Environmental Impact Assessment of Materials Used for Buildings: A Case Study from France

Chadi Nasrallah

ABSTRACT

Humans are facing problems from climate change that they are responsible for, and these challenges pose a growing threat to sustainable development. The main reason is the global warming rates that have accelerated in the last few decades.

The project compares the global warming potential (GWP) of a green building with a conventional building located in Paris, France. It has been noted that adopting strategies such as environmental product declaration as a criterion for material selection, using material with recycled content and applying life cycle impact analysis for a building, could reduce GWP by about 52%.

Keywords: Environmental impact assessment, Green building, Life cycle assessment, Global warming potential, Sustainable construction

Civil Engineering Department, Order of Engineers, Beirut, Lebanon

Correspondence to: Chadi Nasrallah, chadinasrallah123@gmail.com

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Introduction

Building construction is a complex process composed of many activities and materials. Most of the materials used in construction have a high negative impact on both the environment and human health. Buildings throughout their life cycle contribute to environmental challenges such as global warming, acidification, different kinds of pollution, and resource depletion.

Environmental evaluation of buildings and their materials is one of the most significant factors toward sustainability in the building industry and built environment. Application of an environmental assessment in the construction sector is essential not only because of the complexity of the building construction process and materials, but also because of their long lifetime. This can cause many difficulties and uncertainties in the prediction of the behavior of buildings throughout their life cycle.

The urgency of global climate change has drawn significant attention to the building industry over the last few years. Today, the building sector is responsible for the emission of about 23–40% of the world's greenhouse gases (GHG).[1] This is plausible owing to the various non-environmentally-friendly materials used by the modern building industry and the prevailing design practices.[2]

In response to that, many proposals have been considered to quantify the negative impact of these materials, in order to provide benchmark and sustainable alternatives, including the life cycle assessment (LCA) of the materials and buildings, that takes into consideration all the environmental impacts of any material over its life time, starting from extraction, ending in landfill or in the recycling plant.

The international panel on climate change envisaged that the carbon dioxide (CO_2) emissions from the construction sector could surge from 8.6 billion tons in the year 2004 to 15.6 billion tons in the year 2030,[3] under the speculated rising population growth circumstance, as will be contributed by the developing countries. These risks and negative impacts that have started to appear in different forms, such as natural crises, have drawn attention to the need for serious action against the conventional building sector.

*This paper complies with TITAN Guidelines 2025 that govern the declaration and use of AI[4] *.

LCA Definition

LCA is a relatively new method used in construction since 1990. Due to its comprehensiveness, however, it is an important tool for the evaluation of materials, structures, and buildings. Thus, applying the LCA using different boundaries allows for the various systems with different focuses and objectives. LCA-based methods in the construction sector are used at three levels: Tools to compare environmental performances (GaBi - Germany, SimaPro – Netherlands, TEAM - France); Tools for evaluation of constructions or particular buildings (LISA - Australia, Ecoquantum - Netherlands, Envest - United Kingdom, Athena - Canada). Evaluation tools assessing the whole building systems during their life cycle (BREEAM - United Kingdom, LEED - USA, Grey - Australia, SBToolCZ - CR, BEAS - SR) (Figure 1).[5,6]

The evaluation and consequent environmentally-based choice of materials is one of the key factors for minimizing environmental burdens.[7] Databases assessing the life cycle of building materials can be divided into public, academic, commercial, and industrial. The data may vary due to different system boundaries, anticipated sources of energy, product specifications, and so on. In addition, environmental impacts can also be affected also by geographical factors. Selecting the database can therefore affect the reliability of the results of LCA.

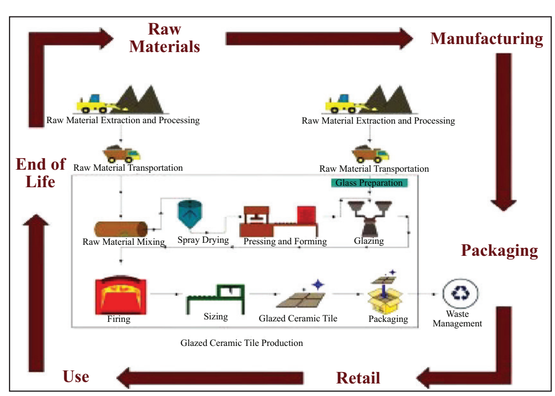

Fig 1 | Illustration of materials life cycle

Various LCA studies conducted in recent years included a study of materials in residential buildings.[8,9] Embodied energy, global warming, and acidification potentials (AP) are of main interest when evaluating the environmental performance of buildings and materials.

Life cycle impact studies the environmental impacts of the material along its lifetime (from cradle to grave), over five phases: extraction (graves and transport raw materials, cradle); manufacturing (from raw to finished product, gate); construction (installation); use (service life, maintenance, replacement); end of life (removed, recycled, disposed, grave).

Green Building and Sustainability Concept

Green buildings and sustainable construction activities have been highly concentrated solutions for reducing GHG emissions and their detrimental effects. The application of approaches, such as LCA helps the understanding of the harms caused by GHGs and also the effectiveness of remedial actions.[10] Despite the variations in the standard definitions of "green buildings" and "sustainability," both concepts are often employed in close association with each other and sometimes interchangeably. "Green" is a specific term and often focuses on products, people, and the environmental impact, while the "sustainable" term has a more encompassing definition that includes the environmental, social, and economic pillars of sustainable development.[11,12] Therefore, any sustainable solution must be able to reduce the devastating consequences of human activities from the standpoints of all pillars (i.e., environmental, social, and economic), since studies have indicated that sustainable building and construction can reduce global warming and water pollution by more than 30%.[13]

Embedding sustainability at the design stage of construction, compared to retrofit stages, often offers immensely higher cost-saving opportunities, reliability, and safety throughout the asset life cycle. Some techniques, such as LCA and building information modeling, are proven to help conduct a comprehensive assessment of the overall needs of construction projects, including safety hazards, sustainability criteria, and the operations and maintenance needs throughout the life cycle.[14,15]

Overview of Previous Research

Several rating systems and research endeavors have aimed at probing into factors influencing the sustainability status of construction procedures. For instance, the Leadership in Energy and Environmental Design (LEED) rating system is a multi-criteria approach for assessing the sustainability of buildings, which adequately recognizes building site, water, material, atmosphere, air quality, and innovation measures, as factors that can easily sway the overall ranking of a building from a conventional to a green project,[16] Energy and carbon design for zero energy communities has also been widely investigated by several researchers. For instance, Balali et al. have studied the passive energy optimization measures in sustainable buildings,[17] while Jie et al. investigated the impacts of wall and roof thicknesses on the calculation of energy consumption and pollutant emissions.[18] Brown et al. studied the greenhouse gas emissions from residential buildings and how such knowledge can support energy efficiency in buildings.

Although many studies have considered some of the factors that affect the main sustainability pillars, very few have thoroughly quantified the sustainability criteria related to the main structural frames of green buildings.

The current study attempts to quantify the environmental impact of main building materials, and provide alternatives and solutions, with numerical comparison in order to find the best alternatives for a sustainable environment and less harmful materials.

This study helps in understanding the integration of LCA of the construction materials, most especially in terms of GHG, using a developed advanced software, One Click LCA, that monetize the social impact of these emissions, which is a new concept representing how the society is affected directly and indirectly through wellbeing, health problems, productivity, disasters, jobs creation, and other factors. In addition to that, it pushes the underdeveloped countries to adopt these strategies and incorporate them in their building regulations and laws.

Building Impact Overview

The present state of construction is complex. There is a wide range of building products and systems that are aimed primarily at groups of building types or markets. The buildings and construction sector accounted for 36% of final energy use and 39% of energy and process-related CO_2 emissions in 2018, 11% of which resulted from manufacturing building materials and products, such as steel, cement, and glass.[19]

The most commonly used material for building structure is reinforced concrete. Reinforced concrete is composed of concrete and reinforcements. Each one of these two materials has its own negative environmental impact, which we will take into consideration and find better alternatives in terms of environmental impact.

Concrete Environmental Impact

Global Warming Potential (GWP): It is estimated that 1.6 billion ton of concrete is produced annually, making the cement industry one of the two largest producers of CO_2, creating up to 8% of worldwide man-made emissions of this gas, of which 50% is from the chemical process and 40% from burning fuel.[20,21] The CO_2 emission from the concrete production is directly proportional to the cement content used in the concrete mix; 900 kg of CO_2 are emitted for the fabrication of every ton of cement, accounting for 88% of the emissions associated with the average concrete mix.[22,23] Cement manufacturing contributes to GHGs both directly through the production of CO_2 when calcium carbonate is thermally decomposed, producing lime and

CO_2,[24] and also through the use of energy, particularly from the combustion of fossil fuels.

This means that transportation only accounts for 7% of the embodied energy of concrete, while cement production accounts for 70%. With a total embodied energy of 1.69 GJ/ton, concrete has a lower embodied energy per unit mass than most common building materials besides wood. It is worth noting that this value is based on mix proportions for concrete of no more than 20% fly ash. It is estimated that 1% replacement of cement with fly ash represents a 0.7% reduction in energy consumption. With some proposed mixes containing as much as 80% fly ash, this would represent a considerable energy saving (Figure 2).[23]

Heat Island Increase: The ingredients of concrete generate a thermal mass that absorbs sunlight and heat that falls upon it. This generated energy, which is given back into the air in the cool of the night. This occurs when concrete absorbs heat during the day and releases it at night.[26]

Steel Environmental Impact

The world produces a lot of steel, over 240 kg for every single person in the world every year. About 1800 million tons in total.27 We pretty much cannot do anything that does not somehow require steel. But the environmental impact of steel is enormous. Steel production is one of the most energy-consuming and CO2-emitting industrial activities in the world.

The main ingredient in the production of steel is iron ore mined from the earth. Over 2000 million tons of iron ore are mined a year, out of which about 95% is used by the steel industry. Iron ore is the world's most produced commodity by volume—after crude oil and coal—and the second most traded commodity—only beaten by crude oil.

In 1950, the annual global steel production was 189 million tons, in 1975, 644 million tons, and by the year 2000, production reached 850 million tons. In 2018, global steel production had doubled compared to 2000 and reached 1808 million tons. That is 57 tons of steel a second around the clock, 365 days a year.[27] Roughly 98% of iron ore on the global market is used in iron and steel production.[28] The environmental impact of iron ore mining in all its phases, from excavation to transportation, may have detrimental effects on air quality, water quality, and biological species.[29]

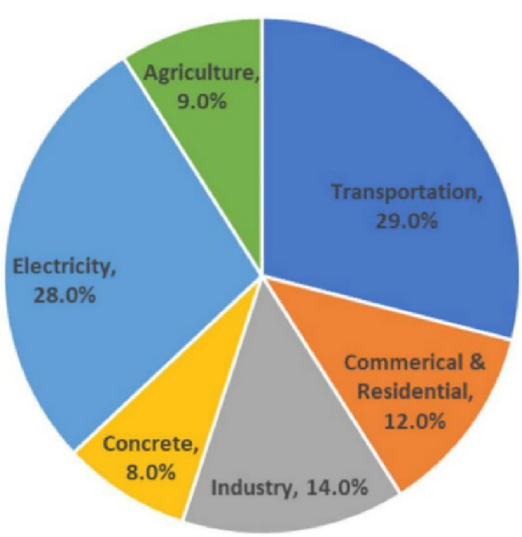

Fig 2 | Distribution of CO_2 emissions worldwide[25]

GWP: Production of steel is the most energy-consuming and CO_2-emitting industrial activity in the world. Steel requires about 20 GJ of energy per ton produced. Three-quarters of the energy comes from burning coal. GHG emissions from steel production: On average, 1.83 tons of CO_2 is emitted for every ton of steel produced, making steel production a major contributor to global warming, adding over 3.3 million tons annually to global emissions.[27]

Air Pollution: The main sources of emissions during both the construction and operation phases include the products of combustion, such as nitrous oxide, CO_2, carbon monoxide, and sulfur dioxide, and fugitive dust from the operation of equipment.[30] The major effects of industrial air pollution on wildlife include direct mortality, weakening, industrial-related injury and disease, and physiological and psychological stress.[31]

Finishing Material Environmental Impact

Apart from structural elements used for building construction, there are various materials used for finishing, which have a significant impact on the environment. Examples of these materials are: paints, tiles, doors, windows, roofing materials, partitions, and ceilings. Each one of these materials has its own environmental footprint, which must not be neglected, in order to perform a whole LCA of a building, and its environmental impact, most especially the contribution to GWP.

A study applied revealed that one conventional masonry house, on average, consumed 310 tons of materials. The average of embodied energy (PEI) in one masonry house reached 567.5 GJ, while the average global warming (GWP) and APs were found as 36.2 tons CO_2 equivalent (CO_2e) and 0.17 t SO_2e, respectively.[32] Analyzing the environmental impacts of substructures in buildings, materials of foundations were identified to be responsible for the most negative environmental impacts, with 29.9% of the total embodied energy, 57.8% of the total GWP, and 30.4% of the total AP;[32] followed by thermal insulation, vertical bearing walls, and finishing. The summation of foundations and walls materials consumed about 50% of the total embodied energy. The obtained results could represent the average environmental impacts of residential houses in Central Europe, because in the region, masonry dominates as the construction type.

González and Navarro estimated that the selection of building materials with low impacts can also reduce GWP - CO_2 emissions by up to 30%.[32] Estokova and Porhincak noted that it is possible to reduce the environmental impacts by up to 61.0% in particular structures and by up to 10.5% overall, just by a simple change of several building materials in the structures.[33]

Proposed Solutions

Material Substitution and Recycled Content

Much research has started in the last few decades in an attempt to reduce the environmental impact. Examples of these strategies are replacing a percentage of the main components of materials or the use of recycled content.

Cement Conservation: The conservation of cement is the first and most important step in decreasing both energy utilization and GHG emissions. Resource productivity consideration stipulates the deduction of the utilization of Portland cement while meeting the future demands for more concrete. It is reported that replacing cement with slag or fly ash by 50% will provide a better durable product compared with that of Portland cement with zero replacement, and consequently, natural resource application is decreased.[34]

Aggregate Conservation: It is claimed that in North America, Japan, and Europe, around two-thirds of construction and demolition waste is composed of old broken concrete and masonry. If these waste materials are reused as a coarse aggregate, material productivity will improve greatly.[34]

Concrete Durability: Many additives can be added to increase concrete durability in order to make it last longer.

Reinforcements: Compared to other building materials, it does not take a lot of steel to hold up a building. Even though structural steel is mainly higher carbon plain steel, all types of steel are strong and highly durable in any form (stainless, carbon, galvanized, mild).[35] It is endlessly recyclable; some steel mills only use scrap to produce new steel.

Steel is the world's most recycled material. Steel can be recycled without losing any of its famous strength or durability. It can be recycled at any point in its life or application. Steel constructions and steel-framed buildings can be dismantled, and the metal reused. Designers can take a measure of responsibility for sustainability by practicing "design for deconstruction," making it more efficient to dismantle and reuse the metal.[35]

Solutions will target the emissions and energy consumption related to the LCA of materials, in order to reduce their environmental impact, and will extend to involve the laws and regulations by governments as enforcement.

Environmental Product Declaration (EPD)

Adopting EPD as a selection tool for materials can serve the target of reducing the environmental impact.

An EPD is a standardized document informing about a product's environmental and human health impact. The general goal of EPDs is to use verifiable and accurate information to encourage the demand for and supply of products that have a lower negative impact on the environment.[36] It functions as proof and/or a claim for a sustainable product, which companies can use for commercial reasons. It is based on the ISO 14025 standard and the scientific foot printing method LCA.[37] An LCA calculates the environmental footprint of a product throughout its life cycle, expressed in more than 15 impact outcomes. The goal of an EPD is to inform and communicate with stakeholders about a product's environmental impact.

An EPD is normally provided by the product manufacturer and must be verified by an independent expert. An EPD normally has a validity of 5 years.

An EPD has different types, like type III EPD. Without performing an LCA, you cannot make an EPD. That is because an EPD is one of the options when you want to certify a product. Therefore, it is subject to a third-party verification process.

An EPD includes: the LCA results, a proper description of the product, the assumptions used in the LCA study for different life cycle stages (e.g., the installation stage, module A5), and the calculation rules used (e.g., a PCR). EPDs are often required in green public procurement, tenders by private companies, and building assessment schemes, such as LEED, BREEAM, and Green Star.[37]

Regulation and Laws

The European Emissions Scheme (EU ETS) is one of the keystones of the European Union's Policy on global warming. It is also the main tool that enables the European Union and its member states to achieve the GHG reduction objectives assigned to them by the Kyoto Protocol.38

Other reporting instruments are also being reported at the international level. The GHG Protocol harmonizes accounting and reporting methods, as well as measurement and action tools to combat climate change.

In France, the most widely used methodology is that of the "Bilan Carbone," a mandatory diagnostic tool adopted since the "Grenelle II Law of July 2010", which makes it possible to analyze the entire life cycle of products and services offered by a public and private player. The carbon balances of public and private groups must be transmitted to the ADEME.[38]

Financial Incentives and Specific Building Certifications

The first financial initiative that can be awarded to green buildings is to reduce taxes for the new building to be constructed that complies with certain guidelines that take into consideration the LCA of the building, and increase the tax for buildings not complying with these regulations.

Another initiative can be adopting building certifications as a distinction tool for buildings, which will increase their market value. Such certification exists in France, for example, like the Energy-Carbon certification and RT.[39]

The Energy-Carbon benchmark is the first step in the implementation of the new climate regulations, which will enter into force in 2020. It aims to enable building professionals to train in the concept and implementation of ecological architecture. In addition, the implementation of this standard is an opportunity to gather feedback to further improve standardization. An observatory and an Energy-Carbon label have therefore been created.

Methodology of the Case Study

Scope of Work

After that we have listed the environmental impacts of the materials related to building construction and finishing, we will proceed with the case study using a typical building in Paris, France using "One Click LCA" software to quantify the impact in terms of GWP (GWP measured in ton CO_2), and provide different alternatives from sustainable and green materials, and represent the difference associated and the contribution of the reduction in GWP.

Table 1 | Description and quantities of materials used in the base case model

Item	Description	Details	Quantity	Unit
Concrete	Foundations	1.5 × 1.5 × 0.4 × 12	10.8	m^3
	Slab on ground	100 × 0.15	15	m^3
	Columns	12 × 0.6 × 0.25 × 3 × 3	16.2	m^3
	Slabs	100 × 0.2 × 3	60	m^3
	Stairs	25 × 0.08 × 1 × 3	6	m^3
	Total		108	m^3
Reinforcements	Assuming 150 kg/m^3 of concrete	150 × 108/1000	16.2	tons
Partition		3 × 250	750	m^2
Paint	Ceiling	100 × 3 × 1.71	513	kg
	Walls	250 × 3 × 1.71	1285.5	kg
	Total		1800	
Tiles		100 × 3 × 1.5	450	m^2
Windows		1.4 × 1.2 × 6 × 3	30.2	m^2
Façade cladding		10 × 9 × 4 – 30.2	329.8	m^2
Mortar	Ceiling	100 × 3	300	m^2
	Walls	250 × 3	750	m^2
	Total		1050	m^2
Roof insulation		100	100	m^2
Doors	Thickness 5 cm, 700 kg/m^3	2.1 × 0.9 × 7 × 3 × 0.05 × 700	1389.15	kg

Software Used

One Click LCA is the number one easy and automated LCA software that helps calculate and reduce the environmental impacts of buildings and infrastructure projects, products, and portfolios. Many options are available, such as: Whole building LCA; Sustainable and circular designs: compare design options, optimize carbon, cost, circularity throughout the design process; Certifications and transparency: Achieve credits from LEED, BREEAM, and 40+ Green Building Certifications.

Model Development and Parameters

In order to quantify the impact of the building under study, we will calculate the environmental impact of a typical 300 m^2 building located in Paris, France, composed of three stories of 100 m^2 each.

Calculation of Quantities of Materials to be Used in the Building

Story area: 100 m2; number of stories: 3; Story height: 3 m.

Table 1 shows the quantities of material used for the base case model.

Base Case Model Material Used

We will specify for each material the type used with its corresponding environmental impact, as calculated in the EPD. In addition to that, we will take into consideration a 5% waste for each material, and the transport distance between the supplier and the site.

Figures 3–6 show the environmental profile of some materials used in the base case model.

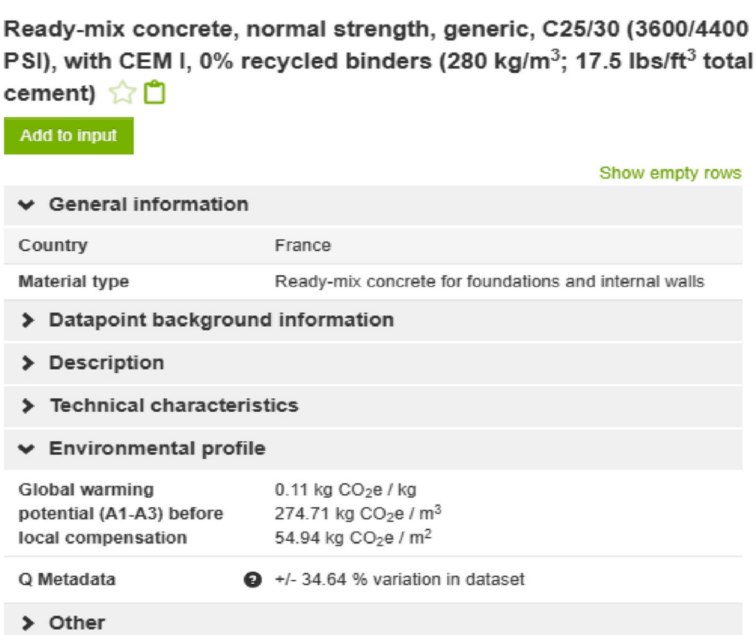

Fig 3 | Environmental profile of concrete used for the base case model

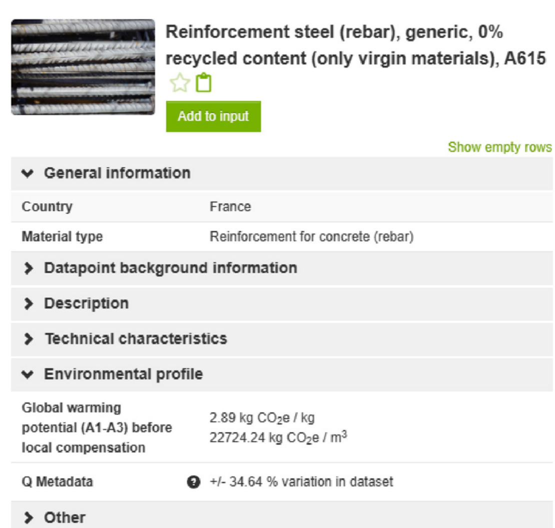

Fig 4 | Environmental profile of reinforcements used for the base case model

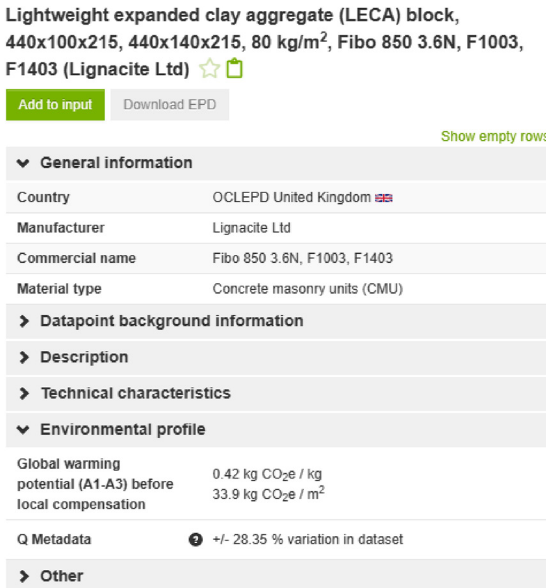

Fig 5 | Environmental profile of the partition used for the base case model

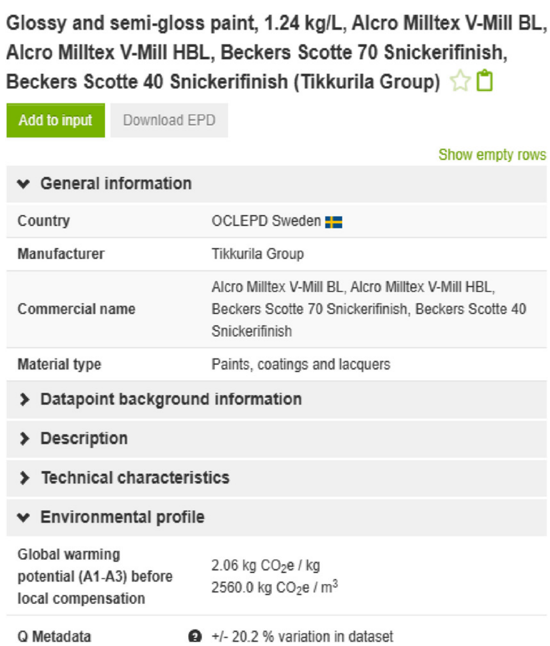

Fig 6 | Environmental profile of paint used for the base case model

Table 2 represents the material input data for the base case model.

Figures 7–9 represent the input of different structural elements in One Click LCA.

Discussions

Base Case Model Results

Results of our base case model are shown in Figure 10. The environmental impact in terms of GWP is equal to 171 tons of CO_2e, or 569 kg CO_2e/m^2.

Based on the classification or benchmark of embodied carbon measured in kg CO_2/m^2, the building is classified in zone E with an embodied carbon of 569 kg CO_2/m^2.

Social Cost of Carbon

One Click LCA offers the option for calculating the social cost of carbon, which will reflect the economic damage caused by additional CO2 emissions. The social cost of carbon is a method of calculating the impacts of additional CO2e emissions, including non-market impacts and human health, based on a value of 50 €/1 ton of CO2e.

The reason for assigning a cost per ton of CO_2 emitted is to aid decision-makers in evaluating whether particular actions designed to reduce climate change are appropriate and justified. For our base model, the social cost of carbon is 8529 €, based on 50 €/ton of CO_2e (Figure 11).

In Figure 12, we can see the most contributing material to the GWP with its LCA (cradle to gate). Materials with red color have the worst environmental impact, while materials with green color have the least environmental impact. Colors will vary from red to green, passing by orange and yellow based on material's environmental profile.

In our case, the ready-mix concrete has a high negative impact since its color is red, while glazed wall tiles have an acceptable environmental impact since the color is green.

Figure 13 is a summary table that represents the environmental impact in terms of tons CO_2e calculated from the formula: Inventory × impact = total.

For example, for the ready-mix concrete we have: 108 $m^3 \times (274.71$ kg $CO_2e/kg)/1000 = 29.6$ tons, which is close to 31 obtained by One Click LCA, since there is a ±34.64% variation in the dataset as indicated in the corresponding EPD.

Based on life cycle stages of materials, taking in consideration only cradle to gate (A1–A3) of each individual material, and by adding the impact of the transport of all the materials together as a separate life cycle stage (A4), and same for construction process impact under A5, we can see from Figure 14 that the steel has the highest impact as well, followed by concrete and other elements. In addition to that, we can notice that transport accounts for 1.7% of total GWP, which must not be neglected, and for that reason, we must pick regional materials that are extracted and manufactured close to the site in early design stages, in order to achieve the best improvement. Construction process constituted 4.7% of total GWP emissions.

Figure 15 shows the contribution in percentage to GWP by the type of material used for construction and finishing. It combines the cradle to gate impact (A1–A3) with the transport (A4) and construction process impact (A5) of each material rather than counting it separately.

After distributing the A4 and A5 impact of each material as entered by the user, the reinforcements

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Table 2 | Material input data of the base case model

Base Case Model Input Materials							
S/N	Item	Quantity	Unit	Description	Environmental Profile (kg CO_2e/kg)	Transport (km)	Waste (%)
1	Concrete	108	m^3	Ready-mix concrete C20-25/2501 – 4000 psi Ready-mix concrete, normal strength, generic, C25/30 (3600/4400 psi), with CEM I, 0% recycled binders (280 kg/m^3; 17.5 lbs/ft^3 total cement)	0.11	60	5
2	Reinforcements	16,200	kg	Reinforcement steel (rebar), generic, 0% recycled content (only virgin materials), A615	2.89	370	5
3	Partition	750	m^2	Lightweight expanded clay aggregate (LECA) block, 440 × 100 × 215, 440 × 140 × 215, 80 kg/m^2, Fibo 850 3.6N, F1003, F1403 (Lignacite Ltd)	0.42	60	5
4	Paints	1800	kg	Glossy and semi-gloss paint, 1.24 kg/L, Alcro Milltex V-Mill BL, Alcro Milltex V-Mill HBL, Beckers Scotte 70 Snickerifinish, Beckers Scotte 40 Snickerifinish (Tikkurila Group)	2.06	470	5
5	Tiles	450	m^2	Glazed wall tiles, Group BIII, 6.5–10 mm, avg weight 13.93 kg/m^2 (Johnson Tiles)	0.59	320	5
6	Windows	30.2	m^2	Insulating glass unit, double glazed, 16.22 mm, 42.5 kg/m^2 (Klaasimeister AS)	1.73	380	5
7	Façade Cladding	30.2	m^2	Floor and façade stone, Finnish average, 2700 kg/m^3 (KIVI ry)	0.31	60	5
8	Mortar	42,000	kg	Tile grout for ceramic tiles and clinker, Kiilto Pro Tile grout 40 (Kiilto Oy)	0.52	110	5
9	Roof insulation	300	m^2	XPS insulation panel with cement mortar and fiber glass mesh facing, L = 0.033 W/mK, R = 0.37 m^2K/W, 12.5 mm, 600 × 2600 mm, 3.54 kg/m^2, Tulppa (Finnfoam Oy)	0.88	380	5
10	Doors	1390	kg	Sliding door system, MDF board, Thickness 66 mm, 73.7 kg, door dimensions 931 × 2060, steel frame dimensions 1935 × 2130, LIUNE-door system with glass/MDF door (Aulis Lundell)	0.404	350	5

Fig 7 | Foundation and substructure data used in the base case model

Fig 8 | Vertical structures and façade materials data for the base case model

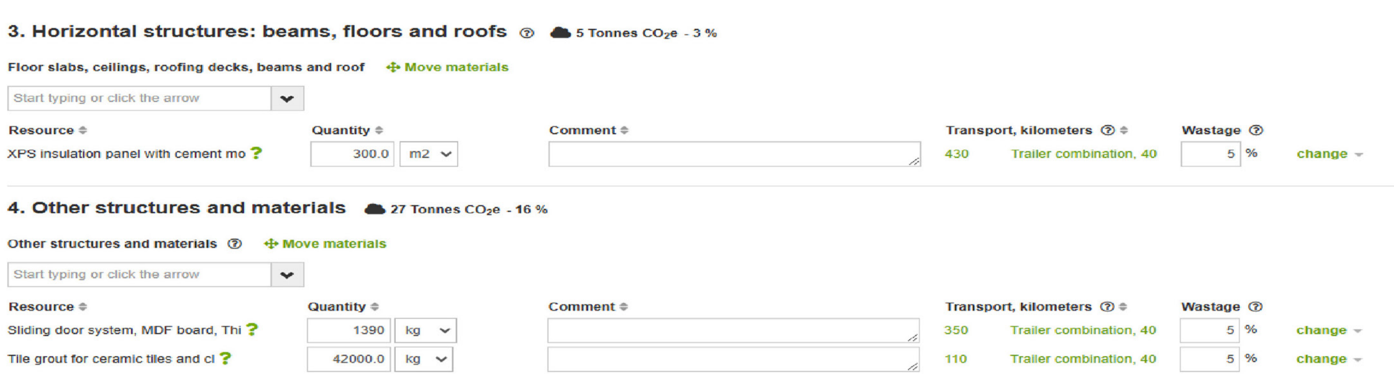

Fig 9 | Other structures and materials data used in the base case model

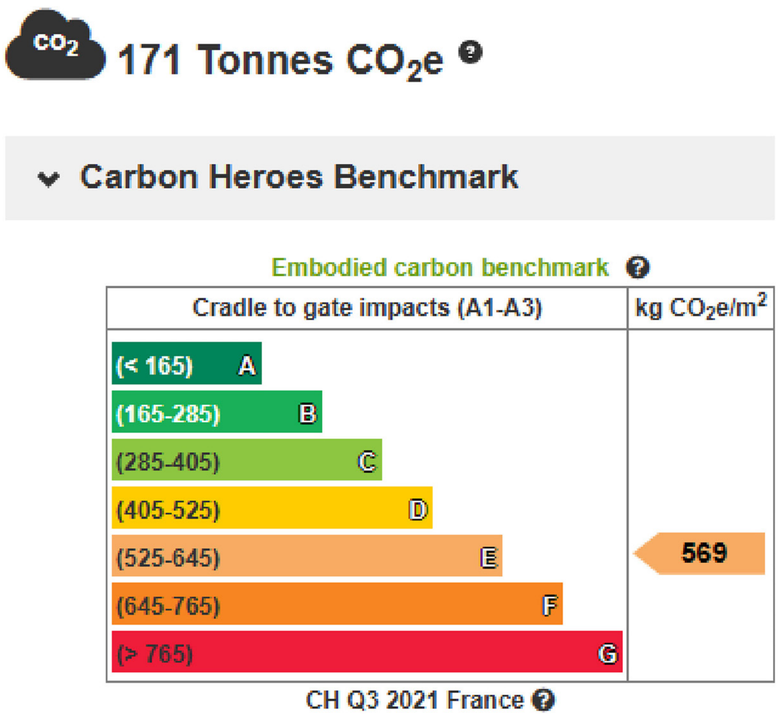

Fig 10 | Embodied carbon benchmark of the base case model

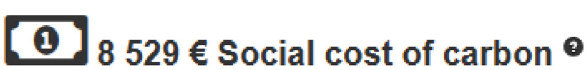

Fig 11 | One click LCA

percentage increased 1.7% from 31.8% to 33.5% of the GWP, while ready-mix concrete increased 2.2% from 18.4% to 20.6%. And it is logical since concrete will be transported each 10 m^3 separately (60 × 108/10 = 660 km) while all the 16.2 tons of steel can be transferred once to the site (370 km).

Optimized Model Material Data

In order to reduce the environmental impact of the materials, we will choose materials with recycled content, steel, and aluminum, or that have cradle to cradle LCA.

For ready mixed concrete, recycled binders, and a partial replacement of cement with other materials were used. Also, for the paint and insulation, we picked ones that have better raw materials and longer service life. For the wood doors, we will try using reused material as wood can be easily reused. For the CMU item, we will go for a lightweight product with the same size but lower emissions.

Table 3 represents the materials used for the optimized model.

Optimized Model Results

The embodied carbon of the building has reduced from 569 kg CO_2/m^2 to 268 kg CO_2/m^2 as shown in Figure 16, representing a 52.89% reduction, which is very remarkable. This has moved the building to a new benchmark from 569 kg CO_2/m^2 to 285 kg CO_2/m^2, from zone E to zone B.

The social cost of carbon has reduced from 8,529 € to 4,022 €. If the difference in cost between alternative

No.	Resource	Cradle to gate impacts (A1-A3)	Of cradle to gate (A1-A3)
1.	Ready-mix concrete, normal strength, generic, C25/30 (3600/4400 PSI), with CEM I, 0% recycled binders (280 kg/m3; 17.5 lbs/ft3 total cement)	2 kg CO_2e	71.0 %
2.	Reinforcement steel (rebar), generic, 0% recycled content (only virgin materials), A615	0,23 kg CO_2e	8.1 %
3.	Tile grout for ceramic tiles and clinker,	0,18 kg CO_2e	6.2 %
4.	Lightweight expanded clay aggregate (LECA) block, 440x100x215, 440x140x215, 80 kg/m2	0,14 kg CO_2e	4.8 %
5.	Glossy and semi-gloss paint, 1.24 kg/L	0,08 kg CO_2e	2.8 %
6.	Glazed wall tiles, Group BIII, 6.5-10 mm, avg. weight 13.91 kg/m2	0,08 kg CO_2e	2.7 %
7.	Floor and facade stone, Finnish average, 2700 kg/m3	0,06 kg CO_2e	2.2 %
8.	XPS insulation panel with cement mortar and fibre glass mesh facing, L = 0.037 W/mK, R = 2.162 m2K/W, 80 mm, 600x2600 mm, 5.9 kg/m2	0,03 kg CO_2e	1.0 %
9.	Insulating glass unit, double glazed, 16.22 mm, 42.5 kg/m2	0,02 kg CO_2e	0.7 %
10.	Sliding door system, MDF board, Thickness 66 mm, 73.7 kg, door dimensions 931x2060, steel frame dimensions 1935x2130	0,02 kg CO_2e	0.7 %

Fig 12 | GWP based on the LCA of each material

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	Result category	Global warming t CO_2e	Global warming kg CO_2e/m^2	Mass of raw materials t	Mass of raw materials kg/m^2
1	Ready mix concrete (A1-A3)	31	105	259	864
2	Precast concrete (A1-A3)	25	85	60	200
4	Steel (A1-A3)	54	181	16	54
6	Bricks (A1-A3)	4	12	6	21
7	Glass (A1-A3)	3	9	1	4
8	Insulation (A1-A3)	5	15	2	6
11	Other materials (A1-A3)	38	125	72	240
A1-A3	Construction Materials	160	532	417	1 389
A4	Transport to the building site	3	9		
A5	Construction/installation process	8	27	21	70

Fig 13 | Results showing the kg of CO_2e of each resource used in the building

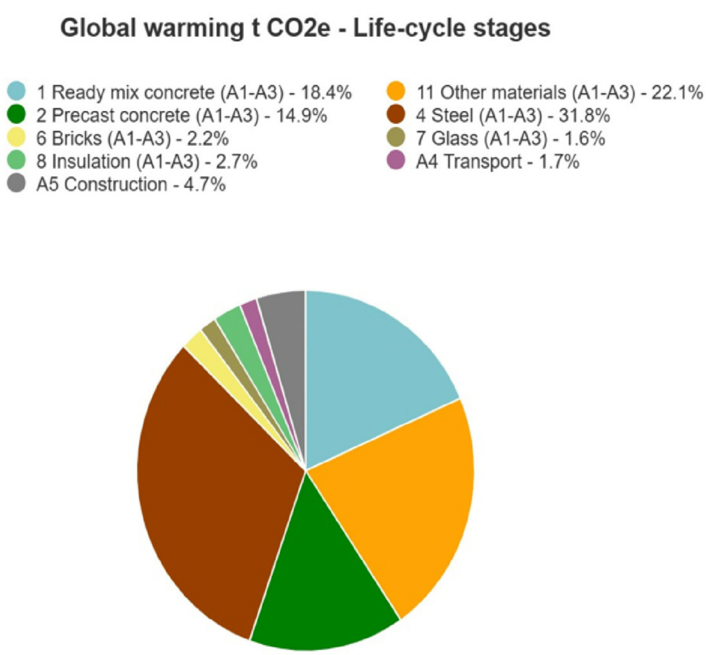

Fig 14 | GWP based on material life cycle stages for the base case model

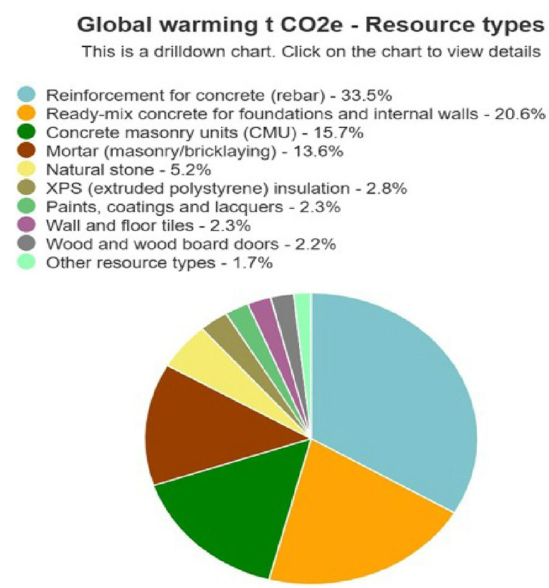

Fig 15 | Contribution to GWP of each material expressed in percentage for the base case model

materials used and base case materials is up to 4507 € (8529 – 4022), then it is justified to choose the alternative materials over the ones used in the base model.

Figure 17 shows the GWP based on the LCA of each material. It is clear that no red color is used again except for insulation.

The reinforcements have become third since it has reduced from 33.5% to 19.1% from Figure 18. While ready-mix concrete is still the second with a percentage of 25.1%.

Since the environmental impact of most of the materials from cradle to gate has reduced, we notice that the impact of transport has become more remarkable, and increased from 1.8% to 3.7%, as in Figure 19.

Comparison and Discussion

The substitution of base case model materials with other sustainable materials has a huge impact, and this is well seen from Figure 20, where we can see the environmental impact reduction percentage between the two models.

Table 3 | Materials used for optimized model

Optimized Model Materials							
S/N	Item	Quantity	Unit	Description	Environmental Profile ($kg\ CO_2e/kg$)	Transport (km)	Waste (%)
1	Concrete	108	m^3	Ready-mix concrete, normal strength, generic, C20/25 (2900/3600 psi), 55% recycled binders in cement (240 kg/m^3/14.98 lbs/ft^3)	0.0616	60	5
2	Reinforcements	16,200	kg	Reinforcement steel (rebar), generic, 97% recycled content (typical), A615.	0.5	370	5
3	Partition	750	m^2	High density concrete block, 440 × 215 × 215, 260 kg/m^2, Lignacrete Hollow 10.4N 215, DH21510, DH2157 (Lignacite Ltd)	0.0996	60	5
4	Paints	1800	kg	Interior paint, 1.331 kg/L, average spreading rate 5.5 m^2/L, Alcro, Beckers, Tikkurila (Tikkurila)	1.33	470	5
5	Tiles	450	m^2	Glazed wall tiles, Group BIII, 6.5–10 mm, avg weight 13.93 kg/m^2 (Johnson Tiles)	0.59	320	5
6	Windows	30.2	m^2	Insulating glass unit, double glazed, 16.22 mm, 42.5 kg/m^2 (Klaasimeister AS)	0.88	380	5
7	Façade Cladding	30.2	m^2	Façade stone slab, from slate, Finnish average, 2700 kg/m^3 (KIVI ry)	0.0767	60	5
8	Mortar	42,000	kg	Cementitious mortar for masonry work, BSEN 998-2 (CPI Mortars)	0.15	110	5
9	Roof insulation	300	m^2	XPS insulation panel with cement mortar and fiber glass mesh facing, L = 0.033 W/mK, R = 0.37 m^2K/W, 12.5 mm, 600 × 2600 mm, 3.54 kg/m^2, Tulppa (Finnfoam Oy)	0.88	380	5
10	Doors	1390	kg	Wooden door with wooden frame, 65.41 kg/unit, 2.069 m^2/unit, Konstruktion 25 (KaliDörren Group AB)	0.24	350	5

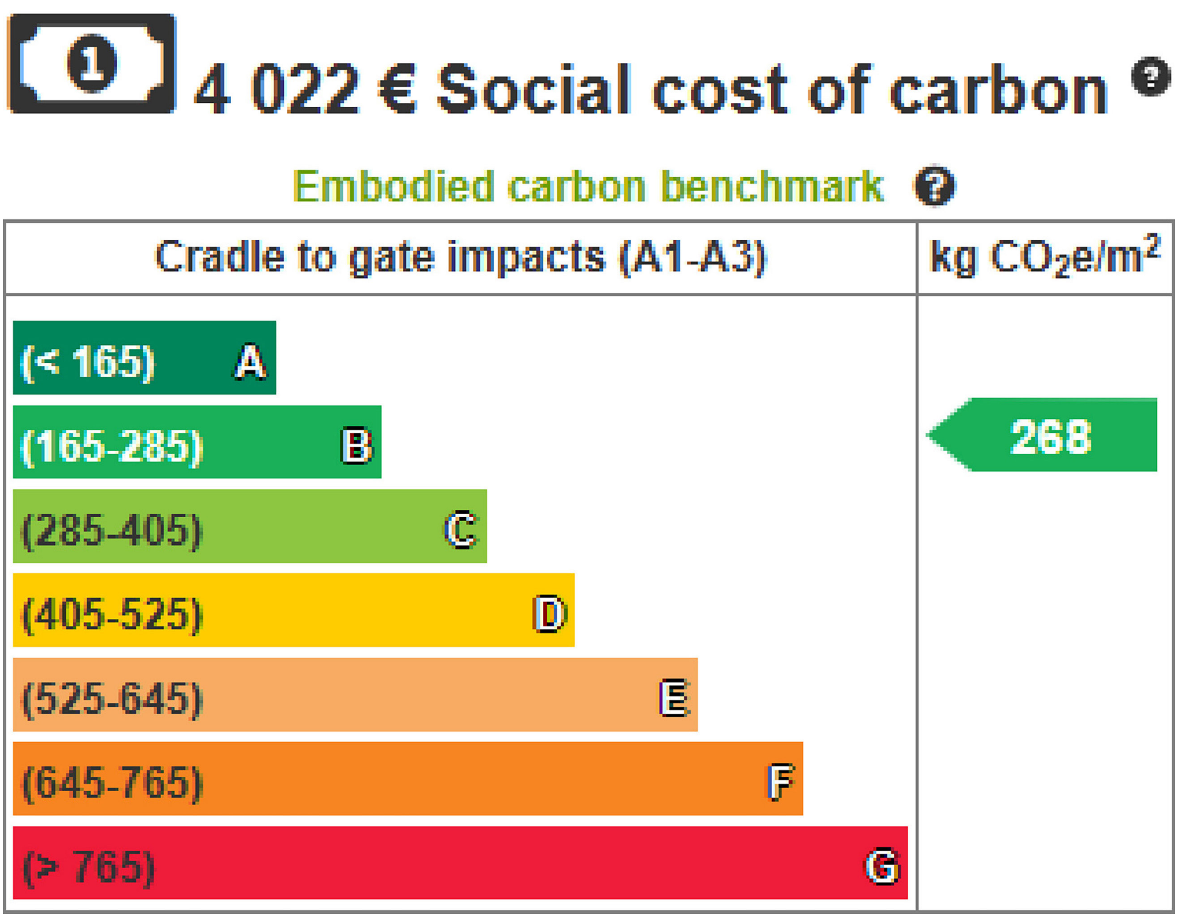

Fig 16 | Embodied carbon benchmark of the optimized model

Where we achieved a reduction, it is marked in green color, while where there was an increase, it is marked in red.

In Figure 21, the improvement in terms of GWP between the two models is obvious, and it is about 50%. As stated before, concrete and reinforcements with

No.	Resource	Cradle to gate impacts (A1-A3)	Of cradle to gate (A1-A3)
1.	Ready-mix concrete, normal-strength, generic, C20/25 (2900/3600 PSI), 55% recycled binders in cement (240 kg/m3 / 14.98 lbs/ft3)	1,9 kg CO_2e	62.2 %
2.	High density concrete block, 440x215x215, 260 kg/m2	0,45 kg CO_2e	15.0 %
3.	Reinforcement steel (rebar), generic, 97% recycled content (typical), A615	0,23 kg CO_2e	7.7 %
4.	Cementitious mortar for masonry work, BSEN 998-2	0,18 kg CO_2e	5.9 %
5.	Interior paint, 1.331 kg/L, average spreading rate 5.5 m2/l	0,08 kg CO_2e	2.6 %
6.	Glazed wall tiles, Group BIII, 6.5-10 mm, avg. weight 13.91 kg/m2	0,08 kg CO_2e	2.6 %
7.	Facade stone slab, from slate, Finnish average, 2700 kg/m3	0,06 kg CO_2e	2.1 %
8.	Insulating glass unit, double glazed, 16.22 mm, 42.5 kg/m2	0,02 kg CO_2e	0.6 %
9.	XPS insulation panel with cement mortar and fibre glass mesh facing, L = 0.033 W/mK, R = 0.37 m2K/W, 12.5 mm, 600x2600 mm, 3.54 kg/m2	0,02 kg CO_2e	0.6 %
10.	Wooden door with wooden frame, 65.41 kg/unit, 2.069 m2/unit	0,02 kg CO_2e	0.6 %

Fig 17 | GWP based on the LCA of each material

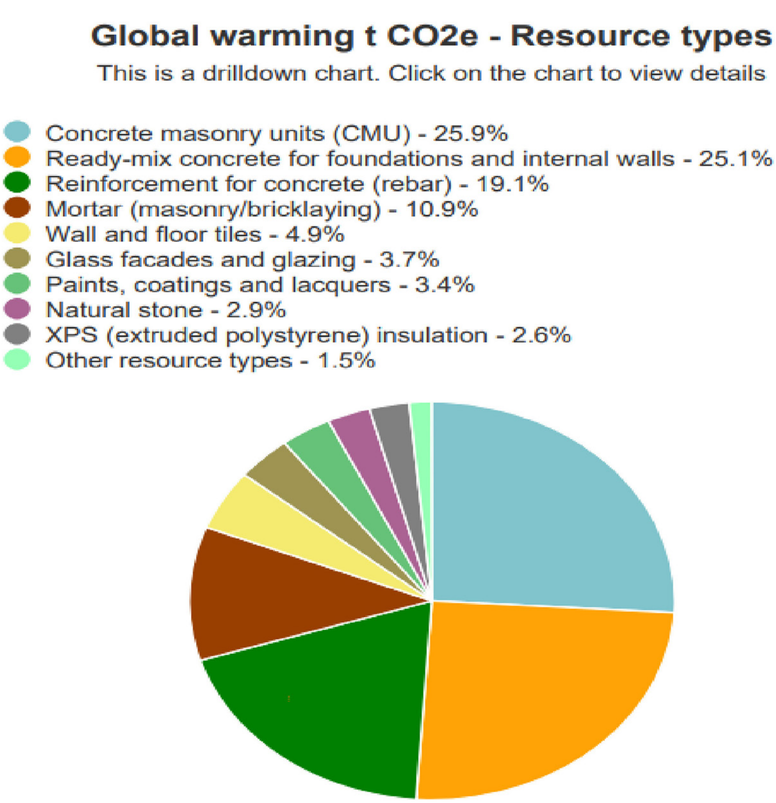

Fig 18 | Contribution to GWP of each material expressed in percentage for the base case model

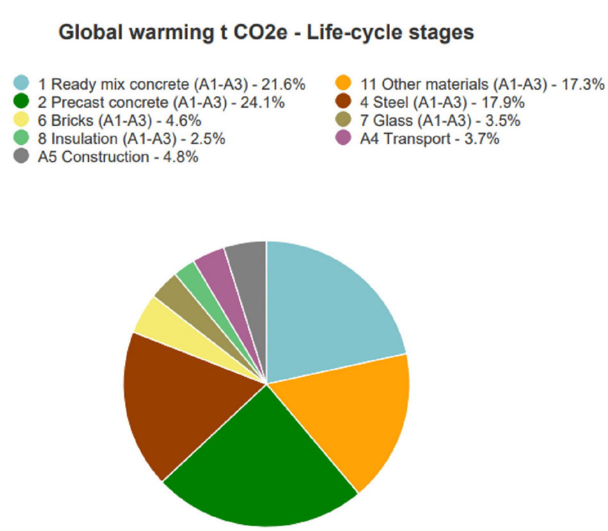

Fig 19 | GWP based on material life cycle stages for the base case model

	Result category	Global warming t CO_2e	Global warming kg CO_2e/m^2	Mass of raw materials t	Mass of raw materials kg/m²
1	Ready mix concrete (A1-A3)	17 | -45 %	58 | -45 %	238 | -8,3 %	792 | -8,3 %
2	Precast concrete (A1-A3)	19 | -24 %	65 | -24 %	195 | +230 %	650 | +230 %
3	Cement (A1-A3)				
4	Steel (A1-A3)	14 | -73 %	48 | -73 %	16 | 0 %	54 | 0 %
5	Aluminium (A1-A3)				
6	Bricks (A1-A3)	4 | 0 %	12 | 0 %	6 | 0 %	21 | 0 %
7	Glass (A1-A3)	3 | 0 %	9 | 0 %	1 | 0 %	4 | 0 %
8	Insulation (A1-A3)	2 | -58 %	7 | -58 %	1 | -40 %	4 | -40 %
9	Wood (A1-A3)				
10	Gypsum (A1-A3)				
11	Other materials (A1-A3)	14 | -63 %	46 | -63 %	72 | 0 %	240 | 0 %
A1-A3	Construction Materials	74 | -54 %	245 | -54 %	529 | +27 %	1 764 | +27 %
A4	Transport to the building site	3 | +4,6 %	10 | +4,6 %		
A5	Construction/installation process	4 | -52 %	13 | -52 %	27 | +27 %	89 | +27 %

Fig 20 | Improvement in % between base case model and optimized model

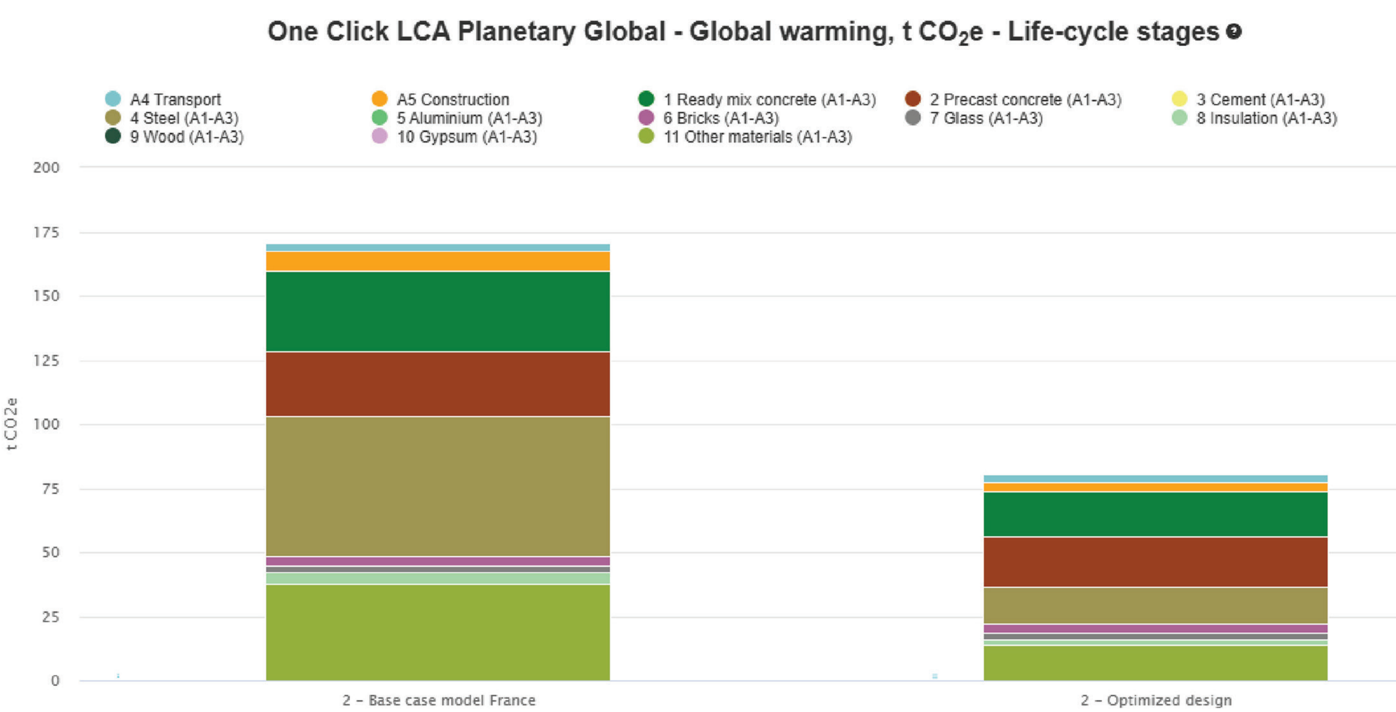

Fig 21 | GWP comparison in terms of life cycle stages

external walls façade have the highest environmental impact, and the reduction is remarkable. Total emissions associated with structural materials reduced from about 100 tons CO_2e to 30 tons CO_2e, while the external walls and façade reduced from about 55 tons CO_2e to 35 tons CO_2e. Other materials have a little contribution, and have reduced from 26 tons CO_2e to 6 tons CO_2e.

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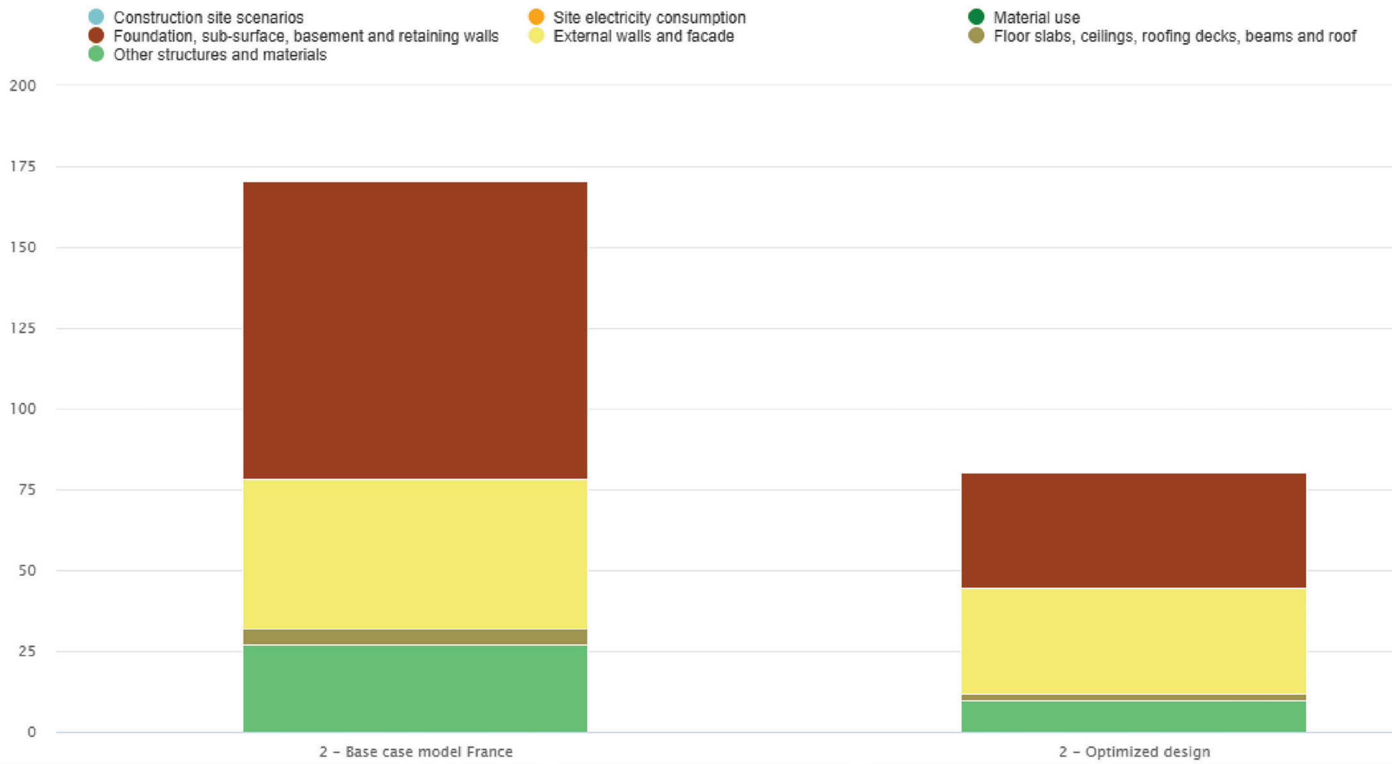

Fig 22 | GWP comparison in terms of most contributing material

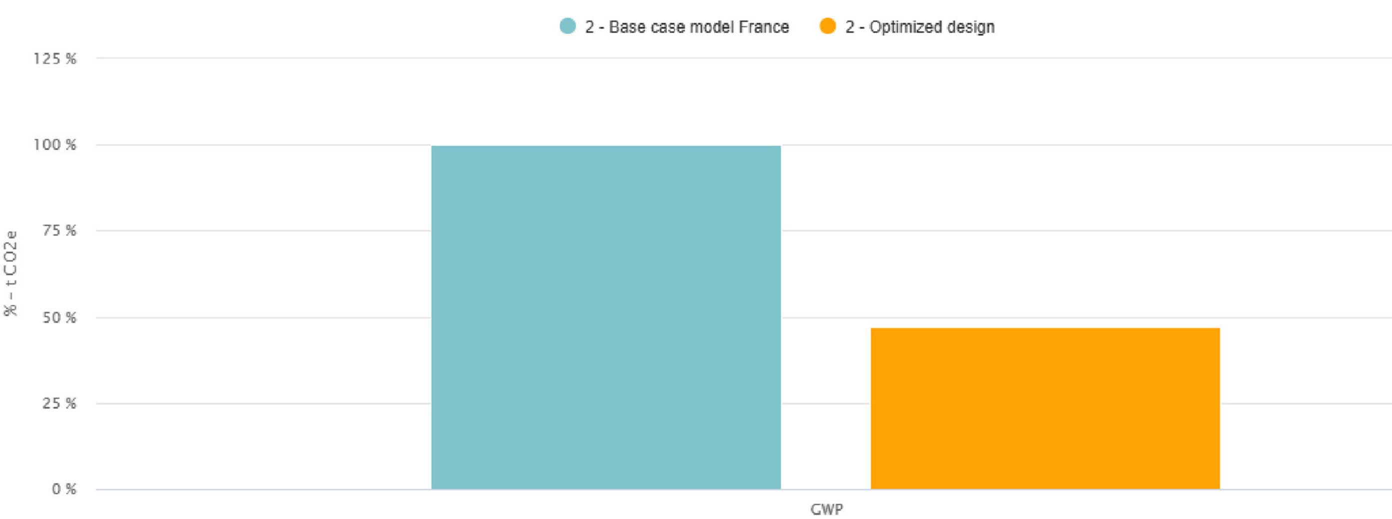

Fig 23 | Environmental impact difference in terms of GWP (% ton of CO_2) between base case model and optimized model

Figure 21 compares the difference between the two models in terms of GWP comparison for the most contributing material (Figure 22).

We can see from Figure 23 that the reduction in GWP is about 52% between the base case model and the optimized model.

Conclusion

Pressure on the environment will continue to rise. Global population increase, rising incomes, and agricultural expansion accompanied by industrial expansion will inevitably produce unanticipated and potentially deleterious ecological, economic, and human health consequences.

Building and infrastructure sectors are not exempt from that aspect, which have high negative consequences on the environment. In order to reduce the environmental impact and limit the negative footprint, serious actions must be taken.

Adopting EPD for materials and applying LCA of buildings, enforced by laws and regulations, with the adoption of building certifications, are promising strategies in order to limit the environmental impact of buildings, and to save what we can save before it is too late.

For our model, using EPD as a selection criterion for materials and applying an LCA of the building, we were able to achieve a reduction of 52% in terms of GWP.

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