

A framework for the preliminary design of structures and structural interventions taking into account the environmental performance

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Abstract

The huge environmental footprint of the construction industry is a well-known problem. Strong efforts are undertaken in all sectors of this industry to reduce such impact, from the development of innovative cements to the study of selective demolition techniques aimed at reusing structural components. Similar efforts are also undertaken at the institutional level, through the publication of tools for assessing the environmental impact of construction activities, such as the FEMA P-58 vol. 4 in the US or the European framework for sustainable buildings (Level(s)). However, these tools are based on the Bill of Materials (BoM), which is very detailed, and prepared at a relatively late stage of design. There is currently a lack of a framework that can help engineers to select low-impact materials and structural solutions at the preliminary design stage. To overcome this limitation, an innovative approach has been developed, relating the environmental parameters to the mechanical performance of materials rather than their volume or mass. Furthermore, the proposed framework guides the designer to select materials, shapes, and layouts that can minimise the environmental footprint while guaranteeing the required performance levels.

1 Introduction

The building and construction sector is one of the major contributors to climate change, accounting for approximately 21% of global emissions of greenhouse gases, 7% of which is related to the materials used in construction, including steel and concrete [1]. According to the Intergovernmental Panel on Climate Change (IPCC), the emissions associated to the construction of new and upgrading of existing urban infrastructure is expected to add between 8.5 GtCO₂ and 14 GtCO₂ every year up to 2030 [2]. Furthermore, the building sector is also estimated to consume 50% by weight of the materials used in the EU and to be responsible for 30% of the waste generation [3]. To tackle this problem significant efforts are being undertaken across different sectors, from scientific research, to policy makers and industrial actors, including the proposal of a Climate Limit State (CLS) [4], the creation of a database specific to the embodied carbon of construction materials [5], and the definition of methodologies to account for the environmental impact of constructions during design, such as the FEMA P-58-4 [6] and the EU “Level(s)” framework for sustainable buildings [7]. The FEMA P-58 consist in a series of reports which provide a methodology to evaluate the probabilistic performance of buildings subject to seismic action taking into consideration the individual characteristics. This methodology can assess the performance according to different measures, including direct economic losses, potential loss of functionality, and potential casualties. The fourth volume of the series, extends this analysis to the environmental impact associated with earthquake damage. Its application and the comparison of different design solutions allows for the selection of the most environmentally effective one. The Level(s) framework, instead, was developed to specifically target the sustainability performance of residential and office buildings throughout their life cycle. It is organised in three levels: level 1 – addressing the conceptual design and providing a qualitative assessment, level 2 –

intended for the detailed design and construction and providing a quantitative assessment, level 3 – addressing the as-built and in-use performance.

These two design methodologies (FEMA P-58-4 and EU Level(s) at level 2), while different in scope, employ similar strategies for the calculation of the environmental impact, i.e., the Bill of Materials (BoM). While this approach can lead to a relatively accurate estimation of the environmental metrics of interest, it is generally produced at a relatively late stage of the design process, which results in reduced flexibility and/or higher costs to implement different solutions. To enable an earlier consideration of the environmental impacts of different design choices an innovative framework is proposed. This framework is intended to be applied in the very early stages of design (i.e., preliminary design), running in parallel with the decision-making and design processes, and allows for the estimation of the environmental impact of structural members, enabling lower-impact environmental choices before the more restrictive constraints of the later, detailed design phases are introduced.

2 Environmental design framework

The proposed framework covers three stages of the preliminary design phase: material selection stage, where appropriate materials are selected; section design stage, where the cross section of members are designed; and member design stage, where structural members are individually taken into consideration. Each stage provides an estimation of the environmental impact resulting from the design choices, enabling practitioners to make informed decisions during a very early phase and, therefore, agilely shift to less impactful alternatives without incurring in significantly higher costs. A schematic overview of the methodology and its intended application phase can be seen in Fig. 1.

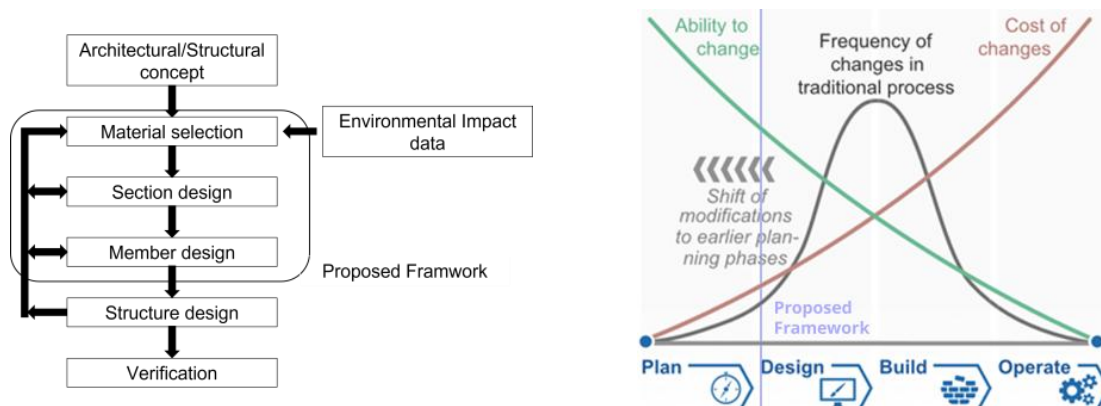


Fig. 1 Schematic depiction of the proposed framework (left) and intended application phase (right, modified from [8])

2.1 Material selection stage

At the material selection stage, the proposed methodology aims at identifying a suitable material for the intended purpose with the least environmental impact. Such impact (generically defined here as O and replaced with the specific acronym when relevant) is measured through common metrics that can be related to specific effects on the environment, such as, for example, Global Warming Potential, Resource Depletion, or Waste Generation. Typically, these metrics are expressed in terms of unit mass (O_m) or unit volume (O_v). While expressing the environmental impact in this manner is very useful in many applications – from the production of Environmental Product Declarations (EPDs) to the calculation of the impact of a structure through the Bill of Materials (BoM) – it does not provide any advantage from a structural performance point of view. To overcome this limitation, the proposed methodology introduces metrics that correlate the environmental impact of the material to its performance (defined as O_p where the subscript P stands for performance) as per (1), where X is the general material characteristics representing its performance.

$$O_p = \frac{O_v}{X} \quad (1)$$

This simple operation can highlight which material has the lowest emission associated with any specific performance and guide a designer towards choices that reduce the overall environmental impact while guaranteeing that the performance requirements are met. As an example, Table 1 and

Fig. 2 show the Global Warming Potential (GWP) per unit volume (GWP_V) for different concrete classes compared to the same emissions expressed in terms of unit design compressive strength (GWP_P). Generic concretes were employed in this work; however, it is important to note that the proposed technique is applicable to any material, provided that the O_V and O_P values are known.

Table 1 GWP for different concrete classes expressed in terms of unit volume (GWP_V) and unit design compressive strength (GWP_P). The data was obtained through the ICE database V3.0 [5] assuming a density of 2300 kg/m³ and a safety coefficient of 1.5

Concrete Class	GWP_V [kgCO ₂ e/m ³]	GWP_P [kgCO ₂ e/kNm]
20/25	257.6	0.019
25/30	273.7	0.016
35/45	342.7	0.015
40/50	365.7	0.014

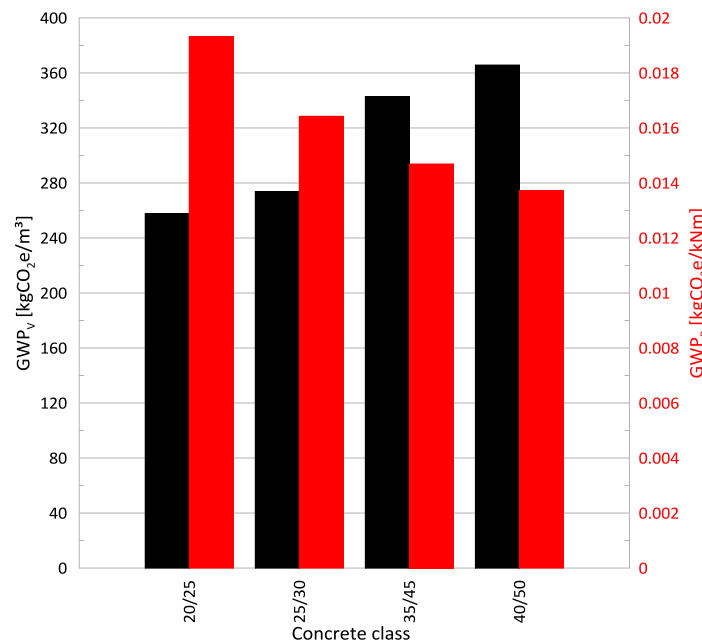


Fig. 2 Comparison of GWP expressed in terms of unit volume (left scale) and unit design compressive strength (right scale).

2.2 Section design stage

Once the first selection of materials has been performed, it is possible to proceed to the design of the cross-section. At this stage a section specific metric is introduced. It can be defined as the impact associated with the unit length of a specific member and can be expressed as:

$$O_S = \sum_{i=1}^n A_i O_{Vi} \quad (2)$$

where A_i and O_{Vi} represent the cross-sectional area and the impact per unit volume of the i -th material, and n is the number of different materials composing the cross-section. This formulation clearly assumes that the materials composing the cross-section extend for the whole length of the structural member. In the case of discontinuous elements, such as, for example, stirrups in RC members, A_i can be calculated assuming an equivalent thickness.

To obtain an acceptable preliminary estimation of the environmental impact, the term A_i should be calculated for the most stressed cross-section as well as considering the minimum requirements prescribed by the national codes.

This parameter, when observed as the sum of the different materials, can offer helpful insights on the efficiency of each of them and, consequently, guide the designer through an optimization process able to reduce both the costs and the environmental impact.

2.3 Member design stage

Lastly, the environmental impacts calculated at the section design stage should be extended to the whole length of the member. A very trivial approach could be to multiply O_S by the length of the element itself. This approach, however, does not provide any further insights that can help reduce the overall impact since, as previously stated, O_S should be calculated for the most stressed cross section. To improve this aspect, the variation of the material volume along the member's axis should be taken into account. This can be done through the introduction of a dimensionless coefficient α_i (i denoting the considered material), representing the ratio between the average material volume needed in the structural member and its maximum. Eq. (2) can therefore be rewritten as follows.

$$O_{S\alpha} = \sum_{i=1}^n \alpha_i A_i O_{Vi} \quad (3)$$

To calculate the coefficient α_i , some assumptions must be made. First of all, it can be inferred that the variation of material along the member can be related to the variation of the generic effect $E_{Ed}(x)$ – i.e., the effect of actions on the structural members (e.g., moment, shear, etc.) as defined in the Eurocode [9] – in the structural member. Secondly, also the minimum code requirements should be taken into account. The following function can then be defined:

$$f(x) = \max(|E_{Ed}(x)|, |E_{Rd,min}(x)|), 0 \leq x \leq L \quad (4)$$

$$c = \max(f(x)) \quad (5)$$

where $E_{Rd,min}(x)$ is the resistance provided to the same effect by the minimum code requirements (e.g., minimum reinforcement prescriptions provided by Eurocode2 [10]). Equation (4), therefore, represents the envelope of the absolute values of $E_{Ed}(x)$ and $E_{Rd,min}(x)$ while (5) is the global maximum of $f(x)$. The coefficient α_i can therefore be calculated as:

$$\alpha_i = \frac{\int_0^L f(x) dx}{cL} \quad (6)$$

Where L is the length of the member. From (6) it can be seen that α_i is a coefficient that can vary between 0 and 1, with 0 meaning that a certain material is completely absent, and 1 meaning that its distribution is constant along the whole length of the member. It is, however, also clear that α_i strongly depends on the relative values of $E_{Ed}(x)$ and $E_{Rd,min}(x)$ and its calculation might be daunting or too resource-intensive for a preliminary design. To overcome this limitation, the values of α_i can be derived as a function of $|E_{Rd,min}(x)|_{max}/|E_{Ed}(x)|_{max}$ for the most common static configurations. As an example, Fig. 3 shows the values of α_i calculated for a discrete number of points on a uniformly loaded beam fixed at both ends.

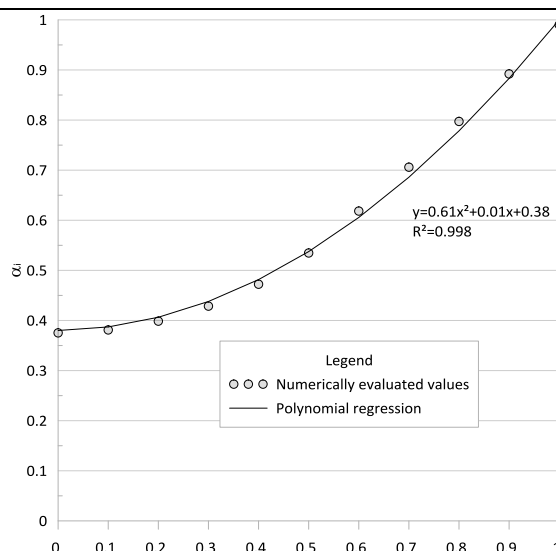


Fig. 3 Values of α_i for the bending moment of a uniformly loaded fixed beam.

At this point, the environmental impact associated to the entire member can simply be calculated multiplying the adjusted section impact by the total length of the member as per (7).

$$O_M = O_{s\alpha}L \quad (7)$$

3 Example

Here, a brief example of application of the proposed methodology is presented. In this example, the preliminary design of concrete beam will be performed. Such member is supposed to have a span L of 5 m, to be fixed at both ends, and to be loaded with a uniformly distributed design load of 50 kN/m. Table 2 and Fig. 4 summarise the main characteristics and results of a beam dimensioned with typical approaches and the same beam preliminarily optimised according to the proposed methodology. The design was performed in accordance with Eurocode2 [10], GWP was chosen as the environmental metric and the specific material related values were taken from Table 1 for concrete, while a GWP_v of 9420 kgCO₂e/m³ was assumed for steel [5].

Table 2 Comparative example of application of the proposed methodology on rectangular RC beams

	Ref	Ex 1	Ex 2
Concrete	C 25/30	C40/50	C35/45
Steel	B 550B	B 550B	B 550B
b [mm]	300	200	200
h [mm]	500	350	300
c _{nom} [mm]	20	20	20
A _s '	2 Ø8	2 Ø8	2 Ø8
A _s	2 Ø18	3 Ø18	4 Ø18
M _{Rd} /M _{Ed}	1.051	1.023	1.057
x/d	0.109	0.232	0.434
ε _s ' [%]	0.189	0.237	0.279
ε _s [%]	2.853	1.116	0.457
ε _c [%]	0.350	0.350	0.350

$GWP_{S,c}$ [kgCO ₂ e/m]	41.06	25.60	20.56
$GWP_{S,s}$ [kgCO ₂ e/m]	5.74	8.14	10.54
$GWP_{S,tot}$ [kgCO ₂ e/m]	46.80	33.74	31.10
α_c	1	1	1
α_s	0.515	0.412	0.391
GWP_M [kgCO ₂ e]	220.06	144.76	123.40

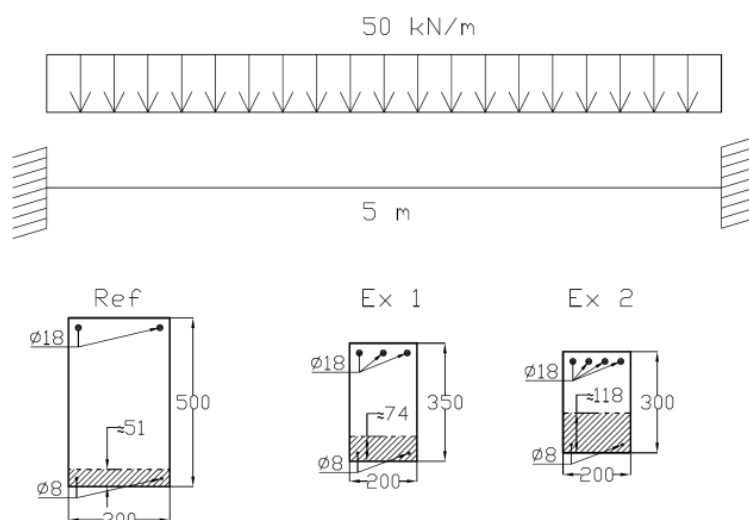


Fig. 4 Schematic drawing of the example beams with cross-section at the support.

As it can be seen, all the beams exhibit approximately the same performance at ULS. The reference beam (Ref), however, while minimising the amount of steel and employing a low strength class for concrete, has the highest environmental impact. This is clearly due to the high volume of concrete that is not used efficiently. Furthermore, the relatively big cross-section also results in more steel required to cover the minimum requirements provided by the code for the tensile zone. In the first example (Ex 1) both the concrete class and the amount of tensile reinforcement were increased. This led to the possibility of reducing the cross section while maintaining a significant ductility, as highlighted by the deformation in the tensile reinforcement. The overall environmental impact of this solution was significantly reduced in comparison to Ref. In the third example, the overall environmental impact was further reduced through the employment of an even smaller cross-section and a lower concrete class (compared to Ex 1). To maintain a satisfactory bending strength, however, the longitudinal reinforcement had to be further increased. The additional reduction of GWP that can be observed in this case is only marginal and comes at the expenses of ductility. A comparison of these results can be seen in Fig. 5.

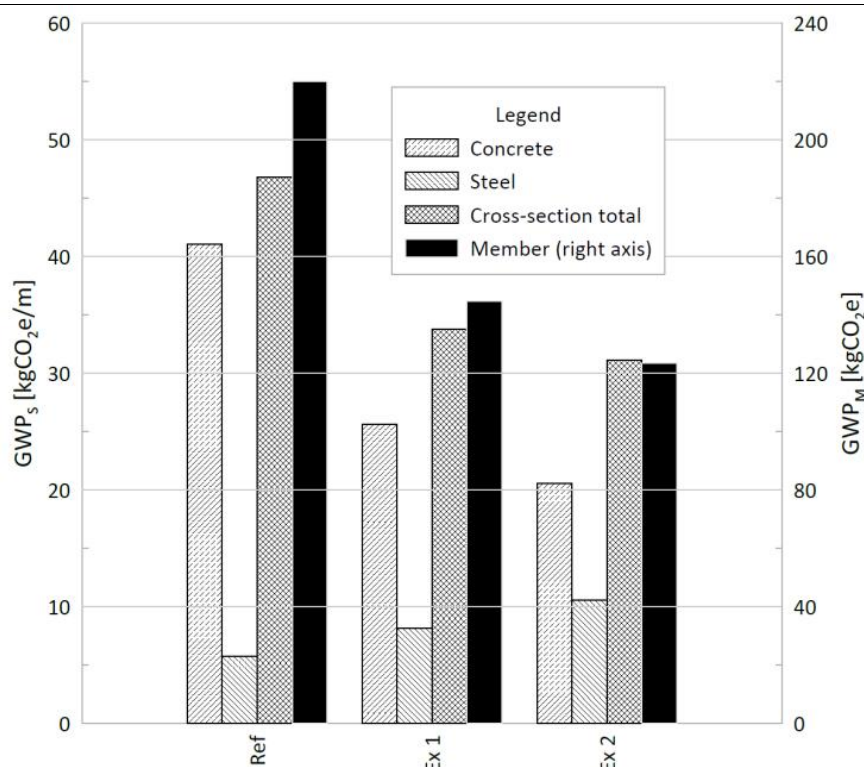


Fig. 5 Comparison of the environmental impact, expressed in terms of GWP, of the different examples.

4 Conclusions

An innovative approach has been developed to assess and consequent reduce the environmental impact of structures and structural interventions during the preliminary design phases. It covers three levels of design, i.e., material selection, section design, and member design. The method is aimed at the very early stages of design and, therefore, the results that are obtained in terms of environmental impact should be treated as a preliminary estimation. Furthermore, it is important to mention that, at present, the methodology does not consider factors such as cost and constructability. These aspects might be incorporated in the future. Nonetheless, the Authors believe that its specific nature makes it a powerful tool for reducing of the environmental impact, as it can be used even without the need for specific software and allows for changes to the initial design to be made at relatively low cost.

Acknowledgements

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List of symbols

A_i	Cross-sectional area of the i-th material
A_s	Cross-sectional area of the steel reinforcement in tension
A_s'	Cross-sectional area of the steel reinforcement in compression
b	Member width
c_{nom}	Nominal concrete cover
d	Effective depth
E_{Ed}	Generic design effect
$E_{Rd,min}$	Resistance to the generic effect provided by the minimum code requirement
GWP	Global Warming Potential
GWP_M	Global Warming Potential of the member
GWP_P	Global Warming Potential per unit performance
$GWP_{S,c}$	Global Warming Potential of concrete in the cross-section
$GWP_{S,s}$	Global Warming Potential of steel in the cross-section
$GWP_{S,tot}$	Total Global Warming Potential of the cross-section
GWP_V	Global Warming Potential per unit volume
h	Member height
L	Member length
M_{Ed}	Acting design moment
M_{Rd}	Resisting design moment
O	Generic environmental impact
O_m	Generic environmental impact per unit mass
O_M	Generic environmental impact of the member
O_P	Generic environmental impact per unit performance
O_S	Generic environmental impact of the cross-section
$O_{S\alpha}$	Corrected generic environmental impact of the cross section
O_V	Generic environmental impact per unit volume
O_{Vi}	Generic environmental impact per unit volume of the i-th material
X	Generic material characteristic
x/d	Relative position of the neutral axis with respect to the effective depth
α_i	Average member material volume correction coefficient
α_c	Average member concrete volume correction coefficient
α_s	Average member steel volume correction coefficient
ε_c	Concrete compressive strain
ε_s	Steel tensile strain
ε_s'	Steel compressive strain