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Service life prediction of building components in the times of climate change

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Abstract. Buildings components and assemblies are prone to decay over time due to the inherent characteristics of the materials, environmental conditions and operational use of them. For this reason, it is very important to know the right time and type of maintenance and adaptation interventions that need to be applied to the specific compounds. The answer to the above issue can be given through the service life prediction (SLP) of the components by using standardized calculation methods.
In historic buildings, the process of SLP takes significant importance because these buildings hold non-renewable cultural heritage value and therefore, the interventions should be performed in a way that preserves the original material and value while enhancing the service life. Nowadays, for such buildings that are predicted to live for centuries, the SLP needs to be corrected by considering the effects of climate change in the construction materials.
The paper presents an overview of the application of the well-known factor method in the estimation of the serviceability of the building components, with a special focus on historic buildings impacted by climate change. The technical compatibility, economic viability, use of the building and the indoor/outdoor environments are considered during the assessment of the service life which is strictly linked with the level of decay. It gives a short explanation of the factors that constitute the method by including the effects of climate change and an example of application to a specific case study in Norway.

1. Introduction

Buildings are prone to both keep materials and components intact and in-use, and to achieve comfortable living requirements. For this reason, it is very important to plan the time milestones of the intervention actions over a long-term horizon. To this aim, the service life prediction (SLP) is an important tool to apply prior to any type of interventions to the structures. The general framework of the SLP for both the new constructions and the existing buildings is expressed in the international standard ISO 15686-1 [1]. Given the variety of structures and materials constituting the built environment, it is of primary importance to set up methods, which use basic data and can be applied to several scenarios under different exposure and user conditions [2]. The factor method, with its constituent factors, as described in the ISO 15686:8, allows such inherent flexibility [3].
The application of the method estimates the service life for a specific component or assembly (in years) by considering its technical conditions in the environment where the component or assembly is located and with its peculiarity of use. Applied to historic buildings, the assessment of the SLP becomes an important heritage management tool to prioritize interventions so that both the integrity and the historic value of the materials is maintained and maximized. The built environment is constituted by different layers such as the site, the structure, the building envelope, the services, the indoor space into the

building, etc. The layers have different rates of change that vary from eternity (site) to a few years (sensitive material/component) [4]. When dealing with historic buildings, beside buildings with indoor sensitive collections (out of the scope of the present work), the layer that holds most of the cultural value is the building envelope. This layer, apart from the historic value, is in direct contact with natural and anthropic degradation agents (e.g. radiation, precipitation, wind, pollutants, etc.) and shows a higher rate of decay. Therefore, its conservation has substantial importance because it does not only preserve the value, but the improvement of the building envelope influences the energy performance of the structure, increases the living comfort and reduces the monetary cost and environmental impact. For this reason, this article is focused on the façade of the buildings, more specifically in the estimation of the lifetime of the outer walls of historic buildings.

Starting from the recommendations of the standard, the SLP method has been applied to different building components such as wooden façade [5], ceramic and stone wall claddings [6, 7], wooden windows [8], thermal insulations systems [9], external paint finishes [10]. This article gives an overview of the use of the factor method in historic buildings by including the most important parameters that influence the level of decay and the building significance. It introduces new correction components and criteria that consider the need of keeping a longer service life for historical materials and their sensitiveness to climate change, as well as subfactors which consider the technical compatibility, the economic viability and the proper use of the building. The method needs to be further refined, especially when dealing with the determination of the list and the value of subfactors used for the analysis. This implies the need for further multidisciplinary research and laboratory tests to validate the results. However, the application of the same methodology to a large group of buildings can be a suitable tool for their categorisation, even though the predicted results can have discrepancy from the real case studies. Finally, an example of a user-friendly SLP application – that does not require huge mathematical background or programming simulations – is reported to a case study in Norway.

2. Materials and methods

2.1. Factor method

There are many ways for calculating the SLP but according to the report "Performance-based methods for service life prediction", they can be divided into two main procedures: factor methods and engineering design methods [11]. According to the factor method, the service life (in years) is calculated by multiplication of a reference service life (RSL) with different modifying factors, which consider the deviation from reference conditions as reported in equation (1):

$$ESL = RSL \cdot f_A \cdot f_B \cdot f_C \cdot f_D \cdot f_E \cdot f_F \cdot f_G \quad (1)$$

where ESL = estimated service life; f_A = factor A: quality of components; f_B = factor B: design level; f_C = factor C: work execution level; f_D = factor D: indoor environment; f_E = factor E: outdoor environment; f_F = factor F: in-use conditions; and f_G = factor G: maintenance level.

The factor method is a useful tool for estimation and comparison of the lifetime of materials and assemblies and it is in continuous improvement through new definitions of the necessary input data for RSL and factor values. In the process of the estimation of ESL, the attention is given to the definition of the RSL, as well as the value of every single factor. According to the standard, the specific values of the factors are independent of each other and it should be aware that the components are not mixed or taken into consideration multiple times. In our work, to better underline the criteria or important components (called subfactors) which influence the service life of external layers of historic buildings, each factor of equation (1) (f_i with i from A to G) is further constituted by j number of subfactors (with j from 1 to n) as reported in equation (2):

$$f_i = f_{i_1} \cdot f_{i_2} \cdot \ldots \cdot f_{i_n} = \prod_{j=1}^{n} f_{i_j} \quad (2)$$

2.2. List of components

In Table 1 it is given a list of the main subfactors that are considered when evaluating the service life of assemblies in a historic building. The list has been compiled by taking into account the results of the literature review [2, 12-14] and of the EU project Climate for Culture (CfC) [15] with a special focus in impacts of climate change on cultural heritage buildings. The table is not to be considered as exhaustive but can be subjected to further improvement and adaptation with respect to the specific case studies.

Table 1. List of subfactors to be considered during SLP of outer components in historic buildings.

Aspect of interest	Factor	Subfactor
Inherent quality characteristics	A – Inherent performance level	A1 – Quality of the original material A2 – Quality of the later material A3 – Quality of the treatment *A4 – Manufacturing* [a] *A5 – Transportation* *A6 – Storage*
	B – Design level	B1 – Technique of design B2 – Sheltering B3 – Decoration B4 – Energy requirements
	C – Execution level	C1 – Level of workmanship *C2 – Implementation of the project* *C3 – Conditions of the site*
Environment	D – Indoor environment	D1 – Temperature (M, W) [b] D2 – Relative humidity (M, W) D3 – Freezing-Thawing cycles (M) D4 – Salt crystallisation cycles (M) D5 – Thenardite-Mirabilite cycles (M) D6 – Time of wetness (M) D7 – Mould (M, W) D8 – Insects (W)
	E – Outdoor environment	E1 – Freezing-Thawing cycles (M) E2 – Salt crystallisation cycles (M) E3 – Time of wetness (M, W) E4 – Dry days index (M, W) E5 – Frost days index (M, W) E6 – Wet days index (M) E7 – Heavy precipitation index (M, W) E8 – Tropical night index (M, W)
Operation conditions	F – Usage conditions	F1 – Type of use F2 – Flux of use F3 – Surrounding activities
	G – Maintenance level	G1 – Easy of maintenance G2 – Type of ownership G3 – Budget limitations

[a] Subfactors in italics apply to new buildings.
[b] Subfactors with index (M) apply to masonry buildings and with (W) to wooden buildings.

For existing components, the evaluation is done only for the actual conservation status of the components, which means that some subfactors that apply to new materials or the project implementation phase such as manufacturing, transport, storage, site conditions, etc. are not included (or taken equal to 1) in the estimation. Such subfactors are reported in italics in the table and can be considered during service life calculations of new buildings or new additional construction works in existing buildings during restoration interventions. In addition, most of the historic buildings, due to their year of construction, have been built with external façade that does not meet the actual thermal conductivity requirements of the latest design codes. In fact, in several cases in existing buildings, the improvement of energy efficiency is the driving factor in retrofitting or refurbishment interventions.

While inherent quality characteristics and operation conditions do not depend on the type of the material, the environmental factors (D and E) can influence the level of the decay with regard on the type of material with whom they interact. The indoors and outdoors climate-induced risks manifest themselves on historical materials and components as mechanical, chemical and biological agents of deterioration and they are represented by a set of sub-factors as indicated in the CfC project [16]. The values of these subfactors, for every risk component linked to a specific climatic area and type of the building, have been determined in this work using the threshold values and the risk maps results of the project [17]. In Table 1, the index (M) represents climate-induced decay components affecting masonry and stone buildings while the symbol (W) for subfactors affecting wooden buildings. For building components that are estimated to live for decades, the value of SLP can be corrected by introducing a correction factor that considers the effects of climate change in construction materials. This can be achieved by using the results of the Near Future (2021-2050) or Far Future (2071-2100) scenarios for determining the subfactors for the indoor or outdoor environment.

The climate conditions, the atmospheric agents (heavy rainfall, hail, wind, etc.), the type and condition of the landscape (e.g. risk-prone areas, vegetation, etc.) as well as the type and frequency of activities conducted in the adjacent area (e.g. pollution, road with traffic density, delivery areas, etc.) can affect the conservation of building materials through similar mechanisms (e.g. mechanical decay caused by freezing-thawing cycles or crystallization-deliquescence cycles in presence of water and salts; chemical decay caused by pollutants; biological decay caused by vegetation, mould and pest infestation; etc.).

Type of use and flux of persons entering the building influence directly the indoor microclimate. A high concentration of people in one room leads to change in temperature and relative humidity and therefore, influences microclimate conditions in the proximity of building materials which in turn, act on triggering indoor decay mechanisms. This is an important factor to be considered in historic buildings subjected to mass tourism which can be affected by direct wear of materials and by indirect decay caused by microclimate modifications. On the other hand, a no-use of the building may preserve the components from wear or tear, but it will influence their service life because of the lack of preventive conservation and scheduled maintenance.

In historic buildings, the maintenance process has, therefore, significant importance because it keeps monitored the rate of decay, it keeps the original material in optimal status and it prevents the loss of cultural heritage value extending the service life of the materials and structure in general. In most of the cases, a good practice in historic buildings maintenance increases the cost of the action (compared with cost of maintenance in existing building with no significance) because of the careful selection of materials which need to be compatible with the original ones or the careful choice of interventions which must be reversible and implemented by craftsmen with unique expertise. These approaches can be economic and inherent performance barriers for most of the owners and heritage managers. Decision-makers, to minimize the risk of stacking in a “no-action” situation, should plan in advance a range of adaption actions under different budget scenarios so that they can choose in a balanced approach between maintenance and budget [13]. Depending on the preservation target and the budget, the heritage managers should select among actions that aim to keep the estimated service life of material and building components the same as the reference one (preventive maintenance); to improve the service life of the component (rehabilitation) or to increase significantly their service life (renovation, restoration).

The prediction of the decay rate on building components becomes, therefore, a necessary step to determine the time of the intervention action before the component or structure reaches the end of technical/functional service life. The categorisation of decay levels (small, medium and high) becomes the starting point in suggesting refurbishment interventions and the frequency of application.

3. Application of the method

3.1. Description of the building

The factor method has been applied here to estimate the service life of an external wall of a historic building in the city of Trondheim in Norway. The prediction of the service life in years forecasts the level of decay of the wall and therefore, it suggests the level of intervention that needs to be applied over the time to come.
In the city of Trondheim, apart from the listed buildings (named Fredet and marked with letter F), there is a large number of protected buildings (Vernet) which are categorised in three main groups (A, B and C) according to the value that they represent [18]. The building (Figure 1) is situated in the Møllenberg area and it has legislation protection of level B. In this category, fall the buildings that have high significance and possess peculiar features. In such cases, intervention works are recommended to be applied from inside in order to hold the original value of the external façade. The external wall is built of wooden material (log-construction) and it has an additional insulation layer of 50mm which has been added in the 80s (Figure 2).

Figure 1. View of the main façade of the building.

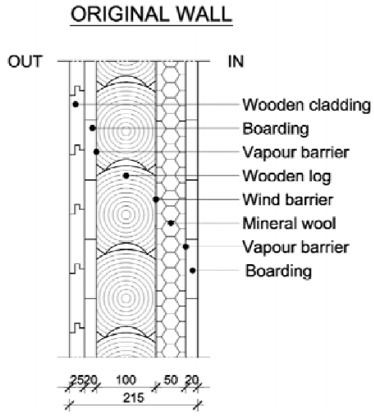

Figure 2. Section of the wall.

3.2. Prediction of the service life
In Table 2 it is given the condition status for each subfactor category that should be considered for the estimation of the service life. Based on the conditions of the wall section, three values have been assigned for each subfactor: the minimum, the most-likely (mode) and the maximum value together with the likely shape of the statistical distribution (e.g. deterministic, normal, log-normal) by using the recommendations from the literature and results of previous research in the field [2, 5]. By using the above information, the values of the subfactors can be estimated for different percentiles of occurrence. In the example, three percentile values (5%, 50% and 95%) have been calculated, following the suggestions of the ISO 15686-8 standard. The most used fractions (50% of the subfactor values) fall under the median value, while 5% and 95% fall respectively above the minimum value and under the maximum value. For the environment-related categories, the values of subfactors and types of distribution have been dispensed by using the maps of the European project Climate for Culture [15]. The effect of climate change has been included by using the projections for the variables in the Far Future scenario (2071-2010) over the Trondheim area.

Table 2. Fractional values of subfactors used for the service life prediction distribution.

Subfactor	Conditions	Factor values			Distribution
		f_{x5}	f_{x50}	f_{x95}	
A1 – Quality of the main material	Normal variation of the component	0.84	1.00	1.16	Normal
A2 – Quality of the insulation	Insufficient quality of the component	0.72	0.80	0.88	Normal
A3 – Quality of the treatment	Good quality of the component	1.09	1.20	1.31	Normal

B1 – Technique of design	Good technique, identical design	1.20	1.20	1.20	Deterministic
B2 – Sheltering	No sheltering for walls	1.00	1.00	1.00	Deterministic
B3 – Decoration	No decoration for walls	1.00	1.00	1.00	Deterministic
B4 – Energy requirements	Poor thermal transmittance	0.69	0.79	0.87	Log-normal
C1 – Level of workmanship	Normal construction, no mistakes	1.00	1.00	1.00	Deterministic
D1 – Temperature T	Heated building, 18°C ≤ T ≤ 25°C	1.00	1.00	1.00	Deterministic
D2 – Relative humidity RH	No risk of condensation, RH≤70%	1.00	1.00	1.00	Deterministic
D7 – Mould	Medium risk	0.97	1.04	1.08	Log-normal
D8 – Insects (RH-dependent)	Very low risk	1.37	1.44	1.48	Log-normal
E4 – Dry days index	Medium risk	0.92	0.96	1.03	Log-normal
E5 – Frost days index	High risk	0.77	0.84	0.88	Log-normal
E6 – Wet days index	Medium risk	0.92	0.96	1.03	Log-normal
E7 – Heavy precipitation index	Medium risk	0.92	0.96	1.03	Log-normal
E8 – Tropical night index	Very low risk	1.37	1.44	1.48	Log-normal
F1 – Type of use	Residential house	0.95	1.00	1.05	Normal
F2 – Flux of use	4 apartments, 9 inhabitants	0.95	1.00	1.05	Normal
F3 – Surrounding activities	No heavy activities around	1.15	1.20	1.25	Normal
G1 – Easy of maintenance	Scaffolding needed from outside	0.69	0.80	0.91	Normal
G2 – Type of ownership	Rental house	0.79	0.90	1.01	Normal
G3 – Budget limitations	Surface treatment every 10 years	0.89	1.00	1.11	Normal
Total		0.29	1.25	4.63	

The assumed reference service life of the wall in residential buildings is considered 50 years [19]. The result of service life estimation is achieved by multiplying the total factors of the percentile 50% with the reference service life as given in equation (3):

$$ESL_{50} = RSL \cdot f_{50} = 50 \cdot 1.25 = 62.7\, years \tag{3}$$

The service life for our case study is estimated 62.7 years with a standard deviation of 8.6 years. This value is calculated by considering the projections of the climate-induced decay components in the Far Future (2071-2100) scenario. In case the calculations are performed using the measured data of the Recent Past (1961-1990) reference scenario, the values of climate-induced risk subfactors and therefore, the values of percentiles, are different as reported in Table 3, with changes also for the other subfactors that however remain within the same risk value range.

Table 3. Fractional values of environmental subfactors if the Recent Past scenario is applied.

Subfactor	Conditions	Factor values			Distribution
		f_{x5}	f_{x50}	f_{x95}	
D1 – Temperature T	Heated building, 18°C ≤ T ≤ 25°C	1.00	1.00	1.00	Deterministic
D2 – Relative humidity RH	No risk of condensation, RH≤70%	1.00	1.00	1.00	Deterministic
D7 – Mould	Low risk	1.12	1.16	1.23	Log-normal
D8 – Insects (RH-dependent)	Very low risk	1.37	1.44	1.48	Log-normal
E4 – Dry days index	Medium risk	0.97	1.04	1.08	Log-normal
E5 – Frost days index	Very high risk	0.57	0.64	0.68	Log-normal
E6 – Wet days index	Low risk	1.12	1.16	1.23	Log-normal
E7 – Heavy precipitation index	Medium risk	0.92	0.96	1.03	Log-normal
E8 – Tropical night index	Very low risk	1.37	1.44	1.48	Log-normal
Total $f_D \times f_E$		1.17	1.78	2.56	

In the Recent Past scenario, the multiplication of the subfactors of environment categories ($f_D \times f_E$) for the 50% percentile is 1.78 instead of 1.60 that it was when using the Far Future projections. For the Recent Past, considering the subfactors of other categories the same, the product of the entire subfactors is 1.39 (instead of 1.25 for Far Future), which corresponds to an estimated service life of 69.6 years. From the results, it can be noted that the climate change impact is expected to reduce the ESL by about 7 years.

In the current situation, the house of our case study is rented to the students and the maintenance does not follow the real needs of the structure. If the owners lived in the building, the maintenance would be more scheduled, and the estimated lifetime would increase to 69.7 years, with an increase of 10% from the first calculation. Another increase in the lifetime is predictable when the budget of the owner allows surface treatment of the façade every 5 years instead of approximately 10 years as it is now. In this case, the estimated lifetime of the wall section would reach 75.3 years (20% higher than the reference calculation of 62.7 years).

The house serves as a residential house. It has a central location in the area and in case of its transformation into a commercial building, the number of people getting access to it would increase the damages caused by wear and tear. For this scenario, the expected service life will drop by 15% with an estimation of 53.3 years.

The differences between the above scenarios are highlighted in Figure 3 for a better understanding of the importance of the subfactors in the process of service life prediction.

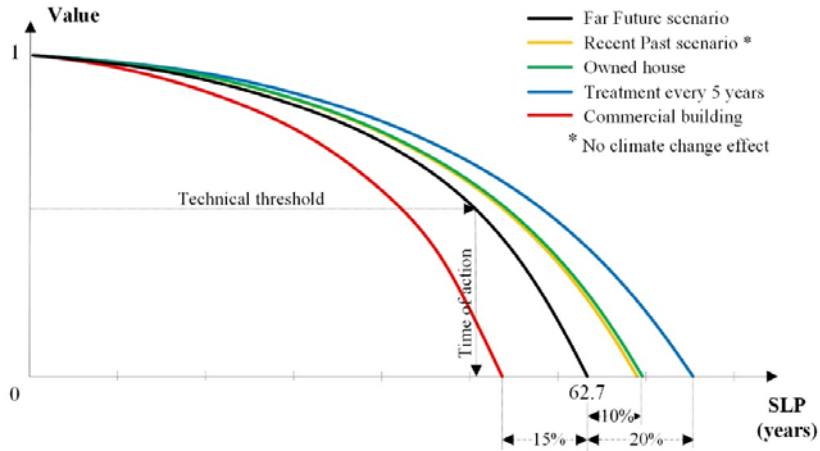

Figure 3. SLP values for different scenarios in the case study building.

4. Discussions and Conclusions

The factor method applied at a wall of a historic building in Trondheim estimates the service life of the component in years. By setting a technical threshold, the calculated value is necessary to determine the time of the intervention action in the wall prior to a high level of decay which would not only degrade the material but also will influence the cultural value of the component. The factor method is a practical method to calculate the service life of new or in-use building components, however, the experts have expressed their reserves towards the method and suggest the improvement of it [20]. One of the biggest issues of the method is the difficulty to determine the factors and therefore, the uncertainty of the results. Another critique of the method is that it considers the factors independent from each other which may not be always appropriate. However, when applying the same method (with the same marge of uncertainty) to a large built environment, e.g. a street or district level, from the results it can be recognized the components that are in a higher risk of degradation, even though the estimation of the lifetime may not be accurate in absolute sense. In a district scale, where the same level of inaccuracy is applied, the prediction allows the grouping of the components with similar values of service life, thus enabling the application of similar refurbishment interventions to components with similar decay status.

In the presented framework, strong emphasis is given to the aspects of indoor and outdoor environments. The subfactors in these categories are estimated by using the results of the Far Future scenario (2071-2100), which considers the climate change impact on building materials in the Trondheim area as calculated by the EU project Climate for Culture. As a result, the expected refurbishment interventions will be planned by considering the predicted climate results, thus increasing the accuracy in the plan of future interventions.
The application of this modified factor method serves to identify the areas that are more vulnerable to decay and take actions before the process becomes irreversible. With the introduction of the subfactors, the main quality, environmental and operational characteristics that influence the service life of historic buildings are taken into consideration. The table of subfactors (Table 1) can be subject to further improvement in order to adapt to the new challenges of the refurbishment process or to the specifics of the cultural heritage under examination. From the example of application, apart for the effect of climate change, it could be noticed that the ESL is sensitive to parameters like use of the building, type of ownership, budget limitations, etc., but it can also be influenced by design solution, conservative conditions of original material or level of craftsmanship. The definition of the value for each of these subfactors and their type of distribution ask for further research in the field through the involvement of multidisciplinary experts in data collection, running analysis and laboratory tests. By doing so, the method can be more exploited and contribute to creating a database for historic buildings to support specialists dealing with heritage site management and preventive conservation.

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