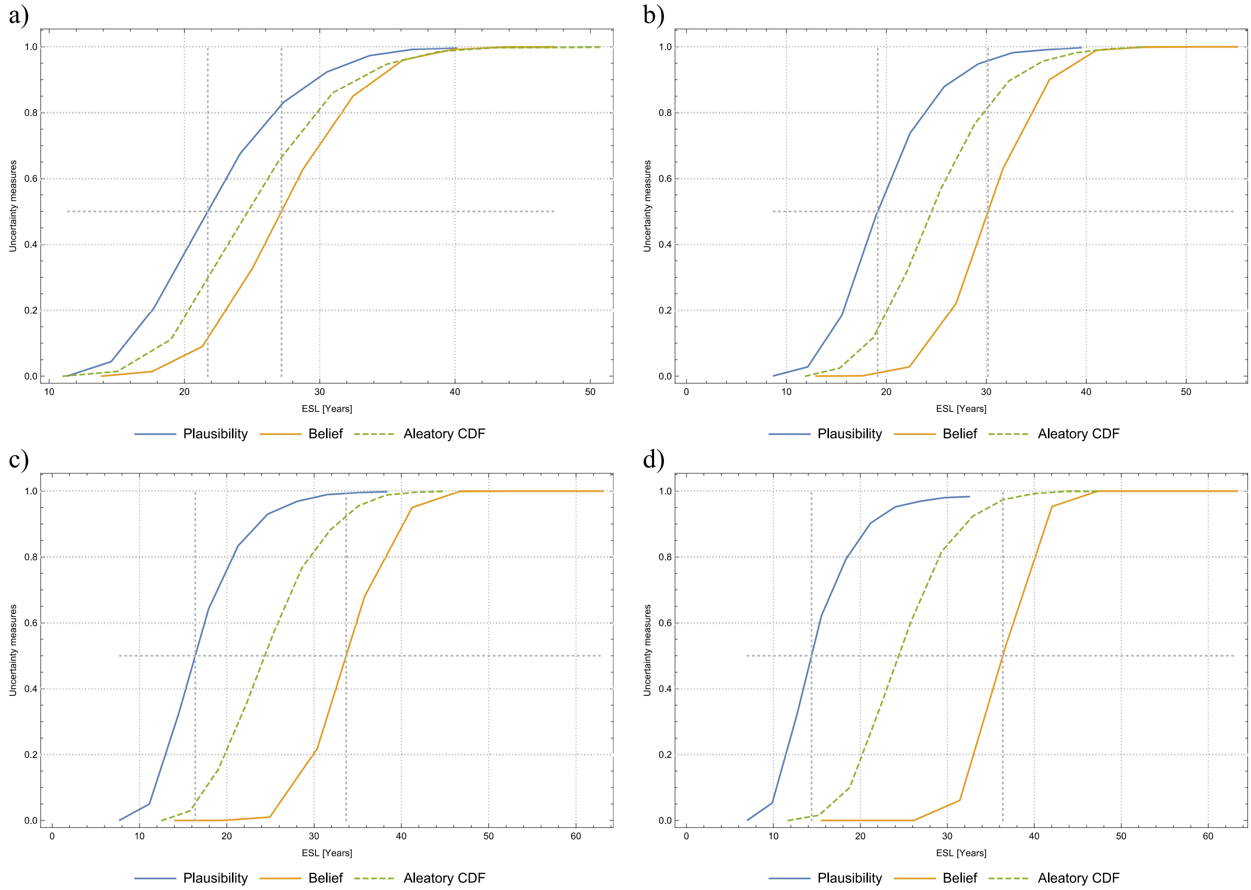


Figure 5.1.5. - Epistemic error propagation in the FM equation with a) one; b) two; c) three and d) four possibilistic distributions

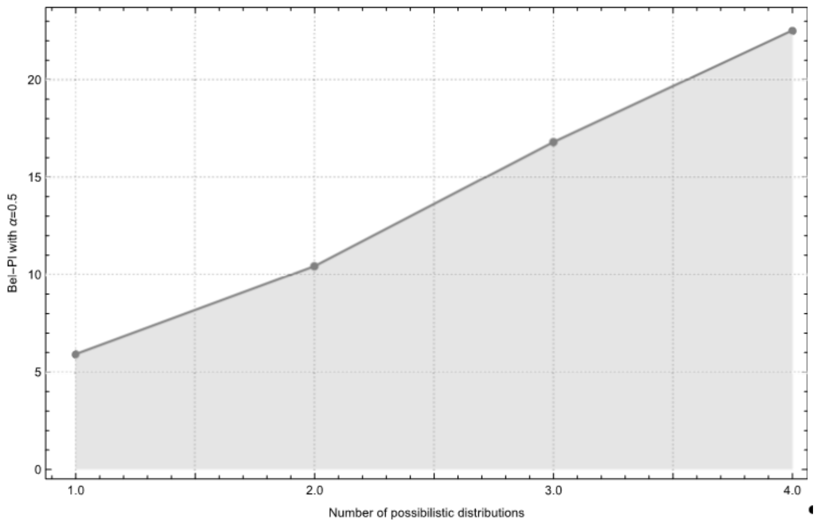


Figure 5.1.6. - Bel-Pl difference increases more than 280% when going from one to four possibilistic distributions

Even without going into mathematical technicalities, what can be seen from the example shown in Figure 5.1.5, is that using probability distributions to represent the epistemic uncertainty, i.e. the lack of knowledge, in estimating the service life with the factor method can lead to greatly overestimate the actual life of the component.

5.1.5 Concluding remarks

An analysis of the two most known abstract and citation databases proved that the number of publications dealing with uncertainty in service life prediction has been constantly rising for more than 25 years (Figure 5.1.2) and most of the research work has been done in the United States, China and Australia (Figure 4).

According to the bibliometric analysis, there are three main topics where uncertainty is linked to service life:

- The design of reinforced concrete structures, a field where the Eurocodes (CEN, 2002) provide a consistent reliability-based assessment framework (Figure);
- The measurement of environmental impact using Life Cycle Assessment (LCA) techniques or the one of Life Cycle Costing (LCC), because both techniques deeply rely on service life prediction (Figure 5.1.3);
- The application of the FM, mainly at the multiplication level (Table 5.1.3).

Many researches deal with uncertainty in the factor method using probability distribution functions instead of numeric values for the seven factors (ISO 15686-8: 2008) but this may seriously bias the outcome of service life estimation in a non-conservative manner (Re Cecconi, 2011).

Acknowledgements

This work would not have been possible without the precious help of MSc Eng. Luca Rampini in preparing the bibliometric analysis.

References

Apostolakis, G.E. (1990). The concept of probability in safety assessments of technological systems. *Science*, V. 250(4986), pp. 1359-1364.

AIJ - Architectural Institute of Japan (1993). *The English edition of principal guide for service life planning of buildings*. In ISO 15686-1: 2011. Buildings and constructed assets, Service life planning part 1: General principles and framework.

Aria, M., Cuccurullo, C. (2017). Bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*, V. 11(4), pp 959-975.

Baraldi, P., Zio, E. (2008). A combined Monte Carlo and possibilistic approach to uncertainty propagation in event tree analysis. *Risk Analysis*, V. 28(5), pp. 1309-1326.

Boussabaine, H.A., Kirkham, R.J. (2008). Whole life-cycle costing: risk and risk responses. Wiley, Blackwell Publishing.

CEN, EN 1990 Eurocode: Basis of Structural Design, (2002), European Committee for Standardization.

Cooper, J.A., Ferson, S., Ginzburg, L. (1996). Hybrid processing of stochastic and subjective uncertainty data. *Risk Analysis*, V. 16(6), pp. 785-791.

de Moya-Anegón, F., Chinchilla-Rodríguez, Z., Vargas-Quesada, B., Corera-Álvarez, E., Muñoz-Fernández, F., González-Molina, A. (2007) Coverage analysis of Scopus: a journal metric approach. *Scientometrics*, V. 73, pp. 53-78.

Diamantidis, D., Sýkora, M., Bertacca, E. (2019). *Obsolescence rate: Framework, analysis and influence on risk acceptance criteria*. In: Frangopol D.M. Caspeele R. TL (ed) Life-Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision - Proceedings of the 6th International Symposium on Life-Cycle Civil Engineering, IALCCE 2018. CRC Press/Balkema, pp 379-386.

Dias Morales, M.F., Reguly, N., Kirchheim, A.P., Passuello, A. (2020). Uncertainties related to the replacement stage in LCA of buildings: A case study of a structural masonry clay hollow brick wall. *Journal of Cleaner Production*, Volume 251, pp. 119649.

Dubois D., Prade H. (2009). *Possibility Theory*. In: Meyers R. (eds) Encyclopaedia of Complexity and Systems Science. Springer, https://doi.org/10.1007/978-0-387-30440-3_413

Hovde, P., Moser, K. (2004). *Performance base methods for service life prediction*: *State of the art report.* CIB Publication 294, ISBN 90-6363-040-9.

Hovde, P.J. (2005). *The Factor Method - a simple tool to service life estimation*. 10th International Conference on the Durability of Building Materials and Components, Lyon, France, TT4-115.

Ianchenko, A., Simonen, K., Barnes, C. (2020). Residential building lifespan and community turnover. Journal of Architectural Engineering, V. 26(3), doi: https://doi.org/10.1061/(ASCE)AE.1943-5568.0000401.

Iftikhar, P.M., Ali, F., Faisaluddin, M., Khayyat, A., De Sa, M. de Sa, Rao, T. (2019). A bibliometric analysis of the top 30 most-cited articles in gestational diabetes mellitus literature (1946-2019). *Cureus*, V. 11(2), pp. e4131.

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

ISO 15686-8 (2008) Buildings and constructed assets - service life planning - part 8: reference service life and service life estimation. International Organization for Standardization, Switzerland.

Lasvaux, S., Giorgi, M., Favre, D., Hollberg, A., Viola, J., Habert, G. (2018). *Review of existing service lives' values for building elements and their sensitivity on building LCA and LCC results*. In Caspeele R., Taerwe L., Frangopol D., Life Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision, CRC Press, ISBN 9781138626331, pp. 879-883.

Marteinsson, B. (2003). Durability and the factor method of ISO 15686-1. *Building Research & Information*, V. 31(6), pp. 416-426.

Moser, K. (1999). *Towards the practical evaluation of service life: illustrative application of the probabilistic approach*. 8th International Conference on Durability of Building Materials and Components; Vancouver, Canada, pp. 1319-1329.

Okubo, Y. (1997). *Bibliometric indicators and analysis of research systems: methods and examples*. OECD Science, Technology and Industry Working Papers, No. 1997/01, OECD Publishing, Paris, https://www.doi.org/10.1787/208277770603.

Re Cecconi, F., (2004). *Engineering method for service life planning: the evolved factor method*. CIB World Building Congress, Toronto, Canada.

Re Cecconi, F., Iacono, P. (2005). 'Enhancing the Factor Method - Suggestions to Avoid Subjectivity'. 10th International Conference on the Durability of Building Materials and Components, Lyon, France, TT4-172.

Re Cecconi, F., (2011). *Epistemic uncertainty propagation in service life prediction using the factor method*. 12th International Conference on the Durability of Building Materials and Components, Porto, Portugal.

Ristimäki, M., Säynäjoki, A., Heinonen, J., Junnila, S. (2013). Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design. *Energy*, V. 63, pp. 168-179.

Schubert, A., Glänzel, W., Braun, T. (1989). Scientometric data files. A comprehensive set of indicators on 2649 journals and 96 countries in all major science fields and subfields 1981-1985. *Scientometrics*, V. 16, pp. 3-478.

Shohet, I.M., Paciuk, M. (2006). Service life prediction of exterior cladding components under failure conditions. *Construction Management and Economics*, V. 24(2), pp.131-148.

Silva, A., de Brito, J., Gaspar, P.L. (2016a). Stochastic approach to the factor method: Durability of rendered façades. Journal of Materials in Civil Engineering, V. 28, doi: https://doi.org/10.1061/(ASCE)MT.1943-5533.0001409.

Silva, A., de Brito, J., Gaspar P.L. (2016b). *Methodologies for service life prediction of buildings*. Springer International Publishing, Switzerland.

Silva, A., de Brito, J., Gaspar, P.L. (2018) A comparative multi-criteria decision analysis of service life prediction methodologies for rendered façades. *Journal of Building Engineering*, V. 20, pp. 476-487.

Silvestre, J.D., Silva, A., de Brito, J. (2015). Uncertainty modelling of service life and environmental performance to reduce risk in building design decisions. Journal of Civil Engineering and Management, V. 21(3), pp. 308-322.

Van Nunen, H., Mooiman, A. (2012). *Improved service life predictions for better life cycle assessments* [Optimierte lebensdauerprognosen zur besseren einschatzung der okobilanz]. *ZI, Ziegelindustrie International Tile Industry*, Issue 6, pp. 10-21.

Wang, W., Klir, G.J., Wang, J. (1998). Neural Networks used for determining belief measures and plausibility measures. *Intelligent Automation & Soft Computing*, V. 4(4), pp. 313-324.

5.2 Artificial intelligence models for the quantification of the durability factors

Johann McDuling; McDuling Consulting Pty Ltd.

5.2.1 The context

"Service life planning is a design process that seeks to ensure that the service life of a building or other constructed asset will equal or exceed its design life." (ISO 15686-1: 2011). Achieving this objective requires an ability to estimate the service life for the material or component under consideration for a particular application.

Change in condition over time is a major driving force that determine the service life of a built asset. There are other less tangible or "fuzzy" driving forces such as technological innovation and socio-economic dynamics that can also contribute, but not considered in this report.

The ability to quantify these changes in condition over time requires an understanding of the variable factors that affect the degradation process and consequently the durability of the material or component. The Factor Method (ISO 15686-8: 2008) modifies a Reference Service Life (RSL) by seven variable modifying factors to calculate an estimated service life. Ever since its inception, considerable work has been done to improve the Factor Method, which depends on the accuracy of the RSL and the seven modifying or durability factors applied to the RSL. The quantification of RSL is not considered in this report.

The biggest challenge is quantifying the modifying or durability factors and this report explores the scope of artificial intelligence (AI) in the quantification of these factors for building components and materials.

5.2.2 The durability factor quantification conundrum

In the Factor Method, *"The factor values ϕ_A, ϕ_B,.... ϕ_G are up to the user to set or find. The user can set factor values from their experience, in which case the multiplication level can be regarded as a refined checklist level. Factor values are often based on known actions of the environment on specific materials (e.g., increased corrosion in salt atmospheres), or on known effects of poor workmanship and maintenance. Alternatively, the user can find documented factor values or, more likely, data enabling the calculation of factor values" (ISO 15686-8:2008(E) §6.4.3).*

Setting or finding appropriate factor values may be the biggest challenge in using the Factor Method to calculate the estimated service life for a specific application, especially for the user who may not have the required experience or knowledge of degradation processes or the variability in durability factors, which are often dependent upon each other and complicates this even further.

The main data sources that enable the calculation of factor values are actual performance data, laboratory tests (accelerated and artificial simulations) and domain expert knowledge. However, collecting actual performance data and conducting laboratory tests are time consuming and therefore costly, often requiring substantial funding and/or investments. Opportunities to collect data using suitable sample sizes are mainly associated with large property portfolios and manufacturers/producers/suppliers. The frequency of assessments depends on availability of funding. Ownership of data and intellectual property often limit access for research purposes. Silva et al. (2016a) elaborated on this conundrum of reliable and consistent performance data availability.

In another publication Silva et al. (2014) pointed out that *"The size of the sample is paramount when establishing SL prediction models. In fact, the more complex the behaviour in terms of the reality one intends to model, the more data are needed. The main disadvantage of all the methods studied is that they react to data modification, so that their ability to generalize increases, in principle, with the size of available data. All the methods can be easily complemented with more data over time."*

Salvaneschi et al. (1996) states that *"Interpreting such data is not easy. Several factors are involved, such as the large amount of data; the uncertainty and incompleteness of information; and the need for engineering judgment, knowledge of the particular structure, experience with the behavior of structures in general, and general engineering knowledge to interpret the data"*.

The consequence of this is that good reliable and consistent data is hard to come by and there are huge gaps that will take substantial time and investment to fill. The question is how do we fill these gaps?

The answer lays in a willingness to share performance data (real and/or artificial simulation) and the ability to build on the available data and domain expertise using deterministic (graphical method), stochastic (logistic regression and Markov Chains), statistic (multiple linear and non-linear regression techniques), artificial intelligence and hybrid models (e.g., Fuzzy Logic, Neural Networks, Neuro-Fuzzy, etc.). Silva et al (2014) provides a comparison of some of these models.

This report looks at the application of AI models in the quantification of durability factors towards service life prediction.

5.2.3 Artificial Intelligence models for the quantification of durability factors

Modern technology, and in particular Artificial Intelligence (AI), has grown substantially, especially over the past two decades and enabled the accumulation, processing, and analysis of vast volumes of data, as evidenced by the large number of research papers and publications on artificial intelligence models for the quantification of durability factors and service life prediction. It is however still early days and there is much work still to do.

The type of AI and its suitability for the quantification of durability factors depend to a large extent on the availability of real performance data. This report only looks at the application of some of the most widely used AI models.

5.2.3.1 Artificial Neural Network models

Negnevitsky (2002) defined an artificial neural network (ANN) as an attempt to *"emulate the biological neural network"* of the human brain in a computer. The attractiveness of an ANN model for the quantification of durability factors lays in its ability, just like the human brain, to learn through experience and become more accurate as databases containing real performance data grow over time.

Based on a literature review of scientific publications and conference proceedings Multilayer Perceptron (MLP) Neural Networks or Deep Neural Networks (DNN), which is an ANN with multiple layers between the input and output layers, appears to be the most widely used AI application with a backpropagation training algorithm (BPA). Dias et al. (2014) noted that *"Many alternatives to BPA have been developed (e.g., the Levenberg-Marquardt algorithm) but their advantages usually lie more in the training speed than the generalisation capability."* Felix et al. (2019) found that the Levenberg-Marquardt training algorithm *"presented the best training speed and network learning."*

There are numerous good examples of ANN models, developed to quantify durability factors and estimate service life of exterior stone cladding (Silva et al., 2011), exterior painted surfaces (Dias et al., 2014), and ceramic claddings (Souza et al., 2020). For further discussions and examples refer to (Silva et al., 2016b).

5.2.3.1.1 Other applications of ANNs

Taffese et al. (2016) used a non-linear autoregressive recurrent neural network with exogenous inputs (NARX) based model to estimate the temporal hygrothermal condition in surface-protected concrete façade members. The model has a capacity in capturing long-term dependencies as it includes inputs at explicit time lags and learns the case-specific features of hygrothermal behaviour using two years temperature and relative humidity data obtained from installed probes.

Kaya et al. (2020) used real pavement performance data obtained from the Iowa DOT PMIS database to develop statistical and ANN pavement performance and remaining service life prediction models for road pavement systems. It was found that network level ANN-based pavement performance models produced greater accuracy compared with network level statistical models.

Tavakoli et al. (2020) proposed a computational model, trained and tested with acquired field data, which forecasts the remaining useful life of water pipelines using Artificial Neural Network (ANN) and Adaptive Neural Fuzzy Inference System (ANFIS).

Srikanth et al. (2020) did a review of deterioration models for the prediction of remaining useful life of timber and concrete bridges. The models reviewed include deterministic, stochastic (Markov chain-based), and AI-based models. However, deterministic models are *"not very close to reality"*, stochastic models are *"memoryless and homogeneous"*, and mechanistic models require a *"lot of computation time and data", while* AI-based models (mainly ANN's) have *"great potential to overcome some of the limitations of the other models." "The trained model is utilized to generate missing condition state data to fill the gaps due to irregular inspections."* Also refer the discussion of the durability factor quantification conundrum above.

5.2.3.2 Fuzzy Logic models

Fuzzy Logic models are AI applications that have the ability to translate non-numerical 'verbal' data (e.g., high, low, fast, worn, good, etc.) into numeric data (e.g., 1, 0.8, 72%). Where the source of data is based on or supplemented by the knowledge of durability domain experts, Fuzzy Logic can be used to translate the non-numerical 'verbal' domain expert knowledge into numeric data (e.g., probabilities) that can be used in the quantification of durability factors and estimation of service life. As Silva et al. (2016a) states "*One of the most important advantages of fuzzy modeling is that it combines numerical accuracy with transparency in the form of linguistic rules"*.

In a study by Silva et al. (2016a) *"a Takagi-Sugeno fuzzy model is used to predict the service life of natural stone claddings"* and illustrates *"its ability to learn and generalize based on experience and examples, combining numerical precision with transparency in the form of linguistic rules" and* ability "to cope with complex phenomena associated with uncertainty, like the degradation of building elements, with higher precision and better performance than the classical linear models". However, *"fuzzy logic models are complex, and their understanding is not always easy for a non-specialist researcher; in fact, the reproduction of the algorithms is clearly as difficult as the application of the model itself. Moreover, the complexity of the mathematical and computational modelling associated to the application of fuzzy models prevents the incorporation of all durability variables within the model. In fact, the inclusion of a large set of variables in fuzzy modelling leads to an extremely complex and unintelligible - even for fuzzy systems experts - model that compromises its applicability in a current professional context. Such limitations need to be put into context though, especially since other available models - simple, straightforward, deterministic models, such as degradation curves (based only on regression techniques) or factorial methods (described in ISO 15686:2000) - can manage a large set of variables but are unable to deal with the uncertainty associated with the degradation phenomena. Fuzzy systems are able to deal with the uncertainty associated with the degradation phenomena and allow the estimation of the degradation of the stone claddings based on a set of learning patterns of input and output (test sample)".*

5.2.3.3 Hybrid models

5.2.3.3.1 Neuro-fuzzy models

"*Fuzzy logic and neural networks are natural complementary tools in building intelligent systems. While neural networks are low-level computational structures that perform well when dealing with raw data, fuzzy logic deals with reasoning on a higher level, using linguistic information acquired from domain experts. However, fuzzy systems lack the ability to learn and cannot adjust themselves to a new environment. On the other hand, although neural networks can learn, they are opaque to the user. The merger of a neural network with a fuzzy system into one integrated system therefore offers a promising approach to building intelligent systems. Integrated neuro-fuzzy systems can combine the parallel computation and learning abilities of neural networks with human-like knowledge representation and explanation abilities of fuzzy systems. As a result, neural networks become more transparent, while fuzzy systems become capable of learning.*" (Negnevitsky, 2002)

Vieira et al. (2004) noted that "All the neuro-fuzzy architectures use the gradient descent techniques for the learning its internal parameters. For a faster convergence of the calculation of these parameters it would be interesting to explore other efficient algorithms of neural networks learning as the conjugated gradient or Levenberg-Marquardt search in spite of the backpropagation algorithm".

5.2.3.3.2 Adaptive Neuro-Fuzzy Inference System (ANFIS)

"ANFIS is normally represented by a six-layer feedforward neural network." (Negnevitsky, 2002).

Tavakoli et al. (2020) proposed an Adaptive Neural Fuzzy Inference System (ANFIS) computational model to forecast the remaining useful life of water pipelines.

Shariati et al. (2020) used an ANFIS to identify the parameters that affect the properties of corroded concrete beams the most due to the large number of these parameters and their interdependence.

5.2.3.3.3 Fuzzy-Markov model

Another application of Fuzzy Logic by McDuling et al. (2008) applied a Fuzzy Logic model to quantify the durability factors of the Factor Method by translating non-numerical domain expert knowledge related to durability/degradation into numeric probabilities to populate the transition matrices of the Markov chain, used to estimate the change in condition over time and subsequently remaining service life.

5.2.3.3.4 Fuzzy-Delphi model

Chen et al. (2017) proposed a Fuzzy-Delphi model to evaluate and predict building service life considering six "obsolescence factors" (i.e., physical, economic, technical, social, functional, and political obsolescence).

5.2.3.4 Other AI Applications

5.2.3.4.1 Genetic programming (GP)

*"Genetic programming (GP) is an evolutionary approach that" … "works by defining a goal in the form of a quality criterion (or fitness) and then using this criterion to evolve a set (or population) of candidate solutions (individuals) by mimicking the basic principles of Darwinian evolution. GP breeds the solutions to problems using an iterative process involving the probabilistic selection of the fittest solutions and their variation by means of a set of genetic operators, usually crossover and mutation" (*Vanneschi et al., 2012).

Gao et al. (2019) proposed a model considering 17 corrosion influence factors for the prediction of service life of tunnel structures *"using data from real engineering examples and genetic programming (GP)."* The model was verified through *"a comparative study with an artificial neural network (ANN) model which is frequently used in chloride-induced corrosion prediction for reinforced concrete structures"* and it is stated that the *"efficiency of the GP method were significantly better than those of the ANN model"*.

5.2.3.4.2 The Internet of Things (IoT)

The Internet of Things (IoT) is an ecosystem consisting of *"web-enabled smart devices that* *use embedded systems, such as processors, sensors and communication hardware, to collect, send and act on data they acquire from their environments. IoT devices share the sensor data they collect by connecting to an IoT gateway or other edge device where data is either sent to the cloud to be analysed or analysed locally. Sometimes, these devices communicate with other related devices and act on the information they get from one another"* (see https://internetofthingsagenda.techtarget.com/definition/Internet-of-Things-IoT).

Taffese et al. (2019) addressed the performance data collection conundrum by employing the IoT for continuous non-destructive in-service monitoring of reinforced concrete structures in a cost-effective manner. *"The availability of long-term monitored data along with the use of intelligent data analysis enables capturing of the complex nonlinear interaction of durability controlling parameters, making the structures' condition assessment more reliable. The reliability of the assessment results is highly beneficial for stakeholders to plan proactive maintenance, which in turn extends the service life of the structures."*

This technology has huge potential for the future collection of durability data in the built environment. Manic et al. (2016) stated that *"Intelligent buildings are quickly becoming cohesive and integral entities of cyber-physical ecosystems. Modern buildings adapt to internal and external elements and thrive on ever increasing data sources such as ubiquitous smart devices and sensors while mimicking various approaches previously known in software, hardware, and bio inspired systems"*.

5.2.3.4.3 Machine Learning

"Machine learning is a major subfield in artificial intelligence that deals with the design and development of algorithms to identify complex patterns from experimental data, without assuming a pre-established equation as a model and make decisions intelligently. Machine learning based models can be either predictive to perform predictions or descriptive to gain knowledge from data, or both." (Taffese et al., 2017)

Taffese et al. (2017) reviewed the capability of machine learning in addressing the limitations of classical prediction models based on the ability of machine learning to capture the complex physical and chemical process of the deterioration mechanism. *"The growing trend of collecting more and more in-service data using wireless sensors facilitates the use of machine learning for durability and service-life assessment"*.

5.2.4 Concluding remarks

The sheer number of research papers and publications available on the internet confirms the scope of AI models for the quantification of the durability factors in the built environment. A review indicated that the most popular AI application is MLP ANNs, but the most suitable type of AI application depends to a large extent on the availability of real performance data.

Many of the current artificial intelligence models for quantification of the durability factors can be applied with some adjustments in other areas still in need. The existing models are also in line with similar developments in other fields (e.g., civil infrastructure, medical diagnosis, driverless vehicles, etc.) and these fields could offer alternative solutions.

5.2.4.1 The short-term future

The short-term future will probably be driven by the need for reliable and consistent durability performance data. Multilayer perceptron (MLP) neural networks and neuro-fuzzy models will most likely continue to dominate for the foreseeable future, with deep (learning) neural network (DNN) algorithms gaining popularity as real performance databases grow.

5.2.4.2 The longer-term future

One of the biggest challenges in the quantification of durability factors is consistency and currency of real performance data. With the rapid technological advancements in the field of convolutional networks (CNN) or deep neural networks, which are currently the state-of-the-art in image processing, drones and DNN algorithms combination with IoT and machine learning could be used to perform assessments and data collection to ensure consistency (consistent interpretation of assessment criteria), currency (shorter intervals between assessments) and affordability (reduced cost of assessments). This technology offers exciting opportunities for the future of service life prediction.

References

Chen, C.-J., Juan, Y.-K., Hsu, Y.-H. (2017). Developing a systematic approach to evaluate and predict building service life. *Journal of Civil Engineering and Management*, Vol. 23(7), pp. 890-901.

Dias, J. L., Silva, A., Chai, C., Gaspar, P. L., de Brito, J. (2014). Neural networks applied to service life prediction of exterior painted surfaces. *Building Research & Information*, V. 42(3), pp. 371-380.

Felix, E.F., Possan, E., Carrazedo, R. (2019). Analysis of training parameters in the ANN learning process to mapping the concrete carbonation depth. *Journal of Building Pathology and Rehabilitation*, V. 4, paper #16. DOI: https://doi.org/10.1007/s41024-019-0054-8

Gao, W., Chen, X., Chen, D. (2019). Genetic programming approach for predicting service life of tunnel structures subject to chloride-induced corrosion. *Journal of Advanced Research*, V. 20, pp. 141-152.

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

ISO 15686-8 (2008) Buildings and constructed assets - service life planning - part 8: reference service life and service life estimation. International Organization for Standardization, Switzerland.

Kaya, O., Ceylan, H., Kim, S., Waid, D., Moore, B.P. (2020). Statistics and artificial intelligence-based pavement performance and remaining service life prediction models for flexible and composite pavement systems. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2674(10). DOI: https://doi.org/10.1177/0361198120915889

Manic, M., Amarasinghe, K., Rodríguez-Andina, J., Rieger, C.G. (2016). Intelligent Buildings of the Future: Cyberaware, Deep Learning Powered, and Human Interacting. Office of Nuclear Energy. U.S. Department of Energy, Idaho National Laboratory, USA.

McDuling, J., Horak, E., Cloete, C. (2008). *Service life prediction beyond the 'factor method'*. 11th International conference on durability of building materials and components, Istanbul, Turkey, T42.

Negnevitsky, M. (2002). Artificial Intelligence, A Guide to Intelligent Systems. Addison-Wesley, Essex, England.

Salvaneschi, P., Cadei, M., Lazzari, M. (1996). *Applying AI to structural safety monitoring and evaluation*. IEEE Intelligent Systems, Vol. 11, pp. 24-34. DOI Bookmark: 10.1109/64.511774.

Shariati, M., Mafipour, M.S., Haido, J.H., Yousif, S.T., Toghroli, A., Trung, N.T., Shariati, A. (2020). Identification of the most influencing parameters on the properties of corroded concrete beams using an Adaptive Neuro-Fuzzy Inference System (ANFIS). *Steel and Composite Structures*, Vol. 34(1), pp. 155-170.

Silva, A., Dias, J. L., Gaspar, P. L., de Brito, J. (2011). Service life prediction models for exterior stone cladding. Research paper. *Building Research & Information*, V. 39(6), pp. 637-653.

Silva, A., Gaspar, P. L., de Brito, J. (2014). *Stochastic, deterministic, statistical and artificial intelligence based models to predict the service life of rendered facades*. 13th International Conference on Durability of Building Materials and Components. São Paulo, Brazil, pp. 351-358.

Silva, A., Vieira, S.M., de Brito, J., Gaspar, P. L. (2016a). Fuzzy systems in service life prediction of external natural stone claddings. *Journal of Performance of Constructed Facilities*, V. 30(5), pp. 04016005-1-9.

Silva, A., de Brito, J. and Gaspar, P. (2016b) *Methodologies for service life prediction of buildings: with a focus on façade claddings*. Springer International Publishing, Switzerland.

Souza, J., Silva, A., de Brito, J., Dias, J.L., Bauer, E. (2020). Evaluation of the deterioration of ceramic claddings by application of artificial neural networks. *Journal of Performance of Constructed Facilities*, V. 34(5), pp. 04020084-1-10.

Srikanth, I., Arockiasamy, M. (2020). Deterioration models for prediction of remaining useful life of timber and concrete bridges: A review. *Journal of traffic and transportation engineering* (English edition), V. 7(2), pp. 152-173

Taffese, Z.W., Sistonen, E. (2016). Neural network based hygrothermal prediction for deterioration risk analysis of surface-protected concrete façade element. *Construction and Building Materials*, V. 113, pp. 34-48.

Taffese, Z.W., Sistonen, E. (2017). Machine learning for durability and service-life assessment of reinforced concrete structures: Recent advances and future directions. *Automation in Construction*, Vol. 77, pp. 1-14.

Taffese, Z.W., Nigussie, E., Isoahob, J. (2019). *Internet of Things based durability monitoring and assessment of reinforced concrete structures*. The 5th International Workshop on the Future of the Internet of Things (FIT 2019), Halifax, Canada.

Tavakoli, R., Sharifara, A., Najafi, M. (2020). Artificial neural networks and adaptive neuro-fuzzy models for prediction of remaining useful life. ASCE, World Environmental and Water Resources Congress, Nevada, USA, pp. 191-204.

Vanneschi, L., Poli, R. (2012). Genetic Programming - introduction, applications, theory and open issues. In: Rozenberg G., Bäck T., Kok J.N. (eds), Handbook of Natural Computing. Springer, Berlin, Germany.

Vieira, J., Dias, F. M., Mota, A. (2004). Neuro-Fuzzy systems: A survey. 5th WSEAS NNA International Conference on Neural Networks and Applications, Udine, Italia.

5.3 Stochastic approach to the factor method

Ana Silva, Jorge de Brito and Pedro Lima Gaspar; University of Lisbon

5.3.1 The context

For decades, the "factor method" was a simple tool to be used by stakeholders, in practice, for the service life of building components, in the absence of more scientific data related with the components' performance under real exposure conditions. However, several authors (Bourke and Davis, 1999; Hovde, 2000; Moser and Edvardsen, 2002; Mc Duling et al., 2008; Silva et al., 2016) discuss the limitations of the factor method, especially when it is applied as a purely deterministic tool, namely: i) the method provides an absolute value to describe the expected service life of a given component, not providing any information about the dispersion and variability of the results; ii) the method does not takes into account the degradation phenomena of the component under analysis, when subjected to real exposure conditions; and iii) the quantification of the durability factors or the reference service life neglects the degradation condition of the component under analysis, and small variations in the quantification of these factors inevitably lead to high deviations in the estimated service life of the component.

ISO 15686-8 (2008) refers that different levels of sophistication can be adopted in the quantification of the durability factors used in the factor method (Re Cecconi et al., 2016). In this sense, various authors (Aarseth and Hovde, 1999; Moser, 1999; van Nunen, 2010; Silva et al., 2016) suggested the adoption of a stochastic approach in the quantification of the durability factors, intending to include the variability associated to the degradation phenomena of the building component under analysis: i) Moser (2004) suggested a hybrid approach, in which the reference service life is given by an absolute value, while each durability factor is described by a given probability distribution function; ii) Re Cecconi (2004) applied a Monte Carlo simulation, with triangular probability distribution functions, in the quantification of the durability factors; iii) Daniotti and Spagnolo (2008) suggested the adoption of random variables in the quantification of the durability factors, in order to take into account the variability of the degradation phenomena, which allow obtaining a more reliable estimation of the service life of the component analysed; iv) van Nunen (2010) assigned to each durability factor the probability distribution function with the best goodness-of-fit, according to a set of statistical parameters; and v) Mc Duling et al. (2008) adopted a neuro-fuzzy artificial intelligence model, in order to obtain probability values to define the durability factors.

Silva et al. (2016) developed a stochastic approach to the factor method, based on the general methodology proposed by Gaspar and de Brito (2008). Therefore, this approach combines the consideration of the degradation phenomena and the condition of the component, when subjected to real exposure conditions, with a stochastic approach to describe the degradation factors and the estimated service life of each case study analysed. In this section of this report, this stochastic approach to the factor method is described in detail.

5.3.2 Methodology for the quantification of the durability factors

The first step for the application of the stochastic approach to the factor method proposed by Silva et al. (2016), is the identification and quantification of the factors that influence the durability and service life of the component under analysis. Once all the relevant durability factors are identified, they are transformed into probability distributions functions, according to the following steps:

I. First, the durability factors identified must be quantified. For that purpose, the method described in section 3.3.5 of this report is adopted. In this method, the durability factors are fine-tuned in order to increase the similarity between the estimated service life predicted by the factor method and the values obtained based on the graphical method (*GM*). The graphical method depicts the degradation phenomena of the component analysed, through the identification of a degradation pattern, based on a large sample collected during a fieldwork survey, which allows understanding the behaviour of the component in real exposure conditions. In the methodology proposed by Gaspar and de Brito (2008) and adopted by Silva et al. (2016), the results obtained using the *GM* are considered as describing the observed reality, and are used to validate the results obtained by using the factor method;

II. Once the durability factors are fine-tuned, a probability distributions function must be assigned to each sub-factor under analysis. In this sense, the first step corresponds to the determination of the first durability sub-factor (e.g. $A1$), as described in equation (5.4.1):

$$A1 = \frac{ESL_{GM}}{RSL \times A2 \times \ldots \times AN \times B1 \times \ldots \times BN \times E1 \times \ldots \times EN \times F1 \times \ldots \times FN \times \ldots \times G1 \times \ldots \times GN} \quad \textbf{(5.4.1.)}$$

Where ESL_{GM} is the estimated service life obtained by the graphical method (*GM*). In the denominator, *RSL* represents the reference service life of the building component, and the product of all other sub-factors ($A2 \times \ldots \times AN \times B1 \times \ldots \times BN \times E1 \times \ldots \times EN \times F1 \times \ldots \times FN \times \ldots \times G1 \times \ldots \times GN$), excluding $A1$, is obtained by multiplying all the sub-factors quantified by the values defined in the previous step, considering the specific characteristics of the component under analysis. This approach intends to ensure that the *ESL* obtained by the factor method is similar to the *ESL* obtained by the graphical method. This process must be repeated for all case studies within the sample analysed, in order to obtain an average value for each category of factor *A*;

III. Afterwards, the values obtained for each sub-factor should be standardised, in order to ensure that the average value of the probability distribution function proposed for each category is equal to the value initially proposed by the optimisation of the durability factors (described in the first step). The optimised or fine-tuned values should always be used as the reference values for the application of the factor method to the service life prediction of the component under analysis, since these values are obtained in order to minimize the deviations between the values predicted by the factor method and the values observed in reality (supposedly depicted by the graphical method). Equation (5.4.2.) shows the procedure adopted to standardise the values of each sub-factor:

$$A_{ic} = \frac{A_i \cdot \bar{A}_{FM}}{\bar{A}_i} \quad \textbf{(5.4.2.)}$$

Where A_{ic} is the value of each case study i for category c of factor A, A_i is the value obtained for factor A in the previous step of calculation, $\bar{A}_{FM}$ is the average value for factor A_i obtained by using the *FM*, adopting the quantification of the durability factors after fine-tuning (as described in the first step of this methodology), and $\bar{A}_i$ the average value of factor A_i;

IV. This calculation process is thus sequentially repeated for all durability sub-factors.

In this process, each case study within the sample presents a given value for each sub-factor. Therefore, each sub-factor has a sample of values, with an average value standardised (as described in point III of the description of the methodology). A probability distribution function was thus assigned to each durability sub-factor. For that purpose, the software EasyFit 5.4 was used, which allows adjusting 65 theoretical probability distributions to a given sample. In this study, only six distributions are analysed, in order to ensure the applicability and usefulness of the proposed model. The stochastic approach to the factor method should be easily used by practitioners, who do not need to be statisticians. In this sense, the most common continuous distributions were selected: i) Normal; ii) Lognormal; iii) Gamma; iv) Weibull; v) Gumbel; vi) Logistic.

Three goodness-of-fit tests were used to select the best distribution for each durability sub-factor (van Nunen, 2010, Silva et al., 2016):

I. *The Anderson-Darling test (A-D test)*, which is appropriate for continuous distributions, leading to accurate results for more than 50 data samples;
II. *The Kolmogorov-Smirnov test (K-S test)*, which is suitable for continuous distributions, even with small samples;
III. *The Chi-square test*, which is the most common test applied to continuous distributions, leading to better results than the previous ones, when a large sample is analysed.

The different tests provide a ranking of the fit of the data to each distribution. In this methodology, the three results are combined into one overall index (sum of the results of each test). When two distributions show the same position in the ranking, the selection of the best distribution is performed based on two additional tests (van Nunen, 2010; Silva et al., 2016): i) the first test contemplates the effect of small samples on the results, thus not considering the chi-square test, and using as indicator the sum of the *A-D* and *K-S* tests; ii) the second test analyses the tail of the distribution, using an index that expresses the sum of twice the result of the *A-D* test and the result of the *K-S* test.

After this procedure, a probability distribution function is then associated to each of the durability sub-factors, allowing obtaining all the dispersion measures for each sub-factor (e.g. mean, standard deviation, variance, among others).

5.3.3 Estimated service life obtained by a stochastic approach to the factor method

In this approach, the estimated service life of a given component is obtained through the multiplication of the reference service life by the probability distribution functions associated to the durability sub-factors that characterise the component under analysis. The reference service life is obtained as described in section 3.3.4 of this report, and is a deterministic value, which encompasses the degradation phenomena of the component, when subjected to current conditions of exposure, use and maintenance. This multiplication is performed using an algorithm generated in Matlab, in which a set of 100,000 random numbers are generated. This algorithm needs to be run to each case study, providing an estimated service life given by a probability distribution function, based on the characteristics of the case study analysed.

Practical examples

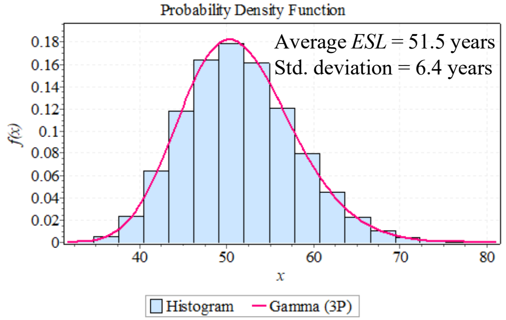
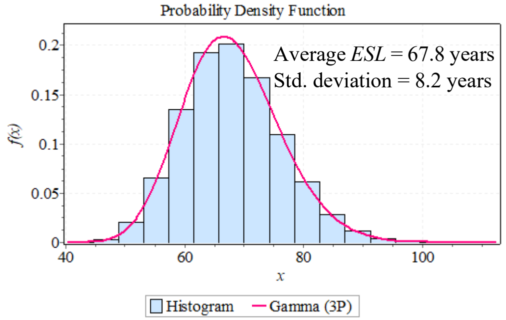
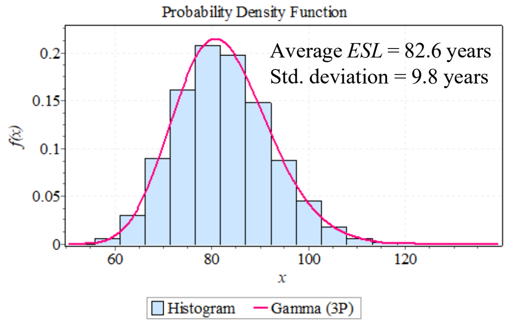
Figure 5.3.1 shows three illustrative examples of the application of the stochastic approach of the factor method to natural stone claddings. For these claddings, Silva et al. (2016) obtained a reference service life of 68 years (see Table 4.1.1. of this report, which shows the mathematical equation to apply the factor method to natural stone claddings). This cladding solution is particularly durable, and the three examples show that the claddings' characteristics are particularly relevant for their *ESL*, and small variations in the claddings' conditions promote significant variations in their *ESL*.

These examples reveal that using an absolute and average value for a cladding solution is excessively simplistic, neglecting the high variability associated with the degradation phenomena. The probability distribution function associated with the *ESL* of the three case studies reveals that: i) case study #1 has a probability higher than 95% of reaching its service life after 42 years, showing a probability lower than 5% of having a service life higher than 63 years; ii) for case study #2, an average service life of 55 years has a probability higher than 95% of being exceeded, and a probability lower than 5% of having a service life higher than 82.2 years; and iii) case study #3 shows a probability higher than 95% of reaching its service life after 67.5 years and a probability lower than 5% of having a service life higher than 100 years.

Moreover, some durability factors have a higher impact on the *ESL* of natural stone claddings than others (i.e. factors in which the variation of the quantification of the most favourable and the most unfavourable situation is higher); the type of stone, the type of finishing, the distance from the sea and exposure to damp, are the factors with higher relevance for the estimation of the service life of a natural stone cladding, while the type of property, exposure to wind-rain action and the colour of the stone are the less significant ones, according to the proposed methodology for service life prediction through the application of the factor method.

5.3.4 Concluding remarks

In the last decades, the factor method has been adopted as a general methodology for service life prediction of buildings and components. This method is a simple tool, easily adopted by practitioners in the construction and maintenance sector, providing a reasonably approximation to reality, in the absence of more precise data. This method has been criticised mainly due to its deterministic nature, neglecting the real degradation condition of the component analysed. In this sense, Gaspar and de Brito (2008) and Silva et al. (2016) proposed new approaches to overcome these limitations; first, by considering the real degradation pattern of the component; and second, by adopting a stochastic approach in modelling the service life of the component. These approaches were illustrated here with three case studies of natural stone cladding.

Illustrative example	Characteristics of the case study	Histogram of the *ESL*
 #1 ESL_{FM} = 59.3years ESL_{GM} = 58.7 years	Stone cladding with 61 years and with a degradation severity index equal to 22.0%; Sub factor A: marble - Lognormal distribution (μ=0.946; σ=0.216); Sub factor B1: light colours - Lognormal distribution (μ=1.024; σ=0.240); Sub factor B2: rough finishing - Lognormal distribution (μ=0.999; σ=0.233); Sub factor B3: medium-sized plate - Lognormal distribution (μ=0.999; σ=0.258); Sub factor B4: more than 2.5 cm - Lognormal distribution (μ=1.093; σ=0.284); Sub factor B5: bottom wall cladding - Lognormal distribution (μ=1.000; σ=0.213); Sub factor E1: cladding facing W/NW - Lognormal distribution (μ=0.900; σ=0.256); Sub factor E2: less than 5 km from the sea - Lognormal distribution (μ=0.998; σ=0.267); Sub factor E3: moderate exposure to wind-rain action - Lognormal distribution (μ=0.999; σ=0.254); Sub factor E4: low exposure to damp - Gumbel distribution (μ=1.000; σ=0.225); Sub factor F: commerce - Lognormal distribution (μ=0.999; σ=0.296); Sub factor G: unfavourable inspection conditions - Gumbel distribution (μ=0.900; σ=0.223).	
 #2 ESL_{FM} = 68.8years ESL_{GM} = 67.5 years	Stone cladding with 26 years and with a degradation severity index equal to 3.9%; Sub factor A: marble - Lognormal distribution (μ=0.946; σ=0.216); Sub factor B1: light colours - Lognormal distribution (μ=1.024; σ=0.240); Sub factor B2: rough finishing - Lognormal distribution (μ=0.999; σ=0.233); Sub factor B3: medium-sized plate - Lognormal distribution (μ=0.999; σ=0.258); Sub factor B4: less than 2.5 cm - Lognormal distribution (μ=1.000; σ=0.241); Sub factor B5: bottom wall cladding - Lognormal distribution (μ=1.000; σ=0.213); Sub factor E1: cladding facing North - Lognormal distribution (μ=0.902; σ=0.197); Sub factor E2: more than 5 km from the sea - Lognormal distribution (μ=1.150; σ=0.263); Sub factor E3: moderate exposure to wind-rain action - Lognormal distribution (μ=0.999; σ=0.254); Sub factor E4: low exposure to damp - Gumbel distribution (μ=1.000; σ=0.225); Sub factor F: commerce - Lognormal distribution (μ=0.999; σ=0.296); Sub factor G: current inspection conditions - Lognormal distribution (μ=0.999; σ=0.248).	
 #3 ESL_{FM} = 84.1years ESL_{GM} = 89.7 years	Stone cladding with 53 years and with a degradation severity index equal to 4.9%; Sub factor A: limestone - Lognormal distribution (μ=1.000; σ=0.219); Sub factor B1: light colours - Lognormal distribution (μ=1.024; σ=0.240); Sub factor B2: smooth finishing - Gumbel distribution (μ=1.100; σ=0.295); Sub factor B3: medium-sized plate - Lognormal distribution (μ=0.999; σ=0.258); Sub factor B4: less than 2.5 cm - Lognormal distribution (μ=1.000; σ=0.241); Sub factor B5: bottom wall cladding - Lognormal distribution (μ=1.000; σ=0.213); Sub factor E1: cladding facing NE - Normal distribution (μ=0.949; σ=0.239); Sub factor E2: more than 5 km from the sea - Lognormal distribution (μ=1.150; σ=0.263); Sub factor E3: moderate exposure to wind-rain action - Lognormal distribution (μ=0.999; σ=0.254); Sub factor E4: low exposure to damp - Gumbel distribution (μ=1.000; σ=0.225); Sub factor F: housing - Gumbel distribution (μ=1.000; σ=0.203); Sub factor G: current inspection conditions - Lognormal distribution (μ=0.999; σ=0.248).	

Where *A*1 is the type of stone, *B*1 the colour, *B*2 the type of finishing, *B*3 the size of stone plates, *B*4 the thickness of stone plates, B5 the location of the cladding, *E*1 the façades orientation, *E*2 the distance from the sea, *E*3 the exposure to wind-rain action, *E*4 the exposure to damp, *F*1 the type of property, and *G*1 the ease of inspection

Figure 5.3.1. - Illustrative examples of the application of the stochastic approach of the factor method to natural stone claddings

The stochastic approach allows obtaining extremely relevant knowledge regarding the service life of a given component. While the factor method, when applied as a purely deterministic tool, provides an absolute value of the estimated service life of the component, the stochastic approach provides relevant information concerning the risk of failure of the component over time, and allows estimating the *ESL* with the highest probability of being reached based on the characteristics of the building component under analysis. This stochastic approach of factor method offers a valuable tool, which can aid the adoption of more rational decisions during the buildings and components life cycle, namely in the design process and in the definition of maintenance and rehabilitation strategies.

References

Aarseth, L.I., Hovde, P.J. (1999). *A stochastic approach to the factor method for estimating service life*. 8th International Conference on Durability of Building Materials and Components; Vancouver, Canada, pp. 1247-1256.

Bourke, K., Davis, H. (1999). *Estimating service lives using the factor method for use in whole life costing*. 8th International Conference on Durability of Building Materials and Components; Vancouver, Canada, pp. 1518-1526.

Daniotti, B. and Spagnolo, S. L. (2008). *Service life prediction tools for buildings' design and management*. 11th International Conference on Durability of Building Materials and Components, Istanbul, Turkey, T72.

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

ISO 15686-8 (2008) Buildings and constructed assets - Service-life planning - Part 8: Reference service life and service-life estimation, International Organization for Standardization, Switzerland.

Mc Duling, J., Horak, E. and Cloete, C. (2008). *Service life prediction beyond the 'Factor Method'*. 11th International Conference on Durability of Building Materials and Components; Istanbul, Turkey, T42.

Moser, K. (1999). *Towards the practical evaluation of service life - illustrative application of the probabilistic approach*. 8th International Conference on Durability of Building Materials and Components; Vancouver, Canada, pp. 1319-1329.

Moser, K., and Edvardsen, C. (2002). *Engineering design method for service life prediction*. 9th International Conference on the Durability of Building Materials and Components, Brisbane, Australia, paper 222.

Re Cecconi, F. (2004). *Engineering method for service life planning: the evolved factor method*. Building the future: 16th CIB World Building Congress, Toronto, Canada.

Re Cecconi, F., Rigone, P. and Vatavalis P. (2016) Factor method for aluminium windows and curtain walls. 14th International Conference on the Durability of Building Materials and Components, Ghent, Belgium.

Silva, A., de Brito, J. and Gaspar, P. (2016) *Methodologies for service life prediction of buildings: with a focus on façade claddings*. Springer International Publishing, Switzerland.

van Nunen, H. (2010). Assessment of the sustainability of flexible building. The improved factor method: service life prediction of buildings in the Netherlands, applied to life cycle assessment. 1st Edition, Aeneas, Netherlands.

CIB General Secretariat
Suite #M164 110 Didsbury Road, Kanata, ON Canada
K2T 0C2 www.cibworld.org | secretariat@cibworld.org

CIB Publication 421