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1 **Application of sensitivity analysis in the life cycle design**
2 **for the durability of reinforced concrete structures in**
3 **the case of XC4 exposure class**

4 **Van-Loc TA^{a,1}, Tristan SENGA KIESSE^b, Stéphanie BONNET^c, Anne**
5 **VENTURA^{a,d}**

6 *^a Université de Nantes, GeM, Institut de Recherche en Génie civil et*
7 *Mécanique – CNRS UMR 6183 – Chaire Génie Civil Eco-construction,*
8 *France.*

9 *^b UMR SAS, INRA, Agrocampus Ouest, 35000 Rennes, France.*

10 *^c Université de Nantes, GeM, Institut de Recherche en Génie civil et*
11 *Mécanique – CNRS UMR 6183, France.*

12 *^d Institut Français Transports Aménagement Réseaux (IFSTTAR – MAST –*
13 *GPEM), France.*

14 **Abstract**

15 The aim of this study is to develop a new design procedure for the durability
16 of the Reinforced Concrete (RC) structures in aggressive environments. The
17 study approach developed here includes: (i) a qualitative analysis phase to
18 characterize the design parameters and environmental exposure conditions of

¹ Corresponding author. Tel.: +33 2 72 64 87 61;
E-mail address : van-loc.ta@etu.univ-nantes.fr

19 RC structures; (ii) a quantitative analysis phase, to establish the relationship
20 between service life and design parameters and environmental exposure
21 conditions using the service life prediction model firstly, and then to
22 determine the most influential design parameters on service life using
23 sensitivity analyses; and (iii) a final design phase, to design RC structures
24 using some favorable values of the most influential design parameters firstly,
25 and then to compare the service life thus obtained with that of RC structures
26 designed using a standardized approach. An application is also proposed on
27 simulated RC structure exposed to carbonation in Madrid (Spain). This RC
28 structure follows the recommendations of the European standard EN 206-1
29 for XC4 exposure class. The sensitivity analysis results are discussed in
30 detail including influence trends, importance ranking, non-monotonic effects
31 and parameter interaction influences. The most influential design parameters
32 obtained are cement strength class (f_{cem}), water-to-cement ratio (W/C) and
33 cement type (CEM). By using W/C of about 0.4, f_{cem} of about 52.5 MPa and
34 CEM I cement type instead of their limiting value as recommended by EN
35 206-1, the service life of the RC structure is significantly improved.

36 *Key words: Carbonation; Durability design; Corrosion; Service life. Morris*
37 *analysis, Sobol indices.*

38 **1. Introduction**

39 In the literature, two basic approaches are proposed for the design of the
40 durability of Reinforced Concrete (RC) structures in aggressive

41 environments [1]: a prescriptive approach and a performance-based
42 approach.

43 The prescriptive approach is primarily based on the acquired experience in
44 the durability performance of existing RC structures. Because experience is
45 generally insufficient to allow for the quantitative requirements, most of the
46 requirements for durability are formulated in a qualitative and empirical way.
47 In the case of reinforcing steel corrosion due to carbonation or chlorides, the
48 prescriptive approach defines an exposure class and subsequent prescriptions
49 including (i) concrete composition (a maximum water-to-cement ratio, a
50 minimum cement content and a cement type); (ii) a minimum 28-day
51 compressive strength of the concrete; and (iii) a minimum concrete cover
52 depth for service life design [2] [3].

53 The key feature of the performance-based approach is to assess relevant
54 concrete material properties using some relevant test methods or service life
55 prediction models. This approach can be used to formulate requirements as
56 regards material properties and structure dimensions. In the case of corrosion
57 of reinforcing steel due to carbonation [4] [1] [5] or chlorides [6] [7] [8], the
58 estimation of the deterioration evolution depending on expected influential
59 parameters is mostly performed by applying a probabilistic approach. This
60 estimation makes it possible to formulate requirements for the structural
61 responses depending on the service life design [3]. Then, durability design
62 can be completed in two ways: (i) using a fully probabilistic method, for
63 which the concrete cover depth and the diffusion coefficient of CO₂ or

64 chlorides are usually considered as main probabilistic design parameters for
65 the required service life design and the reliability level [4] [1] [5] [6] [7] [8];
66 and (ii) using the partial factor method to determine the characteristic values
67 and the partial factors for the design parameters [4] [1] [7].

68 The strength of the prescriptive approach lies in its flexibility to account
69 for experience and its easy application. The obvious weakness of this
70 approach is that: (i) a simple set of general prescriptions cannot be optimal
71 for all the different parts of a structure exposed to different levels of
72 aggressiveness depending on the structure areas [9]; (ii) our understanding
73 of service durability performance of the structure at the design stage must be
74 improved [1]; and (iii) it does not encourage the use of novel materials for
75 durability design. The strength of the performance-based approach, on the
76 other hand, is its relevance for the durability responses so that service life
77 design can be carried out in a more scientific and reliable way. However, two
78 main difficulties must be faced: (i) a better understanding of the deterioration
79 mechanisms must combine the results of both the scientific research with
80 long-term in-situ observations; and (ii) the uncertainty associated with
81 deterioration mechanisms must be properly taken into consideration in the
82 design process. This last issue can be solved by carrying out a sensitivity
83 analysis of service life in relation to modeling parameters. The Sensitivity
84 Analysis (SA) is the study of how the uncertainty of a mathematical model
85 or system (numerical or other systems) results can be apportioned to different
86 sources of uncertainty and variability of the input parameters [10]. In the

87 literature, many studies present the SA of the simplified diffusion-based
88 corrosion initiation model of RC structures exposed to chlorides. This
89 analysis is conducted to identify, among the different parameters like
90 concrete cover depth, chloride diffusion coefficient, chloride threshold level,
91 and chloride concentration at the surface, those which are the most
92 significant [11] [12]. Other studies describe the SA of corrosion rate
93 prediction models [13] or simplified carbonation models [14] conducted to
94 classify the different influences of the input parameters. Some authors use
95 the “One At a Time (OAT)” SA method [11] [12], which provides some semi-
96 qualitative sensitivity information by varying one parameter at a time while
97 keeping the others constant. Sensitivity is observed graphically. Other
98 authors use the SA method based on the regression analysis [13] [14]. This
99 method quantifies the effect of the input parameters on the model results.

100 It is sometimes difficult to distinguish between prescriptive or
101 performance-based design approaches. For instance, if the existing RC
102 structures on a given project site have achieved the objective set by service
103 life design, then the durability design of new RC structures can rely on the
104 rational analysis of the durability measurements carried out on these RC
105 structures. Consequently, determining whether structure design is
106 specifically based on the prescriptive or the performance-based approach is
107 difficult, in this case. The experimental data on the durability performance
108 of the structures thus collected must be integrated into the different phases
109 of the performance-based approach to determine the preliminary dimensions

110 of the structure [3]. Thus, both approaches are useful as regards durability
111 design and are complementary methods in the global design process.

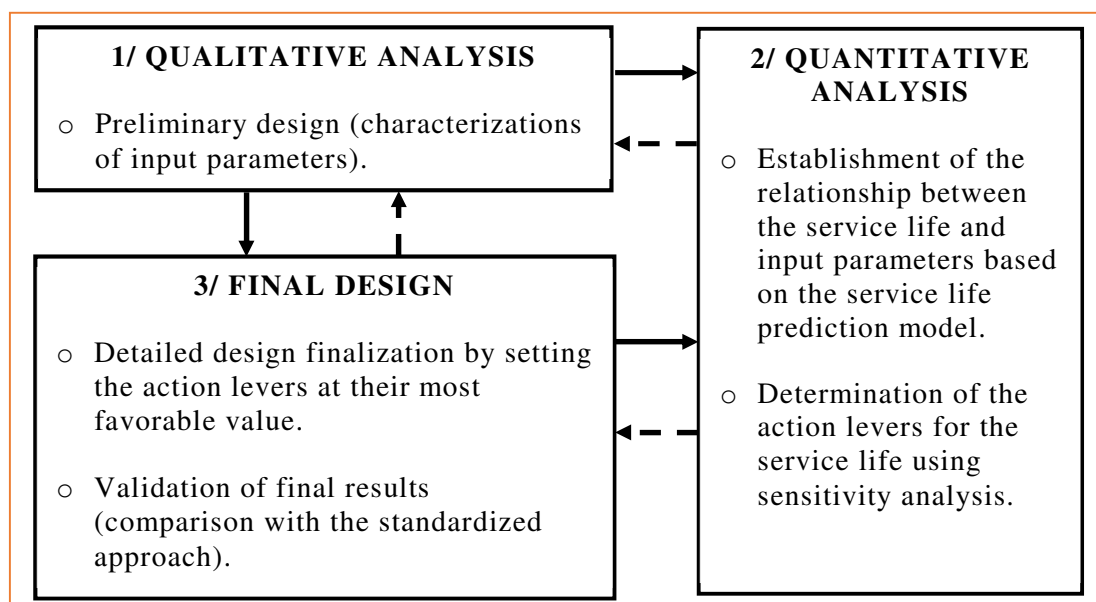
112 The present paper reports a study conducted to develop a new design
113 procedure for the durability of the RC structures in aggressive environments.
114 The procedure discussed here is the result of the combination of both
115 prescriptive and performance-based approaches. Qualitative and quantitative
116 SA methods are integrated into the design procedure to determine durability
117 action levers (refer to definition of “action levers” in *Appendix*). These are
118 used to design the best durable RC structure.

119 The new design procedure for the durability of RC structures in aggressive
120 environments is presented in Section 2. An application of this procedure to
121 a simulated RC structure exposed to carbonation in Madrid (Spain) is
122 described in Section 3. Some recommendations for the durability design
123 according to EN 2016-1 for XC4 exposure class are discussed in Section 4.

124 **2. Development of the new durability design procedure**

125 The durability design procedure proposed here includes: (1) a qualitative
126 analysis, (2) a quantitative analysis, and (3) a final design procedure (*Figure*
127 *1*). The purpose of the qualitative analysis is to determine the preliminary
128 dimensions of a RC structure at a general level within the context of
129 aggressive environments. It also includes the characterizations of the design
130 parameters and the environmental exposure conditions. This analysis is
131 carried out using a prescriptive approach. The quantitative analysis aims at

132 establishing a relationship between the aggressive environment and the
 133 service life of structure using a service life prediction model [4]. The purpose
 134 of the quantitative analysis is to determine the action levers by applying the
 135 SA method to the service life prediction model. The final design phase
 136 consists in using the action levers to redesign the RC structure properties in
 137 order to achieve the longest service life possible. This phase also includes a
 138 comparison between the service life of a structure designed using the
 139 procedure proposed here and that of a structure designed using the
 140 recommended limiting values of EN 206-1 [15].



141

142 *Figure 1. Design procedure for durability of RC structures in aggressive*
 143 *environments.*

144 In order to determine the action levers, suitable SA methods must be
 145 selected. They must provide the trend of action levers in relation to the
 146 service life, the quantization of their influence and the interactions with other

147 parameters. Thus, the SA methods used in the previous studies [11] [12] [13]
148 [14] are not relevant in this context. Consequently, a combination of two SA
149 methods, Sobol's quantitative method [16] and Morris' qualitative method
150 [17] is chosen. This combination has been previously used for the same
151 purpose in environmental design using Life Cycle Assessment (LCA) [18]
152 [19]. It can provide complementary information on the influence of the input
153 parameters on the model results in the decision-making process. Sobol's
154 method is used to quantify the input parameters contribution to model result
155 variations. Morris' method, on the other hand, provides additional
156 information on the trend of the input parameters. Both methods require that
157 all the input parameters are independent of one another. Both methods are
158 summarized in the next subsections.

159 **2.1. Sobol's quantitative sensitivity analysis**

160 Sobol's method [16] is based on the analysis of the variance decomposition
161 of the model f in order to quantify the contribution of variability of the input
162 parameter X_j to the total variance of the output Y . The individual contribution
163 of input parameter X_j is measured using the first order sensitivity index (S_j)
164 such as:

$$S_j = \frac{\text{Var}(\mathbb{E}[Y | X_j])}{\text{Var}(Y)} \quad (1)$$

165 where: $\text{Var}(\mathbb{E}[Y | X_j])$ is the conditional variance of Y produced by the
166 variation of X_j , $\text{Var}(Y)$ is the total variance of Y .

167 The individual Sobol indices lie in the interval [0-1]. Moreover, the overall
168 output sensitivity to the parameter X_j (i.e., including first and higher order
169 effects (interaction) of X_j) can be measured using the total sensitivity index
170 (S_{Tj}) [20] as:

$$S_{Tj} = 1 - \frac{Var(\mathbb{E}[Y | X_{\neq j}])}{Var(Y)} \quad (2)$$

171 where: $Var(\mathbb{E}[Y | X_{\neq j}])$ is the conditional variance of Y produced by the
172 variation of all the input parameters except X_j .

173 Sobol's method requires to have characterized the Probability Density
174 Function (PDF) of each input parameter. The Monte Carlo simulations are
175 carried out by varying simultaneously all the input parameters according to
176 their PDF and by calculating the associated model results. In this study, S_j
177 and S_{Tj} are calculated.

178 **2.2. Morris's qualitative sensitivity analysis**

179 Morris' method [17] is one of the most popular screening method, which
180 consists in developing a randomized experimental design process by varying
181 one parameter while keeping the others constant (OAT method) over a certain
182 number of repetitions k ($k = 1, 2, \dots, r$). Then, the variation coefficients, called
183 the elementary effects ($\mathbb{E}E_j^{(k)}$), are obtained as:

$$\mathbb{E}\mathbb{E}_j^{(k)} \approx \frac{f(\mathbb{X}^{(k)} + e_j \cdot \Delta) - f(\mathbb{X}^{(k)})}{\Delta} \quad (3)$$

184 where: Δ is a pre-defined step, e_j is a vector of zero but with j -th equal ± 1 .

185 The mean value (μ_j) of the elementary effects is calculated to determine the
 186 trend of input parameter X_j . The algebraic sign of μ_j indicates increasing
 187 (positive sign) or decreasing (negative sign) trends of the model output
 188 related to X_j . The standard deviation value (σ_j) of the elementary effects is
 189 the measure of the sum of all the interactions of X_j with the other parameters
 190 and of all non-linear influences. We find:

$$\mu_j = \frac{1}{r} \sum_{k=1}^r \mathbb{E}\mathbb{E}_j^{(k)} \quad (4)$$

$$\sigma_j = \sqrt{\frac{1}{r-1} \sum_{k=1}^r \left(\mathbb{E}\mathbb{E}_j^{(k)} - \mu_j \right)^2} \quad (5)$$

191 In the case of non-monotonic functions, the elementary effects can have an
 192 opposite sign for the considered repetition, which can result in a μ_j close to
 193 zero if the parameter is influential. In order to prevent this, Campolongo et
 194 al. [21] recommend to use the mean value of the absolute value (μ_j^*) of the
 195 elementary effects rather than the usual μ_j .

$$\mu_j^* = \frac{1}{r} \sum_{k=1}^r \left| \mathbb{E}\mathbb{E}_j^{(k)} \right| \quad (6)$$

196 The information about the algebraic sign of μ_j is lost when using μ_j^* .
197 However, it is a good indicator for the assessment of the importance of the
198 input parameters in relation to each other. Morris' method requires a local
199 interval range (minimum and maximum value) for each input parameter. The
200 number of repetitions r ranges from 4 to 10 [22]. In this study, μ_j , μ_j^* and σ_j
201 are calculated.

202 Throughout the rest of the work, Morris and Sobol methods serve to identify
203 input parameters that are major contributors to the variability of service life.
204 More specifically, the controllable parameters related to technological
205 aspects (e.g., concrete mix, size of structure), i.e., the “technological
206 parameters”, are considered as action levers if they are major contributors to
207 the service life.

208 **2.3. Identification of action levers using sensitivity indices**

209 Based on the Sobol indices, the technological parameters are identified as
210 action levers, if the value of S_j is higher than 10%. Moreover, if the value of
211 S_j is lower than 10% but the difference ($S_{T_j} - S_j$) is high, i.e., assumed to be
212 greater than 10%, they can also be considered as potential action levers [18]
213 [19]. This means that parameter X_j is not individually influential but has a
214 non-negligible global contribution because of its interaction with the other
215 parameters. As regards the Morris indices, the parameters with a higher μ_j^*
216 are considered as potential action levers [17]. If the parameters satisfy the
217 condition $\sigma_j \geq |\mu_j|$, they are considered to have a non-monotonic effect. In

218 contrast, non-influential input parameter X_j is assumed to have indices S_{T_j}
219 lower than 10% and μ_j^* low in relation to other indices $\mu_{i,i \neq j}^*$ of input
220 parameters $X_{i,i \neq j}$. Recall that Morris indices μ_j^* and μ_j have the same order of
221 magnitude than the model response while the first order Sobol indices S_j are
222 normalized and lie in the interval [0-1].

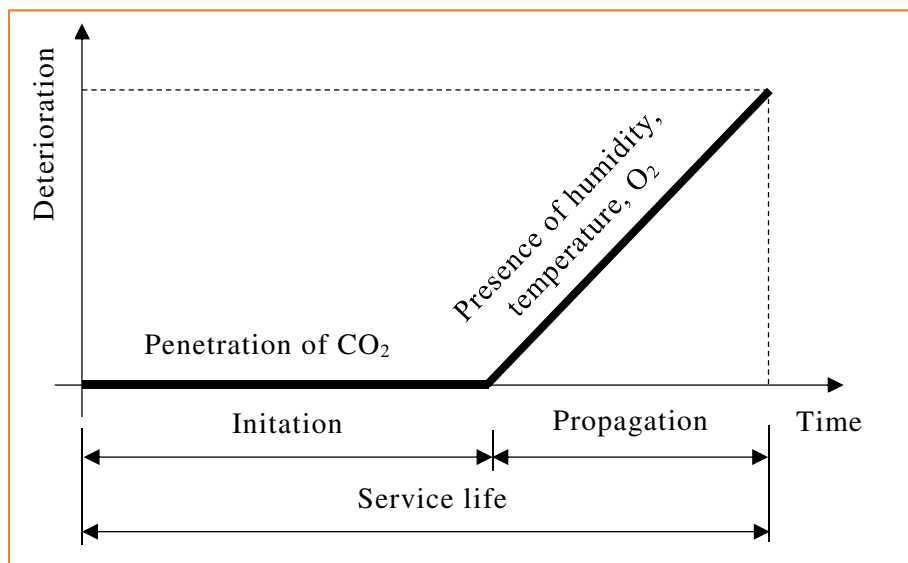
223 **3. Case study**

224 **3.1. Presentation of the case study**

225 The case study studied here consists of a RC structure subjected to
226 carbonation. The structure is assumed to be located in Madrid (Spain)
227 because this location presents optimal environmental conditions for
228 carbonation of concrete [23] [24]. Madrid, indeed, is a place with a high level
229 of carbon dioxide [25] and with an average relative external humidity of
230 about 0.56 [26]. The considered structure follows the recommendations of
231 EN 206-1 for XC4 exposure class [15]: concrete is exposed to the air and the
232 structure is not sheltered from rain. Carbonation is the only alteration
233 phenomenon of RC structure considered in this paper. The objective here is
234 to identify the action levers affecting service life to obtain the longest service
235 life possible by setting the identified action levers at their most favorable
236 value.

237 The service life of a structural component is the period after construction,
238 during which all the structure properties, when routinely maintained, are

239 higher than the minimum acceptable values [2]. Tuutti [27] proposed a
240 simplified model for predicting the service life of RC structures, considering
241 the degradation due to carbonation induced corrosion. Service life is divided
242 into two periods: initiation period and propagation period as shown in *Figure*
243 2. There are two periods because the mechanisms involved are different in
244 physical-chemical terms. The initiation period corresponds to the penetration
245 of CO₂ into the concrete cover until the carbonation front reaches the
246 reinforced layer. The propagation period includes (i) steel corrosion; (ii)
247 cross section loss; (iii) concrete surface cracking; and (iv) spalling of
248 concrete cover.



249

250

Figure 2. Tuutti's service life prediction model [27].

251

Our case study deals with the initiation period only. The service life of RC

252

structure is limited to the corrosion initiation period. Thus, a model for the

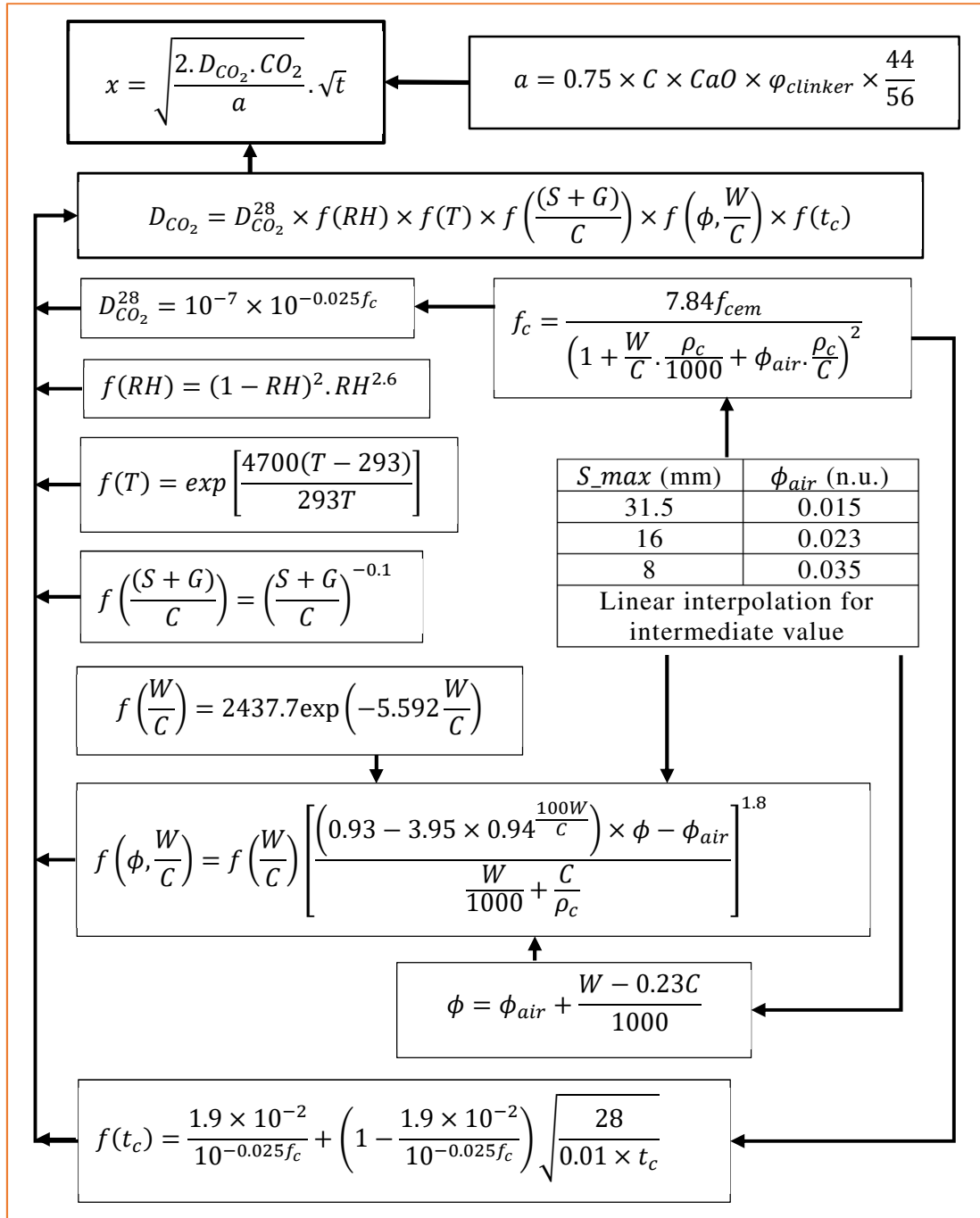
253 initiation period is required: that model calculates at any time the
254 carbonation depth within concrete.

255 **3.2. Qualitative analysis: characterization of input parameters**

256 The service life considered here is predicted using the carbonation model
257 recently developed by Ta et al. [28] (*Figure 3*). This carbonation model is
258 validated using data from the literature on short and long-term natural
259 carbonation exposure conditions. Most of the experimental data concern
260 CEM I, CEM II, CEM III cement types. The prediction of this carbonation
261 model for estimation of carbonation depth is more accurate than Papadakis'
262 model [29] and Yang's model [30]. This model takes many influencing
263 design parameters of the carbonation process into account and predicts the
264 natural carbonation depth. It is based on the analytical solution of Fick's law
265 given by:

$$x = \sqrt{\frac{2 \times D_{CO_2} \times CO_2}{a}} \times \sqrt{t} \quad (7)$$

266 where: x (m) is the carbonation depth within concrete, D_{CO_2} (m^2/s) is the CO_2
267 diffusion coefficient of concrete, CO_2 (kg/m^3) is the CO_2 concentration in the
268 atmosphere, a (kg/m^3) is the amount of CO_2 absorbed in a unit volume of
269 concrete, t (s) is the exposure time.



270

271 *Figure 3. Carbonation model presented in [28] (input parameters are*
 272 *detailed in the text).*

273 When the carbonation depth is equal to the concrete cover depth (d), i.e.,
 274 $x = d$, the corrosion initiation period ends. The steel reinforcement could be

275 then corroded with the presence of O₂, humidity and temperature as defined
 276 by Tuuti's service life prediction model (*Figure 2*). Service life (t_{ser}) can be
 277 written as:

$$t_{ser} = \frac{d^2 \times a}{2 \times D_{CO_2} \times CO_2} \quad (8)$$

278 The purpose then is to design a concrete structure with a maximum service
 279 life value t_{ser} .

280 Many parameters are required for the calculation of D_{CO_2} and a as shown in
 281 *Figure 3*. For the application of Sobol and Morris' methods to the
 282 determination of the sensitivity of t_{ser} to input parameters, we use only the
 283 expression of D_{CO_2} and a in relation to the independent parameters. An
 284 independent parameter does have a relationship with other independent
 285 parameters. The dependent parameters are expressed through the independent
 286 parameters. The time dependency of the input parameters is not taken into
 287 account. Consequently, the expression of t_{ser} takes the form:

$$t_{ser} = f(C, W/C, S/G, S_{max}, CEM, f_{cem}, d, t_c, T, RH, CO_2) \quad (9)$$

288 or

$$t_{ser} = f(X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10}, X_{11}) \quad (10)$$

289 where: C (kg/m³ of concrete) is the amount of cement content, W/C (n.u.)
 290 (n.u. = no unit) is the water-to-cement ratio, S/G (n.u.) is the sand-to-gravel
 291 ratio, S_{max} (mm) is the maximum aggregate size, CEM (n.u.) is the cement

292 type, f_{cem} (MPa) is the cement strength class, t_c (days) is the initial curing
 293 period, T (K) is the ambient temperature, RH (n.u.) is the relative external
 294 humidity.

295 The input parameters, including the technological and environmental
 296 parameters (refer to definition of “technological and environmental
 297 parameters” in *Appendix*), characterized by determining the variability range
 298 and the PDF of each parameter as summarized in *Table 1*. The technological
 299 parameters are characterized by the limiting values recommended by EN 206-
 300 1 [15] for XC4 exposure class and the statistical analysis of the studies
 301 addressing the problem of concrete carbonation found in the literature. To
 302 provide the action levers, a uniform (discrete or continue) distribution is
 303 usually set for the technological parameters because they are chosen by the
 304 designer. Thus, all the values within the distribution interval are considered
 305 equally probable. The interval is determined by minimum and maximum
 306 values.

307 The environmental parameters are characterized from weather data [26],
 308 which include the ambient temperature (T) and the relative external humidity
 309 (RH). The CO_2 concentration in the atmosphere (CO_2) is taken from [25].

310 *Table 1. Input parameter characterization.*

Parameter	Unit	Probability Density Function (PDF)	Reference
Technological parameters			
Group 1: concrete mix			

X_1	C	kg/m ³	\mathcal{U} (min = 300; mean = 404.5; max = 509)	[15]
X_2	W/C	n.u.	\mathcal{U} (min = 0.4; mean = 0.45; max = 0.5)	[15]
X_3	S/G	n.u.	\mathcal{U} (min = 0.5; mean = 1.3; max = 2.1)	
X_4	S_{max}	mm	\mathcal{U} (min = 20 ; mean = 26; max = 32)	[15]
Group 2: cement				
X_5	CEM	n.u.	$d\mathcal{U}$ (10 cement types)	[15]
X_6	f_{cem}	MPa	$d\mathcal{U}$ (3 strength classes)	[15]
Group 3: concrete cover depth and initial curing period				
X_7	d	m	\mathcal{U} (min = 0.05; mean = 0.065; max = 0.08)	[31] [32]
X_8	t_c	days	\mathcal{U} (min = 1; mean = 2; max = 3)	[33]
Environmental parameters				
X_9	T	K	$tr\mathcal{N}$ (mean = 287.4; CoV = 0.03; min = 272.4; max = 309.1)	[26]
X_{10}	RH	n.u.	$tr\mathcal{N}$ (mean = 0.56; CoV = 0.33; min = 0.2; max = 0.88)	[26]
X_{11}	CO_2	ppm	$tr\mathcal{N}$ (mean = 380; CoV = 0.05; min = 304.6; max = 456.8)	[25]

Notes:

1. CoV = Coefficient of Variation; $tr\mathcal{N}$ = truncated Normal distribution; \mathcal{U} = Uniform distribution; $d\mathcal{U}$ = discrete Uniform distribution.
2. The variability range of X_1 , X_2 and X_3 parameters also comes from the statistical analysis conducted by some experimental investigations found in the literature (detailed in the text).

311 **Group 1: concrete mix**

312 The requirements for concrete of EN 206-1 [15] for XC4 exposure class are
313 a maximum water-to-cement ratio (W/C) of about 0.5, a minimum amount of

314 cement content (C) of about 300 kg/m^3 and maximum aggregate size (S_{max})
315 within the range 20-32 mm. Previous studies [4] [34] [35] [36] reveal that (i)
316 CEM I cement type concrete with a water-to-cement ratio (W/C) lower than
317 0.4 has very high carbonation resistance; and (ii) concrete using CEM I
318 cement type has higher carbonation resistance than the other cement types
319 containing additions. In this work, we thus assume the minimum W/C of
320 about 0.4 for cement types considered in order to observe the carbonation
321 phenomenon; however, the carbonation phenomenon can appear for W/C
322 values lower than 0.4 for other cement types. Moreover, concrete casted with
323 such W/C is uncommon. Based on the statistical analysis of seventeen
324 experimental investigations on concrete carbonation [37] [5] [38] [39] [40]
325 [41] [42] [43] [44] [45] [24] [46] [47] [48] [1] [49] [50], the maximum
326 cement content (C) is about 509 kg/m^3 and the sand-to-gravel ratio (S/G)
327 varies between 0.5 and 2.1.

328 **Group 2: cement**

329 In the carbonation model proposed by Ta et al. [28], the cement type (CEM)
330 is considered through the following three parameters: amount of Portland
331 clinker inside cement, amount of calcium oxide per weight of cement and
332 cement density. Therefore, among the 27 cement products presented in [51],
333 ten cement types are considered: CEM I; CEM II/A; CEM II/B; CEM III/A;
334 CEM III/B; CEM III/C; CEM IV/A; CEM IV/B; CEM V/A; and CEM V/B.
335 The characteristics of these cements are presented in *Appendix (Table A1)*.

336 Cement strength class (f_{cem}) of all these cement types is available for strength
337 classes of 32.5 MPa, 42.5 MPa and 52.5 MPa.

338 **Group 3: concrete cover depth and initial curing period**

339 The concrete cover depth (d) must have a minimum thickness to protect the
340 steel reinforcements from the CO₂ attack and to prevent the corrosion of steel
341 reinforcements [52]. This design parameter varies according to the exposure
342 class, the quality of construction and the intended service life [52].
343 Combined to the requirements for concrete of EN 206-1 [15] for XC4
344 exposure class, the minimum recommended concrete cover depth (d) ranges
345 from about 0.05 m [31] to 0.08 m [32] for structure design with an expected
346 100-year service life. Consequently, d can vary between 0.05 and 0.08 m in
347 this study.

348 Because of a limited construction time, the initial curing period (t_c) varies
349 between 1 day and 3 days [33].

350 **3.3. Quantitative analysis**

351 **3.3.1. Service life prediction and sensitivity analysis**

352 *Eq. (10)* is used to establish the relationship between the service life (t_{ser})
353 and the input parameters X_j presented in *Table 1*. In Sobol' method, the t_{ser}
354 values are simulated using *Eq. (10)* by varying all input parameters
355 simultaneously according to their PDF (*Table 1*).

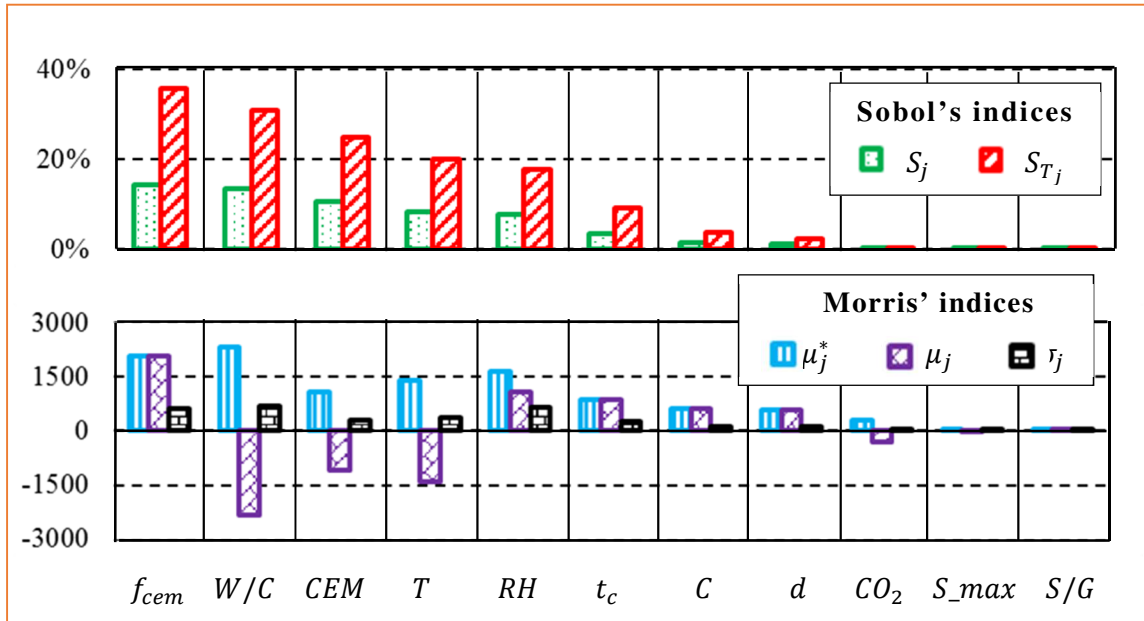
356 The first order Sobol sensitivity index (S_j) (Eq. (1)) and the total Sobol
357 sensitivity index (S_{T_j}) (Eq. (2)) are calculated as described in Section 2.3.
358 They are calculated by means of a bootstrap method with 500 replications
359 from a half-sample (5,000) taken from an initial sample of about 10,000 as
360 recommended in [18].

361 In Morris' method, the t_{ser} values are simulated using Eq. (10) by varying
362 each input parameter one at a time. Then the mean value (μ_j) (Eq. (4)),
363 standard deviation value (σ_j) (Eq. (5)) and mean value of the absolute value
364 (μ_j^*) (Eq. (6)) of the elementary effects are calculated as described in Section
365 2.3. They are calculated by means of discretization of the input parameters
366 X_j in 10 values with a prescribed number of trajectories of about 30 as
367 recommended in [18].

368 **3.3.2. Determination of the action levers**

369 Our results shown in *Figure 4* are related to the case study. It is important
370 to note that SA results depend on both PDF of input parameters given in
371 *Table 1* and on carbonation model chosen.

372 *Figure 4* displays the SA results.



373

374

Figure 4. Sobol and Morris sensitivity indices.

375

Figure 4 shows that cement strength class (f_{cem}), water-to-cement ratio

376

(W/C), cement type (CEM), ambient temperature (T) and relative external

377

humidity (RH) (in descending rank) are the most influential parameters

378

because their S_{T_j} and μ_j^* values are the highest. The difference $S_{T_j} - S_j$ is

379

around 22% for cement strength class (f_{cem}), 17% for water-to-cement ratio

380

(W/C), 14% for cement type (CEM), 12% for ambient temperature (T) and

381

10% for relative external humidity (RH). This means that their interactions

382

with the other parameters are important. Parameters f_{cem} , W/C and CEM are

383

considered the most influent with a S_j value above 10%. They are thus

384

technological parameters (i.e., controllable parameters) identified as action

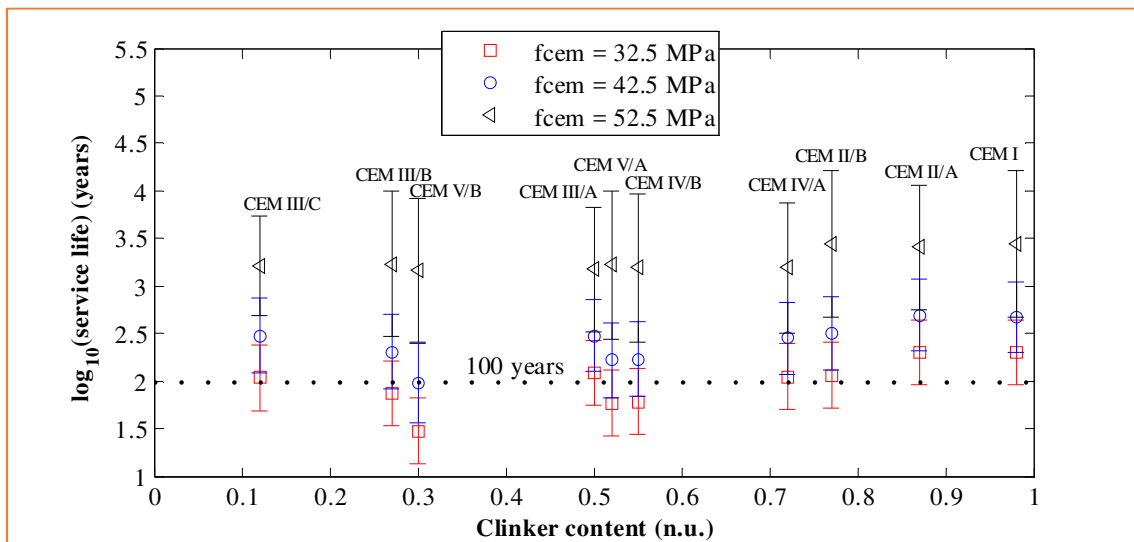
385

levers. T and RH are environmental parameters (uncontrollable parameters)

386

that are uncertain. The less-influential parameters ($S_{T_j} < 10\%$ and low μ_j^*) are

387 initial curing period (t_c), cement content (C), concrete cover depth (d), CO_2
388 concentration in the air (CO_2), maximum aggregate size (S_{max}) and sand-to-
389 gravel ratio (S/G). Based on the algebraic sign of μ_j , we observe that an
390 increase in RH , C , d , t_c , and S/G and a decrease in W/C , S_{max} , T , and CO_2
391 result in the increase of t_{ser} . All parameters have σ_j/μ_j^* within the interval
392 $[0.19 - 0.39]$. It indicates that the effects between parameter are monotonic.
393 Because f_{cem} and CEM are discrete parameters, their algebraic sign of μ_j is
394 not significant. Finding favorable value requires testing all of the values of
395 f_{cem} and CEM . The simulation results are displayed in *Figure 5*. We plot the
396 service life on log scale versus clinker content. The service life is represented
397 by its mean value and standard deviation.



398

399 *Figure 5. Comparison of service lives of cement strength classes and*
400 *cement types.*

401 The highest service life is obtained with cement strength class (f_{cem}) 52.5
402 MPa, followed by 42.5 MPa and 32.5 MPa. The CEM I and CEM II/B cement
403 types are the most favorable to increase the service life with f_{cem} 52.5 MPa.
404 The CEM II/B has lower environmental impacts. These findings are in line
405 with previous study [38]. For both f_{cem} 42.5 and 52.5 MPa we found that
406 service life is higher than 100 years whatever the cement type. However,
407 none of the service lives considering standard deviation obtained with f_{cem}
408 32.5 MPa is higher than 100 years.

409 **3.3.3. Comparison of the sensitivity analysis results to the** 410 **literature**

411 This section compares our SA results with the literature. Cement strength
412 class (f_{cem}) and water-to-cement ratio (W/C), two technological parameters,
413 are key parameters for the determination of the concrete porosity and the 28-
414 day compressive strength of concrete (f_c) [9] [53]. Both values, indeed, are
415 important indicators of the evaluation of the resistance to penetration of
416 carbon dioxide into concrete [54]. Higher cement strength class (f_{cem}) and a
417 decrease in water-to-cement ratio (W/C) result in an increase of f_c . For a
418 given water-to-cement ratio (W/C), it has been shown that service life (t_{ser})
419 increases by 1.89 times when using a CEM II/B cement with a cement
420 strength class (f_{cem}) value about of 42.5 MPa instead of 32.5 MPa [55].
421 Furthermore, the service life (t_{ser}) increases by 2.49 times when using a
422 water-to-cement ratio (W/C) of about 0.4 instead of 0.43, according to the

423 literature [56]. Previous experimental results [55] [56] have confirmed that
424 service life (t_{ser}) is more sensitive to cement strength class (f_{cem}) and water-
425 to-cement ratio (W/C). In addition, a survey of the literature also reveals that
426 the carbonation resistance of concrete depends on the amount of Portland
427 clinker cement in concrete [57]. When using a cement preparation containing
428 more Portland clinker for concrete composition, first, the 28-day
429 compressive strength of concrete (f_c) is higher and the amount of $Ca(OH)_2$
430 and CSH increases [58]. Both observations increase concrete carbonation
431 resistance. Finally, the other technological parameters considered here
432 demonstrate a negligible contribution to the variations of service life (t_{ser}).
433 An increase in cement content (C), obviously causes the presence of higher
434 amounts of Calcium hydroxide ($Ca(OH)_2$) and Calcium-Silicate-Hydrate
435 (CSH) inside the concrete, which lengthens the time of the neutralization
436 reaction between $Ca(OH)_2$ and CSH and CO_2 . The carbonation resistance is
437 thus higher. An increase in maximum aggregate size (S_{max}) generates a
438 decrease in the carbonation resistance. The use of a bigger aggregate size,
439 indeed, induces (i) a reduction in the tortuosity of the flow path, which
440 increases permeability, and (ii) a possibility of internal water bleeding,
441 which increases concrete porosity [59]. As regards the initial curing period
442 (t_c), many previous studies [56] [60] [41] have underlined that the longer the
443 curing period is, the higher the resistance of concrete to carbonation is. An
444 increase in t_c provides a higher degree of hydration and a lower concrete
445 porosity. As regards the concrete cover depth (d), it is widely accepted that
446 service life (t_{ser}) is proportional to the square of concrete cover depth (d) as

447 shown in *Eq. (8)*. An increase in sand-to-gravel ratio (S/G) in one cubic meter
448 of concrete mixed increases sand content, which is responsible for the
449 reduction in air permeability. There also, the carbonation resistance is
450 increased [59].

451 As regards the environmental parameters, previous experimental results
452 [23] [24] have shown that the highest carbonation rate is observed for a
453 relative external humidity (RH) around 57%. We observe that the carbonation
454 rate increases when relative external humidity (RH) increases from 0% to
455 57%, and decreases when relative external humidity (RH) increases from 57%
456 to 100%. This is consistent and corresponds to the highest σ_j/μ_j^* of relative
457 external humidity (RH) (*Figure 4*) that is highlighted by the present
458 sensitivity analysis results. The carbonation rate also increases with
459 increasing ambient temperature (T) due to increased molecular activity [61]
460 [62]. Finally, the carbonation depth is proportional to the square root of
461 carbon dioxide concentration in the air (CO_2) (*Eq. (7)*). The presence of
462 carbon dioxide is necessary for the carbonation of concrete. However,
463 relative external humidity (RH) and ambient temperature (T) play the most
464 important part in the carbonation rate within all the environmental
465 parameters.

466 The influence trend of parameters is consistent with the literature. The
467 important influence of parameters corresponding to their range variation
468 studied corroborates with previous experimental studies.

469 **3.4. Final design**

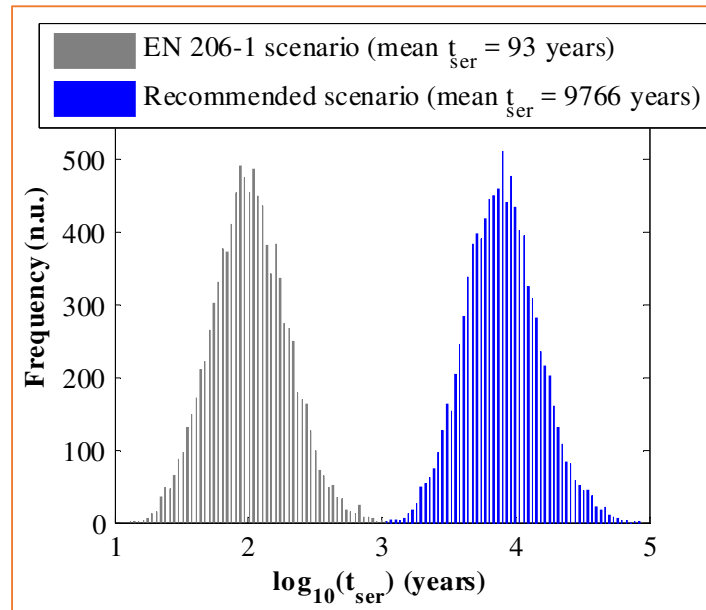
470 Based on the SA results, the action levers of the case study are cement
471 strength class (f_{cem}), water-to-cement ratio (W/C) and cement type (CEM).
472 The final design is carried out by setting the action lever at their most
473 favorable value to increase the service life (t_{ser}) (*Table 2*). As found
474 previously, the most favorable values of the three action levers consist of
475 minimum W/C (about 0.4), higher f_{cem} 52.5 MPa and CEM I or CEM II/B
476 cement type (*Figure 5*). The other parameters are randomly generated
477 according to their PDF presented in *Table 1*. This scenario is called
478 *recommended scenario*.

479 A reference scenario, called *EN 206-1 scenario*, is also developed by setting
480 the action levers at the limiting values recommended by EN 206-1 [15], i.e.,
481 W/C equal to 0.5, f_{cem} 32.5 MPa and CEM I cement type (*Table 2*). The other
482 parameters are randomly generated according to their PDF as with the
483 *recommended scenario*.

484 We compare the distribution of t_{ser} of *EN 206-1 scenario* and *recommended*
485 *scenario* with CEM I cement type in *Figure 6*. The *recommended scenario*
486 with CEM II/B cement type is not illustrated in *Figure 6* as its t_{ser}
487 distribution is very close to that of CEM I cement type. The mean t_{ser} of
488 *recommended scenario* with CEM II/B cement type is of about 9,253 years.
489 The distribution of t_{ser} is simulated using a Monte Carlo simulation with a
490 sample size of 100,000.

491 *Table 2. Values of action levers for both designed scenarios.*

Parameter	Symbol	Unit	Recommended scenario	EN 206-1 scenario
Water-to-cement ratio	W/C	n.u.	0.4	0.5
Cement strength class	f_{cem}	MPa	52.5	32.5
Cement type	CEM	n.u.	CEM I	CEM I



492

493 *Figure 6. Comparison between service life (t_{ser}) distributions of both*
 494 *designed scenarios.*

495 As shown in *Figure 6*, the t_{ser} of the *recommended scenario* is 105 times
 496 higher than that of the *EN 206-1 scenario*. Both distributions of probabilities
 497 are completely separated. The calculated differences are significant. The
 498 simulation results confirmed f_{cem} , W/C as being effective action levers. The
 499 *recommended scenario* corresponds to concrete with higher carbonation
 500 resistance. We consider the high concrete cover depth (d) between 0.05 m
 501 and 0.08 m, that is another reason for finding the mean service life of the

502 *recommended scenario* of about 9,766 years. This finding corroborates with
503 previously experimental results [4] [34] [35] [36]. For example, Houst et al.
504 [34] reveal that more than five years of exposure to the atmosphere of CO₂,
505 concrete with $W/C = 0.3$ is carbonated only to a depth of 0.2 to 0.3 mm.
506 Another study on ultra-high performance fiber-reinforced concrete (porosity
507 about 5%) [63] shows that the t_{ser} is more than 12,000 years. One can assume
508 that this higher t_{ser} is not only due to the individual influence of action levers
509 but also to the non-negligible interactions between the action levers and other
510 parameters (revealed previously through the differences $S_{T_j} - S_j \geq 10\%$).

511 The simulation results of the *recommended scenario* reveal that a durable
512 RC structure can be obtained by setting the action levers at their most
513 favorable values. The durable RC structure is independent on the values of
514 the other technological parameters, which are simulated randomly within
515 their variability range given in *Table 1*. In short, if the RC structure is
516 designed using the *recommended scenario*, the risk for corrosion of
517 reinforcing steels due to carbonation is eliminated throughout the 100-year
518 service life design. In addition, concretes with f_{cem} 52.5MPa and with W/C
519 of about 0.4 are appropriate for the other cement types (*Figure 5*). On the
520 contrary, if the RC structure is designed by setting the action levers at their
521 limiting values as recommended by EN 206-1 [15], a maintenance system
522 could be established in order to ensure the intended 100-year service life.

523 **3.5. Advantages and limits of the design approach**

524 In this particular case, the cement content (C) does not individually
525 contribute to service life (with S_j around 1%), i.e., the service life (t_{ser}) is
526 independent of cement content (C) for a given water-to-cement ratio (W/C).
527 A previous study has revealed that the carbonation of concrete is independent
528 of cement content (C) (from 221 to 450 kg/m³) for a given water-to-cement
529 ratio (W/C) [64]. The present finding, achieved in association with the
530 literature, raises the problem of attempting to impose a minimum cement
531 content (C) of 300 kg/m³ for XC4 exposure class in EN 206-1 [15]. The model
532 developed does not consider that a high cement content (C) may enhance the
533 risk of cracking because of the heat of hydration or the drying shrinkage in
534 the concrete cover. Both can result in a poor carbonation resistance of the
535 concrete cover. Furthermore, from the point of view of the environmental
536 impacts of the concrete, cement, among other constituents of concrete, is
537 mainly responsible for the release of a huge amount of CO₂ during the
538 production [65]. Consequently, in the case of an XC4 exposure class, the
539 requirement for the minimum C in EN 206-1 [15] should be re-examined
540 whereas a maximum limit of C within the mix should also be specified.

541 Our approach is a helpful tool in the life cycle design for the durability of
542 RC structures. Our approach aims identifying action levers for increasing
543 service life. Engineering designers easily increase the service life by
544 focusing on effective action levers.

545 Results of our case study are related both to the carbonation model chosen
546 and to PDF of input parameters. If we use another range variability of input
547 parameters, our results would be changed [66]. However, our approach is
548 general and can be adapted to various service life models.

549 In this study, carbonation is the only alteration phenomenon of RC structure
550 that is considered. However, concrete carbonation can be coupled with other
551 severe deteriorations leading to accelerate its degradation, e.g., the presence
552 of a small amount of chlorides significantly increases the corrosion risk in
553 carbonated mortars [67]. In that situation, the combined effects of various
554 alteration mechanisms integrated in service life model.

555 Finally, this study focuses on individual input parameters that are action
556 levers on the improvement of service life of RC structures. However,
557 interactions between two or more input parameters were shown to be also
558 influential on service life prediction and merit further investigations.

559 **4. Summary and conclusion**

560 The present study was conducted to develop a new design procedure for the
561 durability of RC structures through resistance to carbonation induced
562 corrosion. This innovative approach consists in combining the techniques of
563 the prescriptive and performance-based approaches and in integrating the
564 sensitivity analysis of service life in the design stage. The durability design
565 phase has focused on the most influential parameters with a view to setting

566 them at their most favorable value. With suitable calculation tools, this
567 proposed procedure will be easy to use by designers.

568 Through the case study presented here, we found that cement strength class
569 (f_{cem}), water-to-cement ratio (W/C) and cement type (CEM) are action levers.
570 Design engineers may take these action levers carefully into account during
571 the durability design step of concrete exposed to carbonation. When setting
572 the action levers at their most favorable values instead of their limiting
573 values as recommended by EN 206-1, the service life is significantly
574 improved. The requirement for minimum cement content (C) in EN 206-1 for
575 XC4 exposure class should be re-examined in order to reduce concrete costs
576 and environmental impacts. The most influential parameters, including W/C ,
577 f_{cem} , CEM , ambient temperature (T) and relative external humidity (RH),
578 should therefore be carefully considered in future research works conducted
579 to address the problem of carbonation-induced corrosion damage modeling
580 in RC structures.

581 More research work needs to be carried out to investigate the interaction
582 influences between the parameters. For instance, in the case study presented,
583 the identified action levers have strong interactions with the other
584 parameters. These interactions, however, have not been examined here. The
585 results of studies addressing the problem of interactions between parameters
586 could additionally enhance the durability of RC structures. We are confident
587 that this finding will serve as a basis for future theoretical and experimental
588 works.

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802

803 **Appendix: Definitions**

804 **Durability** is the ability to maintain the serviceability of a structure over a
805 specified length of time, or a characteristic of the structure to function for a
806 given period with required safety and corresponding characteristics
807 providing serviceability [68].

808 **Durability design** makes sure that service life design can be completed in
809 the actual local exposure conditions during the design stage.

810 **Service life design** is the service life that the designer intends for the
811 structures undergoing expected aggressions and service maintenance
812 according to a prescribed maintenance management strategy.

813 **Service life** is the period after construction, during which all the structure
814 properties, when routinely maintained, are higher than the minimum
815 acceptable values [2].

816 **Technological parameters** are controllable parameters (i.e. action
817 possibilities). They are related to the technological aspects (e.g., concrete
818 mix, size of structure).

819 **Environmental parameters** are uncontrollable parameters. They are
820 related to the environmental open-air location (e.g., aggressive agent sources
821 like CO₂ concentration, chlorides, ambient temperature, and relative
822 humidity).

823 **Action levers** are the technological parameter, which are major contributors
824 to the sensitive service life. They are determined by carrying out a sensitivity
825 analysis of the service life prediction model.

826 *Table A1. Cement type characterization.*

Cement type	Clinker (n.u.)	CaO (n.u.)	Cement density (kg/m³)
CEM I	0.98	0.64	3110

CEM II/A	0.87	0.62	3000
CEM II/B	0.72	0.46	3005
CEM III/A	0.5	0.53	2880
CEM III/B	0.27	0.48	2850
CEM III/C	0.12	0.46	2750
CEM IV/A	0.77	0.38	2980
CEM IV/B	0.55	0.31	2890
CEM V/A	0.52	0.47	2870
CEM V/B	0.3	0.47	2870

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