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Environmental and Economic Assessment of Eco-Concrete for Residential Buildings: A Case Study of Santiago de Cali (Colombia)

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Abstract: Although the circular economy principles date back to the late 1960s, only with the recent stimulus from the European Commission and the Ellen McArthur Foundation has this concept gained attention worldwide. The City Hall of Santiago de Cali (Colombia) is implementing a circular economy model through a sustainable construction handbook and its certification. Among others, these stimulate the use of eco-concrete using fly ash and blast furnace slag coming from local industries (industrial symbiosis). Although concretes with these supplementary cementitious materials have been widely investigated regarding mechanical and durability properties, the economic and environmental impacts have been scarcely and independently evaluated, making the material selection a complex process. Therefore, this article presents the environmental and economic assessment of eco-concretes using fly ash and blast furnace slag for the design of a house located in Santiago de Cali (Colombia). The environmental and economic impacts are estimated by means of the environmental life cycle assessment (LCA) and life cycle costing (LCC), which are methodologies based on the ISO and ASTM standards implemented in the online software Building for Environmental and Economic Sustainability (BEES), which was selected for this case study. The results indicate that 40% fly ash concrete or 50% blast furnace slag would be recommended for reducing acidification or global warming potential, respectively. However, considering the existing public policies, the best option for the case study is 50% slag concrete. These results are of significant importance as they allow providing data-based recommendations for designers during the selection of the different eco-concretes. Additionally, these results might help establish a national roadmap to reduce carbon dioxide emissions from the construction sector, which are projected to continue increasing until 2050.

Keywords: supplementary cementitious materials; ordinary Portland cement; eco-concrete; LCA; LCC; fly ash; blast furnace slag; planetary boundaries; industrial symbiosis; circular economy

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1. Introduction

The implementation of sustainable development principles in the design of buildings and infrastructure brings important challenges but also huge opportunities regarding innovation in construction materials that balance environmental, social and economic impacts. A current approach to integrate these concepts is circular economy (CE), which is a development paradigm that started to be built by the Club of Rome in 1968 with their MIT report "The limits to growth" published in 1972 [1]. Later, these principles were also incorporated in the Brundtland Report "Our Common Future" published by the World Commission on Environment and Development in 1987. Moreover, the United Nations Organization implicitly included CE principles in the Millennium (2000) and Sustainable Development Goals (2015), respectively. More recently, the European Commission and

Ellen MacArthur Foundation have designed important initiatives to develop the circular economy in different sectors worldwide. This is also supported by the advances in life cycle thinking, planetary and social boundaries [2,3]. A more detailed timeline for CE can be found in Figure 1.

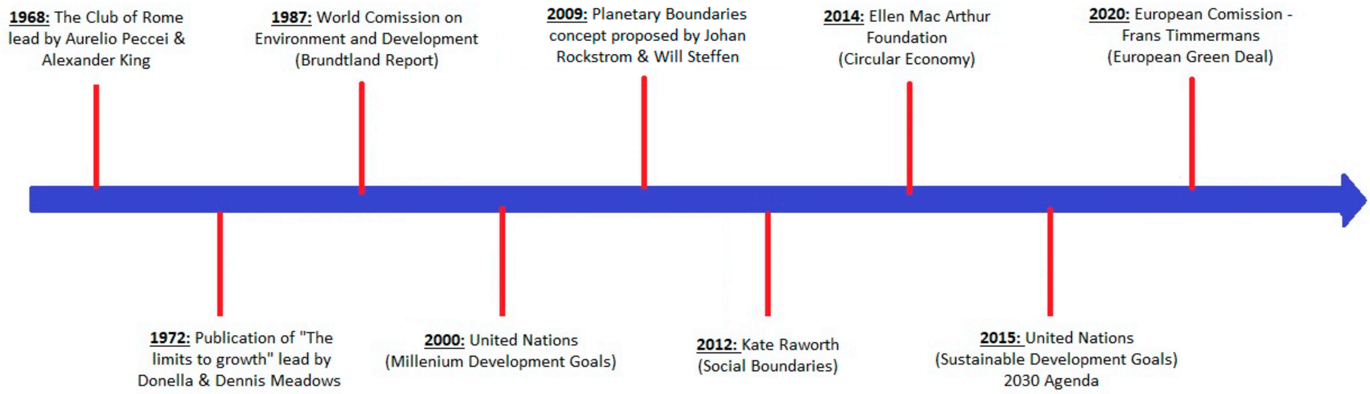

Figure 1. Circular economy timeline.

Using a public policy, consisting of a sustainability construction handbook and its certification, the City Hall of Santiago de Cali (Colombia) is implementing a CE model for the construction sector, which understands the circular economy as a consumption and production system that works for the efficiency in the consumption of materials, energy and water, considering the circular use of material flows and the resilience of ecosystems [4,5]. To do so, alliances and collaborations among different stakeholders are required for the implementation of technological innovations and the promotion of business models that respond to the fundamentals of sustainable development [5]. In addition to other strategies, the CE stimulates products such as recycled aggregates or eco-aggregates, eco-concretes and eco-mortars, eco-prefabricated products and modules, and smart construction materials [6]. These products satisfy the construction sector demand but also consider the following local waste valorization and material development experiences:

(a) Design of a system to generate air purification and self-cleaning on the surfaces of the tunnel of Colombia Avenue (Cali) using a photocatalytic mortar and UV-A lighting. This design project includes economic and environmental performances [7].
(b) Evaluation of semi-intensive green roofs with drainage layers made out of recycled and reused materials. Recycled rubber, recycled polyethylene (PET) bottles and recycled high-density polyethylene (HDPE) trays were evaluated as drainage layers regarding their hydraulic, thermal and mechanical performances in prototyped green roofs [8,9].
(c) Evaluation of the mechanical properties of concrete using recycled aggregates obtained from old paving stones coming from Almaguer (Cauca, Colombia). The results showed promising results with a mix replacing 50% of the natural fine aggregate with recycled ones [10].
(d) Evaluation of the effect in mortars of the partial replacement of Portland cement by ash from the paper industry. In particular, the fly ash was coming from the coal combustion in the manufacturing process of a local paper company [11].

Based on the previous technical results, making decisions about the best construction material for a specific application on a building or infrastructure is a complex process which is normally based on the designer's experience. Moreover, although sustainable building materials have been intensively investigated regarding their mechanical and durability properties, their environmental and economic impacts have been scarcely and independently evaluated. For example, although several articles have been recently published to evaluate the environmental impact of ordinary Portland cement (OPC) replacements with FA and BFS [12–15], few articles have applied the life cycle assessment (LCA) and life cycle costing (LCC) results to the materials selection for buildings and infrastructure.

This is because these studies used a cradle to gate approach, which does not include the construction, use and operation, and end of life of buildings or infrastructure. Moreover, few articles have integrated LCA and LCC results to the planetary boundaries and national development strategies [16].

In relation to the cases which applied LCA and LCC for materials selection with a wider system boundary, the environmental impacts and cost analysis of using copper slag as cement replacement (5%, 10%, and 15%) in concretes with compressive strengths of 20.7 MPa, 27.5 MPa, 34.5 MPa, and 41.40 MPa at 28 days for low-rise and mid-rise structures in the Philippines was performed. Based on the results, the use of copper slag was established as being beneficial to the abiotic depletion potential (fossil) and global warming potential, but it exerted damaging effects on abiotic depletion and human toxicity potentials, respectively. Moreover, the use of the copper slag as a partial cement replacement was found to reduce building costs by 1.4% and carbon emissions by 12.8% [17]. Similarly, the environmental, economic, and social impacts of using 20% fly ash as cement replacement (7FA20) in early-age high-strength concretes with compressive strengths of 55 MPa at 7 days (7OPC) and 28 days (28OPC) for two bridges in the Philippines were analyzed. The results show a higher impact of 7OPC on 17 midpoint and 3 endpoint indicators when compared to 28OPC. The most significant midpoint impacts based on normalization are fossil resource scarcity, global warming potential, ozone formation, human carcinogenicity toxicity, and terrestrial ecotoxicity. The global warming potential of 7OPC was quantified to be 636 kg CO_2 eq compared to 549 kg CO_2 eq of 28OPC concrete. Utilizing fly ash decreased the damage to resources (11%), human health (16%), and the environment (16%). Analysis of concrete constituents indicated that using chemical admixtures to obtain early high strength contributed significantly to fossil resource scarcity and resource damage [18]. In addition, the environmental impacts from building materials for the construction of a residence project in Brazil were determined. The results indicate a substantial waste of non-renewable energy, increasing global warming and harm to human health in this type of construction [19].

It is worth mentioning that FA and BFS are local wastes that have the potential of significantly reducing the current consumption of ordinary Portland cement (industrial symbiosis), which is projected to continue increasing in the global south region until 2050, as indicated by the recent Global Consensus on Sustainability in the Built Environment [20]. So, by systems to exchange waste and by-products, industrial symbiosis is a promising tool for innovative green growth of the construction sector, as this engages diverse organizations in a network to foster eco-innovation, long-term culture change and mutual benefits [21,22].

Therefore, taking into account that using life cycle assessment and life cycle costing allows consolidating, comparing, and assessing sustainability impacts [23], this article presents the selection process of eco-concretes with blast furnace slag (BSF) and fly ash (FA) to be used in a sustainable house in Santiago de Cali (Colombia).

2. Case Study

In the course of Sustainability in Construction from the Master of Civil Engineering of PUJCali, a sustainable house was designed for a family of five persons in Santiago de Cali (Colombia). To do so, a flat land of 150 m^2 and a budget of 100,000 USD were available. Considering the above indicated requirements and the local climatic conditions, students designed a one-floor house, which includes energy and water efficiency strategies, with four bedrooms, two bathrooms, a visitor´s toilet, living room, dining room and terrace. In addition, considering the high seismic risk of Santiago de Cali and high probability of an earthquake occurrence, and looking for a flexible architectural design, the following structural elements with 28 MPa compressive strength were considered: aerial beams (0.30 m × 0.35 m), columns (0.30 m × 0.30 m) and foundation beams (0.40 m × 0.3 m). Finally, for selecting the best eco-concrete, a matrix with their environmental impact categories, concrete products and associated scores that range from 1 for the best option (with lower environmental impact values), 2 for the second-best option, and so on was used. A general view of the designed house is given in Figure 2.

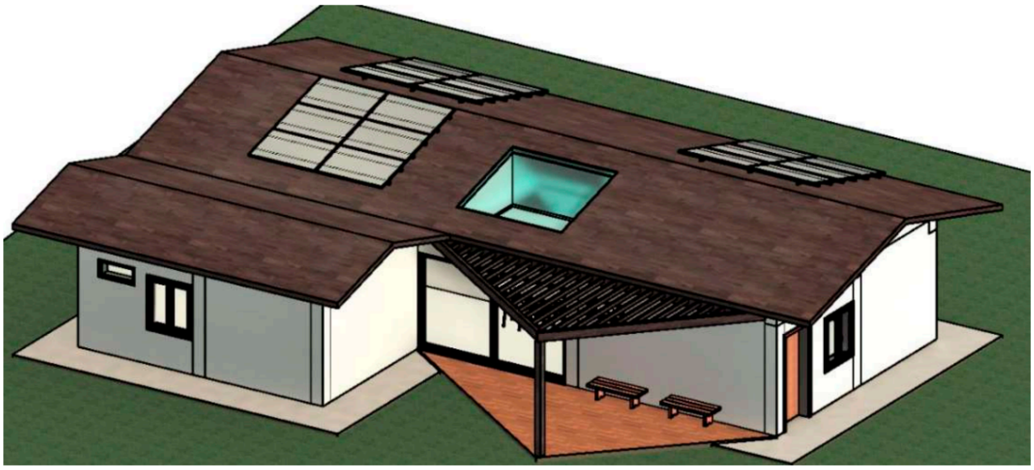

Figure 2. Three-dimensional (3D) view of the proposed sustainable house in Santiago de Cali (Colombia) [24].

3. Methodology

The LCA and LCC standard methods developed by the American Society for Testing and Materials (ASTM) and the International Organization for Standardization (ISO) were followed in this research, respectively. In both cases, the open access and online software Building for Environmental and Economic Sustainability (BEES) version 2.1, developed by the National Institute of Standards and Technology (NIST) from the U.S. Department of Commerce, was selected for the integrated development of LCA and LCC [25]. Using a Microsoft SQL server, BEES integrates Simapro version 8.0 and Ecoinvent 2017, which was recently ranked among the top databases for construction supplies [18]. For this case study, the following concrete mixes with a compressive strength of 28 MPa using Portland cement (reference), fly ash and blast furnace slag were assessed (Tables 1 and 2). More details about the technical challenges and limitations of using FA and BFS in concrete can be found in the recent state-of-the-art book which focus on the properties of concrete containing supplementary cementitious materials in the fresh and hardened state [26].

Table 1. Mix design for concrete with different contents of fly ash and compressive strength of 28 MPa [25].

Material	No Fly Ash or Slag (Kg/m^3)	20% Fly Ash (Kg/m^3)	30% Fly Ash (Kg/m^3)	40% Fly Ash (Kg/m^3)
Portland cement	365.2	307.3	276.5	243.2
Slag cement	0	0	0	0
Fly ash	0	77.1	118.7	162.6
Crushed coarse aggregate	678.6	678.6	678.6	678.6
Natural coarse aggregate	316.2	316.2	316.2	316.2
Crushed fine aggregate	87.4	87.4	87.4	87.4
Natural fine aggregate	656.4	656.4	656.4	656.4
Light weight aggregate	0	0	0	0
Accelerator (accel.)	0.37	0.56	0.56	0.93
Air entrainer	0.04	0.04	0.06	0.06
Water reducer and accel.	0.11	0.11	0.11	0.11
High range water red. and accel.	0	0	0	0
Water	154.8	154.8	154.8	154.8

Table 2. Mix design for concrete with different contents of blast furnace slag and compressive strength of 28 MPa [25].

Material	30% Slag (Kg/m^3)	40% Slag (Kg/m^3)	50% Slag (Kg/m^3)	20% FA, 30% Slag (Kg/m^3)
Portland cement	255.6	219.1	182.6	192.2
Slag cement	109.6	146.1	182.6	115.1
Fly ash	0	0	0	77.1
Crushed coarse aggregate	678.6	678.6	678.6	678.6
Natural coarse aggregate	316.2	316.2	316.2	316.2
Crushed fine aggregate	87.4	87.4	87.4	87.4
Natural fine aggregate	656.4	656.4	656.4	656.4
Light weight aggregate	0	0	0	0
Accelerator (accel.)	0.56	0.93	1.11	1.11
Air entrainer	0.04	0.04	0.04	0.04
Water reducer and accel.	0.11	0.11	0.11	0.11
High range water red. and accel.	0	0	0	0
Water	154.8	154.8	154.8	154.8

3.1. Life Cycle Assessment (LCA)

In particular, ISO indicates following four phases for LCAs: (a) objective and scope (ISO 14041), (b) inventory analysis (ISO 14041), (c) impact assessment (ISO 14042), and (d) results interpretation (ISO 14043) (Figure 3).

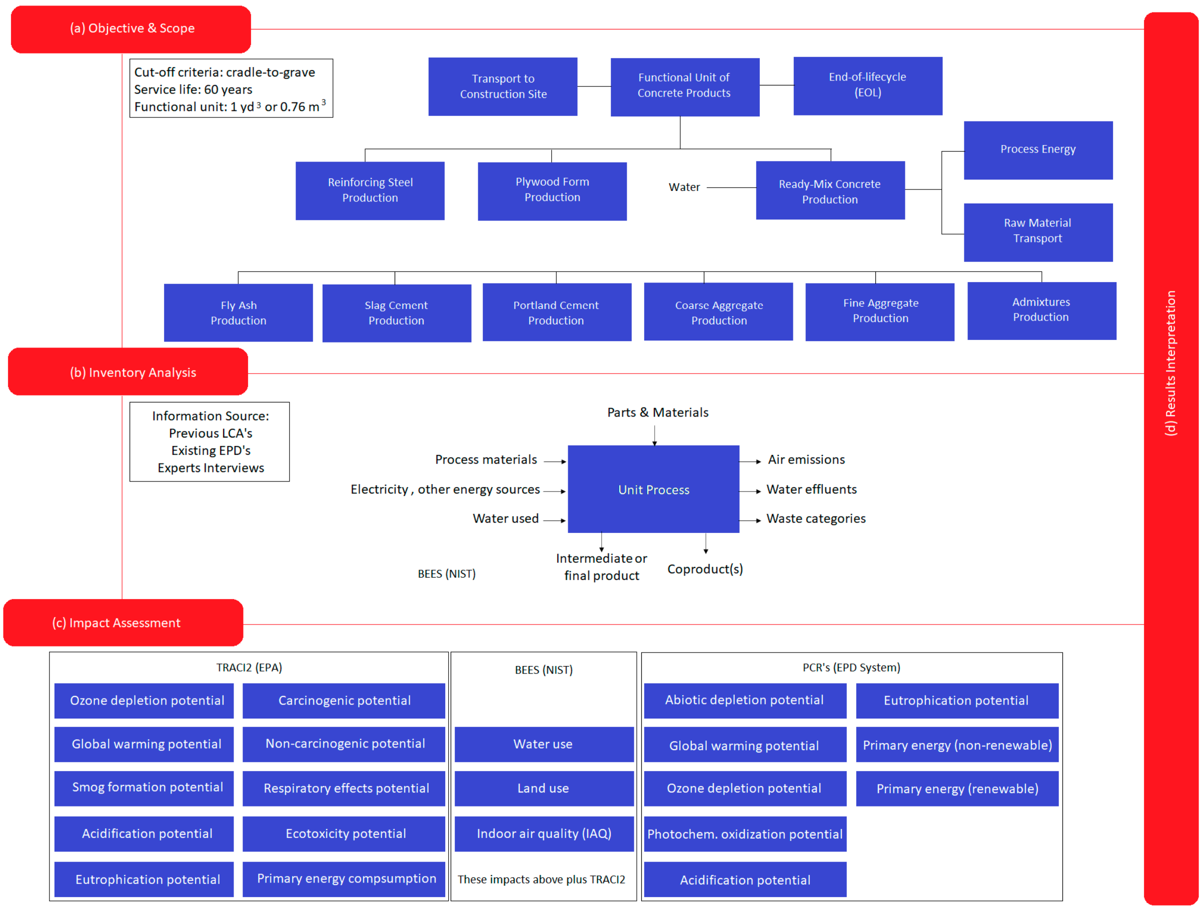

Figure 3. LCA phases (in red boxes) including system boundaries, functional unit and environmental impact categories (in blue boxes).

First, in relation to the objective and scope, the case study was performed using a cradle-to-grave approach, a service life of 60 years (without maintenance or reparation activities), and a functional unit of 1 yd^3 or 0.76 m^3 for beams and columns. Also, the system boundaries include all concrete mix components (fly ash, blast furnace slag, Portland cement, coarse and fine aggregates, admixtures), steel reinforcing and plywood forms. Second, regarding the inventory analysis, the inlet and outlets from the functional unit were estimated using several information sources such as previous LCAs, existing EPDs, and expert interviews, which were information already included and validated in the software BEES. Moreover, a distance of 120 km (74.6 mi) was set based on the concrete and the cement average delivery distance reported within Latin America and the Caribbean [27]. Third, considering the environmental impact categories developed by the U.S. Environmental Protection Agency (EPA), National Institute of Standards and Technology (NIST) and International Environmental Product Declaration System (EPD System), the BEES environmental impact categories were selected for this case study. Finally, in order to interpretate the results, the relative importance weights based on the BEES stakeholder panel were used (Table 3).

Table 3. Relative importance weights based on the BEES Stakeholder Panel [25].

Impact Category	Relative Importance Weight (%)
Climate change	29
Primary energy consumption	10
Human health criteria air	9
Human health cancer	8
Water consumption	8
Ecological toxicity	7
Eutrophication	6
Land use	6
Human health non-cancer	5
Smog formation	4
Acidification	3
Indoor air quality	3
Ozone depletion	2

It is worth mentioning that in this case study, the following conceptualization and monitoring units of the impact categories were used:

Acidification: Acidifying compounds such as sulfur and nitrogen, hydrogen chloride and ammonia can reach water, air and soil from ecosystems attacking flora and fauna. For example, a reduction in coniferous forests and an increase in fish mortality due to acidification has been reported, which is normally indicated by kilograms of SO_2 equivalents (kg SO_2 eq).

Climate change: Also identified as global warming potential (GWP), climate change refers to the increase in the average global temperature as consequence of the greenhouse gas emissions (GHGs). Major GHGs come from the combustion of fossil fuels (e.g., oil, coal and natural gas). The GWP from the GHG emissions is estimated by kilogram of carbon dioxide equivalent (kg CO_2 eq).

Ecological toxicity: This impact indicates the potential damage to land and water ecosystems, which is estimated by comparative toxic units for ecosystems (CTUe). This estimates the potentially affected fraction (PAF) of species integrated over time and volume per unit mass of a chemical released.

Eutrophication: This indicator refers to the potential toxic impacts caused by the excessive presence of mineral nutrients (i.e., nitrogen and phosphorous) on soil or water from an ecosystem. This phenomenon enhances algae growth in water, which normally block fishes' access to oxygen, causing their death. Eutrophication potential is normally estimated in kilograms of nitrogen equivalents (kg N eq).

Human health: This impact refers to potential effects on human health, which can be associated to cancer, non-cancer, or respiratory problems. The characterization factors for human toxicity are estimated by comparative toxic units for human toxicity (CTUh). These estimate the increase in morbidity (i.e., cancer or non-cancer) in the total human population per unit mass of a contaminant released. On the other hand, inhaling fine particulates from air might result in serious health problems (e.g., asthma). This impact category is reported in kilograms of particulate matter of size less than or equal to 2.5 µm equivalents ($PM_{2.5}$ eq).

Indoor air quality: This impact, also known as (IAQ), is associated with the respiratory problems caused by the excessive concentration of pollutant gases inside buildings or even infrastructure (e.g., tunnels and parking lots). Although there is no general consensus about the estimation method, this indicator is normally associated with the presence of volatile organic compounds (VOCs), which is very much controlled in building materials.

Land use: Although this is a composed factor normally measuring impacts on soil properties, BEES only considers the surface area of land occupied or transformed within the system boundaries. So, this is estimated by square meters (m^2).

Ozone depletion: This impact measures the damage potential caused by depleting gases (e.g., chlorofluorocarbons—CFCs) on the ozone layer, which protects life on earth from short wave radiation. Ozone depletion is reported in kilograms of trichlorofluormethane, also known as Freon-11, equivalents (CFC-11 eq).

Primary energy consumption: This refers to the required energy along the production system and the embodied energy in the products. Primary energy consumption can include non-renewable (e.g., coming from fossil fuels and nuclear power) and renewable energies (e.g., coming from hydropower, wind power and biomass). So, these impact categories are estimated using the cumulative energy demand method (CED) in megajoules (MJ).

Smog formation: This impact is associated with the photochemical oxidation potential caused by the formation of photochemical oxidants, including ozone (O_3), under certain environmental conditions (e.g., UV radiation) and air pollutants (e.g., NO_X, VOCs). This is estimated in kilograms of O_3 equivalents (O_3 eq) or ethylene equivalents (C_2H_4 eq).

Water consumption: Although water access and availability are different from region to region, this factor is associated with the consumption of freshwater, which controls the availability or scarcity of water in the system boundaries. The impact potential is estimated in liters (L).

3.2. Life Cycle Costing (LCC)

Determining the economic impacts of concrete products with BEES is an easier process than measuring the environmental ones. This because available data and standard methods for developing economic performance evaluations exist. The most appropriate method for determining the economic impacts of building products is the LCC method following the ASTM standard for the life cycle costing of building related investments [28].

In this case study, the total LCC of a concrete product (C_{LCC}) is the sum of the present values of first cost (C_{First}) and future costs (C_{Future}) minus the residual value (RV), as shown in the following equation:

$$C_{LCC} = C_{First} + C_{Future} - RV \tag{1}$$

Based on the LCC methodology and BEES requirements, the study period was defined as 60 years (in agreement with the LCA), installation costs of approx. 77.59 USD (343,315 COP per m^3), discount rate of 3%, and social cost of CO_2 emissions was \$12/ton (Table 4), as suggested by BEES.

Table 4. Social cost of carbon per metric ton [25].

Time (Year)	Cost (USD)
2010	12
2015	13
2020	15
2025	17
2030	19
2035	22
2040	26
2045	28
2050	32

4. Results

The online software BEES was set using the conditions previously described in the LCA methodology for the selection of the best eco-concrete using BFS and FA for a sustainable house to be constructed in Santiago de Cali (Colombia). With this aim, concrete products (i.e., beams and columns) were classified for each environmental category from 1 to 8 based on the environmental impact, where 1 indicated the smallest and 8 indicated the biggest impact, respectively. For instance, the results of the environmental impact on global warming potential from the house beams and columns can be seen in Figures 4 and 5, respectively. In this case, numbers 1 and 8 were assigned to 50% slag concrete and 100% OPC concrete (reference), respectively. These results were the same for all environmental impact factors evaluated except for acidification, in which the trend was different with number 1 assigned to 40% fly ash concrete as can be seen in Figures 6 and 7 for beams and columns, respectively.

On the other hand, the economic performance of the beams and columns for the sustainable house can be seen in Figures 8 and 9. It is evident that there are no significant differences between the cost of the evaluated concrete mixes even when including social carbon costs. So, based on this LCC, there is no evidence to conclude that using by-products in concrete might substantially increase the construction costs.

So, following the proposed methodology to select the best eco-concrete for the sustainable house, a matrix which displays the environmental and economic impact categories and different concrete products was elaborated (Table 5). Based on this, the 1st option is the 50% slag concrete, which is followed by the 20–30% fly ash–slag concrete and the 40% slag concrete (3rd option). This result does not apply for acidification, where the lowest environmental impact is obtained with the 40% fly ash (1st option), which is followed by the 30% fly ash concrete (2nd option), and the 20–30% fly ash–slag concrete (3rd option).

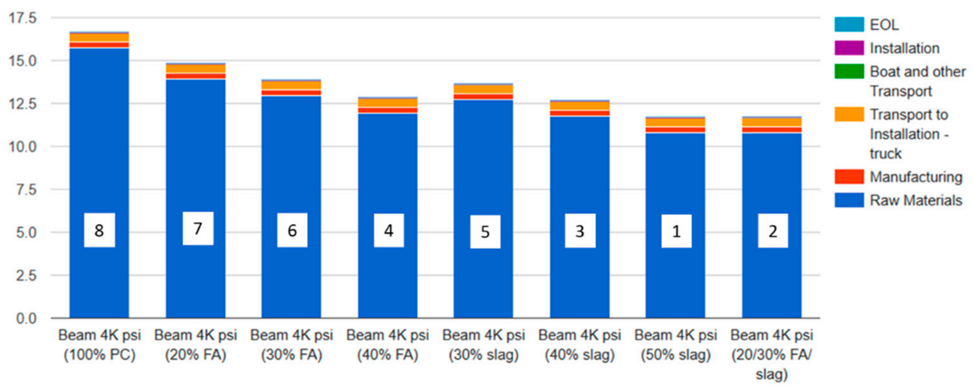

Figure 4. Comparative environmental impact based on the global warming from the different concrete products (beams). Numbers 1 to 8 were assigned from the lowest to the highest impacts, respectively.

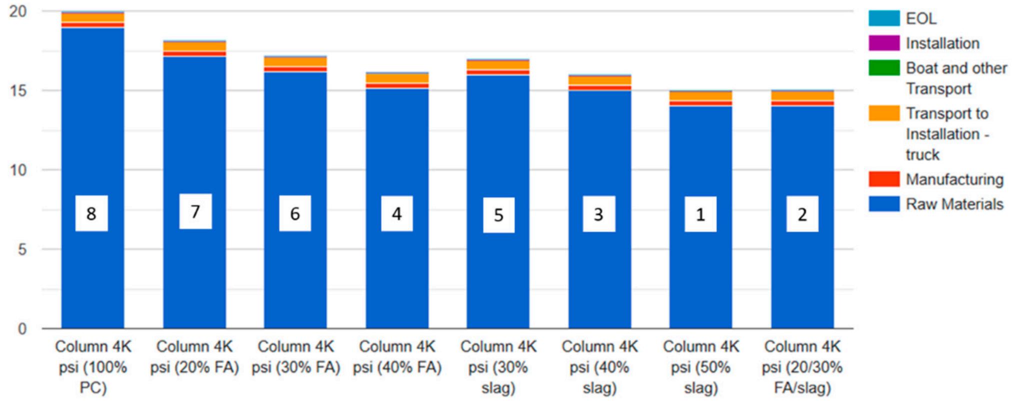

Figure 5. Comparative environmental impact based on the global warming from the different concrete products (columns). Numbers 1 to 8 were assigned from the lowest to the highest impacts, respectively.

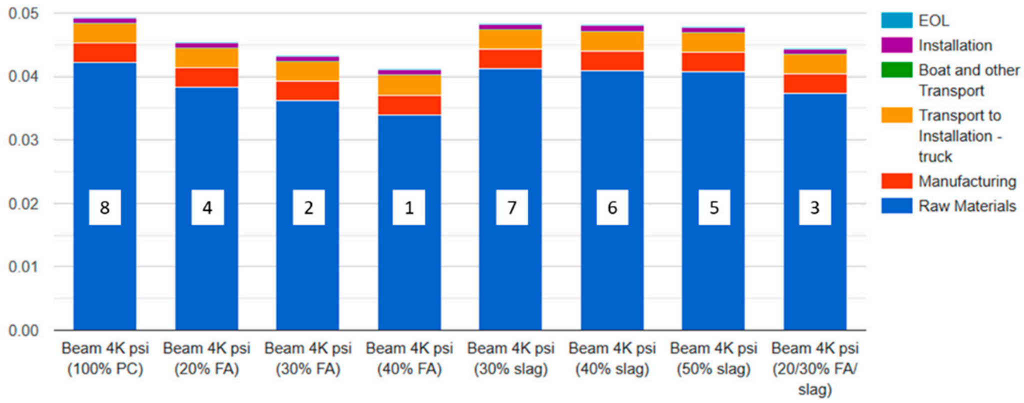

Figure 6. Comparative environmental impact based on the acidification from the different concrete products (beams). Numbers 1 to 8 were assigned from the lowest to the highest impacts, respectively.

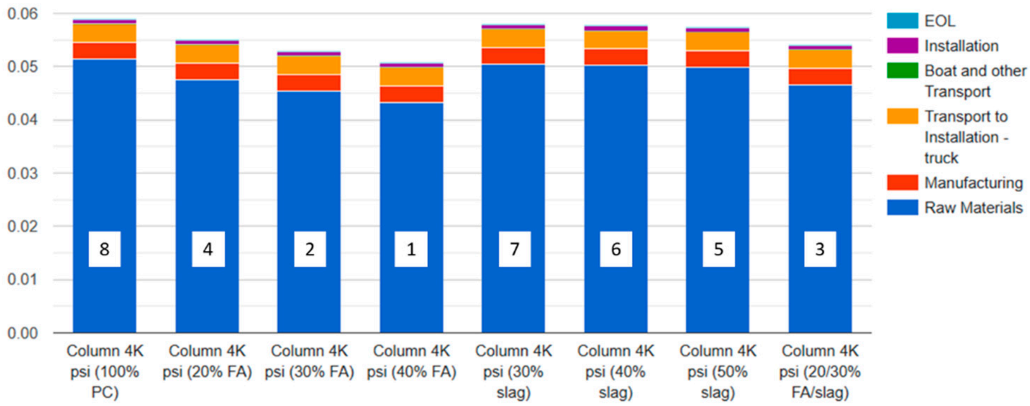

Figure 7. Comparative environmental impact based on the acidification from the different concrete products (columns). Numbers 1 to 8 were assigned from the lowest to the highest impacts, respectively.

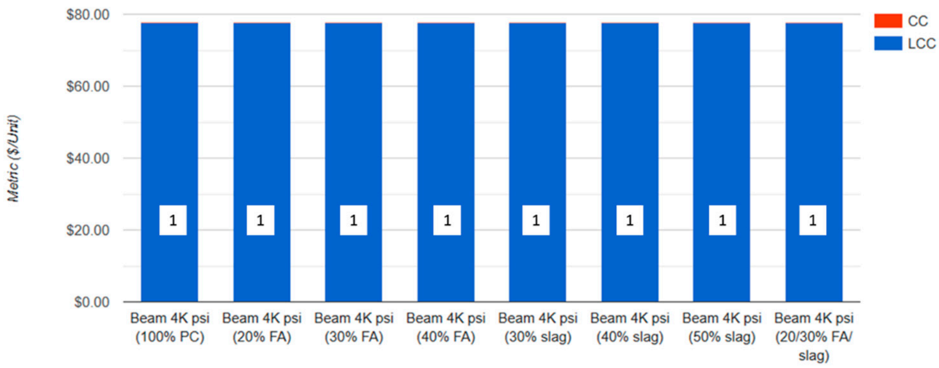

Figure 8. Comparative economic impact of beams using fly ash, blast furnace slag and OPC. As there is no difference between the costs, number 1 was assigned to all concrete mixes.

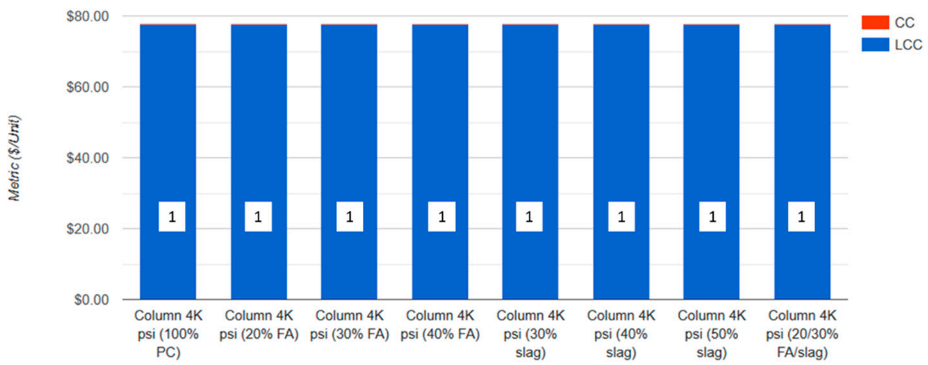

Figure 9. Comparative economic impact of columns using fly ash, blast furnace slag and OPC. As there is no difference between the costs, number 1 was assigned to all concrete mixes.

Table 5. Concrete products scores for the different environmental and economic impact categories.

Impact Category	100% PC	20% FA	30% FA	40% FA	30% Slag	40% Slag	50% Slag	20% FA, 30% Slag
Global warming	8	7	6	4	5	3	1	2
Primary energy consumption (nr)[1]	8	7	6	4	5	3	1	2
Primary energy consumption (r)[2]	8	7	6	4	5	3	1	2
Human health criteria air	8	7	6	4	5	3	1	2
Human health cancer	8	7	6	4	5	3	1	2
Water consumption	8	7	6	4	5	3	1	2
Ecological toxicity	8	7	6	4	5	3	1	2
Eutrophication	8	7	6	4	5	3	1	2
Land use	8	7	6	4	5	3	1	2
Human health non-cancer	8	7	6	4	5	3	1	2
Smog formation	8	7	6	4	5	3	1	2
Acidification	8	4	2	1	7	6	5	3
Ozone depletion	8	7	6	4	5	3	1	2
Indoor air quality	8	7	6	4	5	3	1	2
EP[3]: beams and columns	1	1	1	1	1	1	1	1

Abbreviations: (nr)[1]: non-renewable, (r)[2]: renewable, EP[3]: economic performance.

In order to make a final decision about the best eco-concrete for the selected case study, global and local scales were considered. At the global scale, the concept of planetary boundaries stated by Rockstrom et al. (2009) was considered [2]. The nine planetary boundaries are: climate change, ocean acidification, stratospheric ozone depletion, biogeochemical flows, global freshwater use, change in land use, biodiversity loss, atmospheric aerosol loading and chemical pollution. From these boundaries, climate change, biogeochemical flows (nitrogen cycle) and biodiversity loss have been already exceeded (Figure 10). As the transgression of one or more planetary boundaries may be deleterious or even catastrophic due to the risk of crossing thresholds that will trigger non-linear and abrupt environmental change within continental to planetary scale systems, the most important environmental problem for the selected case study would be climate change compared to acidification. Similarly, at the local scale, it was considered that Santiago de Cali is implementing a net zero carbon building program sponsored by the World Green Building Council [29]. Based on the previous considerations, the best option for the beams and column's project is the 50% slag concrete. However, attention has to be paid to the release of hydrogen chloride, ammonia, sulfur and nitrogen, which may, in gaseous state or dissolved in water or fixed on solid particles reach ecosystems through dissolution in rain or wet deposition, affecting trees, soil, buildings, animals and humans.

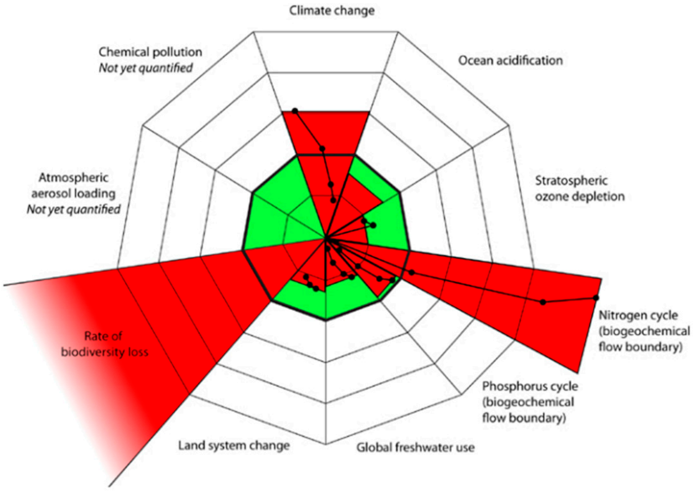

Figure 10. Planetary boundaries stated by Rockstrom et al. (2009) [2].

On the other hand, based on the order of magnitude of the environmental impacts from the house, particularly on global warming, the amount of CO_2 equivalent produced by the concrete structure made with 50% slag concrete is 379.3 kg equivalent CO_2 (Table 6), which is approx. 27% smaller than the equivalent CO_2 that might be released by traditional concrete (100% OPC). This percentage is slightly higher than the average obtained in Colombia (3 to 25%) with other waste valorization strategies in the cement industry [30].

Table 6. Equivalent CO_2 released by different concrete elements from the designed sustainable house in Santiago de Cali (Colombia).

Element	kg CO_2/yd^3	kg CO_2/m^3	Concrete (m^3)	kgCO_2/House
Beams 50% slag concrete (aerial)	12	15.8	7.88	124.5
Beams 50% slag concrete (foundation)	12	15.8	9.00	142.2
Columns 50% slag concrete	15.3	20.1	5.60	112.6
Total				379.3

Therefore, considering the current use of fly ash and blast furnace slag in Colombia, which are 3.5 and 72.3 kg per ton of cement, a gradual and safe transition plan for the cement industry should be designed to achieve the sustainable development goals in 2050, particularly regarding climate change. In order to do so, it is important to indicate that the growing annual CO_2 emissions from Colombia in 2021 were 91.7 million tons, which is 2.5 times smaller than the decreasing CO_2 annual emissions from Spain, which is a country belonging to the European Union with a similar population size (Figure 11). Moreover, with 5.87 million CO_2 tons in 2021, the Colombian cement industry had lower emissions than the oil, gas and coal sectors (Figure 12).

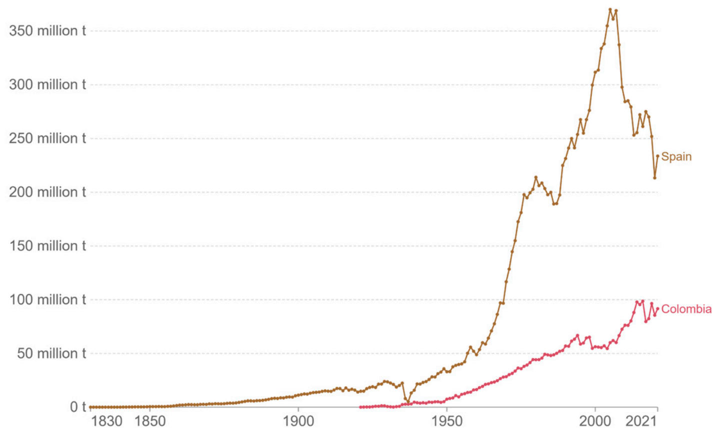

Figure 11. Annual CO_2 emissions from fossil fuels and industry of Colombia and Spain taken from Our World in Data based on the Global Carbon Project (2022) [31].

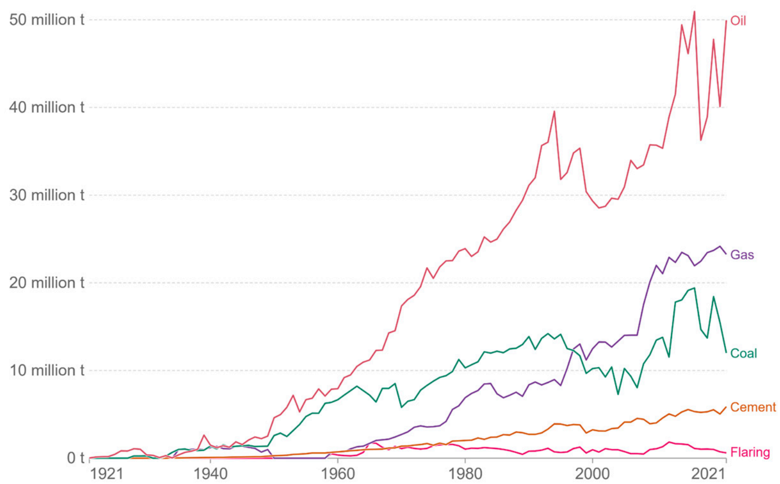

Figure 12. CO_2 emissions by fuels and industry of Colombia taken from Our World in Data based on the Global Carbon Project (2022) [31].

5. Conclusions

First, the performed LCA and LCC using the software BEES allows estimating the environmental and economic impacts of using fly ash and blast furnace slag as replacements of Portland cement in concrete. In this case study, 40% fly ash concrete or 50% blast furnace slag concrete would be recommended for reducing acidification or global warming potential, respectively. Second, considering the net zero carbon program signed by Santiago de Cali and the planetary boundaries, the best option for the sustainable house is the 50% blast furnace slag concrete.

Third, the article describes the environmental and economic differences from valorizing wastes potentially coming from thermoelectric power plants and steel plants in the construction sector under the concept of industrial symbiosis. Future research includes durability differences between concrete using blast furnace slag and fly ash. Also, the social impacts of eco-concretes are taken into account for future works. Finally, considering the current and projected consumption of cement in Colombia, detailed roadmaps to decarbonize the construction sector of Santiago de Cali and other major cities such as Bogotá, Medellin and Barranquilla are required. These roadmaps should work on decarbonizing construction materials as performed with FA and BFS, reducing the needed quantity of materials for new developments and stimulating the rehabilitation of existing buildings and infrastructure. The last strategies can be implemented through public policies that stimulate the use of sustainable building materials as used with the CE model from Santiago de Cali, but they also limit the embedded CO_2 per area in new developments, reduce taxes for building and infrastructure rehabilitation, stimulate research and development in the construction sector, and support standardization committees such as on sustainability life cycle assessment, which is urgently required at the national level to develop Colombian databases.

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