Comprehensive environmental comparison of different structural systems for multistorey buildings in Italian and French contexts

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Abstract

Considering the path of sustainable development, it is necessary to make a step towards integration of multi-criteria design rules with assessment of environmental impact. This achievement is attainable through consideration of the whole building, with a broad perspective that aims at exploring critical points. One of the discussion topics is the utilization of bio-based materials, such as timber, which along with several environmental benefits, intrinsically carries some weaknesses that call out the necessity of combination with other materials. Starting from a benchmark of a reinforced concrete building, structural components are redesigned on an iso-performance basis, accounting for three alternatives: using only timber, a hybrid timber-steel solution and a hybrid timber-steel-reinforced concrete solution. According to the obtained results, the feasibility of the studied buildings considering the known established conditions (e.g., location, specific national regulations, etc.) is assessed. This is conducted with a constant monitoring of the environmental impact through cradle-to-cradle Life Cycle Analysis (LCA). The first focus is the assessment of uncertainties linked to the LCA, since the scenario adopted for the End-of-Life stage and for the manufacturing procedures drives the total environmental impact. The second target is establishing, according to external normalisation approach, relevance of other pollutants apart from carbon dioxide. The paper provides a comprehensive perspective concerning design of new multistorey buildings, where the potential benefits of composite solutions, both at level of single members and of the whole buildings, are fully exploited by assessing both structural and environmental performances at once.

1 Introduction

The issue of climate change is now very well-known to everyone, and it is widely acknowledged the role of human being in exponentially accelerating this process: this fact did come to the attention in the last years, since COP conferences became popular even in non-scientific contexts. Tracing the path of climate change negotiations, the first international meeting dates back to 1972, when the United Nations Conference on the Human Environment took place in Stockholm; this was the kick-off point that led first to make the scientific population aware of modifications on the Earth's surface, and then, with some delays, the government started to develop policies to limit greenhouse gases emissions, up to the newest aims of carbon neutral society [1]. Focusing on the European context, the negotiations speeded up in the last years: starting from aim of cutting at least 40% greenhouse gases (GHG) emissions by 2030 (with reference to 1990 values), established according to Paris Agreement [2], in 2021 the goal was improved to a reduction of 55% within 2030, in order to reach carbon neutrality before 2050 [1].

As one of the largest CO_2 emitters, the building sector carries out a key role in driving new policies, practical actions, and innovative solutions in order to counteract climate change and its harmful consequences. This sector is one of the most promising ones in guarantying remarkable lowering in CO_2 emissions, so that it is necessary to continuously update methodologies, on the one hand with strict regulations and on the other hand through constant scientific research. Considering European countries, they are welcome to develop regulations tailored on regional needs and specific aims: the framework remains the European guidelines, but even more ambitious goals can be targeted. An illustrative set of two virtuous examples addressing regulations for building materials, waste processing and environmental impact of new and existing buildings is collected and hereby listed:

- In Italy according to the last update of Piano Nazionale Integrato per l'Energia e il Clima (PNIEC – National Integrated Plan for Energy and Climate) [3], the energy efficiency of buildings is targeted to reach every two-year period higher savings. The financial investments are planned to be 70% aimed for improving energy efficiency of existing building and 30% to build high energy efficiency buildings with low carbon footprint. Concerning building materials, some guidelines were established according to a decree on minimum environmental criteria for construction projects [4], requiring a minimum value of recycled materials for concrete (5%) and steel (the percentage varies according to the manufaturing procedures and the use). Considering e.g., an alloy steel for structural use manufactured in an electric arc furnace, the minimum quantity recycled is 75% and certifications of sustainable forest source (e.g., Forest Stewardship Council® or Programme for Endorsement of Forest Certification schemes) for timber products.
- In France the Stratégie Nationale Bas-Carbone (SNBC) [5] is specifically tailored for the building sector with the RE 2020 Environmental Regulations [6]. In this case, a specific focus is devoted to dynamic consideration of climate change effects: the increase in the number and intensity of heatwaves is taken into account, and the additional energy consumption to guarantee summer thermal comfort is calculated. Moreover, considering new energy efficient buildings, emissions related to construction and demolition stages embrace 60% to 90% of their whole life impact. Thus, the regulations enforce decreasing maximum thresholds for GHG emissions; considering e.g., residential buildings GHG emissions from energy consumption were 14 kg CO_2/m^2/year, they must be reduced to 6.5 kg CO_2/m^2/year by 2025. On the other hand, the use of wood and bio-based materials is strongly encouraged, and it is foreseen to be a common choice by 2030: this expectation is motivated by challenging targets established by national regulations.

Considering both regulations at the European and at the national levels highlights the importance of always considering the specific conditions that shape a regional framework: common guidelines are the usual way to set and to reach mutual objectives, but this cannot be pursued disregarding necessities, peculiarities, local conditions, etc.

Considering new buildings, choice of the structural system is a major driving parameter that affects the whole design process and consequently environmental impact, costs, and easiness in requirements fulfilment. One of the increasingly widespread solution is the use of engineered timber products (ETP) for structural elements [7], often combined with other traditional materials, as reinforced concrete, and steel, in order to arise hybrid solutions [8]. Therefore, timber used as a structural and engineered material should be properly investigated, to reach a knowledge comparable to other more widespread materials. It is essential to assess timber environmental impact according to Life-Cycle Assessment (LCA) analysis, focusing on different End-of-Life (EOL) stage options (Hart & Pomponi, 2020); traditionally, timber can be reused, recycled, incinerated (with energy recovery) or landfilled, but it is practically unrealistic to foresee 100% EOL scenario (e.g., 100% reuse scenario), so that mixed scenarios became of primary importance. In this context it is worth mentioning the France case study [9], since an established mixed scenarios is available for timber EOL stage, according to collected data on nowadays practices; timber members are hereby recycled (57%), incinerated with energy recovery (26%) and landfilled (17%).

This research focuses on a holistic comparison carried out on two equivalent multistorey buildings with four different structural systems located in two European countries (Italy and France), in order to evaluate the effects of site specifics requirements on structural members design, environmental impact according to LCA analysis, and different seismic behaviours. Investigated structural systems are:

1. Full reinforced concrete solution (RC);
2. Full timber solution (T);
3. Hybrid timber-steel solution (T-S);
4. Hybrid timber-steel-reinforced concrete solution (T-S-RC).

The novelty introduced within this research is focus on two tailored scenarios for every considered material, since standard and traditional solutions are compared with sustainable and environmentally optimised options.

Concerning Italian context, a special attention is devoted to design the building in Ductility Class High (DCH, according to Eurocode 8) [10], while for this French case study no particular concern is required for seismic design, so that DCL (Ductility Class Low) is applied for design. Considering that Italian case study is designed in DCH, thicknesses of shear walls are dominated by seismic requirements, while for French one shear walls design is driven by fire regulations [11]. Moreover, in timber and hybrid Italian solutions slabs are fully made of timber, while in the French ones they are characterised by timber-concrete composite solutions, in order to maintain limited thickness and optimise acoustic insulation. These structural differences should be considered when carrying out environmental comparison, as an acknowledgement of the fact that deconstestualizing building design from its environment is meaningless.

The paper is organised as follows: methodology, hypotheses and relevant differences between Italian and French buildings are addressed in section 2, obtained results are outlined in section 3, discussion and comparisons are presented in section 4, and conclusions with foreseen future development are provided in section 5.

2 Method

The investigation presented in this paper firstly assesses the feasibility of different structural systems, according to site-specific requirements and considered regulations. Characteristics of each solution are listed in Table 1.

Table 1. Structural systems characteristics of different investigated solutions for Italian (IT) and French (FR) case studies. GLT=glued-laminated timber; CLT=cross-laminated timber.

Building structural system		Beams	Columns	Slabs	Walls	Foundations
RC		Reinforced concrete	Reinforced concrete	Reinforced concrete	Reinforced concrete	Reinforced concrete
T		GLT	GLT	CLT	CLT	Reinforced concrete
T-S		Steel	Steel	CLT	CLT	Reinforced concrete
T-S-RC		Steel	Steel	CLT	Reinforced concrete	Reinforced concrete

RC solution is considered since it is the most widespread structural systems in Italy and France, while T solution is studied in order to provide a low-carbon emission target for new buildings. On the other hand, T-S solution is basically equivalent to solution 2, where beams and columns are optimised with steel sections. Eventually, T-S-RC solution is provided with RC shear walls, to make it easily suitable for regions characterised by medium and high seismicity.

Thereafter, in order to provide a comprehensive environmental assessment, two alternatives – “traditional” and “low-carbon” – for each considered material (timber, steel, and concrete) are presented. Engineered timber products (e.g., CLT and GLT) are already low-carbon impacts materials, so the focus is on the End-of-Life scenario; on the other hand, steel and concrete carbon emissions are mainly detected in the manufacturing phases, so that the focus is on LCA stage A. Description of each materials environmental alternative is presented in Table 2.

Table 2. Structural materials environmental assessment.

Material	Traditional solution (1)	Low-carbon solution (2)
Timber (X)	FCBA scenario is adopted for timber EOL [9]. Recycling (57%), incineration with energy recovery (25%), landfilling (17%)	"High-reuse prospective scenario" is developed, starting from FCBA one. Reuse (40%), recycling (24%), incineration with energy recovery (24%), landfilling (10%)
Steel (Y)	Steel manufacturing is processed in blast furnace, data from AIE4B software [12]	Steel manufacturing is processed in electric arc furnace supplied by 100% renewable energy, data averaged from selected European EPD [13], [14], [15], [16]
Concrete (Z)	Concrete is produced with traditionally manufactured cement (with high-clinker content), data from AIE4B software [12]	Concrete is produced with cement characterised by low-clinker content, data averaged from selected European EPD [17], [18], [19]

According to each material's scenario, a set of scenarios for every building is hereby assessed, considering that every building structural system is followed by a triphlet in the form X(=timber).Y(=steel).Z(=concrete), where each variable can assume one of these three values:

- 1, the material is considered according to its traditional solution
- 2, the material is considered according to its low-carbon solution
- 0, the material is not present (e.g., X=0 for RC building)

LCA analysis is carried out considering stages A to D ("cradle-to-cradle") in terms of different parameters, in order to provide a comprehensive overview of the environmental impact of the structural part of a building. Choice of the parameters was motivated by the necessity to investigate other environmental fields apart from climate change and the listed parameters are the ones available for every material according to the involved sources and software:

- Global Warming Potential (GWP), measured in kg CO_2 eq.;
- Acidification Potential (AP), measured in kg SO_2 eq.;
- Ozone Depletion Potential (ODP), measured in kg CFC-11 eq.;
- Fossil Fuel Consumption (FFC), measured in MJ.

To improve interpretation of the LCA analysis results, the building impact is compared with the impact of a person during a European average lifespan, according to external normalisation approach [20] as listed in Table 3.

Table 3. Environmental impact of a person during the whole lifespan (lifespan assumed as a European average value).

LCA parameter	Impact per capita (average European lifespan)	Geographical and temporal accuracy
GWP (kg CO_2 eq.)	44.000 [21]	European Union (EU27), 2020 data
AP (kg SO_2 eq.)	3.390 [22]	Worldwide, 2010 data
ODP (kg CFC-11 eq.)	4.84 [22]	Worldwide, 2010 data
FFC (MJ)	5.200.000 [22]	Worldwide, 2010 data

2.1 Italian building design

Design of Italian building is developed starting from reinforced concrete (RC) solution and subsequently assessing the alternatives. It is a residential building located in Milan and characterised by 8 storeys with interstorey height of 3.35 m; the structural plan is approximately 64x14 m and regularity in plan and elevation is guaranteed. The building is designed according to Eurocode 8 DCH.

French building design

Design of French building is made using a tool developed for study [22]. Starting from the drawing of a building geometry, spans and loads are deduced for each structural element. The dimensions of each structural element are then deduced from a pre-established database of pre-calculated structural elements (according to Eurocodes and to French Regulations). The geometry of the building was chosen similar to the Italian residential building mentioned above.

3 Results

Results are presented in terms of structural masses and LCA parameters defined in section 2, considering each structural element (beams, columns, slabs, shear walls, and foundations) impact.

3.1 Structural masses

According to results presented in Figure 1, the major share of masses comes from the slab for RC solutions, since in Italian and French buildings they represent respectively 50% and 56% of the total masses. On the other hand, in case CLT slabs are used, the total mass building reduction is significant, given that in Italian and in French buildings the slabs masses respectively shift from 3.880 and 4.170 tons to 833 and 1.486 tons.

Considering different structural alternatives, the noticeable gap between RC and other solutions acknowledges that, according to structural masses perspectives, focusing on slabs is already sufficient to emphasise a consistent mass reduction. On the other hand, in T, T-S and T-S-RC solutions the percentage mass share of other structural elements becomes more important, leading to a major level of attention in the environmental analysis; considering T and T-S solutions, the foundations account approximately for 35% of the total masses, since they are always made with reinforced concrete. The same rationale is valid for RC shear walls in T-S-RC building, which mass share accounts approximately for 25%.

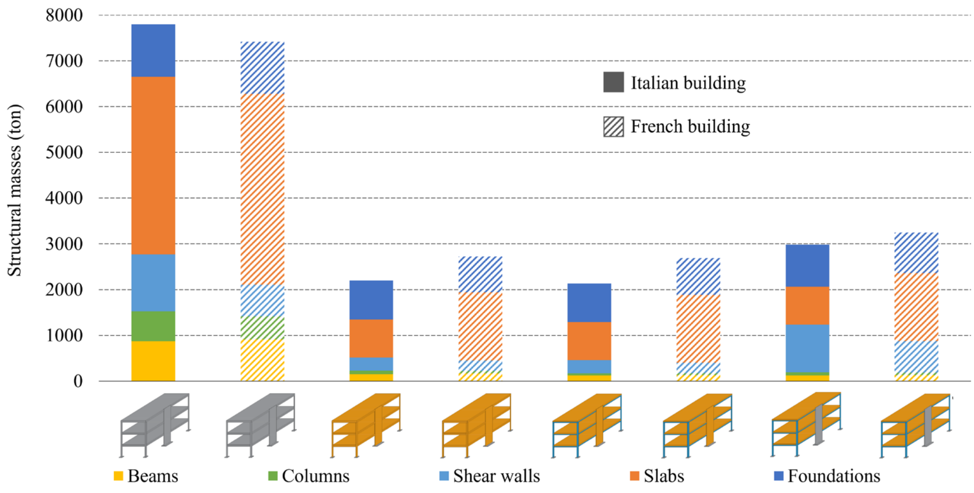

Figure 1. Masses of structural elements for studied structural systems in Italian and French buildings.

3.2 LCA analysis

The environmental analysis focuses firstly on GWP, and successively comparisons with other parameters impact are carried out. GWP impact of each case study is presented in Figure 2; considering RC-0.1.1 cases the slabs impact is approximately 1E06 kg CO_2 eq., while their contribution in Italian and French timber buildings (T-2.2.2) respectively decrease up to 5.5E04 and 9.2E04 kg CO_2 eq., driving the overall environmental impact. It is also worth comparing results of the same structural systems characterised by materials with different environmental impacts, according to assessment outlined in Table 2; 0.2.2 RC alternative is characterised by 65% GWP impact reduction with respect to 0.1.1, with a decrease in the range of one order of magnitude. On the other hand, also in the other structural systems the use of low-carbon building material alternatives results in significant reduction in terms of kg CO_2 eq., but GWP order of magnitude remains the same since it is already low due to the presence of timber.

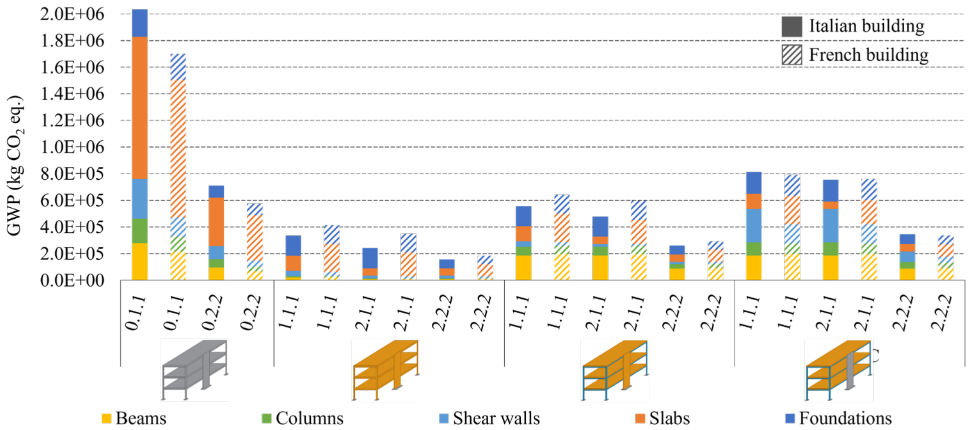

Figure 2. Percentage environmental impact, in terms of GWP, clustered by structural elements.

Considering that LCA analysis aims at providing a comprehensive overview of the environmental impact of a product, buildings impact according to a wider range of parameters is calculated, with reference to impact per capita, as shown in Table 4.

Table 4. LCA analysis results of buildings' structural systems with reference to equivalent people impact during an entire lifespan.

Structural system and scenario	GWP impact	AP impact	ODP impact	FFC impact
RC – IT (0.1.1)				
RC – FR (0.1.1)				
T – IT (2.2.2)				
T – FR (2.2.2)				

According to results presented in Table 4, it is possible to cluster LCA parameters in two classes of importance, regarding relevance in terms of harmfulness and improvements achieved moving from reinforced concrete to timber buildings:

- Class 1 includes GWP, AP, and FFC. All parameters highlight a reduction shifting from T to RC building, where impact of the studied full timber solution is always lower than 1 person;
- Class 2 includes ODP. In this case the impact is just minimally affected by the structural system, and it is always extremely low.

4 Discussion

The results carried out in the context of this analysis confirm the correctness of the prioritization methodology adopted, as slabs optimisation is the main reason behind GWP decrease. Slabs optimisation is intended in a wide context, since different solutions are considered, starting from use of concrete with low clinker cement, up to material substitution in the case of full CLT slabs. Another observation noticeable from the results is the broad range of advantages derived from slabs masses reduction when shifting from RC building to other solutions. The first and most evident result is cross section reductions in both vertical and horizontal elements, consequently followed by lighter foundations. Timber material offers the possibility of high level of prefabrication with better control of the whole manufacturing process. This allows reduced construction times, higher construction quality. Moreover, waste and materials consumption are reduced, leading to economical and environmental benefits.

This investigation aims at being holistic, and to develop comparative and comprehensive analysis. Comparability is guaranteed by the presence of buildings in two different European countries, both assessed with different structural systems and studied with several material scenarios. On the other hand, comprehensiveness is ensured by considering other parameters for LCA analysis apart from GWP: this way the environmental impact of a building is evaluated not just in terms of climate change, but also considering indicators related to ecosystem quality (AP and ODP), human health (ODP), and resources depletion (FFC).

5 Conclusions

The initial aim of this investigation – comparing two equivalent residential buildings in the European context – revealed a much wider variety of topics that were investigated, starting from concept of equivalent buildings, which should be tailored, case by case, to the geographical location, building site, national regulations, etc. Moreover, the importance of considering more than a single scenario for LCA analysis is highlighted by significant gaps in the results, comparing both traditional and low-carbon solutions and reinforced concrete with timber ones; this conclusion arises from the fact that a product environmental impact is the result of a process where reusing and recycling practices establish key points.

On the other hand, it is worth considering that availability of low-carbon materials (e.g., concrete produced with low-clinker content cement) may not be homogeneous, so the prioritization of elements environmental impact is once again a key point. Another issue is linked with costs, as engineered timber products are, for now, more expensive than concrete, so considering barely the economic perspective timber and low-carbon reinforced concrete buildings results unfavourable with respect to traditional reinforced concrete one; on the other hand, it is necessary to consider also other parameters that support the benefits of such alternative solutions, not just from environmental outlook. Considering e.g., T-S-RC building with respect to RC one, it results in a total mass much lighter due to timber slabs and steel beams and columns, but lateral stiffness in case of strong lateral loading – e.g., earthquakes – is still ensured; on the other hand, presence of CLT shear walls may result in insufficient lateral stiffness and consequent excessive lateral drifts with exntended and expensive damages.

It is worth mentioning that optimisation of carbon impact is not a fixed and permanent path, but it should be shaped as a function of building characteristics and site features; methodology standardisation is a desirable target, carried out with proper consideration of such characteristics that make each building unique and which lead to proper optimisation of environmental impact.

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