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Comparative Life Cycle Assessment of ceramic versus concrete roof tiles in the Brazilian context

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ABSTRACT

The Brazilian ceramic industry is responsible for providing more than 90% of the roof coverings and wall bricks in the country, producing more than 15 billion pieces per year. In order to compare the life cycle impacts of ceramic versus concrete roofing tiles and identify potential improvements in ceramic products, we carried out a life cycle impact assessment of both products. This study aimed to compare the life cycle impacts of ceramic and concrete roof coverage over 1 m^2, with an assumed life time of 20 years in Brazil. Nine different sensitivity analyses were carried out followed by a Monte Carlo uncertainty analysis to verify the robustness of the study. The results show that ceramic tiles appear to have less impact than concrete tiles on Climate Change, Resource Depletion and Water Withdrawal, while for the remaining damage categories, Human Health and Ecosystem Quality, the difference between the two alternatives was too low to be considered significant. The use of wood chips led to significant impacts, mainly related to respiratory inorganics. Assessment of the data quality identified that the data is of generally high or acceptable quality. The sensitivity analysis and uncertainty assessment show that the conclusions are robust.

1. Introduction

The construction industry is increasingly concerned with the environmental impacts over a building's life cycle and is aiming for the improvement of environmental indicators of sustainability (Gabaldón-Estevan et al., 2014; Koroneos and Dompros, 2007; Nicoletti et al., 2002; Ortiz et al., 2009; Sharrard et al., 2008; Traverso et al. 2010). The construction sector is the one that most consume raw materials by weight (Koroneos and Dompros, 2007) and ceramic and concrete elements are among the ones mostly used in buildings (Koroneos and Dompros, 2007; Wattanasiriwech et al., 2009). Therefore, the choice for greener products and ways of cleaner production is at priority (Shu et al., 2010) and environmental assessments can provide information needed for the choice of specific processes or materials. Life Cycle Assessment (LCA) is a recognized approach to assess the environmental impacts associated with a product life cycle or a service from the extraction of raw-materials through to the end-of-life treatment (Curran et al., 2011; EEA, 1997), helping with the identification of potential improvements of the product and involved unit process environmental performance. It has also been applied as a tool to guide decision-making, aiming at better environmental performance of products and the comparison of different alternatives of building elements (Asif et al., 2007; Kellenberger and Althaus, 2009; Mithraratne and Vale, 2004).

Following the publication of a few studies evaluating the environmental performance of roofs (Bribián et al., 2011; Kosareo and Ries, 2007; Saiz et al., 2006), and two Life Cycle Assessments of ceramic tiles in Spain (Ibáñez-Forés et al., 2011; Bovea et al. 2007), the Brazilian National Ceramics Industry Association (ANICER) identified the need to evaluate the potential environmental

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impacts associated with the life cycle of ceramic roof tiles, in order to compare them with an equivalent concurrent product (concrete tiles). The Brazilian red ceramic industry consists of more than seven thousand companies from micro to medium size enterprises, being responsible for more than 90% of the roof coverings in the country (Schwob et al., 2009). In 2011 the production of roofing tiles contributed 36% of the total production in the sector, represented by 1,300,000,000 pieces/month and the use of 30 Mt of clay/year (ANICER, 2011).

The aim of this study is to compare the life cycle impacts of ceramic roof tiles with equivalent concrete tiles in the Brazilian context. Moreover, the analysis helps one to understand the effects on different impact and damage categories of the ceramic and concrete life cycle stages. The influence of the central assumptions and variables selected was assessed by carrying out a sensitivity analysis. The results of the study were reviewed by ceramic and concrete specialists from Brazil to enhance quality and credibility.

2. Materials and methods

2.1. Goal of the study

The goal of the study is to compare the life cycle environmental impacts of roof covering over a 1 m^2 area using ceramic roof tiles with the same function fulfilled with similar concrete roof tiles.

2.2. Scope of the study: functional unit and system boundaries

The functional unit was defined as the “coverage of one square meter of roof with tiles, for a duration of 20 years in Brazil”, aiming to protect a building interior from weather events and to assure thermal insulation. The assumptions made in this study are based on average conditions present in the country. Due to the lower thermal performance of concrete tiles when compared to ceramic ones (Mariane, 2012), it may be necessary to apply an aluminum insulation layer to reduce heat radiation of concrete tiles. In this study, the baseline scenario assumed that building energy use is similar between the two systems without the insulation layer. However, the assumption of adding an aluminum layer for the concrete tiles system was tested in the sensitivity analysis. For the ceramic tiles, it was assumed that 16 tiles are needed to cover an area of 1 m^2 of roof, amounting to a total weight of 38.4 kg (i.e. 2.4 kg per ceramic roof tile), while for concrete roof tiles these values corresponds to 10.4 tiles and 46.8 kg (i.e. 4.5 kg per concrete roof tile), respectively (Table 1). The structure built to support the roof is considered equivalent for both alternatives.

The boundaries for both systems were defined from the extraction and processing of raw materials to the end-of-life stage, i.e. landfilling. The ceramic tile system boundaries are represented in Fig. 1, for which clay extraction was assumed to be done with the aid of retro-excavators, wheel loaders and bulldozers. Four processes were considered in the manufacturing of ceramic tiles. The preparation of the clay dough was assumed to be carried out with a loading shovel and by means of mechanical mixing. This operation is followed by the mechanical shaping of the tiles using molds. During the drying phase, the water content is reduced from 25% to 3% (SEBRAE, 2008) and tiles are finally cooked to reach its solid final outcome. The elimination of water is done via natural evaporation, through the use of an air current. During the firing stage, carried out in furnaces, with temperatures nearing 950 °C, (Monteiro and Vieira, 2004) wood chips supplied by the wooden furniture industry are used as fuel. The losses reach 1.5% and are reprocessed and reincorporated into the dough to a maximum of 5% or sold for tennis court terrain. Details of material and energy inputs of the life cycle of ceramic roofing tiles are available in Table A.1, of Appendix A.

For concrete tile manufacturing (Fig. 2), clay is assumed to be obtained in the same way as for the ceramic tiles, while sand is assumed to be either extracted from river sand pits or artificially produced by crushing rocks (artificial sand). For the latter, a sensitivity analysis was carried out in order to verify differences in the results. Limestone, the main raw-material for cement production, is extracted from quarries with the use of explosives. Seven main processes were identified in the production of concrete tiles: from crushing and grinding of limestone to coating of the tiles. Limestone (90%) is crushed before being kept in storage bays, along with clay (10%). This mix is then crushed and grinded to obtain a particle size of about 0.050 mm. The resulting flour, or raw meal, is introduced in an oven and initially heated to be then introduced in a rotary kiln, with temperatures up to 1450 °C to obtain the clinker (SNIC, 2011). Cooling then takes place, down to 80 °C, and then the clinker is mixed with gypsum and additives to obtain the commercial cement mix. The latter is mixed with sand (70%) and water (10%) to produce the concrete to shape the tiles. A coating agent is applied on the tiles as a protection layer. The material and energy inputs to the life cycle inventory of concrete roofing tiles are available in Table A.2 of the Appendix A.

For the transportation average scenarios, trucks are assumed to run a total distance of 108 km each way between the clay quarry and the ceramic tiles manufacturing plants, and 150 km from the places of extraction of sand, limestone and clay to the cement plant. Moreover, an additional distance of 300 km was considered in the transportation of cement to the concrete tile manufacturing plant. After the final products are ready, ceramic roof tiles are dispatched in bulk to storage silos and to the end customer (depots), over a distance of 5 km. Concrete tiles are transported after packaging.

For ceramic tiles, a total 120 km average distance was assumed for the transportation from manufacturing plants to storage and then to end customer, while for concrete the total distance was assumed to be 450 km. These differences in transport distances were defined based on national data, provided by ANICER, for the main producing states. The differences between ceramic and concrete industries are mainly due to the higher number of ceramic production facilities per area, as ceramic production units are mainly small and medium size enterprises, mostly family-owned business (FIESC, 2011) and long-distance transport is not economically viable (FIEMG, 2013). The data has gone through a peer review process, validated by external independent experts, from the concrete and ceramic industry. A sensitivity analysis was also carried out and the final result would have not changed up to a 500 km transport distance for ceramic tiles. For both case scenarios, the transport weight was adjusted to the heavier tiles. An end-of-life scenario was built upon the current practice of landfilling the lost pieces or disassembled ones and a transportation distance of 50 km was assumed. Losses during the laying were estimated to be 1% for both alternatives, but were not considered in this study, based on the cut-off criteria used. Table 2 displays the general system description for ceramic and concrete roof tiles, containing details for each of the life cycle stages.

Table 1
Key characteristics (weight, tiles per area, lifespan) of the studied roof tiles (ceramic and concrete), based on average data in the Brazilian context.

Characteristics	Ceramic roof tiles	Concrete roof tiles
Weight (kg)	2.4	4.5
Roof coverage (tiles/m^2)	16	10.4
Total weight per m^2 (kg)	38.4	46.8
Lifespan (years)	20	20

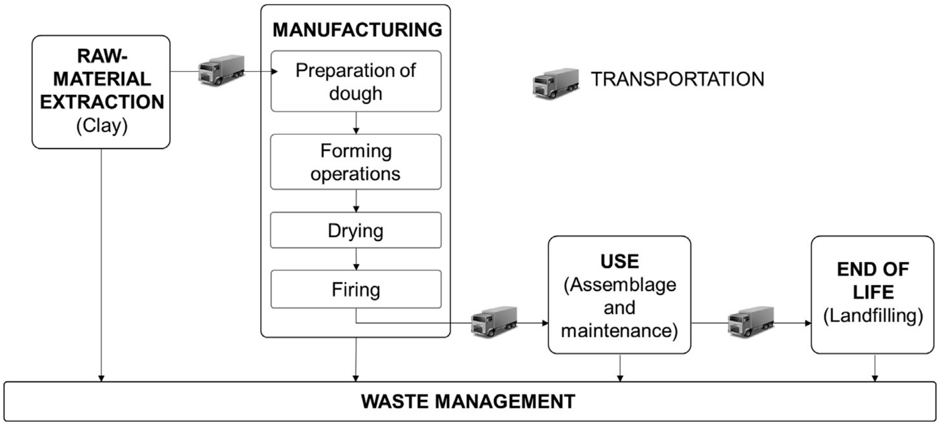

Fig. 1. Scheme of the life cycle system boundaries of a ceramic roof tile.

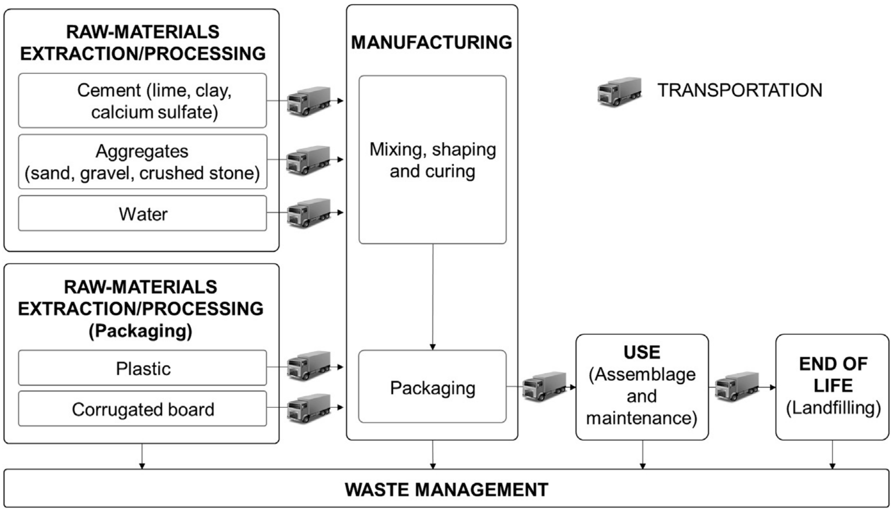

Fig. 2. Scheme of the life cycle system boundaries of a concrete roof tile.

Table 2
General system description for ceramic and concrete roof tiles, with details of life cycle stages.

Life cycle stages	Ceramic roof tiles	Concrete roof tiles
Raw-material extraction	Clay	Clay, sand, limestone
Transportation	120 km distance from clay quarry to manufacturing plants	150 km distance from raw-materials extraction location to cement plant and 300 km from those to manufacturing plants
Manufacturing	Preparation of clay dough, shaping, drying and firing	Crushing and grinding, clinkerization, cooling, milling, shaping and drying and coating
Distribution	Distance from manufacturing to depots, in bulk, and to end-customer	Distance from manufacturing to depots in bulk, and to end customer, in packaging
Use	Manual installation; negligible maintenance	Manual installation; negligible maintenance
End-of-life treatment	Landfilling	Landfilling

2.3. Life cycle inventory data quality and data collection

The study was carried out in 2010–2011 and it was assumed that the end-of-life impact is generated after a period of 20 years, when tiles are removed from the roof and transported to a landfill. Data input into the model is based on average roof tiles in the Brazilian context for both alternatives. Primary data on average ceramic tile production and concrete tile production was collected and provided by ANICER. Missing, incomplete or non-accessible data was completed from secondary data, extracted from Ecoinvent (SCLCI, 2010), an international life cycle database on industrial data, public available databases, literature review and expert judgment.

Road transportation data was extracted from Ecoinvent and adapted to the North American context (BEEP, 2010), based on published data with average payload and fuel consumption for all types of trucks. The average long distance transportation truck is a 53-dry box truck. Payload was specified by ANICER for most transportation stages, whereas when no data was available, an average payload of 17.56 ton was assumed. The conformation of data required a significant amount of information and statistics about the transportation industry in a given region. Consequently, this was outside of the scope of this study. However, we assumed that the North American conditions were a better approximation for South America than the European context.

The Brazilian electricity grid mix used on the calculations is presented on Table 3. This data was used specifically for all foreground processes. For background processes, an adapted version of the Ecoinvent database was used, in which all the grid mixes used by all the process in the database by the North American average grid mix were modified. However, adjusting background processes to the regional Brazilian grid mix was outside the scope of this project, due to the complexity of this procedure.

Data on emissions for cement and concrete production was extracted from Ecoinvent. The appropriateness of this dataset was validated by the GHG emission ratio per ton of cement of 0.838 t CO_2 eq/t (SCLCI, 2010), which coincides with the international weighted average of 0.83 t CO_2 eq/t (IEA, 2007). For the first, an adapted Brazilian fuel mix (CCAP, 2009) was integrated into the dataset, replacing the Swiss average (Table 4). For flue gas emissions, as no data was available for the Brazilian context, Ecoinvent data was directly used. A similar procedure was done for the concrete manufacturing process, for which Ecoinvent data flow (“Concrete roof tile, at plant/CH”) was used and adapted according to transport distances, sand and cement proportions. Data quality assessment was carried out in order to identify data requiring improvement.

2.4. Allocation procedures

For the allocation procedure, the cut-off approach was applied to the residues (e.g. tires and used oils) that are burned for energy recovery in cement production. For the use of residual wood chips in firing, Ecoinvent data was used, considering an economical allocation of 5% for most of the impact. A correction based on volume (11.5%) was added to account for the mass and energy balance that is ignored by the economic allocation.

Table 3
Brazilian energy grid mix, used for all foreground processes.

Source of energy	Share
Hydropower	83.70%
Natural gas	4.83%
Biomass (Bagasse)	3.96%
Nuclear	2.33%
Diesel in co-generation	1.93%
Hard coal	1.90%
Oil	0.74%
Industrial gas	0.60%
Wind power	0.01%

Table 4
Average fuel mix used in the clinkerization process. Data from Ecoinvent was adapted to the Brazilian context.

Source of heat	Share
Petroleum coke	76.60%
Other sources (such as used tires)	11.00%
Charcoal	7.39%
Steam coal	1.98%
Diesel oil	1.35%
Fuel oil	0.86%
Natural gas	0.81%
Firewood.	0.00%

2.5. Method applied

SimaPro 7.3 (Pre-Consultants, 2013) was used as the mean to conduct the assessment. For the life cycle impact assessment, IMPACT 2002 + VQ2.2 (Humbert et al., 2012) was employed, and the assessment of impacts and results was expressed according to four endpoint categories (Climate Change (in kg CO_2-eq), Human Health (in DALY), Ecosystem Quality (in PDF.m^2.yr) and Resources Depletion (in primary MJ)); and one inventory indicator (Water Withdrawal (in L)). For Human Health, only the impacts resulting from the release of substances into the outdoor environment and the exposure to humans within that environment were considered; direct exposure through indoor air or dust was excluded. Although recent developments in indoor exposure are moving forward (Hellweg et al., 2009), the lack of an established method in LCA limited the assessment of these impacts. No weighting of endpoint indicators was performed.

2.6. Sensitivity and uncertainty analysis

With the purpose to check the influence of methodological choices on the final results, sensitivity analyses were carried out. We have tested the assumption of a longer lifespan of concrete roof tiles and of shorter simulating different distances for distribution of finished products to storage. We have also tested the change of raw materials used in different processes: the use of argillite in the extraction process for ceramic roof tiles and the use of artificial sand in the concrete tile production. The addition of other components in the process was also verified, such as the use of packaging material for ceramic roof tiles and the use of an insulation layer under concrete tiles. With regard to the use of emission data, mainly based in data available in the United States, a sensitivity analysis was carried out with data from the Cement Association of Canada (CIEEDAC, 2011) to test the scale of variability. The whole analysis was also carried out with another LCIA method (ReCiPe) to check for differences in the results.

Uncertainties related to inventory data and the use of characterization models were assessed, respectively, by means of a Monte-Carlo simulation and the translation of inventory into environmental impacts. Most of the data used was obtained from the Ecoinvent database and the variability of most of them was represented by a lognormal distribution around the central value specified, characterized by its standard deviation. The variability was estimated by applying a pedigree matrix, describing the data quality by its origin, its collection method and its geographical,

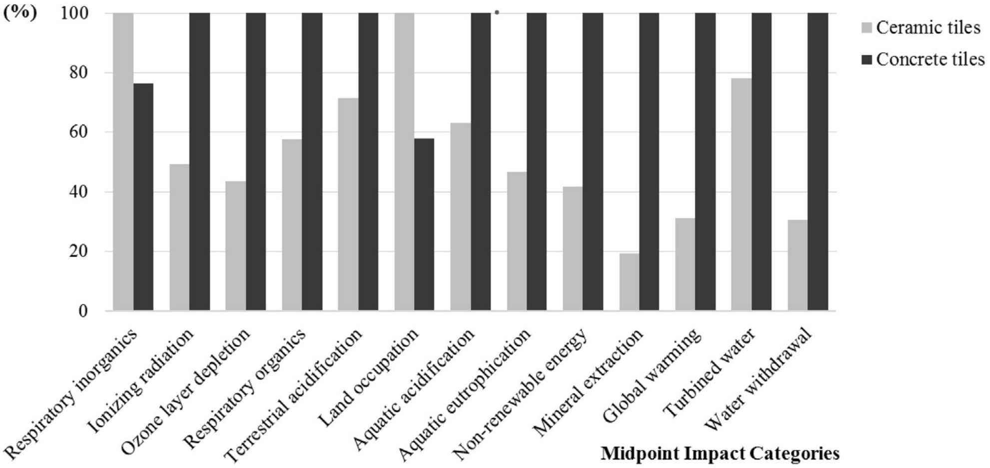

Fig. 3. Comparative midpoint LCA results for ceramic and concrete roofing tiles. The analysis was carried out with IMPACT 2002+.

temporal and technological representativeness (Weidema and Wesnæs, 1996).

3. Results and discussion

The results of ceramic and concrete tiles were compared in their baseline scenarios and the contribution of their life cycle stages to each endpoint indicator were analyzed. An inventory data quality assessment and a sensitivity analysis were carried out in order to respectively identify data requiring improvement and to verify the influence of modeling assumptions on the results. The LCA study identified some key parameters to be considered when deciding between the use of two different roofing options: ceramic and concrete tiles. The outcomes of the result are a function of many factors, such as the definition of the functional unit, data used, modeling assumptions and specification of system boundaries.

3.1. Comparative analysis

The ceramic and concrete tiles were compared in their baseline scenarios, for assessment of midpoint and endpoint impact indicators (Fig. 3). The results show that ceramic tiles have less impact in most impact categories, except for “respiratory inorganics” and “land occupation”, for which concrete tiles presented a lower contribution. Higher impact in these two categories is mainly caused by the use of wood as fuel.

The comparative endpoint LCA results (Fig. 4) show ceramic roof tiles have a lower impact on climate change and resource depletion than concrete equivalents. Greenhouse Gas (GHG) emissions over the life cycle of 1 m^2 of ceramic roof tiles are roughly one third those of 1 m^2 of concrete roof tiles. The resource depletion score of ceramic roof tiles, which mainly refers to consumption of non-renewable energy, is around 40% of the level for concrete tiles. The Water Withdrawal indicator also shows the same tendency, but its significance is to be considered with caution considering the incomplete and less reliable generic inventory data for water use. It can be observed, however, that ceramic roof tiles seem to require a lower amount of water withdrawn when compared with concrete equivalents.

Regarding damage to Human Health and Ecosystem Quality, the difference in the results between roofing materials is lower than the uncertainty related to the impact assessment model. Indeed, taking into account impact modeling uncertainty, (Humbert et al., 2012) sets a minimal difference required between score results to allow the drawing of a robust conclusion. For Human Health, a significant difference must be at least of 40% between options and the midpoint category respiratory inorganics, linked to the emissions of fine particles and nitrogen oxides, are the main contributor to the endpoint results. Terrestrial ecotoxicity is the main contributor to the impacts on Ecosystem Quality and a clear distinction requires a difference of at least an order of magnitude. Therefore, when taking into account these two indicators, one product cannot

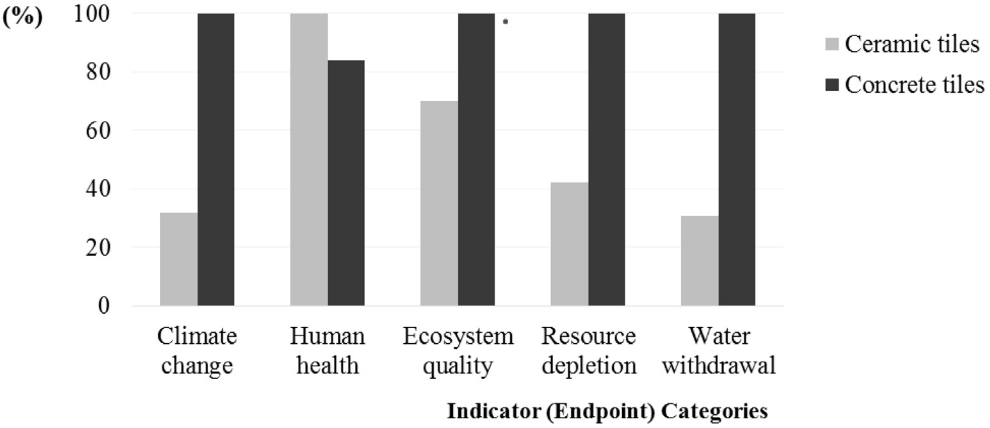

Fig. 4. Comparative endpoint LCA results for ceramic and concrete roofing tiles. The analysis was carried out with IMPACT 2002+.

Table 5

Percentage contribution of ceramic tile life cycle stages to each of the endpoint and inventory indicators: Climate Change, Human Health, Ecosystem Quality, Resource Depletion, and Water Withdrawal. The percentage is relative to total impacts, for each indicator.

Life cycle stages (ceramic tile)	Climate change	Human health	Ecosystem quality	Resource depletion	Water withdrawal
Extraction	10%	8%	4%	10%	4%
Transportation from extraction	30%	13%	23%	30%	23%
Dough preparation	1%	1%	1%	1%	11%
Forming operation	7%	2%	4%	5%	7%
Drying	0.1%	0.03%	0.03%	0.09%	0.10%
Firing	9%	58%	37%	6%	11%
Distribution	31%	12%	22%	31%	25%
End-of-life	12%	6%	9%	17%	19%

be considered better than the other. However, the results still provide valuable information to better understand the environmental impacts caused by the life cycle of each product. The impact of Ecosystem Quality is mostly attributable to the terrestrial ecotoxicity midpoint impact category.

Numerical results are presented in Table B.1 and Table B.2 in Appendix B.

3.2. Contribution analysis

The contribution of each life cycle stage of the ceramic tiles to five endpoint and inventory indicators in IMPACT 2002+ is shown on Table 5.

The main sources of impact on Climate Change are the exhaust CO_2 emissions due to fuel combustion during transportation at both extraction and distribution phases. This is also reflected in the end-of-life stage, during which transportation takes place of over 50 km. Biogenic CO_2 released by the combustion of wood chips (12.4 $kgCO_2/m^2$) were not included in this analysis. Impacts upon Human Health were mainly due to the release of particulate matter ($PM_{2.5}$) during wood combustion in the firing stage and the emission of nitrogen oxides (NO_x) during transportation during extraction and distribution phases. The firing and transportation steps are the main contributors to the impacts on Ecosystem Quality, due to metal emissions during both wood combustion (e.g. zinc) and tire abrasion. Fossil fuel consumption during transportation (extraction, distribution and end-of-life) contributed to almost 80% of the total Resource Depletion impacts. The contributions from each stage of the life cycle is rather even, since no important quantity of water is required for any of them. The transportation stages presented a slightly higher impact, due to the water used in the cooling steps of the petroleum refining process. For the concrete tiles, the contributions are displayed in Table 6.

The contribution of emissions to Climate Change are mainly observed during the Portland cement production, specifically in the clinkerization process. Around 60% of the CO_2 emissions associated with this step are a product of the chemical reactions occurring during calcination, which also requires a great deal of heat, for which fossil fuels are used. Transportation (intermediate transport, distribution and transport to landfill) accounts for around 40% of climate change emissions. Impacts on Human Health are mainly caused by NO_x emissions from transportation and the clinkerization during the Portland cement production, while Ecosystem Quality is lowered by metal (e.g. zinc) and NO_x emissions during the transportation steps. Transportation is also the largest contributor for Resource Depletion, followed closely by Portland cement production. However, the CO_2 released chemically in the Portland cement production does not contribute to the depletion of resources. Water withdrawal mainly occurs during sand extraction for the tile production, followed by water use in the clinker production (12%).

Some considerations are important to understand these results. Due to the low reliability of existing ecotoxicity models for metals released into soils and water bodies, high uncertainty was identified in the Ecosystem Quality damage indicator calculated for both ceramic and concrete tiles. Therefore, metals from agricultural processes were excluded. Moreover, water withdrawal is an inventory indicator and does not represent impact to the system without characterization of the impact.

3.3. Inventory data quality assessment

A data quality assessment for the LCA of ceramic and concrete tiles was carried out in order to identify data requiring improvement, clarify limitations in the robustness of the LCA results and facilitate the selection of the sensitivity analysis to be performed. The results are summarized in Table C.1 of Appendix C and show that data and parameters with the highest contribution to potential environmental impacts globally have a high or acceptable level of reliability while geographic representativeness is sometimes low. However, these are processes that have been around for decades and more, in such a way that technology transfer across borders insures a degree of representativeness that is acceptable. Data on clinker and cement production could however benefit from further precision, to reach the quality level of data provided for ceramic production, especially in terms of geographical representativeness. This is one of the limitations of this study.

3.4. Sensitivity analysis

Due to limitations of the baseline analysis, attributable to inventory data of lower quality, nine sensitivity analyses were carried

Table 6

Percentage contribution of concrete tile life cycle stages to each of the endpoint and inventory indicators: Climate Change, Human Health, Ecosystem Quality, Resource Depletion, and Water Withdrawal. The percentage is relative to total impacts, for each indicator.

Life cycle stages (concrete tile)	Climate change	Human health	Ecosystem quality	Resource depletion	Water withdrawal
Portland cement	54%	24%	22%	35%	22%
Intermediate transport	10%	16%	17%	14%	17%
Tile production	3%	6%	5%	4%	5%
Concrete roof tiles, packaging	2%	3%	4%	2%	4%
Distribution	26%	42%	44%	36%	44%
End-of-life	5%	9%	8%	9%	8%

out. The aim was to verify the influence of modeling assumptions on the conclusions of the study.

Lifespan of tiles. In principle, the longevity of both tiles was assumed to be 20 years. However, due to a lack of statistical data and the association of the time of replacement with many different variables related to the user, it was difficult to establish accurate times. Therefore, a sensitivity analysis was carried out, varying the lifespan of concrete tiles between 10 and 30 years, to understand the scale of variation in the results. The results show that a lifespan 50% greater for concrete would not significantly influence the comparison, as only the impact on Ecosystem Quality would show a different conclusion. However, the difference between the compared options would remain too small to be considered significant. Therefore, the outcome of the comparison holds even if lifespan varied by up to ten years (Fig. D.1, Appendix D).

Use of argillite in clay extraction. In Brazil, harder clay called argillite is often used as an alternative to regular excavated clay in order to increase the quality of the final product. A sensitivity analysis carried out with the aim of evaluating the impact of this blasting step revealed a relatively low impact of blasting on the results, except for "Ecosystem Quality". It should be noted that we assumed the lifespan of the ceramic tile would remain the same, i.e. the minimum requested by national standards (Fig. D.2, Appendix D).

Use of artificial sand in concrete production. Although the use of artificial sand, made of crushed natural rocks, adds a further extra crushing step, it was shown to have negligible influence on the results (Fig. D.3, Appendix D).

Transport distances for tile distribution. Apart from the baseline scenarios (distribution of ceramic and concrete roof tiles, respectively over 120 km and 450 km distances) different scenarios were tested with diverse maximum transportation distances: distribution of ceramic roof tiles over a distance of 250 km and of concrete roof tiles over 120 km. The results showed that the impact on ecosystem quality could be lower for concrete if the distribution distances were the same, however, the difference would still be too low in magnitude to be significant. However, if distances were the same (e.g. 120 km for both tiles), the impact on "Human Health" would be significantly higher for ceramic tiles (30% for respiratory inorganics) making concrete tiles more advantageous for that damage category (Fig. D.4, Appendix D).

Use of packaging around ceramic tiles. The use of packaging for ceramic tiles was shown to have little impact on the overall results (Fig. D.5, Appendix D).

Emissions from cement production. Due to the lack of data for emissions caused by the fuel mix used in the clinkerization process in Brazil, a sensitivity analysis was conducted on different emission data, as provided by the Cement Association of Canada (CIEEDAC, 2011) to compare with the original US emission data included in the Ecoinvent dataset, from 1998, to test the scale of variability. The results show that the use of data provided by the Cement Association of Canada had a variation of over 10% for impact on "Human Health" while the results for most indicators remained the same. The different scenarios for cement production do not reverse the trend of the results (Fig. D.6, Appendix D).

Use of an insulation layer with concrete tiles. The additional use of thermal insulation (insulation with an 8 μm coating of aluminum) associated with concrete roof tiles was shown to not alter the conclusions of the study (Fig. D.7, Appendix D).

Results using a different allocation method. The sensitivity of the results to the allocation method was tested by expanding the system boundary to assign the benefit of the waste recovery to the first use of the residual waste (e.g. the original use of the tires reused in energy recovery), while the full impact of functionality equivalent fuels was included. In this case, the impact (or lack thereof) associated with using 11% residual waste in the fuel mix was replaced by the production of an energy equivalent quantity of coal. Emissions from combustion were assumed to remain the same, as separate studies conducted by US governmental agencies and engineering consulting firms have indicated that tire firing either reduces or does not significantly affect emissions of various contaminants from cement kilns (PCA, 2008). Because of the small contribution to the total fuel mix, the results confirm that the choice of allocation method has a relatively insignificant impact on overall results (Fig. D.8, Appendix D).

Results using ReCiPe as LCIA method. A sensitivity analysis was carried out to verify the results of the analysis using another life cycle impact assessment method, ReCiPe (Goedkoop et al., 2009). For the damage category "Resource Depletion", no differences were found, while for "Human Health" and "Ecosystem Quality", the contribution of concrete roof tiles was shown to be much greater. ReCiPe considers that Climate Change ultimately impacts both Human Health and Ecosystem Quality. As a result, the greater CO_2 emissions for concrete tile production tops the list as the main contributor in each of these categories (Fig. D.9, Appendix D).

3.5. Monte-Carlo uncertainty assessment

The variability of most of the data was represented by a lognormal distribution. 70.4% of the data model is represented by a distribution on data variability. The remaining 29.6% of the data have no uncertainty and therefore were considered as fixed data. The results show that the probability that the impacts related to the functional unit for ceramic roof tiles generate more damage than the corresponding impacts of concrete roof tiles are 0% for the "Climate Change" impact indicator, 0% for "Resource Depletion", 80.7% for "Human Health", 9.07% for" Ecosystem Quality", and 0% for "Water Withdrawal". All the results are shown in Table E.1 (Appendix E) for the damage indicators and in Table E.2 (Appendix E) for the impact category indicators.

4. Conclusions and recommendations

The main purpose of this study was to compare, under contemporary production infrastructure and logistics conditions in Brazil (year 2010), the environmental implications of choosing ceramic roof tiles over functionally equivalent concrete roof tiles to cover a surface of 1 m^2. The results are valid for tiles produced in Brazil and help in the identification of key parameters and hotspots in both systems, including life cycle stages and material categories. Moreover, the sensitivity analyses conducted helped the understanding of the influence of the assumptions and selected variables in the results.

Both products analyzed have similar processes, based on the use of natural resources and applying different degrees of transformation to obtain the final solid and durable product. Due to the high temperatures used during the calcination of cement and the need of more intensive combustion, the concrete manufacturing process has a great impact on Climate Change and Resource Depletion. Conversely, the use of residual wood chips as a heat source in the manufacturing of ceramic tiles reduces the impact on Climate Change, but generates a higher impact on Human Health. A higher impact on Water Withdrawal is linked to concrete tiles. For Ecosystem Quality and Human Health, since the difference in the results was not large enough, it was not possible to conclude which product had a higher or lower impact. However, with the use of the ReCiPe LCIA method which includes contribution of climate change to Ecosystem and Human Health damages, ceramic tiles show a distinctively better environmental performance than concrete tiles on these two indicators.

The assessment of data quality concluded that data quality was high or acceptable. The sensitivity analyses performed for data with higher uncertainty indicated that changes in the baseline scenario had no or insignificant influence on the results for the variation in lifespan, the use of alternative raw-materials, the alternative use of packaging for the transportation of ceramic tiles, and the use of an insulation layer under concrete tiles. The use of an alternative LCIA method did not influence the final results.

However, a significant drop in the distribution distances for concrete tiles, associated with a higher distance for ceramic tiles could lead to a potentially significant higher impact on Human Health for ceramic tiles. Moreover, the uncertainty assessment performed with Monte-Carlo iterations showed that the conclusions of the LCA study are robust.

Some limitations should be considered along with the context of the study, when interpreting the information and results. Firstly, several parameters are assumed to remain constant across the Brazilian geography evaluated, which may or may not be entirely accurate. This applies namely to manufacturing processes, transportation distances, fuel mixes for firing and clinkerization and the building structure required to support the weight of tiles. Secondly, the processes used in cement and concrete manufacturing were modeled based on Ecoinvent data. Only transportation distances and the grid mix and fuel mix for the Brazilian context were adapted. However, emissions from fuel combustion were not adapted. Moreover, some LCI data implemented describe European operations, implying that the study here may not be 100% representative of Brazilian practices (and thus impacts). However, a database of equivalent quality, transparency and robustness is not yet available for Brazil or other geographies (beyond Europe) from which the Brazilian building industry may source its materials. Finally, although an allocation methodology was applied in the study, several others exist and could be assumed.

LCIA methodologies such as IMPACT 2002+ do not and cannot characterize the wide array of emissions released to soil, air and water from the various processes. However, it does characterize the most well-known pollutants and in doing so provides the best estimate to evaluate environmental impact;

We emphasize this study does not support or provide definitive comparisons of the environmental performance of specific products or materials or of building designs, practices or related decisions beyond the central question of average ceramic roofing tiles versus concrete roofing tiles produced in Brazil. LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

Albeit its limitations, we believe this work contributes, not only to the development of a national life cycle inventory database, and more accurate Life Cycle Assessments in the construction sector, but also on the environmental impact evaluation of material and process choices in the life cycle of both evaluated tiles. The information obtained through this LCA can lead to the undertaking of various actions to reduce the life cycle environmental impact associated with ceramic and concrete tile production, focusing on the specific leads. For the ceramic tiles, for example, since the emission of fine particles released during the combustion of wood chips is the main contributor to Human Health impact, a focus on filtration of fines could be beneficial. Moreover, due to the importance of the transportation steps in all impact categories, alternative measures could be investigated, such as shipment by boat or train, and the use of renewable sources, such as biofuels. Environmental relevance of these alternatives should always be validated with a life cycle approach specific to the context. With regard to the concrete tiles, the option of a renewable source of energy during clinkerization process could reduce the CO_2 emissions during this step, improving the indicators' results for Climate Change, Human Health, Ecosystem Quality and Resource Depletion. We strongly expect this work to be an incentive to the construction sector in Brazil on its role in assessing the environmental impacts of building materials and elements.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2014.11.029.

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