The Carbon Footprint of Ceramic Products

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Abstract Nowadays it is generally recognized that human activities increase anthropogenic greenhouse gas (GHG) emissions to dangerous thresholds, leading to climate change due to an increase in global temperatures. In an industrial context, the product carbon footprint concept has been emerging as a relevant tool to support the development and implementation of GHG management strategies throughout product life cycles, in order to reduce GHG emissions along the supply chain, improve energy efficiency, and improve product competitiveness in different markets. This chapter focuses on the carbon footprint of ceramic products and has the following purposes: (1) to present general information on ceramic manufacturing, in particular a characterization of the European ceramic industry with regard to energy sources and production value, and a description of the general ceramic manufacturing process; (2) to carry out case studies in which the carbon footprint of different ceramic products (ornamental earthenware piece,

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brick, roof tile, wall and floor tile, sanitary ware) is quantified; (3) to identify improvement measures and best available techniques (BAT) to reduce the total carbon footprint of some products; (4) to analyze the specific GHG emission of each of the ceramic products studied, considering a cradle-to-gate approach; and (5) to present some methodological challenges related to carbon footprint quantification.

Keywords European ceramic industry · Best available techniques · Sanitary ware · Roof tile · Ornamental earthenware piece · Wall and floor tile

1 Introduction

The world energy mix is based on a model of fossil fuel consumption that is responsible for anthropogenic greenhouse gas (GHG) emissions. The Intergovernmental Panel on Climate Change (IPCC) in its Fourth Assessment Report (IPCC 2007) confirmed that global warming is an unequivocal fact: the global atmospheric concentration of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in the atmosphere has drastically increased since 1750, and nowadays provides a contribution of about 60 % to global warming.

This is evidenced by the increase in the global average air and ocean temperatures and rising sea level. To stop this trend and to reduce the current climate change development, several governmental and nongovernmental initiatives have been implemented, such as the introduction of emission trading programs, voluntary programs, carbon or energy taxes, and regulations and standards on energy efficiency and emission measurements (European Commission 2012, 2013; WRI/WBCSD 2011a).

The carbon footprint concept emerged from the ecological footprint discussion introduced in the 1990s by Wackernagel and Rees (Rees and Wackernagel 1994; Wackernagel and Rees 1996) and has become widely known over the last decade (East 2008).

Although many definitions for carbon footprinting are currently available, it is currently accepted that it refers to the sum of GHG emissions resulting directly and indirectly from a person, organization, or product (Carbon Trust 2010; Pandey et al. 2010). The product carbon footprint quantifies the GHG emissions over the product life cycle following a cradle-to-gate or a cradle-to-grave approach, as illustrated in Fig. 1. The cradle-to-gate approach includes all processes from the raw and ancillary materials extraction and energy production through product manufacturing including packing (gate of the mill), whereas the cradle-to-grave approach includes all processes from the raw and ancillary materials extraction and energy production through product manufacturing including packing, distribution, use phase, and eventually recycling, reuse, recovery, and final disposal.

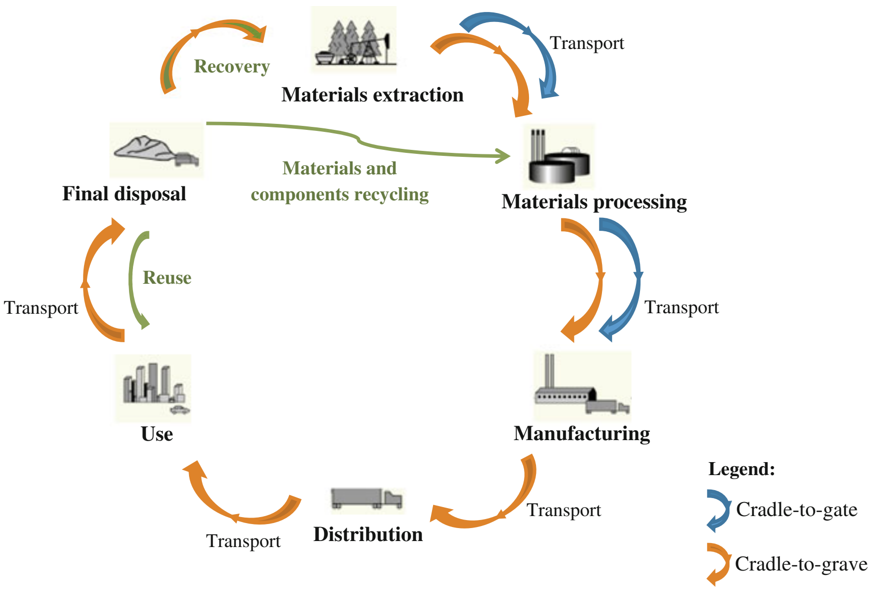


Fig. 1 Life cycle of a product following cradle-to-gate and cradle-to-grave approaches. Adapted from Remmen et al. (2007)

The GHG emissions are converted to their carbon dioxide equivalent (CO_2e) value using the global warming potentials defined by the IPCC (2007).

The product carbon footprint can be applied to:

- identify hotspots over the life cycle (i.e., main unit processes where GHG emissions occur);
- identify improvement measures for GHG mitigation, promoting energy efficiency and economic sustainability;
- communicate the carbon footprint to consumers;
- establish an opportunity for product differentiation and/or market penetration.

The ceramic industry plays a key role in sustainable development, considering its three main components: environment, economy, and society. The ceramic industry recognizes the need to mitigate GHG emissions and increase energy efficiency. These goals can be achieved by conducting an environmental impact assessment throughout the product life cycle, and therefore implementing environmental and energy improvement measures into the manufacturing process.

The carbon footprint of ceramic products emerges as a powerful tool to perform the systematic integration of energy efficiency and environmental consideration in the product design process and decision-making (European Commission 2011). In addition, it can also provide information for planning and assessing the sustainability of buildings, as it is one of the indicators included in the European standards, namely in EN 15804:2012 (CEN 2012).

Several methodologies to estimate the carbon footprint of a product have been developed. In 2011, the British Standards Institution (BSI) published the Public Available Specification (PAS) 2050, which specifies the requirements to assess the life cycle GHG emissions of goods and services (BSI 2011). The GHG Protocol Initiative convened by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) developed a standard to quantify and report the GHG emissions throughout the life cycle of a product (WRI/WBCSD 2011b).

The International Organization for Standardization (ISO) in 2013 published the ISO/Technical Specification (TS) 14067, which specifies principles, requirements, and guidelines for the quantification and communication of the carbon footprint of a product. These three methodologies have been built based on the existing life cycle assessment (LCA) methodology established through the ISO 14040 and 14044 standards (ISO 2006a, b). ISO/TS 14067:2013 is also based on environmental labels and declarations—ISO 14020 (ISO 2000), ISO 14024 (ISO 1999), and ISO 14025 (ISO 2006c)—for communication.

PAS 2050 was applied by some companies in pilot projects to measure and report the carbon footprint of bricks (e.g., Ceram 2011; Best Foot Forward 2011). This methodology was also used to calculate the carbon footprint of an ornamental earthenware piece (Quinteiro et al. 2012a), which is, currently, the only published study that deals with this type of ceramic product.

Due to primary data (data that refers to direct measurements made along with the supply chain, from processes owned, operated, or controlled by the organization under study) confidentiality, there are only a few published studies concerning the quantification of ceramic products. Most of these available studies have been performed following ISO 14040 and ISO 14044, and are limited to the analysis of GHG emissions and the corresponding global warming impact category, such as Almeida et al. (2010a, 2011) and Koroneos and Dompros (2006), who estimated the carbon footprint of bricks; Almeida et al. (2011) and Bribilán et al. (2011), who estimated the carbon footprint of roof tiles; Almeida et al. (2010b), Bovea et al. (2010), Ibánez-Forés et al. (2011, 2013), Nicoletti et al. (2002) and Tikul and Srichandr (2010), who calculated the carbon footprint of wall and floor tiles; and Kaleseramik (2012), who calculated the carbon footprint of sanitary products. Furthermore, the application of cut-off criteria, as well as allocation procedures, is not commonly referred to in those studies.

Concerning to the content of this chapter, Sect. 2 presents general information on ceramic manufacturing, characterizing the European ceramic industry relative to its energy sources and production value, and explaining the general ceramic manufacturing process. In Sect. 3, some case studies are presented, with the carbon footprint for ornamental earthenware pieces, bricks, roof tiles, wall and floor tiles, and sanitary ware products being calculated, and, when justifiable, identifying some environmental and energy improvement measures and best available techniques (BAT). Section 4 discusses the specific GHG emission of each of the ceramic products studied, the different contribution of the manufacturing stage of the different products being analyzed for the total carbon footprint considering a cradle-to-gate approach, and a synthesis of the improvement measures and BAT studied. Section 5 presents challenges to carbon footprinting ceramic products. Section 6 presents the main conclusions of this study.

2 General Information on Ceramic Manufacturing

A brief characterization of the ceramic industry, identifying the main ceramic products manufactured and their production value, is made in this section. Moreover, the general manufacturing process of ceramic products is explained, identifying the specific manufacturing characteristics of each ceramic sub-sector analyzed.

2.1 Characterization of Ceramic Industry

The ceramic industry in the European Union (EU)-27 (an economic and political union of 27 European member states) accounts for 23 % of global ceramics production (Cerame-Unie 2012).

The ceramic industry has a wide range of product applications: structural—including bricks, pipes, wall and floor tiles, and roof tiles; refractories—such as kiln linings; table and ornamental ware (household ceramics); sanitary ware; expanded aggregates; inorganic bonded abrasives; technical—such as insulators, biomedical implants, and ceramic capacitors; among others (European Commission 2007; Rahaman 2006; Remmey 1994). This classification of subsectors has evolved in accordance with the ceramic technological evolution.

All these ceramic industry subsectors are energy intensive, namely due to the drying and firing processes, which involve firing temperatures between 800 and 2000 °C (European Commission 2007). From a generic point of view, the energy costs of the European ceramic industry represent an average of 30 % of the total manufacturing costs, where the energy mix is around 85 % of natural gas to 15 % of electricity (Cerame-Unie 2012). However, the energy sources and their percentages vary depending on the ceramic subsectors and their products, as well as on the specific country considered. For instance, in the case of Portugal, about 3 % of the brick mills operate on fuel oil, about 11 % with petroleum coke, 15 % with biomass, 70 % with natural gas, and the remaining 1 % corresponds to the use of liquefied petroleum gas (Dias 2008).

The production value of the EU-27 ceramic industry has been fluctuating over the last few years, as illustrated by Fig. 2. After the economic crisis of 2008, the production values of ceramic products, namely wall and floor tiles, bricks, and roof tiles, dropped and have been recovering slowly since 2009. In addition, some ceramic subsectors, such as table and ornamental ware, have been experiencing strong competition from new emerging markets (European Commission 2007).

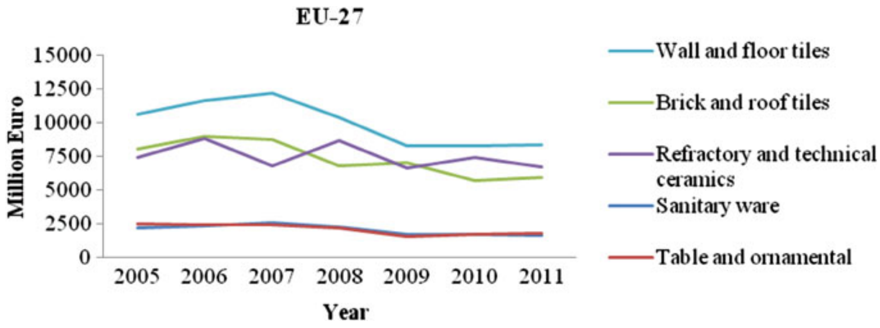


Fig. 2 Trend in the production values of the EU-27 ceramic subsectors (Eurostat 2013)

2.2 Ceramic Manufacturing

The manufacture of ceramic products is a complex interaction of raw materials, technological processes, people, and economic investments. It takes place in different types of kilns (e.g., continuously operated tunnel and periodically operated shuttle), with a wide range of raw materials and in numerous shapes, sizes, and colors. The manufacturing includes the transport and storage of raw materials, ancillary materials and additives (e.g., deflocculating agent—sodium silicate for the preparation of raw materials), preparation of raw materials, shaping, drying, surface treatment, firing, and subsequent treatment.

Figure 3 schematically shows the typical steps in the manufacturing of ceramic products. The following steps are identified: transport and storage of raw materials, ancillary materials and additives (e.g., deflocculating agent—sodium silicate for preparation of raw materials), preparation of raw materials, shaping, drying, surface treatment, firing, and subsequent treatment. However, the manufacturing operations can vary according to the specific requirements of ceramic products and raw material characteristics, as explained below.

2.2.1 Preparation of Raw Materials

The preparation of raw materials consists of mixing several raw materials and additives, with the aim of obtaining a material with a homogenous composition and an appropriate granulometric distribution. Even in the case of bricks (typically red ceramics) that use almost only clay as the raw material, two or more types of clay with different composition are used.

2.2.2 Shaping

The shaping of the ceramic product depends on the product type and the technique applied:

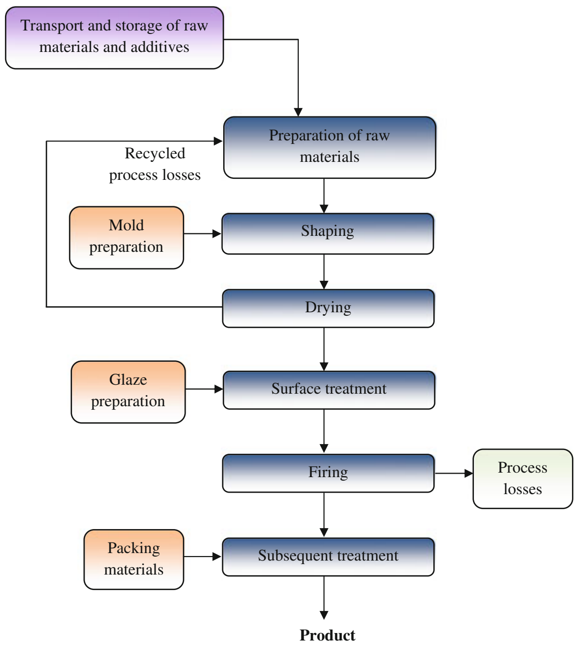


Fig. 3 General steps in the manufacturing of ceramic products. Adapted from Quinteiro et al. (2012a)

(1) slip casting process for ornamental ware, sanitary ware and refractory ceramics;
(2) dry pressing for ornamental ware and wall and floor tiles;
(3) plastic shaping for ornamental ware, bricks and roof tiles (European Commission 2007; Serrano et al. 2009).

In the slip casting process, body formation takes place in a mold made of gypsum plaster, and the mold is placed on a bench with a closed pipe system for warm water circulation. This water warms the mold and the capillary suction of the mold draws a portion of the liquid from the slip casting to form a high solid cast on the inner surface of the mold. The wall thickness increases progressively with time; when the piece has an appropriate wall thickness, the operator proceeds to the draining of the remaining slip casting, which is reintroduced in the production process. In the case of dry pressing, the powder (moisture content 5–7 % of water after the spray drier) is pressed into the molds (pressing unit process), whereas in plastic shaping, the 'extrusion paste' (moisture content 20–25 %) is formed in jigger machines.

After the shaping step, the green ware of ornamental, sanitary, and technical ware undergoes a dressing process, which consists of the removal of the surface roughness and mold marks from the ceramic.

2.2.3 Drying

The next step is the ceramic product drying. Green ware still usually contains water from the preparation of the raw materials. Therefore, to avoid tension and consequently nonconforming pieces, it is necessary to remove this water, slowly and gradually, in intermittent dryers, continuous dryers, or stoves at temperatures varying between 50 and 350 °C (European Commission 2007; Serrano et al. 2009). Heat for air drying is mainly supplied by gas burners and by hot air recovered from the cooling zone of the tunnel kilns or by using heat exchangers in shuttle kilns.

The ceramic industries, such as ornamental, bricks (less usual), roof tiles, and sanitary ware, use intermittent chamber dryers, which consist of a battery of chambers with close-fitting entry doors, usually served by rail tracks carrying kiln-cars. These kiln-cars are loaded with ceramic products. In the ornamental drying unit process, the piece is dried for a period of about 12 h. Until this unit process, unfired broken ware (nonconforming pieces without heat treatment) are reintroduced into the mixing process as a raw material. For bricks and roof tiles, the drying cycles are in the order of 16–24 h, with a temperature of about 100 °C.

For ceramic wall and floor tiles, it is common to use a vertical dryer, in which the green tiles are fed into baskets consisting of several decks of rollers. The groups of baskets move upwards through the dryers, where they meet hot drying gases. The temperature in this type of dryer is normally less than 200 °C, and the drying cycles range from 35 to 50 min. Horizontal multideck roller dryers can be also used in the manufacturing of wall and floor tiles. These tiles are fed onto different decks within the dryer, being conveyed horizontally by driven rollers. The maximum temperature in these dryers is usually higher than in the vertical option (around 350 °C), and the drying cycles are shorter (between 15 to 25 min).

2.2.4 Surface Treatment and Firing

After drying, the green ware undergoes surface treatment by glazing, engobing, and/or other decorating techniques (screen printing, gravure, and flexo space printing) (European Commission 2007; Serrano et al. 2009). Engobing is mainly employed in the manufacture of roof tiles and wall and floor tiles, whereas glazing is mainly used in ornamental and sanitary ware.

In the glazing unit process, the green ware is covered with a thin glaze layer followed by a firing cycle, which seals the porous ceramic body. The surface of the piece becomes watertight and smooth. In the case of ornamental products, before glazing the pieces undergo a preliminary firing cycle, a biscuit firing cycle. This first heat treatment gives the piece the strength and absorbency required for glazing. During biscuit firing, some pieces undergo undesirable structural changes, like local defects and cracks, and cannot be reintroduced into the manufacturing cycle. This fired broken ware is generally sent to the cement industry. After glazing, the fired piece undergoes a second heat treatment (glost firing). Some nonconforming pieces resulting from glost firing can be retouched and then submitted again to glost firing (refiring).

The wall and floor tiles can undergo the following firing cycles: (1) unglazed firing cycle; (2) double fired (less used), in which the green ware undergoes a biscuit firing cycle, glazing, and a glost firing cycle; (3) single fired glazed, in which the green ware is glazed and then goes through one firing cycle (European Commission 2007).

Sanitary green ware is also glazed and, therefore, undergoes a single firing. However, some resulting nonconforming pieces can be retouched and submitted to a new firing cycle (refiring). The bricks and roof tiles are unglazed. However, it should be noted that a small fraction of roof tiles is glazed and then submitted to a single or double firing, depending on the technology implemented in the mills.

The firing is a key process in the manufacturing of ceramic products because it encompasses the chemical and physical changes in the ceramic body, so that the final product has the appropriate characteristics to be handled (dimensions, geometry, mechanical strength, abrasion and fire resistance, and porosity). Shuttle kilns are used in ornamental and sanitary ware and in refractory ceramics, where the pieces are placed on kiln-cars on fireproof firing auxiliaries (also called kiln furniture). Tunnel kilns are used in bricks, roof tiles, sanitary ware, and refractory products, where the green ware is placed in kiln-cars, on which there are refractory decks. These kiln-cars are pushed through the kiln at set intervals. Incoming ware is preheated by hot gases from the firing zone, whilst incoming air cools the fired ware and is itself preheated for its combustion role. The roller kilns are mainly used for wall and floor tiles, as well as for table and sanitary ware.

Table 1 shows the specific temperature profiles of ceramic subsectors.

2.2.5 Subsequent Treatment

After firing, some products require additional processing to address certain features that cannot be achieved during its manufacture. This subsequent treatment can

Table 1 Ranges of temperature profiles of firing unit processes (European Commission 2007; Remmey 1994)

Ceramic subsector	Firing temperature (°C)
Ornamental ware	
• Biscuit firing cycle:	1,000–1,100
• Glost firing cycle:	1,000–1,080
Table ware	1,180–1,350
Brick	850–900
Roof tile	1,000–1,200
Wall and floor tile	1,050–1,200
Sanitary ware	1,250–1,300
Refractory and technical ceramics	1,250–1,850

include polishing, cutting, drilling, and sawing, among others (product finishing). Afterwards, the ceramic products are sorted, labeled, packaged, and delivered to distribution.

3 Case Studies

This section presents case studies that quantify the carbon footprint of ornamental earthenware pieces, bricks and roof tiles, wall and floor tiles, and sanitary ware based on the Quinteiro et al. (2012a), Almeida et al. (2010a, b, 2011) and Almeida (2009) studies, respectively.

All case studies were performed following the ISO 14040 and ISO 14044 standards, and are limited to the analysis of GHG emissions and the corresponding global warming impact category. The goal, functional unit, system boundary, data collection, multifunctionality and allocation, and carbon footprint results are presented for each case study. Moreover, some improvement measures and best available techniques (BAT) for the ceramic manufacturing industry are also identified and evaluated, such as the incorporation of more energy-efficient technologies in the manufacturing stage and the use of alternative energy sources (European Commission 2007).

3.1 Carbon Footprint of Ornamental Earthenware Pieces

3.1.1 Goal of the Study

This case study aims to estimate the carbon footprint of an ornamental earthenware ceramic piece, manufactured and consumed in Portugal. The carbon footprint hotspots are identified, improvements in environmental measures are suggested, and their feasibility, performance, and economic viability are evaluated.

3.1.2 Functional Unit

The functional unit has been defined as one ornamental earthenware ceramic piece (cubic vessel) ready to be sold, with a mass of 0.417 kg and dimensions of $10 \times 10 \times 10$ cm.

3.1.3 System Definition and Boundary

Following ISO 14040 and ISO 14044, a cradle-to-grave approach is adopted; that is, GHG emissions are considered from the extraction of raw materials, through

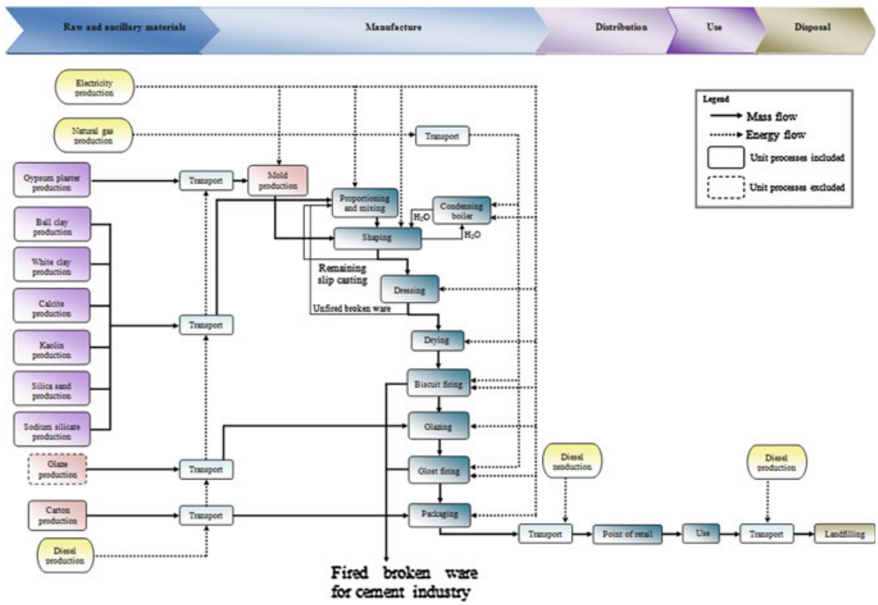


Fig. 4 System boundary for ornamental earthenware pieces. Adapted from Quinteiro et al. (2012a)

manufacturing, use, and the disposal of the used product. The cut-off criteria allow the decision of which processes should be included within the system boundary. Although ISOs do not suggest quantified thresholds, they state that the cut-off criteria should be based on mass, energy, and environmental significance. Therefore, in this study, the mass flows that represent less than 0.5 % of the functional unit were excluded from the defined system boundary. The system boundary also excludes the transport of consumers to and from the point of retail and the transport of employees to and from the manufacturing mill, as well as the production of capital goods (machinery and equipment).

As shown in Fig. 4, the following stages are considered:

- Raw and ancillary materials—which includes cradle-to-gate GHG emissions (from the raw material extraction through the production stage up to the gate of the company) for the production of the raw materials—white and ball clays, calcite, kaolin, silica sand, and sodium silicate—consumed in the manufacturing of the ceramic piece, namely in the proportioning and mixing unit processes. This stage also includes cradle-to-gate GHG emissions for the production of the gypsum plaster needed for mold production, the production of carton board used to pack the ceramic piece, the production of diesel necessary for transporting the raw materials to the ceramic mill and the GHG emissions released during this transport by the truck, and the production of electricity and natural gas.
- Manufacture—includes GHG emissions by the ceramic mill and by the operational activities such as lighting, administrative activities, heating, ventilation,

Table 2 Data sources used in secondary data collection (Quinteiro et al. 2012a)

Unit process	Data source
Kaolin production	Ecoinvent database v.2.2 (Ecoinvent 2012)
Silica sand production	
Calcite production	
Black clay production	
White clay production	
Sodium silicate production	
Cartonboard production	
Landfilling	
Gypsum plaster production	GaBi 6.0. software database (PE International 2012)
Electricity production (Portuguese mix)	
Natural gas production	
Diesel production	
Transport	• Distances: provided by the mill • GHG emissions factors: GaBi database (PE International 2012)

and air conditioning. This stage also includes cradle-to-gate GHG emissions from the auxiliary unit process mold production.

- Distribution—includes GHG emissions as a result of the transport by truck of the piece to the point of retail, and by the production of diesel used in this transport.
- Use—it was assumed that there is no energy consumption and/or GHG emissions expended during the usage of the ceramic piece.
- Final disposal—the piece was assumed to be landfilled at the end of its life cycle; this stage includes GHG emissions arising from the landfill, from the truck transportation of the piece to the landfill, and from the production of diesel used in this transport.

3.1.4 Data Collection

All data from each unit process comprised in the ceramic piece's manufacturing stage were collected at the mill that produces the analyzed piece. For the remaining unit processes, secondary data have been collected from databases (Table 2). Secondary data refers to external measurements that are not specific to the product but represent an average or general measurement of similar processes or materials (e.g., generic data from peer-reviewed publications, databases, industry reports, or aggregated data from trade associations, among others).

In the production of the ceramic piece, the CO_2 emissions arising from the consumption of energy (natural gas and electricity) and from the decomposition of calcium carbonate ($CaCO_3$) contained in the piece during biscuit firing (Aiazzi and

Aiazzi 1988). Natural gas is consumed in the condensing boiler to heat the water used in shaping and during biscuit and glost firing.

3.1.5 Multifunctionality and Allocation

The ornamental earthenware ceramic manufacturing is typically a multifunctional system because several pieces with different dimensions and geometries are manufactured in the same production line, at the same time (co-products). The data on energy consumption (electricity and natural gas) provided by the mill includes the energy needed to produce the piece under study, but also for all the other pieces manufactured during the reference year. As we are faced with multifunctional processes, it is necessary to allocate the GHG emissions due to energy consumption in the ornamental manufacturing processes to the piece under analysis. To solve the allocation problem in carbon footprint studies, a hierarchy of procedures shall be compiled (BSI 2011; ISO 2006b). Wherever possible, allocation should be avoided by unit process division or by system boundary expansion. Where allocation cannot be avoided, the GHG emissions of the process should be partitioned according to physical relationships. Where physical relationships cannot be used, the allocation should be done using other criteria, such as the economic value of the products. In this study, the application of unit process division and system boundary expansion are not feasible due to an absence of data.

The physical relationships usually employed in manufacturing processes are the mass, volume, number of items, or time of processing, as stated by the European Commission JRC (2010). However, the ornamental earthenware ceramic manufacturing process does not allow the employment of a single allocation criterion to all energy consumption flows (Quinteiro et al. 2012b).

The single mass and volume criteria seem not to be a rational choice because the energy consumption in each manufacturing stage is not always proportional to the mass or to the volume of the ornamental earthenware ceramic pieces manufactured. For example, the mass criterion is adequate for the biscuit firing cycle but not for the glost firing cycle. In the biscuit firing cycle, the pieces can touch each other, so that smaller pieces can be placed inside larger ones. Therefore, the energy consumed during the biscuit firing cycle is proportional to the mass of each ceramic piece, with the mass the being critical issue. On the other hand, during the glost firing cycle, the critical issue is the piece volume; the pieces cannot touch each other or they would vitrify together.

An allocation based on the number of items is also not applicable to all manufacturing stages, because some ornamental earthenware ceramic pieces require more energy and generate more emissions than others. For example, hard running and handling pieces are very susceptible to deformations and imperfections, requiring several firing cycles to obtain the final product.

The time of processing criterion also seems not to be a reasonable option from an operational point of view, because the mill under study produces several ceramic pieces at the same time (the mill has, on average, hundreds of different pieces in processing), and each piece has a different time of processing in each manufacturing stage. On average, the total time of processing of each piece varies between 2 to 3 weeks.

An allocation method based on the market price of the pieces was also disregarded because the market price of the pieces changes according to market demand. This allocation criterion would result in a poor time-related representativeness of the energy consumption and costs and the GHG emissions by each studied piece, as market prices change over a short time, making it necessary to reformulate the study whenever the market price changes.

Therefore, a hybrid allocation model based on the mass, volume, and/or number of pieces manufactured at the mill has been applied (Quinteiro et al. 2012b). Electricity is consumed in all the unit processes and has two components: a nonpermanent component, which occurs directly due to the piece production, and a permanent component, which represents the electricity consumed in the absence of production. This last component refers to the existence of equipment permanently in operation (e.g., stove fans) and to the mill lighting system.

The mass allocation criterion has been used to estimate the nonpermanent component of electricity and natural gas consumption during biscuit firing, the volume allocation criterion has been considered to calculate natural gas consumption in glost firing, whereas the number of pieces manufactured at the mill has been used in the calculation of the permanent component of electricity consumption. Table 3 presents the consumption of electricity (nonpermanent and permanent components) and natural gas in each unit process allocated to each piece.

As mentioned in Sect. 2.2, fired broken ware cannot be reintroduced in the production process and is sent to the cement industry. Because this material is considered waste and not a co-product, all the GHG emissions arising from the ceramic piece manufacturing stage have been allocated to the ceramic piece.

Table 3 Electricity and natural gas consumption of each unit process included in the ceramic piece manufacturing stage

	Electricity (kWh/piece)		
Unit processes	Nonpermanent component	Permanent component	Natural gas (kWh/piece)
Mold manufacture	0.007	0.011	–
Proportioning and mixing	0.059	–	–
Condensing boiler	0.001	0.011	1.06
Shaping	–	0.167	–
Biscuit firing	0.006	–	1.39
Dressing	0.003	0.045	–
Glazing	0.002	–	–
Glost firing	0.007	–	0.71
Packaging	0.002	0.033	–
Total	0.086	0.267	3.16

3.1.6 Results

The carbon footprint of the selected ornamental earthenware ceramic piece is 1.22 kg CO_2e per piece. The manufacturing stage is the main contributor to this carbon footprint, accounting for 88 % of the total carbon footprint. The raw and ancillary materials (10 %), the distribution (1 %), and the disposal (1 %) stages are the other main contributing stages to the total carbon footprint.

The unit processes that contribute more than 1 % to the total carbon footprint of the ornamental earthenware ceramic piece are shown in Fig. 5. The biscuit firing and condensing boiler (shaping stage) unit processes are the hotspots, as they contribute 18–30 % of the total carbon footprint of the ceramic piece, respectively.

The emissions of the biscuit and glost firing result from electricity consumption, natural gas burning, and the decomposition of $CaCO_3$ during biscuit firing. The $CaCO_3$ decomposition emits 0.12 kg CO_2e per piece, which corresponds to 10 % of the total carbon footprint. The shaping unit process also has significant emissions, being responsible for 10 % of the total carbon footprint of the ceramic piece. Insignificant GHG emissions (less than 1 % of the total carbon footprint) arise from the dressing, packaging, glazing, landfill, diesel production, and transportation of all the materials and products.

3.1.7 Improvement Measures and BAT

The identified hotspots in the life cycle of the ornamental earthenware ceramic piece should be preferably targeted for reducing the carbon footprint of the piece. Therefore, improvement measures and BAT to reduce the energy consumption and GHG emissions were identified and assessed, such as (1) incorporation of a gas pressure control system in kilns; (2) optimization of the lightning system; (3)

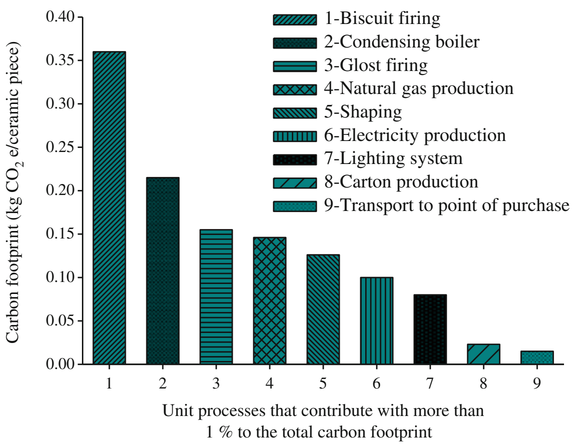


Fig. 5 Contribution of each unit process that contributes more than 1 % to the total carbon footprint of the piece

Table 4 Economic indicators to assess the implementation of the gas pressure control system in the shuttle kilns and the optimization of the lighting system

Economic indicators/improvement measures	Gas pressure control system	Lighting system
Investment	8000.00 €	2793.09 €
Cost savings	8315.00 €/year	505.00 €
Maintenance	<500 €/year	<300 €/year
Pay-back	<1 year	6 years

changing the temperature profile of the biscuit firing cycle; and (4) recovering excess heat from kilns. However, it should be noted that the type and integrative procedure of the improvement measures and BAT into the ceramic manufacturing process should be assessed cautiously. Their incorporation in the manufacture should be well-suited to the specific characteristics of the slip casting and mill installation; otherwise, they can damage the quality of the ceramic product, contributing to an increase in nonconforming pieces.

The incorporation of a gas pressure control system would result in a decrease of 10 % in both natural gas consumption and GHG emission for each biscuit and glost firing cycle, based on operating data of the mill, contributing to a carbon footprint reduction of 3 %.

With regard to natural gas costs, they would decrease by about 8 € for each biscuit and glost firing cycle.

To reduce electricity consumption at the mill, the lighting system should be optimized; for example, conventional ballasts should be replaced by electronic ones, as suggested by Sá (2008). A decrease, on average, of 2 % of the total carbon footprint of the ornamental earthenware ceramic piece is expected with the implementation of this measure.

Table 4 presents the indicators considered to assess the economic sustainability optimization improvement measures of both the gas pressure control system and lighting system. The avoided costs consist of cost savings in energy. The simple pay-back is defined as the period of time needed to recover the initial investment, dividing the initial investment costs by the annual energy costs savings. The payback is considered profitable when it is equal to or shorter than 3 years (European Commission 2006). The calculated payback for the incorporation of the gas pressure control system in kilns is usually lower than 3 years. This means that this measure emerges as the most profitable and economically sustainable because it combines the least expensive investment with the highest annual savings. Although the lighting system optimization requires a lower investment cost, its implementation would result in a payback twice that required to consider this measure profitable.

Another measure aimed to reduce the GHG emission during biscuit firing is a change in its temperature profile. The temperature profile has been adjusted considering both thermogravimetric analysis (Mansfield et al. 2010) and differential thermal analysis (Gabbott 2007) of the slip casting in order to understand its behavior when submitted to heating and cooling operations. This measure was

Table 5 Economic indicators to assess the sustainability of the thermal energy recovery system

Scenario/improvement measure	Thermal energy recovery system		
Reduction rate of natural gas consumption (%)	Investment (€)	Annual profit (€/year)	Pay-back (year)
25	.	1807.59	<3
50	4124.23	3615.19	1
75	.	5422.78	<1

applied at the studied mill and resulted in an energy efficiency of 2 % of the natural gas consumption per firing cycle. However, this measure was disregarded after conducting some experimental tests that showed that it caused an increase in broken ware and a decrease in the mechanical strength of the ceramic pieces.

To recover the excess heat from the kilns, the implementation of heat exchangers in the kiln chimneys is an option that should be considered. This BAT (European Commission 2007) would contribute to heating the water used in the shaping stage, thus reducing the natural gas consumption during this stage. However, this would require a long-term period to restructure and optimize the temperature profile of the biscuit and firing cycles, as it would cause severe changes to the kiln's atmosphere. Therefore, as an alternative, the installation of a thermal energy recovery system around the chimneys of the kilns has been analyzed. To evaluate the sustainability of this BAT, three reduction rates of natural gas consumption during the shaping stage have been simulated (25, 50 and 75 %) due to the absence of real data. The corresponding GHG emissions from the shaping stage would have the same reduction rates (25, 50 and 75 %).

These reduction rates lead to a total decrease in the GHG emissions of 2, 8, and 10 % for the ceramic piece under study, respectively. Table 5 shows the economic indicators used to assess the profitability of this improvement measure. The investment costs are the same for all scenarios. All defined scenarios present a simple payback lower than 3 years, arising as economic and environmentally sustainable options.

However, the reduction of 75 % in natural consumption appears to be the most profitable, since it results in the highest annual profit and has the lowest simple payback.

3.2 Carbon Footprint of Bricks

3.2.1 Goal of the study

This case study aimed to quantify the carbon footprint of a ceramic brick manufactured in Portugal and to identify the environmental hotspots throughout the brick's life cycle. In addition, some improvement measures are presented and discussed. The study follows a cradle-to-gate approach, considering GHG emissions from the extraction and processing of raw and ancillary materials until reaching the ceramic mill gate.

3.2.2 Functional Unit

In this case study, the functional unit is defined as one brick ready to be sold, with a mass of 4.21 kg and dimensions of 30 × 20 × 11 cm.

3.2.3 System Boundary and Data Collection

The cut-off criteria allows the decision as to which processes should be included within the system boundary. Although ISOs do not suggest quantified thresholds, they state that the cut-off criteria should be based on mass, energy, and environmental significance. Therefore, in this study, mass flows that represent less than 0.5 % of the functional unit were excluded from the defined system boundary (Almeida et al. 2010a, 2011). The distribution stage and the production of capital goods (building, machinery, and equipment) are excluded from the system boundary. The transport of consumers to and from the point of retail and the transport of employees to and from the manufacturing mill were also excluded.

Primary data (direct measurements made along the supply chain, from processes owned, operated or controlled by the organization under study) concerning brick manufacturing were collected from brick mills and quarries. Moreover, data concerning lightning and other activities, such as maintenance and cleaning, were also collected. The transport profiles (distance traveled, load state of the truck on the return journey) for the raw and ancillary materials were also provided by brick mills.

Secondary data for the raw and ancillary materials stage, such as data on clay, packing film, wood pallet, diesel, natural gas, and electricity production, as well as the GHG emissions factors for transport, were collected from the Ecoinvent database v.2.2 (Ecoinvent 2012).

As shown in Fig. 6, the system boundary includes the following stages:

- Raw and ancillary materials—consist of cradle-to-gate production of clays, packing film, and pallet. It also includes cradle-to-gate GHG emissions from the diesel production necessary for the transport of the raw materials to the ceramic mill and GHG emissions released during this transport by truck, and the production of natural gas and electricity.
- Manufacture—includes GHG emissions by the ceramic mill and by the operational activities such as lighting, administrative activities, heating, ventilation, and air conditioning.

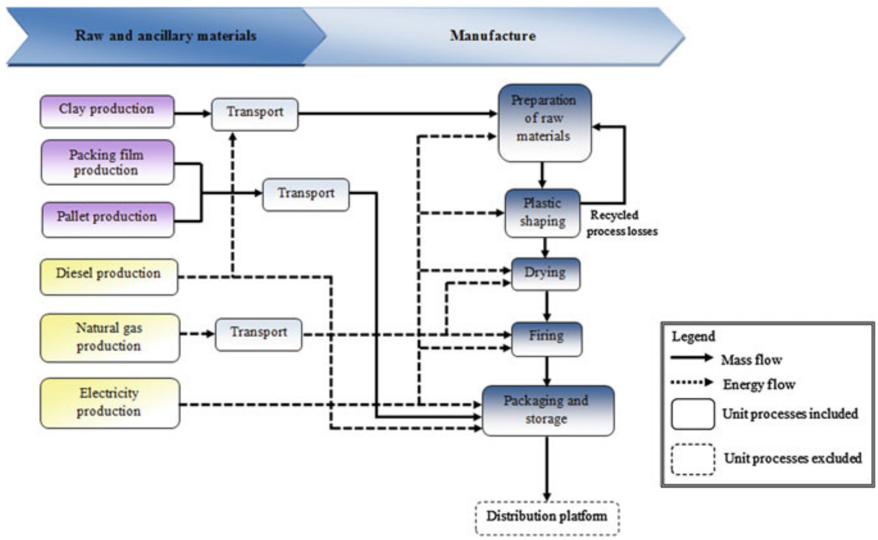


Fig. 6 System boundary for ceramic brick

3.2.4 Multifunctionality and Allocation

The manufacturing of bricks is a multifunctional system as the mill under study produces bricks with dimensions other than 30 × 20 × 11 cm (co-products). Therefore, it is necessary to allocate the GHG emissions of the manufacturing stage to the brick under analysis, as the energy consumption provided by the mill includes all the bricks manufactured. The choice of the most appropriate allocation criterion depends, among others, on the available data and the characteristics of the multifunctional system (European Commission JRC 2010). Therefore, bearing in mind these aspects and following the hierarchy of procedures to solve the allocation issues referred to in Sect. 3.1, an allocation based on the mass criterion was applied. In contrast to the manufacturing stage of ornamental earthenware pieces (case study presented in Sect. 3.1), in brick manufacturing the energy consumption in each manufacturing stage is proportional to the mass of the brick manufactured.

3.2.5 Results

The average carbon footprint of the brick manufactured in Portugal is 0.51 kg CO_2e per brick, using natural gas as the energy source for the drying and firing unit processes. The processes that contribute more than 1 % to the total carbon footprint of the brick are shown in Fig. 7. The firing process is responsible for about 60 % of the total carbon footprint (hotspot process), mainly due to the burning of natural gas in the kilns.

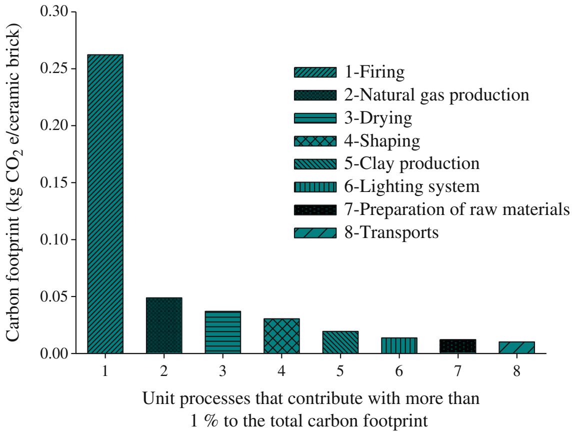


Fig. 7 Unit process that contribute more than 1 % to the total carbon footprint of the ceramic brick

Although the functional unit is one brick, to allow the comparison of the result of this carbon footprint of the brick with other published studies, it was converted to 1 kg of brick. Therefore, the carbon footprint of the brick manufactured in Portugal is 0.12 kg CO_2e per kg of brick. A higher value has been found by Koroneos and Dompros (2006), 0.20 kg CO_2e per kg of brick. These differences can be due to: (1) the definition of the system boundaries and cut-off criterion; (2) use of distinct energy sources; and (3) different manufacturing technology implementation due to the use of different energy sources and the specific composition of the raw materials. Koroneos and Dompros (2006) included distribution and use stages within the defined system boundary, whereas in the Portuguese brick study these stages were disregarded. Additionally, no information is given concerning whether the study uses any of the cut-off criterion. Also, the main source of energy used is different than that of the Portuguese brick because petroleum coke represents almost 100 % of the total energy consumption in the manufacturing stage (Koroneos and Dompros 2006). Petroleum coke is composed of a higher carbon ratio than natural gas, which means that when burned petroleum coke releases higher levels of CO_2, therefore having a higher warming potential than natural gas.

3.2.6 Improvement Measures and BAT

The switch from natural gas to biomass as the energy source in the brick industry was analyzed.

Although more than 80 % of brick kilns are fired with natural gas (Schimmel 2010), a growing number of companies have been using biomass as an alternative energy source to promote the environmental and economic sustainability of the mills (Fernandes et al. 2004). Table 6 presents the total carbon footprint of the brick either by using natural gas or biomass in the manufacturing stage. The carbon footprint of the brick using biomass as the energy source was calculated by

Table 6 Carbon footprint of the ceramic brick using different energy sources

Energy source	Carbon footprint (CO_2e per brick)
Natural gas	0.51
Biomass	0.28

considering the same functional unit, system boundary, and applying the same cut-off criterion. Primary data were collected from a similar brick mill, i.e., producing the same type of bricks, with the same implemented technology, the same kiln load capacities, and using the same raw materials, which already uses biomass as an alternative energy source.

According to Table 6, energy source switching from natural gas to biomass leads to a reduction of 55 % in the total carbon footprint of the brick. However, the use of biomass in the ceramic mills depends on long-term availability of forestry residues. Although the use of biomass appears to be suitable to reduce GHG emissions, biomass burning could lead to other environmental impacts. For instance, biomass burning generates higher emissions of particulate matter to the atmosphere than natural gas. In addition, it should be noted that the brick mill had to install a unit of biomass preparation, which requires an initial investment cost that needs to be assessed from an economic sustainability point of view.

In the calculation of the carbon footprint of the brick using biomass as the energy source, biogenic carbon (i.e., carbon that is captured and stored across the biomass growth) was considered neutral. This approach is valid because neutral biogenic CO_2 emissions are balanced by CO_2 sequestration in the forest, providing that the forest is sustainably managed (e.g. Bribián et al. 2011; Dias et al. 2007, 2012; González-García et al. 2010; Ross and Evans 2002).

3.3 Carbon Footprint of Roof Tiles

3.3.1 Goal of the Study

The purpose of this case study is to calculate the carbon footprint of roof tiles manufactured in Portugal over its life cycle, from the extraction of raw materials through to the manufacturing stage (cradle-to-gate approach). Also, the identification of the main unit processes that contribute to the total carbon footprint is the intention of this case study.

3.3.2 Functional Unit

The functional unit (i.e., the reference flow to which all flows are assigned), is a 22×40 cm roof tile ready to be sold with a mass of 2.50 kg.

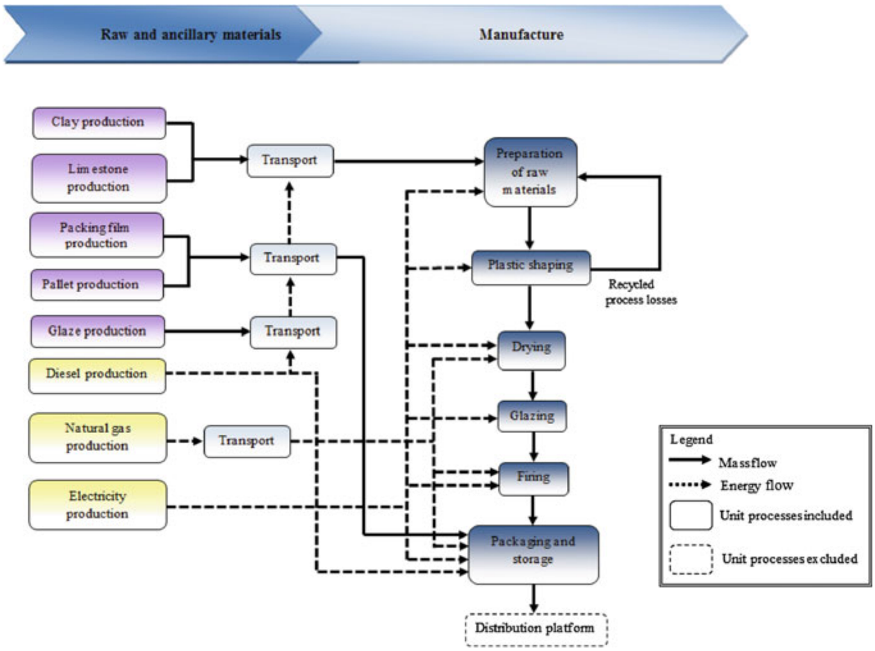


Fig. 8 System boundary for roof tiles

3.3.3 System Boundary and Data Collection

The system boundary, schematically presented in Fig. 8, includes the raw and ancillary materials and the manufacturing stage (cradle-to-gate approach). As in Sects. 3.1 and 3.2, in this study the mass flows representing less than 0.5 % of the functional unit are excluded from the defined system boundary (cut-off criterion). The system boundary also excludes the transport of consumers to and from the point of retail and the transport of employees to and from the manufacturing mill, as well as the production of capital goods (machinery and equipment).

The inventory of primary data for the manufacturing stage, including the transport profiles, consisted of data obtained from on-site measurements.

Secondary data for the raw and ancillary materials stage (i.e., data on clay, limestone, packing film, wood pallet, glaze, diesel, natural gas and electricity production), as well as the GHG emission factors for transport, were collected from the Ecoinvent database v.2.2 (Ecoinvent 2012).

3.3.4 Multifunctionality and Allocation

Roof tile manufacturing is a multifunctional system because it produces different types of roof tile. The measured primary data is related to all types of roof tiles

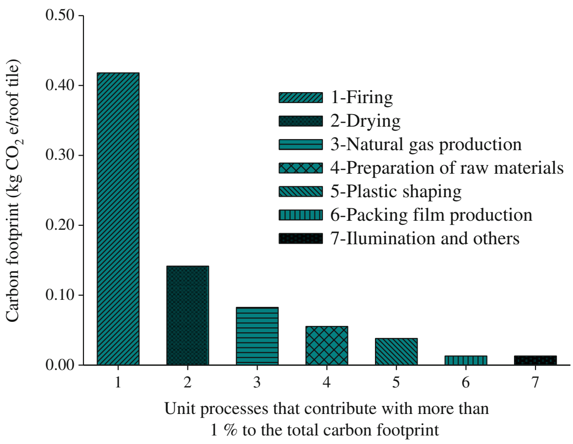


Fig. 9 Unit process that contributes more than 1 % to the total carbon footprint of the roof tile

manufactured. Therefore, in order to quantify the inputs and outputs of the roof tile under analysis, an allocation procedure based on mass criterion was applied. In this case, it was assumed that the energy consumption in each manufacturing stage is proportional to the mass of the roof tile manufactured (Almeida et al. 2011).

3.3.5 Results

The carbon footprint of the roof tile manufactured in Portugal is 0.78 kg CO_2e per roof tile. The unit processes that contribute more than 1 % to the total carbon footprint of roof tile are shown in Fig. 9. Firing emerges as the unit process that most contributes to the total carbon footprint of the roof tile, with 54 %. The burning of natural gas needed to achieve the firing temperature profile into the kilns (Sect. 2.2) is responsible for this GHG emissions hotspot.

The Portuguese roof tile mills studied have already the most suitable BAT incorporated into the manufacturing stage (e.g., recovery heat from hot flue gases from the kilns).

Although the functional unit is a roof tile, to allow the comparison of the result of this carbon footprint of roof tile with other published studies, it was converted to one kilogram of roof tile. Therefore, the carbon footprint of a roof tile manufactured in Germany is 0.31 kg CO_2e per kg roof tile (Creaton 2012), which is slightly higher than the Portuguese roof tile, which is 0.28 kg CO_2e per kg of roof tile. Both studies were performed considering a cradle-to-gate carbon footprint assessment, considering both similar raw and ancillary materials as well as the manufacturing stage.

This slight difference between German and Portuguese roof tiles can be explained by the specific features of each manufacturing process, such as load capacity of kilns and firing temperature profiles, which result in different energy source consumption rates, as well as their different transport profiles.

3.4 Carbon Footprint of Wall and Floor Tiles

3.4.1 Goal of the Study

In this case study, the carbon footprint of the wall and floor tiles is assessed from a cradle-to-gate perspective. The main unit processes that contribute to the total carbon footprint of the wall and floor tiles are also identified.

3.4.2 Functional Unit, System Boundary, and Data Collection

The data used refers to 1 m^2 of wall and floor tile as the functional unit. In this study, the mass flows that represented less than 0.5 % of the functional unit are excluded from the defined system boundary (cut-off criterion). The system boundary also excludes the transport of consumers to and from the point of retail, and the transport of employees to and from the manufacturing mill, as well as the production of capital goods (machinery and equipment).

The system boundary illustrated in Fig. 10 was, therefore, considered to comprise the following stages:

- Raw and ancillary materials—includes cradle-to-gate GHG emissions (from raw materials extraction through the production stage up to the gate of the company) for the production of the raw materials—clay, kaolin, calcium carbonate, quartz, and feldspar—consumed in the manufacture of the wall and floor tiles, namely in the preparation of the raw materials unit process. This stage also includes cradle-to-gate GHG emissions for the production of the glaze, production of carton, packing film and wood pallet, production of diesel necessary for the transport of the raw materials to the ceramic mill and GHG emissions released during this transport by truck, and the production of electricity and natural gas.
- Manufacture—includes GHG emissions by the ceramic mill and by operational activities, such as lighting, administrative activities, heating, ventilation, and air conditioning.

Primary data concerning wall and floor manufacturing were collected from mills. Moreover data concerning the lightning and other activities, such as maintenance and cleaning were also collected. The transport profiles (distance traveled, load state of the truck in the return journey) for the raw and ancillary materials were also provided by wall and floor tile mills.

Secondary data for all the unit processes considered within the raw and ancillary materials stage (Fig. 10), as well as the GHG emissions factors for transport, were collected from the Ecoinvent database v.2.2 (Ecoinvent 2012).

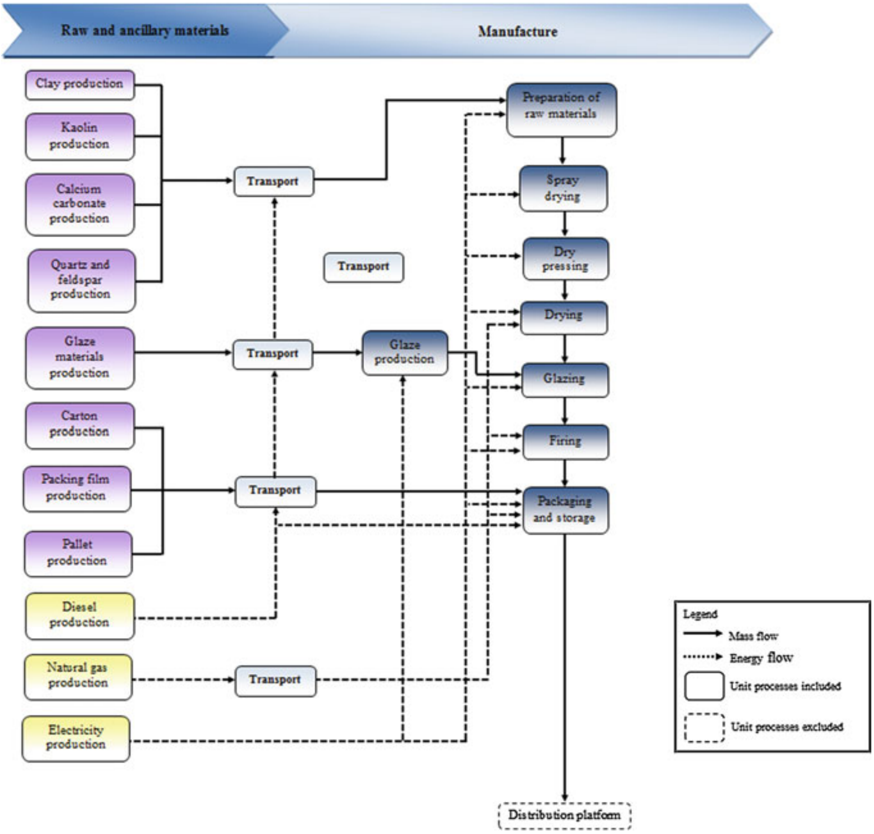


Fig. 10 System boundary for wall and floor tiles

3.4.3 Multifunctionality and Allocation

In this cradle-to-gate analysis, an allocation procedure based on mass criterion is required, as wall and floor tile mills produce more than one co-product (produce wall and floor tiles with different characteristics and dimensions) (Almeida et al. 2010b).

3.4.4 Results

The carbon footprint of the wall and floor tiles manufactured in Portugal is 11.29 kg CO_2e per m^2 of tile. Fig. 11 shows the contributions of the unit processes that contribute more than 1 % to the total carbon footprint of wall and floor tiles. As observed in this figure, firing emerges as the main hotspot in terms of GHG emissions, with 41 % of the total carbon footprint. Besides, the drying unit

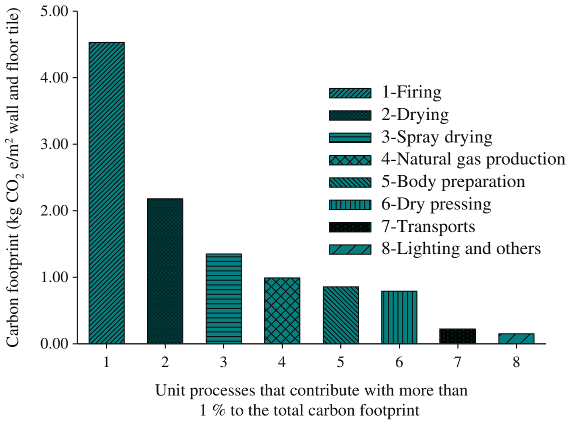


Fig. 11 Unit process that contributes more than 1 % to the total carbon footprint of 1 m^2 of wall and floor tile

processes assumes a relevant role because it is responsible for 19 % of the total carbon footprint of 1 m^2 of wall and floor tile.

The studied tile mills have incorporated into their manufacturing process the majority of suitable BAT. The use of fast-firing kilns, roller kilns, lead to reduced energy consumption due to the lower residence time and the reduced amount of material needed to load tiles in the kilns (IEA 2007). Moreover, electronic variable speed drives are connected to the main electric motors.

The carbon footprint result of this study is compared with other published studies concerning the quantification of the carbon footprint for wall and floor tiles.

Comparing the result obtained in this study, the carbon footprint of a wall and floor ceramic tile manufactured in Thailand, 39.43 kg CO_2e per m^2 of ceramic tile (Tikul and Srichandr 2010), it can be seen that this one is more than 3 times higher than the carbon footprint of the ceramic tile manufactured in Portugal. These discrepant results can be explained by the use of different production techniques, firing technology, and energy sources. The wall and floor tiles are manufactured in Thailand using double firing, in which the green ware goes through a biscuit firing cycle, glazing, and a glost firing process, whereas the manufacturing of the wall and floor tiles manufactured in Portugal only requires a single fired glaze, in which the green ware is glazed and then undergoes a single firing cycle. Portuguese tile mills use roller kilns, whereas Thai ceramic tile use tunnel kilns. Moreover, the manufacturing of wall and floor tiles in Thailand uses liquefied petroleum gas for the firing processes and furnace oil for the preparation of raw materials, whereas Portuguese mills use natural gas with slower emission factors.

The preparation of raw materials (gridding and spray drying) is the unit process that contributes the most to the total carbon footprint of the wall and floor tiles manufactured in Thailand, with 34 %. The preparation of raw materials is a hot-spot because it consumes electricity and also furnace oil; it also includes GHG emissions resulting from the consumption of diesel in the internal transport of raw materials. However, both biscuit firing and the glost firing unit processes assume a relevant role because they are responsible for 27 and 29 % of the total carbon footprint of ceramic tile manufactured in Thailand.

Another study carried out by Bovea et al. (2010) reported a carbon footprint of a wall and floor tiles manufactured in Spain of 8.46 kg CO_2e per m^2 of ceramic tile, which is lower than the carbon footprint of the wall and floor tile under analysis. Both studies perform a cradle-to-gate carbon footprint assessment, but there are some differences. With regard to the system boundaries, the study performed by Bovea et al. (2010) considers: (1) the distribution unit process, which is disregarded in the present study and (2) an average distance of 20 km for raw materials and glaze transportation to the ceramic mill, in contrast to the wall and floor tile Portuguese study that considers higher average distances (150 km). Concerning energy consumption, the ceramic tiles manufactured in Spain consume 78 % of natural gas and 22 % of electricity during the manufacturing stage (Bovea et al. 2010), whereas tiles manufactured in Portugal consume 85 % of natural gas and 15 % of electricity. These aspects and specific features of ceramic mills, such as different capacity of kilns and firing temperature profiles, can explain the differences presented in the studies performed in Portugal and Spain.

3.5 Carbon Footprint of Sanitary Ware Products

3.5.1 Goal of the Study

The aim of the current case study is to estimate the carbon footprint of sanitary ware manufactured in Portugal, as well as identify the hotspots that exist across the life cycle of the sanitary ware products.

3.5.2 Functional Unit, System Boundary, and Data Collection

The functional unit, which allows comparison between products without bias, refers to 1 kg of manufactured sanitary ware product. The material flows representing less than 0.5 % of the functional unit are excluded from the defined system boundary (cut-off criterion). The mold is not considered in the system boundary. For these processes, primary data are confidential and secondary data are lacking. Also, the distribution stage and the production of capital goods (building, machinery, and equipment) are excluded from the system boundary. The transport of consumers to and from the point of retail and the transport of employees to and from the manufacturing mill were also excluded.

As shown in Fig. 12, the system boundary (cradle-to-gate) includes the following stages:

- Raw and ancillary materials—includes cradle-to-gate GHG emissions (from the raw materials extraction through production stage until the gate of the company)

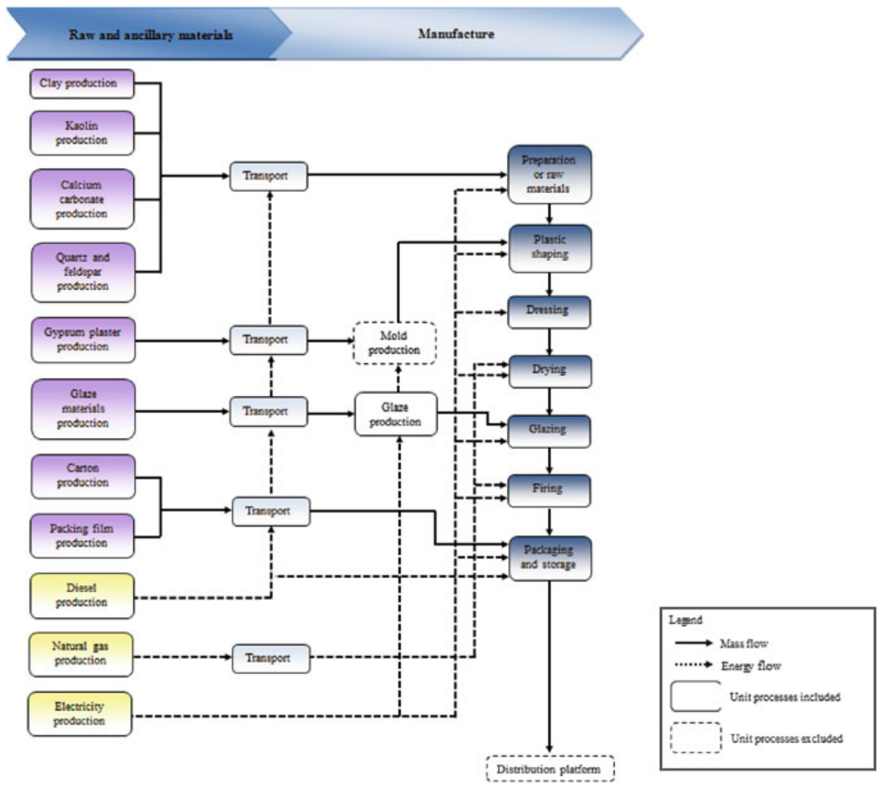


Fig. 12 System boundary for sanitary ware products

for the production of the raw materials—clay, kaolin, calcium carbonate, quartz, and feldspar, gypsum plaster—consumed in the manufacture of the sanitary ware, namely in the preparation of raw materials unit process. This stage also includes cradle-to-gate GHG emissions for the glaze material's production (raw materials used in glaze production such as aluminum oxide, silicon dioxide, magnesium oxide, among others), production of cartons, packing film and wood pallets, production of diesel necessary for the transport of the raw materials to the ceramic mill and GHG emissions released during this transport by truck, and production of electricity and natural gas.

- Manufacture—includes GHG emissions by the sanitary ware mill and by the operational activities such as lighting, administrative activities, heating, ventilation, and air conditioning.

Primary data (direct measurements made along the supply chain, from processes operated or controlled by the organization under study) including lighting and other activities (e.g., cleaning and maintenance) as well as trucks transport profiles, were collected from sanitary mills.

Secondary data for the raw and ancillary materials stage, as well as the GHG emissions factors for transports, were collected from the Ecoinvent database v.2.2 (Ecoinvent 2012).

3.5.3 Multifunctionality and Allocation

The sanitary mills produce different pieces (co-products) with different dimensions and geometries at the same time in the same production line. Therefore, in order to quantify the inputs and outputs of the sanitary ware products, an allocation procedure based on mass criterion was applied (Almeida 2009).

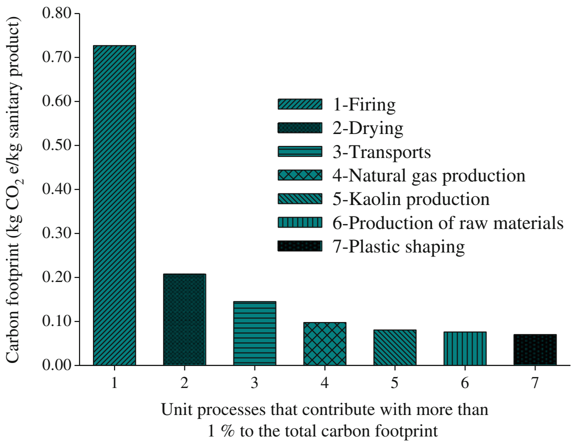
3.5.4 Results

The carbon footprint of a Portuguese sanitary ware product is 1.50 kg CO_2e per kg of sanitary product. For instance, a wash basin of 48 × 48 cm, with an average mass of 15.0 kg, has a carbon footprint of 22.5 kg CO_2e.

Figure 13 shows the unit processes that contribute more than 1 % to the total carbon footprint of sanitary ware products. The firing unit process emerges as the largest contributor to the total carbon footprint of 1 kg of sanitary product, with 49 %. The drying is the second unit process that contributes the most to the total carbon footprint of 1 kg of sanitary product, with 14 %. Both unit processes assume the primordial role due to natural gas consumption. The sanitary ware industry follows a sustainable development policy, having incorporated the majority of BAT in their manufacturing system. Therefore, an analysis of improvement measures was not carried out.

Although there is a general lack of published studies concerning the quantification of the carbon footprint of sanitary ware, we can compare the results

Fig. 13 Unit process that contributes more than 1 % to the total carbon footprint of 1 kg of sanitary product



obtained in this study with the study by Kaleseramik (2012), which estimates the carbon footprint of sanitary ware manufactured in Turkey. The carbon footprint of a sanitary ware manufactured in Turkey is 1.34 kg CO_2e per kg of sanitary product (Kaleseramik 2012), which is slightly lower than that obtained for the sanitary ware manufactured in Portugal. The system boundaries considered in both studies are similar. Therefore, this slight difference in carbon footprint results can be explained by different technologies used, as well as different transport profiles.

4 Discussion

The carbon footprint of ornamental earthenware pieces, bricks, roof tiles, wall and floor tiles, and sanitary ware products were quantified. In addition, hotspots across the life cycle of ceramic products were identified. Moreover, for earthenware pieces and bricks, some improvement measures and BAT were identified and evaluated. For the remaining products, the ceramic mills analyzed had already installed the majority of the BAT suggested for the ceramic industry (European Commission 2007).

4.1 Specific GHG Emissions of Ceramic Products

Table 7 shows the specific GHG emissions (GHG emissions per mass of product) of each ceramic product analyzed, considering a cradle-to-gate approach. The earthenware piece emerges as the ceramic product that is responsible for the highest specific GHG emissions (i.e., 2.87 kg CO_2e per kg of ceramic product) because its manufacturing leads to the highest specific energy consumption (natural gas plus electricity). This type of product requires several firing cycles for the manufacture of one piece. After the biscuit and glost firing cycles, the piece needs to be retouched, undergoing a new or even two further glost firing cycles. Therefore, to increase energy efficiency, the development of new technologies, allowing the manufacture of ornamental products with a single fired glaze, was identified as an important issue to reduce their carbon footprint and has been the subject of scientific research.

Table 7 Specific GHG emissions of the ceramic products under analysis

Product	Specific GHG emissions (kg CO_2e/kg)
Ornamental earthenware pieces	2.87
Sanitary ware products	1.50
Wall and floor tiles	0.58
Roof tiles	0.31
Bricks	0.12

The sanitary ware products ranked second with regard to specific GHG emissions. This can be explained by the process specific requirements, namely the temperature profile, in which the maximum temperature is higher than for the other products studied. Although their manufacture only requires a single firing cycle, it is common practice to retouch pieces that present some imperfections, leading to the need for a second firing cycle, which represents additional consumption of energy and, consequently, GHG emissions.

The remaining ceramic products have lower specific GHG emissions, as they are manufactured using only a single firing cycle. Moreover, brick has the lowest specific GHG emissions (i.e., 0.12 kg CO_2e per kg), because it is the ceramic product that requires the lowest temperature profile for the firing unit process. Wall and floor tiles present higher specific GHG emissions than bricks and roof tiles because their manufacture requires an additional process of spray drying that consumes natural gas and requires a higher temperature for the firing unit process (Fig. 10).

4.2 Contribution of Manufacturing Stage to the Carbon Footprint of Ceramic Products

The manufacturing stage is the stage responsible for the largest carbon footprint of all the ceramic products investigated (Table 8). The manufacturing stage of the earthenware ceramic piece represents almost 90 % of the total carbon footprint when a cradle-to-gate approach is considered. This significant contribution can be explained by the several firing cycles needed to manufacture the piece. For the remaining ceramic products, the manufacturing stage presents a contribution ranging from 73–89 % of the total carbon footprint of each ceramic product. Although the sanitary products present the second highest specific GHG emissions, its manufacturing stage has the lowest contribution to the total carbon footprint of ceramic products. This can be explained by the fact that in studied sanitary ware, the distance traveled to deliver raw and ancillary materials to the ceramic mill is significantly higher than in the other ceramic products analyzed, which results in

Table 8 Contribution of the manufacturing stage to the total carbon footprint of ceramic products, considering a cradle-to-gate approach

Product	Raw and ancillary materials stage (%)	Manufacturing stage (%)
Ornamental earthenware pieces	11	89
Sanitary ware products	27	73
Wall and floor tiles	12	88
Roof tiles	16	84
Bricks	19	81

higher GHG emissions; this contribution (10 % of the total carbon footprint of sanitary ware) is considered in the raw and ancillary materials stage.

4.3 Improvement Measures and BAT

Although the analyzed ceramic subsectors have been focusing on environmental and economic sustainability by incorporating improvement measures and BAT in their manufacturing processes, this study identifies a few further improvement measures and BAT that could be implemented for ornamental earthenware pieces and bricks.

For earthenware pieces, one of the suggested BAT consists of the incorporation of a gas pressure control system into the shuttle kilns. This measure would result in a decrease of 3 % in the total carbon footprint of a ceramic piece. Another measure is the recovery of excess heat from kilns (using heat exchangers), which could decrease the total carbon footprint up to 10 %. Both measures appear to be economically sustainable as they present simple pay-backs shorter than 3 years (European Commission 2006), as explained in Sect. 3.1. The optimization of the lighting system was also analyzed. However, although requiring a lower investment cost, its implementation would result in a simple pay-back that is two times more than what is required to consider this measure profitable. In addition to these measures, experimental tests were performed in order to optimize the temperature profile of the biscuit firing cycle. However, this measure was disregarded because it results in an increase in nonconforming ornamental pieces.

For bricks, the switch from natural gas to biomass leads to a reduction of 55 % in the total carbon footprint of brick. However, the use of biomass in brick mills depends on the long-term availability of forestry residues, as explained in Sect. 3.2. Also, the economic sustainability of this BAT still needs to be assessed.

It is not feasible to apply the switching of energy sources to the other ceramic products analyzed, due to product quality reasons. Biomass burning results in higher dust emissions than natural gas burning. Some of these dust emissions would become lodged into the kilns, increasing the number of nonconforming products during the firing cycles. Furthermore, there are some technical constraints to maintaining a constant temperature during the firing cycles.

4.4 Cradle-to-Gate and Cradle-to-Grave Assessments

In order to understand the repercussions of considering only part of the life cycle (cradle-to-gate) or the full life cycle of the product (cradle-to grave) in the carbon footprint results, a complete assessment of cradle-to-grave life cycle of bricks and wall and floor tiles was also performed, in addition to the cradle-to-grave carbon footprint study for the ornamental pieces as explained in Sect. 3.1. All the considerations explained in Sects. 3.1, 3.2, and 3.4 relating to ornamental pieces, bricks, and wall and floor tiles, respectively, are valid for the cradle-to-grave studies. Beyond these considerations, in the cradle-to-grave studies, it was assumed that bricks and wall and floor tiles are distributed within 100 and 500 km respectively, whereas ornamental pieces within 250 km. The distribution stage includes the GHG emissions from transport by truck of the ceramic products to the point of retail and by the production of diesel used in this transport.

During the use stage of these three products, it was considered that no energy consumption or GHG emissions occur. However, in practice, the cleaning of ornamental and wall and floor tiles could emit GHG, but these emissions were excluded due to the high uncertainty related to the type of detergent used, and the times and frequency of cleaning.

The final disposal (end-of-life) of ceramic products was considered to be landfill. In this stage, the GHG emissions include those arising from the landfill, truck transport of ceramic products to the landfill, and production of diesel used in this transport.

Table 9 presents the contributions of each stage to the total carbon footprint of ornamental pieces, bricks and wall and floor tiles when cradle-to-gate and cradle-to-grave approaches are applied. The carbon footprint of these ceramic products increased by 2–14 % when compared to the carbon footprint results using a cradle-to-gate approach. In the case of ornamental pieces and bricks, the distribution stage represents 2 and 3 % of the total carbon footprint of the piece, respectively, whereas in wall and floor tiles, the distribution represents 11 %. This higher contribution than the ornamental pieces and bricks can be explained by the higher distances traveled, as referred to above. It should be noted that even in the cradle-to-gate approach, the manufacturing stage appears as main hotspot, in which environmental measures and BAT should be a priority.

Table 9 Carbon footprint of some ceramic products following cradle-to-gate and cradle-to-grave approaches

Carbon footprint of products	Cradle-to-grave					
	Cradle-to-gate		Gate-to-grave			Total
	Raw and ancillary materials stage (%)	Manufacturing stage (%)	Distribution (%)	Use	Disposal (%)	
Ornamental pieces (kg CO_2e per piece)	0.13 (10)	1.06 (87)	0.02 (2)	0	0.009 (1)	1.22
Bricks (kg CO_2e per brick)	0.10 (19)	0.41 (77)	0.014 (3)	0	0.0079 (1)	0.53
Wall and floor tiles (kg CO_2e per m^2 of tile)	1.35 (11)	9.94 (77)	1.37 (11)	0	0.17 (1)	12.83

5 Challenges in Calculating the Carbon Footprint of Ceramic Products

During the quantification of the carbon footprint of ceramic products, the practitioner deals with several methodological aspects and questions, such as:

(1) specifying the cut-off criteria
(2) collecting primary and secondary data during the inventory
(3) determining how to treat multifunctional and allocation procedures

The cut-off criterion decides which processes should be included within the system boundary. In all the case studies presented, a mass criterion was applied, wherein the mass flows that represent less than 0.5 % of the functional unit were excluded from the system boundaries. However, the selection of cut-off criteria can be a challenge that needs harmonization. On the one hand, ISO 14040:2006 and ISO 1044:2006 do not define any mass, energy, and environmental criteria thresholds. This can hinder or make difficult comparisons between products. On the other hand, applying only a mass criterion can lead to the exclusion of important inputs; that is, an excluded input mass flow can encompass significant energy consumption and GHG emissions. Therefore, a general understanding of how to correlate mass, energy, and environmental significance to define an ambiguous cut-off criterion remains a challenge.

The inventory data can be one of the most labor- and time-intensive stages of carbon footprint quantification (Finnveden et al. 2009). Collecting primary data for a specific product can be a challenging task due to the confidentiality measures imposed by mills, as well as due to the absence of intermediate sampling locations along the manufacturing stage for measurements of mass, energy, and emission flows related to the manufacture of the product under analysis. Although there are databases to facilitate the inventory when primary data are not available, the majority of databases are based on average data representing the average environmental burdens for manufacturing a product (Finnveden et al. 2009), leading to a high uncertainty in the inventory. In addition, databases covering the several ceramics subsectors are still lacking.

Multifunctional processes occur when several co-products are manufactured within the same unit process. Although there is a recommended hierarchy of procedures (ISO 2006b) to attribute GHG emissions to a certain product, allocation is still scientifically a challenge. The ceramic subsector is not an exception. For some manufacturing processes, such as ornamental earthenware pieces, the application of a single allocation criterion does not seem appropriate (Quinteiro et al. 2012b); thus, it is necessary to develop and apply a hybrid approach, as explained in Sect. 3.1. This hybrid approach can be applied to other ceramic subsectors, such as sanitary ware. However, some adaptations should be performed due to the specificities of the different manufacturing processes, which involve on-site tests and measurements. Due to this "constraint," the carbon footprint estimated in this study for the remaining ceramic products was based on a single mass allocation criterion. However, it should be noted that when a mass allocation is adopted, the inventory data should be collected for an annual temporal basis to guarantee that the GHG emissions are not under- or overestimated due, mainly, to fluctuations in the ceramic products load during firing unit processes.

6 Conclusions

The main conclusions drawn from this study are as follows:

- The product carbon footprint is a strong tool to aid the ceramic industry to better understand the GHG emission of their products and identify GHG emissions hotspot processes and improvement measures to reduce the carbon footprint of ceramic products, thereby promoting the energy efficiency and competitiveness of ceramic mills.
- Direct measurements in mills increase the accuracy of product carbon footprint results because they decrease the need to collect secondary data from databases, which represent an average or general measurement of similar processes or materials.
- The manufacturing stage emerges as the main contributor to the total carbon footprint of ceramic products, with the firing unit process being the hotspot for all the ceramic products studied.
- The ornamental earthenware piece has the highest specific GHG emissions, whereas the brick has the lowest specific GHG emissions, due to the requirement of different numbers of firing cycles and temperature profiles.
- All improvement measures and BAT should be assessed from an environmental, technical, and economic point of view. Moreover, the trade-off between improvements measures and BAT and the quality of the ceramic product should be assessed. For instance, in the performed carbon footprint calculation of the ornamental earthenware, the optimization of the biscuit firing cycle was disregarded because it leads to an increase in nonconforming pieces.

Although some core challenging questions dealing with the harmonization of the quantification of the carbon footprint of ceramic products remain, this tool is currently being used by industries for decision making, marketing purposes, and labeling as well as energy efficiency improvements.

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