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RESEARCH ARTICLE

A conceptual framework for service life prediction of reinforced concrete structures

E. Possan[1] · D. C. C. Dal Molin[2] · J. J. O. Andrade[3]

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Abstract
This paper presents a conceptual framework methodology concerning service life prediction of concrete structures by using deterministic or probabilistic processes, which are included from collecting data until the decision-making. This methodology provides guidelines to generate new degradation models and accomplish new service life studies of either existing structures or new ones in literature. In the first case, it is possible to estimate how many years are necessary for the structure to reach the desired limit state (durability, service or of security). It can also provide support in project design by selecting durability requirements such as covering thickness, concrete strength, type of cement, water–cement ratio, among other factors that influence the service life of concrete structures.

Keywords Degradation · Service life prediction · Simulation · Limit state · Mathematic model

1 Introduction

The premature degradation of buildings or their parts, and the resultant performance decrease, is a frequent problem all over the world. This deterioration happens mainly due to the early aging of those parts, which is usually caused by the poor quality of the materials used during construction, regarding design and execution problems and lack of maintenance. The early degradation of buildings has direct influence on maintenance and repair costs.

Regarding structural systems in reinforced and prestressed concrete, it should be highlighted that activities related to maintenance, repair and restoration of structures and their parts correspond to 35% of the total work volume of construction sector, and this number has been increasing in recent years [1]. Mehta and Monteiro [2] point out that, in industrial developed countries, 40% of the total resources in construction industry have been estimated to interventions of existing structures and less than 60% in new facilities. According to these authors, the increase on cost to replace structures and the growing emphasis on life-cycle cost, rather than the initial cost, are pushing engineers to pay more attention to durability issues.

Data collected by NACE International [3] show that, in the United States, the annual cost associated to the corrosive process of civil infrastructures (bridges, airports, ports, among others) is estimated at US$ 22.6 billion. In Brazil, Meira and Padaratz [4] observed that investments in maintenance interventions, in a structure with a high degree of deterioration, could reach approximately 40% of costs to run a degraded component. It is common to find constructions with higher degradation levels than intended, with problems related to quality and durability due to execution failures and the appearance of pathological manifestations, which affect safety, usability, aesthetics and the service life Andrade et al. [5].

Studies concerning estimate of degradation and to the service life prediction can reduce problems associated with durability of constructions. Life expectancy is a complex problem, since structures with their components and systems deteriorate at different rates, and there are several uncertainties related to material properties, degradation mechanisms,

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✉ E. Possan
epossan@gmail.com

[1] Graduation Program of Civil Engineering, Federal University of Latin American Integration (PGCEI/UNILA), Foz do Iguaçu, Brazil

[2] Counseling Center for Innovation of Buildings, Engineering School of UFRGS, Federal University of Rio Grande do Sul (NORIE/UFRGS), Porto Alegre, Brazil

[3] Graduation Program in Materials Engineering and Technology, Pontifical Catholic University of Rio Grande do Sul (PGETEMA/PUCRS), Porto Alegre, Brazil

structural response, environmental load and conditions of use, maintenance and operation, among others. According to these uncertainties, there have been advanced in service life prediction studies of these structures, which are strongly related to the modeling of, both deterministic and probabilistic, concrete degradation.

Pang and Li [6] emphasizes that in marine environments, the service life of reinforced concrete structures is mainly influenced due to the chloride-induced corrosion of reinforcement, and the development of chloride penetration model is essential for its assessment. Possan [7] and Dal Molin et al. [8] have also corroborated on the need for employment or development of representative degradation models for each potential aggressive agent (chlorides, CO_2, sulfates, alkalis, etc.). Based on this context, and in accordance to what has been reported in Fib 53 [9], which alludes that in order to reach the service life project, it is necessary both understanding of the deterioration mechanisms that act out in a given structure and an appropriate model to represent the behavior over time. Thus, this research presents a methodology (see flowchart of Fig. 3) for predicting service-life of concrete structures, including also the modeling aspects of degradation.

2 Service life of concrete structures: current status

In general, service life consists of measuring the expected life of a structure or its parts, within permissible design limits, throughout its life cycle. The life cycle corresponds to all stages of a product's service life, in which case the product is the building.

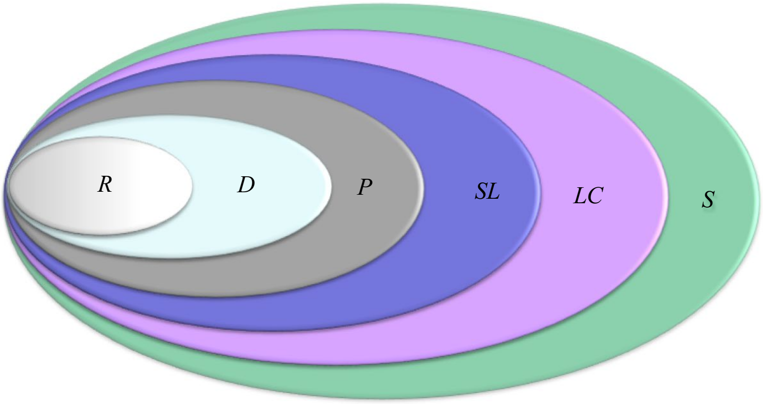
It is important ranging from design until construction, operation, maintenance, repair to demolition and disposal of waste. ISO 13823 [10] defines service life as the effective period of time during which a structure or any of its components achieves the project performance requirements without unforeseen maintenance or repair. In summary, service life is the time period between the beginning of operation and use of a building until the moment its performance fails to meet user's requirements. It is directly influenced by the maintenance and repair activities and the environment exposure. In general, service life is expressed in years, it is established by most concrete standards and codes [11–13], as a minimum service life design (SLD) of 50 years for most structures and 100 years for civil structures, such as infrastructure works, bridges, viaducts, dams, among others.

The actual or effective service life of a structure may not necessarily be equal to the originally specified service life design (SLD), due to the uncertainties inherent to the structure degradation process (such as degradation mechanisms, loads, etc.). In order to be sure of achieving LSD, it is necessary to consider an adequate time frame or performance level, considering not only aspects from the engineering point of view, but also from the economic and non-technical aspect.

According to the technical viewpoint, it is fundamental that service life (SL) is considered at the project level, since buildings performance depends on it [9, 12]. In addition, although service life tends to reduce overall cost when defined at the project level, the builder, in order to reduce the initial cost, tends, in many cases, to build a construction at the lowest cost, choosing alternatives that do not favor durability and consequently the building service life.

Figure 1 presents the conceptual evolution of concrete structures design. At the beginning of the development and diffusion of reinforced concrete, the structures were designed using common sense and professional experience, where the main controlled characteristic was compressive strength or resistance (R), which for a long time was considered as a single source and design specifications.

Fig. 1 Conceptual evolution of concrete structures design



***R**esistance (R)| **D**urability (D) |**P**erformance (P) |**S**ervice **L**ife (SL) | **L**ife **C**ycle (SC) | **S**ustainability (S)*

Throughout the years, there have been great changes in building materials, exhibition environment, and calculation procedures. Therefore, it was observed that the reinforced concrete presented limitations and that only the resistance parameter (R) was inadequate to meet the design requirements. Then, durability (D) of these structures and their constituent materials were emphasized, later associating this concept to their performance (P), that is, to the behavior in use. However, it was still necessary to insert the variable "time" into the projects, so, service life studies (SL) came to light.

Currently, factors such as competitiveness, costs and environmental preservation are again imposing changes on how structures are designed, requiring them to be designed holistically, considering their life cycle (LC) and associated costs (LCC—Life Cycle Cost). From the LCC, several studies can be carried out, with emphasis on estimates of maintenance costs throughout service life, studies of environmental impact, among others, helping to select the best design alternative for new structures or maintenance, repair, rehabilitation or final destination for existing structures. Consequently, the project for sustainability (S) becomes possible. As structures with a long service life contribute to sustainability, the present research describes a methodology for estimating service life of concrete structures, in order to contribute to the studies improvement in the area [7].

Concerning sustainability, Fib 53 [9] presents the conceptual model shown in Fig. 2, which systematically matches with concepts of quality (durability), functionality, Life Cycle Cost and environmental impact. The design of a building/structure should pursue a balance among these three factors as well as achieve the desired level of excellence (level 3).

In order to reach this balance, it is essential to design buildings with high service life, because the longer service life, the less resources are needed to build new structures. This preserves natural resources (due to non-extraction of virgin raw materials) and generates the least volume of waste (due to the non-demolition of structure).

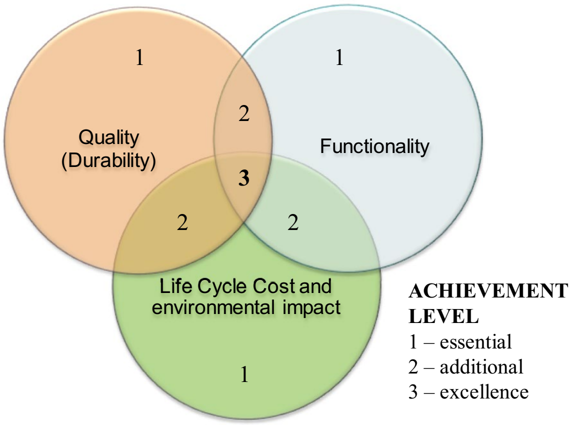


Fig. 2 Systematic combination of components for building sustainability [9]

3 Methodology for service life prediction

Based on the concepts presented by Clifton [14] and Helene [15] and other researchers [16, 17]; and assuming that, in order to predict SL, there is a need for a mathematical model representative of degradation [7–9], proposes a methodology for modeling and SL prediction of reinforced concrete structures (see flowchart in Fig. 3). The methodology has four steps: (1) collection of degradation data; (2) degradation modeling; (3) simulation of degradation; and, (4) decision making.

Service life prediction of concrete structures can begin in step 1, when the goal is obtaining or improving a specific degradation model (Model development), or in step 3, when there is a need to make predictions with already existing models (Model application). The applied methodology proposes to first collect concrete degradation data (such as chlorides penetration, carbonation depth, among others), generating a database for each aggressive agent (chlorides, carbonation, sulfates, aggregated alkali). From these answers, damage modeling (step 2) is carried out, in which the representative model of concrete degradation, in general, will be generated due to the prevailing aggressive agent (chlorides, carbonation, sulfates, alkali aggregate, etc.). Once the model has been generated, it should be observed and validated, and it is suitable to use the degradation database of a concrete to do so. If the model satisfactorily describes the concrete degradation, it moves on to step 3, otherwise it goes back to the modeling.

As soon as the representative model of degradation is defined (selected from literature or developed), the degradation estimative can be finally carried out and predict the structure service life. Therefore, approaches such as deterministic, semi-probabilistic or probabilistic can be applied.

The first one generates service life results considering the degradation average. While the last one, since it inserts uncertainties that are inherent to degradation, results in an interval over time, associating probability of damage occurrence to service life. The semi-probabilistic approach mixes characteristics of the previous ones. Finally, it is possible a decision making via technical analysis or using the analysis of life cycle cost (LCC), based on the definition and study of scenarios for a given structure.

Each step related to the applied methodology will be presented and discussed in the next sections.

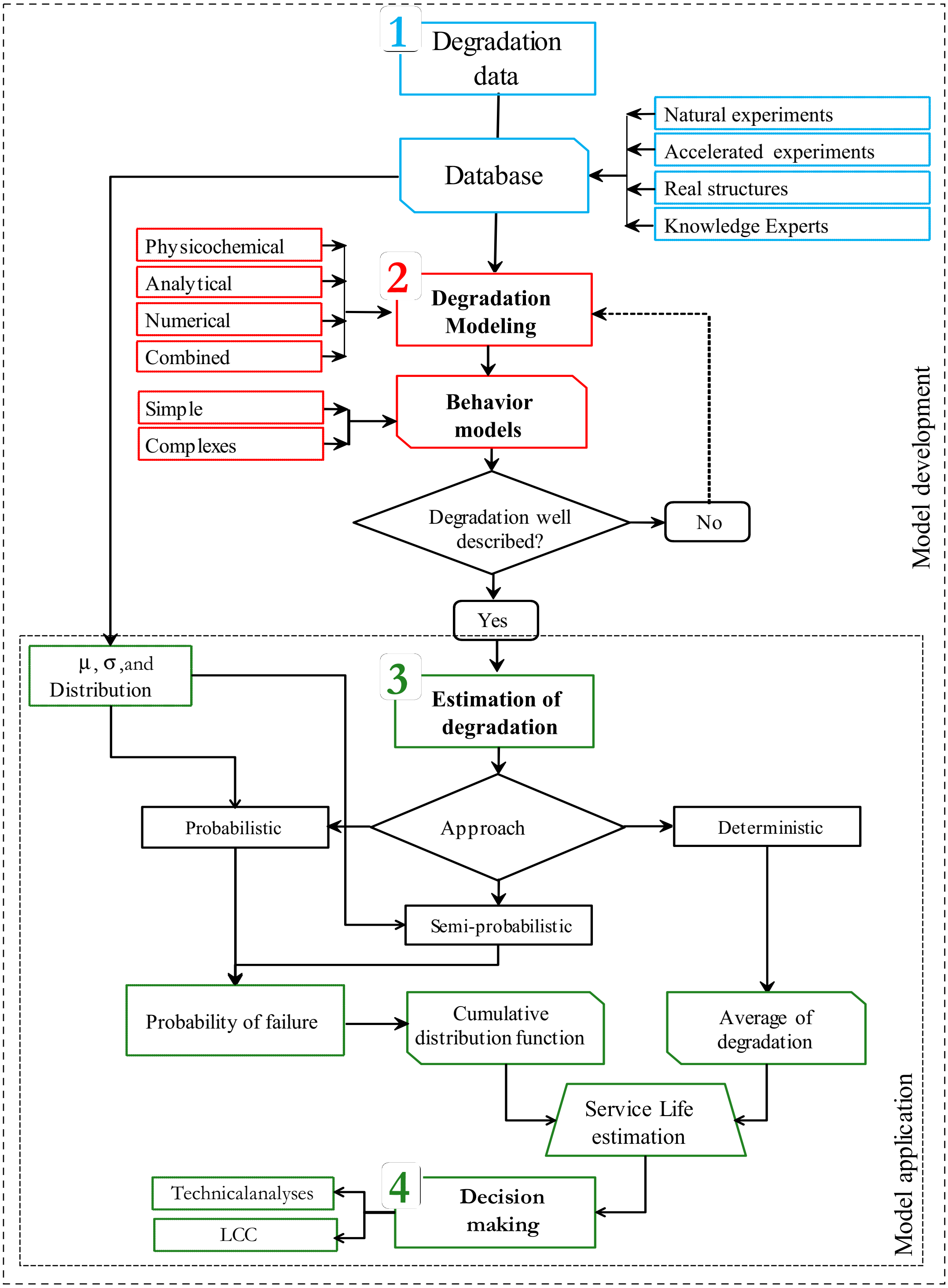


Fig. 3 Flowchart for service life prediction of reinforced concrete structures

3.1 Step 1: degradation data

Data collection is one of the essential phases to studies concerning service life prediction. It also requires the compiling information (objective or subjective—see Table 1) about the factors that take part of the project (such as covering thickness, water/cement ratio, compressive strength), during the building process (quality control level of the work), durability (type and content of

Table 1 Possible sources of degradation data of concrete structures

Information, data or indicators		
Type	Origin	Observations
Objective	*Accelerated tests*[a] of material performance, providing: –performance indicators of maintenance, repair and rehabilitation actions; –durability indicators[b]; –indicators of protection performance (paints in steel, anodic and cathodic protection, among others); –aggressiveness of the environment; etc.	Information from these sources has a high potential to be applied. Although, it is better that they should be clustered into databases, as they make ease the access to information and, consequently, increase reliability of the stated results These databases can be formed with data from theses, dissertations, academic papers, case studies, among other reliable sources. However, accelerated test data need to be used carefully, since, for prediction studies, it is necessary to use an acceleration coefficient[c] of degradation
	In situ research providing: –the abovementioned indicators; –speed and intensity of degradation process in real buildings	
	Performance and efficiency Indicators provided by the manufacturer or maintainer of component, subsystem and system	This information is also useful for determining or evaluating warranty periods
Subjective	*Expert knowledge*	When there is no real data, information from experts' knowledge can be used in the studies. Thus, the focal group technique and the Delphi Method[d] are used

[a] Accelerated tests are comparative tests concerning durability performance of a given material data, in order to provide results in short time frames

[b] Durability indicator: properties such as pore structure, CO_2 diffusion coefficient, Ca $(OH)_2$ content, among the others, determined by laboratory tests, which help in qualitative or quantitative evaluation of durability potential of a material [18]. Technique to find a consensus of opinions regarding a certain group of experts for a given topic

[c] Expresses the number of times that the accelerated test represents natural degradation, and it is related to concretes studied and the exposure conditions imposed in both test procedures [19]. Their determination is quite complex due to the viability inherent to degradation

[d] This method assumes that the collective judgment, when well organized, is better than a single individual opinion. Based on the structured consultation using a questionnaire to a group of specialists, who are questioned until a convergence of the group's answers is obtained

aggressive agent, exposure condition) and in operational actions, maintenance and repair of concrete structures.

According to Table 1, the data or indicators of degradation required for modeling and prediction of service life have different origins, such as experiments (accelerated or not), real structures, experts' knowledge, literature, data history, among others. This information, isolated or clustered in database, helps the generation, standardization, verification and validation of models, as well as allows comparing service life estimates obtained in simulations. They are also essential in the statistical characterization of variables (determination of variation, and probability distributions coefficients). In general, engineering studies are carried out based on the objective data from laboratory or field trials, among others. However, subjective information from expert knowledge can also be used in these studies.

As an example, estimative models of concrete degradation are highlighted due to carbonation [7] and chlorides action [5, 16] to predict life expectancy, they are also developed based on focus groups. Focus groups are forums that bring together a small group of individuals to discuss about a subject of interest.

Basically, they can be considered an interview in group, but without the sense of alternation where a researcher inquiries and the participants answer. On the other hand, its essence consists in interacting individuals, based on topics that are fomented by the researcher, who usually assumes the role of moderator during the session [20]. Therefore, Altmann et al. [21] emphasize that, in the absence of information from laboratory tests or real structures (in situ research or natural testes), it is essential a transparent inclusion of additional sources of information such as expert knowledge, subjective assessment, and the transfer of experience and available knowledge for ordinary concrete.

3.2 Step 2: degradation modeling

Mathematical modeling can be physical–chemical, numerical, analytical or combined [22–25] and results in empirical mathematical [7, 16] or complex [25, 26] models. Empirical models, also called simplified models, are based on field or laboratory data adjustments or based on expert knowledge. In general, they have analytical solution.

Complex or phenomenological models are based on physical–chemical laws, such as laws of mass conservation of CO_2 and water, and due to their complexity, they require numerical solutions. Other factors that differ from mathematical models are presented in Table 2, whose information was compiled from several papers according to the literature [22–26].

In general, empirical models are easier to be applied, however, they show simplifications, which can lead to less

Table 2 Empirical models × complex models

Factor	Empirical models	Complex models
Grounding	Experts knowledge, historical data, field and laboratory tests	Nature laws (physical and chemical), algebraic formulations, etc.
Input parameters	Mostly simple and easy to obtain	Usually require tests for determination—some are difficult to be obtained
Accuracy	An associated error can be high	Tend to reduce errors
computational Simulation	Simple and, in general, analytical	Complex, usually numerical, and it demands longer simulation periods
Practice Application	Easy	Difficult
Extrapolation	It can intervene in reliability	If it is well prepared and written, it accepts extrapolations
Generalization	Applicable to the intervals of information that created the model	Applicable to all situations governed by the laws that compose it

accurate results. On the other hand, the complex ones consider a greater number of variables of influence during the degradation process, and tend to a greater precision and generalization, but are more difficult to be applied. Step 2 of Fig. 3 regards about degradation modeling, where concrete behavior models are generated against degradation, which are confronted with database in order to check whether the model represents or not the actual degradation. If so, simulation continues, otherwise, it returns to the modeling.

As far as concrete degradation is concerned, both modeling sequences are important, but they have limitations, which must be considered when selecting the model that will be used as a function of the desired response. The association of a probabilistic approach to these models is a way of inserting inherent variability in concrete degradation modeling, leading, in general, to a greater approximation of service life of the structure.

3.3 Step 3: estimated degradation

The degradation estimate is obtained from a mathematical model, (step 3, Fig. 3), which can be driven by probabilistic, semi-probabilistic or deterministic processes, regardless of how the model was generated.

In probabilistic processes, it is considered the joint distribution of all variables of influence during the degradation process. In semi-probabilistic processes, variables of influence are considered in a partial way, through their mean values. In deterministic ones, they do not consider the variability of influence factors during the degradation process (see Fig. 4).

In the first two cases, it is necessary to know the probability distribution of variables considered as randomized, as well as their parameters—mean (μ), standard deviation (σ) or coefficient of variation (CV)—and, due to a probability of occurrence, service life of the structure is estimated. While, in this approach, uncertainties of the process are inserted in simulation, in the deterministic, only the mean values of input variables are accounted, which leads to an average estimate of the structure degradation.

The variability of degradation process is not taken into account to estimate service life by deterministic ways. From the mean values of the input variables, these models provide mean values answers of degradation (carbonation depth) or performance (coating thickness, service life). However, there are cases where instead of the mean a lower or higher percentile is adopted. Besides, information from the deterministic models is not enough in many situations, especially when it is required to evaluate the risk of a project reaching or not a certain period of SL.

Although the deterministic methods are the most used [27] for more than two decades, the probabilistic ones have been applied by several researchers [7, 16, 28–30] for predicting service life of concrete structures. It is observed that the reliability analysis [31], Monte Carlo simulation [6], finite element analysis (FEA) [27], Markov chains [31], fuzzy probability theory [21] and artificial neural networks [32] are tools applied for this purpose.

3.4 Step 4: decision making

This step is not mandatory, but of great importance in complex engineering projects. According to several authors [33–35], life cycle cost analysis (LCC) is an important method to evaluate the economic performance with high potential to be applied in engineering projects, especially in decision making, and it is important to:

(a) select alternatives for new projects and intermediate in existing ones;
(b) replace or repair systems, subsystems and components of building;
(c) reduce LCC of a construction or its parts;
(d) define deadlines for interventions of maintenance, repair and rehabilitation of the construction or its parts;
(e) analyze environmental costs from the early demolition of a construction and environmental impact studies;

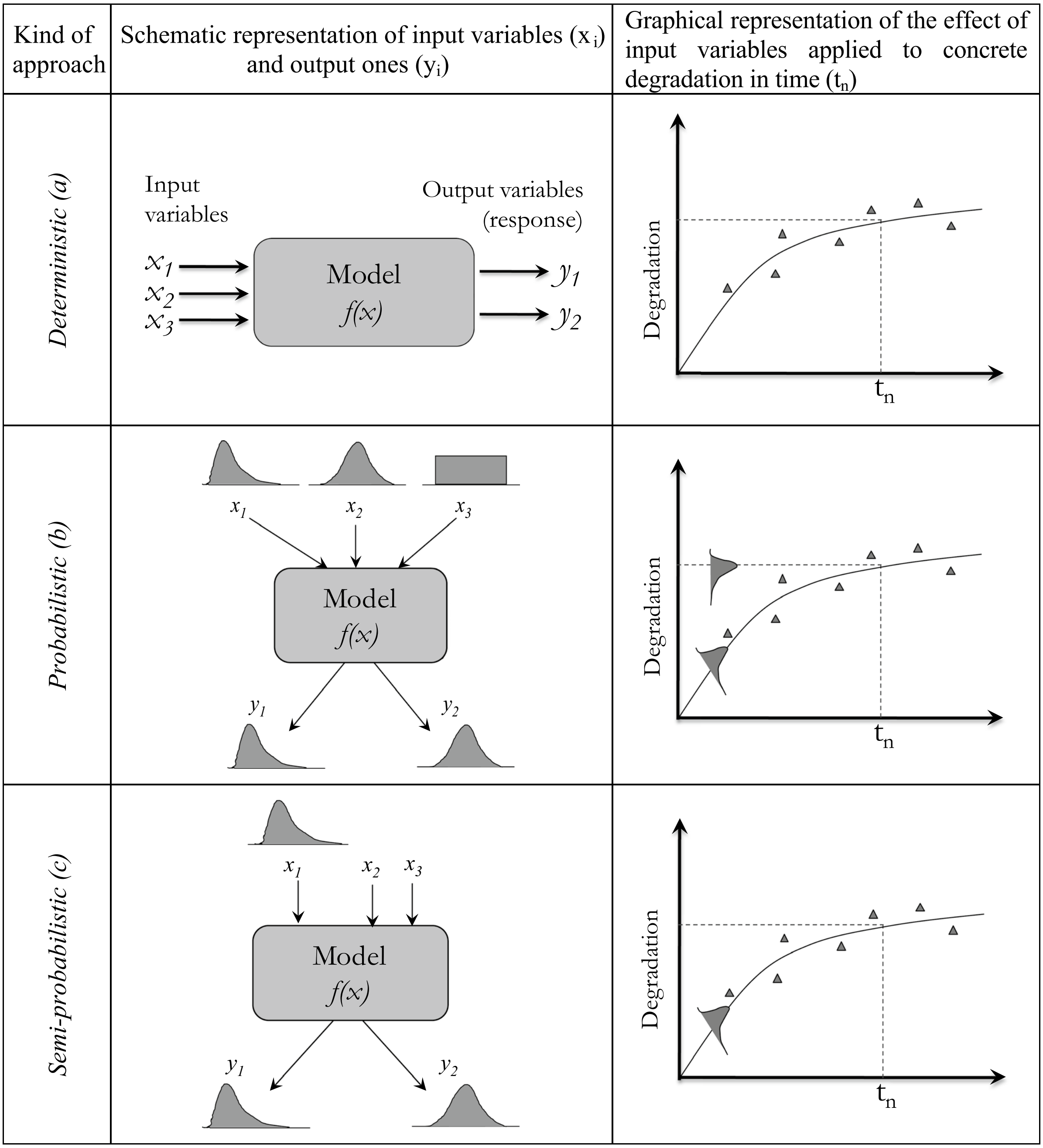


Fig. 4 Approaches to service life

(f) decide about a project, select or refute a high initial investment, verify its performance and costs in the horizon of plan or service life.

Life cycle cost analysis is a technique to evaluate economic performance and occurs by solutions of direct and simple equations, converting the relevant costs of the studied object into equivalent present value. With regard to concrete structures, life cycle cost is of great interest to identify project alternatives (such as thickness of cover, compressive strength, structural system, etc.), which can lead to lower operating costs, maintenance, repair and rehabilitation during the structure service life to help on decision making. It is also important to justify the high initial investments of a project, due to the economic benefits that come over time (Fig. 5). In high investment projects, these studies are usually carried out, probabilistically, by sensitivity and risk analyses, in order to give greater reliability to the results when considering the uncertainties of a degradation process.

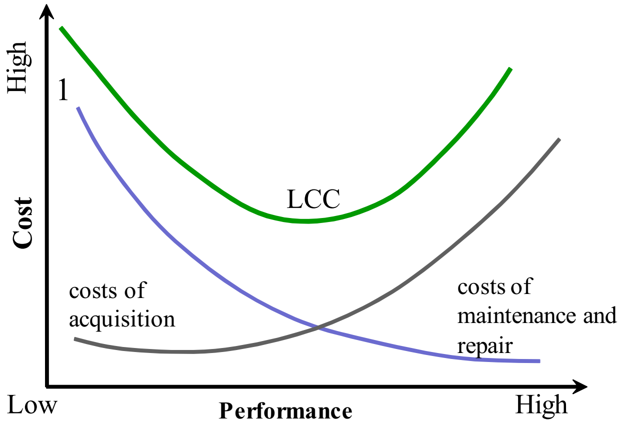


Fig. 5 Relation schematic among the costs of acquisition and maintenance and repair over life cycle cost (LCC) point

The LCC advantages in service life predicting studies are better understood when different design alternatives can be compared, and the greatest benefits of this analysis are achieved in new building projects [35]. However, there are no problems on applying them in existing buildings. Several authors [33–36] use life cycle analysis to study durability and service life of reinforced concrete structures for different design alternatives and maintenance actions. Most of these studies were carried out on a probabilistic approach, considering the main variables of influence on degradation of a structure and costs over time. According to the authors, programming and scheduling maintenance costs are the main benefits of this technique. Nevertheless, LCC, the predicted service life of structures and concrete degradation modeling require a systemic and multidisciplinary view, since, besides engineering knowledge, basic knowledge in materials science, stochastic processes and economic engineering are necessary.

Dal Molin et al. [8] have described that since Brazilian standards do not provide predictive models for estimating service life of concrete structures. On the other hand, they require a service life project of at least 50 years, which is believed to be an important initial step to afford simple application models that can simulate some degradation. Even though in a deterministic way, until there is enough knowledge of variability's related to the materials characteristics, to the reinforcement obtained on the construction, to the environmental load, among other parameters, considering Brazilian reality.

4 Methodology application

The study of Andrade et al. [5] was selected to exemplify the methodology described in item 3, which contemplates the development of a new model for the concrete degradation by chloride ions estimation, encompassing the complete example of the proposed methodology. However, if the intention is to use a model already published in the literature for estimation of degradation and/or service life prediction, steps 4.1 and 4.2 do not need to be conducted.

Table 3 Values of K_1 in function of the cement type

K_1	ASTM cement type
0.98	I (SM)
1.05	I (PM)
1.21	IS
1.17	IP
0.95	III

4.1 Collection of degradation data

By using a structured questionnaire applied to 11 experts, the authors [5] collected concrete degradation data due to the action of chloride ions (subjective data collection using expert knowledge by focal group technique).

4.2 Degradation modeling

The data collected by Andrade et al. [5] were tabulated and using combined mathematical modeling (statistical and physicochemical modeling) the degradation model was proposed (see Eq. 1).

$$y_{0.4\%} = \frac{7.35 \cdot UR^{0.7} \cdot T^{0.1} \cdot Cl^{0.7}}{K_1 \cdot f_{ck} \cdot K_2 \cdot (1 + Ad)^{0.2}} \cdot \sqrt{t} \qquad (1)$$

where $y_{0.4\%}$ = position of critical chloride concentration (C_{cr}) from the concrete surface (mm); UR = relative humidity of the atmosphere (%); T = environmental temperature (°C); Cl = environmental chloride concentration (%); K_1 = factor that varies in function of the type of cement used in the concrete production; f_{ck} = compressive strength (28 days) (MPa); K_2 = factor that varies in function of the admixture type used in concrete production; Ad = amount of admixture in concrete (%); and t = time (years).

The factors K_1 and K_2, obtained from the *Focus Groups* analysis are presented in Tables 3 and 4, respectively.

At the end of this step, the degradation model obtained must be verified, using a different database than the one that originated the model. If the model is not representative of the degradation (check coefficient of correction, which should be greater than 80%), the modeling process must be resumed by making the necessary adjustments to the model or its coefficients. If the model represents the concrete degradation satisfactorily, one can move on to the next step.

Table 4 Values of K_2 in function of admixture type

K_2	Type of admixture
1.00	Silica fume (SF)
0.97	Metakaolin
0.76	Rice husk ash (RRA)

Andrade et al. [5], used Guimarães [37] data to verify the model proposed in Eq. 1 and obtained satisfactory results for the estimation of concrete degradation, as shown in Table 5.

It is emphasized that the larger the number of cases represented by the model, the greater the chances of the same being generalizable and, consequently, to be diffused in the literature as a model that adequately describes the degradation of the concrete.

4.3 Simulation of degradation

From the degradation model of Eq. 1, obtained in previous steps (4.1 and 4.2) or from a model already published in the literature, it is possible to simulate concrete degradation as well as conduct service life prediction. For durability studies, it is assumed that the concrete degradation (y) must be equal to or less than the thickness of concrete cover (d) of the structure ($y \leq d$). For the service life study, the degradation model (Eq. 1) is inverted, in which time (t) becomes the response variable, thus representing the service life of the structure in years.

As an example of application the scenarios in Table 6 are used. Table 7 presents the results of the model application (Eq. 1).

4.4 Decision making

Based on the results obtained (Table 7), the decision can be made using simple analysis or life cycle assessment methodologies. In a simple analysis, it is observed that the structure projected with the conditions exposed in "scenario A" will not reach the service life design, since the degradation ($y_{0.4\%}$) in 50 years of environmental exposure is greater than the cover thickness (40 mm). On the other hand, "scenario B" conditions ensure that service life design is achieved (cover thickness (d) is greater than concrete degradation (y) in 50 years).

Table 5 Penetration depth of the critical concentration of chloride ions ($y_{0.4\%}$) measured and calculated l [5]

Point	$y_{0.4\%}$ (cm)	
	Measured in situ [37]	Calculated (Eq. 1)
P1	2.55	2.94
P2	3.63	3.25

Table 6 Characteristics of the structural element and environment

Property	Scenario A	Scenario B
Compressive strength at 28 days (MPa)	25	40
w/c ratio	0,55	0,40
Cement type	ASTM Type IP	
Mean temperature (°C)	25	
Relative humidity (%)	75	
Environmental chloride concentration (%)	1,3	
Time (years)	50	
Thickness of concrete cover (mm)	40	

Table 7 Concrete degradation for the scenarios under analysis ($y_{0.4\%}$)

Response	Scenario A	Scenario B
Position of critical chloride concentration (C_{cr}) from the concrete surface (mm)	60	38

5 Concluding remarks

It is highlighted that the proposed methodology for the prediction of useful life, represented in the flowchart of Fig. 3, describes up from the data collection, including degradation modeling (models generation), until service life estimate and the decision making. It is a simple method that allows the constant verification of the results. The methodology provides guidelines to generate new degradation models and to carry out service life studies of new or existing structures. But, regarding new structures, it provides subsidies to select cover thickness, concrete strength, cement type, water/cement ratio, among other factors that influence service life of concrete structures. For existing structures, it is possible to estimate how long will be required for the structure to reach the desired threshold state (durability, service or safety).

The proposed methodology can be applied to two different scopes: (1) need to develop a model for the estimation of concrete degradation and service life prediction of a concrete structure; (2) need to estimate concrete degradation and conduct service life prediction studies f of a concrete structure. In the first case the methodology is started in step 1, fulfilling all subsequent steps. In the second, the methodology is started in step 3, accomplishing the following steps.

It also provides subsidies so that service life studies are carried out in a deterministic or probabilistic way. This choice is associated to the desired result: and, if the interest is determining the structure service life considering the degradation mean, the deterministic method is suggested; Otherwise, when it is desired to predict service life considering the process uncertainties due to a probability of damage occurrence, it is recommended to use probabilistic processes.

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