DATA AVAILABILITY, DATA QUALITY IN LCA

Service life prediction of residential interior finishes for life cycle assessment

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Abstract

Purpose Service life of building products has an important influence on life cycle assessment (LCA) results of buildings. The goal of this study was to propose a systematic approach to estimate service life of building products by including both technical and social factors.

Methods A hybrid service life prediction method, combining the statistical approach described in American Society for Testing and Materials standard G166 with the Factor Method adopted by International Organization for Standardization standard 15686, was proposed. In their current forms, the two methods are not suitable to provide reliable lifetime estimates for the wide variety of products that are used in buildings. Statistical analysis was preferred over a deterministic approach. Regression analysis was used to define Weibull distribution parameters for each product. These distributions were then used to calculate the mean estimated service life of products with an 80% confidence interval. Using actual lifetime observed from practice instead of design lifetime for reference service life was preferred. This enables the use of a smaller range of coefficients for each factor affecting service life, which decreases subjectivity and increases reliability of results.

Results and discussion Example median service life estimates were demonstrated for common residential interior finishes that are replaced more frequently, and therefore require more maintenance planning and potentially have significant environmental impacts. Probability of renovation distributions was also presented for interior finishes. The proposed method inherently includes social factors in the dataset used to define lifetime distributions, which could be as important as durability for some building product categories. Another advantage is that choosing reference service life based on real-life conditions decreases the range of coefficients necessary for modifying factors in comparison to when design lifetime is used, thus decreasing the subjectivity of results due to variations in assigned values by different users.

Conclusions The Factor Method is the most promising method available to estimate service life of products. Unless additional data points were gathered for investigated products, the presented lifetime distribution results can be directly applied to LCA studies. The proposed hybrid method can also be applied to other products that are studied within the Factor Method. Products whose lifetimes are influenced by social factors are prime candidates to apply this method.

Keywords Factor method · Interior finish · Life cycle assessment · Residential building · Service life prediction

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1 Introduction

The construction industry and the built environment are two key areas to achieve true sustainable development from an environmental, economic, and societal perspective. The sheer size of the construction industry and the dependence of other industrial sectors on the built environment make

them critical for the social and economic development of countries (Fernandez 2003). However, the built environment is also a primary source of environmental impacts, not just due to initial construction phase but also from emissions occurring during the use phase to provide comfort and serviceability to occupants. The existing building stock requires continuous investments for repair and renovations, which increases life cycle impacts (Hovde and Moser 2004).

Life cycle assessment (LCA) is a tool that can quantify the environmental impacts of products, processes, and also buildings (Optis and Wild 2010). However, many building LCA studies do not adequately address service life, the period for which the product is actually in use, for buildings and building products but rather assume typical values, e.g., 50 years for residential building lifetime (Keoleian et al. 2001; Adalberth 1997; Thormark 2002; Winther and Hestnes 1999). Such assumptions for building and building product lifetimes introduce additional uncertainty into the study and have the potential to alter results. The existing approach to address uncertainty in LCA studies is to conduct a sensitivity analysis for variables.

Compared to the structural frame or permanent components of a building, interior finishes including but not limited to paint or floor covering are replaced more frequently over the life cycle of a building, and potentially have significant environmental impacts. Lifetimes of interior finishes are affected by consumer behavior to a much higher degree compared to permanent components of a building, such as roofing or insulation. Therefore, it is vital to accurately estimate service life of interior finishes in an LCA study. This study proposes a tool to estimate service life of products that are affected by consumer behavior.

Knowledge about expected service life of building products would enhance sustainability of the built environment by presenting a better understanding of service life to designers, builders, and asset managers that make decisions on infrastructure assets, their repair, or refurbishment (Lacasse 2008). Asset managers are responsible for a significant amount of construction and maintenance work. Costs accrued during the use phase of a building may be comparable to or even exceed initial design and construction costs (Chown et al. 1996). Service life prediction of building products offers great benefits for facility managers in terms of providing a means of foreseeing future expenditures related to renovation. The ability to predict future expenditures would reduce budgetary pressures and would also allow construction work to be scheduled accordingly. Service life is a key metric that is utilized for economic decision making for return on investment or investment planning for maintenance (Moser and Edvardsen 2002).

This study addresses a gap by modifying the commonly accepted service life prediction method, namely, the Factor Method, to determine service life of building products that

can be used within LCA. Statistical use of published lifetime data that inherently includes both social and technical factors that influence lifetime would improve the reliability of calculated service life estimates. Including objective lifetime information into LCA allows a better understanding of life cycle impacts, ultimately enhancing the accuracy of LCA studies. The discussions herein were supported by examples for residential interior finishes.

1.1 Service life prediction and LCA

For building products, lifetime has the potential to influence LCA results and even alter the results of product comparison studies. The extended use duration of buildings and building products compared to daily consumable products necessitates that service life be taken into account during analysis. Therefore, reliable data on service life of building products would improve LCA results (Strand and Hovde 1999).

Due to lack of service life data and a systematic method to predict the service life of interior finishes, LCA practitioners rely on limited data, or use arbitrary product lifetimes in their analyses. In addition to providing a more engineered approach to the problem of service life prediction, the proposed method and results calculated for interior finishes would also find applications within building LCA. LCA and service life prediction can be used in conjunction to identify and optimize service life and environmental impacts of building products (Hovde and Moser 2004).

1.2 Existing service life prediction methods

As suggested by Masters and Brandt (1987), service life prediction methods should be generic enough to be applicable to a wide range of materials, should clearly state their boundaries and document assumptions, and should guide users for interpretation of results. In addition, service life predictions need to be made by using standardized methods to ensure objective and comparable results (Frohnsdorff and Martin 1996). There are different approaches to service life prediction that can be grouped under four categories, each having unique applications and limitations: analytical models, statistical models, empirical methods, and experimental methods (Shohet and Paciuk 2004).

The analytical models proposed by various researchers to estimate service life of building products or components include predictive equations to estimate deterioration progress of building materials, methods that use Markov chains or Laplace transformation of time-dependent variables, computer programs that use adaptive importance sampling and fault tree analysis (Hovde and Moser 2004). Statistical models that predict the amount of deterioration based on data from laboratory test results were also proposed. However, unless a large dataset is available, the use of a purely

statistical approach may not be the best approach (Rudbeck 1999). The Factor Method originally developed by the Architectural Institute of Japan and later adopted by International Organization for Standardization (ISO) standard 15686 for service life prediction is an example of an empirical method. The lifetime of a product can also be determined experimentally by testing for expected in-use conditions or unfavorable conditions for accelerated testing (Shohet and Paciuk 2004). Daniotti and Cecconi (2010) have published a state-of-the-art report on test methods for service life prediction having a focus on accelerated laboratory test procedures and their correlation to service life data.

The two American Society for Testing and Materials (ASTM) standards on statistical analysis of service life data, namely, ASTM G166 and ASTM G172, provide guidance on estimating service life of products when an adequate sample size has been obtained through testing, either under normal conditions or in an accelerated test setup (ASTM 2005; 2003). The two standards were not developed for service life prediction and are more suited towards lab testing of products to obtain lifetime distribution curves. However, a detailed description was presented for a statistical procedure to define service life distributions from lifetime data, which was used in this study.

Although there are a multitude of different methods and approaches, the existing trend in service life estimation has been to focus on material durability as a means of estimating service life (Sjostrom et al. 2002; Shohet and Paciuk 2004; 2006; Hooper et al. 2002; Sjostrom et al. 2001; Lacasse and Sjostrom 2005). This represents a purely technical approach, where subjective behavior of consumers is excluded. Although such a technical approach may be valid for structural frame of a building, it is limited in scope for interior finishes where the effects of consumer behavior may influence product lifetime to a much higher degree.

Among the listed methods, the Factor Method stands out as a versatile tool that can incorporate the effects of consumer behavior to assess service life. In addition, the method has been adopted by ISO 15686 for service life prediction. Another contributing factor was that LCA, also described by the same international standardization organization (under ISO 14040), would be a primary area for application of results.

Existing service life prediction studies focus on structural frame elements, such as concrete, steel, and wood, or on external building components such as roofing or insulation (Lacasse and Sjostrom 2004; Abu-Tair et al. 2002; Daniotti and Cecconi 2010; Pommersheim and Clifton 1985). Building products that are replaced more frequently, therefore having the potential of higher environmental impact over the life cycle of a building, currently lack viable service life research results. The goal of this study was to integrate existing techniques, standards, and reports and apply them

to residential interior finishes to estimate service life that can then be used to improve LCA studies.

1.3 Factor Method

In ISO 15686, the Factor Method is defined as a way of bringing together various factors that influence service life of products in order to make lifetime estimates. The purpose of the Factor Method is to provide an estimate of service life, which is different than service life prediction. By definition, estimated service life is calculated for a set of specific in-use conditions, whereas predicted service life is recorded past performance which should ideally be equal to the reference service life used during calculations (ISO 2000; Lacasse and Sjostrom 2004; Hovde and Moser 2004; Davies and Wyatt 2004).

In order to estimate service life using the Factor Method, the reference service life of a product is multiplied with coefficients that are assigned to factors A through G given in Eq. 1 (see Table 1 for definition of factors). A coefficient of 1.0 is assigned to factors that are found to not influence service life. Coefficients can be increased or decreased according to the specific application in comparison to the reference case. Conditions that should be considered while assigning coefficients to residential interior finishes have also been presented in Table 1. According to ISO 15686, the user is free to choose a suitable coefficient for factors that affect service life. Product specific guidelines have not been developed until now due to the complex nature of the problem (ISO 2000). Selection of a suitable starting point, the reference service life, is thus crucial to obtain reliable results.

$$\text{ESLC} = \text{RSLC} \times A \times B \times C \times D \times E \times F \times G \quad (1)$$

where ESLC is estimated service life of a component or product, and RSLC is reference service life of a component or product.

In the comprehensive state-of-the-art report by Hovde and Moser (2004), estimation of reference service life has been identified as a topic that needs improvement. Establishing reference service lives for commonly applied residential interior finishes has been one of the outcomes of this study.

ISO 15686 requires service life estimations to be given with an 80% confidence interval (ISO 2000). The use of confidence intervals facilitates interpretation of the reliability and accuracy of results and provides a more statistical approach to the method. However, the current form of the method, where the user assigns deterministic coefficients to each factor affecting lifetime, would not produce meaningful results since reliable probability distributions cannot be set up from a single value assigned to a factor. Therefore, the

Table 1 Definition of factors and their relation to residential interior finishes (ISO 2000; Masters and Brandt 1987; Marteinsson 2003)

Agents	Factors	Conditions relevant to residential interior finishes
Inherent quality characteristics	A—Quality of components	Manufacture, storage, transportation phases
	B—Design level	Sub-layer, physical incompatibility
	C—Work execution level	Level of workmanship
Environment	D—Indoor environment	Biological factors, condensation, sustained or random stress
	E—Outdoor environment	Solar radiation
Operation conditions	F—In-use conditions	Occupant demographics, wear and tear
	G—Maintenance level	Quality and frequency of maintenance/ cleaning

use of confidence intervals together with deterministic values would create a false sense of accuracy in lifetime estimates (Marteinsson 2003). Statistical distributions were defined and used for reference service life calculations in this study. Distributions defined from multiple data points allowed the use of an 80% confidence interval as suggested by ISO 15686.

Applications of service life prediction techniques, and of the Factor Method in specific, have been fairly limited. One aspect that limits the use of the method is a lack of knowledge of the tool and its capabilities by potential practitioners such as architects, consultants, building owners, and managers (Hovde and Moser 2004). Additionally, the current deterministic approach gives too much independence and minimal guidance to users in selecting both the reference service life and lifetime modifying factors and is another barrier preventing the widespread use of the method. Objective, reliable results cannot be obtained by using the Factor Method in its current form, where users subjectively assign deterministic values with minimal guidance to calculate confidence intervals to assess the reliability of results. These shortcomings of the Factor Method have been improved in this study by the use of statistical distributions, in addition to determining reference service life by including the effects of consumer behavior as an additional factor.

1.4 Impact of consumer behavior on service life

Product service life is affected by two categories: durability-related factors and social and economic factors (Nicastro and Surovek 2005; Cooper 2004). Products may be replaced due to failure or poor performance, as in the case when a painted surface fades excessively or starts to blister or peel. On the other hand, some durable products that are functioning well from a technical standpoint could also be replaced due to social and economic factors, such as when an occupant wishes to change the color or tone of a painted surface. The existing Factor Method successfully captures factors related to durability, but excludes the effects of social factors and occupant behavior.

Service life of building products is seldom determined by their durability (Hovde and Moser 2004). Research on repair projects has found that only 17% was initiated due to deterioration (Marteinsson 2005). The subjective perception of a building was identified as the main cause in 44% of renovations. Other contributing factors were change in use and change in economic circumstances with 26% and 13%, respectively. Therefore, the reference service life of a building product cannot be solely based on its design life or technical properties. The effects of consumer behavior, which are not currently covered within the Factor Method, have a significant influence on product service life (Gaspar and de Brito 2008).

2 Methods

The proposed method is a hybrid approach combining the statistical procedure outlined by ASTM G166 to define reference service life distributions, together with the use of triangular distributions to define factors that influence lifetime given by ISO 15686. Using a range of values or a distribution to define coefficients instead of deterministic values is a necessary step towards improving the reliability of results obtained from the Factor Method (Moser and Edvardsen 2002; Aarseth and Hovde 1999; Moser 1999). A triangular distribution defined by a minimum, maximum, and the most expected value is suggested. The straightforward form of a triangular distribution provides an advantage for the interpretation of results by users that may be from a wide range of backgrounds. In addition, when distributions are defined based on judgment or experience of the user, the use of more complex distributions may be unnecessary from a practical point of view.

Subjective coefficient selection by users relies heavily on the experience or perception of users. While users would still have flexibility on assigning different coefficients in the proposed method, reducing the range of values that can be assigned to coefficients would also decrease the sensitivity of results to variations caused by different users. For building products that are used for extended durations, choosing a suitable starting point, a reference service life based on average practices that take the effects of consumer behavior into account, becomes a crucial first step in lifetime estimations.

Data sources used to demonstrate examples for interior finishes together with the procedure used to define distributions were described in this section. A hypothesis test conducted to verify the relationship between calculated service life and the probability of renovation was also described.

2.1 Data sources

Multiple data sources were used to collect information on service life of interior finish products. Lifetime values suggested by trade associations as well as values used in peer-reviewed journal articles were used as data points in the current study. The fact that the majority of research papers found to contain product lifetime information were related to LCA signifies that service life prediction and LCA are interconnected and can be used together to improve the reliability of results.

Design lifetimes and product guarantee durations published by manufacturers were not included into the dataset. Lifetime data based on actual service life were used to define distributions. Published service life data that were obtained through analysis of an existing building were used. Although several data points that were logically supported by other facts such as a statement on average practices may also have been included, purely arbitrary data points that were not reliable were not included into the dataset. Design lifetime published by manufacturers or studies that states the use of such lifetime values was not included into the dataset. Actual service life of products inherently includes the effects of consumer behavior as well as technical criteria or durability. Therefore, the proposed method incorporates the effects of consumer behavior into reference service life calculations, and thus into the results of the Factor Method.

2.2 Products investigated

Service life prediction of products should be differentiated according to type of building. Residential and commercial buildings have different occupant demands and renovation cycles. Residential buildings have been proposed to have a renovation cycle of 20–50 years, whereas the interval decreases to 10–20 years for offices and 5–10 years for department stores (Anderson and Brandt 1999). Industrial buildings also have different occupant needs depending on the type of industry. In addition to the design life and durability of interior finishes, the building type also determines service life and therefore cannot be disregarded when making lifetime estimates.

Interior finish products that are commonly applied within residential buildings were investigated. Interior building paint, together with multiple flooring alternatives, was studied. Table 2 provides the list of interior finishes studied, data points, and their sources. Some sources indicated that

Table 2 Data points for lifetime of interior finishes

Interior finishes	Lifetime in years (source)
Paint	3 (NYC Housing Maintenance Code 2006), 4 (Lippiatt 2008), 5 (Kelly 2007; Scheuer et al. 2003), 7 (Pullen 2000), 8 (Mithraratne and Vale 2004), 10 (Adalberth 1997; Keoleian et al. 2001; Hed 1999; Fay et al. 2000)
Carpet	5 (Gunther and Langowski 1997; Anderson et al. 2002), 8 (Keoleian et al. 2001; Potting and Blok 1995), 8–10 (Seiders et al. 2007), 9 (Petersen and Solberg 2004), 10 (Pullen 2000), 11, 15 (Lippiatt 2008), 12 (Scheuer et al. 2003; Mithratne and Vale 2004), 17 (Adalberth 1997)
Linoleum	7–40 (Gunther and Langowski 1997), 15 Potting and Blok (1995); Petersen and Solberg 2004), 20 (Gorree et al. 2002; Paulsen 2003), 23 (Petersen and Solberg 2004), 25 (Jonsson et al. 1997; 1999; Seiders et al. 2007), 30 (Lippiatt 2008)
Vinyl	7–40 (Gunther and Langowski 1997), 8 (Potting and Blok 1995), 9, 23 (Petersen and Solberg 2004), 17 (Mithraratne and Vale 2004), 18 (Scheuer et al. 2003), 20 (Pullen 2000; Keoleian et al. 2001; Paulsen 2003; Jonsson 1999; 1997), 40 (Lippiatt 2008), 50 (Seiders et al. 2007)
Hardwood	10 (Nebel et al. 2006), 20 (Anderson et al. 2002; Nebel et al. 2006), 25 (Nebel et al. 2006), 40 (Jonsson 1999; 1997), 45 (Petersen and Solberg 2004; Scharai-Rad and Welling 2002), 50 (Mithraratne and Vale 2004; Nebel et al. 2006; Adalberth 1997), 50+ (Gunther and Langowski 1997), 100+ (Seiders et al. 2007)

Multiple references after a data point indicate multiple occurrences in different studies

+ after a number indicates that expected lifetime was more than the given value

hardwood flooring was expected to last as long as the building itself, therefore not necessitating any interior renovation (Seiders et al. 2007). Due to the large uncertainty associated with predicting building lifetime, the lower lifetime limit was selected, i.e., 50 years was used when lifetime was given as 50 or more years. The average was used when a range of lifetime values was given.

ASTM G166 requires a minimum of ten data points in order to properly fit a distribution (ASTM 2005). This criterion was adhered to in this study as well. Reliable lifetime data for interior finishes were not readily available in large quantities. Therefore, data points were collected from multiple sources for each product.

2.3 Distributions

The use of distributions to model variables enables a more elaborate analysis of events compared to arbitrarily choosing deterministic values. Statistically, multiple distributions can be used to represent data, but the selection should be based on how well the distribution fits existing data and

whether it leads to logical projections when extrapolated beyond existing data (ASTM 2005).

Normal distributions are widely used to describe naturally occurring distributions. However, ASTM G166 advises caution when using normal distributions for service life data (ASTM 2005). The symmetrical shape of a normal distribution facilitates calculations and interpretation but creates a shortcoming for use on service life data since most distributions are skewed, not symmetric (ASTM 2005). The use of Weibull distributions was supported by other studies as well and was adopted in the current study (Jernberg et al. 2004; Marteinsson 2003, 2005; Rudbeck 1999; Lounis et al. 1998).

There are two parameters necessary to define a Weibull distribution, namely shape and scale parameters, analogous to using mean and standard deviation to define a normal distribution. The statistical analysis method described in ASTM G166 was applied separately to each interior finish product to determine Weibull distribution parameters necessary to estimate service life based on actual conditions (ASTM 2005).

The original form of a Weibull distribution shown in Eq. 2 can also be written as given in Eq. 3. This is in the form of an equation describing a line, $y = mx + n$.

$$F(t) = 1 - e^{-\left(\frac{t}{c}\right)^{b}} \tag{2}$$

where $F(t)$ represents the probability that an interior finish would be replaced by time t. t is service life of products given in years. b and c are shape and scale parameters, respectively, necessary to define a Weibull distribution.

$$\ln\left[\ln\frac{1}{1 - F(t)}\right] = b\,\ln(t) - b\,\ln(c) \tag{3}$$

The set of equations in the form given in Eq. 3 would be solved for parameters b and c in order to calculate probability of renovation, $F(t)$. This creates a recursive problem which was overcome by using the median rank estimate given in Eq. 4 to initially estimate $F(t)$ (ASTM 2005).

$$F(t) = \frac{j - 0.3}{n + 0.4} \tag{4}$$

where j is the order of data points when the lifetime dataset is sorted in ascending order and n is the total number of data points in the dataset.

Since there are multiple data points for product lifetime, linear regression analysis was used to determine shape and scale parameters of a Weibull distribution. After a product-specific Weibull distribution has been defined, probability of renovation with respect to observed service life was plotted using the cumulative distribution function.

ISO 15686 also suggests an 80% confidence interval in estimated service life results (ISO 2000). This limit is set for maintainable components, which would apply to interior finishes. An 80% confidence interval was used in this study to determine the lower and upper bounds of reference service life estimates.

2.4 F test hypothesis testing

Hypothesis testing is a statistical procedure to decide whether to reject or not to reject a hypothesis. In this study, hypothesis test was applied to determine whether the correlation between probability of renovation calculated from the dataset and the independent variable of product service life occurred by chance.

The term alpha is used to denote the probability of rejecting a true hypothesis; in this case concluding that there is no strong relationship when it is otherwise. A typical value of 0.05 was chosen for alpha.

The critical F value ($F_{critical}$) can be read from F-distribution tables by using the assigned alpha value together with degrees of freedom of the dataset (NIST 2010). If the calculated F value ($F_{calculated}$) greatly exceeds $F_{critical}$, then it is unlikely that strong correlation among variables occurred by chance. The probability of a higher $F_{calculated}$ occurring by chance (P value) was also calculated.

3 Results and discussion

The proposed method has been applied to multiple interior finish products to determine reference service life that can be used in the Factor Method described in ISO 15686. Regression analysis has been used to determine the coefficients necessary to define Weibull life distribution for each product. These coefficients together with the resulting Weibull distributions are given in Table 3.

Parameters and distributions in Table 3 should not be taken as definitive solutions. Reliable and publicly available sources were used in this study. Distributions were defined by using at least ten data points. However, future research supported by a trade association, or involving a residential survey to determine product lifetime, would be able to collect additional data points. The above given values are

Table 3 Weibull life distributions of interior finishes

Interior finishes	Shape parameter, b	Scale parameter, c	Weibull life distribution
Paint	2.44	8.24	$F(t) = 1 - e^{-\left(\frac{t}{8.24}\right)^{2.44}}$
Carpet	2.92	11.4	$F(t) = 1 - e^{-\left(\frac{t}{11.4}\right)^{2.92}}$
Linoleum	4.71	24.3	$F(t) = 1 - e^{-\left(\frac{t}{24.3}\right)^{4.71}}$
Vinyl	2.23	25.3	$F(t) = 1 - e^{-\left(\frac{t}{25.3}\right)^{2.23}}$
Hardwood	1.88	48.4	$F(t) = 1 - e^{-\left(\frac{t}{48.4}\right)^{1.88}}$

expected to change when such findings are incorporated into the existing dataset.

Figure 1 shows the cumulative distribution function of each interior finish. It can be used to determine the cumulative probability of renovation for a given service life. These data would find applications in the field of investment planning for buildings or in economic cost–benefit analysis.

Use of distributions enables a detailed analysis for estimating product lifetime. Especially when combined with the Monte Carlo method, distributions can provide a robust statistical analysis that cannot be captured with the use of deterministic values. Statistical properties of a distribution could be reported to enhance interpretation of the variable. For normal distributions, the calculated mean point also corresponds to the midpoint, which also has the highest probability of occurrence. This is not the case for a Weibull distribution since probability distributions are not symmetric around the midpoint. Median service life of products can be estimated by drawing a horizontal line at the 50% probability of renovation in the cumulative distribution functions presented in Fig. 1. Average service life of interior finishes estimated from the median of these distributions is given in Table 4. The 80% confidence interval required by ISO 15686 was used to locate upper and lower boundaries of the range of results. The given distributions or the corresponding average and range values can be used in the Factor Method for reference service life to depict real-life conditions when analyzing residential buildings.

The guarantee period provided by the manufacturer may be the only indicator of design life for some products (Nicastro and Surovek 2005). Paint products for interior surface applications that are guaranteed for lifetime can be encountered in the market today. A painted surface must be kept under ideal conditions (e.g., low to no UV radiation, water damage, biological factors, wear and tear, etc.) in order not to require repainting over the lifetime of the building. In addition to difficulties in achieving such conditions in real life, the influence of social factors on lifetime
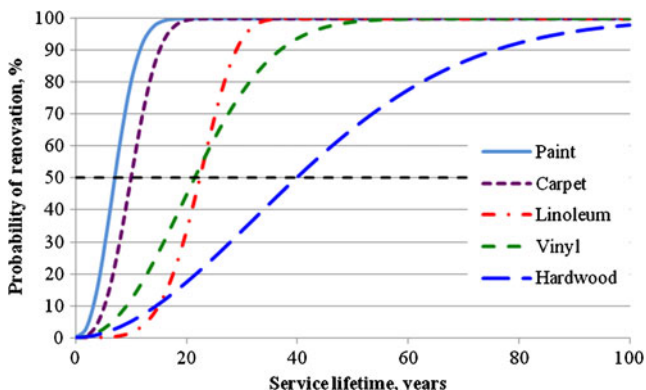
Table 4 Average service lifetime of interior finishes with an 80% confidence interval

Interior finish products	Lower bound (years)	Average service lifetime (years)	Upper bound (years)
Paint	3.3	7.1	12
Carpet	4.1	10	16
Linoleum	15	22	29
Vinyl	9.2	21	36
Hardwood	15	40	73

of products cannot be disregarded. A new or an existing occupant might wish to change the color or tone of a painted surface, even though the existing layer of paint may technically be performing satisfactorily. An average repainting interval of 7 years for residential buildings was presented in Table 4 based on reported past experience. The example for paint demonstrates the potential difference between actual service life and design life or guarantee duration provided by manufacturers. Using design lifetime as reference service life for interior finish products in the Factor Method would necessitate the use of a wider range of coefficients to account for real-life, average conditions. The use of theoretical reference service life combined with the need to use a larger range of coefficients increases subjectivity and decreases accuracy of results. The proposed method and examples presented in this study were based on average conditions and therefore provide a more reliable starting point for service life estimations.

3.1 Hypothesis test

The F test was applied as the hypothesis test to check the correlation between the interior finish service life data points as the independent variable and the probability of renovation calculated from the dataset. $F_{calculated}$ values were found to be much higher than $F_{critical}$ values found from F-distribution tables, as shown in Table 5. The calculated P values show the minute probability that results occurred by chance, indicating that there is a strong relationship between product service life and the probability of renovation distributions calculated in this study.

Table 5 F statistic values for interior finishes

Interior finishes	$F_{calculated}$	$F_{critical}$	P value
Paint	112	5.32	5.5×10^{-6}
Carpet	181	4.96	1.0×10^{-7}
Linoleum	93	5.3	1.1×10^{-5}
Vinyl	64	4.75	3.8×10^{-6}
Hardwood	129	4.6	2.0×10^{-7}

Fig. 1 Probability of renovation cumulative distribution functions for interior finishes

3.2 Actual life compared to design life

The proposed reference service lives are based on average use conditions and environments. They inherently include an average amount of unfavorable conditions observed in real life. This needs to be taken into account when deciding on coefficients to calculate the estimated service life of a product. Unless it is known that the product would be used in a significantly different environment or use conditions compared to the average, the values of factors A–C and G may be taken as 1.0 as the coefficient for modifying factors in the Factor Method where a statistical approach is used. However, decisions for factors should be made specific to each product and application to ensure that all factors in Table 1 have been addressed in the analysis. Statistical analysis of data enables calculation of an average service life, and perhaps equally important, a confidence interval to denote the associated uncertainty and expected variability of results.

An added benefit of using actual life instead of design life as reference lifetime is that the user is required to make fewer assumptions regarding factors affecting lifetime. In addition, the chosen coefficients are limited to a narrower range. Both of these help reduce subjectivity of results.

An analysis involving hardwood flooring could use the 100+years design lifetime as suggested by the National Association of Home Builders (Seiders et al. 2007). However, average service life distribution shows that 50% of hardwood flooring is expected to be renovated within 40 years and the probability of flooring being used for 100 years is low. The 40 years service life estimated for hardwood flooring was based on existing practices. Although it is possible to modify the 100-year design life down to 40 years of actual use, the range of coefficients necessary to do so is larger than using actual lifetime as the reference service life. Furthermore, actual life calculated using distributions that are based on past experience inherently includes the effects of social factors that may be as important as durability for some products. It must be stressed that the effect of consumers may not be completely captured within the existing coefficients of the Factor Method, and that the proposed method would be a viable approach to overcome this problem.

4 Conclusions

There is a need for service life prediction of building products both from industry and academia. Facility and asset managers would benefit from a greater ability to foresee and plan for future expenditures, and for economic decision making to make informed decisions on investment planning.

Researchers studying building LCA would be among those that can apply service life estimates in their analysis.

The Factor Method is the most promising method available to estimate service life of products. However, the current deterministic approach is an important barrier preventing the widespread use of the Factor Method. Objective and reliable results cannot be obtained by using the method in its current form. Without a systematic approach, applications of the Factor Method would be limited.

A hybrid method combining statistical procedures described in ASTM G166 with the Factor Method adopted by ISO 15686 was proposed. The proposed method has several advantages. Existing service life prediction models do not capture the effects of social factors on lifetime of products. However, for certain building product categories including interior finishes, the effects of social factors may be as important as durability. Excluding the effects of social factors reduces the accuracy and reliability of results. The proposed method inherently includes the effects of social factors in the dataset used to define lifetime distributions. Another advantage is that choosing reference service life based on real-life conditions decreases the range of coefficients necessary for modifying factors in comparison to when design lifetime is used, thus decreasing the subjectivity of results due to variations in assigned values by different users.

When analyzing a building assuming average conditions, or in cases where detailed information may not be available, reference service life calculated based on average conditions could be used which would be equivalent to setting lifetime influencing factors equal to 1. However, when project specific data are available, the reference service life should be modified by coefficients described in ISO 15686. Triangular distributions, defined by a minimum, maximum, and an expected value, can be used for each coefficient in the Factor Method. A Monte Carlo analysis would then provide the mean estimated lifetime together with a confidence interval, which would allow the user to interpret the reliability of results.

The proposed approach has been presented with example calculations for several interior finish products. The individual lifetime distributions of these products have been developed. Average estimated service life together with an 80% confidence interval was also presented. Reliable sources including peer-reviewed research articles were used to gather data. However, the need for further reliable data points must be stressed in order to improve the accuracy of coefficients used to define distributions. Since both the dataset used during calculations and the resulting parameters of the Weibull distributions have been presented, it is possible to update distribution parameters given that additional data points are collected through a residential survey or through trade associations. Although the Weibull distribution parameters

would differ somewhat, the overall method would remain the same. The proposed hybrid method can also be applied to other products that are studied within the Factor Method. Products whose lifetimes are influenced by the effects of social factors are prime candidates to apply this method.

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