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The role of service life in Life Cycle Assessment of concrete structures

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Abstract

In comparative Life Cycle Assessment (LCA) of concrete structures it is of crucial importance to provide the functional equivalence of compared alternatives. Most commonly, the comparison is performed between the structures made of conventional and green concrete mixtures. Since they have different mechanical and durability properties, corresponding structures have different strength and service life. While resolving this problem, two approaches are generally possible: either correction of the functional unit volume or correction of the calculated environmental impacts with compressive strength and duration of service life, if functional unit has the same volume. In this work, in order to assess the effect of service life modeling in LCA, both approaches were tested. As a demonstration, comparison of both slabs and beams made of conventional and high volume fly ash concrete exposed to carbonation was carried out. LCA was performed for 94 different mixtures from reported experimental research and calculated environmental impacts **(climate change, acidification, eutrophication, photochemical-oxidant creation, and abiotic depletion of fossil fuels)** for both approaches were compared. Results showed that different modeling of service life in LCA can result in totally different, even opposite conclusions. With slightly larger volume of functional unit **(7%-20%)**, all normalized environmental impacts of high volume fly ash concrete structural members were lower for an order of magnitude **(6 - 7 times)** compared to those obtained on the basis of the same volume approach. Therefore, drawing conclusions only on the basis of service life modeling with the same volume approach may be misleading. The proper choice of the best alternative should be based on the integrated assessment which includes structural, environmental and cost assessment of the structure as a whole.

Keywords: concrete structure, service life, LCA, environmental impact, integrated assessment

1. Introduction

It is well recognized today that human activities cause major environmental impacts. Among many others, the construction industry places a large burden on the environment: huge consumption of natural resources, especially non-renewable fossil fuels, large emissions of substances that pollute the air, soil, and water, as well as the generation of substantial amounts of inert and toxic waste.

More specifically, the concrete industry plays a leading role in this process: concrete production is not especially harmful per unit of concrete; however, the global production and utilization of concrete is very high – roughly 25 billion tons of concrete are produced globally each year, or over 3.8 tons per person per year (WBCSD, 2009), only second to water in mankind's consumption. In developed countries, structural concrete (concrete utilized in reinforced concrete structures) constitutes over 50% of all concrete, and developing countries will follow this trend (UN Environment, 2018). The cement industry causes approximately 10% of the overall anthropogenic CO_2 emissions (UN Environment, 2018) in the world – more than 50% of the yearly CO_2 is related to building activities. The IEA study (IEA, 2018) found that CO_2 emissions in the cement industry, consistent with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100, would require an overall reduction of 24% in the CO_2 direct emission from current levels by 2050.

For these reasons it is of crucial importance to find way(s) of greening the concrete industry, i.e., to decrease its impact on the environment. These efforts can be divided into three major groups: (1) recycling of construction and demolition waste as a way to reduce the amount of waste and consumption of natural resources, (2) on the material level, by introducing green concretes, and (3) on the structural level, by design for longer service life and reuse.

Green concretes are developed with the following aims:

- to reduce the natural aggregate's (NA) consumption and waste generation – for the production of these green concretes recycled concrete aggregates (RCA) are used instead of NA; they are called recycled aggregate concretes (RAC);

- to reduce CO_2 emissions which originate mostly from cement production, namely by using a low content of cement.

Part of the cement is usually replaced by the so called supplementary cementitious materials (SCMs) with low embodied CO_2. The most common SCMs are reactive wastes from other industries; for instance, fly ash (FA), the by-product of the electricity production in coal-burning power plants, can be used for this purpose because it has pozzolanic properties. Granulated blast furnace slag (GBFS), a by-product of pig-iron production in blast furnaces, is also commonly used. Fillers, inert or weakly reactive fine particulate materials, can partially replace cement or other reactive SCMs; the most commonly used is limestone filler.

The cement content in concrete can also be reduced by appropriate mix design methods such as particle packing methods (Fennis and Walraven, 2012; Sunayana and Barai, 2017). These methods enable better concrete properties with a smaller amount of cement. Recently, research has focused on the possibility of replacing large parts of cement with inert fillers and super plasticizers, in combination with particle packing methods (John et al., 2018).

Due to the high global production of concrete, CO_2 mitigation strategies require material alternatives to be available in large amounts. According to a UN report (UN Environment, 2018) there is not much future in replacing cement with common SCMs such as GBFS and FA, because of their limited global availability. The estimate is that quality sources of GBFS and FA will be limited globally to only about 15–25% of cement production by 2050 and are unlikely to increase. This amount is hardly enough for the production of composite cement (CEM II) (CEN, 2008) which contains up to 35% of SCMs and is highly utilized in structural concrete. For that reason, this report recommends recently developed alternative SCM systems that use a combination of calcined clays and ground limestone or a combination of filler, super plasticizers, and particle packing mix design methods. Beside limestone, many other minerals can be used as fillers in concrete, so they are abundantly available everywhere.

However, there are regions in the world where FA availability is significantly above the global average. These are regions where most of electricity is produced in coal-fired power plants, with rapid technology change that is unlikely to occur in the near future. For instance, in Serbia, 70% of electricity is produced in such plants. The annual production of FA and bottom ash is 7 million tons, with 300 million tons of FA already deposited on an area of more than 1500 ha. On the other hand, the annual production of cement in Serbia is about 2 million tons. Only 3% of FA is utilized, mostly in cement production. Much larger utilization of FA is therefore urgently needed in some regions of the world. For this reason, high volume fly ash concrete (HVFAC) was developed as a concrete which contains more than 40–50% of FA in the total mass of cementitious materials. With proper mix design and quality FA, this concrete can have properties necessary for structural applications.

Whichever SCM, filler, aggregate type, or mix design method is used, the aim is to keep the structural performance of concrete at a desired level. Up to now extensive research was performed regarding the properties of HVFAC and RAC (see references for databases) and regarding the behavior of structural elements containing them (Ajdukiewicz and Kliszczewicz, 2007; Arezoumandi and Volz, 2013; Arezoumandi et al., 2014; Dragaš et al., 2016; Ignjatović et al., 2013, 2017a; J. Pacheco et al., 2015; Knaack and Kurama, 2015; Sadati et al., 2016; Seara-Paz et al., 2018; Tošić et al., 2016, 2018; Xiao et al., 2012; Yoo et al., 2015). Although the production technologies are readily accessible and properties are well investigated, their application in structural concrete is not yet standardized (or it is allowed but with strong limitations canceling possible benefits). They are slowly entering the structural codes and, for instance, the new version of Eurocode 2 (CEN, 2004) planned for 2020 introduces RAC as a viable structural concrete.

2. Effect of service life on the life cycle environmental impacts of concrete structures - choice of functional unit

A lot of research in the last decade was devoted to the environmental assessment of conventional and green concretes and it was, almost exclusively, performed by using Life Cycle Assessment (LCA) in comparative assessments (Knoeri et al., 2013; De Schepper et al., 2014; Celik et al., 2015; Jiménez et al., 2015; Turk et al., 2015; Teixeira et al., 2016; Braga et al., 2017; Marinkovic et al., 2017; Van den Heede et al., 2017; Vieira et al., 2018; Zhang et al., 2019). Various commercial and non-commercial LCA software, including Life Cycle Inventory (LCI) databases **(SimaPro (www.pre.nl), Gabi (www.gabi-software.com), Athena (www.athenaSMI.ca), TEAM (www.ecobilan.com), JEMAI (www.jemai.or.jp/english/index.cfm),) and LCI databases (Ecoinvent (www.pre.nl/ecoinvent), ELCD (http://lca.jrc.ec.europa.eu), BEES (www.nist.gov/el/economics/BEESSoftware.cfm), etc.** were developed. Although the environmental aspect is not the only pillar of sustainability, it is the most investigated one, because the social aspect is hard to quantify. On the other hand, it is easy to include **the economic aspect (cost) in the assessment, and in fact it has always been included in the decision making process**.

Unlike most other products, structures generally have very long service life – period of time in which the structure has to satisfy the required performance criteria. It ranges between 10 and over 100 years depending on the type of structure and its importance. For instance, according to European standard Eurocode 0 (CEN, 2004) design service life is 10 years for temporary structures, 50 years for buildings and other common

structures of average importance, and 100 years or more for structures of greater importance e.g. monumental buildings, large bridges, other special or important structures.

Today we are able to successfully estimate service life of concrete structures for different deterioration mechanisms using probabilistic approaches such as those given in, for instance, *fib*-Bulletin 34 (2006). In design of concrete structures service life is one of the functional requirements and therefore it has to be included in LCA when defining the functional unit (FU).

This is especially important in LCAs where concrete structures made of conventional and green concretes are compared. Since they usually have different mechanical and durability related properties which influence service life of a structure, FU with same volume would obviously not provide the same function of compared alternatives - comparison based on the same volume approach is not justified.

In previous research, this problem was recognized and dealt with in several ways. Some researchers adapted the functional unit (FU) to include properties of the concrete as material **(Panesar et al., 2017; Zhang et al., 2019)**. **These authors included service life by correcting calculated impacts per unit volume with chosen concrete durability related property, such as rapid chloride permeability or chloride diffusion coefficient. However, in that way the behavior of the material (plain concrete durability) and not the behavior of the structure (its service life), is taken into account. Concrete structures are made of reinforced concrete (RC) and in the most common case of steel reinforcement, basic deterioration mechanisms affecting service life are carbonation or/and chloride induced reinforcement corrosion. For these commonly investigated mechanisms the service life of RC structural member depends only on the quality of concrete in cover (in standards usually expressed through the minimum compressive strength or minimum**

cement content) and its depth. So, there is no linear relationship between the whole chosen volume of RC member and its service life, but there is a certain, non-linear relationship between the depth of concrete cover and duration of RC member service life. And this is not the same at all since concrete cover makes only a small part of any chosen unit volume.

Therefore, when assessing concrete on the "material" level it is justified to apply FU based only on the material properties. Such FU can be used **only** for generic comparisons in order to evaluate the environmental potential for material substitution. Beside, such comparative LCAs should clearly state that performance of a specific application of assessed material is not taken into account.

As for concrete used in RC structures, its area of application is known – it is a concrete structure with specific functional requirements regarding safety, serviceability and service life. The assessment of structural concrete cannot be performed independently of the structure in which the concrete is applied because service life is not the property of material but a function of the concrete structure.

In comparative LCA same functional requirements should be satisfied for all compared alternatives. In ISO 14041 terminology (ISO, 2006), all reference flows of compared alternatives should be corrected for FU which reflects all relevant functional aspects of the concrete structure. So in comparative assessments of structural concretes, FU based on a specific concrete structure performance should be applied. **This is valid for all construction materials, only in the concrete case there is rather large difference between the "nature" of material and the "nature" of the structure.**

Generally, two approaches for obtaining the functional equivalence when comparing structures made of concrete with different properties are possible: either correction of the FU volume (Approach B in this work) or normalizing the calculated environmental impacts with compressive strength and duration of service life if FU has the same volume (Approach A in this work). What however can lead to a very different assessment results is a fact that for the service life prediction in the case of deterioration mechanisms which cause the reinforcement corrosion, only the depth of the concrete cover in reinforced concrete (RC) member matters (as already mentioned).

The most applied way to model the impact of service life of concrete structures in LCA in previous research was Approach A. For instance, in Garcia-Segura et al. (2014) and Vieire et al. (2018) work, an RC column with chosen size dimensions was applied. Silva et al. (2012) performed the service life prediction for a linear member with specified length and cross section size. These assessments were based on the FU which represents the same volume of compared RC alternatives, i.e. same depth of concrete cover, resulting in different service lives of compared alternatives (Approach A in Figure 1). With this approach the functional equivalence regarding **service life** is not achieved and environmental impacts must be calculated per year of service life for proper comparison.

The problem with such approach is that alternatives with poorer resistance to chosen deterioration mechanisms (whether conventional or green concrete) can have much shorter service lives and therefore significantly larger environmental impacts per year of service life. To avoid this situation (to be negative on green concrete performance) which is generated by employing Approach A solely, researchers often choose to compare conventional and green concretes in the exposure conditions for which green concretes have superior behavior (for HVFAC that would be resistance to chloride ingress). But if the comparison is performed for the exposure condition less favorable for green alternative (for HVFAC that would be carbonation resistance and carbonation is practically unavoidable), green concrete would be (unfairly) assessed as much less environmentally 'friendly' when service life is taken into account. In a word, commonly

used Approach A can significantly overestimate the effect of durability related properties of concrete on the LCA environmental impact results of a concrete structure. On the other hand, there is another possible and correct approach to service life modeling within LCA. Same service lives of compared alternatives can be obtained with different cover depths (keeping the same member's strength), Approach B in Figure 1. Since the depth of concrete cover is usually equal to several centimeters, this causes small changes of volume in FU and different impact of service life on the environmental assessment compared to Approach A. If there is a large difference between calculated service lives of compared alternatives, results of the impact assessment using Approaches A and B (which are both correct) would differ for an order of magnitude. To the best of the authors knowledge this fact was not recognized in the previous research and Approach B was not applied in assessment of concrete for structural use, i.e. concrete structures.

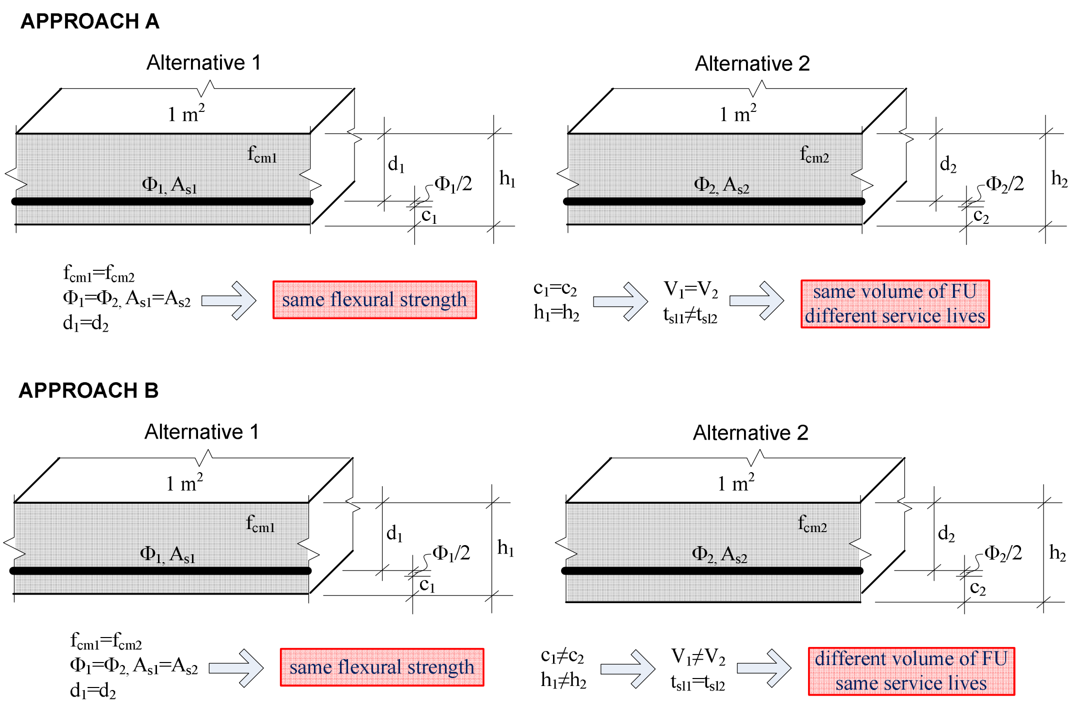

Figure 1. Different approaches to modeling of RC slab service life in LCA

Following symbols are used in Figure 1:

f_{cm} – mean concrete compressive strength

Φ – radius of reinforcement bar

A_s – area of reinforcement

d – effective depth of RC slab

h – total height of RC slab

c – depth of concrete cover

More generally, as Approach A can be considered every approach in which the depth of concrete cover is assumed to have the same value for all compared concrete alternatives. Required service life duration can be set as target and additional repair activities are than included in LCA for those alternatives which don't fulfill this requirement (Van den Heede and De Belie, 2014). **Again, if there is a large difference between calculated service lives this can end in large number of necessary repairs and consequently larger impacts of alternatives with short service life.**

Besides, general conclusions on the structure's service life effect in LCA can hardly be drawn. **They depend on the type (beam, slab, column…) and size of the RC member/structure because the participation of the concrete cover depth in the unit volume is not same for beam and slab for instance – the effect of service life is case-dependent.** As it was stated in Purnell's work (2012) "there is no such thing as a green structural material". In fact, the most proper way in comparative assessments of RC structures is to choose the whole structure as FU (Garcez et al., 2018) while multiple structural designs are unavoidable.

To demonstrate this fact, this work shows how service life prediction affects the life cycle environmental impacts of different RC structural members, and how different such results can be compared to assessments based on the same volume approach or based on the material properties only. For this demonstration two different concrete mixes, conventional concrete

(CC) and HVFAC, and one deterioration mechanism - carbonation, were chosen. This was considered as good demonstration example since these two concrete mixtures have very different carbonation resistance. For two types of structural members, slab and beam, relationships between the chosen impact category indicators and compressive strength were derived taking into account the effect of carbonation on the service life. This was performed on the basis of experimental results from literature, using LCA and regression analyses. Impact category indicators were calculated for approximately 50 different mixtures of each concrete mix, with input LCI data chosen to represent average European production technologies.

3. Databases

The uncertainty regarding the relationship between mixture proportions and compressive strength of concrete is rarely tested. Almost exclusively in the previous research only one mix design per each alternative was assessed and compared. Usually, three samples are tested for determining the compressive strength of the mixture and standard deviation is obtained. But this standard deviation (which is commonly small) includes the variability due to concrete technology and not due to the concrete mix design.

The problem is that the same compressive strength can be obtained with different mixture proportions, i.e. different amounts of component materials which are essential for the impact assessment. This is especially important for the cement amount, because it practically determines the main environmental impacts of concrete. The cement amount in the mix design is influenced not only by the strength, but also by the workability requirement. If workability (slump value for instance) is not equal, same compressive strength can be obtained with (very) different cement content, depending also on the

amount of water reducing admixture. So, results of the previously published comparative LCA studies treating several specific concrete mixtures are valid only for those mixtures - if different workability requirement is set as target, different mix designs and different impacts are obtained. This fact can introduce relatively large variability of the impact results.

For that reason it was decided to calculate impacts on a database of concrete mixtures with broad range of strengths and workability classes collected from published experimental research. The other reason was to assess the influence of the concrete compressive strength on the impact results.

Experimental results on the mixture proportions and properties of CC and HVFAC were collected from available research papers, technical reports, master and doctoral theses. From all available studies only those which contained all necessary data for LCA were selected. These are:

- type and amount of cement, FA, aggregate, and plasticizer
- slump and compressive strength of concrete (at 28 days)

Only concrete mixes with mean compressive strength f_{cm} larger than 38 MPa were chosen for the LCA analysis. This value corresponds to concrete strength class C30/37 which is the lowest strength acceptable for XC3 exposure class (concrete inside buildings with moderate or high air humidity) according to Eurocode 2 (CEN, 2004). Concrete mixes with slump values between 50 and 210 mm (classes S2, S3 and S4 according to EN 206-1 (CEN, 2011)) were selected for further analysis. Only class F fly ash according to ASTM C618 (ASTM C618, 2015) was taken into account. As for plasticizer, all results with a plasticizer amount below 2.5% of cement+FA mass were included in the databases. The type of curing regime can influence HVFAC properties and therefore for these mixtures the most common type was selected – standard wet curing: 95–100% RH and temperature 20±2ºC for the first 28 days. Application of these filters led to:

- 51 different mixtures in the HVFAC database (**database provided in Supplementary**) out of 440 collected results, with following ranges of parameters: FA/(cement+FA) = 40–60%, plasticizer 0–2.5% of the cement+FA mass and mean compressive strength at 28-days 38–67 MPa.

As for CC, the results were compiled of control concrete mixes from experimental campaigns which were used to obtain the HVFAC results (**database provided in Supplementary**). It contains 43 different mixes with following ranges of parameters**:** plasticizer 0–2.5% of the cement mass and mean compressive strength at 28 days 38–66 MPa.

In selected concrete mixes, FA specific gravity ranges from 2075 kg/m^3 to 2750 kg/m^3. All compressive strength results were recalculated for a 15 x 30 cm cylinder, as per Eurocode 2 (CEN, 2004).

4. Modeling of carbonation resistance

4.1 Carbonation depth model

Carbonation is one of the most important depassivation processes. It represents the process of cement matrix neutralization which destroys the chemical protection of reinforcement (thin oxide layer produced in the hydration process). A good reinforcement protection can be achieved with adequate concrete quality and cover depth, depending on the exposure conditions. The expected carbonation depth in natural conditions directly influences the concrete cover depth required for the design service life.

There are several ways to predict the carbonation depth over time (natural carbonation test, a wide range of prediction models), but the probabilistic approach suggested in *fib*-Bulletin 34

(2006) is the most widely used. Service life is defined through limit state function for carbonation induced reinforcement depassivation:

$$g\left(c, x_c(t)\right) = c - x_c(t) = c - \sqrt{2 \cdot k_e \cdot k_c \cdot \left(k_t \cdot R_{ACC}^{-1} + \varepsilon_t\right) \cdot C_s \cdot t} \cdot W(t) \tag{1}$$

where,

c concrete cover (mm),

$x_c(t)$ carbonation depth at the time t (mm),

k_e environmental function (-),

k_c execution transfer parameter (-),

k_t regression parameter (-),

ε_t error term ((mm^2/year)/(kg/m^3)),

R^{-1}_{ACC} inverse effective carbonation resistance of concrete ((mm^2/year)/(kg/m^3)),

C_s CO_2 concentration (kg/m^3),

$W(t)$ weather function (-).

For carbonation depth calculation, *fib*-Bulletin 34 (2006) model takes into account the macro-climate conditions, curing conditions and concrete properties. The impact of environmental conditions is represented by two parameters: k_e representing the influence of relative humidity and W(t) representing the influence of atmospheric precipitation. Taking into account that in this study the indoor concrete members were considered, the value of the parameter W(t) was adopted as 1. The environmental function parameter (k_e) is defined as:

$$k_e = \left(\frac{1-\left(RH_{real}/100\right)^{f_c}}{1-\left(RH_{ref}/100\right)^{f_c}} \right)^{g_c} \tag{2}$$

where,

RH_{real} environment relative humidity (%),

RH_{ref} referent relative humidity (%),

f_c exponent (–),

g_c exponent (–).

Execution transfer parameter (k_c) takes into account concrete curing conditions:

$$k_{cur} = \left(\frac{t_c}{7}\right)^{b_c} \quad (3)$$

where,

t_c period of curing (days),

b_c regression exponent (-).

The curing period (t_c) of 7 days was adopted because it is assumed that this is the standard time of curing on site, as well as the time defined in *fib*-Bulletin 34 (2006) required for the accelerated carbonation test.

Parameters k_t and ε_t represent the relationship between natural and accelerated carbonation resistance and they differ for different concrete mixtures. Values of these parameters for CC are defined in *fib*-Bulletin 34 (2006) while for HVFAC values proposed in (Carević et al., 2019) were used in this study. The only parameter that represents the concrete quality is the inverse effective carbonation resistance (R^{-1}_{ACC}), which is determined based on accelerated carbonation tests:

$$R^{-1}_{ACC} = \left(\frac{x_c}{\sqrt{2 \cdot C_s \cdot t}}\right)^2 \quad (4)$$

where

x_c accelerated carbonation depth (mm),

C_s CO_2 concentration (kg/m^3),

t test duration (s).

In order to analyze the impact of concrete type and compressive strength, it is necessary to establish a relationship between R^{-1}_{ACC} and 28 days concrete's compressive strength (f_{cm}). To establish this relationship, a database of available accelerated carbonation test results for CC and HVFAC was formed. This database contained results from 15 studies for CC (Atis, 2003; Bouzoubaâ et al., 2010; Bucher et al., 2017; Carević et al., 2019; Dhir et al., 2007; Durán-Herrera et al., 2015; Jiang et al., 2000; Katz, 2003; Khunthongkeaw et al., 2006; Kuosa et al., 2008; Leemann and Moro, 2017; Ohga and Nagataki, 1989; Pedro et al., 2015; Ribeiro et al., 2009; Shah and Bishnoi, 2018) and 8 studies for HVFAC (Atis, 2003; Bentur and Jaegermann, 1991; Bouzoubaâ et al., 2010; Carević et al., 2019; Ignjatović et al., 2017b; Jia et al., 2012; Jiang et al., 2000; Ribeiro et al., 2003). A total of 115 carbonation depth measurements for CC and 59 for HVFAC were collected for samples with compressive strength ranging from 11.5 to 67.0 MPa (measured on a standard cylinder sample Ø150·300 mm). The relationship between R^{-1}_{ACC} and f_{cm} for CC and HVFAC is presented in Figure 2.

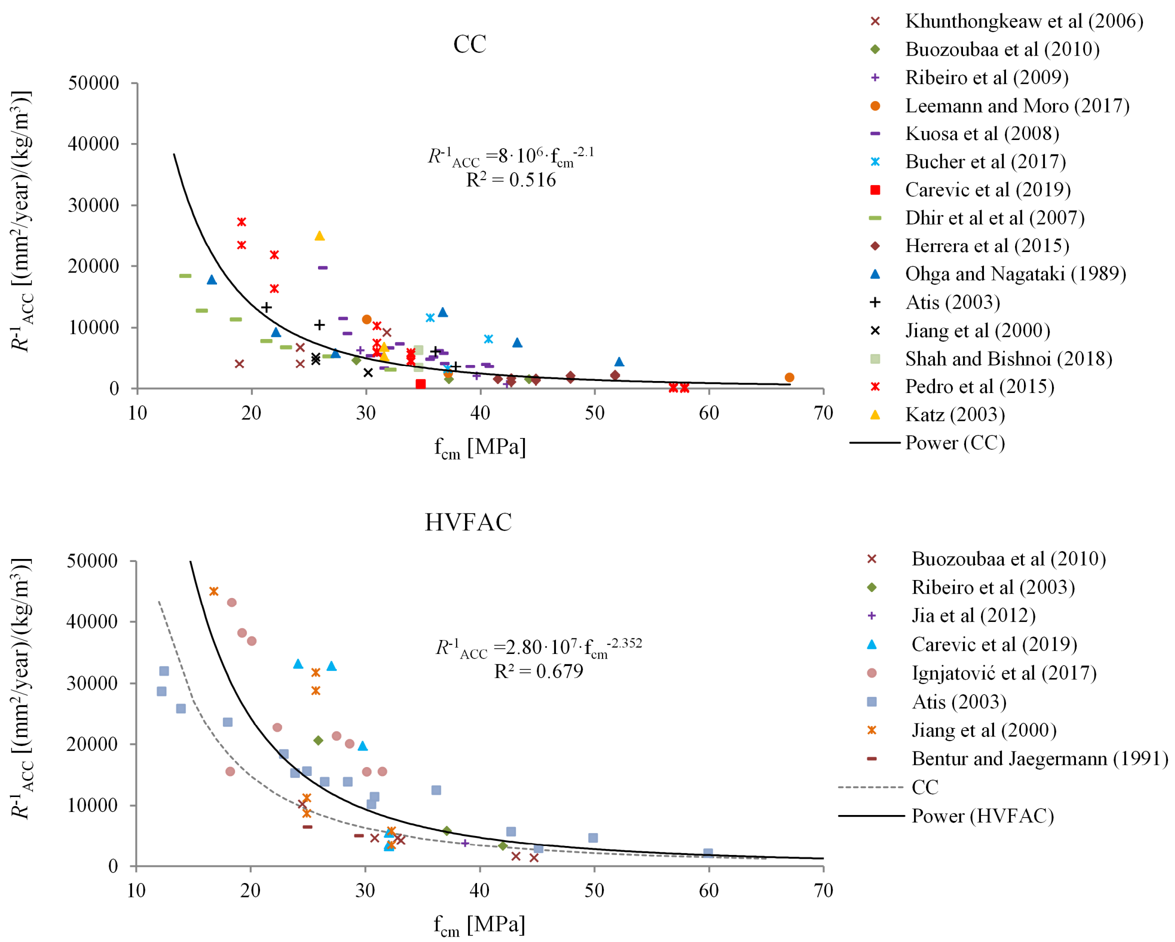

Figure 2. The relationship between inverse effective carbonation resistance and 28 days concrete's compressive strength for CC and HVFAC

For both types of concrete power regression function was used, which is in agreement with the research of other authors (Silva et al., 2015). Coefficient of determination of 0.516 and 0.679 were achieved for CC and HVFAC mixtures, respectively. As expected, HVFAC has a lower carbonation resistance compared to CC with same compressive strength. However, as compressive strength increases, the differences between CC an HVFAC are reduced. In further analysis the relationships proposed for CC and HVFAC and shown in Figure 2 will be used for the calculation of R^{-1}_{ACC}.

4.2 Service life prediction

After establishing these relationships, a prediction of the carbonation depth and the service life based on concrete compressive strength can be made using Eq. (1). Since Eq. (1) represents a probabilistic approach, the input parameters of the model should be stochastic variables. Distributions and characteristic parameters for some variables (f_c, g_c, RH_{ref}, t_c, b_c, C_s, k_t and ε_t) are given in *fib*-Bulletin 34 (2006) **for CC and in (Carević and Ignjatović, 2020) for HVFAC.** An overview of the applied distributions and their characteristic parameters is shown in Table 1.

The result of the limit state function is the probability of an event occurring, which in this case means probability that the carbonation depth will be equal to the concrete cover depth. The acceptable probability of failure according to *fib*-Bulletin 34 (2006) is 0.10, which corresponds to a reliability index (β) of 1.3. The reliability index of limit state function was calculated using the *First Order Reability Method* (FORM). **The results of this analysis, which serve as input for LCA, are presented in Figures 3 and 4.**

Table 1. Input parameters of the limit state function for service life prediction

Parameter		Distribution	μ	σ	Unit
RH_{real}		Beta	65 (40*)	10 (100*)	%
RH_{ref}		Constant	65	–	%
f_c		Constant	5.0	–	–
g_c		Constant	2.5	–	–
t_c		Constant	7	–	days
b_c		Normal	–0.567	0.024	–
C_s		Normal	0.0008	0.0001	kg/m^3
t		Constant	1÷100	–	year
k_t	CC	Normal	1.25	0.35	–
	HVFAC	Normal	3.05	0.85	–
ε_t	CC	Normal	315.5	48	(mm^2/year)/(kg/m^3)
	HVFAC	Normal	16264	2440	(mm^2/ year)/(kg/m^3)
R^{-1}_{ACC}		Normal	Fig. 2	CoV 10%	(mm^2/ year)/(kg/m^3)

* Lower and upper limit of the beta distribution

The relationship between calculated carbonation depth (x_c) and f_{cm} for CC and HVFAC mixtures is shown in Figure 3. With increasing compressive strength, the carbonation depth decreases. For the same compressive strength CC has lower carbonation depth for more than two times compared to HVFAC. As a consequence, a higher concrete cover depth for HVFAC is required to achieve the same service life as CC. On the other hand, if the same concrete cover depth was used for both types of concrete, the service life of HVFAC would be more than four times smaller compared to CC (Figure 4).

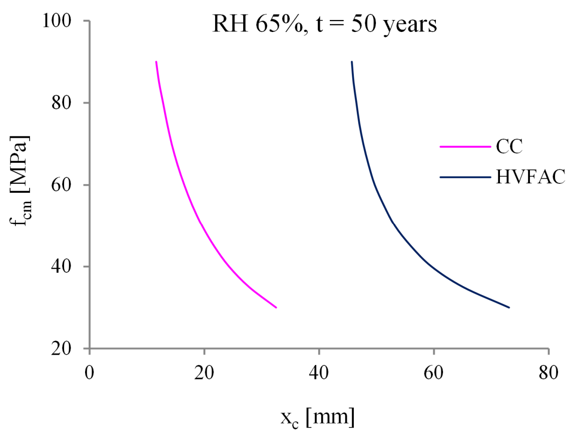

Figure 3. The relationship between carbonation depth and compressive strength of CC and HVFAC for RH 65% and t=50 years

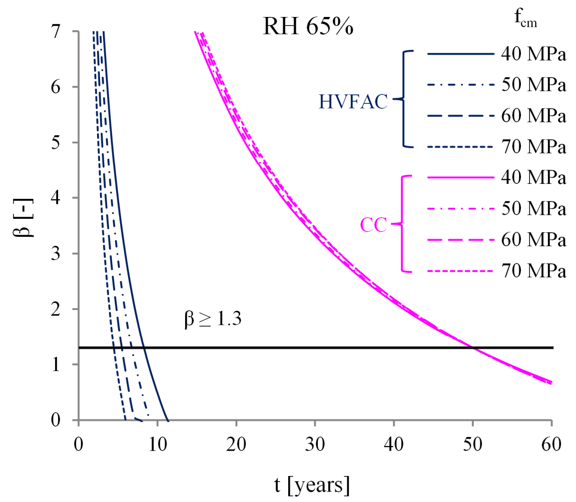

Figure 4. Reliability index β during time of exposure for CC and HVFAC

5. LCA model

LCA analysis was performed with a goal of calculating the environmental impacts of RC slab and RC beam made of different CC and HVFAC concrete mixes, taking into account two approaches to modeling of service life. Impacts were calculated for 43 CC and 51 HVFAC mixes, collected from previous research and compiled in databases. Impact category indicators were normalized with concrete compressive strength and duration of service life for different concrete mixtures and RC member types, and expressed as functions of compressive strength applying regression analyses.

5.1 System boundaries

The analysis was performed for the production stage of the concrete structure life cycle. System boundaries were chosen in accordance with the attributional LCI modeling approach and shown in Figure 5. Impacts of the plasticizer production were neglected since its mass was lower than 0.15 % of the concrete mass. Production of reinforcement was also excluded under the assumption that the amount of reinforcement was equal in all compared alternatives, which is required for the same flexural strength of RC members. Impacts from transport to construction site and construction itself were assumed to be equal and therefore excluded from comparison.

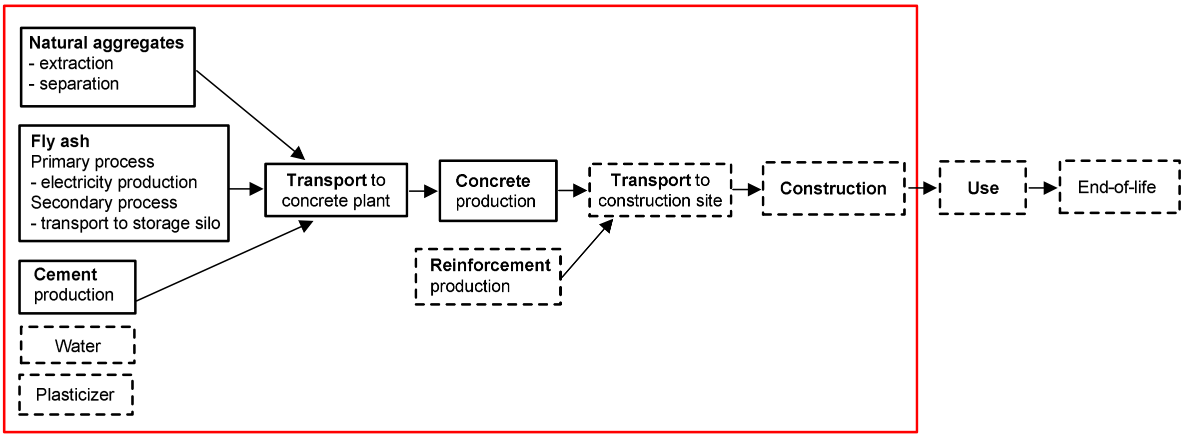

Figure 5. Analyzed part of the concrete structure life cycle

5.2 Functional unit

An RC slab with effective depth equal to 0.15 m and an RC beam with effective depth equal to 0.50 m and width equal to 0.30 m were assumed as typical structural members of residential and commercial buildings structures. Depth of concrete cover required for service life of 50 years and indoor environment with relative humidity equal to 65% was calculated for each CC and HVFAC mixture (Figure 3). One square meter of RC slab and one linear meter of RC beam were taken as FUs.

In the approach B (Figure 1) for achieving the same service life of 50 years, volume of concrete in FU differed, depending on the type of concrete mixture (CC or HVFAC). Total height of CC slab's cross section varied from 0.1723 m to 0.1829 m while total height of HVFAC slab' cross section varied from 0.2087 m to 0.2189 m, depending on the mean compressive strength. Similarly, total height of CC beam's cross section varied from 0.5333 m to 0.5438 m while total height of HVFAC beam's cross section varied from 0.5697 m to 0.5799 m, depending on the mean compressive strength. Larger concrete cover and consequently, larger total height of cross section was required for HVFAC than for CC member due to much lower carbonation resistance of HVFAC. However, the volume increase in the slab case was 20.4% on average while only 7.3% in the beam case.

In the approach A, the concrete cover depth required for service life of 50 years of CC slab/beam was adopted for HVFAC slab/beam. Consequently, the FU for both CC and HVFAC slab/beam had the same volume of concrete. However, service life of HVFAC slab/beam with such concrete cover was much lower than 50 years – calculated values varied between 4.5 and 8.6 years, Figure 4. Impact category indicators in this approach must be calculated per year of service life. To enable comparison between approaches A and B, category indicators calculated according to approach B were also divided by duration of service life (in this case 50 years for all alternatives).

5.3 Life cycle inventory

The intention was to perform LCA in the European context. All Life cycle inventory (LCI) data were taken as average European data, mostly from the Ecoinvent database (Dones et al., 2007; Kellenberger et al., 2007; Spielmann et al., 2007) or from European organizations, with the exception of the FA LCI data. It is very hard to define average data for FA production and economic allocation – they depend on the particular coal-burning plant technology and cost of FA and electricity, which differ significantly between European countries. So, Serbian site-specific data for FA production and allocation were used instead. It was calculated that the difference in revenue from electricity and FA was over 25%, in which case economic allocation should be applied (CEN, 2016). Hence, economic allocation, based on the market prices of FA and electricity, was applied (Marinkovic et al., 2017).

Information about LCI sources is summarized in Table 2. **Detailed information on inputs, outputs and resources use for each considered process per unit (kg, m^3 and MJ) and**

quantities of all elementary flows per FU and each concrete mixture are provided in Supplementary.

Transport distances were estimated as 100 km (and doubled to account for the return trip) for all concrete components and presented in Table 3. For all concrete mixes, it was assumed that river NA (sand and round gravel) is transported by barge, while crushed NA (sand and crushed gravel) is transported by trucks as is cement and FA.

Table 2. Sources of LCI data

Type of data	Source (process name in Ecoinvent V2.0)	Geography
Energy		
Diesel production, distribution, and usage	Ecoinvent (diesel, at regional storage/kg/RER) (diesel, burned in building machine/MJ/GLO)	EU average
Electricity	Ecoinvent (production mix RER/kWh/RER)	EU average
Concrete components		
Cement production	CEMBUREAU (the European Cement Association) EPDs for CEMI and CEMII	EU average
Fine and coarse aggregate production	Ecoinvent (gravel, round, at mine /kg/CH) (gravel, crushed, at mine /kg/CH)	estimated as EU average
FA production	Industry	Serbia
Concrete		
Concrete production	Ecoinvent (concrete, normal, at plant/m^3/CH)	estimated as EU average
Transport		
Road and river	Ecoinvent (transport, lorry 16–32t, EURO5/tkm/RER) (transport, barge/tkm/RER)	EU average

Table 3. Transport distances and types

Material	Route		Transport distance (km)	Transport type
	From	To		
Cement	Cement plant	Concrete plant	100 x 2	Truck 16–32 t
River NA	Place of extraction	Concrete plant	100 x 2	Barge 10000 t
Crushed NA	Place of extraction	Concrete plant	100 x 2	Truck 16–32 t
FA	Power plant	Concrete plant	100 x 2	Truck 16–32 t

5.4 Life cycle impact assessment

The problem-oriented (mid-points) methodology was chosen for the impact assessment. In the damage-oriented approaches (such as for instance Ecoindicator, ReCiPe, etc.), it is not possible to avoid normalization, grouping and weighting. Weighting is not a scientifically based operation, but it relays upon the opinion and attitude of experts towards different environmental effects. On the other hand, the relationship between midpoint category indicators and LCI results is easily established through appropriate, scientifically based, characterization models.

If the use phase is excluded, the most significant emissions in the course of a concrete structure's life cycle originate from cement production and transport: green-house gasses (carbon dioxide, methane, and nitrogen dioxide), sulphur dioxide, nitrogen oxide and non-methane volatile organic compounds (NMVOC). Relevant midpoint impact categories related to these emissions are climate change, acidification, eutrophication, and photochemical-oxidant creation (Marinković, 2013). Beside them, energy consumption and especially fossil fuels consumption are of interest when assessing concrete structures. Therefore, the impact category indicators calculated in this work were global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), and photochemical-oxidant creation potential (POCP). They were calculated using the characterization models within baseline CML methodology (Guinée et al., 2002) which is most commonly used.

Beside these, abiotic depletion of fossil fuels potential (ADPFF) was calculated using the cumulative energy demand method. For the ADPFF calculations, the following heating values of fossil fuels were used: 42.0 MJ/kg for diesel, 19.1 MJ/kg and 8.8 MJ/kg for hard and soft coal respectively, and 39.0 MJ/m^3 for natural gas. For life cycle inventory and life cycle impact calculations, original Excel-based software was used.

5.5 CO_2 uptake

Due to carbonation, certain amount of CO_2 will be reabsorbed or taken up by the concrete structure over its life cycle. This process has been investigated a lot as an aspect of concrete durability, but it was rarely taken into account when assessing CO_2 emissions in course of the life cycle of concrete structures (Garcia-Segura et al., 2014).

To assess the CO_2 uptake, it is necessary to consider the use and end-of-life phase of the life cycle of the concrete structure. The CO_2 uptake generally depends on the earlier uptake during service life, exposure conditions and time perspective as well as on the size of debris pieces. For instance, if concrete waste is crushed and temporarily stockpiled for a new application the exposure time is limited. If it is landfilled, the exposure time is much longer – it is not limited and concrete will eventually fully carbonate. For a very long time perspective, maximum total potential CO_2 uptake (for all life cycle phases) is estimated as 75% of the maximum clinker uptake (CEN, 2016). For CEM I concrete, this theoretical maximum CO_2 uptake is about 0.37 kg CO_2/ kg cement. This amount obviously affects the GWP indicator calculated for the whole life cycle of the concrete structure.

In this work the CO_2 uptake impact was not taken into account since the whole life cycle must be considered and many assumptions regarding the CO_2 uptake potentials for different concrete mixtures, service and end-of-life phase scenarios and eventual post-use applications must be made. While this is acceptable for the purposes of this comparative study, the influence of CO_2 uptake over the whole life cycle should not be neglected in the sustainability design of concrete structures.

5.5 Uncertainty in LCA

According to Huijbregts (1998) three types of uncertainty can be distinguished within LCA. First one is parameter uncertainty caused by the imprecise, incomplete, outdated

or missing values of LCI data. The second is model uncertainty, for instance adoption of linear models instead of non-linear for environmental phenomena modeling. The third is uncertainty due to choices such as, for instance, choice on system boundaries (which upstream and downstream flows are included), methodological choices (attributional or consequential modeling), choice of FU, allocation approaches, etc.

Generally, the parameter uncertainty can be dealt with using simplified approach which includes a qualitative assessment of data quality indicators based on a pedigree matrix (Weidema & Wesnaes, 1996). Then uncertainty factors are attributed to each of the quality indicator depending on their scores (1-5) and the square of geometric standard deviation can be calculated for assumed probability function for each elementary flow. Such procedure is applied in Ecoinvent database where uncertainty factors based on expert judgments are used (Frischknecht et al., 2007). The uncertainty estimations on the level of a unit process are then obtained using Monte Carlo simulation. Monte Carlo analysis is a probabilistic model parameter uncertainty analysis which requires distribution functions for each elementary flow or unit process. However, it is stated in this report that "the reliability of the mean values of the unit process raw data is judged to be much higher as compared to the roughly estimated geometric standard deviation", which has to be used for probability function definition and Monte Carlo simulations. Maybe more transparent way to test the uncertainty, especially uncertainty due to choices, is to perform the sensitivity analysis on the main influencing parameters/choices. It means that impact assessment is performed for chosen parameter varied within "realistic" limits and the interval of impact result is obtained instead of one value. This procedure is commonly used for testing the effect of transportation distances and types but also it can be used for testing the effect of the service life model (Vieira et al., 2018, Van den Heede et al., 2017).

In this work the parameter uncertainty of LCI data was not tested and sensitivity analysis regarding transport distances or service life model was not performed. The rational behind these choices is as following.

Majority of LCI data was taken from Ecoinvent data base. Rather wide geography (Europe) was chosen because the goal of the study was a methodological issue, not a comparison between two or more products. Two unit processes that practically determine the chosen impacts are cement production and transportation. Since the contribution of aggregate, concrete and fly ash production is low, usually below 5% each (referenca dodati Eco efficient construction and building materials), the uncertainties regarding the quality of data don't affect the results significantly (not for more than few percents). Cement production technology is today very similar throughout Europe and therefore impact category indicators data from the largest European Cement Association CEMBUREAU EPD's were considered as representative in all aspects for Europe.

Transportation is the second largest source of impacts, but still much lower than cement production in the European context. However, it is not logical to assume that cement, aggregate and fly ash distances differ for two compared alternatives – both structures are constructed at the same construction site and supplied from the same concrete plant. Transportation distances and types other than those assumed will influence both alternatives' impacts in the same way. So, sensitivity analysis regarding transport distances was not performed since the goal of the study was to establish the effect of different service life modeling in comparative LCA and not to calculate the absolute values of impact indicators.

What however may introduce relatively large uncertainties (if FU is defined in relation to service life and compressive strength) is service life prediction model and relationship between mixture proportions and compressive strength of concrete.

Service life prediction in this work is based on a full probabilistic approach where each parameter is introduced with its estimated distribution function. The calculation of service life is performed for the assumed failure probability equal to 0.1 or reliability index equal to 1.3 which is usually requested regarding service life design of concrete structures. Uncertainties regarding relationship between mixture proportions and compressive strength of concrete are taken into account by applying the statistical regression analysis on a database of 43 CC and 51 HVFAC mixtures.

6. Results and discussion

For each CC and HVFAC mixture from databases, impact assessment of the concrete structure production part of the life cycle was performed two times: once with the same volume of FU (Approach A) and once with corrected volume of FU (Approach B). Calculated impact category indicators of CC slab/beam and HVAC slab/beam were normalized relative to their service lives (t_{sl}) and mean compressive strength at 28-days (f_{cm}) and plotted against it. Regression analysis was performed and functions which best fitted the experimental results (with the highest determination coefficient R^2) were selected. Results for Approach B are presented in Figures 6–10.

A trend of decreasing indicator values with increasing compressive strength is clear for all indicators and both concrete mixtures. This means that the effect of compressive strength on indicator values outweighs the effect of the larger cement content needed for the larger strength.

As already stated, the FU volume increase in the HVFAC slab was 20.4% on average while only 7.3% in the HVFAC beam (compared to CC slab and beam, respectively). Despite the larger volume of FU, HVFAC mixtures have lower values of all indicators for both slabs and beams. Significant decrease of cement content ranging between 40% and

60% in analyzed HVFAC mixtures causes such results since cement production is by far the largest contributor to all indicators. Fly ash was considered as a by-product and its contribution consisted of the environmental load allocated from the electricity production and the environmental load from its own treatment prior to the utilization in concrete. The economic allocation coefficient calculated for Serbian market prices was equal to 0.013 (Marinkovic et al., 2017) and all together contribution of the FA production to category indicators was below 5%. Similarly, contribution of concrete and aggregate production was around 5% each, while transport contribution depended on the category indicator: 10-15% of GWP and 30-35% of ADPFF, EP, AP, and POCP originated from transport emissions and resources use.

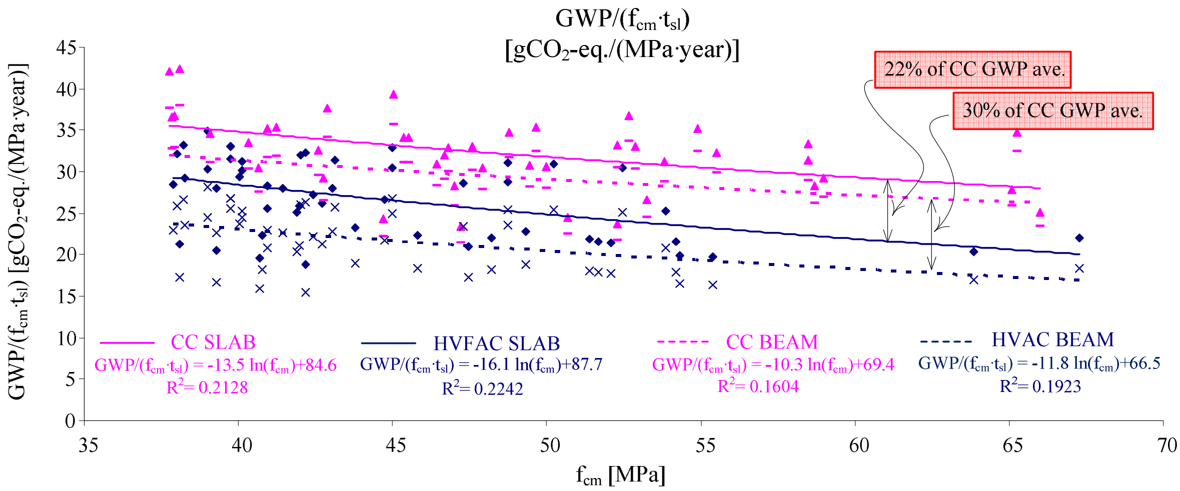

Figure 6. Normalized GWP of CC slab/beam and HVFAC slab/beam per FU – Approach B

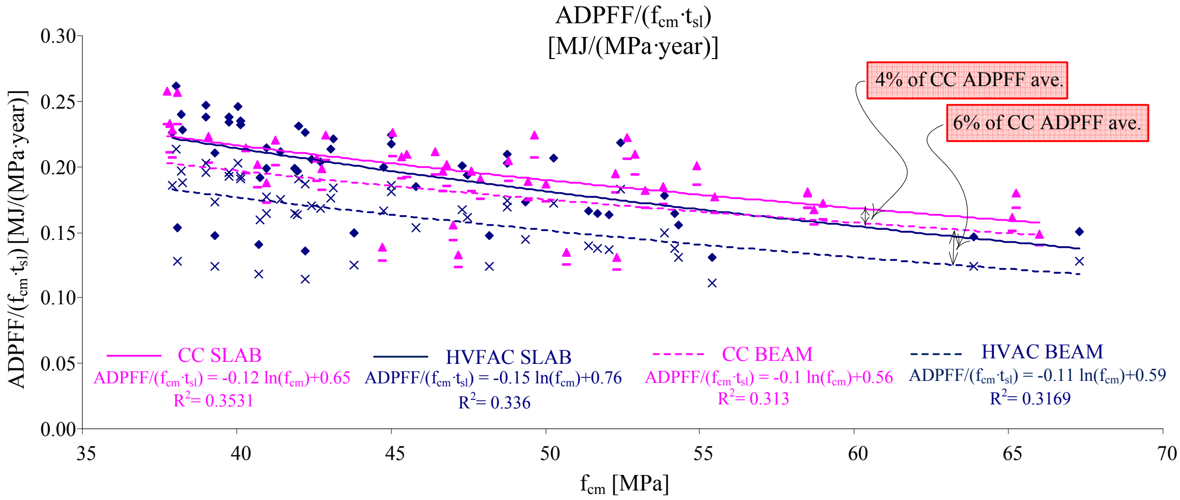

Figure 7. Normalized ADPFF of CC slab/beam and HVFAC slab/beam per FU – Approach B

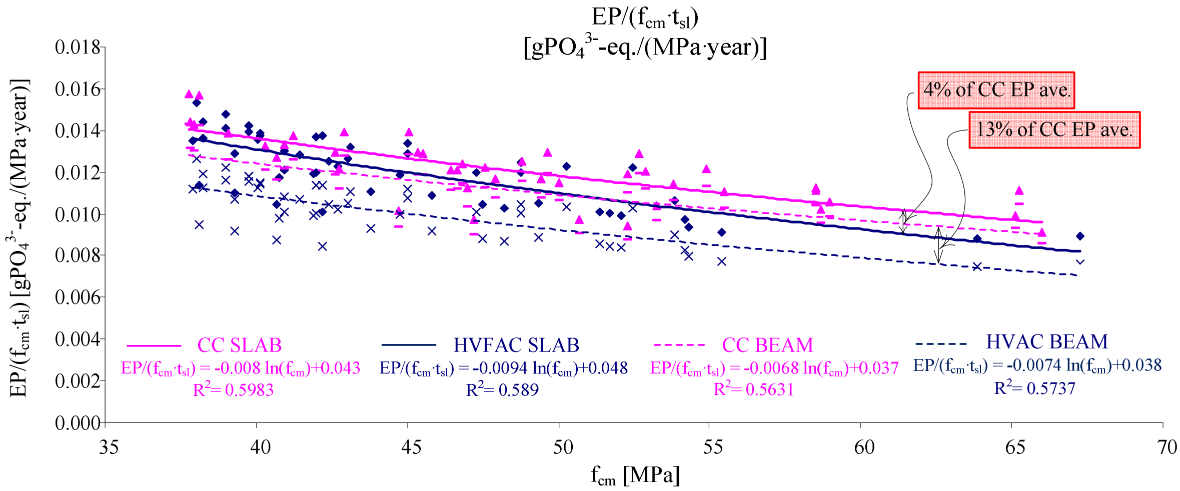

Figure 8. Normalized EP of CC slab/beam and HVFAC slab/beam per FU – Approach B

However, the effect of service life is more pronounced for slabs than for beams. For instance, normalized GWP of HVFAC slab is lower for 22% on average, while GWP of HVFAC beam is lower for 30% on average compared to CC slab and CC beam, respectively. Although LCA was performed for same CC and HVFAC mixtures in both cases, the volume increase in the HVFAC slab FU relative to CC slab FU, is larger than in the beam's case. **This is expected since concrete cover makes larger part of the unit volume in the slab's case than in the beam's case.** So, if Approach B is applied, the effect of service life in LCA depends on the size and type of a structural member.

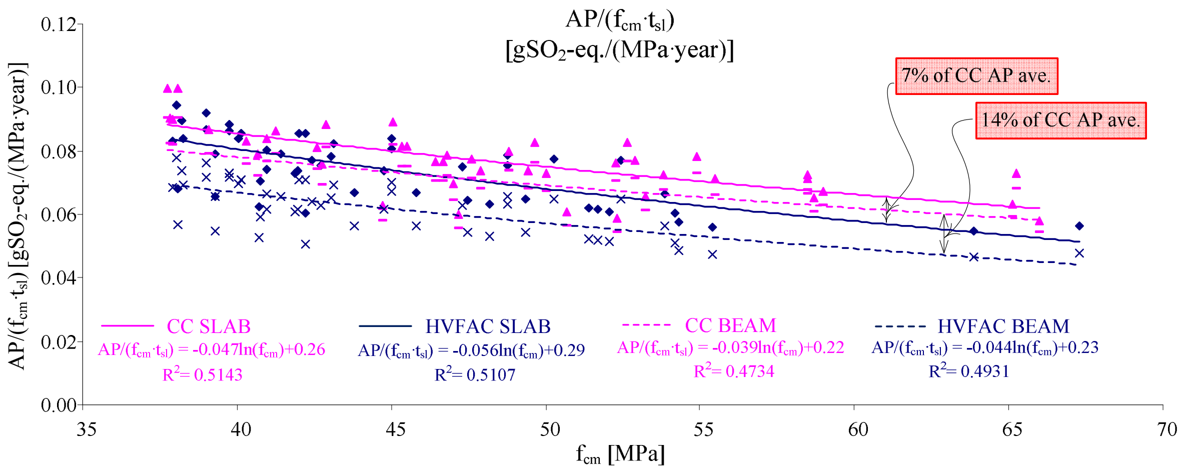

Figure 9. Normalized AP of CC slab/beam and HVFAC slab/beam per FU – Approach B

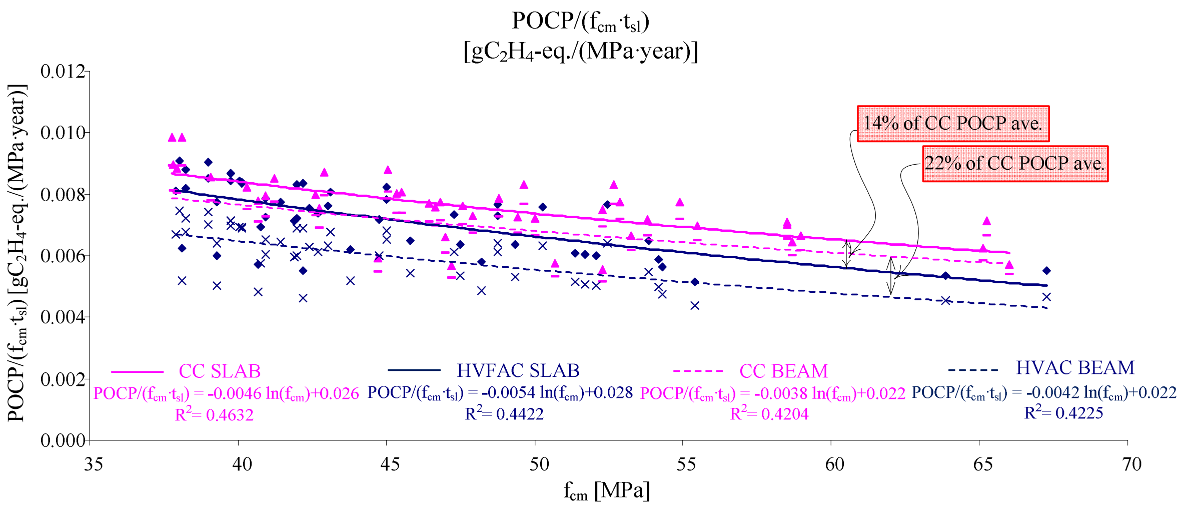

Figure 10. Normalized POCP of CC slab/beam and HVFAC slab/beam per FU – Approach B

Results for normalized GWP of slab and beam when applying Approach A are shown in Figures 11 and 12. For the sake of comparison, obtained results for Approach B are also shown in these Figures.

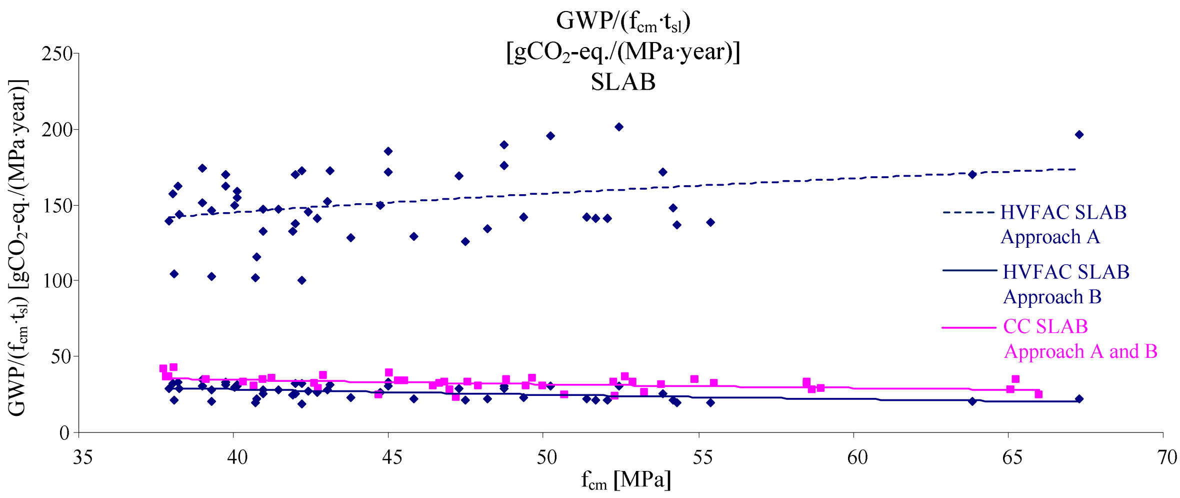

Figure 11. Normalized GWP of CC and HVFAC slab per FU – Approach A and B

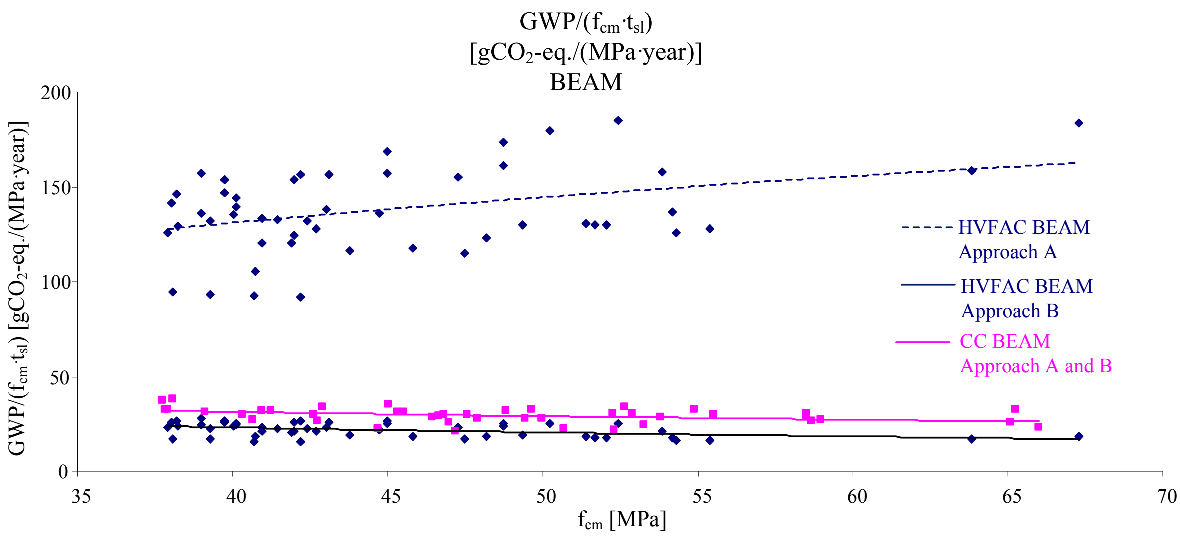

Figure 12. Normalized GWP of CC and HVFAC beam per FU – Approach A and B

Similar results were obtained for other impact category indicators. Values of the normalized indicators for CC slab/beam are equal regardless of the approach due to the methodology applied in this study. However, normalized GWP for HVFAC slab is 6.5 times larger on average in Approach A than in Approach B, although it was calculated for same HVFAC mix proportions. In the beam's case this ratio is even larger: 7.1 on average. This is the consequence of very short service lives obtained for the HVFAC alternatives, if the concrete cover depth is assumed equal to required value for CC alternatives and service life of 50 years.

It is more than obvious that Approach B is favorable for service life modeling of green concretes which have poorer durability properties compared to CC. However, it should be kept in mind that the volume of concrete required for the same structural performance in this approach is larger for HVFAC alternatives: for 20.4% / 7.3 % on average in the slab/beam case, respectively.

Results of comparison with other published results are presented in Table 4. Among the published research, papers in which compared alternatives had significantly different service lives were chosen for comparison with own results. In all cases, deterioration mechanism was chloride attack (favorable for green concrete alternative), Approach A was applied and several green alternatives (different replacement ratios of fly ash or slag, but one mix design per alternative) were compared with referent, conventional cement concrete. Only one impact category indicator was chosen for comparison – GWP, except for the work of Vieira et al. (2018) where a single score expressed in points (Pt) obtained with ReCiPe methodology was used. Although Vieira et al. (2018) reported also results for midpoint categories including GWP, it was not clear to authors for which FU these results were obtained. In Van den Heede et al. (2017) GWP was calculated for FU which included volume, and for FU which included volume, strength and service life. To eliminate the impact of compressive strength, from all analyzed alternatives in their work, only concretes with same compressive strength were chosen.

Table 4. Comparison with published research

Author	Environ. impact (EI) (mechanism) (1)	Concrete mixture (2)	Durability property (DP) (3)	Service life (SL) (4)	EI(GC)/EI(CC) FU1[1] average values (5)	EI(GC)/EI(CC) FU2[2] average values (6)	(5)/(6)
Panesar et al. (2017)	GWP (chloride ingress)	cement concrete (CC[3])	28-day rapid chloride permeability (3186 C)	/	0.65	0.09	7.2
		25% of cement replaced with slag and 8% of silica fume (GC[4])	28-day rapid chloride permeability (421 C)	/			
Vieira et al. (2018)	Pt[5] (chloride ingress)	cement concrete (CC)	/	8.4 years	1.07	0.30	3.6
		40% of cement replaced with fly ash (GC)	/	29.1 years			
Van den Heede et al. (2017)	GWP (chloride ingress)	cement concrete (CC)	/	32 years	0.98 (approx.)	0.29 (approx.)	3.4
		15% of cement replaced with fly ash (GC)	/	100 years for FU calculation			
this work	GWP (carbonation)	cement concrete (CC)	/	50 years	/	3.6-9.7 (slab, Approach A)	/
		40%-60% of cement replaced with fly ash (GC)	/	4.5-8.6 years			

[1]FU1 (includes volume and strength)
[2]FU2 (includes volume, strength, and SL or DP)
[3] conventional cement concrete alternative
[4] green concrete alternative
[5] single score including damage to human health, ecosystems, and resources

It can be seen from Table 4 that including the service life into FU significantly changed the impact assessment result expressed as ratio between GC and CC impact, for 3.4 to 7.5 times. In this work the FU including volume and strength was not tested so only the result in column (6) is reported. However, results are similar having in mind that in this work green concrete alternative has poorer durability related behavior – if expressed as ratio EI(CC)/EI(GC), result in column (6) for this work would be 0.10 – 0.28 which is very similar to results of other researchers.

Results shown in Figures 6-12 clearly demonstrate large scatter (R^2 ranges between 0.1604 and 0.5983, where the correlation coefficient R represents the degree of correlation between two variables) especially for the GWP which is most influenced by the cement amount. For the same compressive strength calculated impacts vary a lot both for CC and HVFAC for the reasons explained in Chapter 3. Standard deviation and coefficient of variance (CoV) of GWP prediction (Approach B, slab) are calculated for several strength intervals (38-45 MPa, 45-50 MPa and 50-55 MPa) for both CC and HVFAC and presented in Table 5.

Table 5. **$GWP/(f_{cm} \cdot t_{sl})$, Approach B, slab**

Compressive strength f_{cm}		CC	HVFAC
38-45 MPa	average (gCO_2-eq./(MPa·year))	34.7	28.0
	standard deviation (gCO_2-eq./(MPa·year))	4.72	4.53
	coefficient of variance (%)	13.6	16.2
45-50 MPa	average (gCO_2-eq./(MPa·year))	32.5	27.1
	standard deviation (gCO_2-eq./(MPa·year))	3.99	4.32
	coefficient of variance (%)	12.3	15.9
50-55 MPa	average (gCO_2-eq./(MPa·year))	30.7	23.7
	standard deviation (gCO_2-eq./(MPa·year))	4.18	4.05
	coefficient of variance (%)	13.6	17.1

The uncertainty expressed through standard deviation or coefficient of variance is rather large, larger for HVFAC (CoV ranges between 15.9% and 17.1%) than for CC concrete (CoV ranges between 12.3% and 13.6%). This analysis shows that compressive strength

dependence on the mix design introduces similar, maybe even larger uncertainty than that brought by the LCI environmental data uncertainty if Monte Carlo simulation is performed (see for instance Van den Heede et al. (2017)). All together, this level of uncertainty cannot jeopardize the conclusions' validity since Approaches A and B lead to impacts which values differ for an order of magnitude.

7. Conclusions

In comparative LCA of reinforced concrete structures, it is necessary that compared alternatives fulfill all relevant functional requirements of the concrete structure (safety, serviceability and durability). Since conventional and green concretes have different mechanical and durability related properties, this goal can be achieved either by correcting the volume of FU (Approach B) or by normalizing the calculated impact indicators with compressive strength and duration of service life (Approach A).

In this work both approaches were tested to show how different modeling of service life in LCA affects the environmental impacts of different RC structural members. Two concrete mixes, CC and HVFAC, and one deterioration mechanism - carbonation, were chosen for this demonstration. For two types of structural members, slab and beam, relationships between the chosen normalized impact category indicators and compressive strength were derived. They were developed using a number of experimental results reported in literature regarding the mixture proportions and properties of the mentioned concrete mixes. Regression analyses were applied to the obtained LCA results concerning normalized GWP, ADPFF, EP, AP, and POCP indicators and best-fitting equations relating normalized indicators and concrete compressive strength were selected. Finally, comparison of the results obtained according to these two approaches was performed.

For service life modeling in the case of carbonation a *fib*-Bulletin 34 (2006) model was applied with missing required parameters for HVFAC mixtures adopted according to (Carević et al., 2019). The relationships between inverse effective carbonation resistance and compressive strength for both concrete mixtures were derived on the basis of test results from literature applying regression analysis. Following conclusions are drawn.

1. Results obtained using developed service life prediction model showed that HVFAC mixtures had much lower carbonation resistance compared to CC mixtures. Consequently, for the same depth of concrete cover, RC member made of HVFAC had much shorter service life (6 to 11 times, depending on the compressive strength) than RC member made of CC.

2. LCA was performed on a relatively large number of mixes (43 CC and 51 HVFAC) with a very broad range of involved parameters which caused a high scatter of results. **The uncertainty regarding the relationship between mixture proportions and compressive strength of concrete was assessed. The parameter uncertainty was not assessed which is a limitation of the work. It was considered that this fact did not have a significant effect on the conclusions in this study having in mind its goal and range of obtained results.**

3. If Approach A is applied (same volume of FU) all normalized impact indicators of HVFAC mixtures, for both slabs and beams, were much larger than those of CC mixtures. Depending on the impact indicator and compressive strength this increase ranges between 5 and 8, which is almost an order of magnitude. This is a consequence of a much lower carbonation resistance (shorter service life) of HVFAC compared to that of CC.

4. If Approach B is applied (different volume of FU) all normalized impact indicators of HVFAC mixtures, for both slabs and beams, were lower than those of CC mixtures. This decrease ranges between 4% and 30% depending on the impact indicator and compressive strength. In this specific case, the volume increase in the slab FU was 20.4% on average while

only 7.3% in the beam FU; because of that, the effect of service life was more pronounced for slabs than for beams.

5. Different modeling of service life in LCA of concrete structures can result in totally different - opposite conclusions. With slightly larger volume, which of course increases the weight and cost of the structure, calculated normalized impact indicators of HVFAC structural members were lower for an order of magnitude. Rejection of green concretes with poorer durability properties based only on the service life modeling like in Approach A is not justified, because it is possible to achieve equal structural performance to CC performance with slightly larger volume of RC member. **In a word, a caution is recommended when drawing conclusions based only on an Approach A like type of service life modeling in LCA of concrete structures.**

6. Commonly used Approach A is not applicable for the environmental assessment of concrete structures in practice. This is because compared alternatives must fulfill same functional requirements – these are strength, serviceability (deformations mostly) and service life duration in the case of concrete structures. Normally, concrete structure is designed to fulfill them and results of design are different if different concrete mixtures are used (different size dimensions, different reinforcement amount, different concrete cover depth etc.). So, in practice, FU in comparative environmental assessments should be the structure as a whole – in fact there is no other way. For the final choice of "best" alternative, other aspects should also be included (various specific technical aspects regarding for instance the construction, cost etc.) which implies multicriteria optimization as adequate methodology for integrated assessment.

7. Future research in the area of the environmental assessment of concrete structures should be oriented towards developing CO_2 uptake prediction model for different green concretes such as RAC or HVFAC, and for different end-of-life scenarios. This should

enable proper assessment of CO_2 balance over the whole life cycle of a concrete structure. Also, research should be devoted to life cycle integrated assessment of concrete structures taking into account various possible choices on the importance associated to different functional aspects of the concrete structure.

8. Results and conclusions in this work are valid for analyzed concrete mixtures, deterioration mechanism and exposure conditions as well as for types of structural members chosen in demonstration example. They should not be generalized – results of the environmental assessment of a concrete structure depend on the purpose of the construction project, type of the structure and structural members, exposure conditions, and many other factors - it is a case-dependent issue.

Acknowledgements

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