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Life-cycle-Assessment of Cast Stone Manufacturing: A Case Study

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Abstract

This research paper aims to perform a "cradle-to-gate" carbon dioxide emissions Life Cycle Assessment (LCA) on cast stone products, i.e. to quantify their accumulated CO_2 emissions from the extraction of raw materials to a complete finished product. The collected data is mapped using Energy Value Stream Mapping (EVSM) and Sankey diagrams. Areas of carbon footprint reduction are identified, and transportation, packaging and mold-making recommendations are made. The study was undertaken at a manufacturing facility located in the UK and based on three types of materials.

Keywords: Life Cycle Assessment; Carbon Foootprint; Energy Value Stream Mapping; Sankey Diagram

1. Introduction

Increasing threats posed by global warming due to the anthropogenic Green House Gases (GHG) emissions has led to greater concerns over the impact on the global climate [1]. Carbon dioxide (CO_2) makes 76% of total GHG which makes it focus of study [2]. The current level of CO_2 in the atmosphere is 380-ppm and it is expected to increase more than 800-ppm by the end of the century [3]. Manufacturing sector is accountable for World's 30% energy consumption [4]. A substantial amount of energy is consumed during manufacturing of products that involve cement as a raw material [5]. During the manufacturing process of cement itself, significant amount of GHG are emitted [5]. In some cases manufacturing sector provides its services to the construction sector.

In the UK, construction industry accounts for an estimated 47% of the total CO_2 emission [3]. Each year about 60 billion tons of raw materials are extracted and the construction sector is one of the largest users of these raw materials [6]. The sector is also one of the largest creators of waste materials. Under the Climate Change Act 2008 (2050 Target Amendment) Order 2019, the UK's carbon emissions from the construction sector as well as other sectors are targeted to be cut down to net zero by 2050 [7]. Most of the companies are targeting to cut their carbon emissions as per Government commitment. Under the Kyoto protocol the Government of the UK is legally obliged to cut down its overall emissions by 80% by 2050.

Life Cycle Assessment (LCA) is a methodology used to evaluate environmental impact of a product or a process from "cradle to grave" i.e. from extraction ("cradle") to the disposable phase ("grave") [8]. However, this paper uses "cradle to gate" approach where environmental impact of a product is studied from extraction ("cradle") till it's out of the factory gate ("gate") [9]. The benefit of LCA is that it helps in analyzing and quantifying the environmental consequences of a product from extraction of its raw material to the final product. This could benefit the policy makers with LCA as a tool to legislate for more environmentally friendly solutions overall.

Cast stone is defined as manufactured stone with natural aggregates and cement as a binder that is made to resemble as natural stone [10]. It is used in a similar ways as natural stone, but instead of carving, it is casted into the desired shape. Cast

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stone is widely used in the construction sector and gardens. It consists of limestone of different grades and cement as a binding agent [10]. As per the data provided by the UK cast stone association, in year 2017, 15,853 m^3 of cast stone was produced which is slightly higher than 15,692 m^3 produced in year 2016 (UK) showing the increased demand of the cast stone [10]. The aim of this paper is to investigate, map, assess the carbon footprint of cast stone from "cradle-to-gate" and present the findings. It also provides some suggestions to reduce the carbon footprint for cast stone. A literature review is presented in the next section followed by the methodology. A case study section and finally the conclusion is presented at the end of the paper.

2. Literature review

2.1. Benefits of assessing carbon footprint to business

LCA benefits in several ways such as assessment of the raw material and energy efficiency of the entire system, providing benchmarks for improvement and identifying polluting process [8]. There are additional benefits of LCA to a business. As Onat describes carbon footprint is the CO_2 emitted from the processes related to the products, services or regions [11]. A carbon footprint is standardized indicator of GHGs emissions. A study published by Moss et al. [12] highlighted the financial benefit an enterprise can achieve specially Small and Medium Enterprises (SMEs) by reducing environmental impact. As per the study, to grow business, SMEs can supply their products to a big enterprise who have green and ethical supply chain requirements. Therefore, it is important for those SMEs to operate greenly to enhance relations with larger companies and in addition the companies may also gain some reductions in energy and waste. The big enterprise gain popularity among its customer by advertising green and ethical supply chain requirements. In Mourtzis [13], production scheduling is done by considering energy consumption. That allows a company to monitor their energy consumption and provide opportunity to reduce it.

2.2. Life Cycle Assessment (LCA)

As defined before, LCA is a tool used for evaluation of environmental impact of a product or a process [9] .Salonitis suggests that a study that only covers the manufacturing or the use phase will not provide an understanding of the environmental impact of a product [14]. However, for the manufacturing of the construction products a partial product life cycle i.e. "cradle-to-gate" approach is used as the pointed out by C. Cao [15]. The reason for such an approach is based on three factors, extensive variety of raw materials, various type of processing to create the finish product and multiple ways finished product will be used in. Cast stone is a construction product and thus this study must follow the "cradle-to-gate" approach.

In product lifecycle, before a raw material is used in a manufacturing company, it needs to be extracted, processed, and then transported to the facility. To extract, process and transport materials a certain amount of CO_2 is released into the atmosphere. Thus, CO_2 emissions can be classified as "embodied" within those materials. [17]

The embodied carbon calculated can be normalized with the mass of the product to calculate carbon footprint for 1 kg of material from ores and feedstock. Therefore, this study will include the assessment of embodied CO_2 emissions within the raw materials used in cast stone manufacturing. In order to identify how much carbon is emitted from a unit of resource, conversion factors are used, which are multiplier values. Using conversion factors, the amount of CO_2 released from 1 kWh can be identified. The conversion factors are used to eliminate the impracticality of measuring emissions directly that are emitted from a process. [12]

Once the item reaches the manufacturing facility the energy consumed by each process during manufacturing is needed to be identified to assess GHG's emissions. Priarone [16] for their study, included pre-manufacturing phase for the production of the incoming feedstock materials and all manufacturing steps. The economic as well as environmental aspect is included in the study. Further the paper uses multi-criteria decision making to assess environmental and cost impact of a product manufactured by additive manufacturing approach and traditional machining approach. Papers such as Huntzinger [8], Menoufi [17] and Stafford [18] follows methodology laid out in ISO 14040 [19]. The methodology in ISO 14040 is described in four major steps which are (1) determining the scope and boundaries of the assessment, (2) Life cycle Inventory analysis, (3) Calculating the environmental impact, (4) Result interpretation and suggestions for improvement.

Energy oriented LCA use EVSM for effective analysis of the energy flow [20]. Tools such as Energy Value Stream Map (EVSM) and Sankey diagram can be used to show the consumption and the flow of energy. Verma and Sharma [21] described EVSM as a tool developed from Value Stream Mapping, which highlights energy utilization as well as wastage in processes. It allows the user to identify the possibilities to reduce the energy usage and potential gains and savings. A typical EVSM includes materials, energy, time and arrows showing direction of energy flow. For the same purpose Sankey diagrams are used which allows a better visualization of the several flows in the system [22]. By identifying the source of highest carbon emissions and waste, this could help businesses achieve lean and green manufacturing. Setting improvement goals will help the business in achieving the most benefits of a new technology implementation [12].

A majority of environmental impact studies published focus primarily on cement production, aggregate processing [23-25] and limestone quarrying process [22]. However, none of the studies consider LCA of cast stone where cement, aggregates and limestone are raw materials. In this context this paper aims to evaluate the environmental impact of the cast stone as a case study.

3. Methodology

LCA can be carried out in number of ways. According to ISO 14040 a flexible approach must be taken by an organization to implement LCA in accordance with their own requirements [19, 27]. Major steps in the study are showed below in figure 1 and then discussed.

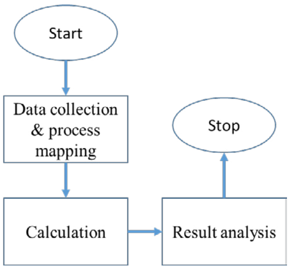

Fig. 1.Methodology used in the study

3.1. Data collection and process mapping

In this step data regarding raw materials, embodied carbon, energy rating of the equipment and transportation is collected. A manufacturing facility that fabricates according to the customer's demand could have high variability in its products. In this case the product range is higher as each one is made to order. So, uptime of an equipment used within a process will be different. Also, the amount of raw material that goes into making each product is different. By creating product families, each family can be classified on the basis of shape, size, or weight. By focusing on a family the energy consumed by that equipment can be calculated. Once the energy consumed and the amount of raw material is known, CO_2 emission can be calculated. However, if a company produces single product type, the equipment uptime will be easily known for producing each unit.

The manufacturing process is mapped from "cradle-to-gate" for a better understanding of the processes involved in manufacturing. Software such as GaBi [28] or open LCA [29] are used in assessment. Such software have an inbuilt standard database for embodied carbon. If a particular raw material is not found within the database, other open source databases such as ICE database from circular ecology [30] can be used.

3.2. Calculations and mapping

Total emission is calculated including the transportation of the raw material. After finishing calculations, the data is mapped on EVSM and Sankey diagrams. EVSM benefits in different ways. It identifies the level of energy utilization and it also points out the energy wastage in each process. EVSM provides the opportunity to conserve energy and hence helps in reducing carbon emissions. Whereas Sankey diagram allows better visualization of the energy within the system. In LCA it can be used to provide the embodied carbon within the raw materials based on their quantity. It points out the dominant CO_2 contributors in relative magnitude hence it creates an area of opportunities to improve in emissions.

3.3. Result analysis

After calculating the carbon footprint the data is represented into pie charts and graphs. The result is broken down into different processes during manufacturing which highlights contribution of each process towards net carbon footprint. This allows a better understanding of results and makes the interpretation easy for the decision-makers to improve on the area of more carbon footprint.

4. Case study

4.1. Data collection

The above-mentioned methodology was applied to a cast stone manufacturing company which is based in the UK. The data regarding embodied carbon in raw materials, energy consumption, transportation is collected during data collection phase. The company has three product lines Dry mix, Wet mix one and Wet mix two. All three product types are made in batches called a mix. Each mix has a recipe i.e., each mix consists of raw materials which are blend together in a fixed proportion in an electric mixer. Once ready, the mix is then poured or packed into molds to create a cast stone product. The company deals with two types of molds which are fibre glass-rubber molds and wooden molds. Each product is made according to the customer's demand at this cast stone company which makes every product unique. Cast stone production is measured in terms of weight. So, due to such high variability in the product sizes, cast stone ranges from 1 kg to several tons. This could also result in variation in cycle times. With the aim of providing the overall image of the company's carbon footprint, finding the most common and representative product size is crucial. It will provide an accurate estimation and a realistic result. The graph in figure 2 shows the frequency distribution of the overall production from the last 5 years. The

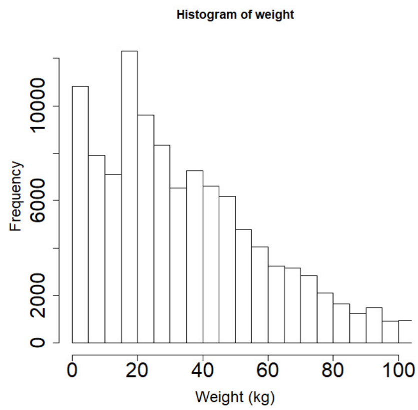

Fig. 2. Frequency distribution of cast stone products (kg) manufactured in last five years

Fig. 3. Cast stone manufacturing process

mode is 20 kg, which means that it is the most common product size produced in the company. The carbon footprint of the cast stone production is calculated using the data such as raw material, power consumption, waste, transportation, and the utilized database. It is worth noting that the use stage of cast stone products does not typically have any associated carbon footprint. In addition, these products last for decades and are not considered to be recyclable. Therefore, these two life stages of the product do not have any impact on the overall carbon footprint calculations.

4.1.1. Dry Mix

Dry mix is a dry powder like product which is filled in molds. Figure 3 shows the process to create a cast stone on a Dry mix production line.

First, a mix of limestone, cement, sand, and water along with admixtures are mixed in an electric mixer for 4 minutes. The input power of the electric mixer is 11 kW, and a batch of dry mix is 150 kg. The batch is taken to workstation from mixer via a wheelbarrow. Once reached, the packing begins where the dry mix is rammed into a mold using pneumatic rammers. Rammers help to compress the dry powder into the mold as they thump. Once the mold is filled completely it is left for overnight curing. During this process the concrete starts to cure and gain strength. Once cured, the molds move onto demolding, where the molds are opened using an electrically powered wrench, the cured cast stone is taken out of the mold and inspected for defects. Each electric powered wrench is battery operated and consumes 0.54 kW of power. The batch of cast stone demolded on the same day, go through a vapor curing process. During vapor curing it is placed for 8 hours in an enclosed chamber in the presence of water vapor. A temperature of 40˚C is maintained within the vapor curing chamber using a setup specially designed for curing process. This kind of curing process accelerates the curing of concrete and helps the cast stone take its final properties [31]. Finally, the cast stone is packed on an Expanded Polystyrene Sheet (EPS), shrink wrapped on a wooden pallet and shipped to the customer using company's own transportation system. During shrink wrap 0.0039 kg is consumed of Propane gas is consumed each time.

4.1.2. Wet mix one and Wet mix two

Dry Mix	
Raw Material	Amount kgCO2e/kg
Cement	0.91
P25 Limestone	0.032
A4 Limestone	0.032
Sand	0.004
Water proofer	2.67
Colouring Additive	8.12
Water	0.344

Wet mix one	
Raw Material	Amount kgCO2e/kg
Cement	0.91
Fibre glass	1.35
Plasticiser	1.88
Hardener	2.28
Sand	0.004
Additive	1.89
Hydrochloric acid	0.91
Water	0.34

Wet mix two	
Raw Material	Amount kgCO2e/kg
Cement	0.91
Limestone 4-10 mm	0.032
Aggregate	0.007
Sand	0.004
Water proofer	2.67
Colouring Additive	8.12
Hydrochloric acid	0.91
Water	0.344

Packaging & moulds	
Raw Material	Amount kgCO2e/kg
EPS board	3.29
Shrink wrap	2.6
Propane	2.99
Timber	0.306
Ply board	0.681
Varnish	5.35
Fibre glass	1.35
Acetone	2.24
Rubber	2.85
Clay	0.39

Fig. 4. Embodied carbon in raw material [30]

Wet mix one and Wet mix two products share a similar production process which is shown in figure 3. The difference between the two products are raw material, mix batch size and properties of the final product. In Wet mix one, a blend of cement, sand, water, glass fibers and admixtures is mixed in different proportions altogether weighing 60 kg for 8 minutes. Whereas for Wet mix two, a batch of 400 kg is mixed for 11 minutes. Wet mix two uses aggregates instead of glass fibers which is the only difference in terms of raw materials. Both Wet mix one and two use an electric mixer with similar power inputs i.e. 11 kW. When compared to Dry mix, Wet mix one and two are completely different products and have different manufacturing process. As the name suggests Wet mix is a liquid blend whereas dry mix is a dry blend.

Once a batch of Wet mix one or Wet mix two is made, it is taken for the process of pouring where the mix is poured into a mold. After the pouring process the mold is left for the overnight curing. Next day, the cast stone is removed from the mold (demolding process) using electric wrench and is taken for acid etching. In the acid etching process, the cast stone is sprayed with Hydrochloric acid and then washed down with water. Acid etching is done to remove the top surface of the cast stone and expose the better-textured surface. After acid

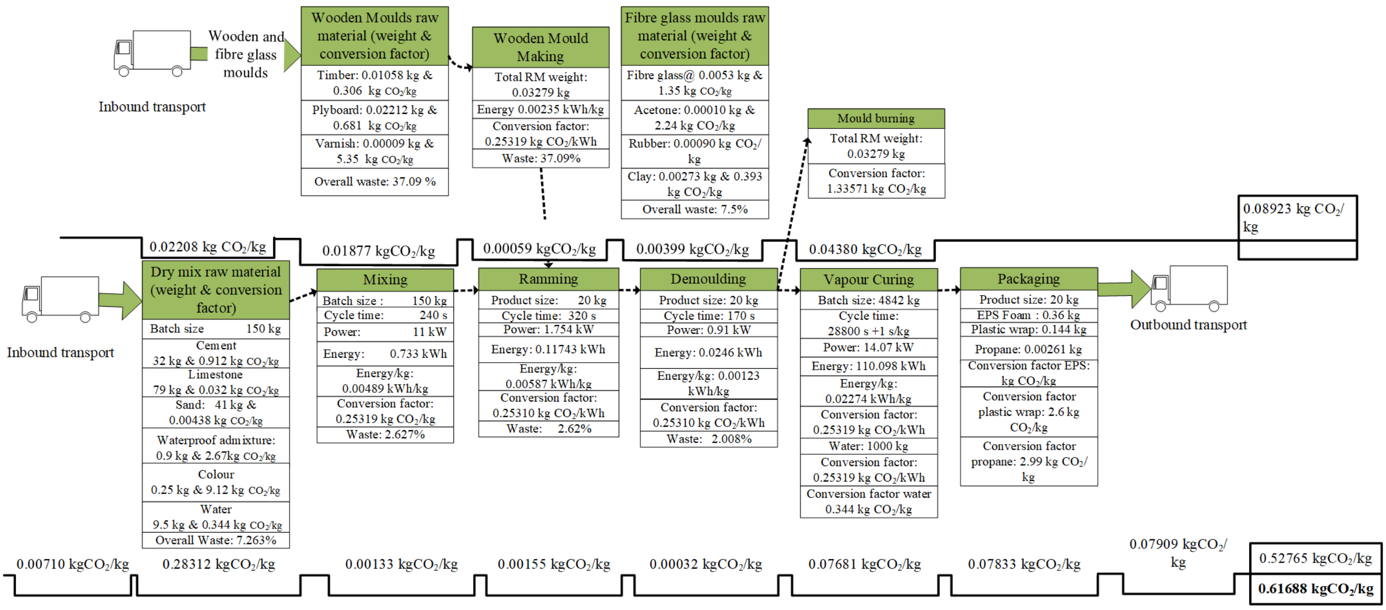

Fig. 5. Energy Value Stream Map for Dry mix

etching, the cast stone goes to the next process of surface finishing where the final touch is given by hand. Finally, the cast stone is packed on an Expanded Polystyrene Sheet (EPS), shrink wrapped on a wooden pallet and shipped to the customer using the company's own transportation system.

4.1.3. Mold Making & Transportation

The wooden molds are made using several types of wood working machinery. For each machine their power input and cycle times are collected. The machines used in mold making include planer, shaper, spindle molder, band saw, etc. Also, once a mold is made it goes through varnishing process which is done by a UV varnishing machine. Before going for pouring or packing all the molds are applied with an oil-based degreaser which is also included in the study.

A majority of the wooden molds are destroyed once they have been used because they are made to customer specifications and cannot be use for another order. Redundant molds are chipped and burnt in a boiler. The heat produced by burning of molds is used to heat the entire building. The emissions from the process of chipping and burning the wooden molds are included in the process. However, the study does not consider the energy saved for heating.

The transportation system of the company is divided into two categories i.e. inbound and outbound transportation. The inbound transportation is used to move the products internally. Whereas the outbound transport is used to deliver finished goods and receive the raw material from the suppliers.

4.2. Calculations and mapping

In order to conduct LCA, the embodied carbon footprint in the raw materials has to be included within the calculations. Such data was not available in the company's database.

However, several databases for certain geographic locations are available, as the embodied carbon in the raw materials could differ from location to location. Therefore, the Inventory of Carbon and Energy (ICE) database was utilized for this study [30]. ICE has a database for all the materials that are specifically designed to be used in the United Kingdom. One other key element to calculate the carbon footprint is the conversion factor. They are used to calculate the carbon footprint associated with water, energy, and transportation. Therefore, latest United Kingdom Government's GHG conversion factors [32] were used for the final conversion. The raw material's embodied carbon figures acquired from ICE used in the cast stone manufacturing process are summarized in figure 4.

EVSM a tool used to map the data gathered during the data collection step. It is used to map all three product types which are Dry mix, Wet mix one and Wet mix two. EVSM for Dry mix is shown in figure 4. Processes such as overnight curing, pouring, and finishing are excluded from the EVSM because they do not consume energy. The embodied carbon and energy consumption during the other processes is included in the EVSM. While making a fibre glass mold only the raw material is consumed as no machine is used in this production process. So, for the fibre glass molds only the embodied carbon for the raw materials is included in the study. At first the carbon footprint involved in the mold making was calculated as an overall and then later it was broken down to be included in the production on per kg of cast stone basis. Then, the production of both types of molds was included by adding them to the three EVSM as separate production lines, and the outcome was added to the final results. The result from EVSM is represented in the form of Sankey diagram. As shown in figure 6, the Sankey diagram shows embodied carbon as well as CO_2 generated for per kg of cast stone during the manufacturing process of Dry mix product.

4.3. Result and recommendations

After three EVSMs and Sankey diagrams were created, one for each product, the carbon footprint was calculated for per kg of cast stone produced. For Dry mix, Wet mix one, Wet mix two the carbon footprint are 0.618, 0.862 and 0.524 kg CO_2/kg cast stone respectively. These results include the carbon footprint from mold production. However, separately the wooden molds account for 0.0152 kg CO_2/kg cast stone and fibre glass molds 0.0739 kg CO_2/kg cast stone.

The results can be categorized into nine different categories as shown is figure 7. It is clear from the percentage figures that the production process of Wet mix one mix generates the

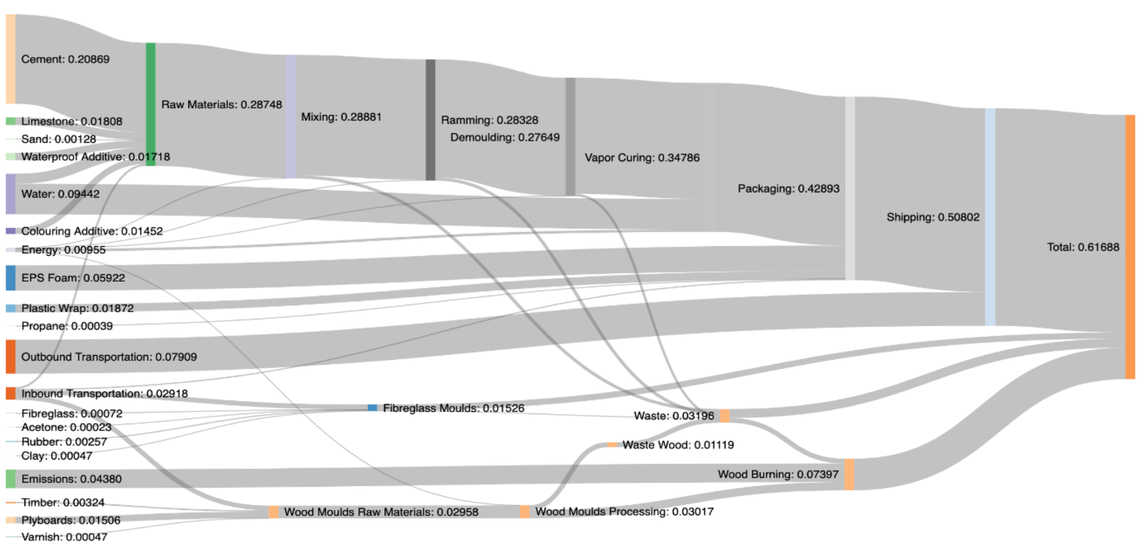

Fig. 6. Sankey diagram for dry mix (kg CO_2/ kg cast stone)

highest percentage of CO_2. Overall, Wet mix two has the lowest carbon footprint followed by Dry mix. The reason for such a trend is the embodied carbon of the raw materials with cement being the one with the highest embodied carbon. The second most CO_2 releasing process is the transportation. As the company own their own delivery vehicles once they have made a delivery, they come back empty which increases the carbon footprint per delivery.

From the above results some recommendations can be made to the cast stone manufacturing company, such as finding greener options of packaging, and finding alternatives to wooden molds or using wooden molds more than once. It should be noted that the data gathered from the secondary source such as different papers may vary such as the embodied carbon.

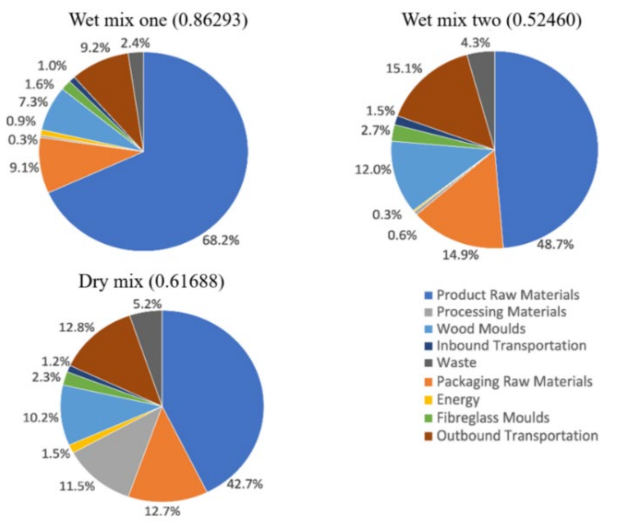

Fig. 7. Percentage carbon contribution per mix (kg CO_2/ kg cast) stone)

5. Conclusion

Reducing the sources of carbon emission due to human activity will help to reduce the GHG levels worldwide. This study has performed LCA of the cast stone manufacturing. A methodology that allows quantification of the CO_2 emissions from “cradle-to-gate”. It could be concluded from the case study that the Wet mix two is the most eco-friendly material as it has the lowest carbon footprint. Much of the absolute environmental impact will depend on the raw material consumed during the manufacturing process and may vary from one manufacturing facility to another. By following the stated methodology one can obtain the carbon footprint for cast stone from “cradle-to-grave”.

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