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# **Service life assessment of building components:**

## **Application of evidence theory**

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**Abstract:** This paper deals with the assessment of the service life of in-service building components subjected to known environmental and usage conditions. This assessment is complex because of two primary features. Firstly, the assessment has to be carried within a multi scale context: the geometric scale that ranges from the material or elemental scale to that of the building; the range in the complexity of the degradation (phenomena that varies from a single phenomenon to the consideration of several degradation scenarios); the range of possible performance requirements, from one function to several; and consideration as well, to the time over which the process is carried out that may span from the design stage to that of management and repair. Secondly, this assessment must also take into consideration the availability and features of service life data that by nature is heterogeneous, imprecise, uncertain and incomplete. In this context, a comprehensive methodology is developed using all available data on service live derived from existing methods of service life assessment of materials, elements or building components. Such data may, for example, be extracted from fundamental studies on durability, accelerated short-term exposure tests, statistical methods, factorial methods, feedback from practice, or expert opinion or other sources. The main stages of this methodology are: (i) identification of all possible degradation scenarios provided by failure mode and effects analysis (FMEA); (ii) collection of all available service life data (SL-data) associated to these degradation scenarios, transformation of this data into a fuzzy set format and assessment of its quality; (iii) processing of unification of data and aggregation of data and; (iv) assessment of the service life of building components. The case study of a window unit allows: (i) service life assessment of building component to be processed by unification of data and aggregation of data and; (ii) conclusion to be deduced.

*Key words:* building components, service life, data quality, multi scale approach, data unification, data aggregation.

**Résumé:** Cette publication s'intéresse à l'évaluation de la durée de vie des produits de construction en service dans les conditions environnementales et d'usage auxquels ils sont soumis. Deux caractéristiques principales rendent cette évaluation complexe. Tout d'abord, cette évaluation est faite dans un contexte multi-échelle : la granularité géométrique s'étend du niveau du matériau ou de celui-ci du composant jusqu'au bâtiment ; les dégradations sont plus ou moins explicitées (l'échelle des dégradations varie d'un seul phénomène à plusieurs scénarii) ; l'échelle des performances fonctionnelles varie d'une seule fonction à plusieurs ; le temps doit également être considéré, l'échelle temporelle s'étendant de la phase de conception à la phase d'inspection, de

maintenance et de réparation. La deuxième caractéristique est que cette évaluation se fait à partir de données disparates, imprécises, incertaines et incomplètes. Dans ce contexte nous proposons une méthodologie utilisant toutes les durées de vie disponibles provenant de méthodes existantes d'évaluation de la durée de vie des matériaux, composants ou produits de construction. De telles données peuvent provenir, par exemple, de modèles de durabilité, de tests en exposition de courte durée accélérée, de méthodes statistiques, de méthodes des facteurs, de retours d'expérience, de dires d'experts ou d'autres sources. Les principales étapes de cette méthodologie sont : (i) l'identification de l'ensemble des scénarii de dégradation obtenu par l'analyse des modes de défaillance et de leurs effets (AMDE) ; (ii) le recueil de l'ensemble des données de durées de vie disponibles associées à ces scénarii de dégradation ; (iii) l'unification et l'agrégation des données et ; (iv) l'obtention de la durée de vie des produits de construction. Nous appliquons cette méthodologie au cas d'une fenêtre afin de montrer : (i) la durée de vie obtenue en appliquant les méthodes d'unification et d'agrégation des données et ; (ii) les conclusions d'une telle évaluation.

*Mots clés* : produits de construction, durée de vie, qualité des données, approche multi-échelle, unification de données, agrégation de données.

## **1. Introduction**

### **1.1. Sustainable development in construction**

The construction domain is increasingly involved in attaining objectives for ensuring sustainable development (Charlot-Valdieu et al. 1999) that allows for satisfying the needs of present and, in particular, future generations. The principles espoused by those focused on sustainable development necessarily influence on building design and the need to maintain the functional performance of the building over time. That is, to carry out the process of inspection, maintenance and repair over the service life of the built asset. As a matter of fact, one has to know “how” and “when” buildings and their components (building components) will be degraded or fail, in order to know “how”, “when” and “on which” component one should intervene. Without this information, the design and management process can not easily be optimized thus potentially generating significant management costs that otherwise could be reduced.

These objectives can be interpreted in terms of defining the “technical requirements for performance” as suggested by the concept of the “Performance Based Building” (Lee et al. 2003).

## **1.2. Problem to be solved**

More precisely, this paper deals with assessing the multi performance profile of a building component (i.e. building components are multi-functional hence need to meet more than one performance requirement) as well as quantifying the temporal performance (i.e. performance over time) that together provide an assessment of the service life of a building component.

The context of the building domain, as detailed in Talon (2006b), implies some difficulties to obtain the assessment of long-term performances of building components in-service. Indeed: *(i)* there are numerous types of building components and numerous building actors who influence design and implementation qualities; *(ii)* building components are subjected to random environment and have to ensure several performance requirements; *(iii)* instrumentation of a large sample of building component could allow service life to be assessed but should be economically unrealistic. However, several methods had been developed to assess these long-term performances and so the service life of building components. These methods are presented and discussed in § 1.5. Moreover, a review of available SL-data is done in § 1.4. A methodology that manages all available SL-data, at any scales and in any formats, is proposed as: *(i)* when assessing the service life of a specific building component in-service a SL-data with a great quality to is more often that not difficult to find and; *(ii)* SL-data sets at other scales (SL-data of the elements that compound the studied building component, or SL-data of phenomena that are occur in the considered scenario) are often available. The basic hypothesis of this methodology are detailed in § 1.6. Available and used SL-data may be defined at other scales than at the scales of the studied building component, so, a multi scale formalisation is proposed in § 1.3. This formalisation can be applied to any service life assessment of building components.

## **1.3. Multi scale approach of the problem**

When a designer has to assess a service life, the quality of the assessment will increase with the clearly definition, one the one part, of the kind of assessment to provide and, on the other part, of the availability of data. We consider that each service life assessment of an in-service building component can be considered as a

multi scale problem that can be defined within a 3D discrete space (i.e. “universe”) within a process that evolves over time as presented in Figure 1. The range of possible user solutions (*US*) is found in this space and is essentially an organisational model of the interrelation among different sets of service life information that directly relate to the assessment process. Such a model provides context between the different possible existing solutions, referred to as assessment points (*AP*), and a solution for a service life assessment that is of specific interest to a user, defined as the objective point (*OP*). These points can be identified in the *US* defined space by three values and the phase in the time process, referred to as organisational ‘scales’ given that these may vary, conceptually, in ‘size’ from lower to higher values of their respective attributes. These organisational scales include the degree of granularity of the item for which an assessment is sought, specifically the geometrical scale. Another scale refers to the number of performance functions associated with a particular item and either be a single or a multi-functional item. The third axis relates to the different degradation phenomena associated to the item; again only a single phenomenon may be considered or a scenario or a set of scenarios. Hence given an *OP* and *APs* representative of a specific problem of service life assessment (examples are provided on Figure 1 and explained underneath), discrete solutions for service life assessment can be interrelated and contextualised in the *US* space. The respective scales of the *US* space are further described in the following sections as are the *OP* and *APs* and their relation to the respective scales of the *US* defined space.

#### *Organisational scales of the US defined space*

a) A first axis represents the geometrical scale for which information is available; it is relevant to subsequently performing an organisational analysis. The geometrical attribute, is representative of the actual scale of the system being considered. Using a generic format and in an ordered manner, one can define various geometrical scales including, from lowest to highest the following:

(1) Material level; being representative of the basic building materials from which products are manufactured or produced, e.g.: soil, steel, PVC or compound of materials (concrete, etc.),

(2) Element level; being representative of manufactured products that may comprise several types of materials of e.g.: glass lite, steel beam, plastic tube, mineral fibre, etc.

(3) Building component level; being representative of an assembly of elements, e.g.: roof, wall, floor, window, joint, etc.

(4) Building level; being representative of a system of components.

b) A second axis deals with the aims and concerns of the user as related to the expected performance of the material, element, component or building system. It is relevant to the steps in which a functional analysis and performance assessment of a building component are carried out. It may contain two levels:

- (1) Single function (thermal insulation, loading capacity, etc.),
- (2) Multi function (e.g. a glass lite may need to fulfill a set of functions related to providing thermal, acoustical and visual performances).

c) A third axis is that of degradation mechanisms that influence the service life of the building component. It can be defined with the use of methods such as failure mode and effects analysis (FMEA). It may contain three levels:

- (1) Single phenomenon (e.g. corrosion, settlement),
- (2) Single degradation scenario, defined as a chain of several phenomena,
- (3) Set of degradation scenarios containing those scenarios present having the greatest criticality in respect to duration, probability of occurrence and gravity of consequences, of those scenarios, on the considered geometrical attribute and its environment.

d) The 3D space may evolve with time over the life of the building; hence time is the fourth axis that defines the *US* space.

It may be considered then, that during the design stage the problem becomes one of assessing a virtual building component, within a poorly known or indeed unknown environment. It may also be considered during the in-service life of the building component when some degradation has occurred and when thereafter further deterioration may come about. In the later instances then, the process focuses on definition of the inspection planning, or the definition of the strategy of maintenance and repair.

#### *Selected points in the range of user solutions*

A specific point in the *US* space represents a location in the *US* space that is defined by its location along each of the respective four axis. The assessment (*AP*) and objective points (*OP*) are two points each of which is described below.

a) Assessment point (*AP*)

An Assessment Point represents a point within the *US* space that is a result of, for example, a fundamental study of the service life of the component, or an accelerated short-term exposure test, feedback from practice, an expert opinion based on practical experience, a statistic model, or some other such information that may provide an estimate of the service life of the component. At any time, *t*, several *APs* may be available; the set of assessment points is then noted as  $\{AP\}$ .

b) Objective point (*OP*)

The Objective Point is a point, chosen by the user, where the service life of the building component being studied is to be assessed within the *US* space. As a first example (*cf.* “*OP* ex. 1” in Figure 1), one can choose to assess the service life of a window unit (level of building component on the geometrical scale) and specifically regarding a single function (functional scale), such as its degree of transparency taking into account the scenario of condensation within a double-glass unit (level of scenario on the degradation scale) when subjected to environmental conditions consistent with those of an urban environment (in-service stage of the time scale). As a second example (*cf.* “*OP* ex. 2” in Figure 1), the service life of butyl can be searched (level of material on the geometrical scale) regarding the mechanical resistance (level of single function on the functional scale) taking into account the phenomenon of hardening (level of phenomenon on the degradation scale) when subjected to hot temperatures (design stage of the time scale).

The problem is that it is not always possible to directly reach the *OP* and at times, it has to be deduced from  $\{AP\}$ . Consider the first example (“*OP* ex. 1”): (i) SL-data of the *OP* window unit is not available; (ii) six SL-data of elements of the window unit, as glass lite or sealing joint, are available and are provided on one part from long-term exposure tests and on other part from expert opinions. In that instance, the  $\{AP\}$  regroupes these six SL-data.

It is to be noted that some points within the *US* space have not a great interest and then will not be chosen. For instance, the service life assessment of the butyl is often provided in regards to the phenomena that have the greatest impact on its performance requirements. On the contrary, to consider all the possible degradation scenarios of that butyl for the assessment of its service life has not a great interest.

#### **1.4. Two primary features of the problem**

The two primary features of this problem concern the different points in the *US* space at which information is available and, typically, the quality of such information. Firstly, the Objective Point can be located at different points of the *US* space (*cf.* § 1.3) and data from other points of the *US* space may be used to achieve the assessment of this *OP*. Secondly, the other primary feature of the problem is the lack of useful data. Service life data may be heterogeneous, imprecise, uncertain and incomplete. One needs to capitalize on all the available information relative to the entire set of degradation states, for all the building components of concern, and for all the performance functions of interest to the user; this data may be obtained from different sources and may have different formats. Martin et al. (1996), Lair et al. (1998) and Jernberg et al. (2004) have studied the different sources of aging data that may include:

- (1) Artificial and natural tests (“short term laboratory based exposure”) (Eurin et al. 1985),
- (2) Field tracking studies, in-situ weathering, expert knowledge (“long-term in-service or outdoor exposures”) (Ishizuka 1983),
- (3) Fundamental mechanistic studies (Martin et al. 1994),
- (4) Reliability studies (Siemes et al. 1985).

#### **1.5. Critical analysis of existing approaches and methods**

The current primary approaches and methods to evaluate the service life of a building component and their main usage include the following six methods:

- (1) Methods based on a probabilistic approach (Siemes et al. 1985); these are currently used, for example, as the basis for standards and guidelines regarding the calculation of structures,
- (2) Statistical approaches (Brandt and Wittchen 1999) that may be used when data on several equivalent building components are available,
- (3) Comparisons between long-term and short-term exposure tests (Jernberg et al. 2004) typically a standard practice for the treatment of the results derived from laboratory and in-service tests,
- (4) Feedback from practice considered a standard practice for the diagnosis of building component failure,
- (5) Factorial method for service life estimation and for which there exists several formulations and associated research are synthesized in Jernberg et al. (2004). This method is commonly used for the assessment of the

service life of in-service building components and in-service buildings. The factor method is a standard method given in ISO 15686 (ISO 2006),

(6) Methods based on possibility theory (data fusion) as detailed in Lair (2000) and Jernberg et al. (2004); such methods, developed by the authors are presented in § 3 of this paper.

The probabilistic approaches are well adapted when the studied phenomenon is well known, that is to say when enough information is available to define the relevant probability law and its parameters. Several probability laws are well known and well fitted to the more common degradation phenomena of classical materials in civil engineering. Meanwhile the definition of the probability law and its parameters is difficult when a complex building component is studied and when no or only few information is available, which is usual in the construction domain.

The statistical approaches are well adapted when sufficient observations of a specific building component are available to consider that a coherent sample is done and that the statistical principles can be applied. Meanwhile, even if in some civil engineering domains such statistics exists (for example, road, dams and railways) this is not a current practice in the building domain.

Moreover, the first four methods and approaches have two primary similarities:

(1) They proceed to a direct assessment of service life, that is to say that the service life of a building component can be determined from the use of probability functions, statistics, tests results or inspection results relevant to this specific building component. For example, if considering a statistical approach, the service life of a window unit can be deduced from the observation of the behaviour or response of the unit over time to a set of similar window units;

(2) Their results are difficultly transposable to others related in-service environments and to others building components. For example, the results of an accelerated short-term exposure tests of a rubber component subjected to U.V. radiation cannot be used to evaluate the service life of this same type of rubber component when, exposed to freeze-thaw conditions.

The fifth method (factorial method) proposes a direct assessment of service life and permits taking into account the specific effect of each in-service condition. However, a significant drawback of this method is the subjective manner in which the factor values are estimated.

The last method (data fusion) for determining the service life of building components, and proposed by Lair (2000), allows a direct assessment of the component. Hence, the main focus is to further develop this method for

other types of data (service life, probability and performance data) and at other geometrical levels (material, element and building component).

Our primary objective is to be able to assess the service life in service of all geometrical entities (from materials to building) considering all their possible degradation scenarios and all their possible functions (as mechanical resistance, thermal isolation or esthetical function,...). Among existing approaches, the approach based on possibility theory is the only one to allow this objective to be reached.

## 1.6. Basic hypothesis

The main goal is to prove that it is possible to provide an assessment of the service life of a given material, element, component using the different kinds of knowledge available at different points of the *US* space. To achieve this, two complementary methods have been explored: service life data unification and data aggregation methods.

(1) The method for the unification of service life data is a procedure that allows deducing new information from information that provided at the same point in the *US* space and from different sources. For instance, the duration of hardening of a sealing joint can be deduced from several durations providing from expert opinion, experimentations, theoretical models, etc.

(2) The method for the aggregation of service life data is a procedure that allows deducing new information from information at other points in the *US* space, specifically when *OP* differs from the *APs*. For example, the duration of a scenario of oxidation of a low-emissive coating of a window can be deduced from the durations of the different phenomena that compound this scenario (hardening and cracking of sealing joint, corrosion and perforation of spacer, saturation of humidity absorber, condensation on low-emissive coating, oxidation of low-emissive coating).

An assessment of the service life of a building component often needs the use of the methods of data unification and data aggregation. Indeed, consider for instance: (i) an objective point and no SL-data available at this *OP*; (ii) six SL-data available at  $AP_1$ , a first assessment point different from *OP*, that form an  $\{AP_1\}$  set; (iii) four SL-data available at  $AP_2$ , a second assessment point different from *OP* and from  $AP_1$ , form an  $\{AP_2\}$  set. To assess the service life at the *OP*, the unification procedure is to be applied: (i) to the  $\{AP_1\}$  in order to obtain a consensual service life  $SL(AP_1)$  and; (ii) to the  $\{AP_2\}$  in order to obtain a consensual service life  $SL(AP_2)$ . Then, the aggregation of  $SL(AP_1)$  and  $SL(AP_2)$  permits to obtain  $SL(OP)$ , the service life at the *OP*.

## **1.7. Overview of paper**

The methodology for service life assessment being proposed allows one not only to obtain a multi performance profile that corresponds to the failure of a building component but also the time to reach this profile, i.e. the service life of the building component. This is first discussed and then, the two methods for treatment of service life data, data unification and data aggregation, are presented. Thereafter, details of the different types of service life assessments that one can obtain using this methodology are provided. Finally, the proposed methodology is applied to a specific case of a window unit.

## **2. Overall methodology**

The proposed methodology allows deducing the service life of building components, i.e., the time to reach the multi performance profile that corresponds to the failure of this building component. The methodology is comprised of four primary steps:

- (1) System analysis; it provides an overview of the functioning of the building component that is indispensable to complete an FMEA,
- (2) Failure mode and effects analysis (FMEA); it identifies all possible degradation scenarios of the building components as well as their causes and consequences,
- (3) Collection and preparation of data (service life, probability and performance); it prepares the fourth step,
- (4) Service life assessment.

### **2.1. System analysis**

A system analysis results in modeling the behaviour of the building component when subjected to environmental stresses (climatic and usage) over its in-service stage. It is from this stage that a “functional model” of the building component of interest can be developed; such a model provides a means to link actions causing deterioration to that of loss in functional performance and is a prerequisite for carrying out the failure mode and effects analysis.

The first step of this analysis is to build an organisational model. This requires assessing the mechanical, physical, chemical characteristics of the individual elements of which is comprised the building component and

the respective geometrical scales in which these elements are constituted and then determining the interrelation among all elements. In a second step, the environmental stresses that may cause degradation of the building component are characterized; this step includes first determining the environments to which the building component may be subjected. For example, establishing the environments that exist on the inside and exterior surface of a wall. Then, the environmental agents that may cause degradation of the building component are identified (e.g. snow, wind, solar radiation,...). The final step is to develop a “functional model” based on the identification of the performance functions that are ensured by the building component and its elements. This permits knowing the behaviour in terms of the functional performance of the building component when subjected to the previously defined stresses.

In order to aid the user to complete the system analysis, both a database of environmental agents and a database of performance functions for building components was developed by the authors as described in Talon et al. (2003).

## **2.2. Failure Mode and Effects Analysis**

The purpose for completing the failure mode and effects analysis (FMEA) is to obtain as complete a list as possible of degradation scenarios or chains of degradation that could damage the building component during the in-service stage. The FMEA is a risk analysis method, developed during the 1970's and still be used in different industrial fields, such as the spatial, nuclear, and medical fields (Dyadem press 2003). The application of this method to the building field was initiated by Lair (2000) who modified the chaining of the analysis that now allows benefiting from results of FMEA. Nowadays, the application of the FMEA to the building domain is increasingly of interest as was demonstrated in the state of the art report on FMEA in construction domain prepared by the research working commission CIB W080 (Talon et al. 2006a).

As a first step in applying the principles of FMEA consists in defining the potential degradation modes, the causes (stresses, incompatibilities between materials, errors during the building implementation) and the consequences for each function, component  $\{f, c\}$  pair. It is to be noted that all the  $\{f, c\}$  pairs and all the stresses have been identified as a result of completing the system analysis. The second step consists in determining the degradation scenarios in an iterative way. The iterative principle, from step  $i$  (step  $i = 0$ : beginning of the in-service stage) to step  $i+1$ , aims to determine if the degradation consequences at step  $i$  could be the cause of degradation at step  $i+1$ .

### **2.3. Collection and preparation of data (service life, probability and performance related)**

The collection and preparation of data is an important step of the methodology that is summarised here but is provided in more detail in Talon et al. (2003, 2004, 2006b).

All available data useful to the service life assessment and that may be derived from different sources of information are collected and organised in the following manner: (i) service life of each set of scenarios, each single scenario and each single phenomenon that have been identified from the previous step of the methodology; (ii) in order to deduce the most probable scenarios to be considered for the service life assessment, one needs to determine the probability of occurrence of each set of scenarios, each single scenario and each phenomenon; (iii) performance versus degradation functions of each pair {phenomenon; function} that have been identified from the FMEA and that allow deducing the multi performance profile of the building component from the knowledge of the degradation states of its elements, as developed in § 2.4.

Given that this data may be obtained from several sources, it may be heterogeneous, imprecise, uncertain and incomplete in nature. It is for this reason that the quality of each data must also be evaluated.

Both the concept of the *US* space and the quality assessment tool (detailed in § 3.1) are useful to guide the data collection procedure. Indeed, one of the principle uses of the procedure is to obtain data (e.g. service life, probability or performance based data) at the objective point of the *US* space. If the quality of this data is sufficient, then the service life assessment can proceed. However, if the quality of the data at the objective point is not sufficient, then it is necessary to obtain available data at others points in the *US* space (i.e. when  $APs \neq OP$ ). Consequently, the concept of the *US* space thus imposes on the user of the methodology a requirement to clearly define both the problem and the availability of data, and as well, it provides a guide to the use of the procedure (unification or aggregation) in order to complete the service life assessment, as presented in § 2.4.

### **2.4. Service life assessment**

The set of principle outputs of this last step of the service life assessment methodology include the following: (i) to assess the service life of the entire set of scenarios of the building component, without considering their probability of occurrence, (ii) to assess the probability of occurrence of each scenario in order to only retain the more probable in the pursuit of the methodology, (iii) to deduce the multi performance profile at a specified time in the life of the building from the duration of the retained scenarios, based on the outputs derived from the performance versus degradation functions.

Finally, the service life of the building component is obtained when the multi performance profile corresponds to the failure profile, that is to say when the performance level of one function or a combination of functions reaches its failure threshold.

Our approach is rather similar to the life cycle optimization that uses probabilistic approach, see for example (Rackwitz 2000), except that: (i) an approach based on possibility theory is proposed; (ii) all the possible degradation scenarios of the consider entity (material, element, building component) are taken into account and; (iii) several types of functions, such as mechanical resistance with thermal and acoustic isolations, are managed together.

This portion of the service life assessment methodology is initiated using methods for the unification of data and the aggregation of data as provided in detail in the two next paragraphs.

### **3. Unification of service life data**

The principle underlying the method for the unification of service life data is to exploit the fact that all the available data at a same assessment point of the *US* space may be complementary; this approach uses the concept of a belief mass (Shafer 1976) that is an indicator of the quality of this data, and that provides both a measure of consensus of the data (service life, probability or performance) and as well as, an indicator of the quality of this result. In this paragraph, the unification procedure is described for the case of service life data.

#### **3.1. Quality assessment of service life data**

The quality assessment of service life data aims to evaluate the imprecision, uncertainty and incompleteness associated to each data set as well as its preparation and treatment for use in the proposed service life assessment methodology. This proposal is based on an adaptation by Lair (2000) of the Numerical Unit Spread Assessment Pedigree (NUSAP) tool described in Funtowicz et al. (1990). As far as the simplification and homogeneity of data quality assessment is concerned, a criterion assessment grid is proposed, as presented in Table 1.

The Entropy referred to in Table 1 is derived from that defined in Shannon and Weaver (1972), and is calculated using equation [1], where:  $X$  represents the interval of durations (e.g. [5;10] years);  $x$ , is a discrete value of the interval  $X$  (e.g. 5 years);  $\Theta$ , the “frame of discernment” (i.e. observation period,  $[t_{\min}; t_{\max}]$ );  $f_{mc}(x)$ , the belief function associated to the value  $x$ . An example of belief function is given in Figure 6.

$$[1] \quad \frac{\sum_{x \in X} f_{mc}(x) \ln(f_{mc}(x))}{\ln(1/\Theta)}$$

In that proposal, the quality assessment that is associated to a specific data is defined as a belief mass expressed as  $m(S)$ , where  $S$  is a SL-data set, that is equal to the average of all criteria values.

### 3.2. Unification of SL-data based on evidence theory

In order to take into account the uncertainty in the SL-data, the use of evidence theory is proposed as proposed in Shafer (1976). Indeed, evidence theory and belief functions are tools of “modeling and quantifying the belief we can have in events for which the probability of occurrence is unknown” (Bouchon-Meunier 1995). According to Pearl (1990), belief “consists of assertions about a specific situation inferred by applying generic knowledge to a set of evidence sentences.”

As an initiation point, assume that a set  $\Theta$ , representative of the “frame of discernment”, is a finite set of alternatives for service life (e.g. when searching a building component service life,  $\Theta$  is the temporal scale, expressed as  $[t_{\min}, t_{\max}]$ , with  $t_{\min}$  the arbitrary lower bound and  $t_{\max}$  the arbitrary upper bound). Associate to each subset  $S$  or  $T$  of  $\Theta$ , a basic probability assignment  $m(S)$  or  $m(T)$ , a belief  $Bel(S)$  or  $Bel(T)$  and a plausibility of belief  $Pl(S)$  or  $Pl(T)$ . The probability assignment,  $m(T)$ , represents the strength of the evidence, belief,  $Bel(T)$ , the reasons to believe  $T$  if all unknown facts were not to support  $T$ , and plausibility of belief,  $Pl(T)$ , the reasons to believe  $T$  if all unknown facts were to support  $T$ . The relation between  $Bel(T)$  and  $m(S)$ , where  $S \subseteq T$ , is defined in equation [2]:

$$[2] \quad Bel(T) = \sum_{S \subseteq T} m(S)$$

$Pl(T)$ , given in equation [3], and satisfies the following formula (where  $\neg T$  is “Not  $T$ ”):

$$[3] \quad Pl(T) = 1 - Bel(\neg T)$$

The use of belief functions results from assigning probabilities to sets rather than to individual points. With evidence theory, it is possible to model the nearness of an hypothesis set with the accumulation of evidence.

A support function  $Bel(T)$  is associated to each SL-data set on  $\Theta$ . The degree of support are straightforward to specify, as presented in equation [4]. In this case, the data “points precisely and unambiguously to a single non-empty subset  $T$  of  $\Theta$ ” (Shafer 1976):

$$[4] \quad Bel(S) = \begin{cases} 0 & \text{if } S \text{ does not contain } T \\ m(S) & \text{if } S \text{ contains } T \text{ but } S \neq \Theta \\ 1 & \text{if } S = \Theta \end{cases}$$

This is illustrated with an example. Consider the following SL-data of an unspecified building component, for which:  $T = [25, 100]$  years having a corresponding mass  $m(T) \neq 0$ ; this yields: (i) if  $S = [0, 20]$  years, then  $Bel(S) = 0$  and  $Pl(S) = 0$ ; (ii) if  $S = [0, 50]$  years, then  $Bel(S) = 0$  and  $Pl(S) \neq 0$ ; (iii) if  $S = [0, 110]$  years, then  $Bel(S) \neq 0$  and  $Pl(S) \neq 0$ .

The decision criterion is provided by the confidence interval  $[Bel, Pl]$  (Dromigny-Badin et al. 1997). It expresses the knowledge one has about an assumption. The closer the decision criterion is to  $[1, 1]$ , the more one is confident about the assumption one’s made; whereas, the closer the decision criterion is to  $[0, 0]$ , the less probable the assumption; a decision criterion of  $[0, 1]$  gives no information.

When unifying  $n$  data sets, Dempster’s rule (Shafer 1976) is applied to combine all support functions  $Bel(S_1)$ ,  $Bel(S_2)$ ,  $Bel(S_n)$ , that focus, respectively, on  $S_1, S_2, \dots, S_n$ .

The resulting support function is independent of the combination order and it is given by equation [5]:

$$[5] \quad Bel(S) = (((Bel(S_1) \oplus Bel(S_2)) \dots) \oplus Bel(S_{n-1})) \oplus Bel(S_n)$$

Expert data on the durability of building components are usually conflicting data (Lair 2000). This is a disadvantage when using Dempster's combination as the results may appear to be incoherent. It is for this reason why Lair (2000) proposed a set of substitution combination rules and a strategy based on a set of choices derived from a tree-structure in order to select the more pertinent combination rule as regards the data.

A third indicator of quality, included in the  $[Bel, Pl]$  interval, is introduced in order to assess the resulting quality of the aggregation procedure, as illustrated in § 6. This indicator ( $P(T)$ ) is referred to as the Smets probability (Dubois and Prade 1980) and is defined in equation [6]:

$$[6] \quad P(T) = \sum_{T \in S} \frac{m(S)}{|S|}$$

## 4. Aggregation of data

The aggregation of data is carried out when no SL-data is available directly at the user defined  $OP$ . The aggregation procedure takes into account all available information related to other  $APs$ . The aggregation can be applied to the different kind of SL-data that one is required to process in the proposed methodology (i.e. service life, probability of occurrence and performance). The results of an aggregation procedure provide for both a consensus of the data and an indicator of quality of the data. In this section, the aggregation procedure is described only for the case when considering service life data, not probability nor performance-related data.

### 4.1. Principles for the aggregation of SL-data

Considering that one has to assess the service life of a scenario comprised of  $n$  phenomena and that one knows the function of the degradation mechanism of these  $n$  phenomena, then one has to define the service life of each phenomenon in this scenario and the resulting service life.

Consider the following, and let: (i)  $S_j$ , represents a degradation scenario; (ii)  $Ph_i$  and  $Ph_{i+1}$ , two degradation phenomena from the  $S_j$ , where  $Ph_{i+1}$  occurs following  $Ph_i$ ; (iii)  $E_i(t)$ , the degradation function related to  $Ph_i$ ;

(iv)  $\tau_i$ , the degradation rate having a specific value for  $E_i(t)$  at which  $Ph_i$  appears and; (v)  $t_i^{S_j}$ , the transition time from  $Ph_i$  to  $Ph_{i+1}$ , achieved when  $E_i(t) = \tau_i$ .

Then, the service life of the scenario,  $T_{S_j}$ , is given by the sum of the times that separate the phenomena of this scenario. This is formalized in equation [7] as:

$$[7] \quad T_{S_j} = \sum_{i=1}^n t_i^{S_j}$$

where  $n$  corresponds to the number of phenomena associated with  $S_j$ .

This result is evident only under the hypothesis that the degradation states are not combined.

#### 4.2. Illustration of aggregation of SL-data

A more detailed overview of the aggregation procedure is provided in Talon et al. (2006b). However, the concept of transition rate can be illustrated with an example. Consider a reinforced concrete structure, in which the steel reinforcement corrodes over time. The corrosion process may evidently start before the resulting cracking of the concrete of this structure. In this case, the degradation rate between the phenomenon of concrete cracking and the phenomenon of reinforcement corrosion is the depth of the crack for which the corrosion can start.

The aggregation procedure is illustrated on the example of a scenario comprised of three phenomena as presented in Figure 2.

### 5. Set of possible service life assessments

The proposed methodology allows assessing the service life of in-service building components considering the entire set of degradation scenarios and all the functions ensured by the specified building component. Moreover, the main advantage of this methodology is that one can assess the service life of all  $OP$  in the  $US$  space. For

example, one can assess the service life of a butyl in regards to: (i) the mechanical resistance function; (ii) the stresses of hot temperatures and; (iii) the hardening phenomenon.

This section provides information on the different assessments that one can obtain using this methodology by varying the user defined  $OP$  on the four scales of the  $US$  space. The different locations that  $OP$  takes in this section are formalised in Figure 3 and illustrations for each  $OP$  location are provided in Table 2.

Consider the following: (i)  $SL(X)$ , represents the assessment of the service life ( $SL$ ) at point  $X$  in the  $US$  space, where  $X$  is equal to  $AP$  or  $OP$ ; (ii)  $\mu_{SL}(X)$ , is the quality of the assessment of the service life ( $SL$ ) at  $X$  point.

When  $AP$  is a single data set and coincides with the  $OP$ , then  $SL(X)$  and  $\mu_{SL}(X)$  are defined in equation [8] as:

$$[8] \quad \begin{cases} SL(OP) = SL(AP) \\ \mu_{SL}(OP) = \mu_{SL}(AP) \end{cases}$$

### 5.1. Considering only the scale of degradation in the $US$ space

Here, a specified function (or a specified set of functions) at a specified geometrical scale (e.g. material, element or building component) is considered. Then, the  $OP$  on the degradation scale may vary from the phenomenon level to the entire set of more critical scenarios.

#### a) Assessment at the phenomenon level

Here, the service life assessment is initiated with the unification procedure, given that the  $AP$ s coincide with the  $OP$ .

#### b) Assessment at the scenario level

Here, the problem is to assess the service life of a building component when a specified scenario occurs; this assessment may be carried out either directly or indirectly:

(1) Directly, if data is available at the  $OP$ , the assessment is obtained using the unification of data procedure about this degradation scenario coming from different sources,

(2) Indirectly, if data is obtained from phenomenon level, the assessment is obtained by the unification of data procedure for each phenomenon of this degradation scenario and then by the procedure of aggregation of data from the phenomenon level to the scenario level.

*c) Assessment at the level of an entire set of scenarios*

Here, all the scenarios are taken into account by the user and the goal is to assess the  $\{SL(OP), \mu_{SL}(OP)\}$  pair. The service life of the building component can be considered as the duration of the most probable and rapid degradation scenario. Consequently the service life of the building component is the minimum service life of all the most probable scenarios that were established following the FMEA. This is formalized in equations [9] and [10].

Given: (i)  $\{AP\}$ , the set of assessments of service life for the most probable scenarios; (ii)  $SL(AP)$ , the assessment of a service life for a specified scenario of the  $\{AP\}$ ; (iii)  $AP^*$ , a point in  $\{AP\}$  from which  $SL(AP^*)$  is defined as follows:

$$[9] \quad SL(AP^*) = \min\{SL(X) \quad \forall X \in \{AP\}\}$$

Then

$$[10] \quad \begin{cases} SL(OP) = SL(AP^*) \\ \mu_{SL}(OP) = \mu_{SL}(AP^*) \end{cases}$$

It is to be noted that the assessment of the most probable scenarios is comprised of four steps:

- (1) Assessment of the service life of each scenario as described in § 4,
- (2) Assessment of the probabilities of occurrence of each scenario using the aggregation procedure with probability data,
- (3) Obtaining the degradation versus performance functions related to all related pairs {phenomenon; function} of all established degradation scenarios,
- (4) Definition of the “failure time” of each scenario, i.e. the time from the beginning of the scenario to when at least one of the performance thresholds of the functions of the building is reached. It is this “failure time” that is noted  $SL(AP^*)$  in equation [9].

## 5.2. Scale of function only

In this case, a specified degradation phenomenon (degradation phenomenon, scenario or set of scenarios), a specified geometry and different functions are considered. Then, the *OP* on the function scale may as being either at the single function level or the multi functions level.

### *a) Assessment at the single function level*

The service life assessment procedure is the same as described in § 5.1 with the exception that only the threshold performance of the established function has to be considered.

### *b) Assessment at the multi function level*

Here, an assessment point in  $\{AP\}$  is defined for each function that the user wants to consider. In this case a multi performance profile is provided and then the service life of the building component can be deduced. A multi performance profile is a static representation of all the functional states at a specific in-service date. Its evaluation consists in determining the service life for each function, then to standardize each result on a performance scale and finally, to represent these performances on a normalized standard profile. When taking into account all the functions of interest, the service life of the building component is reached when the first performance threshold is reached. In this case, the service life assessment and its quality assessment are defined by the previous equations [9] and [10].

In the design stage, from FMEA, the user can go back and change some material or element that first provides the failure of the studied building component. Moreover, the multi performance profile provides the more sensitive and critical functions, that is to say the functions that first reach their performance thresholds. Whereas in the in-service or building management stage, several profiles may be produced. These profiles can be used to simulate the effect on the service life profile of an inspection, maintenance and repair strategy.

## 5.3. Scale of geometry only

In this case, a specified phenomenon, a specified function (or a specified set of functions) and different levels of geometry are considered. Then, the *OP* can vary from the material level to the building component level.

The choice of the geometrical level is decided when undertaking the process of organisational analysis. The decision making is based on a dilemma. The first aspect of this one is that if the level is low, considerable time

could be spent developing the FMEA and then many phenomena then need to be taken into account. On the contrary, too high a level provides a FMEA that is easy to complete. The second aspect of the dilemma is the availability of SL-data related to the phenomena that were provided by FMEA. SL-data are easier to find for a complete description of phenomena, i.e. related to a low geometrical level, than for an overview description of phenomena, i.e. related to a high geometrical level.

*a) Assessment at a material level*

The assessment of the service life of a material is direct; it corresponds to the unification of all the available data related to the studied material.

*b) Assessment at the element level*

The service life may be obtained in two ways. The first, directly, when the *OP* coincides with the *AP*; the second, indirectly, when the *OP* is obtained from the *APs* that are distinct from the *OP*. Here, an assessment point in the  $\{AP\}$  set is defined for each material of which an element is comprised. Because of the interaction between materials, the degradation mechanisms may change and one cannot ensure that the service life of an element is the minimum value of service life of each material. This mean of assessment only provides an inferior result, as described in equations [11] and [12].

Let  $AP^*$  be such as:

$$[11] \quad \begin{cases} SL(AP^*) = \min\{SL(X) \quad \forall X \in \{AP\}\} \\ SL(OP) \leq SL(AP^*) \end{cases}$$

And

$$[12] \quad \mu_{SL}(OP) \approx \mu_{SL}(AP^*)$$

*c) Assessment at the building component level*

The procedure in this case is the same as in the previous one; the assessment at the material level has to be changed into an assessment at the element level and the assessment at the element level to an assessment at the building component level. Note that usually, the assessment of a building component starts from the material through to the elements; hence in most instances it is expected that the three cases (a), (b) and (c) will occur together.

#### 5.4. Scale of time only

The variation on the time scale may only influence the accuracy of the service life assessments and the quality indicator. Indeed in design stage, one may need to be sure that the service life of a building component will be above that of a specified value; consequently the precision in results derived from the service life assessment is not altogether important. Whereas, in the case of maintenance planning, a high precision in respect to results from a service life assessment as well as a high quality indicator are important. Consequently, the choice of time scale will necessarily influence the collection and preparation of SL-data when carrying out the methodology, but not the assessment procedures.

### 6. Example use of methodology – assessment of a window unit

In this section, parts of the proposed methodology are illustrated for assessing the service life of a window unit. A schematic representation of a sectional view of the window unit considered for this case is presented in Figure 4. The different elements of which the window component is made can readily be identified in the Figure 4.

The system analysis and the FMEA of this specific window unit were undertaken together with a selected group of experts in materials and insulated glass units for which a significant list of degradation scenarios were developed as detailed in Talon (2006b). The emphasis here is not placed on the results of the FMEA but on the way to assess the window service life based on the knowledge of the degradation scenarios and also based on the availability of service life data. To simplify the example, focus is made on a specific degradation scenario described in Figure 5. The evolution of the scenario is comprised of six phenomena.

In this instance, the goal is twofold. First of all, the process of data unification is to be applied at a phenomenon level, using different kinds of data that are derived from several sources. Secondly, details on the process of aggregation of data with an *OP* at the scenario level are provided. The data aggregation process is first initiated using available service life data at the phenomenon level. It is to be noted that the following service life data is, on the one part, extracted from books or studies and, for the other part when no data is available, through expert opinion.

The process of data unification is now applied to the degradation phenomenon of hardening and cracking of the butyl-based sealing joint. Five different data sets are available, as summarised in Table 3. As this data is

obtained from an expert opinion, its degree of imprecision is taken into account using fuzzy sets. The use of fuzzy sets to represent the degree of belief for the Data set 1 is illustrated in Figure 6.

The assessment of the quality of the data provides the corresponding outputs from the belief mass of 0.65, 0.64, 0.67, 0.63 and 0.61 for the five respective service life data sets presented in Table 3; their unification leads to the consensus curve shown in Figure 7. The consensus curve is the distribution of the belief masses affected to each service life interval resulting from the fusion procedure.

In this service life assessment approach, the interval which represents 80 % of the maximum of consensus is retained as valid and the associated belief, plausibility of belief and Smets probability are then determined. Here the service life of the phenomenon of hardening and cracking of the sealing joint has been estimated to occur between an interval of [15, 18] years. The associated data quality indicators are: (i)  $Bel([15, 18]) = 0.11$ ; (ii)  $P([15, 18]) = 0.35$ ; (iii)  $Pl([15, 18]) = 0.86$ .

In this instance, the Smets probability is poor and the difference between the belief and the plausibility is high ( $0.86 - 0.11 = 0.75$ ); this means that the result of this service life is only weakly consensual.

A similar unification process was undertaken for the six different degradation phenomena presented in Figure 5 and provides the results, detailed in Table 4, in terms of interval of service life and Smets probability of the interval.

Only the Smets-based probabilities are presented as these are the only indicators to be used further on in the paper.

The service life of a specified degradation scenario is the sum of the service life of its constitutive phenomena. In this instance, degradation phenomena 1 and 2 are concomitant and must appear before the phenomenon 3 is initiated. Consequently it is the phenomenon that provides for the longest value of service life, i.e. phenomenon 1, that is most significant. Furthermore the quality indicator corresponds to the minimum of all the Smets probabilities associated to the phenomena, as described in (Bouchon-Menier 1995). Consequently the aggregated results are the following:

(1) The service life of the scenario is included in the interval of [73, 92] years ( $48 + 22 + 3 + 0, 51 + 18 + 35 + 5 + 1$ ),

(2) The quality indicator is  $m([73, 92]) = 0.25$  ( $\min\{0.28, 0.50, 0.25, 0.25\}$ ).

On the basis of these results, a conclusion is that another service-life data is needed in order to increase the quality indicator, in particular for the degradation phenomena that have the poorest Smets probabilities, i.e.

saturation of humidity absorber and oxidation of low-emissive coating. This conclusion may involve new research among existing SL-data or initiate new durability tests.

Moreover, when the service life of a degradation scenario is obtained on the one hand by aggregation of service life of the phenomena and on the other hand by unification of data at the scenario level, there are two possibilities:

(1) To compare the two results. It may be interesting when there is no doubt in respect to the service life of one of them,

(2) To unify results. Proceeding this way proves that it is possible to combine all the available service life data at each level of the degradation scale.

## 7. Conclusion

The main conclusion of this paper is that a methodological approach has been developed and demonstrated as a convenient mean to assess the service life of building components. It has been shown that this assessment is possible for each specified point within the *US* space based on whatever knowledge is available on the mechanisms of degradation of the component. To be efficient, two methods are associated to this methodology: a data unification procedure and a procedure for data aggregation. The introduction of an attribute of quality associated to each data sets has two main purposes:

(1) To associate a global quality to the assessment that is carried out at the user defined objective point,  
(2) To impose on a user to need to consider the quality attributes of the SL-data and in so doing, analyze the source and quality of the retrieved data.

In some instances this implies that the quality is insufficient or that data is not compatible or that more data is needed.

Although the example of the window unit has not been completely developed in this paper it is noted that all the points of the *US* space have not the same degree of interest for the user. Nonetheless, as far as the points of interest are concerned, the primary result is that all the available data can be captured, unified and integrated to reach the assessment of the objective point.

As a perspective in the development of ideas in this study, some databases on the primary materials, building components and phenomena in the field of building components have been developed; the further development of these databases will be very helpful to assess the service life of building components in the future. Another development concerns the automation of the FMEA to facilitate the production of the entire set of degradation scenarios for different building components. A third development is focused on the concept of criticality that classifies a set of scenarios into several classes (major, significant and minor criticality) by taking into account the duration, the probability and the gravity of the consequences of these scenarios. This classification will allow removing a subset of scenarios to focus on the more critical ones. Fourthly, it will be very interesting to see how to integrate the Bayesian theory in our methodology in order to update the obtained service life of a building component when a diagnosis of this building component is available. Finally, the factor method is one that is presented in the service life planning standard ISO 15686, and it is one that is easy to use and as such, efforts will be made for its improvements. However, fundamentally it remains a subjective method, in particular regarding, the manner in which values for factors are determined and thus any useful improvements would need to address this issue; the proposed methodology in this paper can be an efficient tool for the adjustment of the factor method.

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**Table 1.** Criteria assessment grid

Criteria	Values of criteria			
	1	2/3	1/3	0
Data modeling	Established theory	Non established theory	Statistical study	Non modeled
Hypothesis of modeling	Poor	Fair	High	Very high
Rough data	Experience plan	Feedback	Good estimation	Poor estimation
Source	Referenced	Interne	Conference	Isolated
Censorship	Non censured	Partially censured	Censured	Non take into account
Coherence of the preparation of data	Excellent	Good	Fair	Poor
Correspondence of levels between data ( <i>AP</i> ) and objective point ( <i>OP</i> )	Excellent	Good	Fair	Poor
In-service conditions correspondence between the <i>AP</i> and the <i>OP</i>	Excellent	Good	Fair	Poor
Entropy (Shannon and Weaver 1972)	Calculated value that is continue, as provided in § 3.1			

**Table 2.** Illustration of the set of possible service life assessments

Related paragraph	Scales				Example of service life assessment
	Degradation	Function	Geometry	Time	
Specified (S) or Varying (V)					
5.1.a					Phenomenon of oxidation of low-emissive coating of a window unit
5.1.b	V	S	S	S	Main scenario leading to the oxidation of low-emissive coating of a window unit
5.1.c					All possible scenarios leading to the oxidation of low-emissive coating of a window unit
5.2.a					Mechanical resistance of a window unit
5.2.b	S	V	S	S	All performance requirements of a window unit (mechanical resistance, thermal isolation, aesthetics, etc.)
5.3.a					Material of butyl
5.3.b	S	S	V	S	Element of sealing joint
5.3.c					Building component of window unit
5.4	S	S	S	V	Failure of a glass lite in phase of implementation or failure of a glass lite in phase of in-service

**Table 3.** Service life data to illustrate the unification process at a phenomenon level

N°	Description	Rough service life	Source
Data 1	Local redoing of sealing system of a window unit	All the 5 years	(Perret 1995)
Data 2	Total redoing of sealing system of a window unit	All the 10 years	(Perret 1995)
Data 3	Punctual replacement of packing of a window unit	All the 10 years	(Perret 1995)
Data 4	Total replacement of packing of a window unit	Between 15 and 20 years	(Perret 1995)
Data 5	Service life of a sealing joint in silicone	< 20 years	(Edifice 2003)

**Table 4.** Results of the unification procedure of the six phenomena of the Figure 4

Phenomenon number	Phenomenon designation	Assessed service life	Assessed Smets probability
1	Cracking of frame	[48, 51] years	$P([48, 51]) = 0.28$
2	Hardening and cracking of sealing joint	[15, 18] years	$P([15, 18]) = 0.35$
3	Corrosion and perforation of spacer	[22, 35] years	$P([22, 35]) = 0.50$
4	Saturation of humidity absorber	[3, 5] years	$P([3, 5]) = 0.25$
5	Condensation on low-emissive coating	Instantaneous regarding the service life of the others phenomena	-
6	Oxidation of low-emissive coating		$P([0, 1]) = 0.25$

**Figure caption 1.**

*AP*: Assessment Point

*OP*: Objective Point

**Figure caption 2.**

$E_i(t) = 0$ : non degraded state

$E_i(t) = 1$ : failure state

Fig. 1. Range of user solutions – US

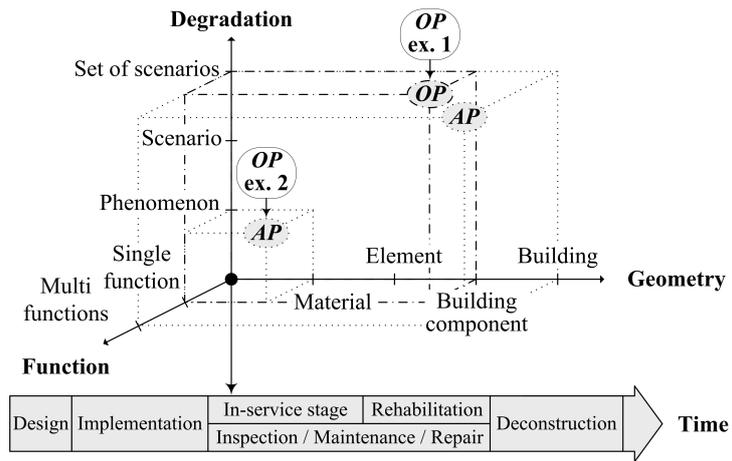
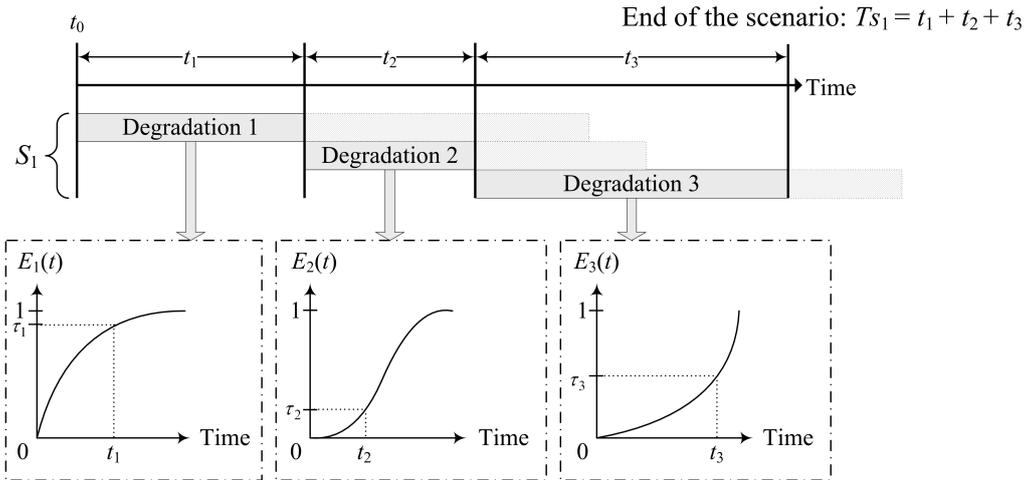


Fig. 2. Principle of service life assessment of a degradation scenario by data aggregation



**Fig. 3.** Formalisation in the *US* space of the set of possible service life assessments

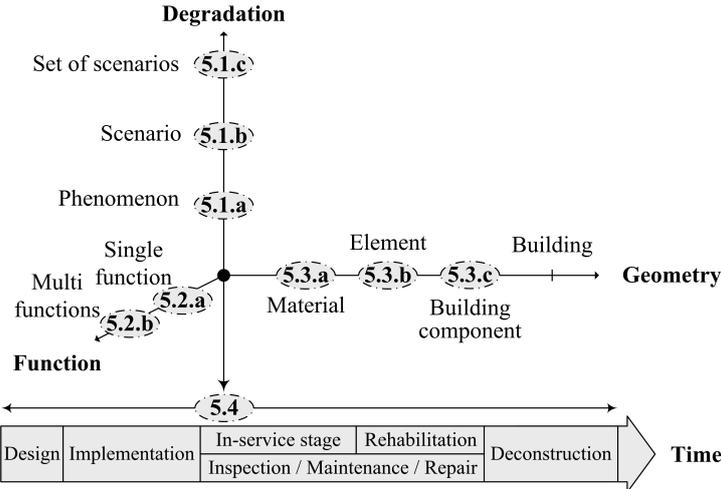


Fig. 4. Schematic representation of the window unit as specified in the case study

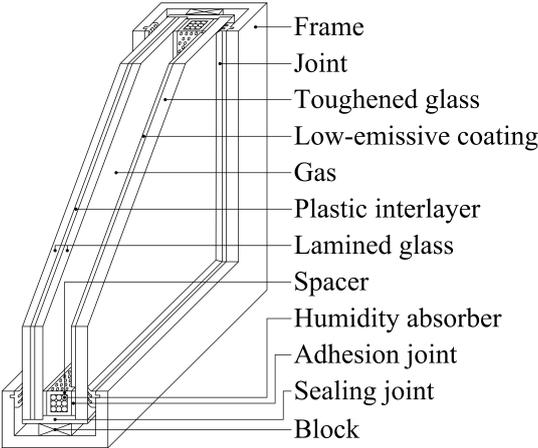


Fig. 5. A selected degradation scenario to illustrate the service life assessment methodology for a specific window unit

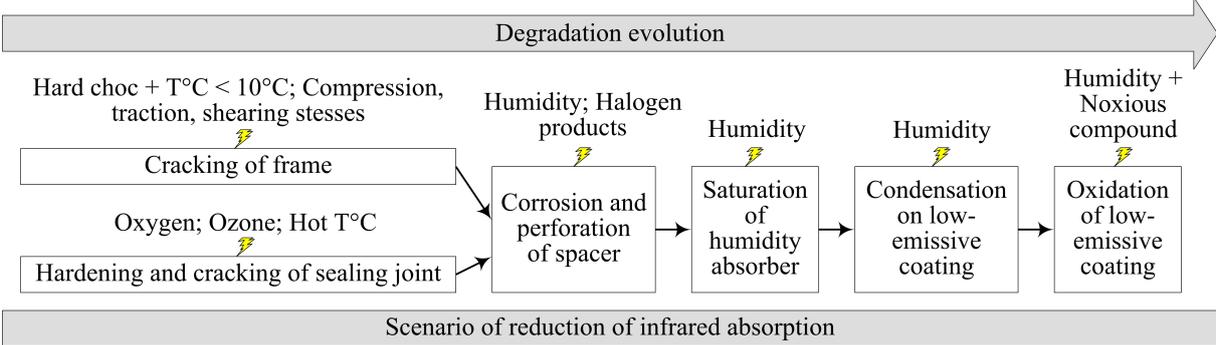


Fig. 6. Representation of an expert opinion – example of data 1

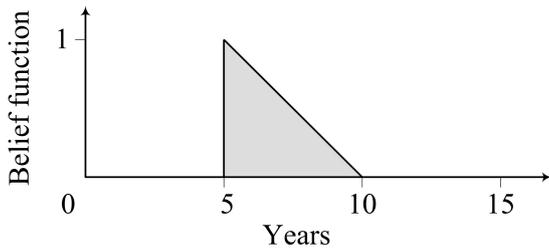


Fig. 7. Consensus curve resulting from unification of five service lives

