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Material selection for ornamental products based on carbon footprint and embodied water

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Abstract. This paper analyses and compares the Life Cycle Assessment of ceramics, bricks, steel, clay, and polypropylene with cast stone widely used in architectural ornaments. Architectural ornaments include, for example, statues, Georgian architectural window surrounds and balustrading etc. A methodology was proposed within this study which was verified after being applied to the case study. The Life Cycle Assessment of all the materials was performed from "cradle-to-gate" for a kilogram of each material. The transportation of the finished goods is also included in this study as that is a crucial part of a business. The selected materials were compared based on the overall carbon dioxide equivalent, water, and energy consumption during the general manufacturing process. Materials were plotted at the end of this study based on each parameter. Concrete showed the lowest contribution towards the carbon dioxide equivalent whereas cast stone had the lowest water consumption. Polypropylene had the highest energy consumption. A few recommendations to make cast stone greener were also made at the end of this paper.

Keywords: Cast stone, life cycle analysis, carbon footprint, embodied water.

1 Introduction

Life Cycle Assessment (LCA) has gained popularity among researchers and companies to estimate the environmental performance of construction materials widely used [1]. The focus of the current LCA studies has mainly been on the energy efficiency of the building and its Green House Gas (GHG) emission during its life cycle [2]. As per Persson et al, in the majority of the European countries, the primary energy consumption by the buildings is 40% of the total energy consumption [3]. However, some recent studies have been used to improve the designs of the buildings[4, 5] and compare different construction materials[2]. Although the operational phase of such a building contributes around 90% of its total life cycle energy use but the construction phase is also responsible for contributing a significant amount of energy consumption[6, 7]. Such a comparison could help in finding a more energy-efficient alternative.

There are several studies done to perform LCA of various building materials where concrete was included. One such study was performed by Bribián et al. where the total embodied energy of 1 kg of commonly used raw materials was analysed. The study measured the energy consumption during the building construction stage with commonly used raw materials and eco-materials [8]. The raw materials in the study include ordinary, light clay and sand-lime brick. It also included ceramic and quarry tiles along with ceramic roof tiles and concrete roof tiles and insulation material. The study assessed Water Demand (WD), Global Warming Potential (GWP) and Primary Energy Demand (PED). Among the tiles, the ceramic tile had 15 MJ-Eq/kg of PED, 14.453 litre/kg of WD and 0.857 kg CO_2-Eq/kg of GWP making it the highest. Concrete tiles are a greener alternative to ceramic tiles with PED 2.659 MJ-Eq/kg, WD of 0.270 kg CO_2-Eq/kg GWP and WD of 4.104 litre/kg. Among the ordinary and sand-lime bricks, the light clay brick had the lowest GWP at -0.004 kg CO_2-Eq/kg but had 1.41 l/kg of water consumption and 6.25 MJ-Eq/kg of PED.

Similarly, a study done by the Souza et al., where ceramic brick, concrete brick, and cast-in-place reinforced concrete for exterior walls were analysed [2]. Cement is an active ingredient of concrete and cement requires 20% more energy than ceramic bricks. The reason being, for concrete, high temperatures reaching 1450 °C is required which is achieved using fossil fuels. Whereas, for ceramic bricks, a temperature of 950 °C is required which is achieved by burning residual wood chips making ceramic bricks greener than concrete. The study also covered steel production as cast-in-place concrete requires steel reinforcement, making cast-in-place concrete less green than ceramic brick walls. To reduce the environmental impact, two recommendations were given by the author. Firstly, the use of a fine particle filtration system for wood chip burner and secondly, the use of biofuels during the shipment of the fuels.

In another study performed by Lasvaux [9] where 28 different materials commonly used in construction were used to perform LCA. The aim of the study was to check if the LCA databases used in the studies display the expected result when compared to the generic databases as it depends on the background impact data. To perform this study, the study assessed numerical and methodological differences between two existing LCA databases for the LCAs i.e., ecoinvent and a French database called Environmental Product Declaration (EPD) database. It was found in the study that a considerable amount of deviation was seen due to assumptions taken in the databases.

Numerous LCA studies have been done to compare the roofing on the buildings [10, 11]. In the study performed by Bianchini et al., roofs made from the greener alternatives such as low-density polyethene and polypropylene polymer are compared. Similarly, Kosareo et al., performed a comparative ‘cradle-to-gate’ LCA of three types of roofing systems i.e., conventional, extensive green, and intensive green. One study performed by Amaral et al., have performed brief LCA on the naturally quarried ornamental stone such as Marble and Granite[12].

Cast stone is a manufactured stone whose mixed composition is designed to replicate the natural stone [13]. It is widely used as an ornamental stone since the 1770s [14]. Recently, the demand of cast stone has also increased [13]. As it is part of the construction sector none of the studies have mentioned cast stone in their studies.

However, none of the studies mentioned above has performed comparative LCA on the ornamental cast stone. The aim of this study is to compare ornamental cast stones to other construction materials used as ornaments for carbon emissions and embodied water. Cast stone would be compared against steel [15], ceramic [16], concrete[17], polypropylene, cast iron, steel, and clay [12] as they are used widely in making architectural ornaments. The system boundary will be from “cradle-to-gate”, but the transportation is also considered as it also a crucial aspect of a business.

LCA could get affected by the data gathered from several uncertain secondary sources [18]. In the LCA studies multiple methods are suggested by Saltelli et al [24] but for this study. As per Cellura et al., the uncertainty could be due to the methodology used, initial assumptions and the system boundaries and the quality of the data collection. In this study a sensitivity analysis is also performed in the results section.

2 Methodology

LCA can be performed in various ways as per the requirements of the organization as per ISO 14040:2006 [19]. The methodology used in this paper was divided into different steps presented below. The steps used in this methodology are shown in the fig below.

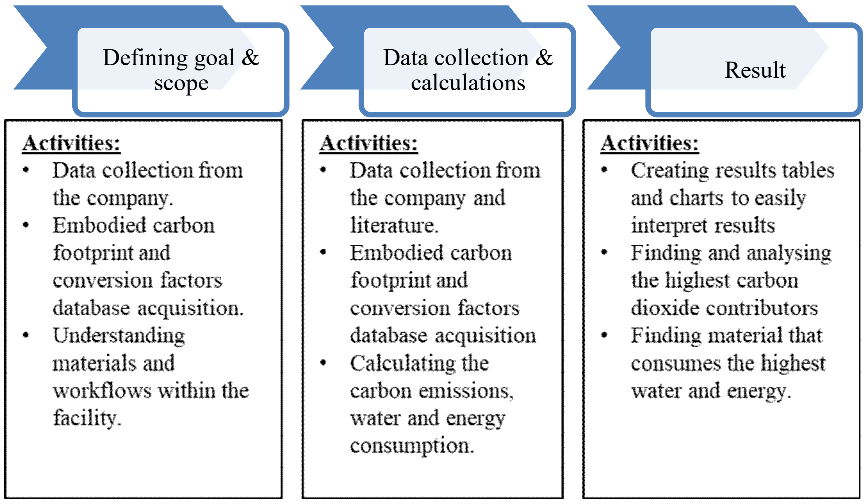

Fig 1. Methodology

2.1 Defining goal and scope

The goal of this study is to compare carbon dioxide emissions and embodied water of different materials used in producing architectural ornaments. The system boundaries for this study are from ‘cradle-to-gate’ i.e., from the point of getting raw material till the final product has been shipped to the customer. To have a valid comparison between different materials, a functional unit is chosen as each material has different density and properties. In this study 1 kg is used as a functional unit.

2.2 Data collection and calculations

For data collection, various databases can be used such as Ecoinvent [20], and Environmental footprints [21] the missing information can also be added to these data bases through the literature review. Data can also be collected from the factory to make the study more accurate. In this step, assumptions are taken (if needed) before calculating the carbon footprint and embodied water. Embodied carbon and water in the raw material is calculated in this step as well. As the study is ‘cradle-to-gate’, the transportation of the product to the customer is also considered within the boundaries of this system.

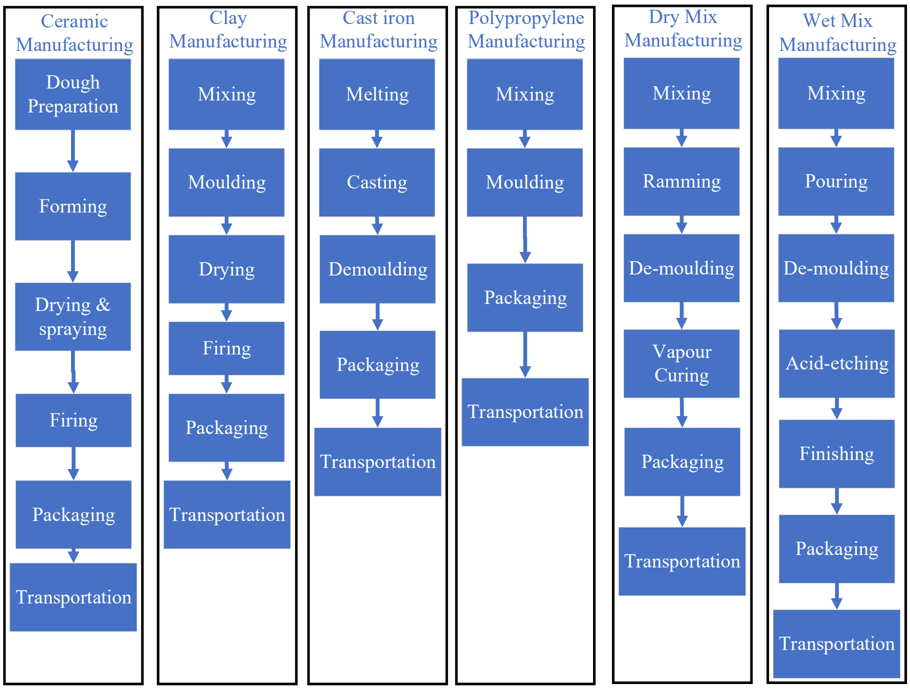

Fig 2. Manufacturing process of different materials and the system boundary

2.3 Result and analysis

After calculating the carbon footprint, in this step, the results are plotted and analysed. For better comparison and interpretation between different materials, the results can be broken down into different sections. Each section will represent separate indicator. For instance, one section would represent carbon footprint and another section embodied water.

3 Case study

3.1 Defining goal and scope

The above-mentioned methodology was applied to a cast stone manufacturing company based in the UK. The study aims to perform comparative LCA on cast stone with clay, ceramic, cast iron, polypropylene, steel, and concrete based on the CO_2 produced per kilogram as well as water consumed and energy demand of the materials. There are 3 types of cast stone i.e., Dry mix, Teclite and Tecstone. The system boundaries for all the materials in this case study are shown in the fig.

In ceramic manufacturing traditionally, a dough is prepared using mechanical mixer. In this step the extracted clay is mixed with other compounds. This step is followed by the mechanical shaping process where mechanical shaping of the ceramic is done. The shape of the ceramic depends on the moulds used. During the drying phase the water content is reduced from 25% to 3% and the ceramic becomes solid. It is also sprayed with a glossy layer that stick to the surface after the firing process. In the firing process, a furnace is used to bake the ceramic with a temperature up to 950°C. Once baked properly the product is packed and shipped [4].

Clay manufacturing follows a similar to ceramics, where a mixture of clay with other additives are moulded into the desired shape. Once it has taken the shape it is baked in a kiln where it becomes solid. Once the final product is made, it is packed and shipped.[22]

Casting process of iron requires melting of iron which is then casted into the desired shape using a mould. Once iron is at the room temperature, mould is opened, and the casted iron goes through a finishing process where any extra metal is removed, or the product is polished. After polishing the product is packed and shipped to the customer.

Polypropylene is an olefin obtained from the fossil fuel[23]. Usually, the granular polypropylene is used for injection moulding process where the granules are melted and injected into a mould where it takes the desired shape. Once it is at the room temperature, the product is packed and shipped.

Cast stone are of three types i.e., Wet mix, Teclite and Dry mix. Teclite and Wet mix follow similar process, where a mix of sand, cement and admixtures are mixed in a calculated proportion. During the mixing stage in Teclite glass fibre is added to the mix whereas, in Wet mix, aggregates are added to the mix. The finished mix is poured into a mould of the desired shape which is demoulded the next day after it is cured. The cast stone is then taken for an acid etching process where Hydrochloric acid (HCl) is used to remove any oil and top surface which exposes aggregates. Once acid etched, the final product is taken for finishing where any imperfections are dealt with as desired shapes made from cast stone can be complex. Once finishing completes the final product is taken for packaging and then it is shipped to the customer. Whereas in Dry mix the no aggregates or glass fibre is added to the mix. As the name suggests Dry mix is a dry powder like substance that is rammed into the mould. Once it is rammed into the mould it is left overnight for curing and then it is de-moulded the next day. After it is de-moulded, it is taken for the vapour curing process where steam is used to fasten the process of curing. This increases the strength of the cast stone. Once cured, it is taken for packaging and then it ready to be transported to the customer. Concrete follows similar procedure where a mix is created which is casted into the desired shape. [13]

3.2 Data collection and calculations

A model of manufacturing process for all the raw materials was created in SimaPro 9 and the ecoinvent data base was used. Ecoinvent database comes with two classifications and three system models. For this case study, market transformation classification was chosen for the material comparison as it considers the transportation of the of raw materials hence the emissions from transportation are included. Also, 'cut-off by classification' system method was used for ease in analysing the default system model. Simapro 9 follows an International Standard ISO 14044:2006 of process-based model with the LCA assessment to be defined in 4 key phases such as 'Define goal and scope', 'Life cycle inventory analysis' (LCI), and 'Impact Assessment' and 'Interpretation'. In the Life Cycle Inventory (LCI), product stage subcategory was selected as it allows the analysis to be performed in a 'cradle-to-gate' boundary. The indicators used were carbon dioxide and climate change biogenic. Company provided any missing data which was entered into the ecoinvent database.

As the concrete's mix design varies for each purpose, it was assumed for this study that no admixtures were added to the concrete block. The composition for concrete and steel was taken from Bribian et al. which were used in SimPro 9 [8]. For this study, the concrete selected is a low strength general purpose concrete. Also, the steel composition selected during the study is chromium steel 18/8 from the ecoinvent database. The method used for carbon dioxide and the water consumption is ReCiPe 2016 v1.1 midpoint whereas to calculate the energy consumption, Cumulative Energy Demand (CED) is used.

3.3 Results and analysis

After performing the calculation in SimaPro 9, the results were obtained. Overall, it was found that the biggest Carbon dioxide emitter was steel at 6.44 kg CO_2-Eq /kg and the lowest being concrete block at 0.158 CO_2-Eq /kg as shown in table 1. The second biggest contributor of carbon dioxide was the Polypropylene (3.68 CO_2Eq /kg) which is a thermoplastic polymer obtained from fossil fuel which justifies the high emissions. Among all the cast stones, the Wet mix was the lowest carbon emitter with 0.478 CO_2 Eq /kg followed by the Dry mix at 0.594 CO_2 Eq /kg.

Table 1. Carbon dioxide, water consumption and energy demand of different materials

Building Material	Carbon dioxide (kg CO_2-Eq /kg)	Water consumption (m^3/kg)	Energy Demand (MJ/kg)
Dry Mix (DM)	0.616	0.000094	4.344
Teclite Mix (TM)	0.824	0.000071	5.47
Wet Mix (WM)	0.478	0.000029	3.228
Cast Iron (CI)	1.93	0.00972	17.5
Ceramics (Cs)	0.825	0.00674	11
Clay (C)	3.49	0.0157	54.7
Concrete Block (CB)	0.158	0.00135	1.28
Polypropylene (P)	3.68	0.0355	97.2
Steel (S)	6.44	0.0276	74.2

Similarly, for the water usage Wet mix uses the lowest amount of water per kg. It uses 0.000029 m^3/kg, whereas polypropylene has the highest water use i.e., 0.0355 m^3/kg. Steel has the second highest water consumption of 0.0355 m^3/kg. Such low water consumption in cast stone is due to the use of super plasticizer. In terms of Energy consumption, polypropylene ranks the highest with 97.2 MJ for per kg and the concrete block ranks the lowest 1.28 MJ/kg. Carbon dioxide, water consumption and energy demand are plotted in fig 3, 4 and 5 respectively for easy comparison for the decision-makers.

However, for this study the density of each material is not taken into consideration so, for instance, if a specific part is produced the density of each material will vary which also would affect the weight of the part.

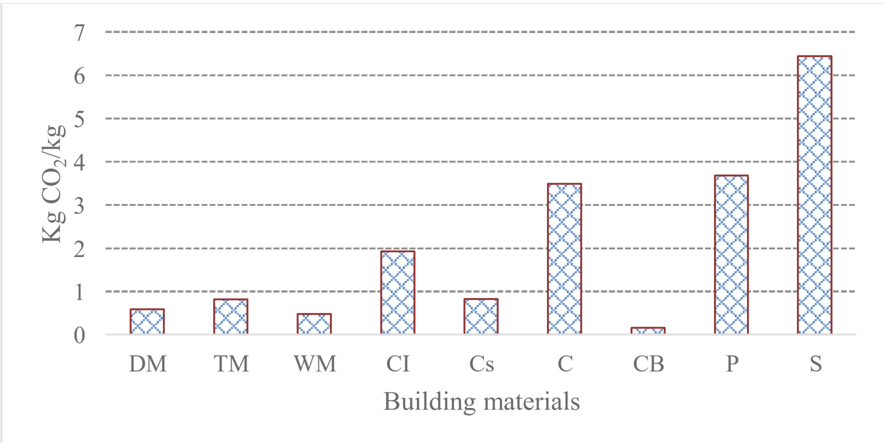

Fig 3. Carbon dioxide emissions where DM- Dry Mix, TM- Teclite Mix, WM-Wet Mix, CI-Cast Iron, Cs- Ceramics, C- Clay, CB-Concrete Block, P- Polypropylene and S-Steel

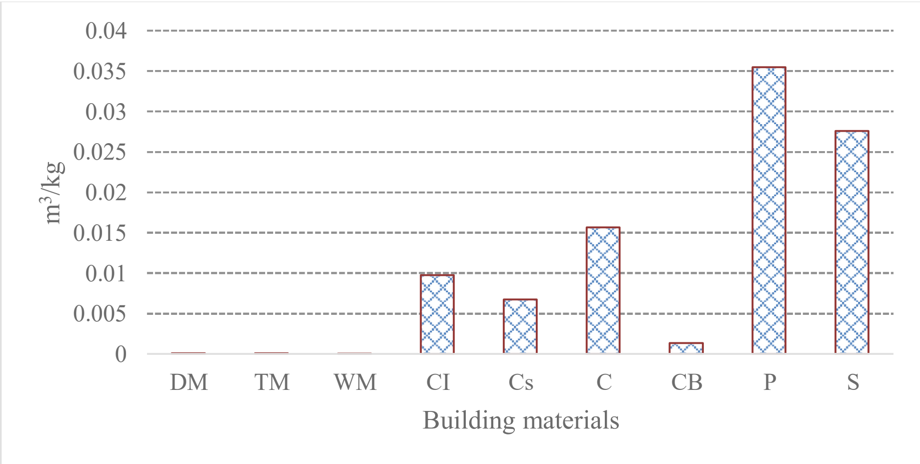

Fig 4. *Water consumption where DM- Dry Mix, TM- Teclite Mix, WM-Wet Mix, CI-Cast Iron, Cs- Ceramics, C- Clay, CB-Concrete Block, P- Polypropylene and S-Steel*

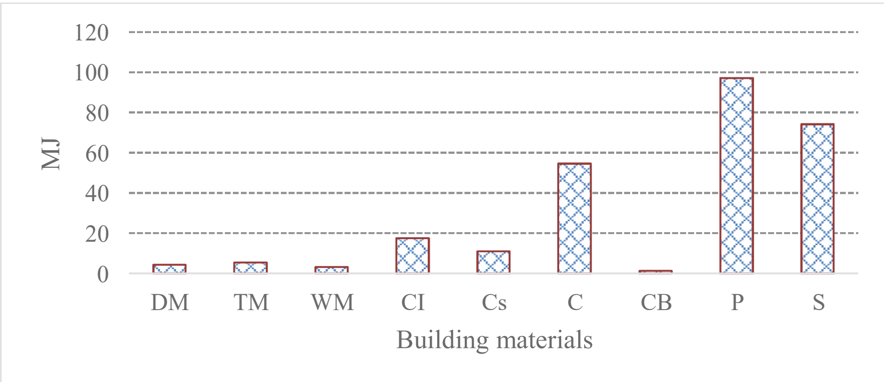

Fig 5. *Energy demand where DM- Dry Mix, TM- Teclite Mix, WM-Wet Mix, CI-Cast Iron, Cs- Ceramics, C- Clay, CB-Concrete Block, P- Polypropylene and S-Steel*

To deal with uncertainty, a sensitivity analysis was performed. The input weight of each criterion was changed. The weight was increased 5%, 10%. 15% and 20% of 1 kg of each material in SimaPro model. The error was plotted in fig 5, where error in Steel is 0.22 and lowest was concrete block with an error of 0.005.

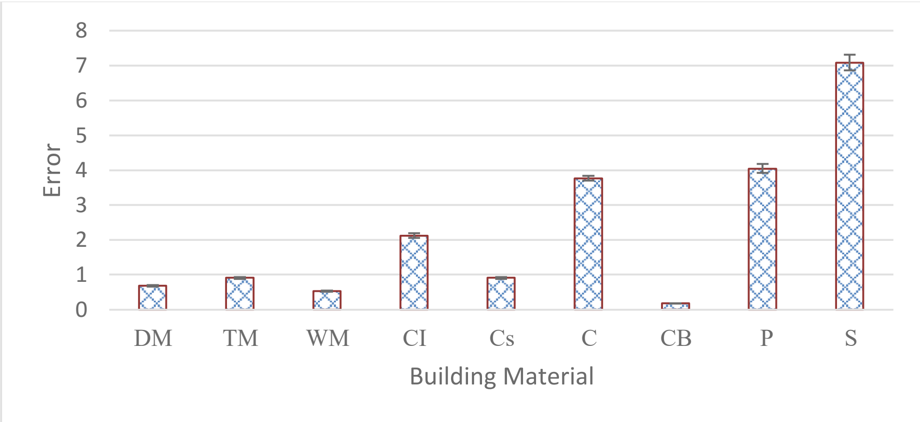

Fig 6. *Error bar chart CO_2-Eq, where DM- Dry Mix, TM- Teclite Mix, WM-Wet Mix, CI-Cast Iron, Cs- Ceramics, C- Clay, CB-Concrete Block, P- Polypropylene and S-Steel*

4 Conclusion

This study aimed to compare LCA of various materials widely used in architectural ornaments. A methodology was proposed in this study which was verified by applying to the case study. From the caste study, it could be concluded that proposed methodology worked for comparing cast stone with different material. From the results, concrete block had the lowest carbon dioxide emissions in among all the raw material followed by Wet mix cast stone. Polypropylene had the highest carbon dioxide emission. Among the cast stone, Teclite had the highest carbon dioxide emissions. However, more improvement can be made to reduce the carbon footprint for cast stone by finding alternatives to the packaging and cement within the raw material of the cast stone's mix. As manufacturing of cement is an energy intensive process. As part of the future work, more parameters can potentially be included into the study which allow better decision making and material selection and for uncertainty analysis.

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