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Méthode innovante pour la conception environnementale et durable de structures en béton armé soumises à la carbonatation

JURY

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LIST OF PUBLICATIONS

This doctoral thesis present the research that the author has carried out in the past 3 years. This research is based on the work presented in the following five publications:

Paper I: **V.-L. Ta**, S. Bonnet, T. Senga Kiesse, and A. Ventura, “A new meta-model to calculate carbonation front depth within concrete structures.” Published by the journal of Construction and Building Materials, vol. 129, pp. 172-181, 2016.

Paper II: **V.-L. Ta**, S. Bonnet, A. Ventura, T. Senga Kiesse, “Application of sensitivity analysis in the life cycle design for the durability of reinforced concrete structures in the case of XC4 exposure class.” Accepted for publication to the journal of Cement and Concrete Composites, Nov. 2017.

Paper III: **V.-L. Ta**, A. Ventura, T. Senga Kiesse, S. Bonnet, “A new design approach for the sustainability of reinforced concrete structures in aggressive environments: case study of carbonation induced corrosion.” Submitted to the journal of industrial Ecology, August 2017.

Paper IV: **V.-L. Ta**, S. Bonnet, A. Ventura, T. Senga Kiesse, “Carbonation of paint coated concrete and sensitivity analysis of carbonation rate model.” Manuscript.

Paper V: **V.-L. Ta**, A. Ventura, S. Bonnet, T. Senga Kiesse, "Environmental impacts of concrete surface preparation: assessment and optimization." Manuscript.

The first author was responsible for model development and writing. All the authors had participated in planning the paper and contributed in the revision.

Besides, the author has also presented in various scientific conferences:

V.-L. Ta, S. Bonnet, T. Senga Kiesse, A. Ventura, « Sensitivity analysis for prediction of corrosion initiation by carbonation » in Proceedings of the International RILEM, PRO. 109, vol. 2, 2016.

V.-L. Ta, A. Ventura, S. Bonnet, T. Senga Kiesse, « Modélisation pour la conception durable des structures en béton armé de classe d'exposition XC4. » 35èmes Rencontres de l'AUGC, ECN/UN, Nantes, France, 2017.

V.-L. Ta, A. Ventura, S. Bonnet, T. Senga Kiesse, « A novel methodological approach towards the sustainable life cycle design of reinforced concrete structures exposed to aggressive environments. » ISIE-ISSST 2017, Chicago Illinois, USA, 2017.

RESUME ETENDU

Selon la Commission mondiale sur l'environnement et le développement des Nations Unies [1]: « le développement durable est un développement qui répond aux besoins du présent sans compromettre la capacité des générations futures de répondre aux leurs ». Or, certaines régions géographiques arrivent au bout des ressources de calcaire, tandis que les grandes régions métropolitaines arrivent au bout des ressources de granulats [2]. Ainsi chaque année, trois milliards de tonnes des matières premières sont utilisées pour fabriquer des produits et des composants de construction dans le monde entier. Celles-ci correspondent à 40 à 50% du flux total de matériaux totaux dans l'économie mondiale [3]. Ces consommations s'accompagnent également de rejets dans l'environnement. Aux Etats-Unis, la production de 76 millions de tonnes de béton génère 9.8 millions de tonnes de CO_2 [3]. Les émissions de CO_2 de la production du ciment représentent actuellement entre 5% et 7% des émissions mondiales de CO_2 anthropique [4]. Ces chiffres rappellent qu'une conception des structures en béton respectueuse des enjeux environnementaux impose une nouvelle façon de penser dans laquelle les constructions actuelles sont conçues pour diminuer leurs impacts environnementaux [5], en prenant en compte leur cycle de vie, et notamment la phase d'usage. L'Analyse de Cycle de Vie (ACV) est la méthode adaptée pour cette démarche car elle consiste en une compilation et une évaluation des consommations d'énergie, de l'utilisation de matières premières et de leur rejet dans l'environnement, et une évaluation de l'impact potentiel sur l'environnement associé à un produit, ou un procédé, ou un service, sur la totalité de son cycle de vie [6]. Ce travail de thèse propose donc d'élaborer un modèle de durée de vie des structures en béton dans un environnement agressif. Ce modèle est ensuite utilisé pour concevoir des structures dont les impacts environnementaux sont évalués par ACV sur la phase de construction, d'entretien et de réparation [7].

Ainsi les questions traitées dans ce travail de thèse sont les suivantes :

1. Comment peut-on intégrer des modèles de durée de vie et de stratégie de maintenance dans l'Analyse de Cycle de Vie (ACV) afin d'évaluer les impacts environnementaux des structures en béton ?

2. Comment peut-on déterminer les leviers d'action augmentant la durée de vie et réduisant les impacts environnementaux des structures en béton ?

Pour identifier les leviers d'action, nous utilisons plusieurs méthodes d'analyse de sensibilité qui, appliquées au modèle, permettent de quantifier la part de variabilité induite par les différents paramètres du modèle sur la variabilité des sorties d'un modèle [8] qui sont, dans notre cas, la durée de vie et les impacts environnementaux. Les paramètres des modèles sont classés en deux catégories :

- **Les paramètres technologiques :** ils sont contrôlables par l'ingénieur concepteur (ex : choix de matériaux, formulations, techniques de mise en œuvre …), et ils sont les leviers d'action potentiels.
- **Les paramètres environnementaux :** ils ne sont pas contrôlables et dépendent des conditions environnantes (ex : la concentration d'agents agressifs comme le CO_2, la température, l'humidité …).

Nous définissons les **leviers d'action** comme étant des paramètres technologiques qui ont une contribution importante sur la variation de la durée de vie et/ou des impacts environnementaux de la structure en béton étudiée. Identifier un levier d’action requiert de quantifier son influence individuelle, et si besoin en interaction avec d’autres paramètres, ainsi que de caractériser ses valeurs les plus favorables dans l’objectif de maximiser la durée de vie et/ou de minimiser les impacts environnementaux.

La Figure 1 représente notre méthode pour la conception environnementale et durable de structures en béton armé.

Le diagramme décisionnel (n°1 Figure 1) décrit l’ensemble des choix possibles et leurs relations, aux mains des ingénieurs concepteurs. Ils concernent les dimensions de la structure, les choix des matériaux (pour la construction initiale et les opérations de maintenance) ainsi que les techniques de maintenance.

Le modèle de la durée de vie (n°2 Figure 1) permet de calculer la durée de vie en fonction des types de matériaux, des aspects technologiques ainsi que des conditions environnantes locales. Il permet également de prédire les interventions de maintenance tout au long de la durée de vie prévue.

Nous utilisons le modèle d’ACV (n°3 Figure 1) pour estimer des indicateurs environnementaux des processus de construction et de maintenance, en fonction des choix du diagramme décisionnel pendant la phase de conception.

La durée de vie et les indicateurs environnementaux sont testés par des techniques d’analyse de sensibilité (n°4 Figure 1), afin d’identifier les leviers d’action augmentant la durée de vie et réduisant les impacts environnementaux. En ce qui concerne les informations sur la contribution de la variation des leviers d’action, nous avons calculé des indices de Sobol évaluant leur influence individuelle et leur influence totale qui inclut l’influence en interaction. Nous avons également calculé des indices de

Morris : (i) la valeur moyenne des effets élémentaires qui indique le sens de l'influence de ces leviers ; et (ii) la valeur moyenne des valeurs absolues et l'écart-type des effets élémentaires pour identifier le type d'effets : linéaire ou non-linéaire, monotone ou non-monotone.

Enfin, la démarche se termine par une étape d'optimisation multicritère en combinant tous les leviers d'action possibles. Cela permet de concevoir la structure dont la durée de vie est maximale et les impacts environnementaux sont minimaux (n°5 Figure 1).

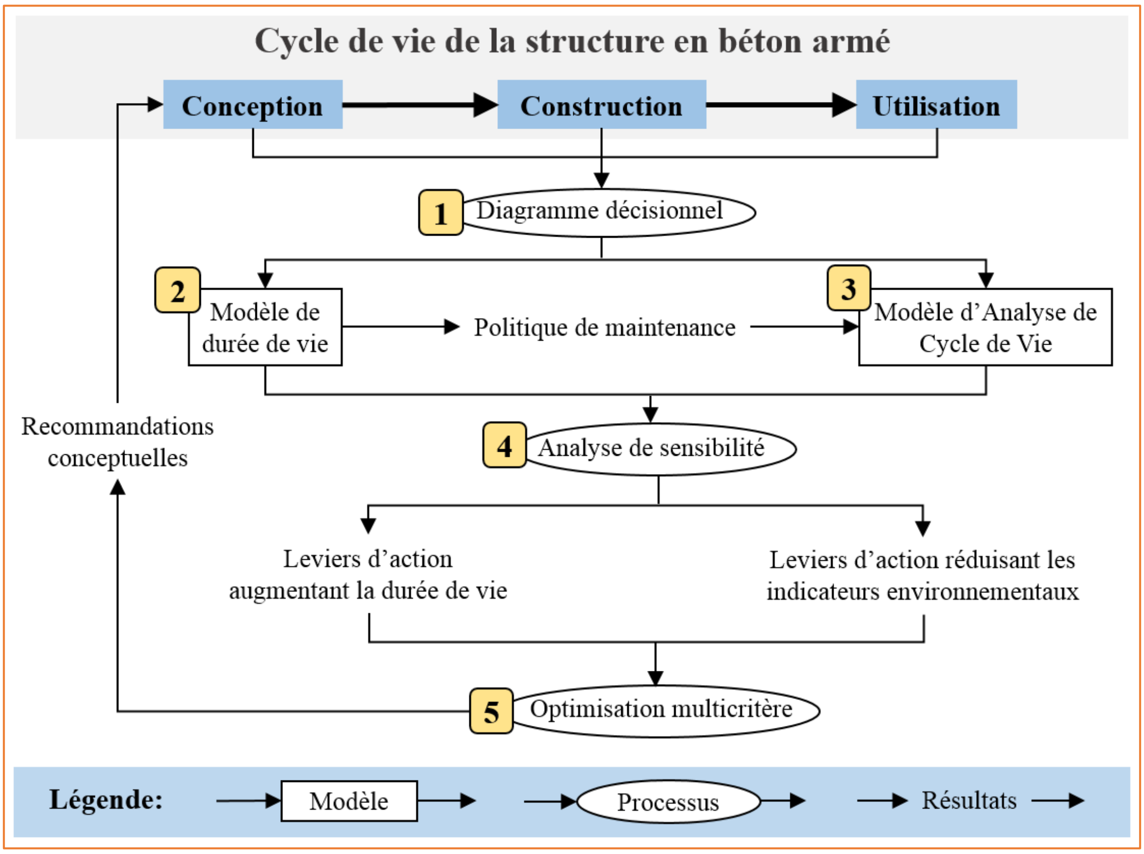

Figure 1. Méthode pour la conception environnementale et durable.

La démarche est appliquée au cas d'étude d'une structure en béton armé située à Madrid et soumise à la carbonatation pour une durée de vie prévue de 100 ans. A Madrid l'humidité relative extérieure d'environ 0,56 [9] est favorable à la carbonatation du béton. Suivant les recommandations de la norme EN 206-1 nous nous plaçons dans la classe d'exposition XC4 [10].

La suite du texte détaille les parties méthodologiques et les résultats selon les étapes indiquées dans la Figure 1.

Etape 1 – Diagramme décisionnel : ce modèle comprend des choix sur les matériaux et techniques utilisés pour la construction, ainsi que sur la politique d'entretien pour une durée de service de 100 ans.

Nous considérons deux alternatives de structures en béton armé : (i) celles pour lesquelles aucune opération d'entretien n'est nécessaire ; et (ii) celles pour lesquelles une politique d'entretien est nécessaire durant la durée de vie prévue. Nous considérons un diagramme décisionnel avec 30 scénarios de béton d'enrobage qui résultent des combinaisons entre 3 classes de résistance associées à dix types de ciment. Nous avons identifié deux cas pour le choix du ciment qui est un paramètre technologique : (i) les classes de résistance de 42,5 et 52,5 MPa, aucune opération d'entretien n'est nécessaire car la durée d'initiation de la corrosion est largement supérieure à 100 ans, et (ii) la classe de résistance de 32,5 MPa où différentes politiques d'entretien doivent être comparées car la durée d'initiation de la corrosion est inférieure à 100 ans.

Dans la première alternative, le diagramme décisionnel peut être réduit au choix de dix types de ciment pour chaque classe de résistance (Figure 2).

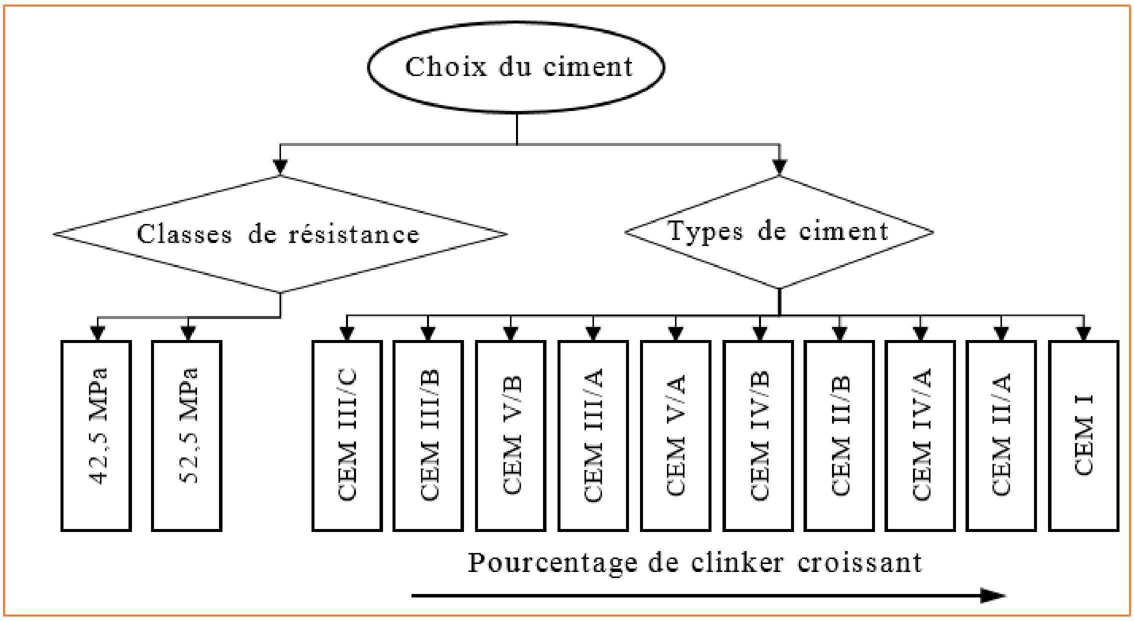

Figure 2. Diagramme décisionnel dans le cas des classes de résistance du ciment de 42,5 MPa et 52,5 MPa.

Tandis que dans la deuxième alternative, pour la classe de résistance du ciment de 32,5 MPa, le diagramme décisionnel de la politique de maintenance est ajouté (Figure 3).

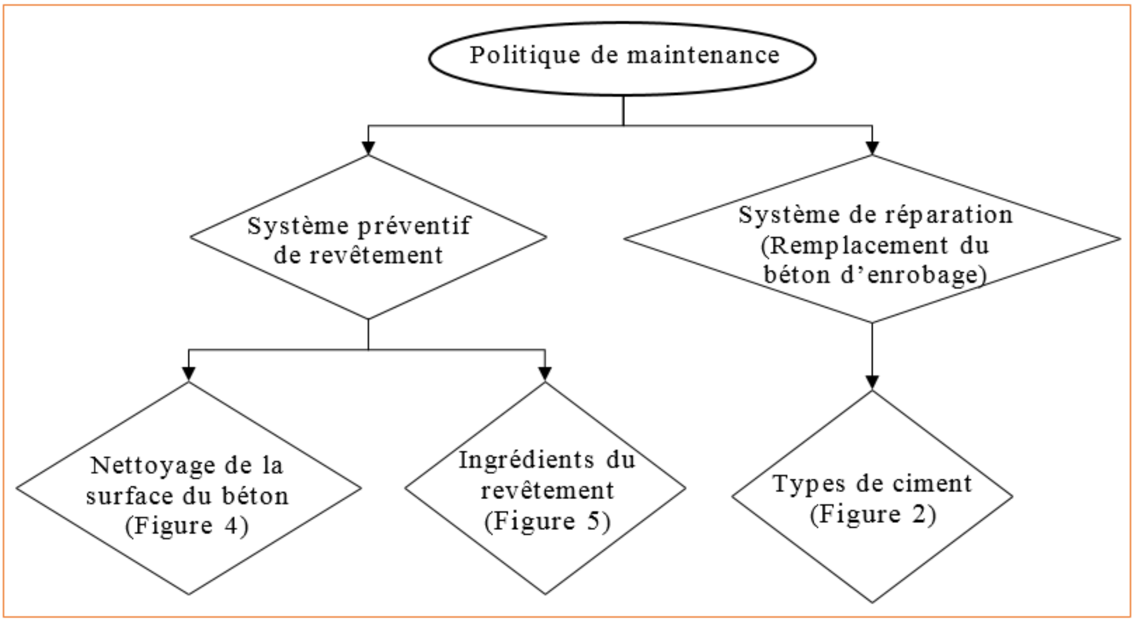

Figure 3. Diagramme décisionnel dans le cas de la classe de résistance 32,5 MPa.

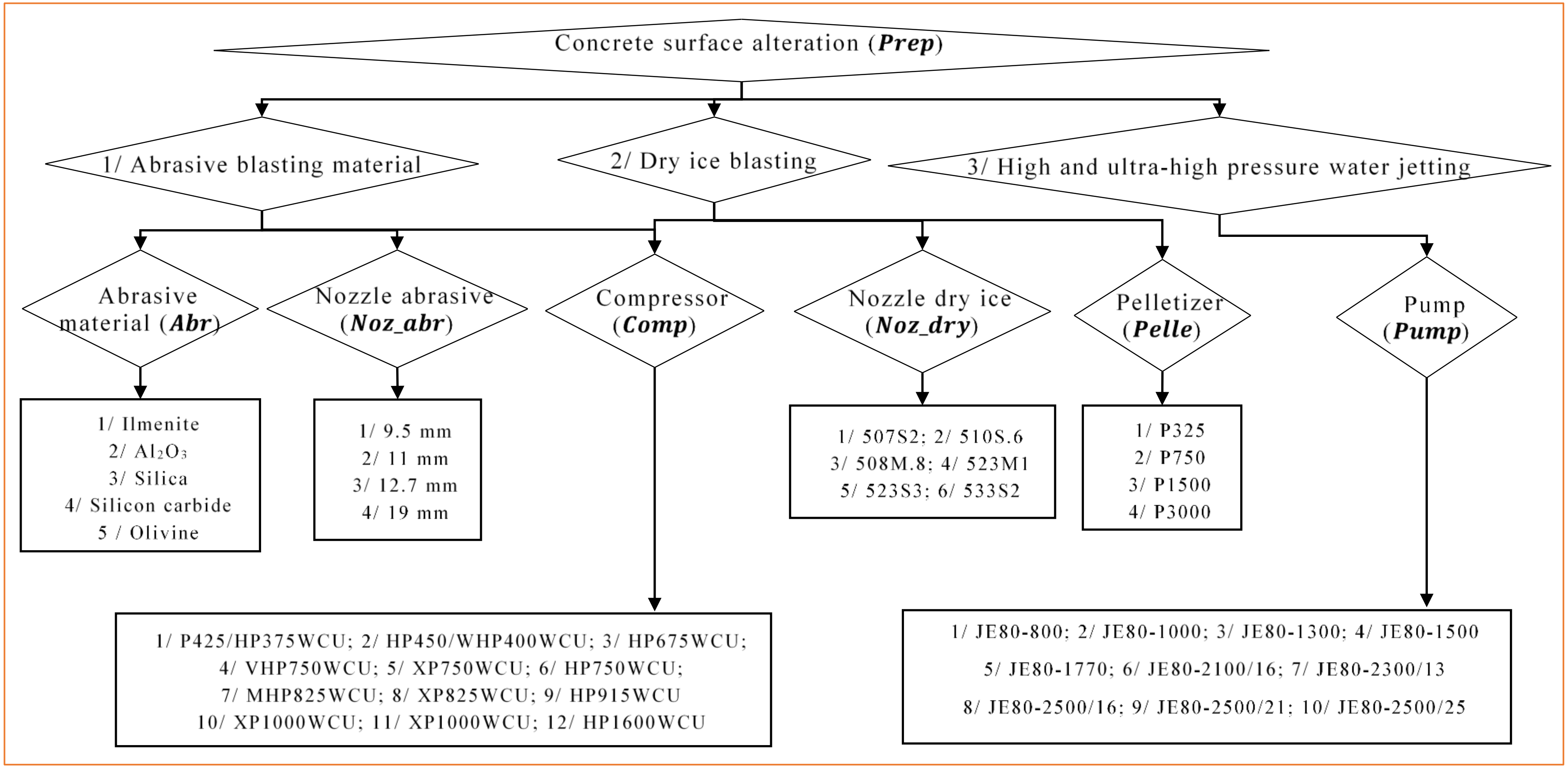

Figure 4. Diagramme décisionnel pour le nettoyage de la surface du béton.

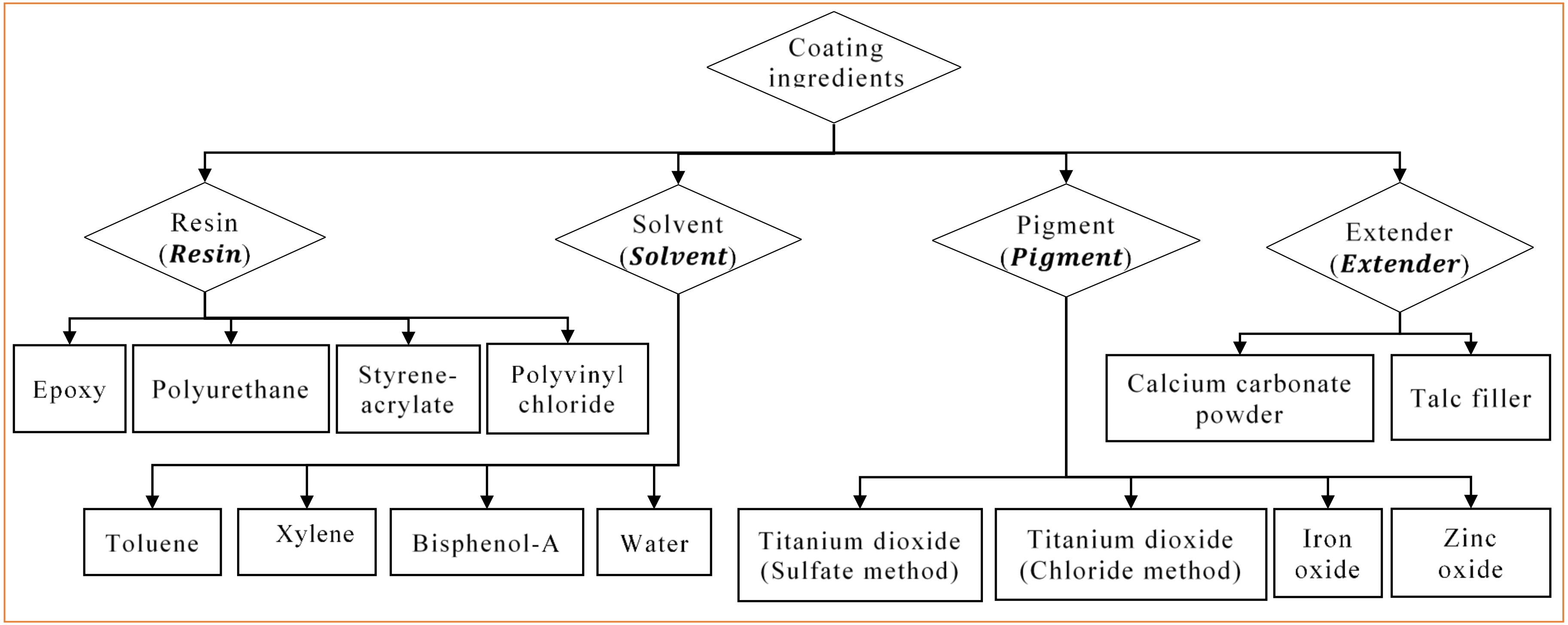

Figure 5. Diagramme décisionnel pour les ingrédients du revêtement.

Etape 2 – Modèle de durée de vie : nous avons développé un nouveau méta-modèle pour calculer la profondeur de carbonatation naturelle dans le béton. Ce méta-modèle considère un maximum de paramètres technologiques et environnementaux influençant la profondeur de carbonatation naturelle. Ce méta-model peut être utilisé par des ingénieurs. Il est basé sur la solution analytique de la première loi de Fick, en s'appuyant sur des modèles existants dans la littérature et en intégrant de nouvelles équations. Notre méta-modèle est validé avec des résultats de la littérature pour des cas de carbonatation naturelle à court et long termes (de 21 jours à 35 ans), trois types de ciment (CEM I, CEM II et CEM III), un rapport eau sur ciment allant de 0,45 à 0,8, le possible remplacement du ciment CEM I par des cendres volantes, une période de cure de 1 jour à 28 jours et différentes conditions environnementales.

Etape 3 – Modèle d'Analyse de Cycle de Vie : nous développons le modèle d'Analyse de Cycle de Vie (ACV) pour estimer les impacts environnementaux d'une structure en béton. Ce modèle est basé sur une unité fonctionnelle correspondant à 1 m^2 de surface d'enrobage en béton sur une durée de service de 100 ans. Le système considéré comprend la fabrication du béton et le transport du béton au site (Figure 6). La fin de vie des matériaux n'est pas prise en compte. Le processus de fabrication du béton provient de la base de données ecoinvent 3.3 [11]. Les indicateurs environnementaux sont calculés selon la gamme recommandée par ILCD [12].

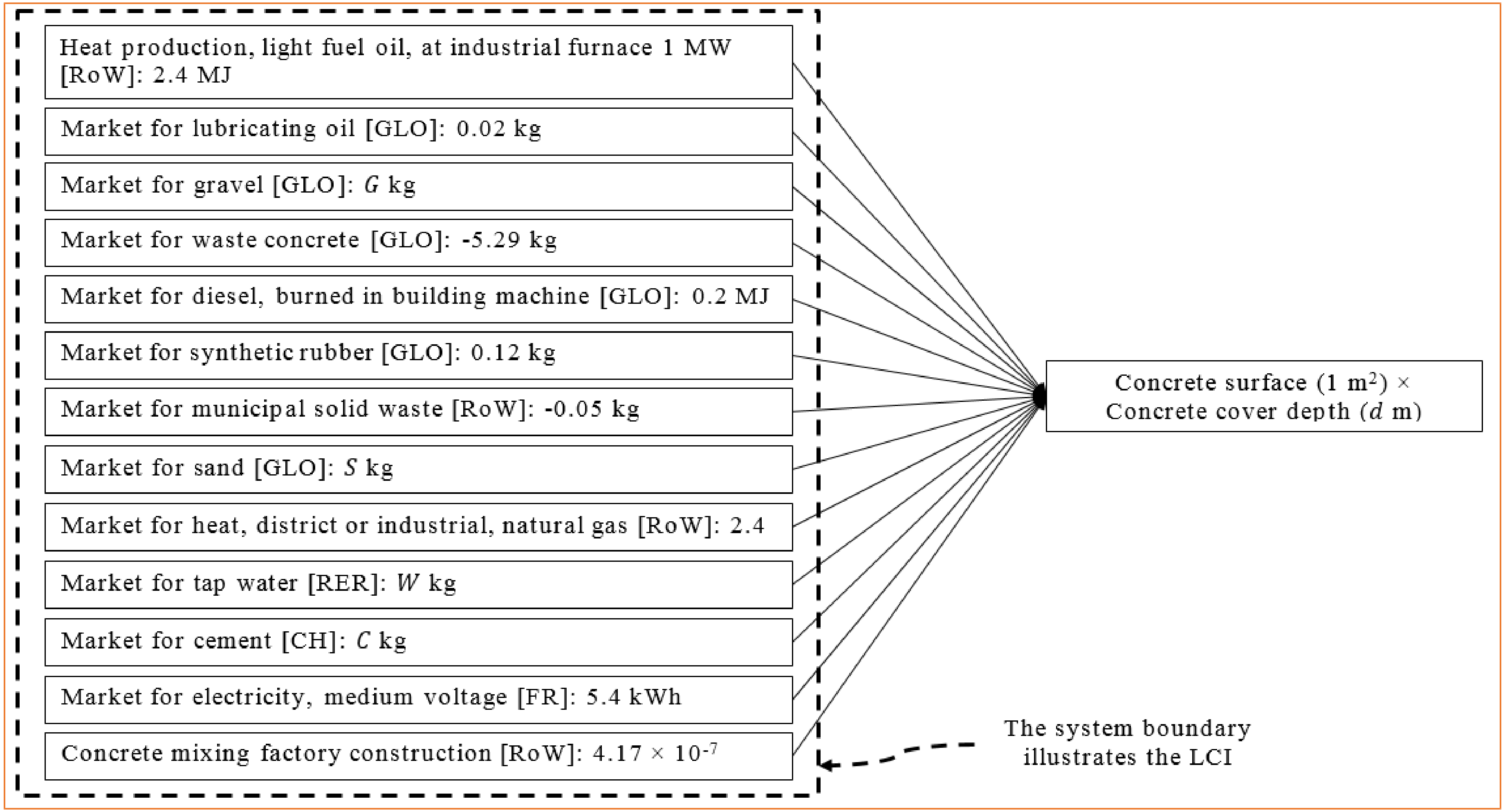

Figure 6. Système d'ACV de la fabrication du béton.

Etape 4 – Analyse de sensibilité

Identification des leviers d'action augmentant la durée de vie : la durée de vie correspond à la durée nécessaire au front de carbonatation pour atteindre l'armature. Afin de déterminer les leviers d'action pour les vingt scénarios décrits (Figure 2), les méthodes d'analyse de sensibilité ont été appliquées sur le méta-modèle de carbonatation. Nous avons trouvé que les leviers d'action sont le rapport eau sur ciment et, la teneur en ciment. En baissant le rapport eau sur ciment et augmentant la teneur en ciment, la durée de vie augmente. Parmi les paramètres environnementaux, l'humidité relative extérieure et la température ambiante ont la plus grande contribution sur la variabilité de la durée de vie et sont donc susceptibles d'introduire une incertitude importante.

Identification des leviers d'action réduisant les indicateurs environnementaux : nous avons effectué l'analyse de sensibilité des résultats issus des modèles d'ACV (indicateurs environnementaux), afin de déterminer les leviers d'action réduisant les indicateurs environnementaux. Dans le cas des classes de résistance de 42,5 et 52,5 MPa, pour lesquelles aucune opération d'entretien n'est nécessaire car la durée d'initiation de la corrosion est largement supérieur à 100 ans, nos résultats d'analyse de sensibilité montrent qu'une baisse de la teneur en ciment, de l'épaisseur du béton d'enrobage et de la distance de transport des bétons diminue l'ensemble des impacts environnementaux. La classe de résistance n'a aucun effet sur les impacts environnementaux.

Enfin, nous avons identifié que le ciment CEM III/C est celui qui obtient les plus faibles impacts environnementaux. Cependant, une analyse plus fine montre que les impacts environnementaux sont en fait liés quasi-linéairement avec le taux de clinker présent dans le ciment, et que le type d'additifs n'a pas d'influence significative.

Etape 5 – Optimisation multicritères : il est important de combiner les leviers d'action pour la durée de vie et les indicateurs environnementaux pour proposer des recommandations pour une conception durable et environnementale. Dans le cas des classes de résistance de 42.5 MPa et 52.5 MPa, pour obtenir une durée de vie importante avec de faibles impacts environnementaux, on peut recommander la classe de résistance de 52,5 MPa et un ciment CEM III/C. La formulation du béton devra utiliser des valeurs minimales de teneur en ciment, de rapport eau sur ciment, d'épaisseur du béton d'enrobage et de distance de transport des bétons. Plus que le type de ciment, la réduction des indicateurs environnementaux dépend en réalité de la teneur en clinker du ciment. Elle est presque indépendante du type d'additif. La formulation optimale proposée ci-dessus permet de réduire considérablement les indicateurs de changement climatique, de déplétion des ressources, d'eutrophisation aquatique et, de toxicité humaine (non-cancérigènes).

EXTENDED ABSTRACT

According to the World Commission on Environment and Development of the United Nations [1], sustainability means "meeting the needs for the present without compromising the ability of the future generations to meet their own needs". Yet, some geographical regions are running out of limestone resources to produce cement, while major metropolitan areas are running out of materials used as aggregates for concrete [2]. In this manner, each year three billion tons of raw material are used to manufacture building products and components worldwide. That is 40-50% of the total material flow in the global economy [3]. In the US, the concrete production is 76 million metric tons and generated 9.8 million metric tons of CO_2 [3]. CO_2 emissions from cement production represents currently about 5%-7% of anthropogenic global CO_2 emissions [4].

These facts recall that sustainable design of infrastructures imposes a new way of thinking for which present constructions have to minimize their environmental impacts, taking their life cycle into account, and especially their service life [5]. Life Cycle Assessment (LCA) is the suitable method for this approach, because it integrates the inputs and outputs of energy and materials, and the potential environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle [6]. This PhD thesis thus elaborates a service life model for Reinforced Concrete (RC) structures into aggressive surrounding conditions. This model is then used to design structures for which environmental impacts are assessed by LCA for construction, maintenance and repairs [7].

Research questions in this PhD thesis are as follows:

> 1. How to integrate the service life model into Life Cycle Assessment (LCA) for assessing the environmental impacts of concrete structures?
>
> 2. How to determine the efficient action levers increasing the service life and reducing the environmental impacts of concrete structures?

To identify action levers, we combine several sensitivity analysis methods that characterize how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be apportioned to different sources of uncertainty and variability in its inputs [8]. In our approach, the studied outputs are service life duration and environmental impacts. We classify our input parameters in two main categories:

- **Technological parameters:** they are controllable by the engineering designer (i.e., choices of materials, composition mixes, working techniques …), and they are potential action levers.
- **Environmental parameters:** they are not controllable and depend from surrounding conditions (i.e., concentration of aggressive agents like CO_2, ambient temperature, humidity …).

We define action levers as technological parameters that have an important contribution on the variation of service life and/or of environmental impacts for the studied RC structure. Identifying an action lever requires quantifying its influence, alone and in interactions with other parameters if needed, as well as characterizing its most favorable values in order to maximize service life and/or minimize environmental impacts.

Figure 1 depicts our approach for environmental and durable design of RC structures.

The decision diagram (n°1 Figure 1) describes the set of choices and their relations that can be taken by the engineering designer. These choices mainly concern dimensions of the structure, choices of materials (for the initial construction and maintenance operations) as well as maintenance techniques.

The service life model (n°2 Figure 1) provides a calculation of service life, according to the type of material, technological aspects as well as environmental exposure conditions. It also predicts times at which a maintenance operation is necessary in order to reach service life design.

We use LCA model (n°3 Figure 1) to estimate the environmental impacts of construction and maintenance processes, as a function of choices from the decision diagram at the design phase.

The service life and environmental impact indicators are tested by sensitivity analysis techniques (n°4 Figure 1), in order to identify action levers for increasing the service life and reducing the environmental impacts. Concerning the information on action levers, we estimated the value of Sobol' indices corresponding to their individual influence and their total influence, including interactions. We estimated Morris' indices, including (i) the mean value of the elementary effects to determine their influential trend; and (ii) the mean value of the absolute value and the standard deviation value of the elementary effects to identify their type of influence (i.e., linear, non-linear, monotonic, non-monotonic).

Finally, a comparison of all possible actions is conducted in an optimization process (n°5 Figure 1) and provides recommendations for sustainable design.

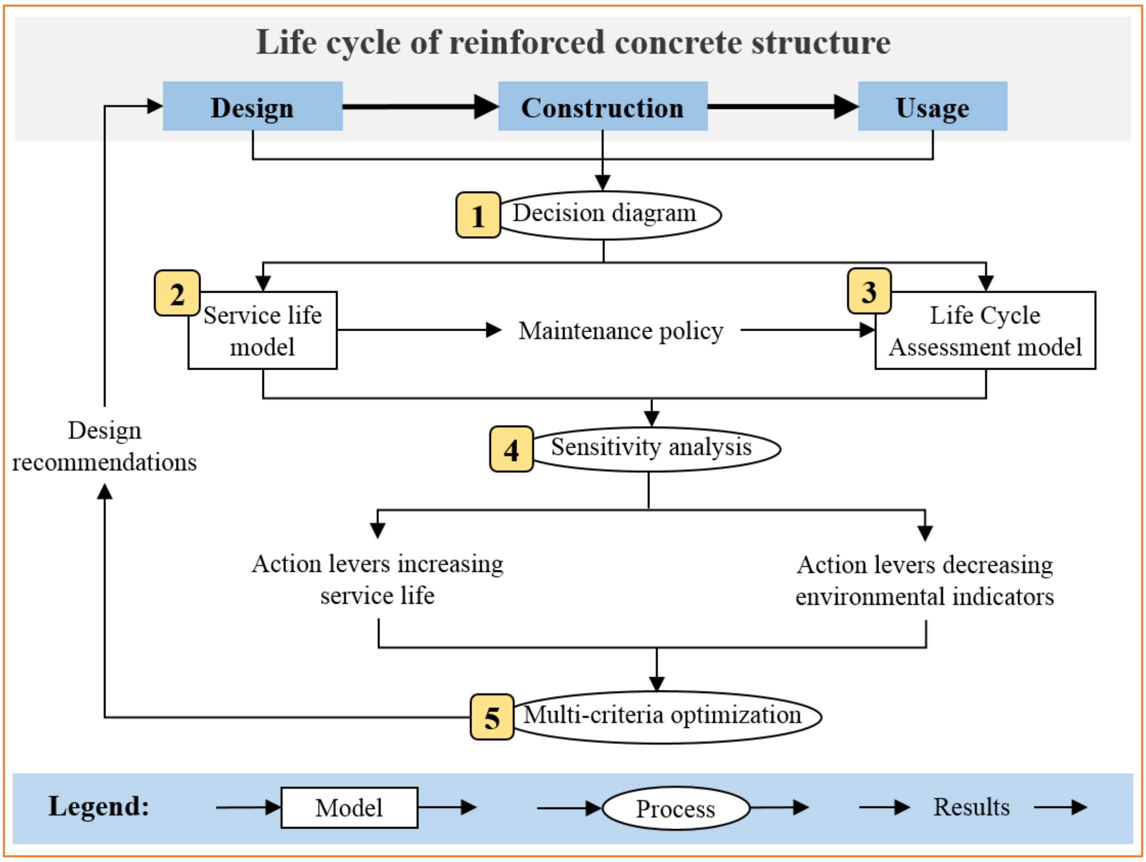

Figure 1. Approach for environmental and durable design.

The case study is a RC structure submitted to carbonation dimensioned for a 100-year service life design. It is located in Madrid (Spain) because environmental conditions are expected favoring carbonation. Following recommendations of EN 206-1 we assumed XC4 exposure class [10].

This thesis is carried out the following steps shown in Figure 1:

Step 1 – Decision diagram: the engineering designer describes choices on materials and techniques used for construction, maintenance and repair of the RC structure for a 100-year service life design.

We consider two alternatives of RC structures: (i) those for which neither maintenance nor repair operations are required; and (ii) the others require the maintenance policy. We consider a decision diagram including 30 scenarios of concrete cover that are the result of 3 possible cement strength classes in association with ten cement types. We identified two cases of RC structure: (i) the RC structure, designed with the cement strength class 42.5 MPa or 52.5 MPa, for which neither maintenance nor repair operations are required because time length of corrosion initiation ignition is largely superior to the 100-year service life design; and (ii) the RC structure, designed with the cement strength class 32.5 MPa, for which various maintenance policies have to be compared because time length of corrosion ignition is inferior to the 100-year service life design.

In the first alternative, the decision diagram is reduced to the choice between 10 types of cements for each cement strength class (Figure 2).

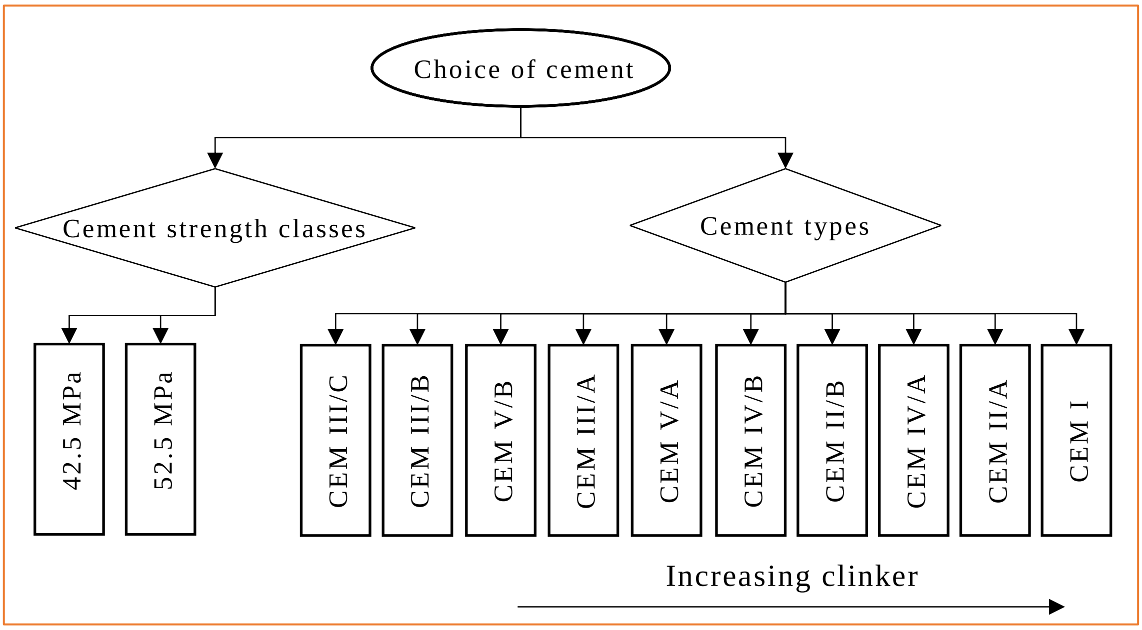

Figure 2. Decision diagram in the case of cement strength classes 42.5 MPa and 52.5 MPa.

In the second case, the decision diagram for maintenance policy must be considered (Figure 3).

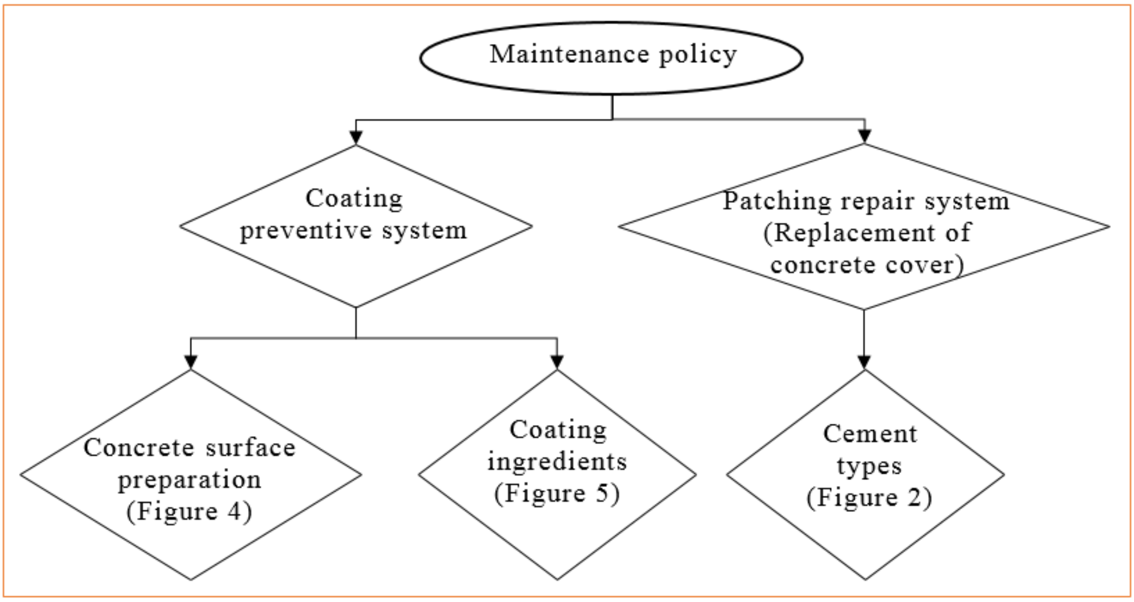

Figure 3. Decision diagram in the case of cement strength class 32.5 MPa.

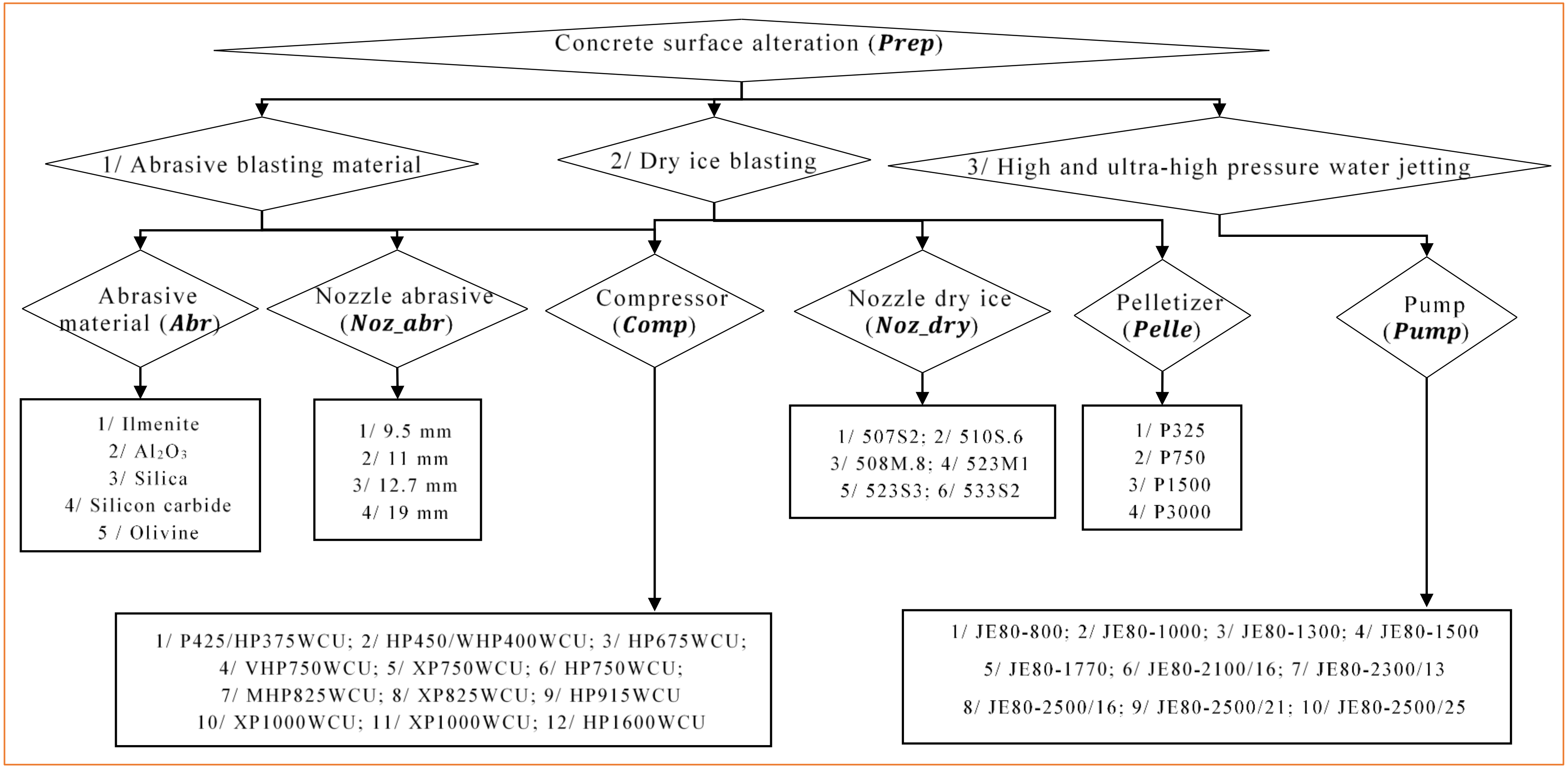

Figure 4. Decision diagram for concrete surface preparation.

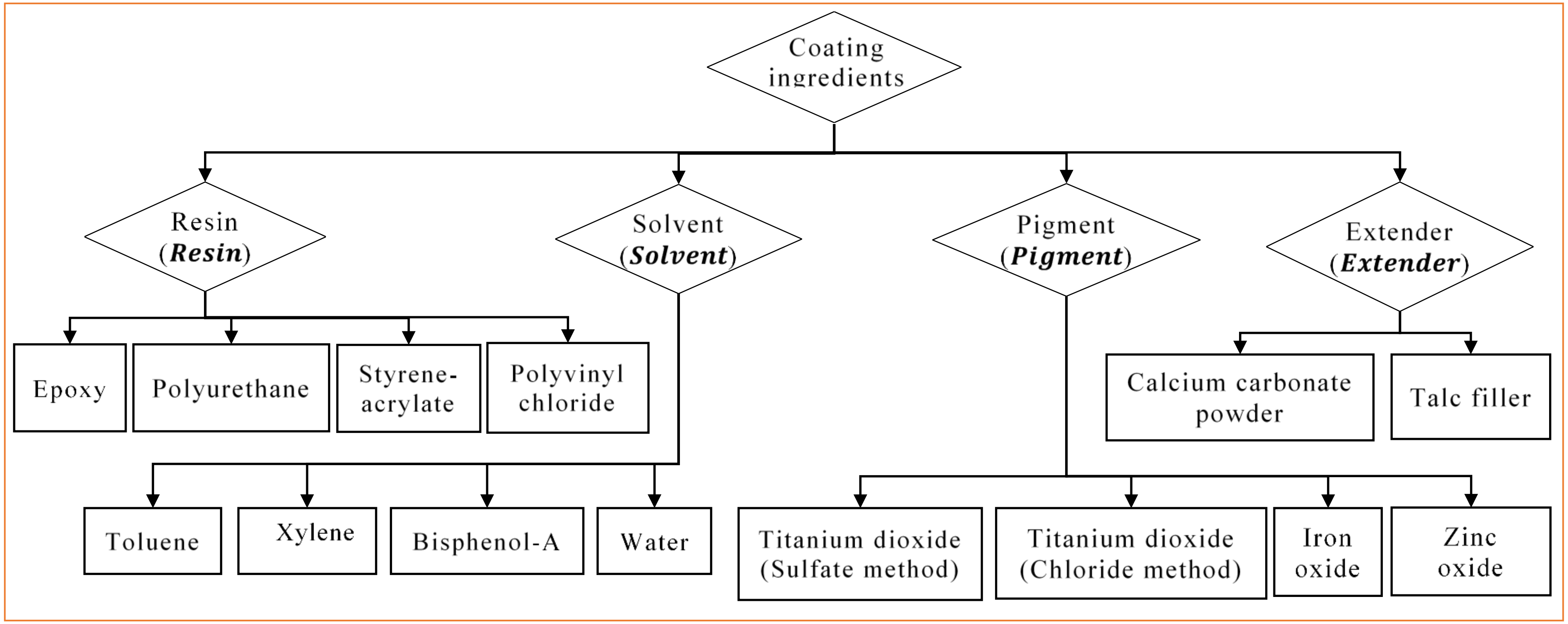

Figure 5. Decision diagram for coating ingredients.

Step 2 – service life model: we develop a new meta-model calculating the natural carbonation depth within concrete structures. The meta-model integrates a maximum of both technological and environmental parameters influencing the natural carbonation depth, and it can be used by civil engineers. The meta-model is based on the analytic solution of Fick's first law. It was validated using data from literature on short- and long-term natural carbonation exposure conditions (from 21 days to 35 years) for CEM I, CEM II, CEM III cement types, and CEM I additives (fly ash), for a wide range of water-to-cement ratio, cement content and exposure conditions. The meta-model predicts concrete carbonation depth for a wide range of curing period (between 1 and 28 days).

Step 3 – Life Cycle Assessment model: we develop LCA model to estimate the environmental impacts of the RC structure. This model is based on a functional unit of 1 m^2 of concrete cover of the RC structure without maintenance activities during 100-year service life design. The considered system is shown in Figure 6. It encompasses the manufacturing process of concrete as well as corresponding transports. The end of life treatment of materials is not accounted. The manufacturing process of concrete comes from the ecoinvent 3.3 database [11]. Environmental impact indicators are chosen from the ILCD method [12].

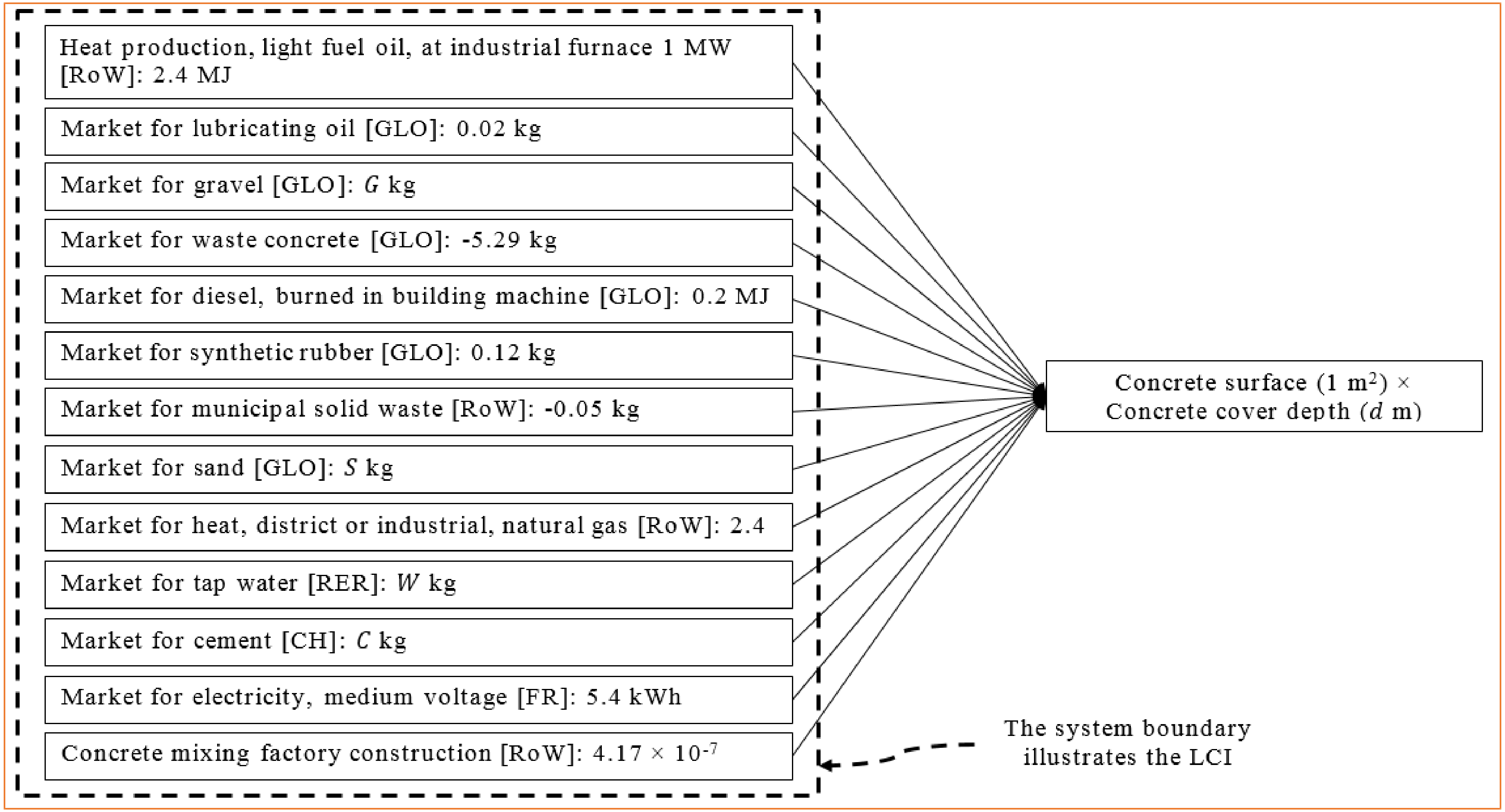

Figure 6. LCA system for concrete production.

Step 4 – Sensitivity analysis

Identification of action levers increasing service life: the service life of the RC structure corresponds to the period of time from initial penetration of CO_2 into the concrete cover until the carbonation front reaches the reinforcement bar. In order to determine the action levers for the service life of twenty scenarios described in Figure 2, we undertake a sensitivity analysis on the service life model. We find that action levers are water-to-cement ratio and amount of cement content. A decrease in water-to-cement ratio and an increase in cement content result in the increase of service life. Among environmental parameters, both relative external humidity and ambient temperature contribute the most to the variation of service life and are thus expected to provoke important uncertainties.

Identification of action levers decreasing environmental impact indicators: we carried out sensitivity analysis of results from LCA models (environmental indicators) to determine the action levers decreasing environmental indicators. In the case of cement strength classes 42.5 MPa et 52.5 MPa for which neither maintenance nor repair operations are necessary during the 100-year service life, our sensitivity analysis results show that a decrease of cement content, concrete cover depth, distance from the concrete factory to the site result in the significant decrease of environmental impact indicators. Cement strength class is found to have no influence on environmental impacts. Furthermore, we have identified that CEM III/C cement type is the one that provokes minimal environmental impacts. However, a closer look on these results show that all environmental impacts are virtually linear with the rate of clinker inside cement, and consequently the type of additives has no significant influence.

Step 5 – Multi-criteria optimization: it is then important to combine action levers for both service life and environmental impact indicators in order to provide recommendations for environmental and durable design. In the case of cement strength classes 42.5 MPa et 52.5 MPa for which neither maintenance nor repair operation are necessary during the 100-year service life, to obtain the RC structure with longest service life and minimal environmental impacts, we recommend to use the highest cement strength class (about 52.5 MPa) and the CEM III/C cement type. In addition, mix concrete should use the lowest values for cement content, water-to-cement ratio, concrete cover depth and transport distance from the concrete factory to the site. Reduction of environmental impacts significantly depends on the average percentage of clinker replaced by the supplementary cementitious material (SCM). Following the previous recommendations allows to considerably reduced the Climate Change (CC), Resource Depletion (RD), Marine Eutrophication (ME) and, Human Toxicity (non-carcinogenics) (HTnc) impact indicators.

INTRODUCTION

Résumé :

Le climat désigne l'ensemble des variations des caractéristiques météorologiques en un endroit donné, au cours du temps. Certaines formes de pollution de l'air, résultant d'activités humaines, menacent de modifier sensiblement le climat, dans le sens d'un réchauffement global. Ce changement climatique peut entraîner des dommages importants : élévation du niveau des mers, accentuation des événements climatiques extrêmes (sécheresses, inondations, cyclones, ...), déstabilisation des forêts, menaces sur les ressources d'eau douce, difficultés agricoles, désertification, réduction de la biodiversité, extension des maladies tropicales.

Le Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC) a été créé en 1988 en vue de fournir des évaluations détaillées de l'état des connaissances scientifiques, techniques et socio-économiques sur le changement climatique, ses causes, ses répercussions potentielles et les stratégies de parade. L'Accord de Paris a été signé en décembre 2015 par 195 pays plus l'Union européenne. Il prévoit que chacun des pays revoit tous les cinq ans ses engagements pour diminuer ses émissions de gaz à effet de serre qui ont un effet différent sur le changement climatique.

Le béton est l'un des matériaux de construction les plus utilisés au monde. L'impact de la construction et donc du béton n'est pas négligeable sur le changement climatique. De nos jours, le béton utilisé comme matériau de construction pose des problèmes en termes de respect de l'environnement.

Le gros de la consommation d'énergie due à l'utilisation du béton provient d'activités consommatrices d'énergie qui entraînent des émissions plus ou moins fortes de CO_2. Le béton est essentiellement composé de sable et de gravier, et d'un peu de ciment (10%). Le ciment est responsable de la majorité des consommations d'énergie et des émissions de CO_2 du béton. Les pays en voie de développement ont une forte croissante économique qui s'accompagne d'une forte croissance des activités de construction. Pour la conception de ces futures constructions il est donc important de prendre en compte des critères d'environnement tels que le changement climatique.

De plus, les structures en béton armé sont dégradées au cours de leur usage par différents agents agressifs. La corrosion des armatures due à la carbonatation ou aux ions chlorures est la principale cause des désordres se produisant sur les structures en béton armé. Afin de prolonger leur durée de vie en service, des opérations de maintenance peuvent être nécessaires tout au long de leur durée de vie. Celles-ci ajoutent des impacts environnementaux lors de la phase d'usage qui peut être longue. Ainsi la conception des ouvrages en béton par les pays émergents est un enjeu pour l'avenir car leurs choix d'aujourd'hui auront des conséquences sur les 100 ans à venir, du fait de la durée de vie des ouvrages construits. Il est donc nécessaire de prendre en compte le critère de durabilité dès la conception.

Actuellement, les recommandations de la norme NF EN 206-1 sont un bon moyen d'assurer la durabilité des structures en béton armé, elles ne prennent pas en compte le fait de minimiser les impacts sur l'environnement. Dans ce contexte, la conception des structures en béton respectueuse des enjeux environnementaux impose une nouvelle façon de penser dans laquelle les constructions actuelles doivent être conçues pour diminuer leurs impacts environnementaux, en prenant en compte leur cycle de vie, et notamment la phase d'usage. L'Analyse de Cycle de Vie (ACV) est la méthode adaptée pour cette démarche. Parce qu'elle consiste en une compilation et une évaluation des consommations d'énergie, des utilisations de matières et de rejets dans l'environnement, ainsi que de l'évaluation de l'impact potentiel sur l'environnement associé à un produit, ou un procédé, ou un service, sur la totalité de son cycle de vie.

Notre objectif est de développer une approche de conception qui permet de minimiser les impacts environnementaux des structures en béton armé en considérant la phase d'usage tout en augmentant leur durée de vie.

Ceci amène aux questions de recherche :

1. Comment intégrer des modèles de durée de vie de et de stratégie de maintenance et de réparation dans l'ACV afin d'évaluer les impacts environnementaux des structures en béton armé ?

2. Comment déterminer les leviers d'action augmentant la durée de vie et réduisant les impacts environnementaux des structures en béton armé ?

La corrosion des armatures induite par le seul phénomène de carbonatation est considérée dans cette thèse.

Cette thèse est structurée en sept chapitres : à l'exclusion de l'Introduction, du Chapitre I, et de la Conclusion, les autres chapitres sont des articles complets édités (le Chapitre II), soumis (les Chapitres III et IV), ou qui vont l'être prochainement (les Chapitres V et VI).

Le Chapitre I présente une méthode innovante pour la conception environnementale et durable des structures en béton armé dans un environnement agressif. Elle est résumée dans le Figure 1 et consiste en cinq étapes.

- L’étape 1 détaille le diagramme décisionnel des ingénieurs concepteurs et permet d’identifier toutes les combinassions possibles.

- L’étape 2 recours à un modèle de l’altération de la structure béton pendant sa durée de vie pour prédire les moments d’interventions de maintenance tout au long de la durée de vie prévue.

- L’étape 3 recours à un modèle d’ACV pour estimer des indicateurs environnementaux des processus de construction et de maintenance, en fonction des choix du diagramme décisionnel.

- L’étape 4 soumet les résultats concernant la durée de vie et les indicateurs environnementaux à une analyse de sensibilité (AS), afin d’identifier les leviers d’action augmentant la durée de vie et réduisant les impacts environnementaux.

- L’étape 5 est une phase d’optimisation permettant de concevoir la (ou les) structure(s) dont la durée de vie est maximale et les impacts environnementaux sont minimaux.

Les Chapitres II, III, IV, V and VI contiennent les articles qui présentent une étape ou des étapes de la méthode développée ainsi que les résultats obtenus.

Le Chapitre II présente le modèle de durée de vie développé pendant la thèse. Ce travail concentre donc sur l’étape 2 (Figure 1). Nous avons développé un nouveau méta-modèle pour calculer la profondeur de carbonatation naturelle dans les structures en béton. Ce méta-modèle intègre un maximum de paramètres de conception ainsi que des paramètres aléatoires liés à l’environnement immédiat du matériau.

Le Chapitre III présente les résultats d’AS du modèle durée de vie. Ce travail concentre donc sur l’étape 4 (Figure 1). Les résultats permettent d’identifier les leviers d'action augmentant la durée de vie. Nous avons identifié deux alternatives principales pour la structure en béton : (i) pour les classes de résistance du ciment de 42,5 et 52,5 MPa, aucune opération d'entretien n'est nécessaire, et (ii) pour la classe de résistance du ciment de 32,5 MPa des interventions sont nécessaires et différentes politiques d'entretien doivent être comparées.

Le Chapitre IV présente les résultats d'ACV de la conception environnementale et durable de la structure pour les cas identifiés au chapitre III, où aucune opération d'entretien n'est nécessaire (classes de résistance du ciment de 42,5 et 52,5 MPa). Ce travail regroupe les étapes 3, 4 et 5 (Figure 1). Nous avons développé un modèle d'ACV pour estimer les impacts environnementaux de la structure. Ce modèle est basé sur une unité fonctionnelle correspondant 1 m^2 de surface d'enrobage en béton. Nous avons appliqué les méthodes d'AS sur les indicateurs d'impacts environnementaux, afin d'identifier les leviers d'action réduisant les impacts environnementaux. Nous combinons les leviers d'action environnementaux et durables (les leviers durables sont présentés dans le Chapitre III) pour proposer les recommandations pour une conception durable et environnementale.

Les Chapitres V et VI se concentrent sur la structure identifiée au chapitre III, qui exige des opérations de maintenance et de réparation (classe de résistance du ciment de 32,5 MPa). Seule la politique de maintenance préventive a été étudiée. Ce type maintenance consiste en la préparation de la surface du béton d'enrobage par décapage, puis en l'application d'un revêtement de protection.

Le Chapitre V détaille le développement d'un modèle de durée de vie avec prise en compte l'effet du revêtement sur la durée de vie de la structure. Ce travail concerne donc l'étape 2 (Figure 1). Le modèle développé permet de prédire la profondeur de carbonatation naturelle des structures en béton protégé par un revêtement. Nous avons utilisé les méthodes d'AS pour réduire le nombre des paramètres d'entrée du modèle de durée de vie et pour réduire les scénarios à étudier.

Le Chapitre VI se concentre sur les étapes 3 et 4 de la méthode (Figure 1). Il se concentre plus précisément sur l'impact environnemental de l'étape de préparation de la surface du béton avant application du revêtement. En effet, cette étape seule est complexe à étudier de façon exhaustive : nous avons identifié, à partir du diagramme décisionnel (Figure 4), 1 594 combinaisons possibles pour cette opération. L'objectif de ce chapitre est donc d'utiliser l'AS pour réduire le diagramme décisionnel de nettoyage de la surface du béton. Nous avons développé un modèle d'ACV évaluant les impacts environnementaux des opérations de l'altération de la surface du béton. Nous avons ensuite appliqué les méthodes d'AS sur les impacts environnementaux. Le scenario de préparation optimal utilise la méthode de traitement par jet d'abrasif avec l'olivine en tant que les matériaux abrasifs en association avec un diamètre et une pression minimales de buse (9.5 mm et 3.4 bar respectivement).

Ce rapport de thèse se termine avec une conclusion générale et des perspectives. Il contient également des annexes avec les informations détaillées concernant les données et calculs.

Today, approximately half of the world’s conventional oil has been consumed [13]. The burning of fossil fuels puts into the atmosphere carbon dioxide (CO_2), which is causing gradual global warming. CO_2 levels in the air are at their highest in 650,000 years (405.25 ppm in 2016 and ascending) [14]. Scientists have high confidence that global temperatures will continue to rise for the decades to come, largely due to greenhouse gases produced by human activities, e.g., nine of the 10 warmest years on record have occurred since 2000 (global temperature increased 1.7˚F in 2016 since 1880 and ascending) [14]. Effects formerly predicted by scientists resulting from global climate change are now occurring: loss of sea ice, accelerated sea level rise and longer, more intense heat waves. Arctic summer sea ice shrank to the lowest extent on record in 2012, Greenland ice loss half of its surface area between 1996 and 2005, and global average sea level has risen nearly 178 mm from about 1870 to 2000 [14].

There are many factors that will be affected by climate change including plant respiration [15], human health [16], hydrology and water resources [17], forest landscapes [18], biodiversity [19], ecosystem [20]. In tropical forests such as Amazonia, where there is abundant biodiversity, even modest levels of climate change can cause high levels of extinction. Climate change is the biggest global health threat of the 21st century. The major threats to global health from climate change is occurring through changing patterns of disease, water and food insecurity, vulnerable shelter and human settlements, extreme climatic events, and massive migrations of populations [21].

In order to evaluate the huge amount of published scientific results on climate change science, the Intergovernmental Panel on Climate Change (IPCC) was established in 1988 to assess the latest scientific and technical information about global warming [22]. Through the IPCC, climate experts from around the world synthesize the most recent climate science findings every five to seven years and present their report to the world’s political leaders. On 12

December 2015, the United Nations Framework Convention on Climate Change (UNFCCC) have ratified Paris climate agreement that deals with greenhouse gas emissions mitigation and adaptation with finances starting in 2020. Each country determines, plans and regularly reports its own contribution it should make efforts in order to mitigate global warming.

The construction sector drastically contributes to both climate change and depletion of essential resources. Some geographical regions are running out of limestone to produce Portland cement, and some major metropolitan areas are running out of natural aggregates [2]. The worldwide contribution from buildings are about 40% of global energy, 25% of global water, 40% of global resources [23]. The primary energy used in United States by commercial and residential buildings is about 41%, it has exceeded the other major sectors: industrial and transportation about 31% and 28% respectively [24]. In United Kingdom, buildings consume about 50% of global energy sold in the country, they are responsible for about 50% of the country's CO_2 emissions [3], and 45% of global CO_2 emissions for Europe [3]. Each year 3 billion tons of raw material are used to manufacture building products and components worldwide. That is 40-50% of the total material flow in the global economy [3]. Around half of all resources humans extract from nature are consumed by construction activities [23]. If current trends continue, expansion of the built environment will destroy or disturb natural habitats on over 70% of Earth's land surface by 2032, driven by population growth, economic growth, and urbanization [23].

Cement concrete is one of the main causes for these important environmental impacts from the construction sector. Concrete is one the most widely used construction materials in the world [2]. Twice as much concrete is used in construction around the world than the total of all other building materials, including wood, steel, plastic and aluminum. Concrete is the second most consumed material after water [25]. Annual global production of concrete is about 3.8 billion cubic meter per year [26]. This means that concrete consumption of our world is approximatively one tone per person per year. 5% up to 20% of concrete is made up of cement. 95% of all manufactured cement is used to make various types of concrete [25]. At the current rate of increase of cement production [27], worldwide cement production is expected to rise from about 2.5 billion tones in 2006 to about 5 billion tones by 2020. Concrete is among the materials with the highest embodied energy content, it is also responsible for large quantities of CO_2 emissions. For instance, in the United States, the concrete production of 76 million metric tons generates 9.8 million metric tons of CO_2 [3]. CO_2 emissions from cement production represent currently about 5%-7% of anthropogenic global CO_2 emissions [4]. If we look at the geographical distribution of CO_2 issues from cement production in the world from 1960 up to 2014: North America (7.9%); Oceania (0.5%); South America (3.6%); Africa (4.1%); Asia (56.6%); Central America (0.6%); Europe (20.8%); Middle East (5.9%) [28]. Developing countries are responsible for 2/3 of total emissions, and more than half of emissions are issued from Asia. This explained by very important construction activities in the developing countries.

Reduction of environmental impacts from cement concrete is thus one of the ways that, combined with others, can contribute to mitigate climate change and energy consumption in the construction sector. However, cement concrete structures have a long service life, several centuries, and the question of their maintenance is crucial. Notably, Reinforced Concrete (RC) structures are exposed to long term corrosion phenomena. This means that environmental impacts provoked by the production of cement concrete do not only occur at the construction step, but also during the service life of the structure, when altered concrete must be replaced by new one. Thus, the ongoing environmental impacts of a RC structure is expected to increase with the amount of maintenance required. A RC structure requiring regular repainting is likely to have increased energy use and CO_2 emissions in comparison with one without these elements [29]. For the developing countries, which have very important construction activities, choices made today will have important effects during the 100 coming years. In other words, RC structures built today, mainly in developing countries, not only generate todays' environmental impacts but ensure additional impacts for the centuries to come.

The corrosion of steel reinforcement is a major cause of the degradation of RC structures [30] [31]. Corrosion phenomena are mainly provoked by penetration of carbon dioxide, chlorides and other chemical agents in the porous bulk concrete covering the metal bars of the RC structure. About 70% of damages to bridge structures are caused by chloride or carbonation induced steel corrosion [31]. This penetration is not avoidable, but it can be more or less rapid according to the exposure of RC to these agents, to climate conditions as well as to concrete properties. Standard EN 206-1 [10] proposes an approach to deal with the durability of RC structure in view of the aggressive agents. This approach is based on the definition of an exposure class and the subsequent prescriptions regarding the water-to-cement ratio (W/C), the cement content (C), and the concrete cover depth (d). There is 6 exposure classes: (i) no risk of corrosion or attack; (ii) corrosion induced by carbonation; (iii) corrosion induced by chlorides other than from sea water; (iv) corrosion induced by chlorides from sea water; (v) freeze/thaw attack with or without de-icing agents; and (vi) chemical attack. Table 1 shows prescriptions for exposure classes referring to carbonation and chloride-induced corrosion.

Another approach deals with the durability of RC structures in aggressive environment, so-called "performance-based approach" [32]. The performance-based approach is to assess relevant concrete material properties, using some relevant test methods or service life prediction models. This approach can be used to formulate requirements as regards material properties and structure dimensions. In the case of corrosion of reinforcing steel due to carbonation [7] [32] [33] or chlorides [34] [35] [36], the estimation of the deterioration evolution depending on expected influential parameters is mostly performed by applying a probabilistic approach. This estimation makes it possible to formulate requirements for the structural responses depending on the service life design [37]. Then, the durability design can be completed in two ways: (i) using a fully probabilistic method, for which the concrete cover depth and the diffusion coefficient of CO_2 or chlorides are usually considered as main probabilistic design parameters for the required service life design and the reliability level [7] [32] [33] [34] [35] [36]; (ii) using the partial factor method to determine the characteristic values and the partial factors for the design parameters [7] [32] [35].

Table 1. Exposure classes related to corrosion of the reinforcement (classes 2, 3 and 4) and prescription on concrete according to the EN 206 standard. The minimum strength class refers to the use of Portland cement of type CEM I 3.25.

Exposure class		**Description of the environment**	**Maximum W/C**	**Minimum strength class (MPa)**	**Minimum cement content (kg/m^3)**
2. Corrosion induced by carbonation	XC1	Dry or permanently wet	0.65	C20/25	260
	XC2	Wet, rarely dry	0.60	C25/30	280
	XC3	Moderate humidity	0.55	C30/37	280
	XC4	Cyclic wet and dry	0.50	C30/37	300
3. Corrosion induced by Cl^- othe than from seawater	XD1	Moderate humidity	0.55	C30/37	300
	XD2	Wet, rarely dry	0.55	C30/27	300
	XD3	Cyclic wet and dry	0.45	C35/45	320
4. Corrosion induced by Cl^- from seawater	XS1	Exposure to airborne salt	0.50	C30/37	300
	XS2	Permanently submerged	0.45	C35/45	320
	XS3	Tidal, splash and spray zones	0.45	C35/45	340

Even though the approaches for the durability design described above are a good step towards the improvement of the durability of RC structures, the long-term durability is not always achieved in comparison to intended service life, e.g., 100 years [38], leading to early failure of RC structures [30]. The relevant damage mechanisms for most concrete structures of infrastructure or industry may be summarized and systematized into (i) those affecting the durability of reinforcement such as electrochemical attacks; (ii) those effecting the durability of concrete such as chemical and physical attacks. Since the exposure of different types of RC structures differs, also their predominant deterioration mechanisms are different. This may reflect non-exhaustive recommendations as regards all aspects of the design process, like, for instance environmental exposure conditions (e.g., the ambient temperature) and quality of execution process. The exposure class proposed by EN 206-1 [10] refers only to the average conditions and to well-cured concrete during the execution process, i.e., a minimum initial curing period of about 7 days [39]. In order to extend the service life of RC structures under those damage types, the maintenance system should be carried out on the RC structures during their service life.

However, durability of RC does not automatically ensure better environmental performances. A previous study has revealed that carbonation of concrete is almost independent of cement content (C) (from 221 to 450 kg/m^3) for a given water-to-cement ratio (W/C) [40]. This raises the problem of attempting to impose a minimum C of EN 206-1 standard, reminding that cement, as explained above, is mainly responsible for the release of a huge amount of CO_2 during the production [41].

In our sense, a RC structure is constructed to ensure that the total environmental impacts concerning both emissions and consumptions, during its whole life cycle, including its use, will be minimal [2]. Environmental design of RC structure should consider the short- and long-term environmental impacts in the design stage.

To face this challenge, Life Cycle Assessment (LCA) is a helpful tool in the design for environment. LCA is an internationally standardized method for compiling and examining the inputs and outputs of energy and materials, and the potential environmental impacts directly attributable to the functioning of a products or service system throughout its life cycle [6]. As stated in the ISO LCA standards, the general LCA framework consists of the four phases: (i) goal and scope definition that defines the aims, product system, and expected result of the study; (ii) inventory analysis that quantify all the emissions related to the product system based on the functional unit of the product; (iii) impact assessment that transforms the inventory result into the environmental impact categories; and (iv) interpretation that explains the results with the goal of the study through the whole analysis procedure.

Many comparative LCA studies are carried out at different levels such as the different kinds of concrete [42] [43] [44], structural elements [45] [46] [47] and bridges [29] [48] [42]. These LCA studies focus on the material extraction and production, because they are well-known in designing a new structure, but the use and end-of-life phases are neglected because they are unknown at the design stage. Other studies [49] [50] [51] [52] integrate service life model into LCA to consider the potential environmental impacts from the maintenance activities in the use phase.

Concerning the environmental impacts with LCA, a traditional design process is based on the comparison of few specific alternatives based on the goal and scope definition. Then, based on the impact indicator results obtained from LCA for each alternative, the best option has the minimum impact indicator value, among the preferred impacts defined by designers.

It should be noted that LCA method compare environmental impacts between existing solutions, but cannot minimize these impacts. Then, the traditional process of design has some limits: (i) the initial scenarios are sometimes set based on subjectivity; (ii) the comparative design is costly when the numerously compared alternatives are considered; and (iii) it will be drastically complex if the design approach needs to consider other aspects in addition to environment, e.g., environmental and social aspects as proposed by the *fib* Model Code 2010 [53]. This leads to multi-criteria decision, for which the balance of the all aspects becomes complicated. Such an approach requires that design decision-makers understand the interrelationships between all aspects. It is therefore necessary to look for a new design process for achieving the environmental and durable RC structures.

Our objective is to develop a novel approach for environmental and durable design of RC structures in aggressive environment. The developed approach allows to assess the environmental impacts of RC structures considering both their construction and use phases. It should maximize the durability (service life) and minimize the environmental impacts of RC structure. The research questions in this thesis are:

1. How to integrate service life model into LCA for assessing the environmental impacts of RC structures?

2. How to determine the efficient action levers increasing the service life and reducing the environmental impacts of RC structures?

In order to provide a service life model, our work focusses on the alteration of RC structures by carbonation. Because Table 2 shows that carbonation is the most current degradation among existing RC structures. In addition, carbonation is a widespread degradation of concrete, which can be coupled with more severe deteriorations [54].

Table 2. Predominant deterioration mechanisms for different concrete structures [55] [56].

type of structure	Corrosion			Freeze /thaw	Alkali aggregate reaction	Sulphate attack	Leaching	Abrasion	Acid attack
	Chloride-induced	CO_2-induced	Biological activity						
Above ground building									
Bridges									
Foundations									
Marine structures									
Dams									
Tunnels									
Tanks and pipes									
Industrial floors									

Commonly

Sometimes affected

Uncommon

This thesis is structured into seven chapters: apart from Chapter I and Conclusion, all other chapters are full articles that are edited (Chapter II), submitted (Chapter III and IV) or still under writing process (Chapter V and VI). We do not establish a chapter of literature review because the overview of specific topic is presented in corresponding appended article.

Chapter I presents a novel approach for environmental and durable design of RC structures in aggressive environment. Our approach consists of five steps (Figure 1). At step 1 a decision diagram represents all possible combinations that engineering designers can have. At step 2 we use a service life model to predict the service life of structures and times at which a maintenance operation is necessary. At step 3 we use LCA model to estimate the environmental impacts of construction and maintenance processes, as a function of choices from the decision process at the design phase. At step 4 the service life and environmental impact indicators are tested by Sensitivity Analysis (SA), in order to identify action levers for both increasing the service life and decreasing the environmental impact of RC structures. Step 5 is an optimization process by comparing all possible actions. This optimization process provides recommendations for environmental and durable design.

Chapters II, III, IV, V and VI contain scientific articles, which present one step or several steps of the developed approach and the obtained results.

Chapter II details the development of a service life model. The work focusses thus on step 2 (Figure 1). We develop a new meta-model to calculate carbonation front depth within concrete structures. This meta-model takes many important parameters influencing the carbonation process into account.

Chapter III presents results of the SA of service life model. The work focusses thus on step 4 (Figure 1). The SA results allow identifying action levers increasing the service life. We identified two alternatives of the RC structure: (i) the RC structure, designed with the cement strength class 42.5

MPa or 52.5 MPa, for which neither maintenance nor repair operations are required, and (ii) the RC structure, designed with the cement strength class 32.5 MPa for which maintenance or repair operations are necessary, and thus various maintenance policies can be compared.

Chapter IV details LCA modeling and results of designing for environment and durability of the RC structure of the case study that do not require maintenance operation before a 100-year service life obtained from Chapter III (cement strength class 42.5 MPa or 52.5 MPa). The work focusses thus on the steps 3, 4 and 5 (Figure 1). In the step 3, we developed LCA model to estimate the environmental impacts of the RC structure. This model is based on a functional unit (FU) of 1 m^2 of concrete cover. In the step 4, we applied the SA methods to environmental impact indicators, in order to identify the action levers decreasing the environmental impacts. In the step 5, we combine the action levers decreasing the environmental impacts and that increasing the service life (presented in Chapter III) to provide the recommendations for environmental and durable design of the RC structure studied.

Chapter V and VI focus on the RC structure design solution that requires maintenance or repair operations obtained from Chapter III (cement strength class 32.5 MPa). Only a preventive maintenance policy have been considered. This type of maintenance consists in preparation of concrete surface by an abrasive operation, and application of a protective coating.

Chapter V concerns the development of service life model to consider the effect of coating on the service life of the structure. The work is thus concentrated on step 2 (Figure 1). The developed service life model allows predicting the carbonation front depth within coated concrete structures. We used SA methods in order to reduce both the number of input parameters of the service life model as well as scenarios of RC structures then, consequently, in order to reduce time-consuming calculation.

Chapter VI is focused on step 3 and 4 of the method (Figure 1). More precisely, it concerns environmental impacts of concrete surface preparation before application of the protective coating. This part is complex to study exhaustively because we identified 1,594 possible combination from the decision diagram (Figure 4). The objective of this chapter is thus to use SA in order to reduce the decision diagram concerning surface preparation to main influent aspects. We developed a LCA model assessing the environmental impacts of the operation of concrete surface preparation. We applied then the SA methods to the environmental impact indicators.

This PhD reports ends with a general conclusion and an outlook on future research needs. It also contains appendixes providing detailed information concerning data and calculations.

I. APPROACH FOR ENVIRONMENTAL AND DURABLE DESIGN OF REINFORCED CONCRETE STRUCTURES

This chapter presents a novel approach for environmental and durable design of reinforced concrete (RC) structures in aggressive environments. The developed approach answers the research questions. Our approach designs a new RC structure taking into account both service life and environmental impacts. The robustness of the developed approach allows identifying effective few solutions among all possible decision combinations for improving both service life and environmental impacts.

Résumé :

Ce chapitre présente une nouvelle méthode pour la conception environnementale et durable. Cette approche est basée sur l'Analyse de Cycle de Vie (ACV). Nous avons proposé donc d'élaborer un modèle de durée de vie des structures en béton dans un environnement agressif. Ce modèle est ensuite utilisé pour concevoir des structures dont les impacts environnementaux sont évalués par l'ACV sur la phase de construction, d'entretien et de réparation.

Nous définissons les leviers d’action comme étant des paramètres technologiques (ex. formulations des matériaux, équipements utilisés, géométrie de l’ouvrage, etc.) contribuant à la variabilité de la durée de vie et/ou des impacts environnementaux de la structure. La structure la plus durable et respectueuse environnement est conçue à partir des leviers d’action. Identifier un levier d’action requiert de quantifier sa contribution individuelle, et si besoin en interaction avec d’autres paramètres, ainsi que de caractériser ses valeurs les plus favorables dans l’objectif de maximiser la durée de vie et/ou de minimiser les impacts environnementaux. Nous utilisons plusieurs méthodes d’analyse de sensibilité qui, appliquées au modèle, permettent de quantifier la part de variabilité induite par des différents paramètres sur la variabilité de la durée de vie et des impacts environnementaux.

Notre méthode est appliquée au cas d’étude d’une structure en béton armé située à Madrid et soumise à la carbonatation pour une durée de vie prévue. A Madrid l’humidité relative extérieure d’environ 0,56 est favorable à la carbonatation du béton. Suivant les recommandations de la norme EN 206-1 nous nous plaçons dans la classe d’exposition XC4.

I.1. General description of the approach

The approach for environmental and durable design of RC structures displays in Figure 1.

The decision diagram (n°1 Figure 1) describes the set of choices and their relationships proposed by the engineering designers. These choices mainly concern dimensions of the structure, choices of materials (for the initial construction and maintenance operations) as well as maintenance techniques.

The service life model (n°2 Figure 1) provides a calculation of service life, according to the type of material, technological aspects as well as environmental exposure conditions. It also predicts times at which a maintenance operation is necessary in order to reach service life design.

The LCA model (n°3 Figure 1) estimates the environmental impacts of construction and maintenance processes, as a function of choices from the decision process at the design phase.

The service life and environmental impact indicators are tested by SA, in order to identify action levers for both increasing the service life and reducing the environmental impacts of RC structures (n°4 Figure 1).

A comparison of all possible actions is conducted in an optimization process (n°5 Figure 1) and provides recommendations for environmental and durable design.

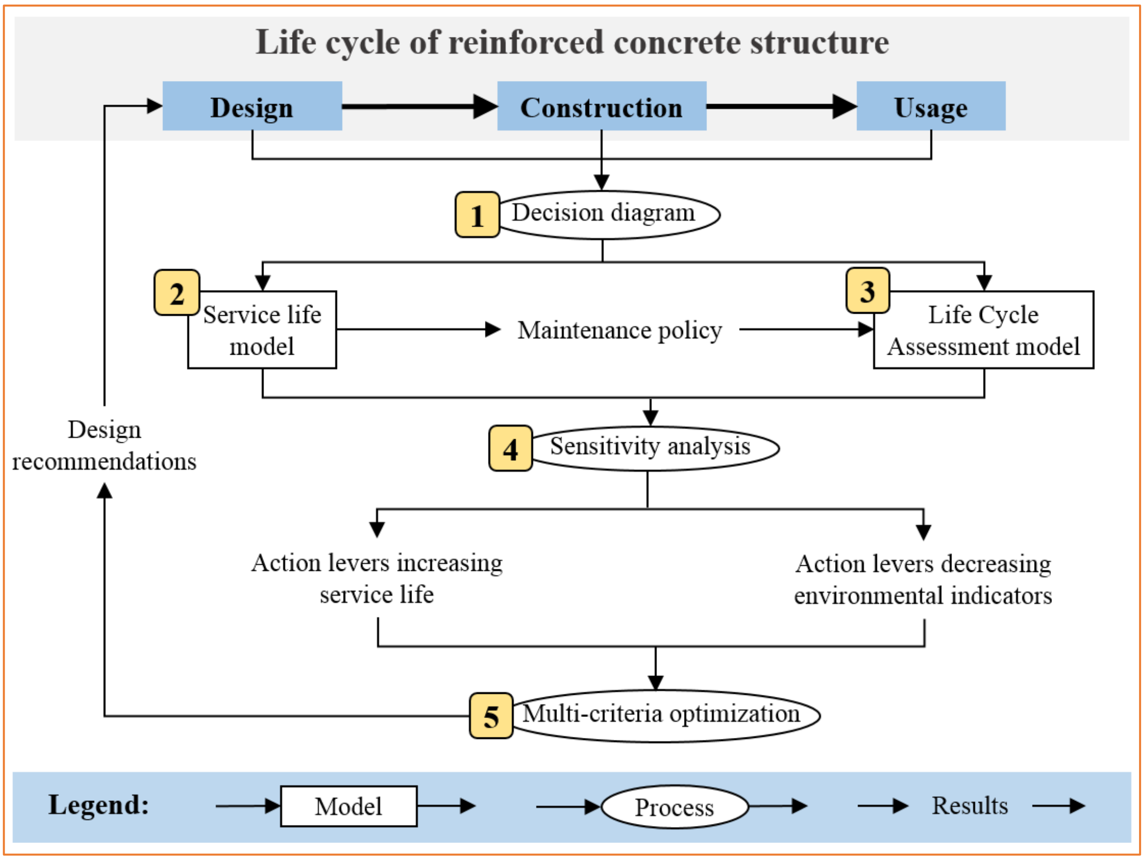

Figure 1. Approach for environmental and durable design.

In this chapter, we detail here the decision diagrams (n°1 Figure 1) for designing a new RC structure in Section I.2. We define technological parameters, environmental parameters and action levers in Section I.3. Other steps and their application to the case study are presented in various articles provided in different chapters of the PhD report as indicated in Introduction.

I.2. Decision diagrams

The decision diagrams described here can be applied to any new RC structure that could be altered by carbonation. First of all, we consider two alternatives of RC structures: (i) the RC structures that do not require a maintenance or repair operations within a service life design; and (ii) the RC structures that require a maintenance or repair operations. Then, we consider 30 scenarios of concrete cover that are the results of three possible cement strength classes in association with ten cement types as shown in Figure 2. The cement characterizations are given in Table A1 in Appendix. The cement types considered here are not forcedly exhaustive, this list has been restricted to the available Life Cycle Inventory (LCI) data for market for cement in the Ecoinvent database [11].

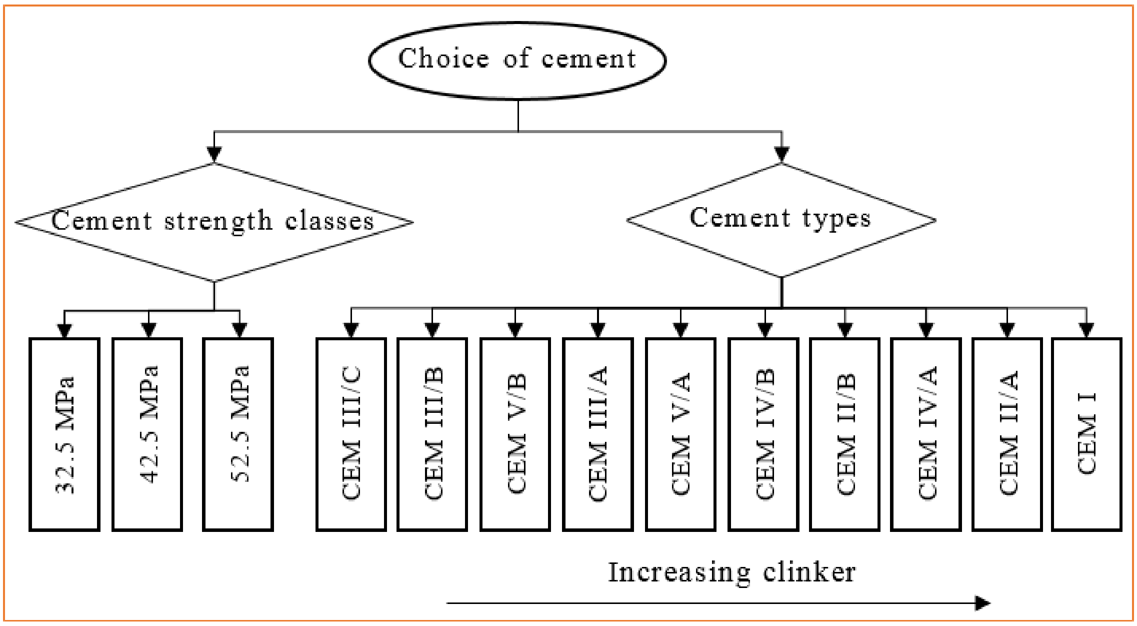

Figure 2. Decision diagram for RC structure design.

When the RC structure requires a maintenance or repair operations in order to achieve the service life design. The decision diagram for maintenance policy is considered (Figure 3). The maintenance policy consists of the preventive coating and patching repair system.

A preventive coating system of RC structures is executed by two process: concrete surface preparation and application of coating products [57]. The preventive coating system is surface treatment that has low permeability to carbonation dioxide and reduce risk of carbonation [58]. The preventive coating system also controls the ingress of liquid water into concrete that is particularly important for two following reasons: firstly, without water the carbonation reaction could not take place. Secondly, because water transports aggressive substances carbonation dioxide into concrete.

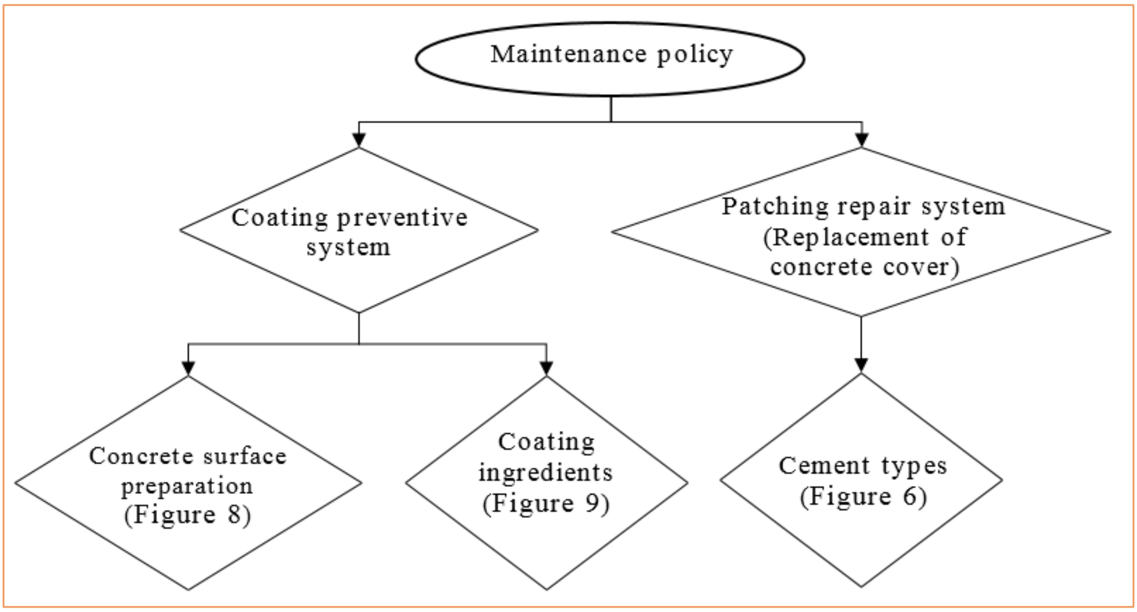

Figure 3. Decision diagram for maintenance policy.

The patching repair is conformed to EN 1504-9 [59]. The patch repair method principle is the carbonated concrete removed to the depth of intact concrete and replaced by fresh concrete. This method can be applied both at local and global levels. A new concrete with low permeability (e.g., concrete with low water-to-cement ratio) reduces further carbon dioxide ingress.

In this thesis, we do not treat the patching repair system. Thus, none of the decision diagram is proposed for the patching repair system. We focus on the preventive coating system.

The concrete surface preparation aims at replicating degree of roughness considered to be suitable for the application of preventive coating system, e.g. three profiles to be used with preventive system coating include light shotblast, light scarification and medium shotblast [60]. That results in a low probability of micro-cracking and pH of concrete unchanged. Consequently, among the types of methods include (i) mechanical surface preparation methods, (ii) chemical surface preparation and (iii) flame cleaning and blasting techniques [61]. Three kinds of blasting cleaning methods including abrasive blasting, dry ice blasting and ultra-high pressure water jetting are the most suitable methods [62]. These methods are detailed in Chapter VI. The decision diagram for concrete surface preparation is shown in Figure 4.

The type of coating constituents varies with the coating product but some common ones are: resins, solvents, extenders, pigments [63]. The experimental investigations revealed that the organic coatings based on epoxy, polyurethane, styrene-arcylate, and polyvinyl chloride reduce the rate of CO_2 diffusion into coated concrete in comparison with uncoated one. Thus, these four resin types are considered. Each resin type is associated with one solvent type, one pigment type, and one extender type to manufacture the coating. Based on the coating's suppliers [64] [65] and the available inventory data of the coating constituents from Ecoivent [11]. We considered the ingredients of coating as shown in Figure 5.

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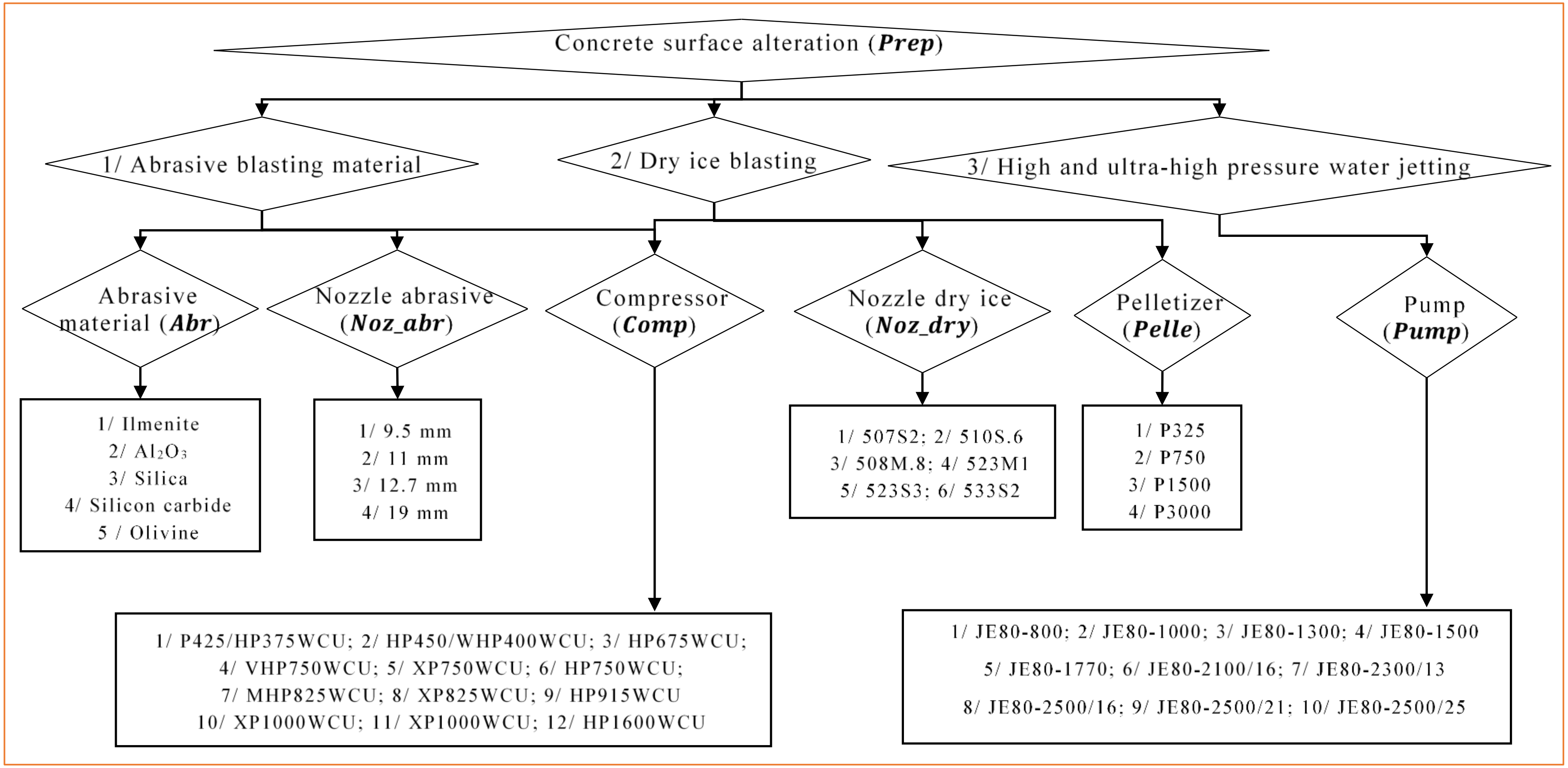

Figure 4. Decision diagram for concrete surface preparation.

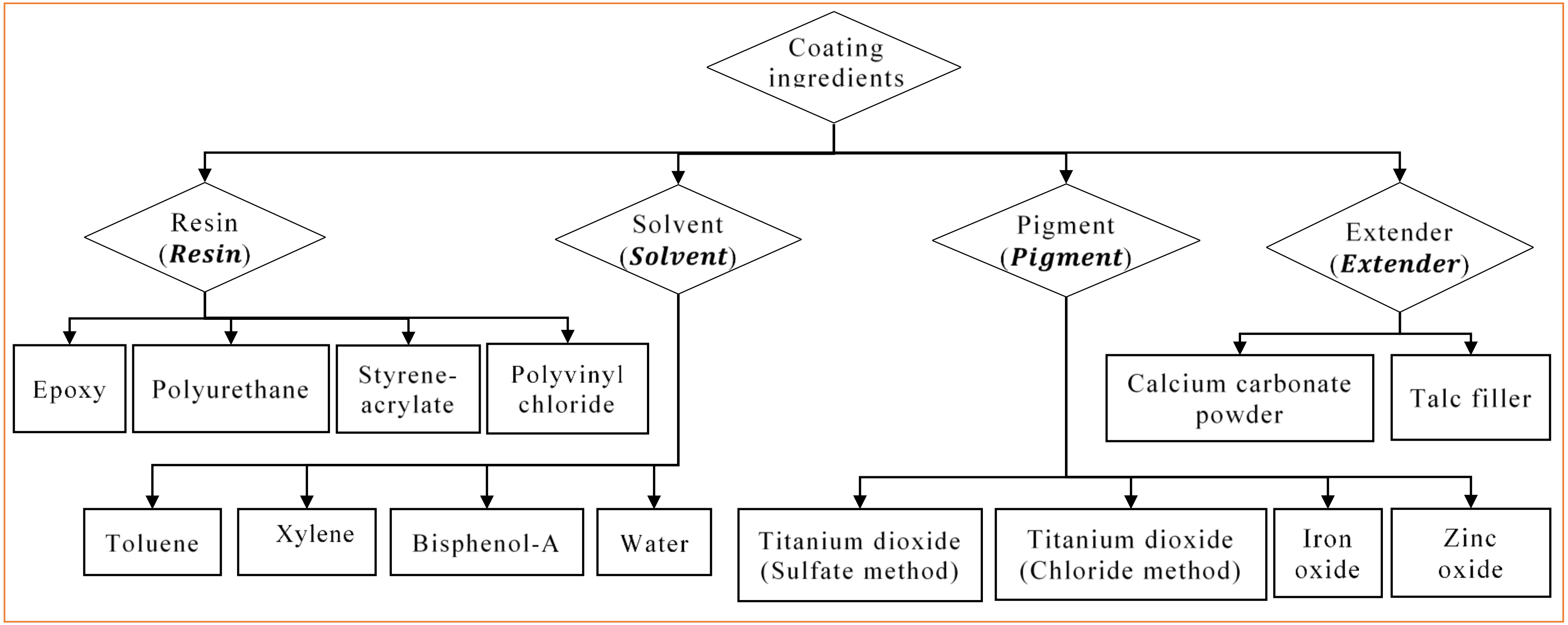

Figure 5. Decision diagram for coating ingredients.

I.3. Definition of technological parameter, environmental parameter and action lever

We define the following three important vocabularies used in our approach:

- **Technological parameters** are those controllable by the engineering designer (e.g., material properties, execution process of material), they thus represent action possibilities.
- **Environmental parameters** are those uncontrollable and depending on the outside environmental location (e.g., aggressive agent sources like CO_2 concentration, chlorides, ambient temperature and relative external humidity).
- **Action levers** as technological parameters that have important contribution on the variation of service life and environmental impacts. The action levers are determined from SA.

Suitable SA methods must be thus selected. They must quantify the contribution alone of action levers and, if necessary, in interactions with other parameters. In addition, they must provide the trend of action levers in relation to service life and environmental impact indicators and, characterize the most favorable values of action levers allowing longest service life and smallest environmental impact indicators. Consequently, a combination of Sobol's quantitative [66] and Morris' qualitative SA methods [67] is chosen. Both methods require that all the parameters are independent of one another. This combination has been previously used for the same purpose environmental design using LCA [68] [69].

I.4. Description of the case study

The case study studied here consists of a RC structure subjected to carbonation. The structure is assumed to be located in Madrid (Spain) because this location presents optimal environmental conditions for carbonation of concrete [70] [71]. Madrid, indeed, is a place with a high level of air pollution [72] and with an average relative external humidity of about 0.56 [9]. The considered structure follows the recommendations of EN 206-1 for XC4 exposure class [10]: concrete is exposed to the air and the structure is not sheltered from rain.

The two structure deterioration periods due to carbonation are corrosion initiation and propagation periods [73]. The first period corresponds to the penetration of CO_2 into the concrete cover until the carbonation front reaches the reinforced layer. Corrosion is then likely to occur because reinforcing steels are not passivated anymore. The second period includes (i) steel corrosion; (ii) cross section loss; (iii) concrete surface cracking; and (iv) spalling of concrete cover. Because the definition of “service life” in Definitions indicates that the service life of RC structure is limited to the corrosion initiation period, this case study deals with this period only.

II. A NEW SERVICE LIFE MODEL

This Chapter focusses on step 1 (n°2 Figure 1). We conducted a literature review on the influential parameters on carbonation process and the existing carbonation models based on Fick's first law. We found that the existing carbonation models consider some of identified influential parameters, but none of them include all. Furthermore, most of the models have been validated using some experimental results obtained with either accelerated carbonation laboratory tests or local concrete used. The carbonation rate obtained with accelerated carbonation is lower than the natural carbonation one. Consequently, those models may not be used for the accurate prediction of the carbonation depth under natural conditions, taking all the influential parameters into account. Therefore, a meta-model to calculate carbonation front depth by using only technological parameters as inputs (as concrete mixtures, cement type, etc.) and environmental parameters (as ambient temperature, relative external humidity and CO_2 concentration in the air) is developed in this paper.

Résumé :

Dans ce papier, nous avons développé un méta-modèle pour prédire la profondeur de carbonatation naturelle en béton. Une analyse bibliographique des modèles existants montre qu'aucun modèle n'intègre l'ensemble des paramètres identifiés comme influents par la littérature. Ce méta-modèle intègre donc un maximum de paramètres de conception ainsi

que des paramètres aléatoires liés à l'environnement immédiat du matériau. Il s'appuie sur des modèles existants dans la littérature et intègre des nouvelles équations. Notre méta-modèle est validé avec des résultats dans la littérature pour des cas de carbonatation naturelle, pour des périodes d'exposition allant de 21 jours à 35 ans, trois types de ciment (CEM I, CEM II et CEM III), un rapport eau sur ciment de 0,45 à 0,8, un pourcentage de ciment portland remplacé par les cendres de volants jusqu'à 50%, une période de cure de 1 jour à 28 jours et différentes conditions environnementales. De plus les profondeurs de carbonatations modélisées présentent une meilleure corrélation avec les résultats expérimentaux qua les résultats obtenus avec deux autres modèles (modèles de Yang [74] et de Papadakis [75]).

II. 1. Abstract

Carbonation processes cannot be ignored as regards durability and service-life of new concrete structures, and their correct understanding and quantification are essential for maintenance and repair works on existing structures. This paper initially presents a new meta-model developed to calculate carbonation front depth based on Fick's first law. The only input data required by this non numerical model are: (i) material variables (concrete mix design, maximum nominal aggregate size, cement type, and chemical composition of cement type CEM I and cement density); (ii) technological parameters (initial curing period (t_c)); (iii) environmental parameter (ambient temperature (T), relative external humidity (RH) and CO_2 concentration in the air (CO_2)). Consequently, this model is fully suitable for the prediction of carbonation depth in the case of new RC structures, for which these required parameters are well-known. The meta-model is validated using data from the literature on short and long-term natural carbonation exposure conditions. Most of the experimental data concern CEM I, CEM II, CEM III cement types, and CEM I additives (fly ash (FA)) with various water-to-cement ratios and initial curing period (t_c). The meta-model is also compared with two already available models: Papadakis' model and Yang's model. The three model predictions are compared with the corresponding values found in the literature. The results confirm that the prediction of the new meta-model proposed here for estimation of carbonation depth is the most accurate in every case.

Key-words: natural carbonation, reinforced concrete, Fick's first law, meta-model.

II. 2. Introduction

The corrosion of steel reinforcements is a major cause of the degradation of RC structures. The corrosion of RC structures is due both to the ingress of chloride ions and to carbonation. It is considered as a two-stage process: (i) corrosion initiation stage; and (ii) corrosion propagation stage [76]. Carbonation is a widespread degradation of concrete, which can be coupled with more severe deteriorations [54]. This paper focuses on carbonation phenomena only: mechanism, influence factors and carbonation modelling.

The carbonation of cementitious materials is caused by carbon dioxide (CO_2) in the air within a range of 350 up to 380 ppm (parts per million), corresponding to a volume concentration ranging between 0.00057 kg/m^3 and 0.00062 kg/m^3 [7]. CO_2 dissolves in the aqueous pore solution and produces carbonic acid (H_2CO_3). Carbonation is the result of a neutralization reaction between basic compounds of hydrated cement (essentially calcium hydroxide ($Ca(OH)_2$) and calcium-silicate-hydrate (CSH)) and H_2CO_3, producing calcite ($CaCO_3$) and water (H_2O) [75] [77]. This provokes a drop in pH. The depth of the carbonated cement concrete front increases with time. When it reaches the reinforced layer, corrosion is likely to occur because steel bars are not passivated anymore.

Carbonation models have been extensively developed to predict carbonation depth. Currently, available carbonation models have been developed with different approaches and for different cases by underlying, for instance, the influence of the material composition, of the environmental conditions, etc. Many papers discussing the different modelling approaches of carbonation process can be found in the literature. The models can be divided into three main categories:

- Empirical [78];
- Semi-empirical [3] [75] [71], [74], [79]–[82];
- Numerical [83]–[86].

Currently, existing models have limitations that prevent some possible applications for civil engineers as regards life cycle design of RC structures. This is for two main reasons: (i) numerical models are difficult to use because they require accurate and complete data (the number and accuracy of input parameters required are too large and time consuming); (ii) semi-empirical models are quite simple but have generally been developed to match specific application cases, like special additives [81], or influence of initial curing period (t_c) [87].

The aim of this paper is to propose a general model for carbonation, which can be used by civil engineers in as many application cases as possible. This model must be sufficiently accurate, physically and chemically correct, as simple as possible and based on information which is available from the structure design. This approach is based on already existing semi-empirical, a more user-friendly format to civil engineers [88].

This paper initially presents a literature review on studies conducted on semi-empirical models based on Fick's first law using the diffusion coefficient of CO_2 and the amount of CO_2 absorbed to predict the carbonation depth of RC structures exposed to given environmental atmospheric conditions.

Then, a simple meta-model to calculate concrete carbonation depth under natural carbonation process based on Fick's first law is described. This meta-model takes many influencing factors, which were previously considered in separate models like concrete mix design, sand to gravel ratio, maximum aggregate size , cement type, and chemical composition of cement of cement type CEM I and cement density, t_c, ambient temperature (T), relative external humidity (RH), and CO_2 concentration in the air (CO_2).

Finally, the meta-model is validated using some data on the short and long-term natural carbonation exposure conditions with different water to cement ratios, t_c, and cement types (CEM I, CEM II, CEM III, and CEM I additives (FA)) found in the literature.

II. 3. Literature review on carbonation models based on Fick's first law

II.3. 1. Fick's first law

After a sufficiently long period of time, the carbonation process can be modeled using the scheme presented in Figure 6 where three zones can be distinguished [89]–[92]. The first zone, close to the surface exposed to air, is considered fully carbonated: its carbonate content is constant. Then, a transition zone, often referred carbonation front, corresponds to the part of concrete material, for which the level of carbonation gradually decreases from its maximum (at interface with the first zone) to zero, and finally, a third where no carbonation is observed.

Because the carbonation is governed by the diffusion of carbon dioxide within concrete, the square root of time formula is commonly used for carbonation modelling. The CO_2 diffusion model proposed by Klopfer [93] is based on the analysis solution of Fick's first law in the form:

$$x_{CO_2} = A.\sqrt{t} \tag{1}$$

where: x_{CO_2} (m) is the carbonation front depth, t (s) is the exposure time and the carbonation coefficient A (m/s1/2) is determined as:

$$A = \sqrt{\frac{2.D_{CO_2}.CO_2}{a}} \tag{2}$$

where: D_{CO_2} *(m^2/s) is the CO_2-diffusion coefficient in carbonated concrete, a (kg/m^3) is the amount of CO_2 absorbed,* CO_2 *(kg/m^3) is the CO_2 concentration in the air.*

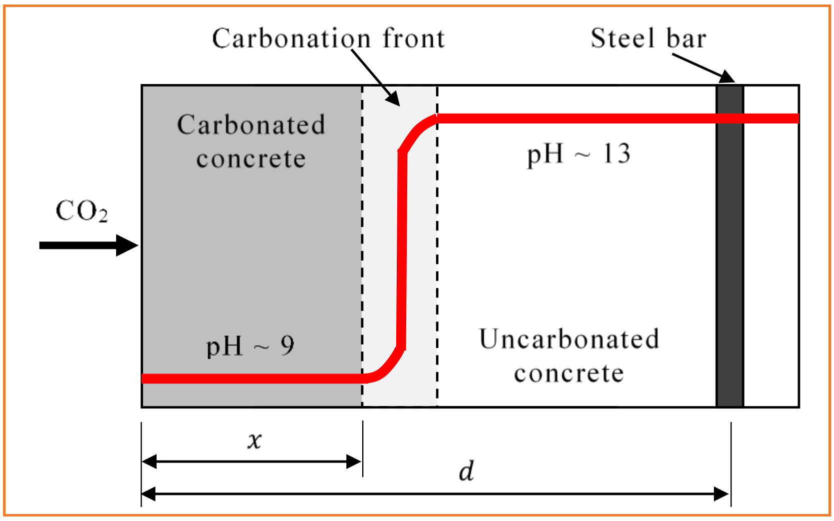

Figure 6. Drop in pH in the concrete cover depth due to carbonation.

Depending on the models developed, more or less material variables, technological and environmental factors are taken into account. The main models used for prediction are summarized in Table 3.

For some of the models based on Fick's law, it is assumed that the medium, in which diffusion takes place, does not change over time and admit the use of a constant diffusion coefficient [80].

The diffusion of CO_2 depends not only on the CO_2 concentration gradient but also on the concrete microstructures. This is a substantial simplification of the description of the carbonation process based on Fick's law, which does not take many additional factors discussed below like change in diffusivity as a function of humidity, qualitative and quantitative characteristics of the material composition of concrete (as water-to-cement ratio (W/C), type of cement, etc.), technological (as t_c) and environmental factors (as T, RH) into account.

The amount of CO_2 absorbed also effects the carbonation rate. The existing models consider different expression of a (Table 3).

II.3. 2. Amount of CO_2 absorbed: a (kg/m^3)

Papadakis [75], Salvoldi et al. [71] and Bakker [80] show that the constituents of hardened cement paste subjected to carbonation are principally $Ca(OH)_2$ and CSH in the presence of moisture, and calcium silicates ($3CaO.SiO_2$ and $2CaO.SiO_2$) prior to hydration. From on the chemical reactions of hydration, they develop some mathematical models based on some experimental parameters to determine the molar concentration of the carbonated constituents of the paste per unit volume of concrete.

Yang et al. [74] and Jiang et al. [81] show that the ultimate value of the molar concentration of the constituents, which can potentially be carbonated, highly depends on the concrete cement content. When increasing the amount of cement, the amount of CO_2 absorbed increases. Consequently, the molar concentration of the carbonated constituents is directly proportional to the cement content.

II.3. 3. CO_2-diffusion coefficient: D_{CO_2} (m^2/s)

As already stated, assuming the diffusion coefficient to be constant like in Bakker [80] is not appropriate in this case. In the model proposed by Millington [94], the CO_2-diffusion coefficient is calculated as the function of the CO_2-diffusion coefficient in the air, the porosity and the concrete saturation level in the form [94]:

$$D_{CO_2} = D^{o}_{CO_2}.\phi^{k}.(1-S)^{g} \quad (3)$$

where: $D^{o}_{CO_2}$ (m2/s) is the CO2-diffusion coefficient in the air (1.6 × 10-5 (m2/s)), ϕ (n.u.) (n.u. = no unit) is the concrete porosity, S (n.u.) is the concrete saturation level or called the internal relative humidity, k and g (n.u.) are empirical constant coefficients ($k = 2.74$ and $g = 4.20$).

During natural carbonation, the concrete drying rate is supposed to be higher than the carbonation rate and the internal relative humidity will reach a steady state with the external relative humidity on a time-averaged basis [71]. Based on that assumption, many studies [81] [74] [84] [95] [96] suggest that RH can be used as the concrete saturation degree ($RH = S$).

Concerning Table 3, we found that the models of CO_2-diffusion coefficient in concrete are based on Eq. (3). Some authors, moreover, have added some material variables and some technological and environmental factors: Papadakis' model [75] [95] [97], for example, takes the decreasing in the concrete porosity due to carbonation into account. In Fib [7], a complex model, where many effects are considered (as t_c, $RH$and the weather function ($W_e(t)$)). Jiang's model [81] takes the high-volume of fly ash content in concrete into account. Yang's model [74] introduces correction factors by considering not just the substitution of supplementary cementitious materials, the finishing materials but the exposure time also.

II.3. 4. Conclusion: needs for a new meta-model

This literature review has been carried out according to the different factors affecting carbonation process. They can be classified as internal or external. The internal factors are: (i) concrete compounds like cement type [82], maximum aggregate size (S_max) [98] (ii) concrete composition like sand-to-gravel ratio (S/G) [98], W/C [75] [77] [99]–[103], cement content [77] [102] [104], and mineral admixture [81] [97] [99] [102] [105]–[113], (iii) concrete properties like porosity and CO_2 diffusivity [96] [114]. The external factors are: (i) environment like CO_2 [115], T [83] [90] [91] [115] [116], RH [75] [117], (ii) technology like structure surface condition (crack) [100], t_c [87] [118]–[120]. This extensive literature review reveals that the rate of carbonation increases with increasing CO_2, T, W/C, S_max, early-aged crack width. However, the rate of carbonation decreases with the increase of the 28-day compressive strength (f_c)), t_c, S/G and cement content. The highest carbonation rates are observed for RH values between 55% and 75%. The incorporation of FA or ground granulated blast furnace slag (GGBFS) in ordinary Portland cement (CEM I) both decreases carbonation resistance of RC structures, though at significantly different levels. The carbonation resistance of RC structures with GGBFS is better than RC structures with FA [113]. The present study concentrates on FA admixture mixed with CEM I only.

The carbonation models presented in Table 3 consider some of these factors, but none of them include them all. None of the models into account the influence of T. The carbonation rate increases with increasing T due to increased molecular activity [121] [122].

Only Fib's model [7] takes into account the effect of t_c, for instance. However, in order to use this model to predict the depth of carbonation under natural condition, an accelerated laboratory test is necessary to determine the carbonation resistance ($R_{ACC,0}^{-1}$) [7].

Most of the models presented in Table 3 have been validated using some experimental results obtained with accelerated carbonation laboratory tests. The carbonation depths have been measured on the local concrete used. Fib [7] indicates that the carbonation rate obtained with accelerated carbonation is lower than the natural carbonation one. Consequently, these models may not be used for the accurate prediction of the carbonation depth under natural conditions taking all the influencing parameters into account. Therefore, a meta-model to calculate carbonation front depth by using only technological parameters as inputs (as concrete mixtures, cement type, chemical composition of cement type CEM I, cement density and t_c) and environmental parameters (as T, RH and CO_2) is proposed in the second part of this article. This model, is contrast, takes many important factors influencing the carbonation process into account. Finally, the model is validated using some experimental results obtained under natural carbonation conditions.

Table 3. Summary table of simplified carbonation models based on Fick's first law.

Amount of CO_2 absorbed: a (kg/m^3)	**CO_2-diffusion coefficient: D_{CO_2} (m^2/s)**	**Validation**	**Ref.**
$a = [CH]$	$D_{CO_2} = 4.8 \times 10^{-7}$	Accelerated	[80]
$a = [CH]$	$D_{CO_2} = 23.32 D_{CO_2}^{ref} (1 - RH)^2 RH^{2.6}$	Accelerated	[71]
$a = (1 - \phi).([CH] + 3[CSH] + 3[C_2S] + 2[C_4AF] + [C_3A])$	$D_{CO_2} = \phi.(1 - \Psi).D_{CO_2}^{o}$	Accelerated	[123]
$a = 0.33.[CH] + 0.214.[CSH]$	$D_{CO_2} = D_o \left(\frac{\phi_{carbon} - \phi_{air}}{\frac{W}{\rho_w} + \frac{C}{\rho_c} + \frac{FA}{\rho_{fa}}} \right)^n \times (1 - RH)^{2.2}$	Accelerated	[75] [95] [97]
$a = \frac{366.7 \times 10^{-3} t.W}{(2 + t).\left(1 - \frac{W}{C}\right)}$	$D_{CO_2} = 158.05 \times 10^{-9}.\beta_s.\beta_f.(1 - RH)^{0.6} \left(\frac{G + S}{C}\right)^{0.1} . \frac{0.1 + 2.62 \left(\frac{W}{C}\right)^{4.2} . t}{1.5t \left(\frac{W}{C}\right)^2}$	Natural	[74]
$a = \Psi \left(1 - \frac{\Psi_{fa} \times FA \times Al_2O_3}{19.06 \times 10^{-3}(1 - FA)}\right)$	$D_{CO_2} = 8165472 \times 10^{-11}(1 - RH)^{2.2} \left(\frac{W}{C} - 0.34\right)$	Accelerated	[81]
$\frac{D_{CO_2}}{a} = \left(\frac{1 - RH^5}{1 - 0.65^5}\right)^{2.5} . \left(\frac{t_c}{7}\right)^{-0.567} . \left(1.25 R_{ACC,0}^{-1} + 10^{-11}\right). W_e(t)^2$		Accelerated	[7]

where:
$[CH]$, $[CSH]$, $[C_2S]$, $[C_4AF]$ and $[C_3A]$ (kg/m^3) are the hydrate and anhydrate contents (C = CaO, S = SiO_2, A = Al_2O_3, F = Fe_2O_3)
$[Al_2O_3]$ (n.u.) is the amount of Al_2O_3 per weight cement;
$D_{CO_2}^{ref}$ (m^2/s) is the CO_2-diffusion coefficient determined with RH value about 0.58;
Ψ (n.u.) is the degree of hydration of cement;
Ψ_{fa} (n.u.) is the degree of hydration of fly ash;
D_o (m^2/s) and n (n.u.) are constant depending on W/C ratio;
β_s (n.u.) is the correction factor for substitution of supplementary cementitious materials;
β_f (n.u.) is the correction factor for finishing materials on concrete surface.
RH (n.u.) is the relative external humidity;
W, C, S, G, FA (kg/m^3) are the water, cement, sand, gravel, fly ash content respectively;
Other parameters are defined in the main text.

II. 4. Meta-model

A new generic model built upon several already available specific models is presented. It is specifically developed to suit any situation by improving some of the former model relationships. That is why we call it “meta-model”.

The assumptions/simplifications are made to develop the meta-model:

1) Carbonation is modeled as a sharp carbonation front moving inwards [124].
2) Carbonation is controlled by the CO_2-diffusion under steady state [115], i.e. the reaction of dissolved CO_2 is much faster than the CO_2-diffusion process [124].

Figure 7 displays the logic of the model. The following sub-section of this part presents a detailed discussion of the fundamental choices and transformations of the equations used in the meta-model.

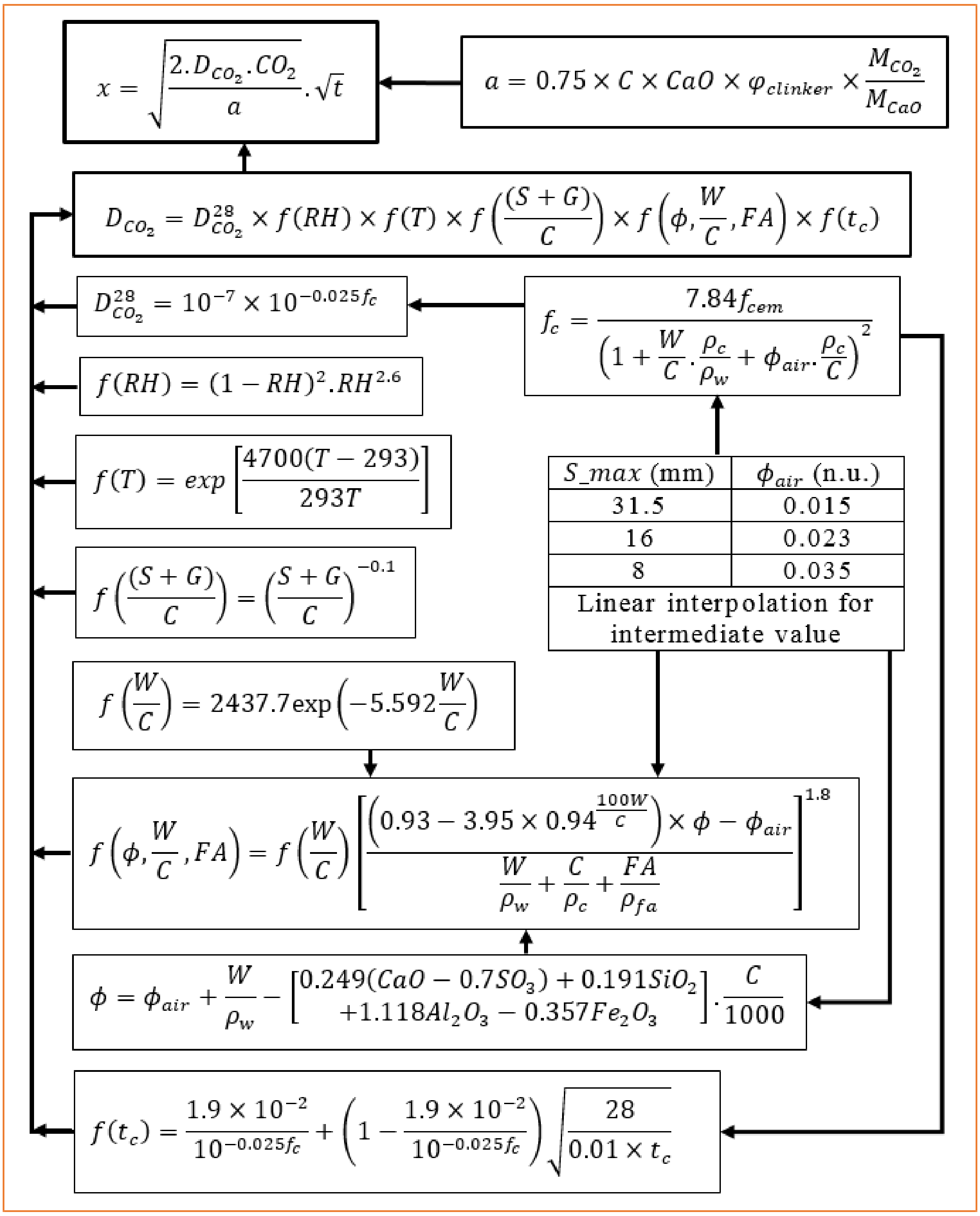

Figure 7. Carbonation meta-model [125].

II.4. 1. Calculation of the amount of CO_2 absorbed: a (kg/m^3)

Pade and Guimaraes [126] have shown that 75% of the original calcium oxide, CaO, in the Portland cement clinker changes into calcium carbonated concrete. Thus, considering the cement paste concrete can be assumed completely carbonated. The amount of CO_2 absorbed per volume of completely carbonated concrete is given by [126]:

$$a = 0.75 \times C \times CaO \times \frac{M_{CO_2}}{M_{CaO}} \quad (4)$$

where: C (kg/m^3) is the cement content, CaO (n.u.) is the amount of calcium oxide per weight of cement, M_{CO_2} and M_{CaO} (g/mol) are the molar weight of CO_2 and CaO respectively.

Eq. (5) was established for Portland cement (CEM I) including the highest cement Portland clinker and CaO content (from 95% to 100% for clinker with an average CaO content of 65%) [126]. The literature review reveals that, the increases in clinker content in cement generally increases the amount of CO_2 absorbed [56] [82]. Natural carbonation tests have been conducted by Hyvert et al. [82] for mortars with a W/C of 0.5 on different cement types like CEM I 52.5N, CEM II A/L 52.5N, and CEM III A 42.5N containing 97.5%, 87%, and 56% of clinker, respectively. The experimental results obtained show that the carbonation rate of CEM I is the lowest, followed by CEM II and CEM III.

Thus, in order to consider the different cement types corresponding to various clinker and CaO contents [127], we introduced the cement clinker content ($\varphi_{clinker}$) into Eq.(5) to obtain the amount of CO_2 absorbed as:

$$a = 0.75 \times \varphi_{clinker} \times C \times CaO \times \frac{M_{CO_2}}{M_{CaO}} \quad (5)$$

II.4. 2. Calculation of CO_2-diffusion coefficient: D_{CO_2} (m^2/s)

In the meta-model, the CO_2 diffusion coefficient is determined by introducing some functions, which depends on the parameters influencing the carbonation process, as:

$$D_{CO_2} = D_{CO_2}^{28} \times f(RH) \times f(T) \times f\left(\frac{S+G}{C}\right) \times f\left(\phi, \frac{W}{C}, FA\right) \times f(t_c) \qquad (6)$$

The expression of those functions is detailed below.

a) Function $D_{CO_2}^{28}$

The function for the CO_2 diffusion coefficient in fresh concrete ($D_{CO_2}^{28}$) has been proposed in [95], which is calculated through 28-day compressive strength (f_c). In this study, we introduce the f_c model proposed in [128] into $D_{CO_2}^{28}$ function as shown in Figure 7.

b) Function $f(RH)$

This function allows to consider the relative external humidity (RH). This function was formed based on the long-term experiments in natural conditions where the same concrete was exposed to the different RH [71] (Figure 7).

c) Function $f(T)$

According to Yan and Jiang [129], we assume that the temperature inside concrete is constant and equal to ambient temperature (T) under natural carbonation. Thus, we introduced the function $f(T)$ (Arrhenius' law [90]) to consider the effect of T on the carbonation process (see Figure 7).

d) Function $f\left(\phi, \frac{W}{C}, FA\right)$

Concrete with Fly Ash (FA) has a higher carbonation rate than plain concrete. The impact of FA on the carbonation rate is obviously affected by the water-to-cement ratio (W/C). In order to consider the replacement of CEM I by FA into mix concrete and the reduction of concrete porosity due to carbonation [130], Papadakis [97] [131] proposes a functional relationship between the porosity of carbonated concrete, the W/C and amount of CEM I replaced by FA is given by:

$$f\left(\phi_{carbon}, \frac{W}{C}, FA\right) = \left(\frac{\phi_{carbon} - \phi_{air}}{\frac{W}{\rho_w} + \frac{C}{\rho_c} + \frac{FA}{\rho_{fa}}}\right)^n \tag{7}$$

where: ϕ_{carbon} (n.u.) is the carbonated concrete porosity, ϕ_{air} (n.u.) is the volume fraction of entrained air into the mix, W (kg/m^3) is the water content of concrete, FA (kg/m^3) is the fly ash content of concrete, ρ_w, ρ_c, ρ_{fa} (kg/m^3) are the densities of water, cement, and fly ash, respectively, and n (n.u.) is an empirical constant: n = 1.8 for 0.5 < W/C < 0.8.

To account for the effects of maximum aggregate size (S_max) used in the mix, we used an approximate estimation of ϕ_{air} from S_max proposed by several studies [132] [128]. In this study, we used the values proposed by Papadakis and Demis [128] (see Figure 7).

From Eq. (7), the expression considering the influence of non-carbonated concrete porosity, the W/C and CEM I + FA contents in concrete, $f(\phi, W/C, FA)$ was established. The solution for ϕ_{carbon} was obtained by combining the function of porosity of carbonated concrete proposed by Park [86] (Eq. (8)) with that of porosity of a concrete with CEM I (ϕ) proposed by Papadakis [133] (Eq. (9)).

$$\phi_{carbon} = \left(0.93 - 3.95 \times 0.94^{\frac{100W}{C}}\right) \times \phi \tag{8}$$

with:

$$\phi = \phi_{air} + \frac{W}{\rho_w} - \begin{bmatrix} 0.249(CaO - 0.7SO_3) + \\ 0.191SiO_2 + 1.118Al_2O_3 - 0.357Fe_2O_3 \end{bmatrix} . \frac{C}{1000} \tag{9}$$

where: SO_3, SiO_2, Fe_2O_3 (n.u.) are the amount of sulfur oxide, silicon oxide, iron oxide per weight CEM I cement type respectively.

For the application of Eq. (7) to the W/C lower than 0.5, a function $f(W/C)$ was introduced. The function values were calculated using experimental data, which were measured at concrete cured of 28 days, by Balayssac et al. [120] for each W/C with the range 0.48 - 0.65 (Figure 8). The law for $f(W/C)$ was determined using the technique of value fitting as shown in Figure 8 (with a determination coefficient R^2 = 0.9849). We obtained:

$$f\left(\frac{W}{C}\right) = 2437.7exp\left(-5.592\frac{W}{C}\right) \tag{10}$$

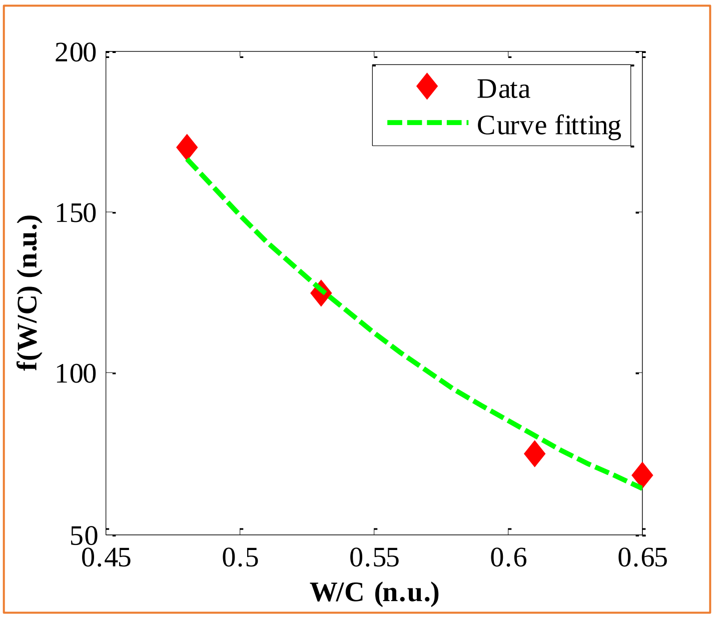

Figure 8. Normalized data from Balayssac et al. [120] showing $f(W/C)$ versus W/C.

Finally, the solution for $f(\phi, W/C, FA)$ is:

$$f\left(\phi, \frac{W}{C}, FA\right) = f\left(\frac{W}{C}\right)\left[\frac{\left(0.93 - 3.95 \times 0.94^{\frac{100W}{C}}\right) \times \phi - \phi_{air}}{\frac{W}{\rho_w} + \frac{C}{\rho_c} + \frac{FA}{\rho_{fa}}}\right]^{1.8} \tag{11}$$

In the particular case of CEM II cement type containing FA, FA value is taken to be zero in Eq. (11) for [120] [134] [135].

e) Function $\boldsymbol{f(t_c)}$

An empirical correction term has been proposed by Fib's model [7] to take the effect of t_c on the carbonation rate into account as follows:

$$f(t_c) = \left(\frac{t_c}{7}\right)^{-0.567} \tag{12}$$

However, this model does not include the influence of the environmental conditions during curing time (e.g. T and RH). In this study, the new model proposed allows for this influence of t_c. Saetta's modelling of the impact of t_c takes the form [84]:

$$f(t_c) = \chi + (1 - \chi).\sqrt{\frac{28}{t_e}} \tag{13}$$

where: χ (n.u.) is a constant varying from 0 to 1 and t_e (days) is defined as the equivalent initial curing period. It is a function of RH and T.

According to Bazant and Najjar [136] t_e is a function of RH and T expressed as:

$$dt_e = \beta_{RH}.\beta_T.dt \tag{14}$$

where: β_{RH} (n.u.) and β_T (n.u.) are functions of RH and T, respectively.

The expression for β_{RH} (n.u.) is given by [136]:

$$\beta_{RH} = [1 + (7.5 + 7.5RH)^4]^{-1} \tag{15}$$

β_T (n.u.) obeys Arrhenius' law and is expressed as [136]:

$$\beta_T = exp\left[\frac{E_a^{hydration}}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \tag{16}$$

where: $E_a^{hydration}$ (J/mol/K) is the hydration activation energy, R (8.314 J/mol/K) is the perfect gas constant, and T_{ref} (293K) is the reference temperature.

Eq. (13) and Eq. (14) can be used in numerical models but not in semi-empirical models. Furthermore, setting the value of constant χ can be tricky. To solve these problems, a new model taking the impact of t_c into account was developed. Eq. (13) was simplified by developing the relationship between t_e and t_c, and setting the constant χ to a constant value.

The hydration activation energy to gas constant ratio, indeed, here taken to be 2500 (K) [136] but depends otherwise on the concrete constituents. Furthermore, concrete tests specimens are generally cured in a temperate room at 20°C and with RH = 0.9 (or 90%) [136]. By introducing these values into Eq. (15) and Eq. (16), and then by calculating the integral of Eq. (14), the solution obtained takes into account the effect of t_c upon concrete carbonation as:

$$f(t_c) = \chi + (1-\chi)\sqrt{\frac{28}{0.01 \times t_c}} \tag{17}$$

Moreover, Kari's study [137] shows that the constant χ can be expressed by the ratio of the CO_2 diffusion coefficient in water around 1.9×10^{-9} m^2/s [138] to that in concrete at an age of 28-day ($D_{CO_2}^{28}$) as shown in Figure 7. Eq. (17) becomes:

$$f(t_c) = \frac{1.9 \times 10^{-2}}{10^{-0.025 f_c}} + \left(1 - \frac{1.9 \times 10^{-2}}{10^{-0.025 f_c}}\right)\sqrt{\frac{28}{0.01 \times t_c}} \tag{18}$$

II. 5. Validation and discussions

To validate the developed meta-model, the carbonation depth predicted by the experimental model was compared with the results data found in the literature and obtained under natural conditions [54] [109] [120] [134] [135] [33] [70] [139] [140] [141]. These data refer to various short and long-term exposure times. When the chemical composition of cement is not indicated, like in [120] [134] [135] [139] [33] [70] [141], the values of chemical composition of cement are assessed from the VDZ Activity Report [142] and [143]. The developed model was compared with the three already available models: Papadakis' model, Yang's model, and Fib's model. The four model predictions were compared with those corresponding experimental values.

II.5. 1. Different initial curing period

The model was validated using experimental data found in Balayssac et al. [120]. Where four different concrete types with a W/C of 0.48, 0.53, 0.61, and 0.65, respectively, are considered. After three different t_c (1-day, 3-day, and 28-day), they are stored at temperature 20°C and humidity of 60% RH (with CO_2 of 0.03% or 0.00049 kg/m^3) for up to 18 months. For each curing time and each concrete specimen, carbonation depths are measured at 90, 180, 360, and 540 days. Figure 9 presents the comparison of the experimental carbonation depths with those calculated by the meta-model using a hypothetical line of perfect equality. This line corresponds to the first bisector, on which both calculated and experimental carbonation depths would superimposed perfectly. Most of the experimental data are above the line of equality, which indicates that the predicted carbonation depth values are generally higher than the experimental ones. However, most results are within a +30%/-20% margin of error. The determination coefficient determined between the 48 plotted points and the line of equality is determined R^2 = 0.85.

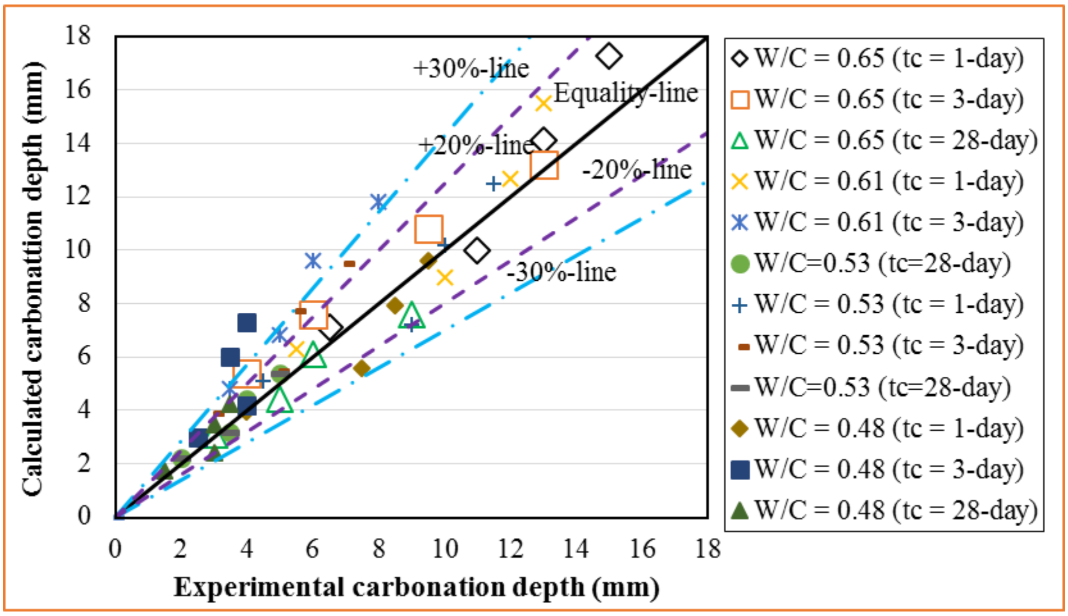

Figure 9. Comparison between calculated and experimental carbonation depths with different t_c.

Moreover, among all the models discussed in Table 3, Fib's model [7] only, takes the effect of t_c into account. If we take the carbonation depth after a 28-day curing period as a reference value, the mean ratio of the carbonation depths to the initial curing period, ranging t_c = 1 day and t_c = 28 days, i.e., for t_c = 3 days and 28 days, is determined using Balayssac's data [120], the developed model and Fib's model for four different water-to-cement ratios (Table 4). The calculated relative errors confirm that the meta-model predictions are more accurate than the Fib's model ones.

Table 4. Comparison between carbonation depth predictions obtained with the meta-model and Fib's model with different t_c.

	Balayssac's data [120]	Developed model	Fib's model [7]
$r_{1-day} = \frac{x_{CO_2}(t_c = 1-day)}{x_{CO_2}(t_c = 28-day)}$	2.38	2.3	2.57
$Relative\ error = \frac{\lvert r_{1-day}^{exp} - r_{1-day}^{model}\rvert}{r_{1-day}^{exp}}$		3.36 %	7.98 %
$r_{3-day} = \frac{x_{CO_2}(t_c = 3-day)}{x_{CO_2}(t_c = 28-day)}$	1.45	1.78	1.88
$Relative\ error = \frac{\lvert r_{3-day}^{exp} - r_{3-day}^{model}\rvert}{r_{3-day}^{exp}}$		22.75 %	29.66 %

II.5. 2. Comparison with different experimental data obtained at short exposure times

A comparison between the meta-model predictions and other experimental results obtained by Rozière et al. [54], Galan et al. [139], Chatveera et al. [140], Valcuende and Parra [134], Jones et al. [135], De Ceukelaire and Nieuwenburg [70], and Khungthongkeaw et al. [109] is made. A large amount of experimental data on CEM I, CEM II, and CEM III cement types, CEM I + FA with different water-to-cement ratios are collected. The results are presented in Figure 10. They reveal that, apart from the data by Jones et al. [135] with CEM I 32.5N and W/C = 0.59, which are above a +20% margin of error and for which the meta-model overestimates the carbonation depth, most other predictions are within the ±20% margin of error.

The determination coefficient determined among all the plotted points (65 points) and the line of equality R^2 = 0.86. The model predictions are reasonably accurate compared with the experimental data with different water-to-cement ratios, cement types and CEM I + FA with a FA content from 0 up to 50%.

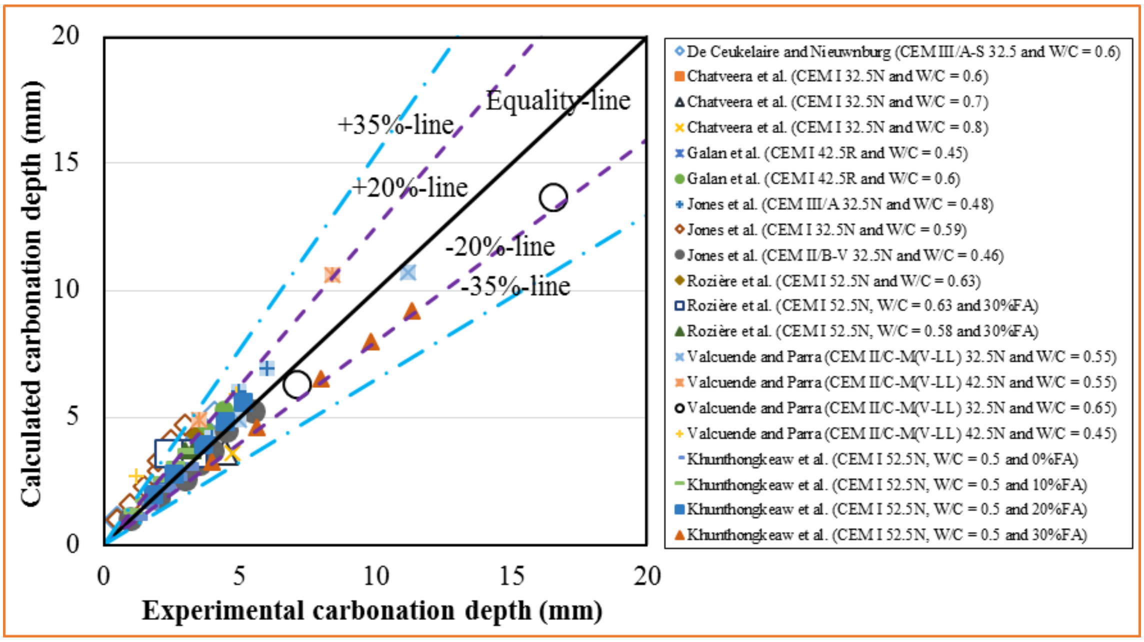

Figure 10. Comparison between calculated and experimental carbonation depths with different water-to-cement ratios and cement types.

II.5. 3. Comparison two different water-to-cement ratios at long exposure time

The reliability of the model, carbonation depth predictions is validated using results measured on actual concrete structure found in the literature [141] (Figure 11). Carbonation depth results of the models proposed by Papadakis et al. [75] [95] [97] and Yang et al. [74], are also plotted in the same figure. Papadakis' model tends to underestimate the carbonation depths whereas Yang's one overestimates them. Model predictions, on the other hand, are in good agreement with measurements.

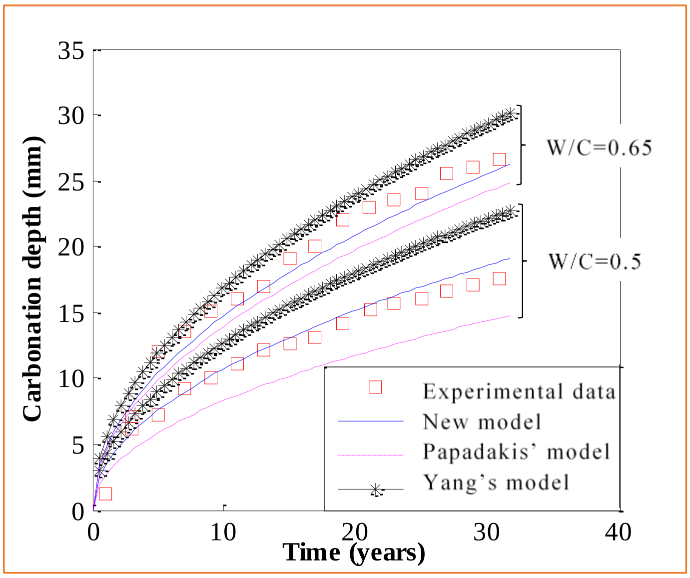

Figure 11. Comparison between calculated and experimental carbonation depths with different water-to-cement ratios.

Figure 12 presents the comparison between the carbonation depth results obtained with the meta-model, Papadakis' model [75] [95] [97], and Yang's model [74] and those measured on a concrete bridge structure located in Seoul (Korea) [33]. The experimental carbonation depth of this concrete structure is examined after 18 years exposure to urban atmospheric conditions. The annual atmosphere concentration of CO_2 in Seoul is 355 ppm (0.00058 kg/m^3). A phenolphthalein pH indicator is used to determine the carbonation depth at 113 sampling points, and the average experimental carbonation depth 11.6 mm with a standard deviation of 2.45 mm [33].

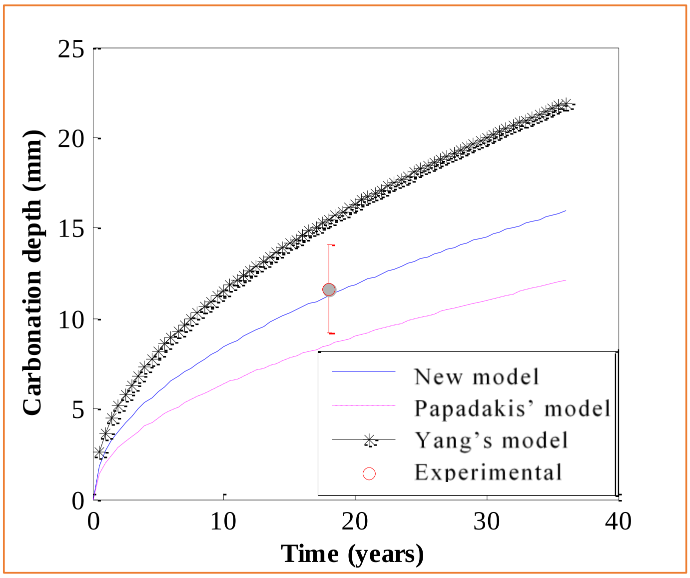

Figure 12. Comparison between calculated and experimental carbonation depths results by Anne et al. [33].

Figure 12 shows that Papadakis' model underestimates the carbonation depth whereas Yang's model overestimates it. Papadakis' and Yang's predictions are both outside standard deviations upper and lower limits. The meta-model predicted values, on the other side, are within a satisfactory range, close to the average value and within the standard deviation.

In both cases studied here and in relation to the experimental results, Papadakis' [75] [95] [97] and Yang's [74] models systematically underestimate or overestimate carbonation depth, respectively. Regarding service times on RC structures, e.g., maintenance repair strategies, etc., Yang's model [74] can be considered more secure.

II.5. 4. Comparison with all collected data (any cases material and environmental cases)

All the data collected are used for comparison in this subsection: 153 carbonation depths measured on different materials, with different t_c and under different environmental conditions. These experimental data are compared with the calculated carbonation depths obtained using the three models (the meta-model, Papadakis' model [75] [95] [97] and Yang's model [74]). Figure 13, Figure 14, and Figure 15 present the results of the different comparison, respectively. For each comparison, the determination coefficient, R^2, is calculated between the data and the line of equality. The R^2 value obtained for the meta-model indicates that the predictions satisfactorily agree with the measured data. Therefore, we can say that the carbonation depth in concrete can be reasonably estimated by the meta-model presented in this paper. Papadakis' and Yang's models may, on the other side, cannot be used against data collected for the experimental investigation carried out to determine the impact of t_c on the carbonation rate like in Balayssac et al. [120]. The comparison results reveal that most of the data on the long-term are overestimated by Yang's model [74]. However, the prediction is more secure for reinforced concrete structures as regards maintenance strategies. Papadakis' model [75] [95] [97], on the other hand, underestimates most of the data.

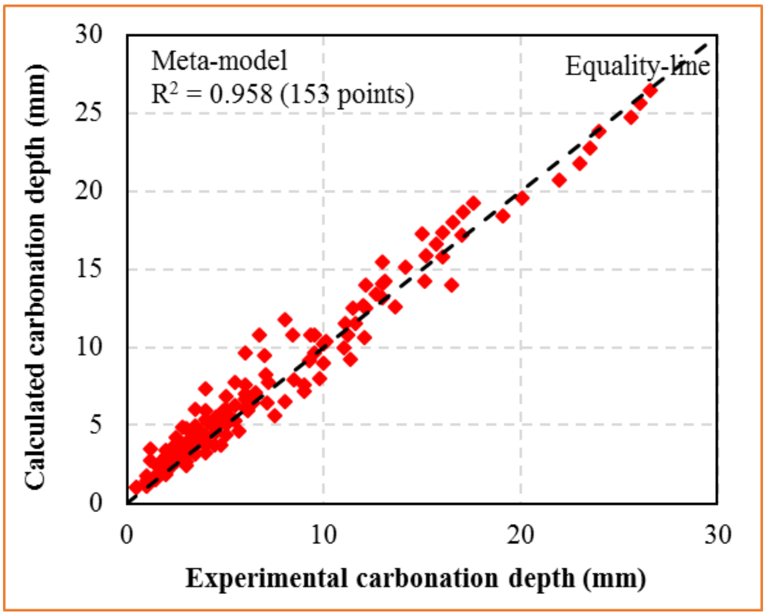

Figure 13. Comparison between calculated and experimental carbonation depths using the meta-model.

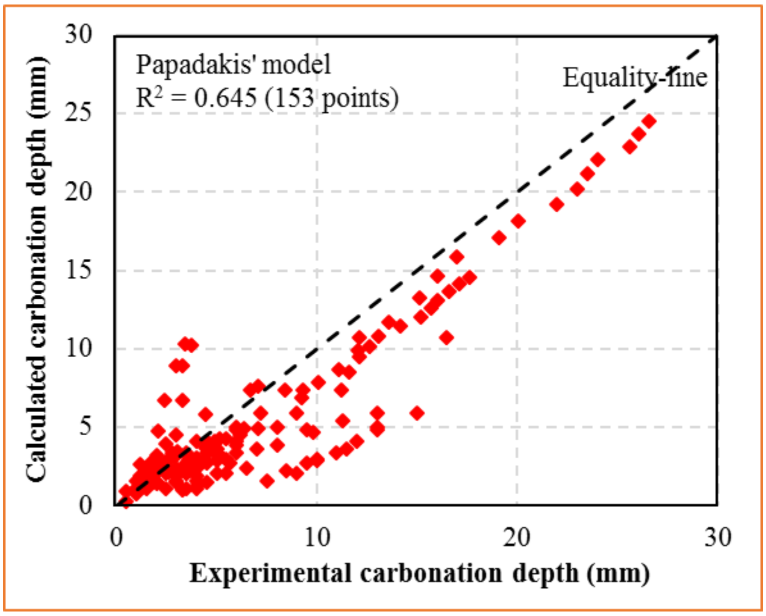

Figure 14. Comparison between calculated and experimental carbonation depths using Papadakis' model.

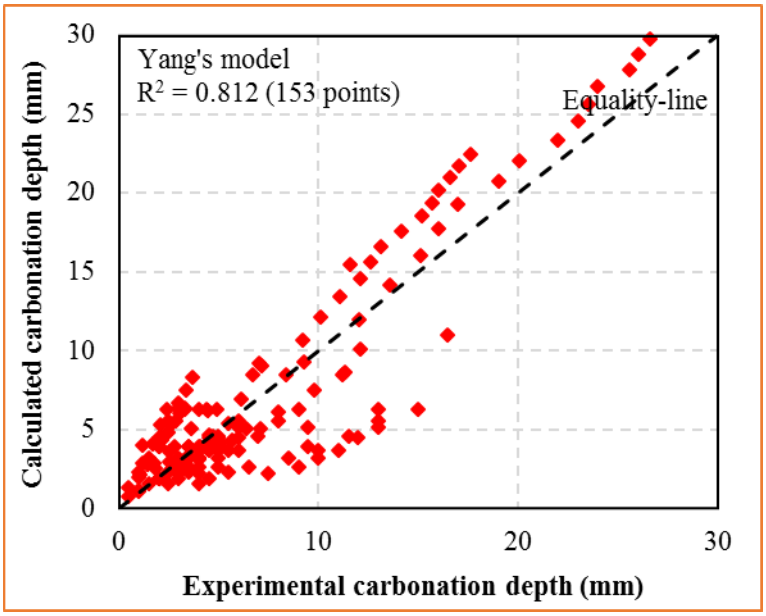

Figure 15. Comparison between calculated and experimental carbonation depths using Yang's model.

II.5. 5. Limits of meta-model

We resumed the range of the input parameters used to validate the meta-model as given in Table 5.

The biggest limit of meta-model is the application to a water-to-cement ratio (W/C) lower than 0.4. This comes from the developed function $f(\phi, W/C, FA)$ for the following reasons:

- We use the expression proposed by Park [58] (Eq. (8)) to take into account the reduced concrete porosity due to carbonation. Eq. (8) is formed by the experimental data range of W/C 0.4 – 0.8.
- We have developed Eq. (10) by using the experimental data range of W/C 0.48 – 0.65.
- Eq. (8) and Eq. (10) are extrapolated outside their experimental data range of W/C used.

Consequently, in order to improve the meta-model prediction, further validation for $W/C \leq 0.4$ is required. Further validation for CEM IV and CEM V cement types is also required.

The meta-model is validated for a maximum natural carbonation period about of 30 years. Thus, it needs to be validated with other long-term natural carbonation data is required.

Table 5. Range of the input parameters used to validate the meta-model.

Parameter			Validation range [mix; max]
Cement content	C	kg/m^3	[207; 504]
Water-to-cement ratio	W/C	n.u.	[0.45; 0.8]
Sand-to-gravel ratio	S/G	n.u.	[0; 1.17]
Maximum aggregate size	S_max	mm	[2; 25]
Cement types	CEM	n.u.	CEM I; CEM II; CEM III and CEM I + fly ash
Cement strength class	f_{cem}	MPa	32.5; 42.5 and 52.5
Initial curing period	t_c	days	[1; 28]
Ambient temperature	T	K	[288; 298]
Relative external humidity	RH	n.u.	[0.38; 0.9]
CO_2 concentration in the air	CO_2	kg/m^3	[0.00049; 0.0011]
Carbonation period	t	years	[0.055; 30]

II. 6. Conclusions

The aim of this paper was to present and validate generic model that can be easily used by civil engineers consider carbonation impact in the life cycle design of reinforced concrete structures. We thus have developed a semi-empirical model based on Fick's first law, which includes as much engineering design options as possible.

The survey of the literature have revealed that: (i) the amount of CO_2 absorbed is not only highly dependent on the cement content, but also on the cement clinker; (ii) the CO_2-diffusion coefficient depends on many influencing parameters like the 28-day compression strength (f_c), the concrete porosity, the water to cement ratio, the coarse aggregate content, the replacement percentage of mineral admixtures, the initial curing period, the ambient temperature and the relative external humidity. If some already available models account for some of these parameters, none of them include them all.

The meta-model predictions for carbonation depth are based on the analytical solution of Fick's first law and take into account many parameters readily available in the case of new reinforced structures. The validation of the meta-model has been conducted using data from literature on short and long-term natural carbonation exposure conditions for CEM I, CEM II, CEM III cement types, and CEM I additives (FA), and for a wide range of water-to-cement ratios, cement contents and exposure conditions. This new meta-model makes it possible to predict concrete carbonation depth for a wide range of curing time (between 1 and 28 days). The predictions obtained are satisfactorily accurate for different types of cement. The good agreement between the calculated carbonation depths and the experimental data found in the literature demonstrates that the meta-model predictions for concrete service life as regards carbonation are reasonably accurate and reliable.

Furthermore, the benefit of using semi-empirical models is that the stochastic nature of all the model parameters can be directly considered in a full probabilistic approach [7]. That is why we will conduct additional researches on the statistical analysis of the meta-model under stochastic variations in order to determine more effective levers for material durability as regards carbonation.

III. SENSITIVITY ANALYSIS OF SERVICE LIFE MODEL

This Chapter focusses on step 4 (n°4 Figure 1). We conducted a literature review on the design approaches for the durability of RC structures in aggressive environment. There are two existing approaches: a prescriptive approach and performance-based approach. Both approaches are useful as regards durability design and are complementary approaches in the global design process. As a result, we combine techniques of the prescriptive and performance-based approaches and in integrating the sensitivity analysis of service life in the design stage, in order to propose a new design procedure for the durability of RC structures. This Chapter presents also an overview of Sobol and Morris' sensitivity analysis methods. We applied Sobol and Morris' methods to the service life model, in order to identify the action levers increasing the service life of the RC structure of the case study. Then, the most durable RC structure is designed by setting the action levers at their most favorable value. With suitable calculation tools, this proposed procedure will be easy to use by designers.

Résumé :

Dans ce papier, nous proposons une méthode de conception des structures en béton armé permettant de maximiser la durée de vie des bétons armés soumis à la carbonatation. Cette méthode consiste en trois étapes. La

première étape est une analyse qualitative dont l'objet est de caractériser les paramètres de conception et les conditions environnantes locales. La deuxième étape est une analyse quantitative qui a tout d'abord pour but d'établir la relation entre la durée de vie et des paramètres et des conditions environnantes locales. Pour faire cela on utilise le modèle de durée de vie développé au chapitre III, sur lequel nous appliquons la méthode d'analyses de sensibilité permettant d'identifier les leviers d'action sur la durée de vie. Dans la troisième étape, les leviers d'action sont fixés à leur valeur favorable afin de calculer la durée de vie la plus longue. La structure conçue par notre procédure est discutée en comparant sa durée de vie avec celle de la structure recommandée par la norme Européenne EN 206-1 [10].

Nous avons mis notre procédure en œuvre pour un béton de classe d'exposition XC4 à Madrid. Nous avons trouvé que le rapport eau sur ciment (W/C), la classe de résistance du ciment (f_{cem}), la teneur en ciment (C) et le type de ciment (CEM) sont les leviers d'action. En utilisant W/C = 0,4, f_{cem} = 52,5 MPa, C = 509 kg/m^3 avec un ciment CEM I au lieu de W/C = 0,5, f_{cem} = 32,5 MPa, C = 300 kg/m^3 avec un ciment CEM I, la durée de vie est significativement augmentée. La durée de vie est trouvée largement et significativement supérieure à 100 ans en utilisant f_{cem} = 42,5 MPa ou 52,5 MPa. Mais elle est inférieur à 100 ans avec f_{cem} = 32,5 MPa.

III. 1. Abstract

The aim of this study is to develop a new design procedure for the durability of the Reinforced Concrete (RC) structures in aggressive environments. The study approach developed here includes: (i) a qualitative analysis phase to characterize the design parameters and environmental exposure conditions of RC structures; (ii) a quantitative analysis phase, to establish the relationship between service life and design parameters and environmental exposure conditions using the service life prediction model firstly, and then to determine the most influential design parameters on service life using sensitivity analyses; and (iii) a final design phase, to design RC structures using some favorable values of the most influential design parameters firstly, and then to compare the service life thus obtained with that of RC structures designed using a standardized approach. An application is also proposed on simulated RC structure exposed to carbonation in Madrid (Spain). This RC structure follows the recommendations of the European standard EN 206-1 for XC4 exposure class. The sensitivity analysis results are discussed in detail including influence trends, importance ranking, non-monotonic effects and parameter interaction influences. The most influential design parameters obtained are cement strength class (f_{cem}), water-to-cement ratio (W/C) and cement type (CEM). By using W/C of about 0.4, f_{cem} of about 52.5 MPa and CEM I cement type instead of their limiting value as recommended by EN 206-1, the service life of the RC structure is significantly improved.

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

III. 2. Introduction

In the literature, two basic approaches are proposed for the design of the durability of Reinforced Concrete (RC) structures in aggressive environments [32]: a prescriptive approach and a performance-based approach.

The prescriptive approach is primarily based on the acquired experience in the durability performance of existing RC structures. Because experience is generally insufficient to allow for the quantitative requirements, most of the requirements for durability are formulated in a qualitative and empirical way. In the case of reinforcing steel corrosion due to carbonation or chlorides, the prescriptive approach defines an exposure class and subsequent prescriptions including (i) concrete composition (a maximum water-to-cement ratio, a minimum cement content and a cement type); (ii) a minimum 28-day compressive strength of the concrete; and (iii) a minimum concrete cover depth for service life design [144] [37].

The key feature of the performance-based approach is to assess relevant concrete material properties using some relevant test methods or service life prediction models. This approach can be used to formulate requirements as regards material properties and structure dimensions. In the case of corrosion of reinforcing steel due to carbonation [7] [32] [33] or chlorides [34] [35] [36], the estimation of the deterioration evolution depending on expected influential parameters is mostly performed by applying a probabilistic approach. This estimation makes it possible to formulate requirements for the structural responses depending on the service life design [37]. Then, durability design can be completed in two ways: (i) using a fully probabilistic method, for which the concrete cover depth and the diffusion coefficient of CO_2 or chlorides are usually considered as main probabilistic design parameters for the required service life design and the reliability level [7] [32] [33] [34] [35] [36]; and (ii) using the partial factor method to determine the characteristic values and the partial factors for the design parameters [7] [32] [35].

The strength of the prescriptive approach lies in its flexibility to account for experience and its easy application. The obvious weakness of this approach is that: (i) a simple set of general prescriptions cannot be optimal for all the different parts of a structure exposed to different levels of aggressiveness depending on the structure areas [145]; (ii) our understanding of service durability performance of the structure at the design stage must be improved [32]; and (iii) it does not encourage the use of novel materials for durability design. The strength of the performance-based approach, on the other hand, is its relevance for the durability responses so that service life design can be carried out in a more scientific and reliable way. However, two main difficulties must be faced: (i) a better understanding of the deterioration mechanisms must combine the results of both the scientific research with long-term in-situ observations; and (ii) the uncertainty associated with deterioration mechanisms must be properly taken into consideration in the design process. This last issue can be solved by carrying out a sensitivity analysis of service life in relation to modeling parameters. The Sensitivity Analysis (SA) is the study of how the uncertainty of a mathematical model or system (numerical or other systems) results can be apportioned to different sources of uncertainty and variability of the input parameters [8]. In the literature, many studies present the SA of the simplified diffusion-based corrosion initiation model of RC structures exposed to chlorides. This analysis is conducted to identify, among the different parameters like concrete cover depth, chloride diffusion coefficient, chloride threshold level, and chloride concentration at the surface, those which are the most significant [146] [147]. Other studies describe the SA of corrosion rate prediction models [148] or simplified carbonation models [88] conducted to classify the different influences of the input parameters. Some authors use the “One At a Time (OAT)” SA method [146] [147], which provides some semi-qualitative sensitivity information by varying one parameter at a time while keeping the others constant. Sensitivity is observed graphically. Other authors use the SA method based on the regression analysis

[148] [88]. This method quantifies the effect of the input parameters on the model results.

It is sometimes difficult to distinguish between prescriptive or performance-based design approaches used to design the RC structures. For instance, if the existing RC structures on a given project site have achieved the objective set by service life design, then the durability design of new RC structures can rely on the rational analysis of the durability measurements carried out on these RC structures. Consequently, determining whether structure design is specifically based on the prescriptive or the performance-based approach is difficult, in this case. The experimental data on the durability performance of the structures thus collected must be integrated into the different phases of the performance-based approach to determine the preliminary dimensions of the structure [37]. Thus, both approaches are useful as regards durability design and are complementary methods in the global design process.

The present paper reports a study conducted to develop a new design procedure for the durability of the RC structures in aggressive environments. The procedure discussed here is the result of the combination of both prescriptive and performance-based approaches. Qualitative and quantitative SA methods are integrated into the design procedure to determine durability action levers. These are used to design the best durable RC structure.

The new design procedure for the durability of RC structures in aggressive environments is presented in Section III. 3. An application of this procedure to a simulated RC structure exposed to carbonation in Madrid (Spain) is described in Section III. 4. Some recommendations for the durability design according to EN 2016-1 for XC4 exposure class are discussed in Section III. 5.

III. 3. Development of the new durability design procedure

The durability design procedure here includes: (1) qualitative analysis, (2) quantitative analysis, and (3) final design (Figure 16). The purpose of qualitative analysis is to determine the preliminary dimensions of a RC structure at a general level within the context of aggressive environments. It also includes the characterizations of the design parameters and the environmental exposure conditions. This analysis is carried out using a prescriptive approach. The quantitative analysis aims at establishing a relationship between the aggressive environment and the service life of structure using a service life prediction model [7]. The purpose of the quantitative analysis is to determine the action levers by applying the Sensitivity Analysis (SA) method to the service life prediction model. The final design phase consists in using the action levers to redesign the RC structure properties in order to achieve the longest service life possible. This phase also includes a comparison between the service life of a structure designed by using the procedure proposed here and that of a structure designed using the recommended limiting values of EN 206-1 [10].

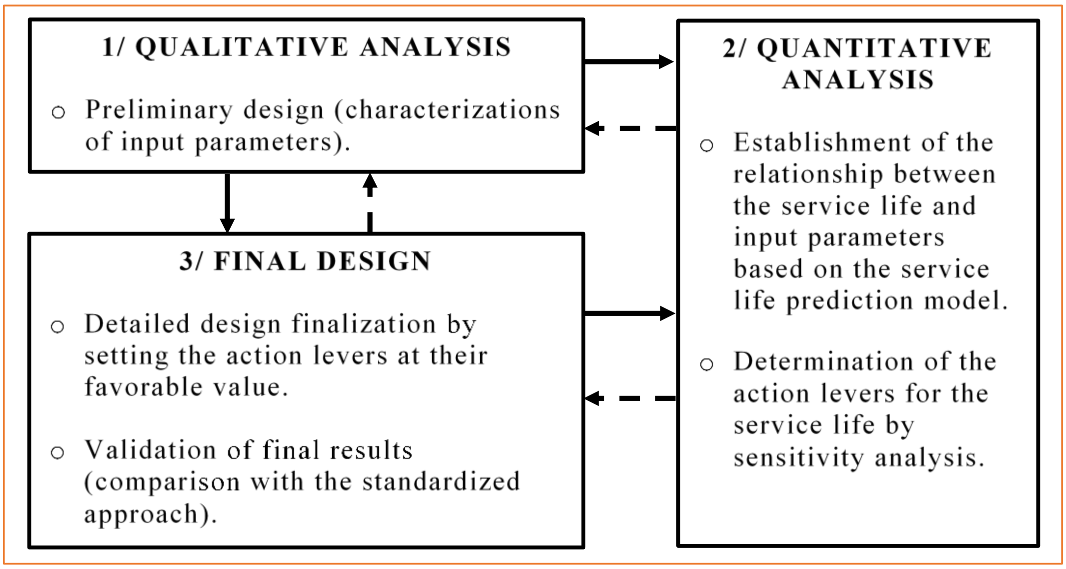

Figure 16. Design procedure for the durability of RC structures in aggressive environments.

In order to determine the action levers, suitable SA methods must be selected. They must provide the trend of action levers in relation to the service life, the quantization of their influence and the interactions with other parameters. Thus, the SA methods used in the previous studies [146] [147] [148] [88] are not relevant in this context. Consequently, a combination of two SA methods, Sobol's quantitative method [66] and Morris' qualitative method [67] is chosen. This combination has been previously used for the same purpose in environmental design using LCA [68] [69]. It can provide complementary information on the influence of the input parameters on the model results in the decision-making process. Sobol's method is used to quantify the input parameters contribution to model result variations. Morris' method, on the other hand, provides additional information on the trend of the input parameters. Both methods require that all the input parameters are independent of one another. Both methods are summarized in the next subsections.

III.3. 1. Sobol's quantitative sensitivity analysis

Sobol's method [66] is based on the analysis of the variance decomposition of the model f in order to quantify the contribution of variability of the input parameter X_j to the total variance of the output Y. The individual contribution influence of parameter X_j is measured using the first order sensitivity index (S_j) such as:

$$S_j = \frac{Var(\mathbb{E}[Y \mid X_j])}{Var(Y)} \tag{19}$$

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

The individual Sobol indices lie in the interval [0-1]. Moreover, the overall output sensitivity to the parameter X_j (i.e., including first and higher order effects (interaction) of X_j) can be measured using the total sensitivity index (S_{T_j}) [149] as:

$$S_{Tj} = 1 - \frac{Var(\mathbb{E}[Y \mid X_{\neq j}])}{Var(Y)} \tag{20}$$

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

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

III.3. 2. Morris' qualitative sensitivity analysis

Morris' method [67] is one of the most popular screening method, which consists in developing a randomized experimental design process by varying one parameter while keeping the others constant (OAT method) over a certain number of repetitions k ($k = 1,2, \ldots, r$). Then, the variation coefficients, called the elementary effects ($\mathbb{EE}_j^{(k)}$), are obtained as:

$$\mathbb{EE}_j^{(k)} \approx \frac{f\left(\mathbb{X}^{(k)} + e_j.\Delta\right) - f\left(\mathbb{X}^{(k)}\right)}{\Delta} \tag{21}$$

Where: Δ is a pre-defined step, e_j is a vector of zero but with j-th equal ±1, its dimension is equal to the number of parameters.

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

$$\mu_j = \frac{1}{r}\sum_{k=1}^{r} \mathbb{EE}_j^{(k)} \tag{22}$$

$$\sigma_j = \sqrt{\frac{1}{r-1}\sum_{k=1}^{r} \left(\mathbb{EE}_j^{(k)} - \mu_j\right)^2} \tag{23}$$

In the case of non-monotonic functions, the elementary effects can have an opposite sign for the considered repetition, which can result in a μ_j close to zero if the parameter is influential. In order to prevent this, Campolongo et al. [150] recommend to use the mean value of the absolute value (μ_j^*) of the elementary effects rather than the usual μ_j.

$$\mu_j^* = \frac{1}{r}\sum_{k=1}^{r}\left|\mathbb{EE}_j^{(k)}\right| \tag{24}$$

The information about the algebraic sign of μ_j is lost when using μ_j^*. However, it is a good indicator for the assessment of the importance of the input parameters in relation to each other. Morris' method requires a local interval range (minimum and maximum value) for each input parameter. The number of repetitions r ranges from 4 to 10 [151]. In this study, μ_j, μ_j^* and σ_j are calculated.

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

III.3. 3. Identification of action levers using sensitivity indices

Based on the Sobol indices, the technological parameters are assumed to have an individual influence (identified as action levers) if the value of S_j is higher than 10%. Moreover, if the value of S_j is lower than 10% but the difference ($S_{T_j} - S_j$) is high, i.e., assumed to be greater than 10%, they can also be considered as potential action levers [68] [69]. This means that parameter X_j is not individually influential but has a non-negligible global contribution because of its interaction with the other parameters. As regards the Morris indices, the parameters with a higher μ_j^* are considered as the major contributors to the model output and as a result, potential action levers [67]. If the parameters satisfy the condition $\sigma_j \geq |\mu_j|$, they are considered to have a non-monotonic effect. In contrast, non-influential input parameter X_j is assumed to have indices S_{T_j} lower than 10% and μ_j^* low in relation to other indices $\mu^*_{i\neq j}$ of input parameters $X_{i,i\neq j}$. Recall that Morris indices μ^*_j and μ_j have the same order of magnitude than the model response while the first order Sobol indices S_j are normalized and lie in the interval [0-1].

III. 4. Case study

III.4. 1. Presentation of the case study

The case study studied here consists of a RC structure subjected to carbonation. The structure is assumed to be located in Madrid (Spain) because this location presents optimal environmental conditions for carbonation of concrete [70] [71]. Madrid, indeed, is a place with a high level of carbon dioxide [72] and with an average relative external humidity of about 0.56 [9]. The considered structure follows the recommendations of EN 206-1 for XC4 exposure class [10]: concrete is exposed to the air and the structure is not sheltered from rain. Carbonation is the only alteration phenomenon of RC structure considered in this paper. The objective here is to identify the action levers affecting service life to obtain the longest service life possible by setting the identified action levers at their most favorable value.

The service life of a structural component is the period after construction, during which all the structure properties, when routinely maintained, are higher than the minimum acceptable values [2]. Tuutti [27] proposed a simplified model for predicting the service life of RC structures, considering the degradation due to carbonation induced corrosion. Service life is divided into two periods: initiation period and propagation period as shown in Figure 17. There are two periods because the mechanisms involved are different in physical-chemical terms. The initiation period corresponds to the penetration of CO_2 into the concrete cover until the carbonation front reaches the reinforced layer. The propagation period includes (i) steel corrosion; (ii) cross section loss; (iii) concrete surface cracking; and (iv) spalling of concrete cover.

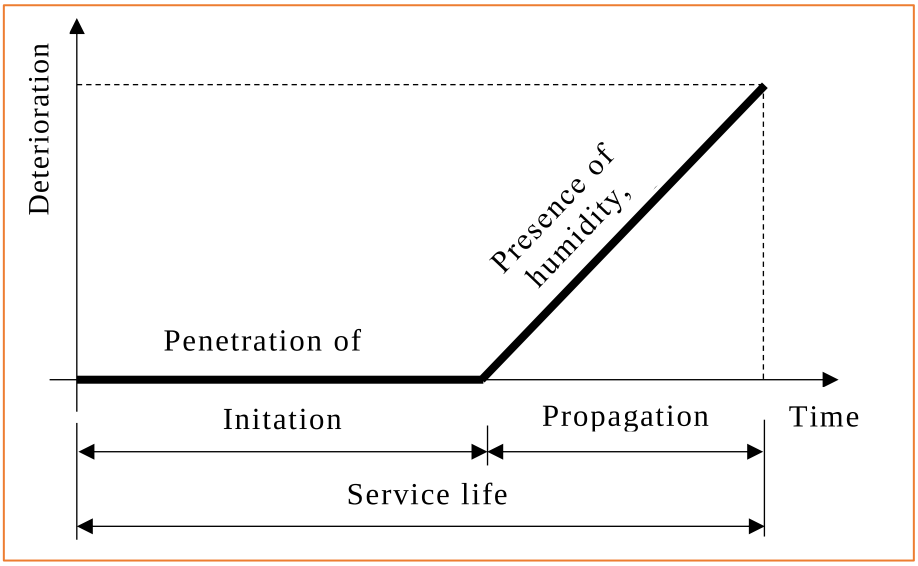

Figure 17. Tuuti's service life prediction model [27].

Our case study deals with the initiation period only. The service life of RC structure is limited to the corrosion initiation period. Thus, a model for the initiation period is required: that model calculates at any time the carbonation depth within concrete.

III.4. 2. Qualitative analysis: characterizations of input parameters

The service life considered here is predicted using the carbonation model recently developed by Ta et al. [125] (Figure 18). This carbonation model is validated using data from the literature on short- and long-term natural carbonation exposure conditions. Most of the experimental data concern CEM I, CEM II, CEM III cement types. The prediction of this carbonation model for estimation of carbonation depth is more accurate than Papadakis' model [29] and Yang's model [30]. This model takes many influencing design parameters of the carbonation process into account and predicts the natural carbonation depth. It is based on the analytical solution of Fick's law given by:

$$x = \sqrt{\frac{2 \times D_{CO_2} \times CO_2}{a}} \times \sqrt{t} \tag{25}$$

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

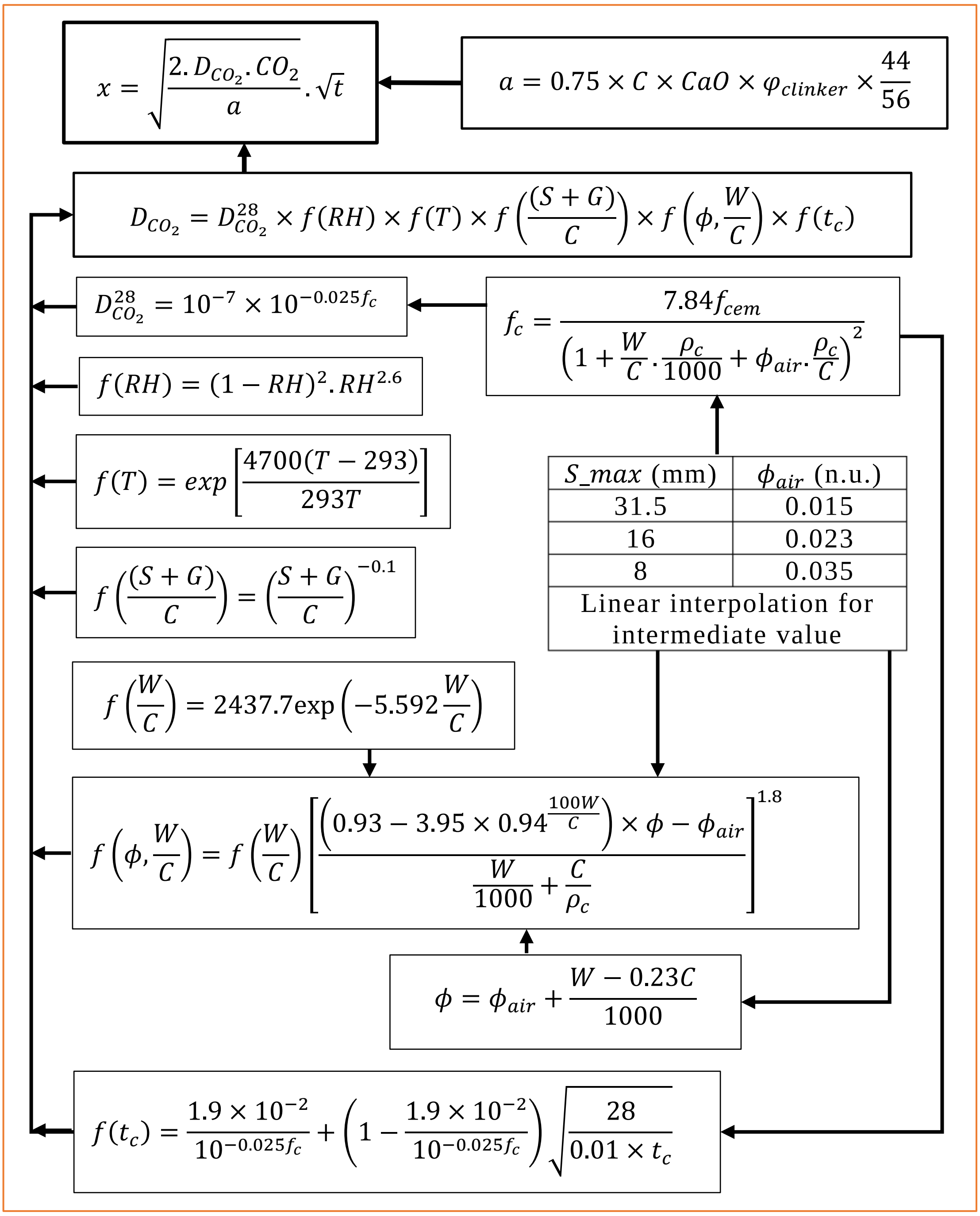

Figure 18. Carbonation model presented in [28] (input parameters are detailed in the text).

When the carbonation depth is equal to the concrete cover depth (d), i.e., $x = d$, the corrosion initiation period ends. The steel reinforcement could be then corroded with the presence of O_2, humidity and temperature as defined by Tuuti's service life prediction model (Figure 17). Service life (t_{ser}) can be written as:

$$t_{ser} = \frac{d^2 \times a}{2 \times D_{CO_2} \times CO_2} \tag{26}$$

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

Many parameters are required for the calculation of D_{CO_2} and a as shown in Figure 18. For the application of Sobol and Morris' methods to the determination of the sensitivity of t_{ser} to input parameters, we use only the expression of D_{CO_2} and a in relation to the independent parameters. An independent parameter does have a relationship with other independent parameters. The dependent parameters are expressed through the independent parameters. The time dependency of the input parameters is not taken into account. Consequently, the expression of t_{ser} takes the form:

$$t_{ser} = f(C, W/C, S/G, S_{max}, CEM, f_{cem}, d, t_c, T, RH, CO_2) \tag{27}$$

or

$$t_{ser} = f(X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10}, X_{11},) \tag{28}$$

where: C (kg/m^3 of concrete) is the amount of cement content, W/C (n.u.) (n.u. = no unit) is the water-to-cement ratio, S/G (n.u.) is the sand-to-gravel ratio, S_max (mm) is the maximum aggregate size, CEM (n.u.) is the cement type, f_{cem} (MPa) is the cement strength class, t_c (days) is the initial curing period, T (K) is the ambient temperature, RH (n.u.) is the relative external humidity.

The amount of CO_2 absorbed in a unit volume of concrete (a) becomes

The full forms of D_{CO_2} and a are not written here because they have been previously discussed [125]. The input parameters, including the technological and environmental parameters (refer to the definition of "technological and environmental parameters" in *Definitions*), characterized by determining the variability range and the PDF of each parameter as summarized in Table 6. The technological parameters are characterized by the limiting values recommended by EN 206-1 [10] for XC4 exposure class and the statistical analysis of the studies addressing the problem of concrete carbonation found in the literature. To provide the action levers, a uniform (discrete or continue) distribution is usually set for the technological parameters because they are chosen by the designer. Thus, all the values within the distribution interval are considered equally probable. The interval is determined by minimum and maximum values.

The environmental parameters are characterized from weather data [9], which include the ambient temperature (T) and the relative external humidity (RH). The CO_2 concentration in the atmosphere (CO_2) is taken from [72].

Table 6. Input technological and environmental parameters characterizations.

Parameter		Unit	Probability Density Function (PDF)	Reference
Technological parameters				
Group 1: concrete mix				
X_1	C	kg/m^3	$\mathcal{U}$ (min = 300; max = 509)	[10]
X_2	W/C	n.u.	$\mathcal{U}$ (min = 0.4; max = 0.5)	[10]
X_3	S/G	n.u.	$\mathcal{U}$ (min = 0.5; max = 2.1)	
X_4	S_max	mm	$\mathcal{U}$ (min = 20; max = 32)	[10]
	Group 2: cement			
X_5	CEM	n.u.	$d\mathcal{U}$ (10 cement types)	[10]
X_6	f_{cem}	MPa	$d\mathcal{U}$ (3 strength classes)	[10]
	Group 3: concrete cover depth and initial curing period			
X_7	d	m	$\mathcal{U}$ (min = 0.05; max = 0.08)	[152] [153]
X_8	t_c	days	$\mathcal{U}$ (min = 1; max = 3)	[154]
	Environmental parameters			
X_9	T	K	$tr\mathcal{N}$ (mean = 287.4; CoV = 0.03; min = 272.4; max = 309.1)	[9]
X_{10}	RH	n.u.	$tr\mathcal{N}$ (mean = 0.56; CoV = 0.33; min = 0.2; max = 0.88)	[9]
X_{11}	CO_2	ppm	$tr\mathcal{N}$ (mean = 380; CoV = 0.05; min = 304.6; max = 456.8)	[72]

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).

Group 1: concrete mix

The requirements for concrete of EN 206-1 [10] for XC4 exposure class are a maximum water-to-cement ratio (W/C) of about 0.5, a minimum amount of cement content (C) of about 300 kg/m^3 and maximum aggregate size (S_max) within the range 20-32 mm. Previous studies [4] [34] [35] [36] reveal that (i) CEM I cement type concrete with a water-to-cement ratio (W/C) lower than 0.4 has very high carbonation resistance; and (ii) concrete using CEM I cement type has higher carbonation resistance than the other cement types containing additions. In this work, we thus assume the minimum W/C of about 0.4 for cement types considered in order to observe the carbonation phenomenon; however, the carbonation phenomenon can appear for W/C values lower than 0.4 for other cement types. Moreover, concrete casted with such W/C is uncommon. Based on the statistical analysis of seventeen experimental investigations on concrete carbonation [141] [33] [54] [139] [140] [157] [158] [90] [159] [135] [71] [160] [85] [92] [32] [161] [162], the maximum cement content (C) is about 509 kg/m^3 and the sand-to-gravel ratio (S/G) varies between 0.5 and 2.1.

Group 2: cement

In the carbonation model proposed by Ta et al. [125], the cement type (CEM) is considered through the following three parameters: amount of Portland clinker inside cement, amount of calcium oxide per weight of cement and cement density. Therefore, among the 27 cement products presented in [127], ten cement types are considered: CEM I; CEM II/A; CEM II/B; CEM III/A; CEM III/B; CEM III/C; CEM IV/A; CEM IV/B; CEM V/A; and CEM V/B. The characteristics of these cements are presented in Appendix (Table A1). Cement strength class (f_{cem}) of all these cement types is available for strength classes of 32.5 MPa, 42.5 MPa and 52.5 MPa.

Group 3: concrete cover depth and initial curing period

The concrete cover depth (d) must have a minimum thickness to protect the steel reinforcements from the CO_2 attack and to prevent the corrosion of steel reinforcements [163]. This design parameter varies according to the exposure class, the quality of construction and the intended service life [163]. Combined to the requirements for concrete of EN 206-1 [10] for XC4 exposure class, the minimum recommended concrete cover depth (d) ranges from about 0.05 m [152] to 0.08 m [153] for structure design with an expected 100-year service life. Consequently, d can vary between 0.05 and 0.08 m in this study.

Because of a limited construction time, the initial curing period (t_c) varies between 1 day and 3 days [154].

For service life prediction and sensitivity analysis, it is important to note that the meta-model is extrapolated outside the range of the input parameters used for the validation (Table 5). For instance, the parameters W/C, S/G, S_max, T, RH, CO_2 (Table 6) are extrapolated from the limiting values recommended by EN 206-1 [10] and statistical analysis of the studies in the literature [9] [72] as follows:

- W/C is extrapolated from [0.4; 0.5] instead of [0.45;0.8].
- S/G is extrapolated from [0.5; 2.1] instead of [0; 1.17].
- S_max is extrapolated from [16; 32] instead of [2; 25].
- T is extrapolated from [272.4; 309.1] instead of [288; 298].
- RH is extrapolated from [0.2; 0.88] instead of [0.38; 0.9].
- CO_2 is extrapolated from [0.0005; 0.007] instead of [0.00049; 0.0011].

Thus, we suppose that the meta-model is relevant outside the limits of validation, to extrapolate its prediction under the recommendations of EN 206-1. In addition, although the meta-model is validated for a maximum natural carbonation period about of 30 years (Table 5) for service life, we extrapolate it to predict a natural carbonation period of 100 years.

III.4. 3. Quantitative analysis

a) Service life prediction and sensitivity analysis

Eq. (27) is used to establish the relationship between the service life (t_{ser}) and the input parameters X_j presented in Table 6. In Sobol's method, the t_{ser} values are simulated using Eq. (27) by varying all input parameters simultaneously according to their PDF (Table 6).

The first order Sobol sensitivity index (S_j) (Eq. (19)) and the total Sobol sensitivity index (S_{T_j}) (Eq. (20)) are calculated as described in Section III.3. 3. They are calculated by means of a bootstrap method with 500 replications from a half-sample (5,000) taken from an initial sample of about 10,000 as recommended in [18].

In Morris' method, the t_{ser} values are simulated using Eq. (27) by varying each input parameter one at time. Then the mean value (μ_j) (Eq. (22)), standard deviation value (σ_j) (Eq. (23)) and mean value of the absolute value (μ_j^*) (Eq. (24)) of the elementary effects are calculated as described in Section III.3. 3. They are calculated by means of discretization of the input parameters X_j in 10 values with a prescribed number of trajectories of about 30 as recommended in [18].

b) Determination of the action levers

Our results shown in Figure 19 are related to the case study. It is important to note that SA results depend on both PDF of input parameters given in Table 6 and on carbonation model chosen. Figure 19 displays the SA results.

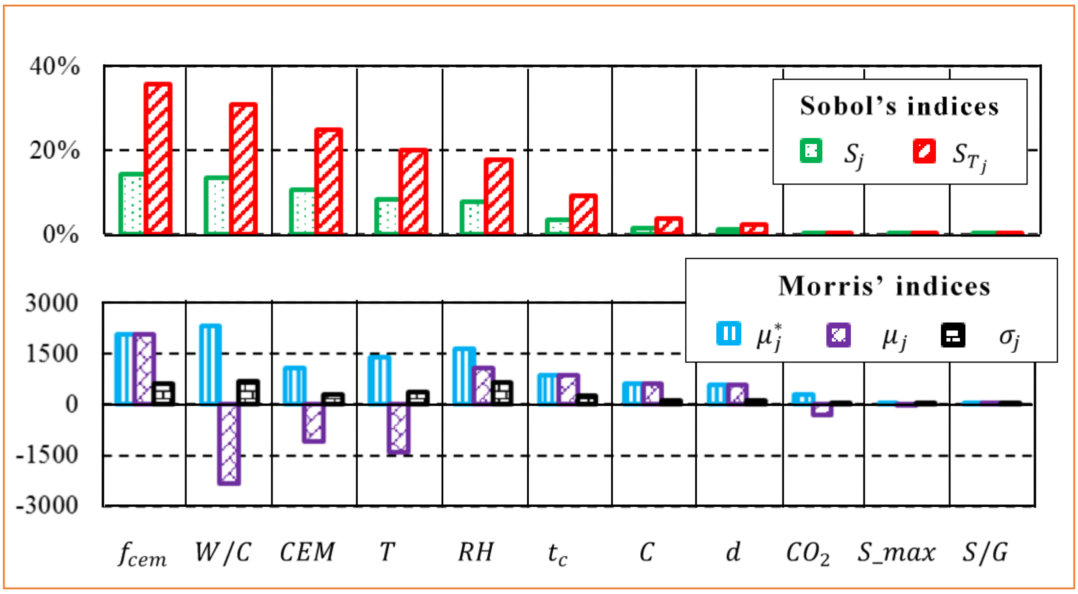

Figure 19. Sobol and Morris sensitivity indices results.

Figure 19 shows that cement strength class (f_{cem}), water-to-cement ratio (W/C), cement type (CEM), ambient temperature (T) and relative external humidity (RH) (in descending rank) are the most influential parameters because their S_{T_j} and μ_j^* values are the highest. The difference $S_{T_j} - S_j$ is around 22% for cement strength class (f_{cem}), 17% for water-to-cement ratio (W/C), 14% for cement type (CEM), 12% for ambient temperature (T) and 10% for relative external humidity (RH). This means that their interactions with the other parameters are important. Parameters f_{cem}, W/C and CEM are considered the most influent with a S_j value above 10%. They are thus technological parameters (i.e., controllable parameters) identified as action levers. T and RH are environmental parameters (uncontrollable parameters) that are uncertain. The less-influential parameters ($S_{T_j} < 10\%$ and low μ_j^*) are initial curing period (t_c), cement content (C), concrete cover depth (d), CO_2 concentration in the air (CO_2), maximum aggregate size (S_max) and sand-to-gravel ratio (S/G). Based on the algebraic sign of μ_j, we observe that an increase in RH, C, d, t_c, and S/G and a decrease in W/C, S_max, T, and CO_2 result in the increase of t_{ser}. All parameters have σ_j/μ_j^* within the interval [0.19 – 0.39]. It indicates that the effects between parameter are monotonic. Because f_{cem} and CEM are discrete parameters, their algebraic sign of μ_j is not significant. Finding favorable value requires testing all of the values of f_{cem} and CEM. The simulation results are displayed in Figure 20. We plot the service life on log scale versus clinker content. The service life is represented by its mean value and standard deviation.

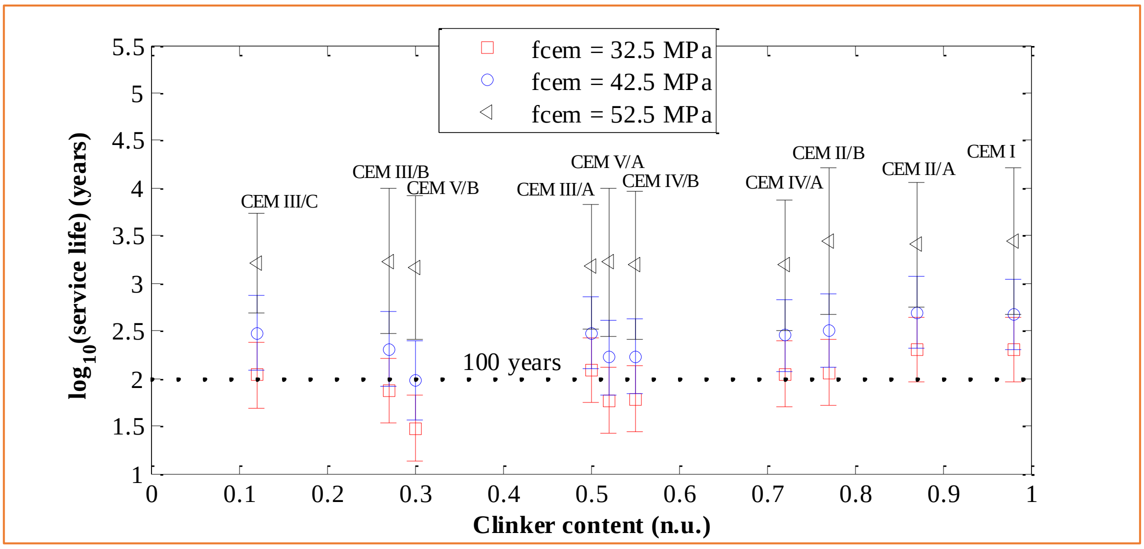

Figure 20. Comparison of service lives of cement strength classes and cement types.

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

c) Comparison of the sensitivity analysis results to the literature

This section compares our SA results with the literature. Cement strength class (f_{cem}) and water-to-cement ratio (W/C), two technological parameters, are key parameters for the determination of the concrete porosity and the 28-day compressive strength of concrete (f_c) [145] [164]. Both values, indeed, are important indicators of the evaluation of the resistance to penetration of carbon dioxide into concrete [165]. Higher cement strength class (f_{cem}) and a decrease in water-to-cement ratio (W/C) result in an increase of f_c. For a given water-to-cement ratio (W/C), it has been shown that service life (t_{ser}) increases by 1.89 times when using a CEM II/B cement with a cement strength class (f_{cem}) value about of 42.5 MPa instead of 32.5 MPa [134]. Furthermore, the service life (t_{ser}) increases by 2.49 times when using a water-to-cement ratio (W/C) of about 0.4 instead of 0.43, according to the literature [166]. Previous experimental results [55] [56] have confirmed that service life (t_{ser}) is more sensitive to cement strength class (f_{cem}) and water-to-cement ratio (W/C). In addition, a survey of the literature also reveals that the carbonation resistance of concrete depends on the amount of Portland clinker cement in concrete [82]. When using a cement preparation containing more Portland clinker for concrete composition, first, the 28-day compressive strength of concrete (f_c) is higher and the amount of $Ca(OH)_2$ and CSH increases [97]. Both observations increase concrete carbonation resistance. Finally, the other technological parameters considered here demonstrate a negligible contribution to the variations of service life (t_{ser}). An increase in cement content (C), obviously causes the presence of higher amounts of Calcium hydroxide ($Ca(OH)_2$) and Calcium-Silicate-Hydrate (CSH) inside the concrete, which lengthens the time of the neutralization reaction between

$Ca(OH)_2$ and CSH and CO_2. The carbonation resistance is thus higher. An increase in maximum aggregate size (S_max) generates a decrease in the carbonation resistance. The use of a bigger aggregate size, indeed, induces (i) a reduction in the tortuosity of the flow path, which increases permeability, and (ii) a possibility of internal water bleeding, which increases concrete porosity [98]. As regards the initial curing period (t_c), many previous studies [166] [120] [157] have underlined that the longer the curing period is, the higher the resistance of concrete to carbonation is. An increase in t_c provides a higher degree of hydration and a lower concrete porosity. As regards the concrete cover depth (d), it is widely accepted that service life (t_{ser}) is proportional to the square of concrete cover depth (d) as shown in Eq. (8). An increase in sand-to-gravel ratio (S/G) in one cubic meter of concrete mixed increases sand content, which is responsible for the reduction in air permeability. There also, the carbonation resistance is increased [98].

As regards the environmental parameters, previous experimental results [70] [71] have shown that the highest carbonation rate is observed for a relative external humidity (RH) around 57%. We observe that the carbonation rate increases when relative external humidity (RH) increases from 0% to 57%, and decreases when relative external humidity (RH) increases from 57% to 100%. This is consistent and corresponds to the highest σ_j/μ_j^* of relative external humidity (RH) (Figure 19), that is highlighted by the present sensitivity analysis results. The carbonation rate also increases with increasing ambient temperature (T) due to increased molecular activity [121] [122]. Finally, the carbonation depth is proportional to the square root of carbon dioxide concentration in the air (CO_2) (Eq. (25)). The presence of carbon dioxide is necessary for the carbonation of concrete. However, relative external humidity (RH) and ambient temperature (T) play the most important part in the carbonation rate within all the environmental parameters.

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

III.4. 4. Final design

Based on the SA results, the action levers of the case study are cement strength class (f_{cem}), water-to-cement ratio (W/C) and cement type (CEM). The final design is carried out by setting the action levers at their most favorable value to increase the service life (t_{ser}) (Table 7). As found previously, the most favorable values of the three action levers consist of minimum W/C (about 0.4), higher f_{cem} 52.5 MPa and CEM I or CEM II/B cement type (Figure 20). The other parameters are randomly generated according to their PDF presented in Table 6. This scenario is called *recommended scenario*.

A reference scenario, called *EN 206-1 scenario*, is also developed by setting the action levers at the limiting values recommended by EN 206-1 [10], i.e., W/C equal to 0.5, f_{cem} 32.5 MPa and CEM I cement type (Table 7). The other parameters are randomly generated according to their PDF as with the *recommended scenario*.

We compare the distribution of t_{ser} of EN 206-1 *scenario* and *recommended scenario* with CEM I cement type in Figure 21. The *recommended scenario* with CEM II/B cement type is not illustrated in Figure 21 as its t_{ser} of *recommended scenario* with CEM II/B cement type is of about 9,253 years. The distribution of t_{ser} is simulated using a Monte Carlo simulation with a sample size of 100,000.

Table 7. 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

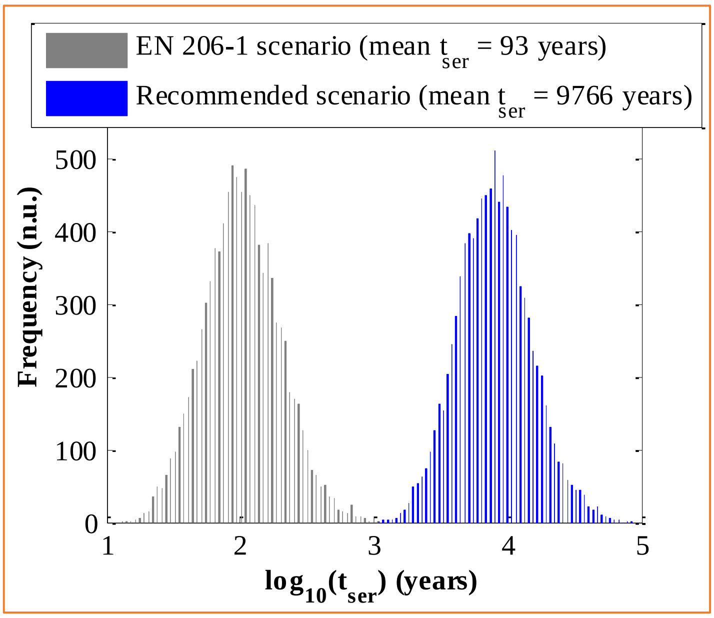

Figure 21. Comparison between service life (t_{ser}) distributions of both designed scenarios.

As shown in Figure 21, the service life (t_{ser}) of the *recommended scenario* is 105 times higher than that of the *EN 206-1 scenario*. Both distributions of probabilities are completely separated. The calculated differences are significant. The simulation results confirmed f_{cem}, W/C as being effective action levers. The *recommended scenario* corresponds to concrete with higher carbonation resistance. We consider the high concrete cover depth (d) between 0.05 m and 0.08 m, that is another reason for finding the mean service life of the *recommended scenario* of about 9,766 years. This finding corroborates with previously experimental results [4] [34] [35] [36]. For example, Houst et al. [34] reveal that more than five years of exposure to the atmosphere of CO_2, concrete with W/C = 0.3 is carbonated only to a depth of 0.2 to 0.3 mm. Another study on ultra-high performance fiber-reinforced concrete (porosity about 5%) [63] shows that the t_{ser} is more than 12,000 years. One can assume that this higher t_{ser} is not only due to the individual influence of action levers but also to the non-negligible interactions between the action levers and other parameters (revealed previously through the differences $S_{T_j} - S_j \geq 10\%$).

The simulation results of the *recommended scenario* reveal that a durable RC structure can be obtained by setting the action levers at their most favorable values. The durable RC structure is independent on the values of the other technological parameters, which are simulated randomly within their variability range given in Table 6. In short, if the RC structure is designed using the *recommended scenario*, the risk for corrosion of reinforcing steels due to carbonation is eliminated throughout the 100-year service life design. In addition, concretes with f_{cem} 52.5 MPa and with W/C of about 0.4 are appropriate for the other cement types (Figure 20). On the contrary, if the RC structure is designed by setting the action levers at their limiting values as recommended by EN 206-1 [10], a maintenance system could be established in order to ensure the intended 100-year service life.

III.4. 5. Advantages and limits of the design approach

The mean service life of the *EN 206-1 scenario* does not reach the prescribed 100-year service life. It is about 93 years as shown in Figure 21. This may reflect non-exhaustive recommendations as regards all aspects of the design process, like, for instance environmental exposure conditions (e.g., the ambient temperature) and quality of execution process. The exposure class proposed by EN 206-1 [10] refers only to the average conditions and to well-cured concrete during the execution process, i.e., a minimum initial curing period of about 7 days [39].

In this particular case, the cement content (C) does not individually contribute to service life (with S_j around 1%), i.e., the service life (t_{ser}) is independent of cement content (C) for a given water-to-cement ratio (W/C). A previous study has revealed that the carbonation of concrete is independent of cement content (C) (from 221 to 450 kg/m^3) for a given water-to-cement ratio (W/C) [40]. The present finding, achieved in association with the literature, raises the problem of attempting to impose a minimum cement content (C) of 300 kg/m^3 for XC4 exposure class in EN 206-1 [10]. The model developed does not consider that a high cement content (C) may enhance the risk of cracking because of the heat of hydration or the drying shrinkage in the concrete cover. Both can result in a poor carbonation resistance of the concrete cover. Furthermore, from the point of view of the environmental impacts of the concrete, cement, among other constituents of concrete, is mainly responsible for the release of a huge amount of CO_2 during the production [41]. Consequently, in the case of an XC4 exposure class, the requirement for the minimum C in EN 206-1 [10] should be re-examined whereas a maximum limit of C within the mix should also be specified.

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

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

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

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

III. 5. Summary and conclusion

We have devised a design procedure for the durability of RC structures through resistance to carbonation induced corrosion.

This innovative approach consists in combining the techniques of the prescriptive and performance-based approaches and in integrating the sensitivity analysis of service life in the design stage. The durability design phase has focused on the most influential parameters with a view to setting them at their most favorable value. With suitable calculation tools, this proposed procedure will be easy to use by designers.

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

IV. ENVIRONMENTAL AND DURALBE DESIGN OF RC STRUCTURES WITHOUT MAINTENANCE AND REPAIR OPERATION

As discussed in Chapter III we identified two alternatives of the RC structure in the case study: (i) the RC structure, designed with the cement strength class 42.5 MPa or 52.5 MPa, neither maintenance nor repair operations are required within the 100-year service life design; et (ii) the RC structure, designed with the cement strength class 32.5 MPa, a maintenance or repair system is required during the 100-year service life design. This chapter treats of the RC structure designed with the cement strength class 42.5 MPa or 52.5 MPa. The works presented here focus on step 3 (n°3 Figure 1), step 4 (n°4 Figure 1) and step 5 (n°5 Figure 1). In step 3, we developed a LCA model to estimate the environmental impacts of the RC structure, designed with the cement strength class 42.5 MPa or 52.5 MPa. This model is based on a functional unit of 1 m^2 of concrete cover. In step 4, we applied Sobol and Morris' method to the environmental impact indicators, in order to identify the action levers decreasing the environmental impacts. In step 5, in association with the action levers increasing the service life presented in Chapter III, we provided the recommendations for environmental and durable design of the RC structure studied.

Résumé :

Dans ce papier, nous avons présenté les résultats d'une application de la méthode de la conception durable détaillée dans le chapitre II sur 1 m^2 de surface de béton d'enrobage de classe d'exposition XC4. Les cas étudiés de béton d'enrobage sont restreints à ceux dont la durée de vie est supérieure à 100 ans selon les résultats du chapitre IV (c'est-à-dire avec des ciments dont les classes de résistance sont de 42,5 MPa ou 52,5 MPa).

La classe de résistance du ciment n'a pas d'influence sur les indicateurs environnementaux, alors qu'elle est très influente sur la durée de vie (chapitre IV). D'autres paramètres tels que la quantité de ciment (C), ou l'épaisseur d'enrobage (d) permettent également d'augmenter la durée de vie, mais de manière moins significative que la classe de résistance du ciment. D'autre part, ces paramètres ont une influence néfaste sur la plupart des indicateurs environnementaux. La solution la plus durable et la plus respectueuse de l'environnent est trouvée en utilisant du ciment CEM III/C, minimisant le rapport eau sur ciment (W/C), l'épaisseur du béton d'enrobage (d), et la distance de l'usine de béton au site. Finalement, nous pouvons recommander une classe de ciment 52,5 MPa dans le cas des ouvrages d'art pour lesquels une durée de vie maximale est recherchée, et une classe de résistance du ciment de 42,5 MPa dans le cas des bâtiments où la durée de vie de 100 ans est souvent suffisante.

IV. 1. Abstract

This paper presents a new design approach for the sustainability of Reinforced Concrete (RC) structure in aggressive environments. Our approach simultaneously integrates a decision diagram, a service life model, Life Cycle Assessment (LCA) method and two Sensitivity Analysis (SA) methods (Sobol and Morris' methods). It allows identifying effective few solutions among all possible decision combinations for improving both service life and environmental performances. The service life model predicts the service life of structure and time at which a maintenance operation is necessary, so that the structure can reach a service life design. We use LCA, with a 1 m^2 of concrete cover reference flow, to estimate the environmental impacts of construction and maintenance operations. We use the SA methods to determine the most influential design parameters, so-called action levers, for both the service life and environmental impact indicators. We design the favorable scenarios using the most favorable values of identified action levers. The purpose of the favorable scenarios is to increase possible service life and decrease environmental impact indicators. The most sustainability of RC is obtained by comparing the environmental impacts of scenarios based on equivalent threshold of service life design requirement. Our approach is applied to a case study of a RC structure following the recommendations of EN 206-1 for XC4 exposure class in Madrid (Spain). The SA results are discussed in detail, including the influence trend, importance ranking, non-monotonic effects and interaction influences of parameters. The environmental impacts of the structure are independent on the cement strength class. The cement strength class 52.5 MPa is recommended for the structures requiring the longest service life possible, the cement strength class 42.5 MPa is suitable for the structures such as buildings. The most favorable solution for the RC structure is designed with the lowest cement content, water-to-

cement ratio, concrete cover depth and distance from the concrete factory to the site, in association with the CEM III/C cement type.

Key words: Service life, Durability, Carbonation, Concrete structure, Life Cycle Assessment, Sustainability design, Sensitivity analysis.

IV. 2. Introduction

Concrete is one of the most widely used construction materials in the world [2]. However, concerning environmental impacts on resource consumptions, some geographical regions are running out of limestone to produce Portland cement, and some major metropolitan areas are running out of natural aggregates for concrete [2]. The worldwide contribution from buildings are about 40% of global energy, 25% of global water, 40% of global resources [23]. If current trends continue, expansion of the built environment will destroy or disturb natural habitats on over 70% of Earth's land surface by 2031, driven by population growth, economic growth and urbanization [23].

The building sector approximately emits 35% of total greenhouse gases (GHG) [23]. In the United States, 9.8 million metric tons of CO_2 is generated to produce 76 million metric tons [3]. In fact, carbon dioxide (CO_2) emissions issued cement production currently represent about 5%-7% of anthropogenic global CO_2 emissions [4].

In our sense, a sustainable concrete structure is thus constructed to ensure that the total environmental impacts concerning both emissions and consumptions, during its whole life cycle, including its use, will be minimal [2]. Design for sustainability should then consider the short- and long-term environmental impacts in the design stage. Life Cycle Assessment (LCA) is therefore a helpful tool in the design for environment. LCA is an internationally standardized method for compiling and examining the inputs and outputs of energy and materials, and the potential environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle [6].

Concerning the environmental impacts with LCA, a traditional design process is based on the comparison of few specific alternatives based on the goal and scope definition. Then, based on the impact indicator results obtained from LCA for each alternative, the best option has the minimum impact indicator value, among the preferred impacts defined by designers. Many comparative LCA studies are carried out at different levels such as the different kinds of concrete [42] [43] [44], structural elements [45] [46] [47] and bridges [29] [48] [42]. These LCA studies focus on the material extraction and production, because they are well-known in designing a new structure, but the use and end-of-life phases are neglected because they are unknown at the design stage.

When environmental impacts of different kinds of concrete are compared, it is very important to ensure that they fulfil similar functional requirements, which is defined as Function Unit (FU) in LCA. Compared concretes should thus have similar mechanical properties, workability and durability related to properties. Nevertheless, current concrete LCA studies do not provide a common, systematic, and comprehensive FU. Common FU in previous concrete LCA studies are discussed below.

The use of one cubic meter of ready-mixed concrete has commonly been chosen as FU in previous studies [167] [168] [169] [44] [170]. This choice without other specifications is not relevant, because if the mix proportions of cement, sand, gravel and water change, the mechanical properties of concrete change as well. Other LCA studies [171] [172] [43] [173] [174] [175] have added the 28-day compressive strength of concrete as an additional specification to the one cubic meter of ready-mixed concrete as FU. However, the service life of such compared structures could be very different because it depends on natural alterations like carbonation or exposure to chloride.

Finally, some concrete LCA studies [176] [177] [178] have added the service life of concrete cover to the one cubic meter of ready-mixed concrete as FU. For example of steel corrosion induced by carbonation, the service life is defined as the period of penetration of CO_2 into the concrete cover until the carbonation front reaches the reinforced layer [176]. By setting an identical volume as FU, these studies indirectly consider that the service life only depends on the concrete properties. It is independent on the concrete cover depth. However, an increase of concrete cover depth results in the increase of service life with a given concrete.

In summary, these choices of FU are not accurate in most practical situations, i.e., such LCA results cannot provide effective decision support in the design for the sustainability of new concrete structures. Instead of providing general comparison of concrete, we need to develop a new method that can be adapted to each particular situation.

The present paper reports a study conducted to develop a design approach for the sustainability of RC structures. The approach discussed here is the results of the combination of a decision diagram, a service life model, LCA method and two Sensitivity Analysis (SA) methods (Sobol and Morris' method [66] [67]). The robustness of our approach is: firstly, instead of setting the initial scenarios as the traditional design process performs, our approach considers simultaneously all possible combinations. We integrate thus a decision diagram and the uncertainties from technological aspects and outside environmental location. Secondly, finding optimized concretes is based on the comparison of environmental impacts with similar functional requirements, i.e., an equivalent function over a service life design. Consequently, the most sustainability of concrete is achieved in a more scientific and reliable way.

Our service life model considers concrete submitted to carbonation. The case study is a RC structure of XC4 exposure class in Madrid (Spain). The scope is to design the most sustainable life cycle design of 1 m^2 concrete cover with the cement strength class 42.5 and 52.5 MPa, without maintenance activities during the 100-year service life design.

The design approach is presented in Section IV. 3. The results are detailed in Section IV. 4. The discussion of SA results are performed in Section IV. 5. The conclusions are drawn in Section IV. 6.

IV. 3. Design approach for sustainability

Figure 22 depicts the design approach for sustainability.

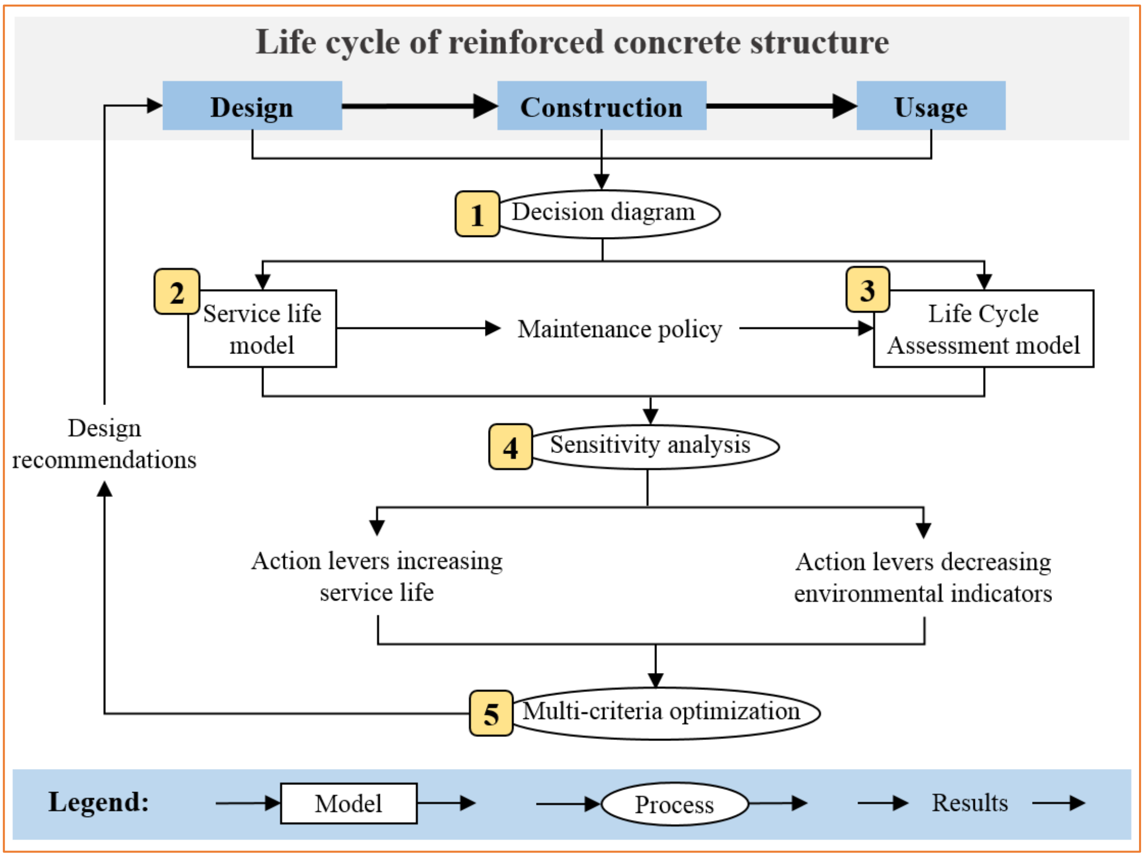

Figure 22. Scheme of design approach for sustainability.

The decision diagram (n°1 in Figure 22) describes the set of choices and their relationship determined by the engineering designer. These choices mainly concern dimensions of the structure, choices of materials (for the initial construction and maintenance operations) as well as maintenance techniques.

The service life model (n°2 in Figure 22) provides a calculation of service life, according to the type of material, technological aspects as well as environmental exposure conditions. It also predicts time at which a maintenance operation is necessary in order to reach service life design.

We use LCA (n°3 in Figure 22) to estimate the environmental impacts of construction and maintenance processes, as a function of choices from the decision process at the design phase.

The service life and environmental impact indicators are tested with sensitivity analyses (n°4 in Figure 22), in order to identify action levers for both increasing the service life and reducing the environmental impacts of concrete structures.

A comparison of all possible actions is conducted in an optimization step (n°5 in Figure 22) and provides recommendations for sustainable design.

In the following sub-sections, we describe in more detail the steps indicated in Figure 22.

IV.3. 1. Description of the case study

The case study is a Reinforced Concrete (RC) structure submitted to carbonation dimensioned for the 100-year service life design. Madrid has high levels of air pollution [72] and the relative external humidity is about 0.56 [9], that is the most favorable surrounding condition for concrete carbonation [70] [71]. We supposed thus that the RC structure is located in Madrid.

Following recommendations of EN 206-1 we assumed XC4 exposure class [10], i.e., concrete is in open air and the structure is not sheltered from rain.

IV.3. 2. Decision diagram

This step is indicated as n°1 in Figure 22. According to previous results [179], a RC structure, designed with the cement strength classes 42.5 or 52.5 MPa, does not have a corrosion risk within the 100-year service life design, whereas, a RC structure, designed with the cement strength class 32.5 MPa, requires maintenance or repair operations in order to reach the 100-year service life design. This paper only focus on concrete designed with cement strength class 42.5 or 52.5 MPa. Concrete designed with cement strength class 32.5 MPa will be the subject of another paper. Consequently, we considered twenty scenarios of concrete cover that are the results of two cement strength classes in association with ten cement types as shown in Figure 23. The cement characterizations are given in Table A1 in Appendix. The cement types considered here are not forcedly exhaustive, this list has been restricted to the available Life Cycle Inventory (LCI) data for market for cement in the Ecoinvent database [11].

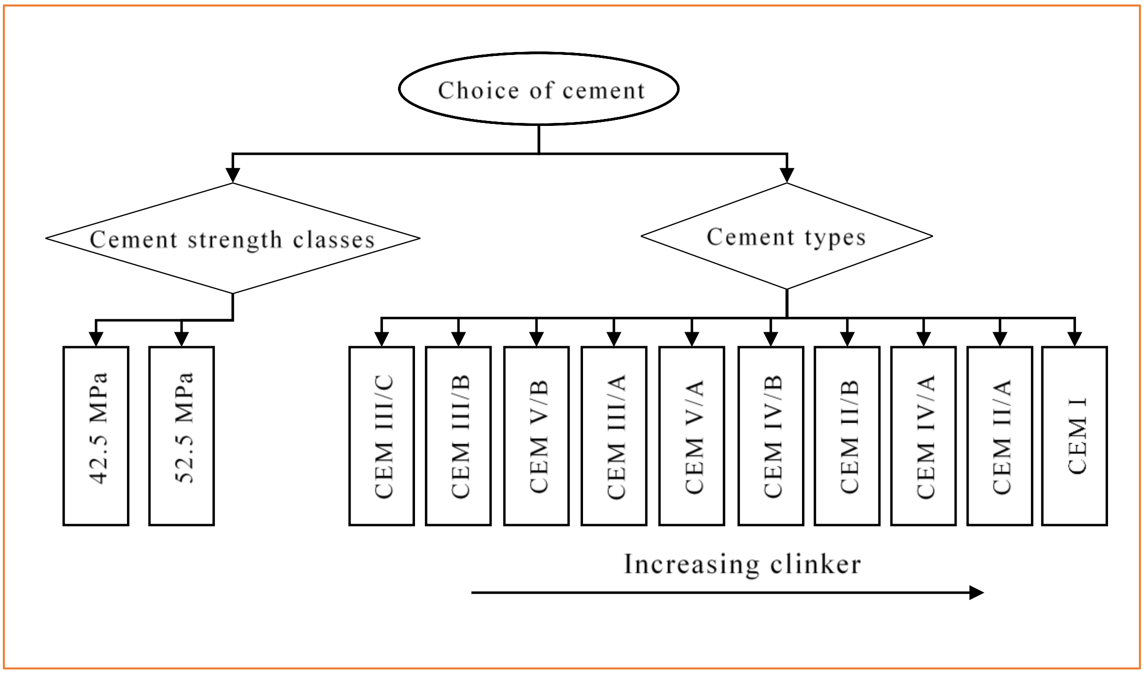

Figure 23. Decision diagram in the case of cement strength class 42.5 and 52.5 MPa.

IV.3. 3. Service life model

This step is indicated as n°2 in Figure 22. In order to predict the service life of structure, we used the carbonation model that was previously published by Ta et al. [125]. This model considers many influencing design parameters, and it is validated with numerous experimental observations of natural carbonation depth from the literature. It is based on the analytic solution of Fick’s law as follows:

$$x = \sqrt{\frac{2 \times D_{CO_2} \times CO_2}{a}}.\sqrt{t} \qquad (29)$$

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

When the carbonation depth is equal to the concrete cover depth (d), the service life (t_{ser}) is expressed as:

$$t_{ser} = \frac{d^2 \times a}{2 \times D_{CO_2} \times CO_2} \qquad (30)$$

We use a model f_1, which links the service life (t_{ser}) and the independent input parameters as described in [125].

$$t_{ser} = f_1(d, C, W/C, S/G, S\_max, t_c, T, RH, CO_2) \qquad (31)$$

where: d (m) is the concrete cover depth, C (kg/m^3 of concrete) is the amount of cement content, W/C (n.u.) (n.u. = no unit) is the water-to-cement ratio, S/G (n.u.) is the sand-to-gravel ratio, S_max (mm) is the maximum aggregate size, T (K) is the ambient temperature, RH (n.u.) is the relative external humidity, CO_2 (kg/m^3) is the CO_2 concentration in the air.

IV.3. 4. Life Cycle Assessment model

This step corresponds to n°3 in Figure 22. FU is the volume. FU is the volume of concrete corresponding to $1m^2$ of concrete cover surface. The system boundaries are illustrated in Figure 24. Transportation of ready-to-use concrete to the site is assumed performed by lorry 16-32 metric ton (database in Ecoinvent3: transport freight lorry 16-32 metric ton EURO5).

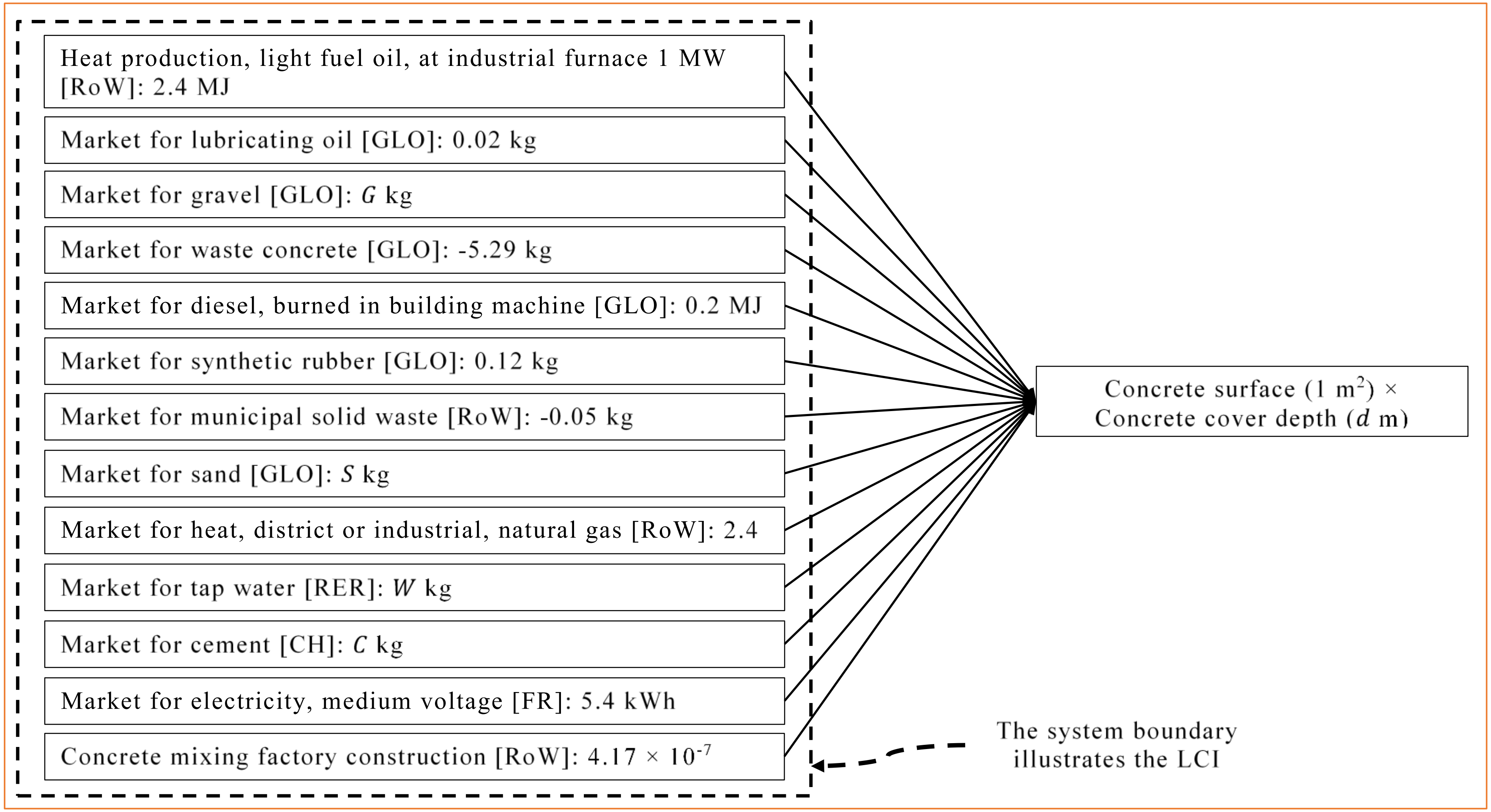

Figure 24. Concrete production system boundary.

Let us suppose that 1 m^3 of fresh concrete is composed of cement, gravel, sand, water and entrained air. The following balance equation should be fulfilled:

$$\frac{C}{\rho_c}+\frac{G}{\rho_g}+\frac{S}{\rho_s}+\frac{W}{\rho_w}+\phi_{air}=1 \tag{32}$$

where: C (kg/m^3 of concrete) is the amount of cement content, ρ_c (kg/m^3) is the cement density, G (kg/m^3 of concrete) is the amount of gravel content, ρ_g (2650 kg/m^3) is the gravel density, S (kg/m^3 of concrete) is the amount of sand content, ρ_s (2600 kg/m^3) is the sand density, W (kg/m^3 of concrete) is the amount of water content, ρ_w (1000 kg/m^3) is the water density, ϕ_{air} (n.u.) is the volume fraction of entrained air into the concrete mix.

The volume fraction of entrained air into the concrete mix (ϕ_{air}) is calculated from maximum size aggregates (S_max) [128]. Based on Eq. (32), we express the amount of gravel content (G), sand content (S) and water content (W) according to the amount of cement content (C), water-to-cement ratio (W/C), sand-to-gravel ratio (S/G) and maximum size aggregates (S_max). The cement density (ρ_c) depends on cement type as given in Table A1 in Appendix.

We use a model f_2, which links the environmental impact indicators ($Indicator$) and the independent input parameters as follows:

$$Indicator = f_2(d, C, W/C, S/G, S\_\mathrm{max}) \tag{33}$$

The environmental impacts are calculated following the ILCD recommendations [12].

IV.3. 5. Sensitivity analysis

The SA approaches are resumed but not detailed in this paper, as they were published previously [68] [69].

a) General principles

Parameters of models are classified in the following groups: (i) **technological parameters** are those controllable by the engineering designer (e.g., material properties, execution process of material), they thus represent action possibilities; (ii) **environmental parameters** are those uncontrollable and depending on the outside environmental location (e.g., aggressive agent sources like CO_2 concentration, chlorides, ambient temperature and relative external humidity).

We define **action levers** as technological parameters, which are major contributors to the sensitive service life and environmental impacts. The action levers are determined from SA. Suitable SA methods must be thus selected. They must quantify the influence alone of action levers and, if necessary, in interactions with other parameters. In addition, they must provide the trend of action levers in relation to service life and environmental impact indicators and, characterize the most favorable values of action levers allowing longest service life and smallest environmental impact indicators. Consequently, a combination of Sobol's quantitative [66] and Morris' qualitative SA methods [67] is chosen. Both methods require that all the parameters are independent of one another. This combination has been previously used for the same purpose environmental design using LCA [68] [69].

Sobol's method [66] is based on the analysis of the variance decomposition of the model f in order to quantify the input parameters contribution to variations of service life and environmental impacts. It quantifies the influence of each input variable on output variable. The individual influence of each input is measured using the first order index S_j and total influence, including interactions with other inputs, is measured using the total order index S_{T_j}. Monte Carlo simulations are performing by varying simultaneously all input parameters, according to their PDF and calculating the associated model output. The Sobol indices are calculated by means of a bootstrap method with 500 replications from a half-sample (5,000) taken from an initial sample of about 10,000.

Morris' method provides additional information on the influential trend of parameters. This method consists in developing a randomized experimental design process by varying one parameter while keeping the others constant (OAT method) over a certain number of repetitions. Then, the elementary effects are obtained. The Morris indices are calculated, including the mean value (μ_j) of the elementary effects, the mean value of the absolute value (μ_j^*) of the elementary effects and the standard deviation value (σ_j) of the elementary effects. The Morris indices are calculated by means of discretization of the input parameters in 10 values with a prescribed number of trajectories of about 30.

b) Characterization of parameters

Results of SA highly depend on Probability Distribution Function (PDF) of input parameters [180]. The characterizations of technological and environmental parameters are synthetized in Table 8.

Table 8. Characterization of technological and environmental parameters.

Parameter	Symbol	Unit	Probability distribution Function	Ref.
Technological				
Cement content	C	kg/m^3	$\mathcal{U}$ (min = 300; max = 509)	[10] [-]
Water-to-cement ratio	W/C	n.u.	$\mathcal{U}$ (min = 0.4; max = 0.5)	[10] [-]
Sand-to-gravel ratio	S/G	n.u.	$\mathcal{U}$ (min = 0.5; max = 2.1)	[-]
Maximum size aggregates	S_max	mm	$\mathcal{U}$ (min = 20; max = 32)	[10] [-]
Concrete cover depth	d	m	$\mathcal{U}$ (min = 0.05; max = 0.08)	[152] [153]
Initial curing period	t_c	days	$\mathcal{U}$ (min = 1; max = 3)	[154]
Transport distance	$Tran$	km	$\mathcal{U}$ (min = 1; max = 50)	
Environmental				
Ambient temperature	T	K	$tr\mathcal{N}$ (mean = 287; CoV = 0.03; min = 272.4; max = 309.1)	[9]
Relative external humidity	RH	n.u.	$tr\mathcal{N}$ (mean = 0.56; CoV = 0.33; min = 0.2; max = 0.88)	[9]
CO_2 concentration in the air	CO_2	ppm	$tr\mathcal{N}$ (mean = 380; CoV = 0.05; min = 304.6; max = 456.8)	[72]

Notes:

1/ CoV = Coefficient of Variation; $tr\mathcal{N}$ = truncated Normal distribution; $\mathcal{U}$ = Uniform distribution; $d\mathcal{U}$ = discrete Uniform distribution. The parameters are detailed in the text.

2/ [-] means that the variability range comes from the statistical analysis conducted by some experimental investigations found in the literature.

All technological parameters are considered chosen by the engineering designer. We assumed all possible choices within the distribution interval are equally probable. Thus, PDF of technological parameters are all assumed uniform. The technological parameters are characterized by the limiting values recommended by EN 206-1 [10] for XC4 exposure class, and from statistical analysis of studies addressing the problem of concrete carbonation found in the literature.

The requirements for concrete of EN 206-1 [10] for XC4 exposure class are a maximum water-to-cement ratio (W/C) of about 0.5, a minimum cement content (C) of about 300 kg/m^3, and maximum size of aggregates (S_max) from 20 mm up to 32 mm. The CEM I cement type concrete with a W/C lower than 0.4 has a higher carbonation resistance [96] [7] [155] [156]. For this reason, a minimum W/C of about 0.4 is considered. Based on a statistical analysis of seventeen experimental investigations on concrete carbonation [141] [33] [54] [139] [140] [157] [158] [90] [159] [135] [71] [160] [85] [92] [32] [161] [162], the maximum C is about 509 kg/m^3 and that the sand-to-gravel ratio (S/G) varies between 0.5 and 2.1.

A concrete cover depth (d) must have a minimum thickness to protect the steel reinforcements from carbonation [163]. This design parameter varies according to the exposure class, the quality of construction and the service life design [163]. Combined to the requirements for concrete of EN 206-1 [10] for XC4 exposure class, the recommended concrete cover depth (d) ranges from about 0.05 m [152] to 0.08 m [153] for structure design with an expected 100-year service life.

Because of limited construction time, the initial curing period (t_c) varies between 1 day and 3 days [154].

The concrete factory is based 25 km from the working site, so round-trips are considered. However, on its way back to the concrete factory, an empty truck weights 20% of the concrete weight transported on its way out [181]. Consequently, the transport distance ($Tran$) of concrete from the plant to the working site ranging from 1 km up to 50 km.

The PDF of relative external humidity (RH) and ambient temperature (T) are characterized from weather data [9]. The PDF of carbon dioxide concentration in the air (CO_2) is taken from [72].

IV.3. 6. Identification of action lever

Based on Sobol indices, the technological parameters are assumed to have an individual influence (identified as action levers) if the value of first order index $S_j \geq 10\%$. Moreover, if the value of first order index S_j is lower than 10% but the difference $S_{T_j} - S_j$ is high, they can also be considered as potential action levers [68] [69]. This means that parameter X_j is not individually influential but has a non-negligible global contribution because of its interaction with the other parameters.

As regards Morris indices, the parameters with a higher mean value of the absolute value (μ_j^*) are considered as the major contributors to the model output and as a result, potential action levers [67]. Parameters have some interaction influences with other parameters if the value of standard deviation (σ_j) is high [67]. If the parameters satisfies the condition $\sigma_j \geq |\mu_j|$, they are considered to have a non-monotonic effect. Finally, parameters are considered as non-influential if μ_j^* is low.

IV.3. 7. Optimization

This step is indicated n°5 in Figure 22. After identifying the action levers for the service life and environmental impact indicators, we designed the favorable and default scenarios (see the definition of favorable and default scenario in Definitions) for each possible combination of the decision diagram. The purpose of favorable scenario is to increase the service life and decrease the environmental impacts. The favorable scenario is carried out by setting (i) the action levers at their minimal or maximal value based on the algebraic sign of the mean value (μ_j), (ii) the other technological parameters (identified as the non-influential parameters) at their mean value, and (iii) the environmental parameters according to their probability distribution. The default scenario provides as a standard scenario to validate the favorable scenario by comparing the service life and environmental impacts of two scenarios. The default scenario is carried out by setting all technological parameters at their mean value and the environmental parameters according to their probability distribution. We predict the service life and estimate the environmental impacts of scenarios.

Among the favorable scenarios, we select firstly the scenarios that have the service life higher than 100 years. Then, we compare their impact indicator results. The most environmentally conscious scenario is that has the minimum impact indicator value.

IV. 4. Results

IV.4. 1. Sensitivity analysis results and identification of action levers

We present the SA results for service life in Figure 25 for the ten cement types. The change in cement strength class does not have effects on SA results. We present the value of the first (S_j) and total index (S_{T_j}) and the algebraic sign of the mean value (μ_j) for the most influential parameters on environmental impact indicators in Table 9.

The most influential parameters on service life are water-to-cement ratio (W/C), ambient temperature (T), relative external humidity (RH). Ambient temperature (T) and relative external humidity (RH) are not controllable environmental parameters. They are susceptible to bring important uncertainties. Water-to-cement ratio (W/C) is a controllable technological parameter. All influential parameters on service life have interaction with other parameters ($S_{T_j} - S_j \in [10\%; 62\%]$ and high σ_j). In addition, the relative external humidity (RH) has a non-monotonic effects on service life ($\sigma_j \geq |\mu_j|$). Based on the algebraic sign of μ_j, we observe that a decrease ($\mu_j < 0$) in water-to-cement ratio (W/C), ambient temperature (T), CO_2 concentration in the air (CO_2) and increase ($\mu_j > 0$) in concrete cover depth (d), cement content (C), initial curing period (t_c), maximum aggregate size (S_max), sand-to-gravel ratio (S/G) result in the increase of service life (t_{ser}). Consequently, water-to-cement ratio (W/C) is the action levers for the service life.

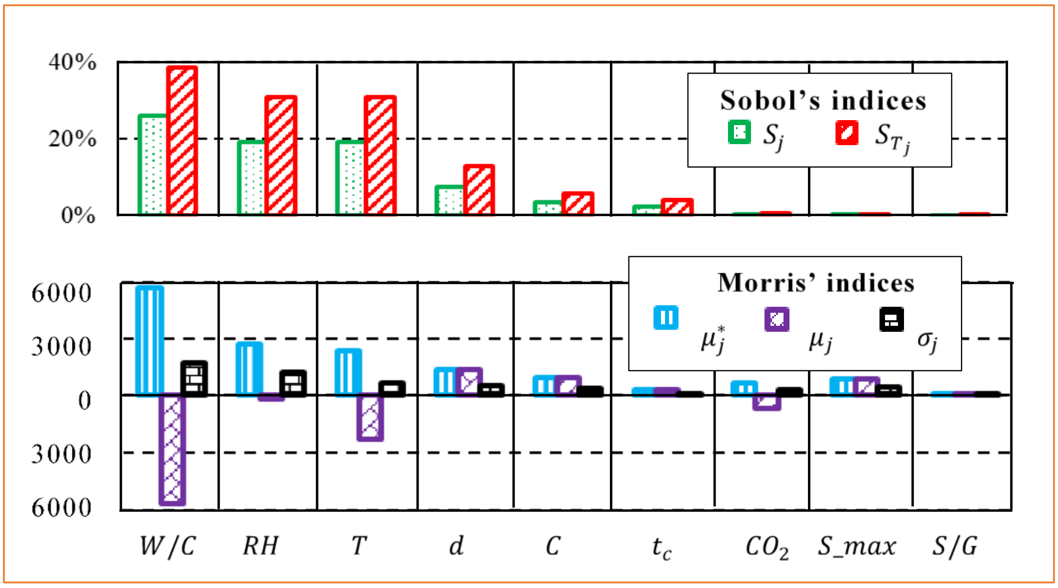

Figure 25. Sobol and Morris sensitivity indices for service life.

Table 9 reports the results for the most influential parameters, which have the highest first (S_j), total (S_{T_j}) order index and mean value of the absolute value (μ_j^*), on environmental impact indicators. Each parameter is presented by the value of S_j, S_{T_j} and the algebraic sign of the mean value (μ_j).

Table 9. Results of the sensitivity analysis for the most influential on impact indicators.

Impact indicator	**Parameters**	**Symbol**	**Unit**	**Algebraic sign of μ_j**	**S_j (%)**	**S_{T_j} (%)**	**Remarks**
Acidification (Mole H^+ eq.)	Transport distance	$Tran$	km	+	80	81	All cement types
	Concrete cover depth	d	m	+	18	19	All cement types
Climate change (kg CO_2 eq.)	Concrete cover depth	d	m	+	62	63	All cement types
	Cement content	C	kg/m^3	+	31	32	All cement types
Resource depletion, fossils (kg Sb eq.)	Concrete cover depth	d	m	+	67	68	All cement types
	Cement content	C	kg/m^3	+	14	14	Except for CEM III/B, CEM IIIC and CEM V/B
	Transport distance	$Tran$	km	+	21	21	All cement types
Freshwater ecotoxicity (CTUe)	Concrete cover depth	d	m	+	60	61	All cement types
	Cement content	C	kg/m^3	+	39	39	All cement types
Marine eutrophication (kg N eq.)	Concrete cover depth	d	m	+	46	47	All cement types
	Transport distance	$Tran$	km	+	44	45	All cement types
	Cement content	C	kg/m^3	+	11	11	Except for CEM III/A-C, CEM IV/B, CEM V/A-B
	Transport distance	$Tran$	km	+	76	77	All cement types

Terrestrial eutrophication (Mole N eq.)	Concrete cover depth	d	m	+	23	24	All cement types
Human toxicity, carcinogenics (CTUh)	Concrete cover depth	d	m	+	67	67	All cement types
	Cement content	C	kg/m^3	+	17	18	All cement types
Human toxicity, non-carcinogenics (CTUh)	Concrete cover depth	d	m	+	53	54	All cement types
	Transport distance	$Tran$	km	+	35	36	All cement types
	Cement content	C	kg/m^3	+	14	14	Except for CEM III/B-C, CEM V/B
Ionizing radiation, ecosystems (CTUe)	Concrete cover depth	d	m	+	98	98	All cement types
Ionizing radiation, human health (kg U235 eq.)	Concrete cover depth	d	m	+	69	70	All cement types
	Cement content	C	kg/m^3	+	17	17	Except for CEM III/C
	Transport distance	$Tran$	km	+	15	15	All cement types
Particulate matter (kg PM2.5 eq.)	Transport distance	$Tran$	km	+	81	82	All cement types
	Concrete cover depth	d	m	+	18	19	All cement types
Photochemical oxidation (kg C_2H_4 eq.)	Concrete cover depth	d	m	+	74	75	All cement types
	Cement content	C	kg/m^3	+	24	24	All cement types

The most influential parameters for environmental impact indicators are cement content (C), concrete cover depth (d) and transport distance ($Tran$). None of them has important interactions (S_{T_j} - $S_j \leq 2\%$ and smaller σ_j). It is also interesting to observe that the cement content (C) and the transport distance ($Tran$) are the most influential parameters according to the considered environmental impact and scenarios. For example, cement content (C) is identified as the most influential parameter for the following indicators: climate change (CC), resource depletion, fossils (RD), freshwater ecotoxicity (Ec), marine eutrophication (ME), human toxicity, carcinogenics (HTc), human toxicity, non-carcigenics (HTnc), ionizing radiation, human health (IRhh), and photochemical oxidation (PO) (Table 9). The transport distance ($Tran$) is identified as the most influential parameter for the following indicators: acidification (Ac), resource depletion, fossils (RD), Marine eutrophication (ME), Terrestrial eutrophication (TE), human toxicity, non-carcinogenics (HTnc), particulate matter (PM). Based on the algebraic sign of μ_j, we observe that a decrease ($\mu_j > 0$) in concrete cover depth (d), cement content (C) and transport distance ($Tran$) results in the decrease of environmental impacts. Consequently, concrete cover depth (d), cement content (C) and transport distance ($Tran$) are the action levers for the environmental impact indicators.

IV.4. 2. Design scenarios

We designed the favorable scenario by setting the technological parameters of the decision diagram at their specific values. The values of technological parameters for favorable and default scenarios are summarized in Table 10.

The action lever are water-to-cement ratio (W/C), concrete cover depth (d), transport distance ($Tran$) and cement content (C). They are set at the minimal value of about 0.4, 0.05 m, 1 km and 300 kg/m^3, respectively, for the favorable scenario. They are set at the mean value of about 0.45, 0.065, 25 km, and 404.5 kg/m^3, respectively, for the default scenario.

Because the maximum aggregate size (S_max), sand-to-gravel ratio (S/G), and initial curing period (t_c) are not found influential for both service life and environmental impact indicators, they are set at their mean value 26 mm, 1.3 and 2 days respectively.

Table 10. Technological parameters value of favorable and default scenario.

Parameter	**Symbol**		**Unit**	**Favorable Scenarios**	**Default Scenario**
Cement content	C	lever	kg/m^3	300	404.5
Water-to-cement ratio	W/C	lever	n.u.	0.4	0.45
Sand-to-gravel ratio	S/G	lever	n.u.	0.5	1.3
Maximum aggregate size	S_max	-	mm	26	26
Concrete cover depth	d	lever	m	0.05	0.065
Initial curing period	t_c	-	days	2	2
Transport distance	$Tran.$	lever	km	1	25.5

IV.4. 3. Service life

We predict the service life (t_{ser}) of twenty sub-scenarios defined from the decision diagram (Figure 23) for both scenarios: favorable scenario (FS) and default scenario (DS). We use Monte Carlo simulations with 50,000 generated values for each environmental parameter. We determine then the mean and standard deviation of service life (t_{ser}). We plot the mean and standard deviation of service life (t_{ser}) on log scale in Figure 26 versus the environmental impact indicators.

The service lives of favorable scenario (FS) overlap that of default scenario in the case of cement strength class 42.5 MPa (Figure 26). In contrast, the service lives of favorable scenario (FS) in the case of cement strength class 52.5 MPa are improved more significantly than the service lives of default scenario (DS) (Figure 26). Consequently, to achieve the highest service life, favorable scenario (FS) in the case of cement strength class 52.5 MPa is recommended. The service lives of favorable scenario are higher than 100 years.

IV.4. 4. Environmental impacts

We estimate the environmental impacts of favorable and default scenario corresponding to ten cement types. The results of environmental impact indicators are plotted versus the service lives in Figure 26. The reduction of favorable scenario is from 20% for ionizing radiation, ecosystems (IRe) up to 62% for acidification (Ac) and particulate matter (PM) impact indicators.

We observe in Figure 26 that acidification, terrestrial eutrophication, particulate matter impact indicators of favorable scenario (FS) reduce more significantly than that of default scenario (DS). The change in cement strength class does not have effects on environmental impacts, but it considerably increases the service life. Each single dot in Figure 26 corresponds to a different cement type as shown in Figure 23. In fact we could see that the increase corresponds to the increase of clinker content inside the cement mix.

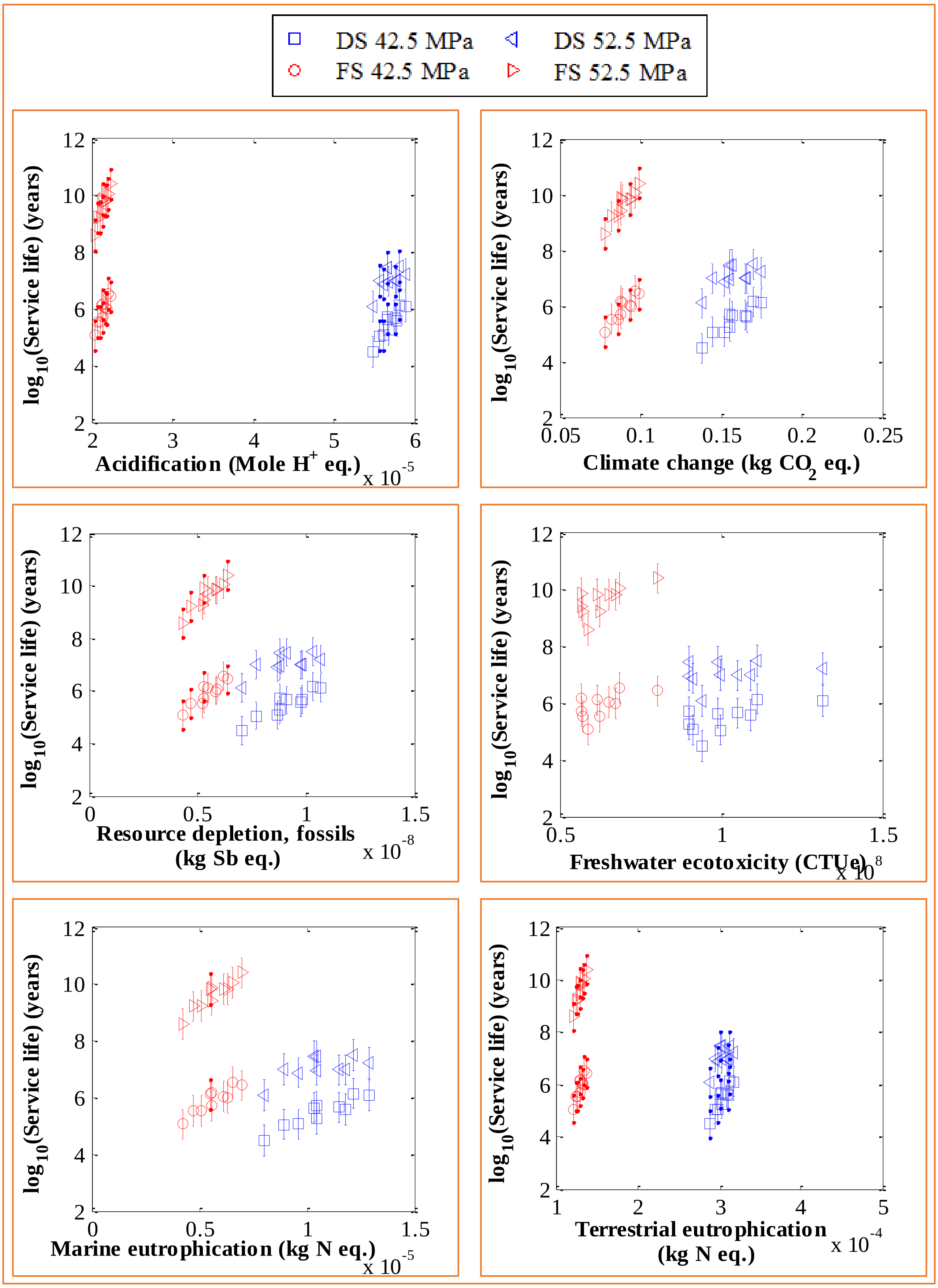

Figure 26. Service life versus environmental impact indicator: DS = Default Scenario and FS = Favorable Scenario.

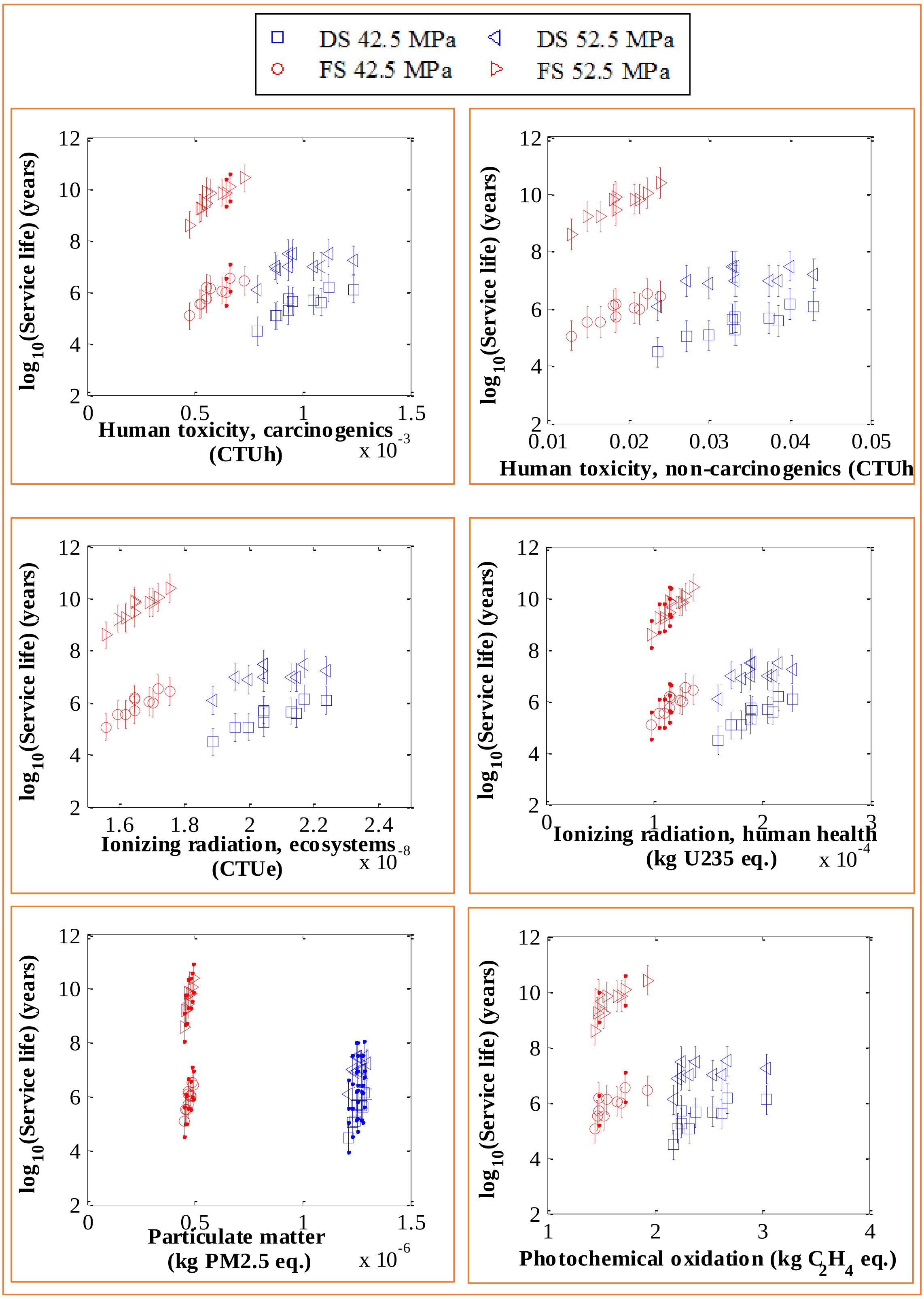

Figure 26 (continue). Service life versus environmental impact indicator: DS = Default Scenario and FS = Favorable Scenario.

Figure 27 shows environmental impacts of favorable scenario corresponding to different cement types. In Figure 27, we use the value of environmental impact indicators of CEM I cement type as reference value. We express the value of environmental impact indicators of the other cement types to CEM I cement type.

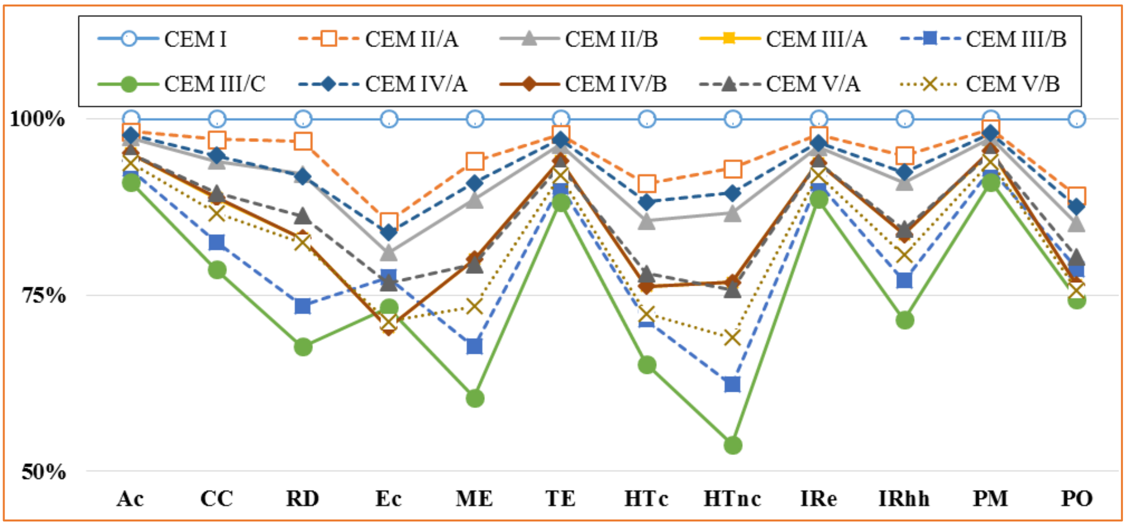

Figure 27. Comparison between environmental impact indicators of favorable scenarios with minimal cement content according to cement types.

The results in Figure 27 reveal that CEM III/C cement type has the lowest environmental impact indicators, except for freshwater ecotoxicity (Ec) impact indicator.

IV. 5. Discussions

IV.5. 1. Comments on the case study

In our case study, we found that water-to-cement ratio (W/C) is the major contributor to the service life. Water-to-cement ratio (W/C) is the key to the resistance to penetration of carbon dioxide into concrete [166] because it is an important indicator to evaluate the concrete porosity and permeability [164]. A decrease of water-to-cement ratio (W/C) results in the decrease of concrete porosity and permeability. This is in line with previous studies [51] [182].

Concrete cover depth (d) and cement content (C) are not found very influential compared to water-to-cement ratio (W/C) on the service life. However, they are major contributor to the environmental impacts. A decrease in concrete cover depth (d) and cement content (C) results in the significant reduction of environmental impacts.

We found that the value of environmental impact indicators linearly depends on the average percentage of clinker (Figure 28). Figure 28 shows the results of the case of the favorable scenario (FS). This means that the reduction of all environmental impacts is almost independent on the kind of supplementary cementitious material (SCM). Our experiments confirm with previous results with regards to climate change impact indicator [51] [182]. In addition, the magnitude of the reduction depends on the kind of impact indicator. Environmental impact indicators, which are the most significantly reduced, are climate change (CC), resource depletion, fossils (RD), marine eutrophication (ME), and human toxicity, non-carcinogenics (HTnc).

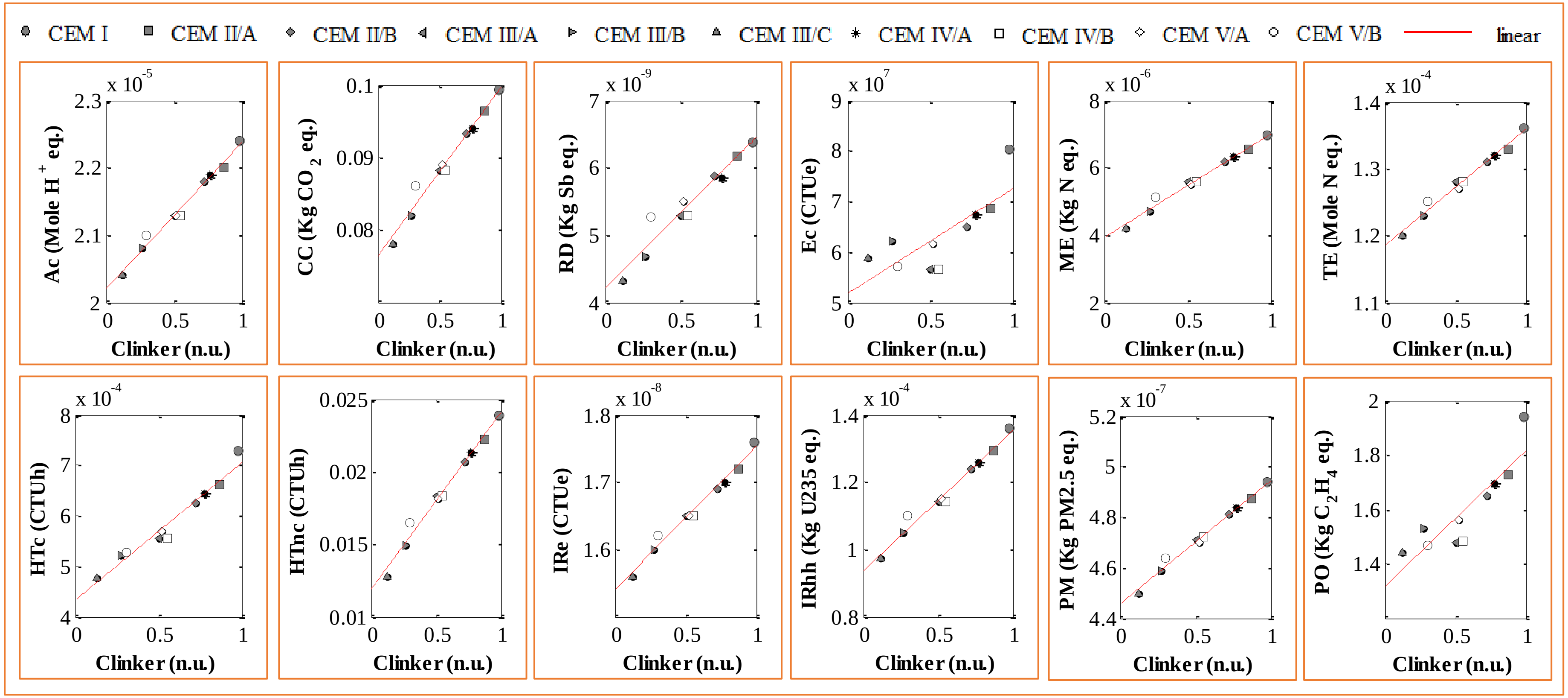

Figure 28. Relationship between environmental impact indicators and average percent of clinker of favorable scenario (FS).

Finally, in order to maximize service life, the favorable scenario with cement strength class 52.5 MPa is recommended. In order to decrease most environmental indicators, the favorable scenario is recommended as discussed above. In our case study, the service lives of both favorable scenarios are higher than 100 years (Figure 26). Thus, for a targeted service life design of 100 years, the favorable scenario with cement strength class 52.5 MPa and CEM III/C cement type are the most favorable solutions for a sustainable design.

IV.5. 2. Comments on the developed approach

Our developed approach is a helpful tool in the life cycle design for the sustainability of RC structures. Our approach aims to identify action levers for both increase service life and decrease environmental impacts. The significant innovation consists of considering the use phase of structure. Engineering designers easily increase the sustainability of RC structures by focusing on effective action levers.

Results of our case study are related to the location. Environmental conditions in Madrid favor carbonation. In another city, e.g., Nantes (France), carbonation is generally slower than in Madrid, due to higher relative external humidity (averaging 0.8 [9]). Thus, RC structures, designed by lower cement strength class (32.5 MPa) in Nantes, could be sufficient to avoid a corrosion risk during the 100-year service life. However, our approach is general and can be adapted to various situations. Optimization of both service life and environmental performances can be adapted according to location.

In this study, carbonation is the only alteration phenomenon of RC structure that is considered. However, concrete carbonation can be coupled with other severe deteriorations leading to accelerate its degradation, e.g., the presence of a small amount of chlorides significantly increases the corrosion risk in carbonated mortars [183]. In that situation, RC structures, designed by cement strength classes 42.2 or 52.5 MPa, could require maintenance or repair operation in order to reach the 100-year service life design. This would indeed change our results because the ongoing environmental impacts of RC structures is approximately proportional to the amount of maintenance required in comparison with one without these elements [29]. Further work should concentrate on the combined effects of various alteration mechanisms integrated in our model.

In addition to this study, further studies on the RC structure of our case study, which is designed with cement strength class 32.5 MPa, are required. It is necessary to find out under which maintenance or repair operation methods leads to improve the environmental performances. This would also allow comparing environmental indicators with the results of the present study, so that we can evaluate if lower initial cement strength class accompanied with maintenance is more interesting than higher cement strength class without maintenance (present case).

Finally, in the Life Cycle Assessment (LCA) methodological perspective, our approach bring a new view on the problem of functional unit. Instead of comparing a restricted number of solution with a rigid functional unit, we developed a method that allows optimizing both functional unit (herein, service life) and environmental impacts.

IV. 6. Conclusion

In this article, we developed a design approach for the sustainability of reinforced concrete (RC) structures, which allows optimizing their environmental performances during their service life, integrating alteration mechanisms. This method combines a decision diagram, a service life model, Life Cycle Assessment (LCA) method and sensitivity analysis methods.

Our approach was applied to a RC structure submitted to carbonation with a XC4 exposure class located in Madrid (Spain). Both cement strength classes (42.5 and 52.5 MPa) can fit with a 100-year service life design without maintenance operation, but cement strength class 52.5 MPa provide longer service life. It can be thus recommended for structures requiring the longest service life such as bridges. Cement strength class 42.5 MPa is however suitable for lowest service life structures such as buildings. To reach the lowest environmental impacts, we found that using the lowest cement content (C), water-to-cement ratio (W/C), concrete cover depth (d) and distance from the concrete factory to the site ($Tran$) are the most efficient levers. The CEM III/C cement type is the most favorable solution for a sustainable design.

This example shows that in a given localized situation, it is possible to define the most adapted solution to both increase service life and decrease environmental impacts. It thus goes beyond classical LCA approaches that compare materials with a rigid functional unit, not accounting for usage situation.

In forthcoming researches, our method should be completed with other alteration mechanisms such as chloride exposure, sulfate attacks or cracking. It should integrate two-dimensional alteration models in order to better reflect localized effects, and be able to extend the approach to a whole engineering structure.

V. DEVELOPMENT OF SERVICE LIFE MODEL CONSIDERING THE PREVENTIVE COATING SYSTEM

This chapter focusses on the step 2 in Figure 1. It treats of the RC structure of the case study that is designed with the cement strength class 32.5 MPa. This RC structure is maintained by a preventive coating system during the 100-year service life design (see Chapter III). We need to develop another service life model that considers the effect of coating system on the propagation of carbonation front depth.

Résumé :

Dans ce chapitre, tout d'abord, nous développons un nouveau modèle pour calculer la profondeur de carbonatation d'un béton protégé par un revêtement. Le coefficient de diffusion du CO_2 dans le revêtement ainsi que son épaisseur de revêtement sont intégrés pour considérer l'effet de revêtement. Puis, nous utilisons la méthode de Sobol et de Morris pour réduire le nombre de paramètres d'entrée en éliminant les paramètres non-influents sur le taux de carbonatation naturelle. Nous avons trouvé que le rapport eau sur ciment (W/C), le type de ciment (CEM), la classe de résistance du ciment (f_{cem}), la température ambient (T), la période de cure

(t_c), la teneur en ciment (C) et l'humidité relative extérieur (RH) (dans l'ordre décroissant) sont les paramètres les plus influents sur le taux de carbonatation naturelle. T et RH sont les paramètres environnementaux (non contrôllable). Pour baisser le taux de carbonatation, il faut diminuer W/C, augmenter f_{cem}, t_c, C and utiliser le type de ciment contenant plus clinker. Le méta-modèle réduit est validé avec des résultats de la littérature pour des cas de carbonatation naturelle de béton sans revêtement avec la période d'exploitation de 21 jours à 35 ans, les quatre de types de ciment (CEM I, CEM II, CEM III et CEM IV), W/C de 0,45 à 0,7 et t_c de 1 jour à 28 jours. Puis il est validé pour des cas de carbonatation naturelle du béton protégé par les différents types de revêtement : acrylique, acrylique modifiée silicium organique et siloxane.

V.1. Abstract

This paper aims firstly at developing a carbonation model considering the effect of coating and relevant parameters influencing natural carbonation rate. Secondly, it presents the results of a Sensitivity Analysis (SA) (using Sobol and Morris' method) of a natural carbonation rate model recently developed by Ta et al. to the input parameters. Natural carbonation rate is found to be most sensitive to water-to-cement ratio (W/C), cement type (CEM), cement strength class (f_{cem}), initial curing period (t_c) and cement content (C) linked to the technological aspects, ambient temperature (T), relative external humidity (RH) linked to the outside environmental location. We used the SA results to reduce a meta-model recently developed by Ta et al. regarding the number of input parameters. Robustness of the reduced model is demonstrated by its ability to apply universally to the various exposure times (from 21 days up to 35 years), CEM (CEM I, CEM II, CEM III, CEM IV), W/C (from 0.45 up to 0.7) and t_c (from 1 days up to 28 days), while maintaining reliable predictions. The SA results provide also effective decision support in the design of durable new structure exposed to carbonation by following European standards (EN 206-1) in Madrid.

Key words: Concrete carbonation; Sobol; Morris; Sensitivity analysis; Surface coating

V.2. Introduction

Nowadays, Reinforced Concrete (RC) structures are widely constructed in the world. Their service life design is mostly like 50-100 years [10]. However, deterioration can begin as little as 10 years due to diverse deterioration mechanisms [184]. The corrosion of steel reinforcements is the major cause of the degradation of RC structures. It is due to both the ingress of chloride ions and carbonation. Concrete carbonation can be coupled with other severe deteriorations leading to the degradation more quickly, e.g., the presence of a small amount of chlorides significantly increases the corrosion risk in carbonated mortars [183]. So, RC structures should be attended by the systems of maintenance in order to reach the scheduled service life. This paper is focused on concrete carbonation phenomena and the use of surface coatings to increase the service life of RC structures.

The use of surface coatings is the relevant and more common method used for damage of RC structures caused by carbonation [59] [30]. In other words, controlling the ingress of liquid water into concrete is particularly important property of coating for the two following reasons: first, because without water the carbonation reaction may not take place. Second, because water helps transport aggressive substances carbon dioxide into concrete.

According to Directive 2004/24/CE [185]: "coating means any preparation, including all the organic solvents or preparation containing organic solvents necessary for its proper application, which is used to provide a film with decorative, protective or other functional effect on a surface." And "film means a continuous layer resulting from the application of one or more coats to a substrate." Dry film thickness (DFT) is measured in microns when film is dry. An adequate DFT is mandatory for the success of any coating system. The recommended DFT depends on the type of coating system and nature of surface [186]. The factors affecting the performance of coating system are its DFT and the durability of coating. The DFT between 100 μm and 5000 μm is recommended depending on application, certain application is required more than 5000 μm [57]. Based on a review of the experimental investigations of paint coated concrete carbonation [187] [188] [86] [189] [190] [158] [191] [122] [192], the coating system is not 100% effective like a carbon dioxide barrier. In practice, the successful performance of coating system depends on the whole system such as the coating type, application methods of coating, conditions of concrete surface geometry and environmental exposure conditions. The anti-carbonation performance of coating can be measured by a coating effectiveness (γ) determined as follows:

$$\gamma = 1 - \frac{x_{coat}}{x} \tag{34}$$

where: x_{coat} (mm) is the carbonation depth of paint coated concrete, x (mm) is the carbonation depth of uncoated concrete. x_{coat} and x are measured at the same time of exposure to the carbon dioxide.

For γ = 1 a coating would be regarded fully effective in restricting ingress of carbon dioxide, in contrast, for γ = 0 a coating is ineffective. The γ of a coating is inconstant, it is time-dependent [187]. Long-term results reveal that the γ around 0.65 [188] and 0.55 [193] after 4-year and 14-year exposure to the atmosphere respective.

More and more service life prediction model can be used either at the initial design of new RC structures or during repair and maintenance of existing RC structures [7]. Consequently, service life prediction model (i) is as simple as possible; (ii) takes as much as relevant parameters influencing on the deterioration processes into account; (iii) must be sufficiently accurate, physically and chemically correct; and (iv) considers the effects of the preventive maintenance and repair systems during the service life.

The use of surface coating to increase the service life of RC structures exposed to carbon dioxide has been subject to major interest over the past decades. Nevertheless, the literature lacks the plausible model for practical prediction of carbonation depth within paint coated concrete structures. Yang's model [74] proposes a constant γ for all kinds of paint ($x = \gamma A\sqrt{t}$) with A is the carbonation rate. Aguiar's model [158] is based on the model of CEB [194], and then the consideration of the effect of coating is completed by determining the carbonation resistance from accelerated test. Monteiro et al. [195] found that there is an initial delay in carbonation of paint coated concrete, as the result, they have proposed an empirical model in the form $x = A\sqrt{t} - x_o$ with x_o is the carbonation depth delayed. These models are semi-empirical, i.e. they are firstly based on the analytic solution of Fick's first law, and then, they are completed by fitting the required parameters to experimental results. To take account of permeation and diffusion of carbon dioxide and also the degradation of coatings, Park [86] has developed a numerical model using the finite element method to estimate the carbonation depth within paint coated concrete. However, numerical model is difficult to use because they require accurate and complete data (the number and accuracy of input parameters required are too large and time-consuming).

Although different researchers identified different parameters affecting carbonation rate (A) [196] [197] [125], there is no published study on the sensitivity of carbonation rate to the various input parameters.

This paper aims firstly to develop a carbonation model considering the effect of coating. Secondly, a Sensitivity Analysis (SA) of the carbonation rate model recently developed by Ta et al. [125] using Sobol and Morris' method [66] [67] is carried out, in order to identify the most influential parameters and quantify their impacts on natural carbonation rate. We used SA results to simplify the number of input parameters of meta-model developed by Ta et al. [125] by eliminating the non-influential parameters.

A carbonation model considering the effect of coating is developed in Section V.3. The implementation of Sobol and Morris' method to study the sensitivity of carbonation rate to the input parameters is presented in Section V.4. The SA results are presented in Section V.5. Section V.6 discuss the SA results and presents the simplified meta-model. The conclusions are drawn in Section V.7.

V.3. Carbonation model considering coating

To develop the carbonation model to calculate the natural carbonation depth within paint coated concrete structures, the basic assumptions were made: (i) coating adds a resistance to diffusion of CO_2 but does not change the carbonation reaction; (ii) CO_2 diffusion is modelled as a steady state transport process; and (iii) CO_2-gas flux through the coating and carbonated concrete is identical. Consequently, a simplified model which illustrates the carbonation process of paint coated concrete is shown in Figure 29. Four zones can be distinguished. The first zone, close to the surface exposed to air, is the thickness of coating. Then, a second zone is considered fully carbonated: its carbonate content is constant. A third zone is a transition zone, often referred carbonation front, corresponds to the part of concrete material, for which the level of carbonation gradually decreases form its maximum (at interface with the second zone). And finally, a fourth zone where non carbonation is observed.

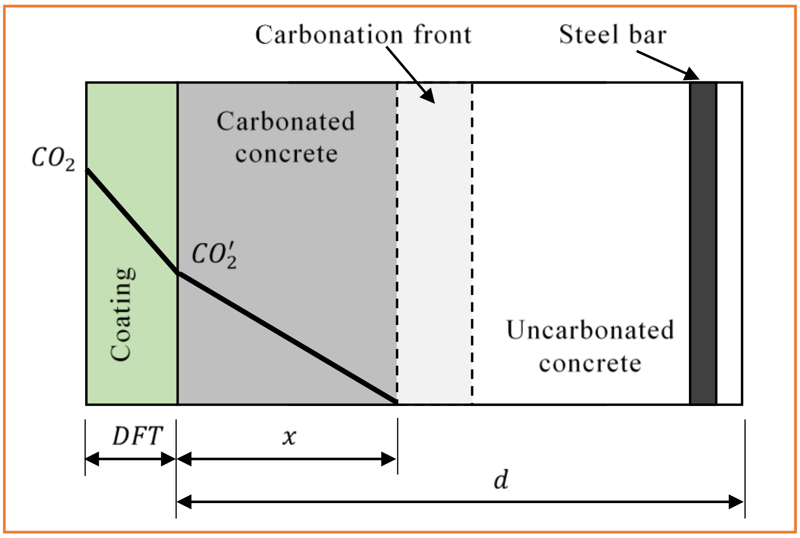

Figure 29. CO_2 diffusion model through paint coated concrete.

Because the CO_2 diffusion through coated concrete is assumed to be the steady state diffusion, thus, the CO_2-gas flux through the unit area of a concrete section, J_{CO_2} (kg/m^2/s), is proportional to the CO_2-concentration gradient dCO_2'/dx (kg.m^{-4}) and the CO_2-diffusion coefficient in concrete, D_{CO_2} (m^2/s) [198]:

$$J_{CO_2} = -D_{CO_2}\frac{dCO_2'}{dx} \tag{35}$$

where: CO_2' (kg/m^3) is the CO_2-concentration at the boundary between the coating and concrete.

The masse balance equation of CO_2 at the carbonation front is:

$$J_{CO_2}.dt = a.dx \tag{36}$$

where: dt (s) is a short time step during which the carbonation front advances dx, a (kg/m^3) is the amount of CO_2 absorbed in a unit volume of concrete.

As Figure 29 shows that the CO_2-concentration changes linearly from CO_2' to zero through the concrete. Thus, Eq. (36) could be written as:

$$\frac{dx}{dt} = \frac{J_{CO_2}}{a} = -\frac{D_{CO_2}}{a} \times \frac{dCO_2'}{dx} = \frac{D_{CO_2}}{a} \times \frac{CO_2'}{x} \quad (37)$$

As aforementioned assumptions that the CO_2-gas flux through a coating and carbonated concrete layer is identical. We obtain the following expression:

$$J_{CO_2} = D_{CO_2} \times \frac{CO_2}{x} = D_{CO_2}^{coat} \times \frac{CO_2 - CO_2'}{DFT} \quad (38)$$

where: $D_{CO_2}^{coat}$ (m^2/s) is the CO_2-diffusion coefficient of coating, CO_2 (kg/m^3) is the CO_2 concentration in the air, DFT (m) is the dry film thickness of coating.

From Eq. (38), we could express the CO_2'/x as follows:

$$\frac{CO_2'}{x} = \frac{D_{CO_2}^{coat} \times CO_2}{DFT \times D_{CO_2} + x \times D_{CO_2}^{coat}} \quad (39)$$

Introducing the expression of CO_2'/x into Eq. (37). We obtained:

$$\frac{dx}{dt} = \frac{D_{CO_2}}{a} \times \frac{D_{CO_2}^{coat} \times CO_2}{DFT \times D_{CO_2} + x \times D_{CO_2}^{coat}} \quad (40)$$

By considering a simplified case where the coating is not degraded, both DFT and $D_{CO_2}^{coat}$ are time-independent, Eq. (40) can be integrated and we obtain:

$$D_{CO_2}^{coat} \times x^2 + 2D_{CO_2} \times DFT \times x - \frac{2D_{CO_2} \times D_{CO_2}^{coat} \times CO_2}{a} t = B \quad (41)$$

where: B (n.u.) is the constant of integration depending on t.

For an initial condition of $x = 0$ at $t = 0$, Eq. (41) becomes:

$$x^2 + 2\frac{D_{CO_2}}{D_{CO_2}^{coat}} \times DFT \times x - 2\frac{D_{CO_2} \times CO_2}{a} t = 0 \tag{42}$$

An analytical solution of Eq. (42) is:

$$x = \sqrt{\frac{2D_{CO_2} \times CO_2}{a} t + \left(DFT \frac{D_{CO_2}}{D_{CO_2}^{coat}}\right)^2} - DFT \frac{D_{CO_2}}{D_{CO_2}^{coat}} \tag{43}$$

Eq. (43) can be used to calculate the carbonation depth within paint coated concrete structures.

The effect of coating on carbonation process is considered by the dry film thickness (DFT) and CO_2 diffusion coefficient of coating ($D_{CO_2}^{coat}$). They depend on the kind of coating.

To determine the expressions of calculating the CO_2 diffusion coefficient of carbonated concrete (D_{CO_2}), and amount of CO_2 absorbed in a unit volume of concrete (a), we carried out a SA of carbonation rate model in the next section.

V.4. Sensitivity analysis

The SA methods are resumed but not detailed in this paper, as they were published previously [68] [69]. Our approach combines two SA methods. Sobol' method enables quantifying the contribution of parameters alone and interaction with other parameters, to variations of carbonation rate. Sobol's method needs the characterization of the Probability Density Function (PDF) for each input parameter in order to run Monte Carlo simulations. It consists in varying simultaneously all input parameters, according to their PDF and calculating the associated model output. Morris' method provides additional information on the influential trend of parameters. Morris' method needs a local interval range (minimum and maximum value) of each input parameter. It is a "one at a time" method, which consists in varying one parameter and keeping constant the others over a certain number of repetitions r (range from 4 up to 10 [151]). The two methods require all parameters being independent.

V.4. 1. Carbonation rate model

Recently, Ta et al. [125] have been developed a meta-model to calculate the natural carbonation depth within uncoated concrete structures. This model is not detailed in this article, as it was previously published by Ta et al. [125].

From the meta-model, we can express carbonation rate (A) as follows:

$$A = \sqrt{\frac{2 \times D_{CO_2} \times CO_2}{a}} \tag{44}$$

where: A (m/s$^{1/2}$) is the carbonation rate, D_{CO_2} (m^2/s) is the CO_2 diffusion coefficient, CO_2 (kg/m^3) is the CO_2 concentration in the air.

We use a model f, which links A and 14 independent input parameters:

$$A = f(C, W/C, S/G, S\_max, CEM, f_{cem}, t_c, SiO_2, Al_2O_3, CaO, SO_2, T, RH, CO_2) \tag{45}$$

where: C (kg/m^3) is the amount of cement content, W/C (n.u.) is the water-to-cement ratio, S/G (n.u.) is the sand-to-gravel ratio, S_max (mm) is the maximum aggregate size, CEM (n.u.) is the cement type, f_{cem} (MPa) is the cement strength class, t_c (days) is the initial curing period, SiO_2, Al_2O_3, CaO, SO_2 are the chemical compositions of CEM I cement type, T (K) is the ambient temperature, RH (n.u.) is the relative external humidity, and CO_2 (kg/m^3) is *the CO_2 concentration in the air, G (kg/m^3 of concrete) is the amount of gravel content, S (kg/m^3 of concrete) is the amount of sand content, W (kg/m^3 of concrete) is the amount of water content.*

V.4. 2. Characterizations of input parameters

Results of Sensitivity Analysis (SA) methods highly depend on Probability Distribution Function (PDF) of studied parameters. The characterizations of technological and environmental parameters are synthetized in Table 11.

Table 11. Input parameter characterizations.

Parameter	**Unit**	**Probability Distribution Function (PDF)**	**Ref.**
Technological			
C	kg/m^3	$\mathcal{U}$ (min = 260; max = 509)	[10]
W/C	n.u.	$\mathcal{U}$ (min = 0.4; max = 0.65)	[10]
S/G	n.u.	$\mathcal{U}$ (min = 0.5; max = 2.1)	[-]
S_max	mm	$\mathcal{U}$ (min = 20; max = 32)	[10]
$\boldsymbol{CEM}$	n.u.	$d\mathcal{U}$ (10 cement types)	[10]
$\boldsymbol{f_{cem}}$	MPa	$d\mathcal{U}$ (3 strength classes)	[10]
SiO_2	n.u.	$\mathcal{U}$ (min = 0.1904; max = 0.2292)	[142]
Al_2O_3	n.u.	$\mathcal{U}$ (min = 0.035; max = 0.0583)	[142]
Fe_2O_3	n.u.	$\mathcal{U}$ (min = 0.0135; max = 0.0658)	[142]
CaO	n.u.	$\mathcal{U}$ (min = 0.6041; max = 0.6591)	[142]
SO_2	n.u.	$\mathcal{U}$ (min = 0.0234; max = 0.0377)	[142]
t_c	days	$\mathcal{U}$ (min = 1; max = 28)	[154]
Environmental			
T	K	$tr\mathcal{N}$ (mean = 287.4; CoV = 0.03; min = 272.4; max = 309.1)	[9]
RH	n.u.	$tr\mathcal{N}$ (mean = 0.56; CoV = 0.33; min = 0.2; max = 0.88)	[9]
CO_2	ppm	$tr\mathcal{N}$ (mean = 380; CoV = 0.05; min = 304.6; max = 456.8)	[72]

Notes:

1. Discrete parameters are in bold.

2. CoV = Coefficient of Variation; $tr\mathcal{N}$ = truncated Normal distribution; $\mathcal{U}$ = Uniform distribution; $d\mathcal{U}$ = discrete Uniform distribution. The parameters are detailed in the text.
3. [-] means that the variability range comes from the statistical analysis of experimental investigations in the literature.

The technological parameters were characterized by the limiting values recommended by EN 206-1 [10] for exposure classes referring to the concrete structures exposed to carbonation. The environmental parameters were characterized from data's weather in Madrid [9] for the ambient temperature (T) and relative external humidity (RH). Because Madrid has high levels of air pollution [72] and the relative external humidity is about 0.56 [9], that is the most favorable surrounding condition for concrete carbonation [70] [71]. The CO_2 concentration in the air pollution (CO_2) was taken from [72].

V.4. 3. Numerical simulations

We estimated the value of Sobol's indices corresponding to individual influence (S_j) and total influence, including interaction, (S_{T_j}). Monte Carlo simulations are performing by varying simultaneously all input parameters, according to their Probability Distribution Function (PDF) and calculating the associated model output. For estimating the Sobol's indices, 500 bootstrap replications of 5,000 in size from a sample initial size about 10,000 were run.

Morris' indices including the mean value (μ_j) and the mean value of the absolute value (μ_j^*) of the elementary effects, and the standard deviation value (σ_j) of the elementary effects are calculated. For calculating the Morris' indices, the input parameters were discretized in 10 values and the prescribed number of trajectories was about 30. The number of repetitions r ranges from 4 up to 10 [151].

V.4. 4. Identification of the most influential parameters

Based on Sobol's indices, technological parameters are considered as having an individual influence if $S_j \geq 10\%$. However, if $S_j \leq 10\%$ combined with a high value of $S_{T_j} - S_j$, parameters are still considered as action levers [68] [69], because the parameter X_j is not individual influence but has a non-negligible total influence due to its interaction with other parameters.

Firstly, Morris' indices can confirm Sobol's results by ranking parameters from most (highest μ_j^*) to least influential (lowest μ_j^*) [67]. Secondly, most influential parameters have an important value of σ_j, compared to μ_j^*, and that it also corresponds to a high value of $S_{T_j} - S_j$ this confirms important influences in interaction with other parameters [66] [67].

V.5. Sensitivity analysis results

The SA results are shown in Figure 30.

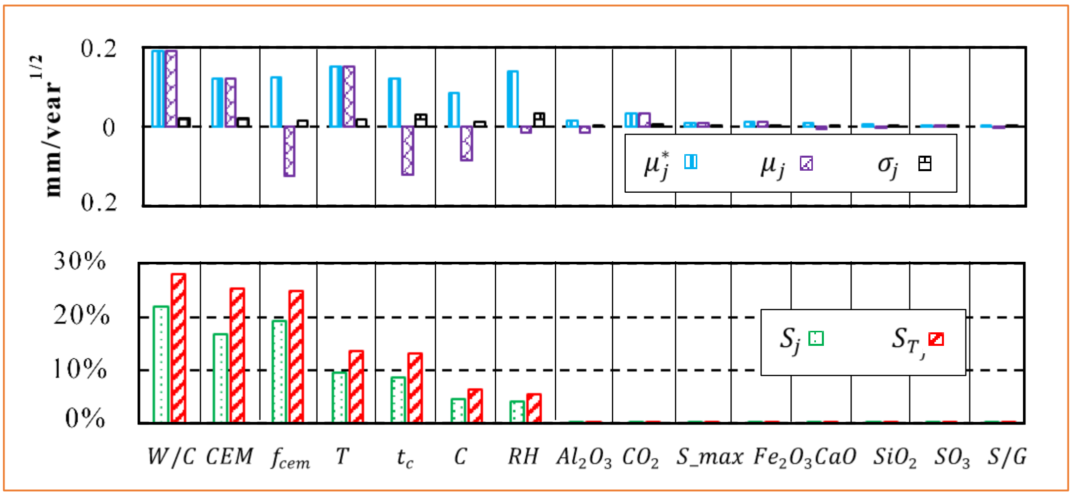

Figure 30. Sensitivity analysis results.

Figure 30 shows that water-to-cement ratio (W/C), cement type (CEM), cement strength class (f_{cem}), ambient temperature (T), initial curing period (t_c), cement content (C) and relative external humidity (RH) (in descending order) are the most influential parameters, because their S_{T_j} and μ_j^* values the highest. The difference $S_{T_j} - S_j$ is lower than 10%, meaning that the interactions with the other parameters are not important. Parameters W/C, CEM, f_{cem} are considered the most influent with a S_j value above 10%. T and RH are the environmental parameters that are uncertain. The less-influential parameters (S_{T_j} < 10% and low μ_j^*) are the chemical compositions of CEM I cement type (Al_2O_3, Fe_2O_3, CaO, SiO_2 and SO_3), sand-to-gravel ratio (S/G), maximum size aggregate (S_max) and CO_2 concentration in the air (CO_2). Based on the algebraic sign of μ_j, we observe that an increase in W/C, T, CO_2, S_max, Fe_2O_3 and SO_3 (μ_j > 0) and a decrease in t_c, C, Al_2O_3, CaO, SiO_2 and S/G ($\mu_j < 0$) result in the increase of carbonation rate (A). Parameters CEM and

f_{cem} are discretes. We rank from lowest to highest according to clinker content for parameter CEM, according to cement strength class for parameter f_{cem} in simulating. Consequently, based on the algebraic sign of μ_j of CEM and f_{cem}, we conclude that using lower cement strength class (f_{cem}) and clinker content result in the increase of A. The parameter RH had the non-monotonic effects (σ_j > $|\mu_j|$). The interactions between the parameters are negligible due to low σ_j and small $S_{T_j} - S_j$.

V.6. Discussion

V.6. 1. Parameters influencing carbonation rate

The SA results above are consistent with the literature. With regards to the technological parameters, firstly, the water-to-cement ratio (W/C) and cement strength class (f_{cem}) are the major contributors to the concrete porosity and 28-day compressive strength of concrete (f_c) [145] [164], which are the important indicators to evaluate the resistance to penetration of carbon dioxide into concrete [165]. An increase in W/C [166] and a decrease in f_{cem} [134] result in the increase of carbonation rate (A). Secondly, using cement type containing lower Portland clinker results in the increase of A [139] [166]. Thirdly, the initial curing period (t_c) has the considerable influence on carbonation rate (A) [118], carbonation rate (A) is increased by increasing t_c. Because a low curing period leads to poor concrete cover, which is favorable to the penetration of carbon dioxide into concrete. Fourthly, for a given W/C, an increase of cement content (C) results in the increase of f_c due to the richness of the mix [132]. Fifthly, the maximum size aggregate (S_max) and sand-to-gravel ratio (S/G) have lower influence on A [98]. Both the literature and our finding reveal that an increase of S_max results in increasing carbonation rate (A), because the reduction in the tortuosity leads to increase the permeability. In addition, the possibility of internal bleeding water takes place, which leads to increase the concrete porosity, if bigger aggregate is used [98]. When S/G is increased in one cubic meter of concrete mixed, the amount of sand content is increased too. This is responsible for the reduction in air permeability [98], i.e. A is decreased. Currently, the literature lacks the experimental investigation of the effects of the chemical compositions of CEM I cement type (Al_2O_3, Fe_2O_3, CaO, SiO_2 and SO_3) on A to validate our results.

The presence of carbon dioxide is necessary to carbonate concrete, but, the ambient temperature (T) and relative external humidity (RH) play the very important roles in the carbonation process. The highest A is observed for the RH around 0.75, the A is increased by increasing the RH from 0 up to 0.57, and the A is decreased by increasing the RH from 0.57 up to 1 [70] [71]. An increase of T results in the increase of A due to increased molecular activity [121] [122].

V.6. 2. Reduction of meta-model and validation

As discussed the SA results above, the chemical compositions of CEM I cement type (SiO_2, Al_2O_3, Fe_2O_3, CaO, and SO_3), maximum aggregate size (S_max) and sand-to-gravel ratio (S/G) are the non-influential parameters on carbonation rate (A). In addition, their interactions with other parameters are negligible. Consequently, these parameters can be eliminated as the input parameters of the meta-model presented in [125]. To do this, they are set at their mean value given in Table 6 in calculating the carbonation depth in any case. Finally, the meta-model is reduced with regards to the input parameters as shown in Figure 31. We use the value of maximum aggregate size (S_max)

of about 26 mm to estimate the volume fraction of entrained air (ϕ_{air}) into the mix from S_max as proposed in [125]. We obtain the ϕ_{air} of about 0.0307. We introduced this value into the 28-day compressive strength of concrete (f_c), function of $f\left(\phi, \frac{W}{C}, FA\right)$ and concrete porosity (ϕ). Secondly, we use the value of sand-to-gravel ratio (S/G) of about 1.3 to calculate the function of $f\left(\frac{S+G}{C}\right)$. We use the value of SiO_2, Al_2O_3, Fe_2O_3, CaO, and SO_3 of about 0.2098, 0.04665, 0.03965, 0.6316 and 0.03055 respectively to calculate the concrete porosity (ϕ).

Let us suppose that 1 m^3 of fresh concrete is composed of cement, gravel, sand, water and entrained air. The following balance equation should be fulfilled:

$$\frac{C}{\rho_c} + \frac{G}{\rho_g} + \frac{S}{\rho_s} + \frac{W}{\rho_w} + \phi_{air} = 1 \tag{46}$$

where: ρ_c *(kg/m^3) is the cement density,* ρ_g *(2650 kg/m^3) is the gravel density,* ρ_s *(2600 kg/m^3) is the sand density,* ρ_w *(1000 kg/m^3) is the water density.*

Because S/G and ϕ_{air} are of about 1.3 and 0.031 respectively. We introduce them into Eq. (46), we obtain the amount of cement content (C) according to water-to-cement ratio (W/C) and cement density (ρ_c) as follows:

$$C = \frac{284.34}{\frac{W}{C} + \frac{100}{\rho_c}} \tag{47}$$

We introduce the expression of C in Eq. (47) into the calculation of amount of CO_2 absorbed in a unit volume of concrete (a) and the function of $f\left(\phi, \frac{W}{C}, FA\right)$. In addition, because $M_{CO_2} = 44$ (g/mol) and $M_{CaO} = 56$ (g/mol) are the molar weight of CO_2 and CaO respectively. Finally, the new models for calculating the carbon dioxide (CO_2) diffusion coefficient (D_{CO_2}) and amount of CO_2 absorbed in a unit volume of concrete are generated as shown in Figure 31. It is important to note that the amount of calcium oxide (CaO) in the calculation of a. That depends on the cement type, it is not thus eliminated. The parameter CO_2 is identified as the non-influential parameter, but it is not eliminated, because it is an environmental parameter (uncontrollable parameter).

INPUT DATA

I. Technological parameters:

1. Cement type (CaO, $\varphi_{clinker}$ = cement clinker content, ρ_c = density of cement).
2. Water-to-cement ratio (W/C).
3. Initial curing period (t_c).

II. Environmental parameters:

1. Relative external humidity (RH).
2. Ambient temperature (T).
3. CO_2 concentration in the air (CO_2).

$$x = A.\sqrt{t} = \sqrt{\frac{2.D_{CO_2}.CO_2}{a}}.\sqrt{t}$$

$$a = \frac{167.56}{\frac{W}{C}+\frac{100}{\rho_c}} \times CaO \times \varphi_{clinker}$$

$$D_{CO_2} = D^{28}_{CO_2} \times f(t_c) \times f\left(\frac{W}{C}\right) \times f(RH) \times f(T)$$

$$D^{28}_{CO_2} = 10^{-(7+n)}$$

$$n = \frac{0.171 f_{cem}}{\left(1+\frac{W}{C}\times\frac{\rho_c}{1000}\right)^2}$$

$$f(t_c) = 1.9 \times 10^{n-2} + (1 - 1.9 \times 10^{n-2})\sqrt{\frac{28}{0.01 \times t_c}}$$

$$f\left(\frac{W}{C}\right) = 5.61 \times 10^3 \times exp\left(-5.592\frac{W}{C}\right) \times \left(\frac{W}{C}+\frac{100}{\rho_c}\right)^{0.2} \times \left\{\left(0.93 - 3.95 \times 0.94^{100\frac{W}{C}}\right).\left[0.02 + \frac{0.284\left(\frac{W}{C} - 0.0235\right)}{\frac{W}{C}+\frac{100}{\rho_c}}\right]\right\}^{1.8}$$

$$f(RH) = (1 - RH)^2.RH^{2.6}$$

$$f(T) = exp\left[\frac{4700(T-293)}{293T}\right]$$

Figure 31. Reduced meta-model (meta-model presented in [125]).

The reduced meta-model in Figure 31 is validated by the largely experimental data from the published literature under natural conditions [33] [70] [140] [139] [135] [54] [134] [120] [109] [141]. Among these data, two field data [33] [141] have not detailed the initial curing period (t_c), so the RC structures was assumed cured a 3-day period [39]. The signification of these data refers to various:

- Exposure times (from 21 days up to 35 years).
- Cement types (CEM I [33] [140] [139] [54] [109] [74], CEM II [199] [135] [134] [120], CEM III [70] [199] [135], and CEM IV [199] [135]).
- Water-to-cement ratios (from 0.45 up to 0.7).
- Initial curing periods (from 1 day up to 28 days).

The comparison of the experimental carbonation depths with that predicted by the reduced meta-model is carried out by using the hypothesis line of perfect equality. The results are shown in Figure 32.

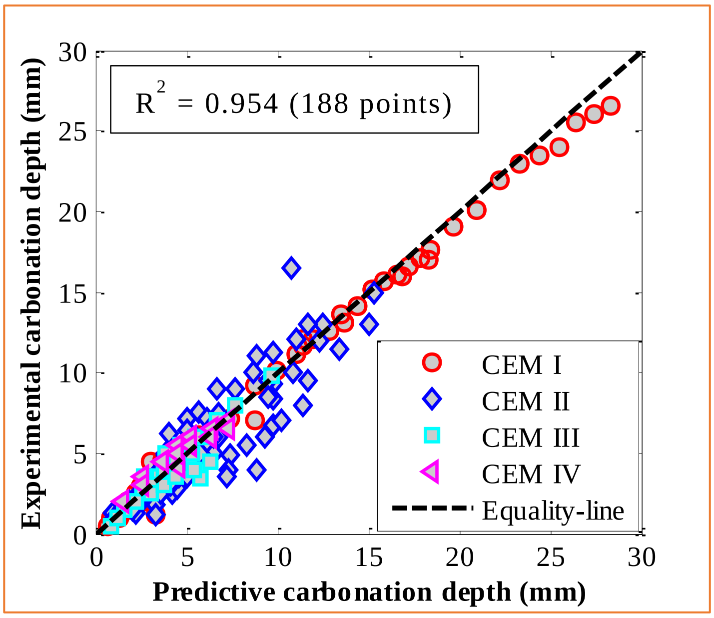

Figure 32. Comparison between predictive and experimental carbonation depths within uncoated concretes.

The determination coefficient determined among all plotted points (188 points) and the line of equality is R^2 = 0.954. This means that the reduced meta-model predicts as accurately as the meta-model (R^2 = 0.958) [125]. The new model predictions are reasonably accurate compared with the experimental data with the various exposure times, cement types, water-to-cement ratios and initial curing periods.

Few data are available concerning the natural carbonation of coated concrete. The developed model as given in Eq. (43) is thus validated by the experimental data from the two previous publications [190] [193]. The first experimental investigation is on the natural carbonation of surface concrete treated by the coatings based on acrylic, silicon acrylic and siloxane during 15 months [190]. The specimens are exposed to physical conditions in laboratory environment. The second one is the carbonation depths measured on the building in Manila

(Philippine) and Tsukuba (Japan) after 14 and 11 years of exposure to the atmospheric respectively [193]. Because the coating characterizations are undefined, thus, we assumed that the coating system has the dry film thickness (DFT) of about 250 μm, and the carbon dioxide (CO_2) diffusion coefficient ($D_{CO_2}^{coat}$) of about 2.4 × 10^{-10} m^2/s for the both buildings. These values are the most common recommended by the coating suppliers [64] [65] [200]. The CO_2 diffusion coefficient of carbonated concrete (D_{CO_2}) and amount of CO_2 absorbed in a unit volume of concrete (a) in Eq. (43) are calculated by their expression in Figure 31. The predictive carbonation depths are compared with the experimental ones by using the hypothesis line of perfect equality. The results are shown in Figure 33.

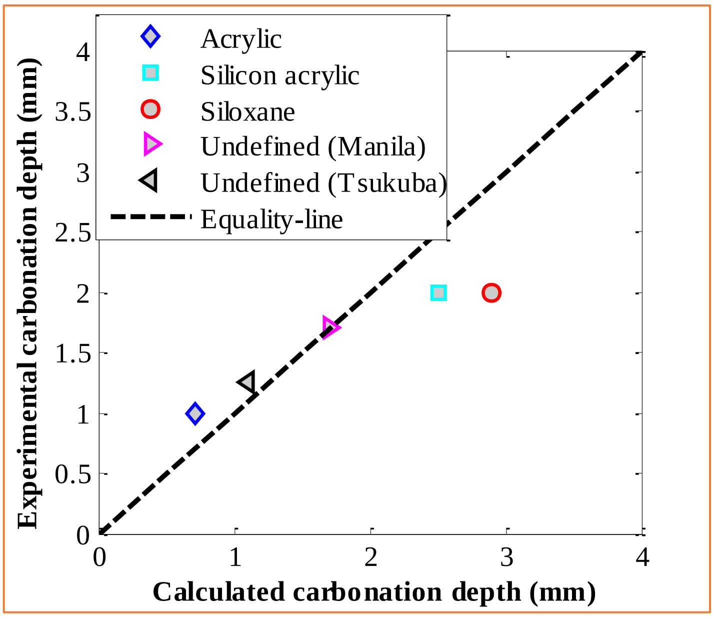

Figure 33. Comparison between predictive and experimental carbonation depths within paint coated concretes.

The predictive and experimental carbonation depths are slightly different for the coatings based on acrylic, silicon acrylic and siloxane [190], i.e., the prediction underestimates in the case of the coating based on acrylic, and overestimates in the case of the coatings based on silicon acrylic and siloxane. As we know, a decrease in $D_{CO_2}^{coat}$ and an increase in DFT result in the increase of protection performance of coating system [86]. The predictive carbonation depths of the coating based on silicon acrylic with the $D_{CO_2}^{coat}$ of about 1.16 × 10^{-8} m^2/s and DFT of about 250 μm has higher protection performance than that based on siloxane with the $D_{CO_2}^{coat}$ of about 9.3 × 10^{-8} m^2/s and DFT of about 200 μm, whereas, the experiment shows the same carbonation depth of 2 mm [190].

V.7. Conclusions

Firstly, we have developed mathematically a new model to calculate the natural carbonation depth within paint coated concretes. The CO_2 coefficient diffusion and dry film thickness of coating are integrated to consider the effect of coating. Secondly, we have used sensitivity analysis to reduce the number of input parameters of the meta-model by eliminating the non-influential parameters. We found that the most influential parameters on natural carbonation rate are water-to-cement ratio (W/C), cement type (CEM), initial curing period (t_c) (they are technological parameters) and ambient temperature (T) and relative external humidity (RH) (they are environmental parameters). The SA results provide effective decision support in the design of durable new structure exposed to carbonation in Madrid. In addition, these most influential parameters should be carefully considered in future research relating to the carbonation depth prediction to enhance the accurate prediction. These parameters will also be recommended incorporated into the numerical model to reduce the input parameters and time-consuming. The validation of the model considering the preventive coating system has been conducted using data from literature on long-term natural carbonation exposure conditions, with different kinds of coating. In order to improve the prediction of model, it is necessary to validate this model with other long-term natural carbonation data.

VI. REDUCTION OF DECISION DIAGRAM FOR CONCRETE SURFACE PREPARATION

This chapter focusses on the step 3 (n°3 Figure 1) and 4 (n°4 Figure 1). It treats of the RC structure designed with the cement strength class 32.5 MPa and maintained with a preventive coating system. It is focused on the first maintenance operation that consists in preparing the concrete surface before coating. However, 1,594 possible combinations of choices can be made according to the decision diagram (see Figure 4 page 27) inducing a huge number of scenarios. The objective is thus to reduce the decision diagram for concrete surface preparation. In the step 3 (Figure 1), we developed a LCA model to assess the environmental impacts of the operation of concrete surface preparation. In the step 4 (Figure 1), we applied Sobol and Morris' method to the environmental impact indicators to reduce the number of scenarios in the decision diagram.

Résumé :

Dans ce travail, nous considérons un béton armé nécessitant des opérations d'entretien pendant sa durée de vie fixée à 100 ans. L'objectif de ce travail est de simplifier le diagramme décisionnel concernant les opérations

d’entretien. En effet, les scénarios d’entretien sont souvent complexes à cause des multiples choix d’opérations. Nous utilisons les modèles de carbonatation et d’ACV développés dans les précédents chapitres auxquels nous ajoutons les modèles liés aux opérations d’entretien curatif de la surface du béton d’enrobage. Nous appliquons la méthode de Sobol et de Morris pour déterminer les leviers d’action permettant de réduire les impacts environnementaux. Cela permet de réduire les champs des décisions parmi les 1594 combinaisons possibles de choix.

Nous trouvons que la méthode de préparation de la surface du béton a une influence sur les indicateurs environnementaux. Le choix du matériau abrasif, le diamètre de la buse lors d’un traitement par jet d’abrasif, ainsi que la pression opérationnelle à la buse sont des leviers d’action permettant de réduire les impacts environnementaux liés aux opérations d’altération de la surface du béton. Le scenario de préparation optimal utilise la méthode de traitement par jet d’abrasif avec l’olivine en tant que les matériaux abrasifs en association avec un diamètre et une pression minimales de buse (9,5 mm et 3,4 bars respectivement).

VI. 1. Abstract

Life Cycle Assessment (LCA) method requires many subjective choices throughout the procedure, which make decision making difficult and LCA results insecure. Our approach consists in combining life cycle thinking and sensitivity analysis (SA) to provide specific options for a decision-maker within a foreground system. The trends and quantified influence on environmental impact indicators are systematically compared to determine the most effective action levers for actors controlling the process. This work aims at simplifying decision diagram of maintenance scenarios since there are various choices of maintenance operations. To this end, the approach combining LCA and SA is applied to determine the most environmentally conscious maintenance operations. This approach has been previously applied to hemp crop production. In this study, we use for 1 m^2 of concrete surface altered. We found that the effective action levers are the concrete surface preparation method (*Prep*), the kind of abrasive materials (*Abr*), the operational pressure at nozzle (*Press*) and nozzle diameter of the abrasive blasting method (*Noz_abr*). The most favorable scenario is recommended to alter concrete surface: abrasive blasting method with olivine in association with a minimal nozzle diameter and minimal pressure at nozzle.

Key words: Concrete surface preparation; Blasting; Life Cycle Assessment; Maintenance; Concrete repair; Sobol; Morris

VI. 2. Introduction

Approximately half of the world's conventional oil has been consumed [13]. Each year, more than 11 million hectares of forests are destroyed, and another

6 million hectares of productive dry land turns into worthless desert [1]. In Europe, acid precipitation kills forests and lakes and damages the artistic and architectural heritage of nations [1]. The burning of fossil fuels puts into the atmosphere carbon dioxide (CO_2), which is causing gradual global warming. According to the World Commission on Environment and Development of the United Nations [1], sustainability means “meeting the needs for the present without compromising the ability of the future generation to meet their own needs”.

Nowadays, Reinforced Concrete (RC) structures are widely constructed in the world [2]. Deterioration can begin as little as 10 years due to diverse deterioration mechanisms [184]. So, for most RC structures with the service life design more like 50-100 years [10] require maintenance or repair operation in order to reach the scheduled service life. Petcherdchoo [49] revealed that the ongoing environmental impacts of a RC structure will be approximately proportional to the amount of maintenance required. The use of preventive coating system is the relevant and more common method used for damage of RC structures caused by carbonation or chlorides [59] [30]. The execution of a preventive coating system mainly consists of two process: concrete surface preparation and application of coating products [57]. Concrete surface preparation includes the removal of laitance, dirt, oil, films, paint, coatings, sound and unsound concrete, and other materials that will interfere with the adhesion or penetration of a sealer, coating, polymer overlay, or repair material [61]. Selecting concrete surface preparation method, equipment, and materials in preparing concrete surface is not only a question of technical performance and economy, but also a question of impacts on environment [201]. It is important to take environmental impacts into consideration both during design and construction as well as in the usage phase for concrete structures. To this end, Life Cycle Assessment (LCA) is a helpful tool in the design for environment. LCA is an internationally standardized method [6] for compiling and examining the inputs and outputs of energy and materials, and the potential environmental impacts directly attributable to the functioning of a products or service system throughout its life cycle.

This paper aims at simplifying decision diagram of maintenance scenarios by applying an approach that combines LCA and Sensitivity Analysis (SA) methods. This approach proposes by Andrianandraina et al. [68] allows to verify and more accurately assessing the influence of parameters used in the foreground system in the frame of an LCA study. We apply this approach to determine the most environmentally conscious maintenance operations. Indeed, at present, there is no published study on the environmental impacts of concrete surface preparation activity, although there are various scenarios choices of maintenance operation that effect environmental impact of RC structures. This paper aims at finding out under which concrete surface preparation methods, equipment, materials as well as manner execution performed better the environmental impacts from the concrete surface preparation activity.

An overview of concrete surface preparation methods is performed in Section VI. 3. LCA models for estimating the environmental impacts of concrete surface preparation activity are developed in Section VI. 4. Section VI. 5 presents sensitivity analysis. The results are detailed in Section VI. 6. The discussion of results are performed in Section VI. 7. The conclusions and recommendations are given in Section VI. 8.

VI. 3. Overview of concrete surface preparation methods

Three profiles to be used with preventive system coating include light shotblast, light scarification and medium shotblast [60]. The concrete surface preparation methods should be capable of replicating these profiles. They result in a low probability of micro-cracking and pH of concrete unchanged. Consequently, the types of methods include (i) mechanical surface preparation methods, (ii) chemical surface preparation and (iii) flame cleaning and blasting techniques [61]. Three kinds of blasting cleaning methods including abrasive blasting, dry ice blasting and ultra-high pressure water jetting are the most suitable methods altering concrete surface [62]. In the next sub-sections, we detail the execution of each method.

VI.3. 1. Abrasive blasting method

The abrasive blasting technique uses compressed air to eject a high-speed stream of abrasive material from a nozzle. A blast machine is a relatively simple piece of equipment that sprays abrasive material particles to the altered surface. A simplified abrasive blasting system schematic can be represented (Figure 34).

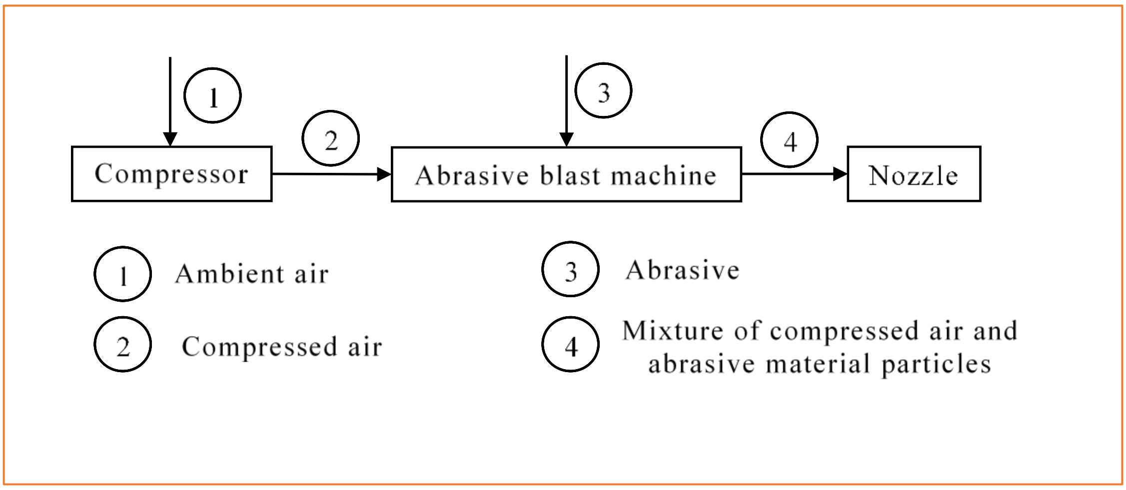

Figure 34. Simplified abrasive blasting system.

VI.3. 2. Dry ice blasting method

The technology of dry ice blasting comprises four key elements: (i) a compressor (generator of compressed air); (ii) a blaster; (iii) transport of pellets; and (iv) a blasting nozzle [202]. The compressor generates the compressed air. The pelletize products the dry ice particles based on liquid CO_2 in pressure vessels at 12-20 bar [203]. The dry ice machine is a relatively simple piece of equipment that prepares dry ice particles for a transport to the contaminated surface [202]. The blasting nozzle allows adjusting the working pressure on the contaminated surface. The compressed air and dry ice feed consumptions depends mainly on the use of nozzle type. A simplified dry ice blasting system was shown in Figure 35.

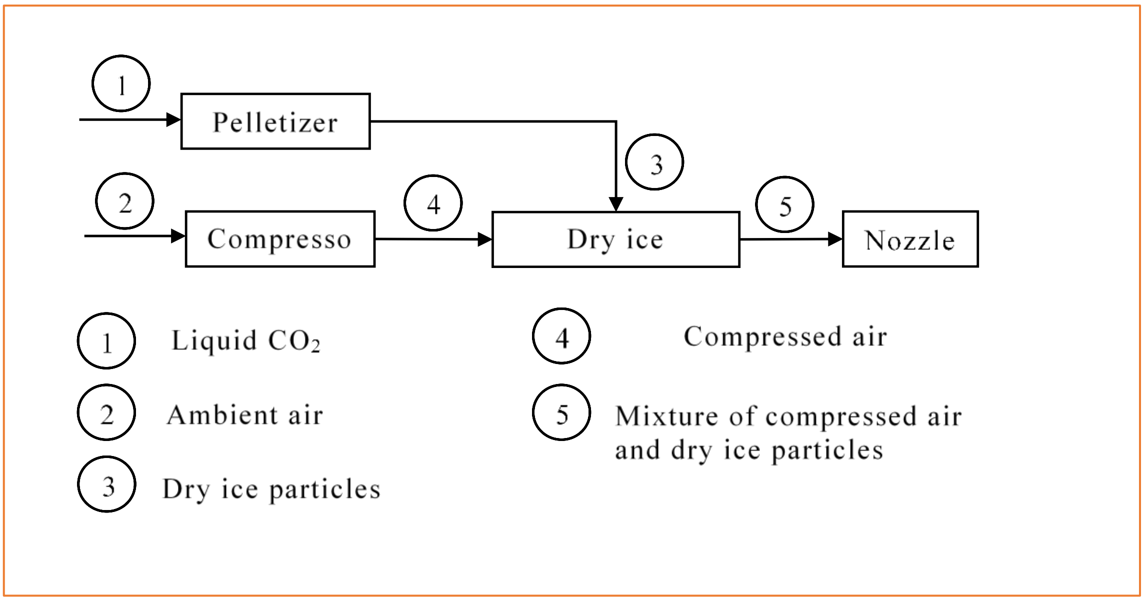

Figure 35. Simplified dry ice blasting system.

VI.3. 3. High and ultra-high pressure water jetting method

The high and ultra-high pressure water jetting is as cleaning with water pressure from 345 to 3105 bar [61]. A high and ultra-high pressure water jetting system consists mainly of a high pressure pump, hose and suitable nozzle as shown in Figure 36. High pressure pump is the most important item to check. It is a fact that the higher the pressure is, the higher the cleaning rate is.

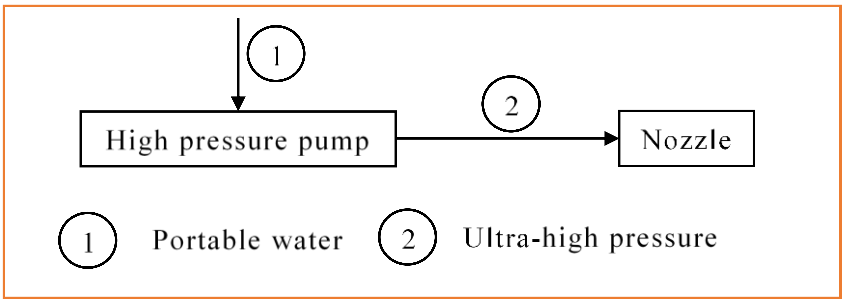

Figure 36. Simplified high and ultra-high pressure water jetting system.

VI. 4. Life Cycle Assessment model

We consider maintenance operations required for 1 m^2 of surface concrete altered, which represents the **Functional Unit (FU)** in LCA. In addition, our study focusses on the production of materials (abrasive materials, dry ice and water) and energy, which are the system boundaries (Figure 37).

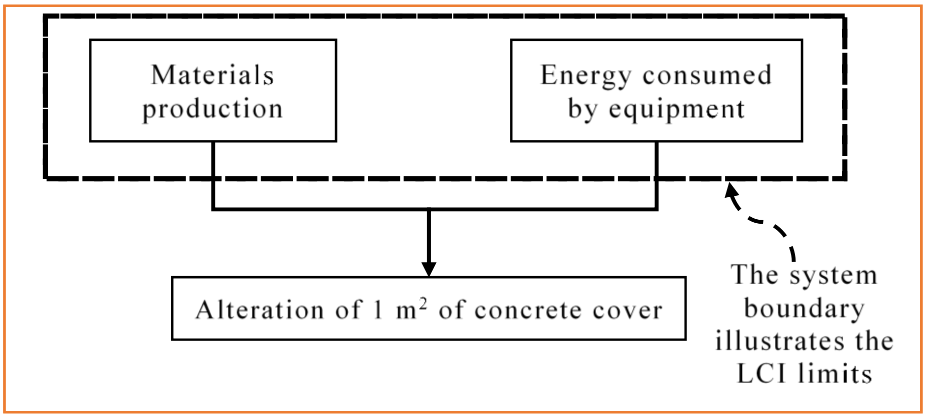

Figure 37. Concrete surface preparation system boundary.

Within the system boundaries, the environmental impacts per FU (Env_{total}) are calculated as follows.

$$[Env_{total}] = [M_a \times Env_{abr} + M_e \times Env_{energy}] \quad (1)$$

where: M_a (kg) is the amount of abrasive materials (abrasive materials or dry ice or water), M_e (kW) is the energy consumption of equipment, Env_{abr} are the environmental impacts per unit quantity of materials (abrasive materials or dry ice or water), Env_{energy} are the environmental impacts per unit quantity of energy (see Table A7 in Appendix).

The environmental impacts are calculated following the ILCD recommendations [12]. For each alteration method, the amount of materials (abrasive materials, dry ice, water) (M_a) and energy (M_e) per FU are calculated and detailed in the next sub-sections.

a) Abrasive blasting method

The amount of abrasive materials is determined by the following steps: firstly, we use the compressed air consumption and abrasive material feed rate of each nozzle corresponding to an operational pressure at nozzle of about 5.5 bar as the reference values (Table A3 in Appendix). When the operational pressure at nozzle is varied from 3.4 bar up to 7.9 bar (Table 12), the relative change in compressed air consumption and in abrasive material feed rate are determined by the fitting models shown in Figure 38 and Figure 39 respectively. Secondly, we use the cleaning rate of about 13.2 m^2/h corresponding to the abrasive material feed rate of about 250 kg/h [201] as the reference values. When the abrasive material feed rate changes, the relative change in the cleaning rate is determined by a fitting model shown in Figure 40.

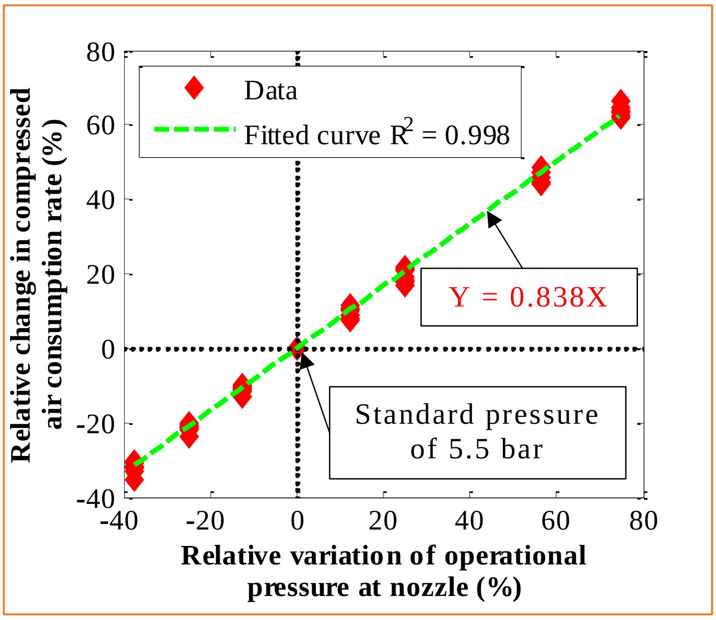

Figure 38. Relative change in compressed air consumption due to the relative variation of pressure at nozzle (data fitted from [204]).

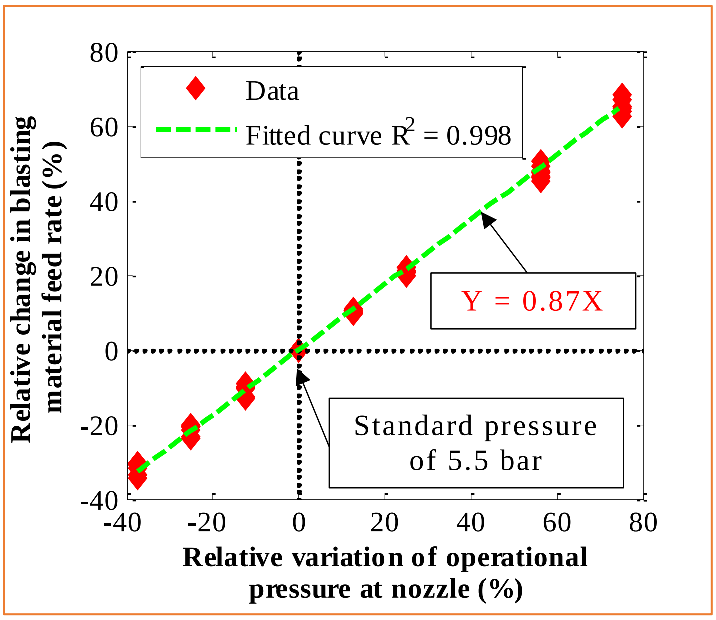

Figure 39. Relative change in blast material feed due to the relative variation of pressure at nozzle (data fitted from [204]).

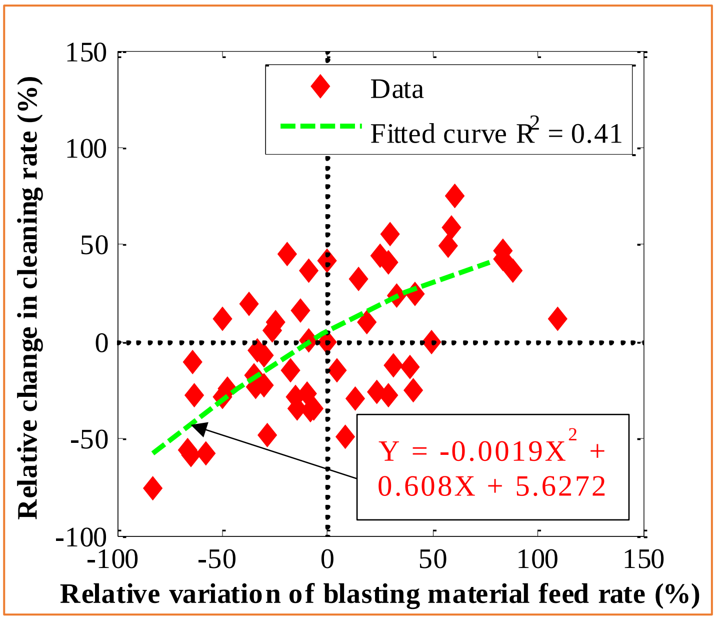

Figure 40. Relative change in cleaning rate due to the relative variation of blast material feed rate (data fitted from [205]).

b) Dry ice blasting method

Similarly to the abrasive blasting method, the amount of dry ice is determined by two following steps: firstly, we use the compressed air consumption and dry ice feed of each nozzle type corresponding to an operational pressure at nozzle of about 5.5 bar (Table A5 in Appendix). When the operational pressure at nozzle varies from 3.4 bar up to 7.9 bar (Table 12), the relative change in compressed air consumption and in dry ice feed rate are determined by the fitting models shown in Figure 38 and Figure 39 respectively. Secondly, we use the cleaning rate of about 6.6 m^2/h corresponding to the dry ice feed rate of about 190 kg/h [201] as the reference values. When the dry ice feed rate changes, the relative change in the cleaning rate is determined by a fitting model shown in Figure 40.

c) High and ultra-high pressure water jetting method

The amount of water is determined by the following steps: firstly, we use the operational pressure, water flow rate and average input power of each high pump pressure from Combijet's supplier as the reference values (Table A6 in Appendix). The cleaning rate depends on the operational pressure, it could be calculated by using a fitting model shown in Figure 41. Secondly, with a 1 m^2 of concrete cover surface flow, the amount of water is calculated by multiplying the cleaning rate and water flow rate.

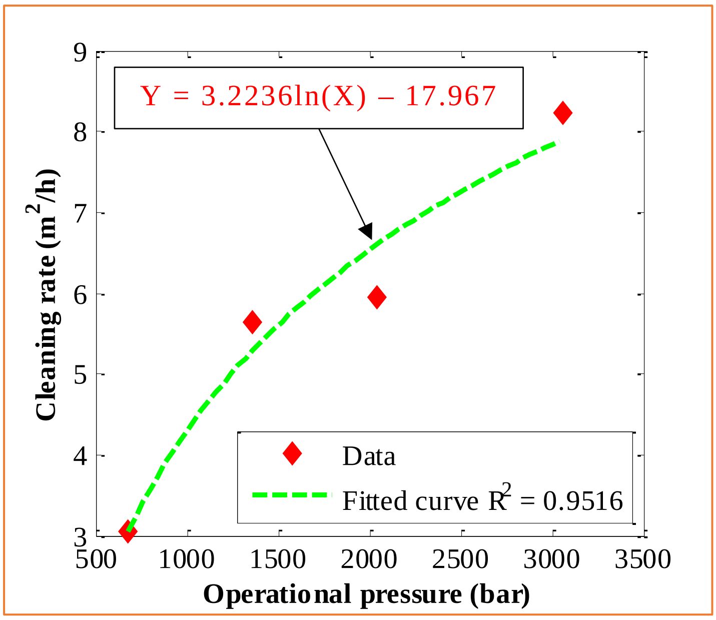

Figure 41. Relationship between cleaning rate and operational pressure (data fitted from [206]).

VI. 5. Sensitivity analysis

In this section, we develop a decision diagram as shown in Figure 42. Our objective is to characterize the influential maintenance operations parameters on the environmental impacts of altering concrete surface. The SA methods of Sobol and Morris are applied; they are not detailed in this paper, as they were published previously [40] [41]. The Sobol's method [66] is used to quantify the contribution of inputs parameters of a model, alone and in interaction with other parameters, to variations of environmental impacts. Then, the Morris' method [67] provides additional information on the influential trend of parameters. The two methods require all parameters being independent.

VI.5. 1. Characterizations of parameters

We consider three concrete surface preparation methods ($Prep$) as reviewed in Section VI. 3, including abrasive blasting, dry ice blasting and high and ultra-high pressure water jetting.

For the abrasive blasting method (Figure 34), in order to stock the abrasive materials, we use an available abrasive blast machine in the market [207], named Big Clem bulk with yard portable model having abrasive capacity about 3.36 m^3 and weight about 1993.2 kg. The compressor type ($Comp$), kind of abrasive materials (Abr) and nozzle type (Noz_abr) are considered in analyzing the sensitivity of environmental impacts as follows:

- We consider twelve portable air compressors available on the website [208] (Table A2 in Appendix).
- We consider five kinds of abrasive materials including ilmenite, aluminum oxide, silica sand, silicon carbide and olivine available on the market [209]. The considered abrasive materials types are not forcedly exhaustive, this list has been restricted to the available Life Cycle Inventory (LCI) data for the production of abrasive materials in the Ecoinvent database [11].
- We consider four nozzle types available in the market [207] (Table A3 in Appendix), because the most commonly-used nozzle orifice sizes ranges from 9.5 mm up to 19 mm for the abrasive blasting method [210].

For the dry ice blasting method (Figure 35), the compressor type ($Comp$), pelletizer machine ($Pelle$) and nozzle type (Noz_dry) are considered in analyzing the sensitivity of environmental impacts as follows:

- We use the same compressor types of the abrasive blasting method (Table A2 in Appendix).
- We consider four pelletizer machines available on the website [211] (Table A4 in Appendix).
- We consider six different nozzle types available on the website [212] (Table A5 in Appendix).

For the abrasive blasting and dry ice blasting methods, we consider the operational pressure at nozzle ($Press$) varying from 3.4 bar up to 9.7 bar (Table 12) [204].

For high and ultra-high pressure water jetting method (Figure 36), we consider ten high pressure pumps on the website [213] (Table A6 in Appendix).

Finally, a decision diagram of altering concrete surface is shown in Figure 42. The parameters characterized are summarized in Table 12.

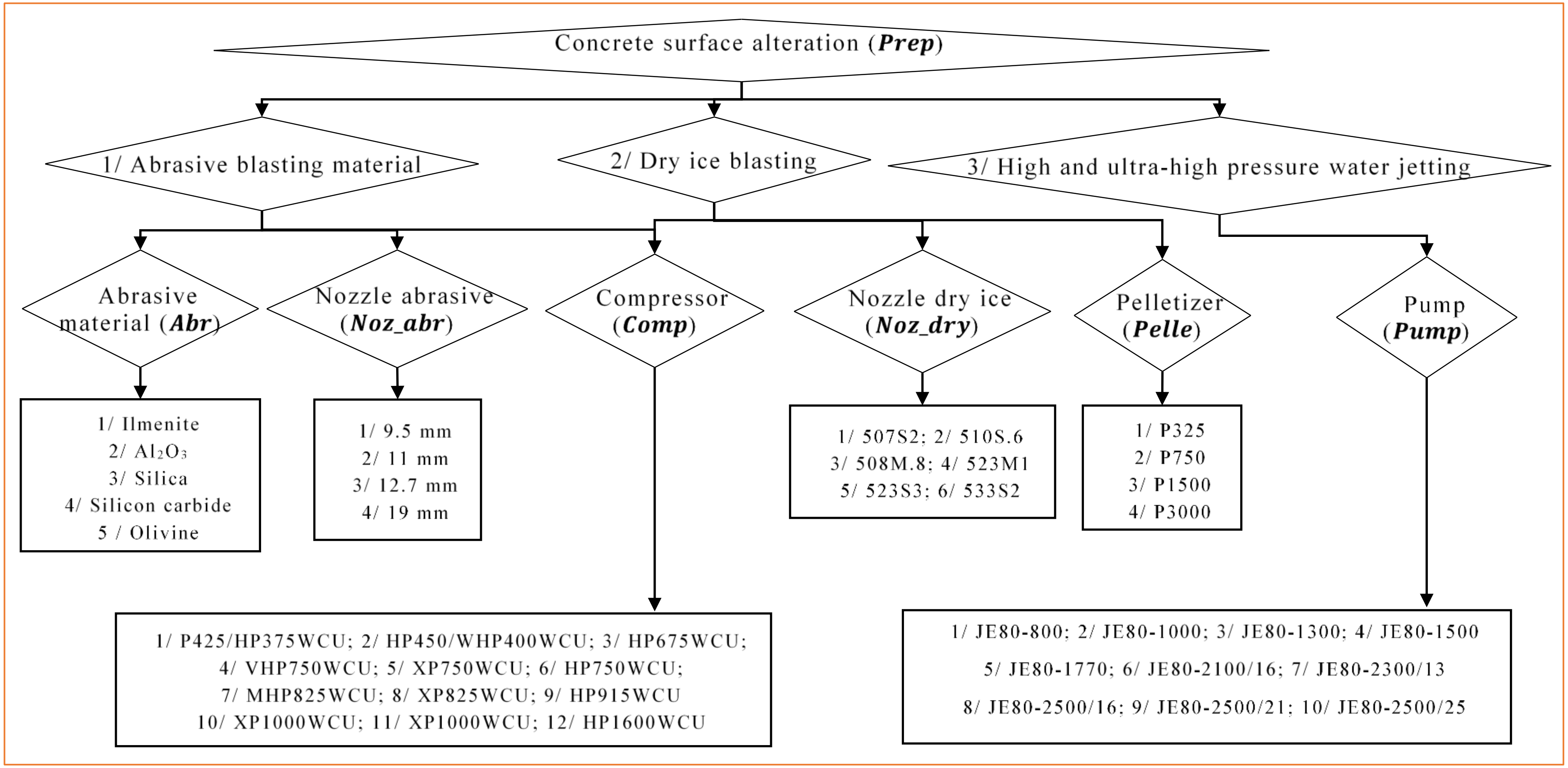

Figure 42. Decision diagram for concrete surface preparation.

Table 12. Characterizations of parameters.

Parameter	Unit	Probability distribution	Ref.
Prep	n.u.	$d\mathcal{U}$ (3 methods)	[61]
Comp	n.u.	$d\mathcal{U}$ (12 compressor types)	[208]
Noz_abr	n.u.	$d\mathcal{U}$ (4 nozzle types)	[204]
Noz_dry	n.u.	$d\mathcal{U}$ (6 nozzle types)	[204]
Pelle	n.u.	$d\mathcal{U}$ (4 pelletizer types)	[212]
Pump	n.u.	$d\mathcal{U}$ (10 pumps types)	[213]
Abr	n.u.	$d\mathcal{U}$ (4 abrasive material types)	[209] [11]
Press	bar	$\mathcal{U}$ (min = 3.4; max = 9.7)	[204]

Note:

1/ Discrete parameters are in bold.

2/ $d\mathcal{U}$ = discrete uniform distribution; $\mathcal{U}$ = uniform distribution.

3/ n.u. = no unit

VI.5. 2. Numerical simulations

We define **action levers** as technological parameters found to be the most influential on environmental impacts of the alteration of surface concrete. Identifying an action lever requires calculating its influence alone and, if necessary, in interactions with other parameters, as well as characterizing their most favorable values allowing smallest environmental impact indicators.

We estimated the value of Sobol's indices corresponding to individual influence (S_j) and total influence (S_{T_j}) including interaction. Monte Carlo simulations are performing by varying simultaneously all input parameters, according to their probability distribution and calculating the associated model output. For estimating the Sobol's indices, 500 bootstrap replications of 5,000 in size from a sample initial size about 10,000 were run.

Morris' indices including the mean value (μ_j) and the mean value of the absolute value (μ_j^*) of the elementary effects, and the standard deviation value (σ_j) of the elementary effects are calculated. For calculating the Morris' indices, the input parameters were discretized in 10 values and the prescribed number of trajectories was about 30. The number of repetitions r ranges from 4 up to 10 [151].

VI.5. 3. Identification of action levers

Based on Sobol's indices, the parameters are considered as having an individual influence (i.e. identified as the action levers) if $S_j \geq 10\%$. However, parameters such that $S_j \leq 10\%$ and $S_{T_j} - S_j \geq 20\%$ (non-negligible interaction), are still considered as action levers [68] [69]; these parameters are not individually influential but have non-negligible total influence due to its interaction with other parameters.

Firstly, Morris' method is a quick screening approach whose results can be confirmed with Sobol's method to rank parameters from most (highest μ_j^*) to least influential (lowest μ_j^*) [67]. Secondly, most influential parameters have an important value of σ_j, compared to μ_j^*; in addition, a high value of $S_{T_j} - S_j$ confirms important influences in interactions with other parameters [66] [67].

VI.5. 4. Optimization

After identifying the action levers, i.e., optimal maintenance operations, for the environmental impact indicators, we design favorable maintenance scenario by setting the action levers at their specific values. The favorable scenario aims at reducing the environmental impacts. It is designed by setting (i) the continuous parameters as the action levers at their minimal or maximal value based on the algebraic sign of mean value (μ_j), and (ii) the discrete parameters as the action levers at the alternatives that they represent, and (iii) the continuous parameters as the non-influential parameters at their mean value, and (iv) the discrete parameters as the non-influential parameters at an equivalently continuous uniform distribution by converting a discrete uniform distribution.

VI. 6. Results

VI.6. 1. Sensitivity analysis results and identification of action levers

The SA results concerning the value of S_j and S_{T_j} and algebraic sign of μ_j on environmental impact indicators for the most influential parameters (due to higher S_j, S_{T_j} and larger μ_j^*) were given in Table 13.

.

Table 13. Sensitivity analysis results on environmental impact indicators (only the most influential parameters).

Impact indicators	**Parameters studied**							
	Prep		***Abr***		***Press***		***Noz_abr***	
	S_j (%)	S_{T_j} (%)	S_j (%)	S_{T_j} (%)	S_j (%)	S_{T_j} (%)	S_j (%)	S_{T_j} (%)
Acidification (Ac)	16	71	14	67	3	33	1	23
Climate change (CC)	12	74	15	75	2	35	1	21
Resource depletion (RD), mineral, fossils and renewables	19	73	12	56	5	38	2	22
Ecotoxicity (Ec)	16	71	13	61	4	34	2	24
Marine eutrophication (ME)	15	73	14	67	3	36	1	24
Terrestrial eutrophication (TE)	14	73	15	72	2	33	1	22
Human toxicity, carcinogenics (HTc)	13	69	14	70	4	36	1	24
Human toxicity, non-carcinogenics (HTnc)	16	72	12	63	4	35	2	23
Ionizing radiation, ecosystems (IRe)	15	71	13	63	4	37	2	24
Ionizing radiation, human health (IRhh)	9	70	15	75	3	35	1	22
Particulate matter (PM)	12	71	15	75	2	33	1	23
Photochemical oxidation (PO)	12	68	14	67	4	37	2	25

Notes:

1/ Discrete parameters are in bold.

2/ an increase in the parameter *Press* highlighted in gray ($\mu_j > 0$) results in the increase of environmental impact indicators.

The concrete surface preparation method ($Prep$), abrasive materials of abrasive blasting method (Abr) have both high individual influence ($S_j \geq 10\%$) and high interaction with other parameters ($S_{T_j} - S_j \geq 10\%$). The operational pressure at nozzle of abrasive blasting and dry ice blasting methods ($Press$), the nozzle type of abrasive blasting method (Noz_abr) have only high interaction with other parameters ($S_{T_j} - S_j \geq 10\%$). We identified thus them as the action levers for all impact indicators. Only the operational pressure at nozzle ($Press$) is a continuous parameter, a decrease in the operational pressure at nozzle ($Press$) results in the decrease of environmental impact indicators. The concrete surface preparation method ($Prep$), kind of abrasive materials (Abr), and nozzle type (Noz_abr) are as the discrete parameters. Finding optimized scenarios requires testing all alternatives of concrete surface preparation method ($Prep$), kind of abrasive materials (Abr) and nozzle type (Noz_abr) in association with a minimal value of operational pressure at nozzle ($Press$) of 3.4 bar.

VI.6. 2. Optimization

a) Simulation scenario

We design the simulation scenarios as follows:

- Concerning the discrete parameters including the concrete surface preparation method ($Prep$), kind of abrasive materials (Abr) and nozzle type of the abrasive blasting method (Noz_abr), they are set at all alternatives as shown in Table 14. The operational pressure at nozzle ($Press$) as a continuous parameter, it is set at a minimal value of about 3.4 bar.

- Concerning the non-influential parameters including the compressor type ($Comp$), nozzle type of dry ice blasting method (Noz_dry), pelletizer type ($Pelle$) and high pump pressure type ($Pump$), they were fixed at an equivalent equipment as follows: (i) based on the compressor models given in Table A2 (Appendix), the equivalent compressor was characterized by the fuel consumption rate varying from 15.5 kg/h up to 259.2 kg/h, free air delivery varying from 636 m^3/h up to 2718 m^3/h and average power input varying from 102.9 kW up to 417.6 kW; (ii) based on the nozzle models given in Table A5 (Appendix), the equivalent nozzle for the dry ice blasting method was characterized by the air consumption at 5.5 bar varying from 234 m^3/h up to 282 m^3/h, average feed rate varying from 81 kg/h up to 135 kg/h; (iii) based on the pelletizer models given in Table A4 (Appendix), the equivalent pelletizer was characterized by the average power consumption varying from 3.2 kW up to 14.2 kW and productivity varying from 136.4 kg/h up to 1090.9 kg/h; and (iv) based on the pump models given in Table A6 (Appendix), the equivalent pump was characterized by the operational pressure varying from 800 bar up to 2500 bar, flow rate varying from 0.94 m^3/h up to 1.8 m^3/h and input power varying from 30 kW up to 130 kW.

Table 14. Description of simulation scenarios regarding the action levers.

Scenario	***Prep***	***Abr***	***Noz_abr***
1	Abrasive blasting method	Ilmenite	9.5 mm
2	Abrasive blasting method	Ilmenite	11 mm
3	Abrasive blasting method	Ilmenite	12.7 mm
4	Abrasive blasting method	Ilmenite	19 mm
5	Abrasive blasting method	Al_2O_3	9.5 mm
6	Abrasive blasting method	Al_2O_3	11 mm
7	Abrasive blasting method	Al_2O_3	12.7 mm
8	Abrasive blasting method	Al_2O_3	19 mm
9	Abrasive blasting method	Silica sand	9.5 mm
10	Abrasive blasting method	Silica sand	11 mm
11	Abrasive blasting method	Silica sand	12.7 mm
12	Abrasive blasting method	Silica sand	19 mm
13	Abrasive blasting method	Silicon carbide	9.5 mm
14	Abrasive blasting method	Silicon carbide	11 mm
15	Abrasive blasting method	Silicon carbide	12.7 mm
16	Abrasive blasting method	Silicon carbide	19 mm
17	Abrasive blasting method	Olivine	9.5 mm
18	Abrasive blasting method	Olivine	11 mm
19	Abrasive blasting method	Olivine	12.7 mm
20	Abrasive blasting method	Olivine	19 mm
21	Dry ice blasting method	-	-
22	High pressure jet water method	-	-

b) Environmental impacts

We estimated the environmental impacts of twenty-two scenarios described in Table 14 using Monte Carlo simulation with a sample size of 50,000. Table 15 reports the mean value and standard deviation (in parentheses) of impact indicators.

Table 15. Mean value and standard deviation (in parentheses) of impact indicators value according to scenarios from Table 14.

Sc	Ac ($\times10^{-7}$) (Mole H^+ eq.)	CC (kg CO_2 eq.)	RD ($\times10^{-9}$) (kg Sb eq.)	Ec ($\times10^{7}$) (CTUe)	ME ($\times10^{-7}$) (kg N eq.)	TE ($\times10^{-6}$) (Mole N eq.)	HTc ($\times10^{-3}$) (CTUh)	HTnc ($\times10^{-3}$) (CTUe)	IRe ($\times10^{-9}$) (CTUe)	IRhh ($\times10^{-5}$) (kg U235 eq.)	PM ($\times10^{-9}$) (kg PM2.5 eq.)	PO (kg C_2H_4 eq.)
1	1.89 (0.10)	2.72 (0.16)	42 (0.09)	8.35 (4.68)	35.7 (0.39)	4.94 (0.66)	1.83 (0.13)	14.9 (0.14)	1.44 (0.24)	3.27 (0.54)	4.3 (0.26)	1.17 (0.58)
2	2.19 (0.12)	3.16 (0.18)	49 (0.11)	9.61 (5.37)	41.6 (0.44)	5.74 (0.75)	2.13 (0.15)	17.4 (0.16)	1.67 (0.28)	3.8 (0.62)	5 (0.3)	1.35 (0.66)
3	2.56 (0.14)	3.69 (0.21)	57.1 (0.13)	11.3 (6.31)	48.5 (0.52)	6.7 (0.89)	2.48 (0.17)	20.3 (0.19)	1.95 (0.33)	4.44 (0.73)	5.8 (0.35)	1.58 (0.78)
4	2.72 (0.23)	3.93 (0.34)	42.2 (0.09)	18 (10.2)	49.3 (0.84)	7.67 (1.43)	2.68 (0.28)	20.6 (0.3)	2.31 (0.53)	5.22 (1.17)	6.2 (0.56)	2.41 (1.25)
5	1026 (0.10)	214 (0.16)	49.2 (0.11)	17.1 (4.68)	1698 (0.39)	19525 (0.66)	5.02 (0.13)	131 (0.14)	111 (0.24)	58.6 (0.54)	2269 (0.26)	7.85 (0.58)
6	1196 (0.12)	249 (0.18)	57.3 (0.13)	19.8 (5.37)	1980 (0.44)	22762 (0.75)	5.85 (0.15)	153 (0.16)	129 (0.28)	68.3 (0.62)	2645 (0.3)	9.13 (0.66)
7	1394 (0.23)	290 (0.21)	57.7 (0.20)	23.2 (6.31)	2307 (0.52)	26522 (0.89)	6.82 (0.17)	178 (0.19)	150 (0.33)	79.6 (0.73)	3082 (0.35)	10.7 (0.78)
8	1400 (0.23)	292 (0.34)	0.81 (0.09)	30 (10.2)	2317 (0.84)	26636 (1.43)	7.03 (0.28)	179 (0.3)	151 (0.53)	80.7 (1.17)	3096 (0.56)	11.5 (1.25)
9	26 (0.10)	4.15 (0.16)	0.94 (0.11)	8.28 (4.68)	7.14 (0.39)	15.3 (0.66)	0.28 (0.13)	2.41 (0.14)	5.31 (0.24)	2.12 (0.54)	57.6 (0.26)	1.11 (0.58)
10	30 (0.12)	4.84 (0.18)	1.1 (0.13)	9.52 (5.37)	8.31 (0.44)	17.9 (0.75)	0.32 (0.15)	2.81 (0.16)	6.18 (0.28)	2.45 (0.62)	67.1 (0.3)	1.27 (0.66)
11	35.4 (0.14)	5.64 (0.21)	1.24 (0.20)	11.2 (6.31)	9.69 (0.52)	20.8 (0.89)	0.37 (0.17)	3.27 (0.19)	7.21 (0.33)	2.87 (0.73)	78.2 (0.35)	1.49 (0.78)
12	35.7 (0.23)	5.89 (0.34)	91.9 (0.09)	17.9 (10.2)	10.3 (0.84)	21.8 (1.43)	0.56 (0.28)	3.49 (0.3)	7.59 (0.53)	3.65 (1.17)	78.9 (0.56)	2.32 (1.25)
13	32.7 (0.10)	695 (0.16)	107 (0.11)	337 (4.68)	1039 (0.39)	6411 (0.66)	27 (0.13)	164 (0.14)	99.4 (0.24)	348 (0.54)	732 (0.58)	70.8 (0.58)
14	38.1 (0.12)	810 (0.18)	125 (0.13)	393 (5.37)	1211 (0.44)	7474 (0.75)	31.5 (0.15)	192 (0.16)	116 (0.28)	406 (0.62)	854 (0.3)	82.5 (0.66)
15	44.4 (0.14)	943 (0.21)	126 (0.20)	458 (6.31)	1411 (0.52)	8709 (0.89)	36.7 (0.17)	223 (0.19)	135 (0.33)	473 (0.73)	995 (0.35)	96.1 (0.78)
16	44.6 (0.23)	948 (0.34)	0.16 (0.09)	467 (10.2)	1418 (0.84)	8747 (1.43)	37.1 (0.28)	225 (0.3)	136 (0.53)	475 (1.17)	9996 (0.56)	97.4 (1.25)
17	0.181 (0.10)	0.27 (0.16)	0.16 (0.09)	8.15 (4.68)	0.67 (0.39)	1.14 (0.66)	0.22 (0.13)	0.24 (0.14)	0.42 (0.24)	0.94 (0.54)	0.45 (0.26)	1.01 (0.58)
18	0.208 (0.12)	0.31 (0.18)	0.19 (0.11)	9.37 (5.37)	0.77 (0.44)	1.32 (0.75)	0.26 (0.15)	0.28 (0.16)	0.49 (0.28)	1.08 (0.62)	0.52 (0.3)	1.16 (0.66)
19	0.245 (0.14)	0.37 (0.21)	0.22 (0.13)	11 (6.31)	0.91 (0.52)	1.54 (0.89)	0.3 (0.17)	0.33 (0.19)	0.57 (0.33)	1.26 (0.73)	0.61 (0.35)	1.36 (0.78)
20	0.394 (0.23)	0.59 (0.34)	0.35 (0.20)	17.7 (10.2)	1.46 (0.84)	2.49 (1.43)	0.48 (0.28)	0.53 (0.3)	0.92 (0.53)	2.04 (1.17)	0.98 (0.56)	2.19 (1.25)
21	49.9 (3.08)	143 (9.15)	20.1 (1.29)	140 (49.4)	181 (11.1)	397 (24.8)	10.4 (1.28)	29.9 (0.19)	57.2 (3.6)	167 (10.2)	113 (6.94)	22.2 (5.99)
22	1.13 (0.41)	1.69 (0.62)	0.95 (0.37)	46.9 (18.2)	4.04 (1.52)	7.03 (2.6)	1.29 (0.5)	0.14 (0.55)	8.29 (2.01)	37.4 (8.85)	2.78 (1.02)	5.85 (2.25)

Based on the results given in Table 15. For the abrasive blasting method: (i) with a given type of abrasive materials, the environmental impacts are increased by using bigger nozzle diameter; and (ii) the use of olivine as the abrasive materials results in the lowest environmental impacts, followed by ilmenite, silica sand, silicon carbide and aluminum oxide, i.e., aluminum oxide and silicon carbide are more critical. The most environmentally conscious scenario is the scenario 17 except for the Human Toxicity, more precisely non-carcinogenics (HTnc) impact indicator, for which the scenario 22 (high and ultra-high pressure water jetting) is more favorable.

VI. 7. Discussions

The SA results revealed that the environmental impacts are more sensitive to concrete surface preparation method (*Prep*) and kind of abrasive materials (*Abr*). They have the highest value of S_j and S_{T_j} (Table 13). More precisely, the simulated results in Table 15 showed that using aluminum oxide and silicon carbide increases significantly the environmental impacts. Producing 1 kg of aluminum oxide (Al_2O_3) and silicon carbide has more impacts on environment than ilmenite, silica sand and olivine.

Although the dry ice blasting method takes advantage of lower waste than the abrasive blasting method with silica sand and high and ultra-high pressure water jetting [201] We found that using dry ice in lieu of silica sand and water has more impacts on environment (Table 15).

Using the minimal pressure at nozzle (*Press*) is one of the effective ways to reduce the environmental impacts. Because an increase in the operational pressure at nozzle (*Press*) results in the increase of the consumption of compressed air (Figure 38) and materials (Figure 39). The nozzle diameter of the abrasive blasting method (*Noz_abr*) is found having high interaction with other parameters, because the consumption of compressed air and abrasive materials feed rate depend on the nozzle diameter (Table A3 in Appendix). An increase of nozzle diameter results in the increase of the consumption of compressed air and abrasive materials, i.e. the environmental impacts are increased.

VI. 8. Conclusions and recommendations

The analysis presented in this paper simulated the environmental impacts of concrete surface preparation activity. For the specific concrete surface preparation methods, equipment and materials and assumptions, we found the following parameters affecting significantly the environmental impacts:

- The concrete surface preparation method among the high and ultra-high pressure water jetting, abrasive blasting, dry ice blasting.
- The abrasive materials among ilmenite, aluminum oxide, silica sand, silicon carbide and olivine.
- The operational pressure at nozzle from 3.4 bar up to 9.7 bar.
- The nozzle diameter of the abrasive blasting method among the types of nozzle given in Table A3 in Appendix.

Engineers and practitioners should focus on them to reduce the environmental impacts in altering concrete surface.

The parameters are identified as the non-influential parameters:

- The compressor of among the models (Table A2 in Appendix).

- The nozzle diameter of the dry ice blasting method among the nozzle types (Table A5 in Appendix).
- The pelletizer machine to alter liquid CO_2 into dry ice particles among the pelletizers (Table A4 in Appendix).
- The high pump pressure among the pumps (Table A6 in Appendix).

The following recommendations are made:

- Using the minimal pressure at nozzle of about 3.4 bar for the abrasive blasting and dry ice blasting method.
- Using the minimal nozzle diameter No. 6 (9.5 mm) for the abrasive blasting method.
- In association with the pressure at nozzle of about 3.4 bar and nozzle diameter of about 9.5 mm, the abrasive blasting method with the olivine is the most favorable solution, followed by the abrasive blasting method with ilmenite, high and ultra-high pressure water jetting, abrasive blasting method with silica sand, dry ice blasting method, abrasive blasting method with silicon carbide and with aluminum oxide.

VII. CONCLUSIONS AND PERSPECTIVES

Résumé :

Dans cette thèse, nous avons développé une méthode de conception environnementale et durable de structures en béton armé. Nous avons proposé d'élaborer un modèle de durée de vie des structures en béton dans un environnement agressif. Ce modèle permet de concevoir des structures dont les impacts environnementaux sont évalués par l'Analyse de Cycle de Vie (ACV) sur la phase de construction, d'entretien et de réparation. Nous avons intégré les méthodes d'analyse de sensibilité de Sobol et de Morris pour déterminer les leviers d'action réduisant les impacts environnementaux et augmentant la durée de vie des structures.

En suivant notre méthode, nous avons tout d'abord développé un modèle de durée de vie des structures en béton armé altérées par la carbonatation. Nous avons développé un méta-modèle pour prédire la profondeur de carbonatation naturelle en béton. Ensuite, nous avons développé les diagrammes décisionnels pour la conception initiale et la politique d'entretien.

Nous avons appliqué notre méthode au cas d'étude d'une structure en béton armé située à Madrid et soumise à la carbonatation pour une durée de vie

prévue de 100 ans. Suivant les recommandations de la norme EN 206-1 nous nous plaçons dans la classe d'exposition XC4. Nous avons appliqué la méthode de Sobol et de Morris sur le modèle de durée de vie pour identifier les leviers d'action augmentant la durée de vie de la structure. En plus, nous avons identifié les deux principales alternatives de conception de la structure : (i) les structures conçues avec les classes de résistance du ciment de 42,5 MPa et 52,5 MPa ne nécessitent aucune opération d'entretien ; et (ii) les structures conçues avec une classe de résistance du ciment de 32,5 MPa nécessitent des opérations d'entretien et différentes politiques d'entretien doivent être comparées.

Pour la première alternative de choix de structures (classes de résistance du ciment de 42,5 MPa et 52,5 MPa ne nécessitant aucune opération d'entretien), nous avons développé un modèle ACV pour estimer les impacts environnementaux. Ce modèle est basé sur une unité fonctionnelle correspondant à 1 m^2 de surface d'enrobage en béton. Nous avons appliqué la méthode de Sobol et de Morris sur les indicateurs environnementaux pour identifier les leviers d'action réduisant les impacts environnementaux. Dans le cas étudié, les recommandations pour une conception durable et environnementale de cette structure sont l'utilisation du ciment CEM III/C, d'un rapport eau sur ciment minimal, d'une épaisseur du béton d'enrobage minimale et d'une distance minimale entre l'usine de béton et le site.

Dans la deuxième alternative de choix de structures (classe de résistance du ciment de 32,5 MPa nécessitant des opérations d'entretien), nous nous sommes exclusivement concentrés sur une politique de maintenance préventive. Nous avons tout d'abord développé un nouveau modèle de durée de vie qui considère l'effet du revêtement de protection. Ensuite, nous avons développé un modèle d'ACV pour estimer les impacts environnementaux de l'altération de la surface du béton. Nous avons appliqué la méthode de Sobol et de Morris sur les indicateurs environnementaux dans le but de réduire le diagramme décisionnel de préparation de la surface du béton avant application du revêtement.

Dans les perspectives à court-terme, il faudrait compléter les études sur les structures conçues avec la classe de résistance du ciment de 32,5 MPa nécessitant des opérations d'entretien, en intégrant un modèle de politique d'entretien curative. En effet, il serait intéressant de comparer les impacts environnementaux des politiques préventive et curative pour ce type de structure, afin de trouver laquelle améliore les performances environnementales.

Dans les perspectives à plus long-terme, il faudrait intégrer d'autres phénomènes d'altération au modèle car aujourd'hui seule la carbonatation est considérée dans le modèle de durée de vie. Il est possible que les résultats diffèrent de ceux trouvés dans cette thèse si les attaques de sulfates, de chlorures ou encore la fissuration étaient intégrées au modèle. Des travaux supplémentaires devraient notamment se concentrer sur la combinaison des effets de ces différents mécanismes d'altérations.

La méthode d'AS pourrait être améliorée en caractérisant mieux les influences en interaction des paramètres qui pourraient améliorer significativement la durée de vie et les performances environnementales.

Enfin, dans une perspective d'application à des méthodes de conception courantes, il faudrait passer de l'échelle matériau à celle de l'ouvrage, en intégrant les modèles d'altération bi- et tri-dimensionnels pour mieux tenir compte d'effets localisés.

General conclusions

In this PhD, we devised a novel approach for environmental and durable design of RC structures in aggressive environment. Our approach allows identifying effective few solutions among all possible decision combinations for improving both service life and environmental performances. It should first be noted that all results and recommendations for environmental and durable design are related to the case study and location (Madrid). In another city, our results would be indeed changed. However, our approach is general and can be adapted to various locations of RC structure by changing probability density profiles of environmental parameters in order to reflect local conditions. Optimization of both service life and environmental performances can thus be adapted to any location. Our approach allows optimizing both functional unit (herein, service life) and environmental performances (herein, LCA indicators).

To reach this objective, we first developed a new meta-model for calculating the natural carbonation depth within concrete structures. The meta-model is based on the analytical solution of Fick's first law. Robustness of meta-model is to consider maximally the influentially technological and environmental parameters. The validation of the meta-model has been conducted using data from literature on short and long-term natural carbonation exposure conditions. The meta-model predictions for concrete service life as regards carbonation are reasonably accurate and reliable. In order to improve the prediction of meta-model, it is necessary to validate the meta-model with other long-term natural carbonation data.

We used our meta-model combined with SA to propose a new procedure for durable design of RC structures in aggressive environment. To do it, we combine the two existing approaches (prescriptive approach and performance-based approach) and integrate the Sobol and Morris' method, in order to identify the action levers increasing the service life of RC structure. We applied the design procedure to the RC structure of our case study. We found that cement strength class, water-to-cement ratio and cement type are action levers. When setting the action levers at their most favorable values instead of their limiting values as recommended by EN 206-1, the service life is significantly improved. We also identified two alternatives of the RC structure of the case study: (i) the RC structure, designed with the cement strength classes 42.5 MPa or 52.5 MPa, for which neither maintenance nor repair operations are required within its 100-year service life design; and (ii) the RC structure designed with the cement strength class 32.5 MPa, for which maintenance or repair operations are required during its 100-year service life design, and for which influence of maintenance policies should be compared. We found that with both cement strength classes (42.5 MPa and 52.5 MPa), the service life of the RC structure is superior to 100 years, but cement strength class 52.5 MPa provides longer service life. It can be thus recommended for structures requiring the longest service life such as bridges. Cement strength class 42.5 MPa is however suitable for lowest service life structures such as buildings.

Then, we provided the recommendations for environmental and durable design of the RC structure of our case study designed with the cement strength classes 42.5 MPa and 52.5 MPa (no maintenance). To reach the lowest environmental impacts, we found that using the lowest cement content, water-to-cement ratio, concrete cover depth and distance from the concrete factory to the site are the most efficient levers. The CEM III/C cement type is the most favorable solution for environment.

In order to study the RC structure designed with the cement strength class 32.5 MPa, we first developed another carbonation model that integrates the effect of coating into CO_2 coefficient diffusion as a function of dry film thickness of coating. The developed model is validated with several data from literature for long-term natural carbonation of coated concrete. However, in order to improve the prediction of model, more data should be necessary. We applied the Sobol and Morris' method to this new model, in order to reduce the number of input parameters of carbonation model.

Finally, we used the Sobol and Morris' method to reduce the decision diagram for concrete surface preparation. The reduction of scenarios of the RC structure and the decision diagram for concrete surface preparation allows reducing the time-consuming calculation.

Perspectives

In the short-term, further studies on the RC structure of our case study, designed with the cement strength class 32.5 MPa, are required. It would be interesting to compare the environmental impacts of the RC structure maintained by the preventive coating system or repaired by the curative patching repair system. This would finally also allow comparing all solutions including cement strength classes 42.5 MPa and 52.5 MPa with no maintenance. Presently, we could not reach this ultimate goal in order to answer the question about the best design, high cement strength class without maintenance or low cement strength class with maintenance.

In a longer term, other alteration mechanisms should be integrated into the model. Carbonation is the only alteration phenomenon of RC structure that is considered in this work. However, the presence of a small amount of chlorides significantly increases the corrosion risk in carbonated mortars [183]. Further work should concentrate on the combined effects of various alteration mechanisms.

In addition, the SA method could be improved to better characterize the interaction influences between the parameters. For instance, in this thesis, the most influential parameters have strong interactions with the other parameters. These interactions, however, have not been examined here. The results of studies addressing the problem of interactions between parameters could additionally enhance the service life and reduce the environmental impacts of RC structures. We are confident that this finding will serve as a basis for future theoretical and experimental works.

Finally, our approach should integrate two- and three-dimensional service life models in order to better reflect localized effects, and be able to extend the developed approach to a whole engineering structure.

ABBREVIATIONS

Ac	Acidification
CC	Climate change
Ec	Ecotoxicity
ILCD	International reference life cycle data system
IRe	Ionizing radiation, ecosystems
IRhh	Ionizing radiation, human health
HTc	Human toxicity, carcinogenics
HTnc	Human toxicity, non-carcinogenics
LCA	Life cycle assessment
LCI	Life cycle inventory
ME	Marine eutrophication
PDF	Probability distribution function
PM	Particulate matter
PO	Photochemical oxidation
RD	Resource depletion, mineral, fossils and renewables
SA	Sensitivity analysis
TE	Terrestrial eutrophication

DEFINITIONS

1. **Sustainability:** humanity has the ability to make development sustainable, to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs [1].

2. **Durability:** it is the capability of maintaining the **serviceability** of a structure over a **service life**, or a characteristic of the structure to function for a **service life** with required safety and corresponding characteristics, which provide **serviceability** [214].

3. **Serviceability:** it is viewed as the capacity of the structures to perform the functions for which they are designed and constructed within normal use conditions [214].

4. **Service life:** it is the period of time after construction during which all properties exceed the minimum acceptable values when routinely maintained [214].

5. **Preventive maintenance system:** a non-electrochemical method used to significantly reduce the carbonation rate of concrete. A typical example is treating the concrete surface. Protection against carbonation is usually achieved by treating the surface with a coating that has limited carbon dioxide permeability or by treating the surface with a material that absorbs carbon dioxide.

6. **Repair system:** a method that restores a deteriorated concrete element to a service level equal to or almost equal to the as-built condition. No effort is made to prevent or significantly retard deterioration mechanisms. A typical example is patch repair. The carbonated concrete is removed and replaced by a new concrete.

7. **Coating(s):** it means any preparation, including all organic solvents or preparations containing organic solvent necessary for its proper application, which is used to provide a film with decorative, protective or other functional effect on a surface [215].

8. **Dry film thickness (DFT):** the dry film thickness is measured in μm on a surface which it is dry [215].

9. **Film-forming coating(s):** viscous materials which form a pinhole-free film on the concrete surface to improve its aesthetic appearance or provide protection by acting as a barrier to the ingress of aggressive agents. Coatings are generally applied in two or more layers. Thin coatings have a DFT of 100-300 μm, high build coatings generally exceed 1 mm, whereas cementitious coatings are generally thick applications ranging from 1mm to 20 mm thick [215].

10. **Protective coating system(s):** these can be either film-forming coatings, surface treatments or combinations of these which can impact protective qualities of the concrete surface against the ingress of aggressive agents [215].

11. **Environmental impact:** consequences for human health, for the well-being of flora and fauna or for future availability of natural resources [216].

12. **Environmental performance:** it refers to the environmental result that are achieved whenever the environmental aspects of activities, processes, products, services, systems, and organizations are managed and controlled [217].

13. **Functional unit:** measure of the performance of the functional output of the product or services system [216]; for example, in the ready mixed concrete LCI the functional unit is one cubic meter of ready mixed concrete.

14. **Impact assessment:** understanding and evaluating the magnitude and significance of environmental impacts [216].

15. **Life cycle inventory (LCI) analysis:** quantification of the inputs and outputs (in this case materials, energy, and emissions) from a given product or service throughout its life cycle [216].

16. **Life cycle:** consecutive and inter (linked stages of a product or service) from the extraction of natural resources to final disposal [216].

17. **Life cycle assessment (LCA):** a systematic method for compiling and examining the inputs and outputs of energy and materials (life cycle inventory) and the potential environmental impacts directly attributable to the functioning of a product or service system throughout its life cycles [216].

18. **System boundary:** interface between the product or service system being studied and its environment or other systems. The system boundary defines the segment of the production process being studied [216].

19. **Sensitivity analysis:** being the study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be apportioned to different sources of uncertainty in its inputs [8].

20. **Technological parameters:** are those controllable by the engineering designer (e.g., material properties, execution process of material).

21. **Environmental parameters:** are those uncontrollable and depending on the outside environmental location (e.g., aggressive agent sources like CO_2 concentration, chlorides, ambient temperature and relative external humidity).

22. **Action lever:** as technological parameters, which are major contributors to the sensitive service life and environmental impacts.

23. **Favorable scenario:** aiming at increasing the service life or/and decreasing the environmental impact indicators. It is designed by setting the action levers at their minimal or maximal value, the other technological parameters (identified as the non-influential parameters) at their mean value.

24. **Default scenario:** aiming at providing as a standard scenario to validate the favorable scenario by comparing the service life and environmental impacts of two scenarios. It is designed by setting all technological parameters at their mean value.

APPENDIX: INPUT PARAMETERS CHARACTERIZATIONS

Table A1. Cement types based on Portland cement content.

Cement type	Clinker (n.u.)	Calcium oxide (n.u.)	Cement density (kg/m^3)
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

Table A2. Portable air compressor studied [208].

Model	Fuel consumption rate (kg/h)	Free air delivery (m3/h)	Average power input (kW)
P425/HP375WCU	15.5	636	102.9
HP450/WHP400WCU	19.6	678	121.6
HP675WCU	125.1	1146	194
VHP750WCAT	125.1	1272	223.7
XP750WCU	125.1	1272	194
HP750WCU	136	1272	209
MHP825WCU	157.8	1404	223.7
XP825WCU	136	1404	209
HP915WCU	149.3	1554	223.7
XP1000WCU	149.3	1698	223.7
HP1300WCU	230.7	2208	380.3
HP1600WCU	259.2	2718	417.6

Table A3. Volumetric capacity required for pressure by nozzle for abrasive blasting [204].

Model	Compressed air consumption rate at 5.5 bar (m^3/h)	Abrasive materials feed rate (kg/h)
No.6 (9.5 mm)	273.7	435.4
No.7 (11 mm)	368.9	595.1
No.8 (12.7 mm)	476	762
No. 10 (19 mm)	768.4	766.6

Table A4. Pelletizer machine on the market [211].

Description	P325	P750	P1500	P3000
Average power input (kW)	3.2	6.1	8.5	14.2
Productivity (kg/h)	136.4	272.7	545.5	1090.9
Liquid to solid CO2 ratio	Approximately 2.5:1 without recovery			

Table A5. Volumetric capacity required by nozzle at pressure 5.5 bar with dry ice feed rate [212].

Model	Air consumption (m3/h) at 5.5 bar	Average feed rate (kg/h)
507S2	282	111
510S.6	234	81
508M.8	252	111
523M1	258	111
523S3	282	135
533S2	258	135

Table A6. Available high pump pressure from Combijets' supplier [213].

Model	**Operational pressure (bar)**	**Flow rate (m^3/h)**	**Input power (kW)**
JE80-800	800	1.08	30
JE80-1000	1000	1.08	30
JE80-1300	1300	0.94	37
JE80-1500	1500	0.94	37
JE80-1770	1770	0.94	45
JE80-2100/13	2100	0.94	55
JE80-2300/13	2300	0.94	75
JE80-2500/16	2500	1.15	90
JE80-2500/21	2500	1.5	110
JE80-2500/25	2500	1.8	130

Table A7. Input data inventory.

Acronyms	Material	Reference in Ecoinvent
Abrasive blasting method		
Env_{abr}	Ilmenite	Ilmenite-magnetite mine operation-GLO/kg
	Aluminum oxide	Aluminum oxide production-GLO/kg
	Silica sand	Silica sand production-RoW/kg
	Silicon carbide	Silicon carbide production-RER/kg
Dry ice blasting method		
Env_{abr}	Liquid CO_2	Carbon dioxide production, liquid-RER/kg
High and ultra-high pressure water jetting		
Env_{abr}	Water	Tap water production underground water with chemical treatement-CH/kg
Energy		
Env_{energy}	Electricity	Electricity, high voltage, production mix-CH/kWh

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Thèse de Doctorat

Van Loc TA

Méthode innovante pour la conception environnementale et durable de structures en béton armé soumises à la carbonatation

A novel approach for environmental and durable design of reinforced concrete structures altered by carbonation

Résumé

Ces travaux présentent une nouvelle méthode de conception dont l'objectif est de maximiser la durée de vie d'une structure en béton armé soumise à la carbonatation et de minimiser ses impacts environnementaux sur son cycle de vie. Cette approche est basée sur le développement d'un nouveau méta-modèle de carbonatation couplé à une approche d'Analyse de Cycle de Vie (ACV). Une recherche de leviers d'actions sur la durabilité et les impacts environnementaux est réalisée via une combinaison de deux méthodes d'analyse de sensibilité. Nous définissons les leviers d'action comme étant des paramètres technologiques influents sur la durée de vie et/ou les impacts environnementaux de la structure en béton armé étudiée. Notre approche est appliquée au cas d'étude d'une structure en béton armé soumise à la carbonatation pour une durée de vie prévue de 100 ans située à Madrid, dans une classe d'exposition XC4 selon la norme EN 206-1. Pour ce cas d'application nous trouvons que la solution la plus durable et la plus respectueuse de l'environnent est celle utilisant du ciment CEM III/C, en minimisant le rapport eau sur ciment, l'épaisseur du béton d'enrobage, et la distance de la centrale fournissant le béton au site de construction.

Mots clés :
Eco-conception ; Morris, Sobol, unité fonctionnelle, optimisation

Abstract

This thesis presents a new design approach of which objective is to maximize service life of reinforced concrete structure and minimize its environmental impacts. This approach is based on the development of a new carbonation meta-model coupled with Life Cycle Assessment (LCA). A search for action levers on both durability and environmental impacts is conducted using a combination of two sensitivity analysis methods. We define action levers as technological parameters that are found influential on service life and/or environmental impacts for the studied reinforced concrete structure. Our approach is applied to a case study of a reinforced concrete structure design for a 100-year service life and located in Madrid within a XC4 exposure class according to the EN 206-1 standard. In that case study, we find that the most favorable solution for the RC structure is designed with the lowest cement content, water-to-cement ratio, concrete cover depth and distance from the concrete factory to the site, in association with the CEM III/C cement type.

Key Words
Eco-design, design for environment, Morris, Sobol, functional unit, optimization