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Environmental profile of Spanish porcelain stoneware tiles

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Corresponding Author:	Teresa Ros-Dosdá, M.D. Instituto de Tecnología Cerámica-AICE Castellón, Castellón SPAIN
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Instituto de Tecnología Cerámica-AICE
Corresponding Author's Secondary Institution:	
First Author:	Teresa Ros-Dosdá, M.D.
First Author Secondary Information:	
Order of Authors:	Teresa Ros-Dosdá, M.D.
	Irina Celades, PhD
	Eliseo Monfort, PhD
	Pere Fullana-i-Palmer, PhD
Order of Authors Secondary Information:	
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Abstract:

Purpose: Porcelain stoneware tile (PST) is currently the ceramic tile of greatest commercial and innovation interest. An environmental life cycle assessment of different varieties of PST was undertaken to enable hotspots to be identified, strategies to be defined, differences between PST varieties to be evaluated, and guidance for PST manufacturers to be provided in choosing the Environmental Product Declaration (EPD) programme that best suited their needs according to grouping criteria.

Methods: Analysis of previous information allowed three main parameters (thickness, glaze content, and mechanical treatment) to be identified in order to encompass all PST variations. Fifteen varieties of PST were thus studied. The coverage of 1 m2 of household floor surface with the different PST varieties for 50 years was defined as functional unit. The study sets out environmental data whose traceability was verified by independent third parties for obtaining 14 EPDs of PST under Spanish EPD programmes.

Results and discussion: The study presents PST inventory analysis and environmental impact over the entire life cycle of the studied PST varieties. The natural gas consumed in the manufacturing stage accounted for more than 70 % Abiotic Depletion-fossil fuels and Global Warming; electricity consumption accounted for more than 60 % Ozone Layer Depletion, while the electricity generated by the cogeneration systems avoided significant environmental impacts in the Spanish power grid mix. The variations in PST thickness, amount of glaze, and mechanical treatments were evaluated. The PST variety with the lowest environmental impact was the one with the lowest thickness, was unglazed, and had no mechanical treatments. Similarly, the PST variety with the highest environmental impact was the one with the greatest thickness, was glazed, and had been mechanically treated.

Conclusions: The PST life cycle stage with the highest environmental impact was the

	manufacturing stage. The main hotspots found were production and consumption of energy, and raw materials extraction. Variation in thickness was a key factor that proportionally influenced almost all studied impact categories; the quantity of glaze strongly modified Abiotic Depletion-elements and Eutrophication, while the mechanical treatments contributed mainly to Ozone Depletion. The study of all PST varieties led to the important conclusion, against the current trend, that differences among them were found to be so significant that declaring a number of PSTs within the same EPD is not directly possible and it needs preliminary verification to ensure compliance with the Product Category Rule.
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LCA COMMUNICATION AND LCA FOR ISO LABELS

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Teresa Ros-Dosdá[1,2] • Irina Celades[1] • Eliseo Monfort[1] • Pere Fullana-i-Palmer[2]

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[1] Instituto de Tecnología Cerámica (ITC), Asociación de Investigación de las Industrias Cerámicas (AICE), Universidad Jaume I. Avda Sos Baynat s/n, 12006, Castellón, Spain

[2] UNESCO Chair in Life Cycle and Climate Change (ESCI-UPF), Passeig Pujades 1, 08003 Barcelona, Spain

✉ Teresa Ros-Dosdá

teresa.ros@itc.uji.es

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Conclusions: The PST life cycle stage with the highest environmental impact was the manufacturing stage. The main hotspots found were production and consumption of energy, and raw materials extraction. Variation in thickness was a key factor that proportionally influenced almost all studied impact categories; the quantity of glaze strongly modified Abiotic Depletion–elements and Eutrophication, while the mechanical treatments contributed mainly to Ozone Depletion. The study of all PST varieties led to the important conclusion, against the current trend, that differences among them were found to be so significant that declaring a number of PSTs within the same EPD is not directly possible and it needs preliminary verification to ensure compliance with the Product Category Rule.

Keywords Ceramic tile • Porcelain stoneware tile • Life Cycle Assessment • Technological variations

1 Introduction

Ceramic tile manufacturing industry is classified as a potentially polluting activity on the environment, and, therefore, is affected by Directive 2008/1/EC of 15 January 2008 concerning integrated pollution prevention and control and greenhouse gas emission trading Directive 2009/29/EC.

The Spanish ceramic tile cluster has long been one of the world's leading tile industries. However, recent years have witnessed increasing competition from new ceramic tile producing countries and new alternative products in the global market.

In 2014, ceramic tile production in the European Union (EU-28) and in Spain was 1192 and 425 million m^2, respectively. Spain was the top European and the world's fourth-largest producer of ceramic tiles (in m^2), behind China, Brazil, and India, accounting for 3.4 % of world tile production. Spain also consolidated its position as the world's second-largest exporter of ceramic tiles by volume and the third-largest tile exporter in value. The main importers of Spanish ceramic tiles in recent years have been Saudi Arabia, France, Algeria, Jordan, and the UK (Baraldi 2015).

The ceramic tile product category comprises a wide variety of products. An accepted classification (EN 14411:2012, counterpart to standard ISO 13006:2012), and the features of the most common ceramic tiles manufactured in Spain are detailed in Table 1.

In the last 15 years, the volume of PST production has grown by about 20 %, GST production has decreased by 15 %, while ET production has remained practically stable (Fig. 1) (ASCER 2015).

PST is currently the ceramic tile of greatest commercial interest, as it exhibits higher technical and functional performance and greater versatility, enabling PST to be used in different environments, both indoor and outdoor (ASCER 2011; ISO 13006:2012; Sánchez at al. 2010). Moreover, PST is considered to provide greater scope for technical and environmental improvement and innovation (da Silva et al. 2014; Martín-Márquez et al. 2010; Gabaldón-Estevan and Hekkert 2013). In fact, this type of tile encompasses a wide variety of sizes, thicknesses, different decorative designs and finishes.

In the context of environmental communication, European Standard EN 15804:2012+A1:2013 "Core rules for the product category of construction products" indicates that several products can be grouped under the same EPD when the differences in the Life Cycle Impact Assessment (LCIA) results are not significant, in this case requiring a description of the range/variability. However, the standard does not establish any limits in this regard. Therefore, EPD programmes usually fix the grouping criteria, either indicating an acceptable variation in percentage of the LCIA results or declaring the environmental profile of the products that exhibit the minimum and the maximum LCIA values. The Spanish EPD programmes establish an additional grouping criterion relating to the water absorption capacity of ceramic tiles according to standard ISO 13006:2012. The considerations made by several EPD programmes with regard to the declaration of a number of construction products are summarised in Table 2.

In order to ensure compliance with standard EN 15804:2012+A1:2013 and the criteria established by the EPD programmes, a preliminary quantification of the LCIA variations is therefore needed.

Based on the exhaustive literature review on ceramic materials reported by Pini et al. (2014), the current study presents an update, focusing on ceramic tile (Table 3). The following may be highlighted:

- Most of the reported studies consider ceramic tile to be a generic product, without differentiating ceramic tile types according to the ISO 13006:2012 classification.
- The year of inventory data is not always reported. The study with the latest primary data is published by Almeida et al. (2016), the information dating from 2012.
- The lifespans of the studies ranged from 20 to 61 years. Moreover, in most studies, the scope and environmental impacts of the life cycle stages were declared as a total sum of the life cycle stages. These facts should be taken into account when interpreting and comparing results of different LCA studies.
- The studies defined the functional unit (FU) as 1 m^2 of ceramic tile, with the sole exception of Tikul and Srichand (2010), who defined this as 1 ton.
- According to the available information, the most popular impact assessment method is definitively the CML2001 (Guinée et al. 2002).

The review also reveals that the most extensive LCA study on ceramic tiles was performed in the period from 2008 to 2010 in the Spanish ceramic cluster by the ITC and UNESCO Chair research groups with the cooperation of the Spanish Ceramic Tile Manufacturers' Association (ASCER). That study was carried out at cluster level with the involvement of 56 tile manufacturers and their suppliers, encompassing 48 % of Spanish ceramic tile production and the three main types of ceramic tiles produced in Spain: PST, GST (red and white body), and ET (red and white body) (Benveniste et al. 2010, 2011; Ros-Dosdá et al. 2010). The study allowed obtainment of scientifically valid and objective reference values for the environmental profile of ceramic tiles, definition of sectoral technological improvements, establishment of the first Product Category Rule (PCR) for ceramic coverings in Spain, and it laid the groundwork for the development of a simplified tool for LCA studies and/or EPDs, thereby reducing implementation times and economic costs.

This tool was successfully programmed in extension i-report GaBi after adapting the LCA model to improve its modularity and flexibility allowing all technological alternatives implemented in the Spanish ceramic sector to be included (Fig. 3).

In parallel, after approval of European standard EN 15804: 2012, another PCR for ceramic coverings was developed under the Spanish Type III environmental declaration programme, GlobalEPD.

In view of the above background, a specific and updated LCA study on PST was deemed of interest for the following reasons: (1) Of the three main types of ceramic tile manufactured in Spain, PST production and demand have increased most over the last 15 years; (2) consistent, robust, third-party verified life cycle inventory analysis (LCI) and LCIA are available; (3) no detailed LCA studies on PST were found in the literature review; (4) owing to the high technical and functional versatility of PST, more than 15 varieties of PST are marketed worldwide; and (5) the environmental study of all PST varieties would enable EPD administrators and producers to foresee whether they could group several PST varieties under the same EPD.

The results of this study were expected to provide updated, harmonised and peer-reviewed representative LCI data and LCIA, which would enable changes to be envisaged at Spanish and European level in the medium or long term based on the identified hotspots, publication of this information for commercial purposes, and positioning of the product in technological, legislative, or regulatory contexts. The results would also allow PST manufacturers to establish continuous improvement strategies and efficiently choose the EPD programme that best suited their needs.

2 Methods

LCA is a tool that identifies, classifies, and quantifies the environmental impacts of a product or activity throughout its life cycle. The method consists of compiling an inventory of inputs and outputs of the system; evaluating the potential impacts associated with these inputs and outputs, and interpreting the results of the LCI and LCIA in relation to the study objectives (ISO 14040: 2006).

2.1 Goal and scope definition

This study aimed to obtain updated, valid, objective data with regard to the environmental profile of PST throughout its life cycle in order to identify the technical aspects of the product or process that would enable companies to influence or improve the product's environmental performance. In addition, the study would allow the magnitude of the differences between PST formats, patterns, designs, and finishes to be verified, and the environmental consequences of these differences to be better understood.

In this study, the LCA of PST was developed according to international standards ISO 14040-44:2006, European standard EN 15804:2012+A1:2013, and the Product Category Rules (PCRs) of two Spanish Programmes GlobalEPD 2013 and DAPcons 2015, both programmes being included in the EcoPlatform (www.eco-platform.org).

PST has an average density of 2300 kg/m^3 and is intended for use as surface covering in both indoor and outdoor environments. The product can be used as floor covering, wall cladding, or even in façades (ISO 13006:2012). Moreover, its versatility allows this type of ceramic tile to be used in a wide range of environments, such as homes, shops, offices, and hospitals.

Based on the information gathered in the present study, the main parameters for identifying the varieties of PST were as follows: (1) Thickness: technically there is no upper limit to thickness. However, there is a practical lower limit of about 5 mm to assure appropriate mechanical behaviour; when thickness is lower, it is highly recommended to reinforce the PST with a fibreglass backing (Pini et al. 2014). (2) Glaze content: the low body porosity of PST allows such tiles to be either glazed or unglazed. (3) Mechanical treatments: mechanical treatments are optional and may consist of cutting large formats into smaller sizes, bevelling, polishing, lappato, etc. Because of the mechanical properties of PST, mechanical treatments are always performed on the fired product, before the construction process stage. The combination of these options gives rise to a great range of aesthetic effects.

Table 4 shows the range of PST characteristics and designations used in this paper. Table 5 details the nomenclature used in the study to identify the different PST varieties.

2.1.1 System boundaries and Functional Unit

This paper sets out environmental information on a group of PST products manufactured in Spain from 2010 to 2015. Data traceability was verified by independent third parties for 14 Environmental Product Declarations of PST under Spanish EPD programmes.

The Functional Unit (FU) was defined as 1 m^2 of household floor surface covering with the different studied varieties of PST for 50 years.

The system includes the modules given in the standards for Sustainability in Construction, as illustrated in Fig. 2.

The following elements were left out of the system:

- Modules B1, B3, B4, B5, B6, and B7, these being considered irrelevant from an environmental point of view in accordance with the PCR for ceramic coverings of the EPD programmes DAPcons® system 2015, GlobalEPD 2013, International EPD® System 2012 and European PCR (CET 2014 and Thurning et al. 2013)
- Industrial machinery and equipment manufacture, owing to the lack of currently available data, the cost/complexity of analysis (BSI PAS 2050:2011), and the relatively low environmental impact per FU compared to other processes in the case of building products (Frischknecht et al. 2007; Wittstock et al. 2012).
- The recycling process of the packaging waste produced throughout the ceramic tile life cycle, because of the allocation method used, known as the cut-off criterion (BSI PAS 2050:2011). However, transport to the treatment facilities and the processes required to the of end-of-waste state were included.
- The environmental burdens associated with ceramic pigments. These were disregarded because of wide-ranging pigment variability, lack of specific, related information, and the relatively low ceramic pigment content in the entire ceramic tile (<1 % by weight).

2.1.2 Selected environmental impact categories

The environmental impact categories analysed and characterisation factors used are those set out in EN 15804:2012+A1:2013, Table 6.

Particulate matter emissions into the air have been included in this study, owing to the significant investments required and maintenance costs involved in meeting the requirements laid down in European Industrial Emissions Directive 2010/75/EU (IED).

2.2 Life cycle inventory analysis modelling

The inventory modelling was performed with the GaBi 4 software (PE International 2008) and the bundled professional databases PE International 2008, ELCD 3.2. (Joint Research Centre 2015), and Thinkstep database 2016 run in GaBi 6 software (Thinkstep 2016) were used as the principal sources of background data.

As per foreground data: i) 75 % was compiled directly from ceramic tile manufacturers; a production-weighted average of all formats yielded the FU described above; ii) 24 % of the data were obtained from literature and cluster averages (Benveniste et al. 2011; EIPPCB 2007; EIPPCB 2012); and iii) very few data (1 %) were obtained from assumptions used in the Product Category Rules for ceramic coverings within the Spanish EPD programmes, DAPcons 2015 and GlobalEPD 2013.

The foreground data included primary data of both a) the PST body and b) glaze life cycles.

a) Table 7 shows the relative values (expressed as percentage by weight) of the studied PST body and glaze compositions (A1). The compositions are averages and encompass all the varieties of PST involved in this study. The body composition data were provided by 10 Spanish spray-dried granule manufacturing companies. The maximum Standard Deviation (SD) in the amount of raw materials was 3 % in one of the components (clay); with regard to origin, the scatter in distances was greater, the maximum SD being 23 %.

b) The glaze compositions were provided by 7 glaze manufacturers. The maximum SD in the amount of raw materials was 5 %, namely in the silicates; the origins of these raw materials also exhibited a maximum 5 % scatter.

All in all, the peer-reviewed inputs and outputs of the foreground system were provided by a total of 26 Spanish spray-dried granule, ceramic frit and glaze, and ceramic tile manufacturing companies to obtain 14 EPDs of PST. The data stem from the period 2010 to 2015. The material and energy inputs and outputs of the PST AAA life cycle are detailed in Table 8.

Primary data of each manufacturing company was compiled in questionnaires and then, treated individually to obtain data referred to the beforehand mentioned FU and allocating the environmental aspects when needed.

It is important to highlight that the individual inventory data were used to calculate a production-weighted average as a representative generic PST, hereinafter referred to as PST AAA, representing an average thickness, average quantity of decoration materials, and average application of mechanical treatments. These data were either obtained from individual unit processes or the aggregation of several processes, depending on data availability or accessibility. The results were therefore not attributable to a single manufacturer, thus safeguarding the confidentiality of individual company data.

The inventory data associated to the rest of PST varieties were obtained from PST AAA by modifying specific inputs and outputs related to each parameter as follows:

- Variation in thickness: proportional difference in the inputs and outputs in the preparation of raw materials, thermal energy consumption in the drying and firing processes, atmospheric emissions, and waste generation in the manufacturing plant.
- Variation in the glaze content: proportional variation in the inputs and outputs associated to the manufacturing of glazes and other decorative materials
- Variation in mechanical treatments: proportional variation in the associated consumption of water and electricity, as well as waste and particulate emissions generated in this process.

Once the inventories of all varieties of PST are defined, scenarios analysis were performed with the GaBi Analyst function in order to facilitate the comparison and analysis of these PSTs.

We want to give attention to some important issues. The first one is related to cogeneration. Ceramic manufacturing plants exhibit different configurations. Some include the whole manufacturing process, i.e. preparation of spray-dried granulates and ceramic tile manufacture, whereas others, which could be termed 'partial cycle' configurations, may prepare either the spray-dried granulates or the actual ceramic tiles (from the pressing stage to sorting). In every case, the glazes and pigments are manufactured in specialised plants. The amount of own-consumed electricity from the cogeneration system therefore varies significantly because of the different configurations of the plants and processes involved, while factors, such as cogeneration system power and management, time distribution, and the economic regime applicable to the sale of electricity, vary highly among the companies (Monfort et al. 2010).

The second issue is related to the optional mechanical treatments on the fired product. These could be carried out either at the manufacturing plants themselves or at specialised companies. Water and electricity consumption and waste generation varied highly depending on the treatment and equipment design. The 50th percentile (Q2) values were therefore considered. These are listed with the SD in Table

9. The data supplied did not distinguish between the different optional processes, i.e. cutting, bevelling, or polishing.

Another issue is about the types of emissions. The studied emission outputs into the air included fugitive and channelled emissions. The pollutants considered in this LCA were particulate matter (PM), acid compounds (HF, HCl, SO_x, and NO_x), and heavy metals. In terms of mass, the most important atmospheric pollutant was undoubtedly PM: 35 % corresponded to fugitive emissions from bulk solids handling, while the rest was emitted through stacks. Table 10 presents the direct PM and PM_{10} emissions (particles which pass through a size-selective inlet with a 50 % efficiency cut-off at 10 μm aerodynamic diameter (ISO 7708:1995)) in the manufacturing stage (A3).

The fourth issue deals with the PST function and use, which was defined as an indoor floor covering in a residential scenario. However, porcelain stoneware tile can also be used for outdoor floor coverings and for cladding outside walls or façades in different contexts, such as commercial, hospital, and educational environments. Obviously, the more stringent the hygienic requirements, the greater the number of required cleaning cycles. Due to the near absence of porosity of PST (e.g. water absorption ≤0.5 %), maintenance operations are independent of the presence of glaze, but it depends entirely on the habits of the end user, place of emplacement and traffic intensity. In order to define a generic scenario, the present study considered cleaning with water and disinfectant once a week in a residential use scenario. For each cleaning cycle, 0.1 l water and 19 ml detergent were considered per square metre. This scenario was the considered in the Spanish EPDs of PST.

Finally, with regard to the wastes generated during the whole PST life cycle, Table 11 lists the quantities generated and waste management operations defined in this study. In the installation stage (A5), packaging waste management depended on the geographic location of the installation site, so that management process uncertainty increased with distance.

Table 12 presents the extra-plant transport data, detailing distances and means of transport used in each life cycle stage. It was generally assumed that all distances over 400 km involved empty returns.

2.3 Description of the PST life cycle

The structure of the PST life cycle stages (modules) was built up according to EN 15804:2012+A1:2013 as shown in Fig. 2, including modules A1-A5, B2, and C1-C4. Fig. 3 shows a detailed flow chart of the PST life cycle.

Ceramic tiles essentially consist of a ceramic body (97 % by weight) and an optional thin layer of ceramic glaze, usually with additional decorative material (3 % by weight). The ceramic body is mostly composed of clay, sand, feldspar, and recycled ceramic material. The most common glaze and decoration materials components are ceramic frits, inorganic pigments, other mineral raw materials, and minor organic additives (these additives being negligible).

These raw materials are transported (A2) by freighter or by truck depending on the distance from the origin. All raw materials are transported in bulk, i.e. they require no packaging.

In the PST manufacturing stage (A3), the raw materials for the ceramic body are mixed, wet milled, and then spray dried. The vast majority (about 90 %) of the spray dryers in the Spanish ceramic cluster (Gabaldón-Estevan et al. 2014; Monfort et al. 2010) are fitted with a heat and electric energy cogeneration system, in which the hot gases are recovered in the spray dryer, part of the generated electric energy being used in the production process itself, while the rest is sold to the grid, allocating the co-product electricity as an expansion of the system (Thuring et al. 2013), in which the electricity sold to the power grid is replacing the marginal technology, i.e. the technology that is most flexible to changes in demand. According to the Spanish Power Grid Mix (SPGM), this is the thermoelectric technology using coal and natural gas (REE 2014).

Most Spanish ceramic tiles are formed by uniaxial semi-dry pressing, the rest being mainly extruded. The freshly formed tiles are then fed into a continuous dryer. In a few cases, a first firing is performed followed by the application of one or more layers of glaze and decorative applications, and subsequent second firing. However, after drying and decorating most ceramic tiles are fired in a single cycle in single-deck roller kilns, optionally followed by mechanical treatments such as polishing and edge-grinding or rectification. Finally, ceramic tile quality is controlled, the tiles being sorted and packaged using cardboard, pallets, and polyethylene films.

The construction stage processes involve transport to the building site (A4) and installation of the product (A5). According to the latest figures from the Ceramic World Review (Baraldi 2015), Spanish ceramic tile export destinations by volume are as follows: Asian countries 29 %, Africa 25 %, the rest of the European countries 15 %, and the Americas 9 %, 22 % being sold in the Spanish domestic market.

The PST are then duly unpacked for installation, ceramic tiles typically being installed using 3.5 kg/m^2 of fast-setting mortars (ASCER 2011), which are mixed with water in a mortar (water ratio of 4:1).

Once PST is installed, only maintenance (B2) operations are needed during the use stage. PST requires neither energy (B6) nor water (B7) input for use and produces no emissions to air, water, or soil during its use phase (B1) and, provided that it is properly installed, repair (B3), replacement (B4), or refurbishment (B5) are either not required or negligible (CET 2014; DAPcons 2015; GlobalEPD, 2013; Thurning et al. 2013).

Standard EN 14411:2012, counterpart to standard ISO 13006:2012, states that the durability ceramic tiles in interior environments may be the same as the building provided that the essential characteristics of this European standard are met. This assertion is based on practical experience of at least 50 years. Therefore, the service life defined in the article has been set at 50 years, regardless of the PST variety.

Nevertheless, it is interesting to note at this point that, in general, the lifespan depends mainly on the type of use and quality of installation. In fact, very thin PST can be used as flooring in indoor areas of high pedestrian traffic for more than 50 years avoiding cracking (the main cause of ceramic tile mortality "end use") if appropriate fixings systems over a firmly supported subflooring are used (Cerurbis project, 2013-2017).

When its service life has ended (modules C1–C4), the product is removed, either as part of building refurbishment or building demolition. In building demolition (C1), the impacts assignable to product disassembly are considered negligible (DAPcons 2015; GlobalEPD 2013). Product waste is transported (C2) by truck to the waste destination (a mean distance of 50 km being assumed). Based on Directive 2008/98/EC on wastes, it was assumed that 70 % of the construction and demolition waste was reused, recovered, or recycled (C3), the remaining 30 % being landfilled (C4).

3 Results and discussion

3.1 Life cycle environmental impact assessment of PST AAA

The absolute values of each environmental impact category, based on the CML 2002 method (Guinée et al. 2002) associated with 1 m^2 of Spanish PST (AAA) installed in a home for 50 years as floor covering, are detailed in Table 13. Fig. 4 shows the relative environmental contribution of each life cycle module of 1 FU of PST AAA.

Table 13 and Fig. 4 indicate that manufacturing stage A3 generated the greatest environmental impacts in every category except ADP-elements. Although this impact category needs to be included in the environmental product declarations (EN 15804:2012+A1:2013), its use is under revision since this is a much disputed impact category in LCA due to the disagreement regarding the parameters that need to be included in the characterisation model (Oers and Guinée 2016). This impact category is mainly influenced by the boron-introducing raw materials in the glaze composition and by the composition of the fast-setting mortars used in PST installation.

The main relative contributions (in %) associated with the direct material and energy inputs and outputs in the PST AAA life cycle are presented in Table 14.

Table 14 shows that *natural gas* consumption in the manufacturing process (preparation of spray-dried granulates and drying and firing stages) accounted for more than 70 % in the ADP-fossil and GWP impact categories. Moreover, in these processes, apart from natural gas combustion emissions, there were also emissions due to raw materials decomposition, such as HF, SO_2, and NO_x, which generated significant impacts on the AP impact category. This occurred mainly in the firing process, in which temperatures of about 1200 ºC are reached (Monfort et al. 2011a). NO_x generated all the nutrifying emissions, contributing to the EP impact category, while SO_2 and NO_x are precursors influencing tropospheric ozone formation (POCP).

With regard to the main potential impacts associated with the *consumption of electricity* from the SPGM in the PST manufacturing process, its ODP was the most sensitive and accounted for over 60 %. This was mainly due to the refrigerant gases used in nuclear power plants, which accounted for about 21 % of the SPGM in 2013, and to fuel production. In addition, the halogenated organic compounds emissions contributed significantly to the formation of photochemical oxidant potential (POCP), while the SO_2 emissions associated with coal-fired power plants (8.5 % of the SPGM in 2013) contributed to the AP.

To be noted are the benefits of the *electricity generated by the cogeneration system*, which was sold to the SPGM. In the allocation process, this electricity sold to the SPGM replaced marginal technology, considered to be thermoelectric technology using coal and natural gas (REE 2014). The cogenerated electricity avoided the SPGM generating the equivalent of 28.5 % ADP-fossil and 28 % GWP of the PST AAA total life cycle (see Table 14). With regard to AP and POCP, the cogenerated electricity avoided more than twice the impact on the SPGM of the potential impact generated by the consumption of natural gas in the spray dryer + cogeneration system; in the case of EP, these impacts virtually offset each other (see Table 14).

In relation to the potential environmental impact of *ceramic glazes*, the results reveal that, besides the contribution to the ADP-elements impact category, the contribution to EP was significant due to the NO_x emissions into the air generated in the fusion of ceramic frits (33 % average content in the glaze composition), accounting for more than 20 % of the PST AAA total life cycle in this impact category. For the same reason, glazes were also significant in AP and POCP. Fig. 5 presents the relative influence of the glazed ceramic tiles on each impact category.

In general, assuming the same material density and the same raw materials composition, a reduction in *thickness* entailed lower raw materials consumption, thermal energy consumption, transportation cost, and air emissions, as well as less stock in the factory and distribution depots. The influence of thickness on all impact categories can be observed in Fig. 6.

The optional mechanical treatments have significant influence in ODP, owing to the high ensuing electricity consumption and to a lesser extent to the production of some body raw materials such as sand and feldspar. The relative influence of mechanical treatments on each impact category is illustrated in a spider diagram in Fig. 7.

3.2 Environmental impact assessment of PST varieties

Figure 8 shows the potential environmental impacts of the different varieties of PST listed in Table 4.

It may be observed in Fig. 8 that the graphs exhibit a similar shape and pattern in every impact category except ODP and the ADP-elements. The ADP-elements basically depended to about 60 % and 40 % on the glaze raw materials and the ceramic tile adhesive, respectively. Fig. 8a shows that, since the amount of adhesive did not vary significantly with the type of PST, this impact remained constant regardless of weight and mechanical treatments, only displaying variations with the quantity of glaze. Fig. 5 shows the clear relationship of the glaze and ADP-elements.

On the other hand, ODP was strongly influenced by electricity consumption from the SPGM and fuel production. Fig. 8f shows the increase in ODP values in the varieties of PST with mechanical treatments.

The differences between all the studied varieties of PST ranged from 31 to 37 % (except ODP, which reached up to 48 %). In the studied PST varieties, the value ranges were as follows: ADP-elements (6.76E-05 – 1.98E-04 kg Sb eq.), ADP-fossil (1.4 – 201.3 MJ), AP (2.05E-02 – 6.26E-02 kg SO_2 eq.), EP (2.55E-03 – 8.15E-03 kg PO_4^{3-} eq.), GWP (5.8 to 16 kg CO_2 eq.), ODP (4.51E-07 – 9.42E-07 kg R-11 eq.), POCP (1.84E-03 – 5.02E-03 kg C_4H_2 eq.).

In Fig. 8 all graphs show that the PST variety with the lowest environmental impact was the one that had the lowest mass (low thickness), was unglazed, and had undergone no mechanical treatment (LUN). In contrast, the PST variety with the greatest environmental impact was the one that had the highest mass (high thickness), was glazed, and had undergone mechanical treatment (HGM).

Therefore, in order to select the PST variety with the highest and the lowest impact from a diverse group, the above result may be deemed valid when the differences in mass and amount of glaze are significant and the product has or has not undergone mechanical treatment. However, when the differences are very subtle, a scenario and sensitivity analysis of the life cycle should be performed to evaluate the system holistically.

As indicated in section 2.1.2., Particulate Matter (PM) emissions were quantified for all Porcelain Stoneware Tile varieties, both, those emitted during the manufacturing process and those emitted throughout the life cycle, in addition to the environmental indicators recommended by the standard EN 15804: 201+A1: 2013.

Figure 9a and Fig. 9b show that, even though some direct PM emissions depended mainly on surface area of the product (i.e. manufacturing processes after forming process), total PM emissions were closely linked to specific mass. This pattern remained similar both in the direct emissions, i.e. emitted during the manufacturing stage (A3 stage) and in the total life cycle emissions. The values between all the studied varieties of PST ranged from 2.5 to 7.6 g/m^2 in the case of direct emissions and from 19 to 62 g/m^2 the indirect emissions related to the whole life cycle of the different PST. Total PM emissions (direct and indirect emissions) had an order of magnitude higher than direct emissions generated in the manufacturing process. Indirect emissions came largely from the combustion of fossil fuels used in transport (fuel oil used on boats and diesel on trucks) and the raw material extraction activities due to the handling of powdery materials.

In spite, direct PM emissions seem to have relatively low contribution from a life cycle perspective, the environmental and economic impact at local level is high. In fact, studies carried out by the Instituto de Tecnología Cerámica at the request of ASCER when Integrated Prevention Pollution Control Directive 96/61CE (IPPC) drove into force, estimated that the 60-70 % of the total investment made by the tile manufacturing industry was addressed to mitigate PM emissions.

4 Conclusions

The life cycle stage with the greatest environmental impact was the manufacturing stage (A3). The main hotspots were production and consumption of natural gas in manufacturing (in A3) for ADP-fossil and GWP; glazes (in A1) for ADP-elements, AP, EP, and POCP; electricity production from the SPGM and consumption (in A3) for ODP and ADP-fossil; distribution (A4) for AP and POCP; body raw materials (in A1) for ODP and adhesives used in the installation stage (A5) for ADP-elements. To be noted are the great number of cogeneration systems installed in the Spanish ceramic tile cluster (an important difference from other countries production systems), which significantly reduced the impacts in the SPGM, especially in the ADP-fossil, AP, POCP, and GWP categories.

PM emissions do not have a direct contribution to the environmental impact categories required by EN 15804:2012+A1:2013 and the RCPs for ceramic products consider neither indirect nor direct emissions PM emissions as an output flow to declare in the EPD. However, PM emissions generated during the manufacturing process have an important environmental and economic significance from an industrial point of view. Therefore, the authors recommend including the mandatory declaration of PM emissions in the EPD for ceramic products as well as for those building products with a similar casuistry in the RCPs.

The study further shows that the variation in PST thickness (i.e. specific weight) was a key factor influencing all studied impact categories except ADP-elements, as it significantly affected the materials and energy inputs and outputs in almost every life cycle stage. PST mechanical treatments particularly increased the values of the ODP impact category, mainly from increased electric energy consumption. Finally, the amount of glaze strongly modified the ADP-elements and EP values, owing to the boron-introducing raw materials in the glaze composition and NO_x emissions in ceramic frit manufacturing, respectively.

Although all studied PST varieties belonged to the same water absorption group (according to ISO 13006) and could, therefore, except in special applications, all perform the same function, the study confirmed that the differences among these commercial PST varieties were quite significant (about 35 %, except ODP, which was about 48 %). Consequently, the possibility of declaring a number of PST varieties in the same EPD is not as obvious as was assumed in some studies (Table 1). This suggests that a preliminary verification is required to ensure compliance with the PCR by comparing the life cycle environmental profile of the PST candidates. In this regard, the authors recommend, firstly, comparing the PST varieties that exhibit the lowest and highest environmental impact profiles, focusing in particular on thickness, amount of glaze, and mechanical surface treatment. If the results of this preliminary comparison do not comply with the grouping rules for PCRs, a new grouping process should then be performed.

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ACRONYMS

A: Average performance, weighted by the production of all thicknesses, patterns, and finishes
A1: Life cycle stage: Raw Materials Supply
A2: Life cycle stage: Transport of Raw Materials
A3: Life cycle stage: Manufacturing
A4: Life cycle stage: Transport to the building
A5: Life cycle stage: Installation into the building
AAA: Average thickness, average quantity of glaze, and average mechanical treatments
ADP elements: Abiotic Depletion–elements
ADP fossil: Abiotic Depletion–fossil fuels
AGM: Average thickness, glazed, and mechanised
AGN: Average thickness, glazed, and non-mechanised
AP: Acidification Potential
ASCER: The Spanish Ceramic Tile Manufacturers' Association
AUM: Average thickness, unglazed, and mechanised
AUN: Average thickness, unglazed, and non-mechanised
B1: Life cycle stage: Use
B2: Life cycle stage: Maintenance
B3: Life cycle stage: Repair
B4: Life cycle stage: Replacement
B5: Life cycle stage: Refurbishment
B6: Life cycle stage: Operational energy use
B7: Life cycle stage: Operational water use
C1: Life cycle stage: Deconstruction and demolition
C2: Life cycle stage: Transport
C3: Life cycle stage: Reuse, recovery, and recycling
C4: Life cycle stage: Disposal
CML: The Institute of Environmental Sciences (CML), Faculty of Science of Leiden University, The Netherlands
Dwt: Dead weight tonnage
E_b: Water absorption
EN: European Standard
EP: Eutrophication Potential
EPD: Environmental Product Declaration
Eq.: Equivalent
ERDF: European Regional Development Fund
ET: Earthenware Tile
EU-28: European Union
FU: Functional Unit
G: Glazed
GST: Glazed Stoneware Tile
GWP: Global Warming Potential (100 years)
H: High thickness
HAA: High thickness, average quantity of glaze, and average mechanical treatments
HGM: High thickness, glazed, and mechanised
HGN: High thickness, glazed, and non-mechanised
HUM: High thickness, unglazed, and mechanised
HUN: High thickness, unglazed, and non-mechanised
ISO: The International Organization for Standardization
IVACE: Institut Valencià de Competitivitat Empresarial
L: Low thickness
LAA: Low thickness, average quantity of glaze, and average mechanical treatments
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory Analysis
LCIA: Life Cycle Impact Assessment
LGM: Low thickness, glazed, and mechanised
LGN: Low thickness, glazed, and non-mechanised
LUM: Low thickness, unglazed, and mechanised
LUN: Low thickness, unglazed, and non-mechanised
M: Mechanised

N: Non-mechanised
ODP: Ozone Layer Depletion Potential (steady state)
PCR: Product Category Rules
PM: Particulate matter
PM_{10}: Particles which pass through a size-selective inlet with a 50 % efficiency cut-off at 10 µm aerodynamic diameter. PM10 corresponds to the "thoracic convention" as defined in ISO 7708:1995, Clause 6.
POCP: Photochemical Ozone Creation Potential
PST: Porcelain Stoneware Tile
Q2: 50^{th} percentile
SD: Standard Deviation
SPGM: Spanish Power Grid Mix
U: Unglazed
UK: United Kingdom

FIGURE CAPTIONS

Fig. 1 Evolution of Spanish ceramic tile production by types (ASCER 2015)

Fig. 2 Life cycle information modules (EN 15978: 2011 and EN 15804:2012+A1:2013)

Fig. 3 Boundaries of the analysed system. Modules according to EN 15804:2012+A1:2013 A1 Raw materials supply; A2 Transport of raw materials; A3 Manufacturing; A4 Transport to the building; A5 Installation into the building; B2 Maintenance; C1 Deconstruction and demolition; C2 Transport; C3 Reuse, recovery and/or recycling; C4 Disposal

Fig. 4 LCIA results (relative units) of covering 1 m2 of household floor surface for 50 years with PST AAA

Fig. 5 Influence of the glaze

Fig. 6 Influence of thickness

Fig. 7 Influence of mechanical treatments

Fig. 8 Environmental impacts of each PST variety

Fig. 9 Emissions of particulate matter of each PST variety

Figure 1

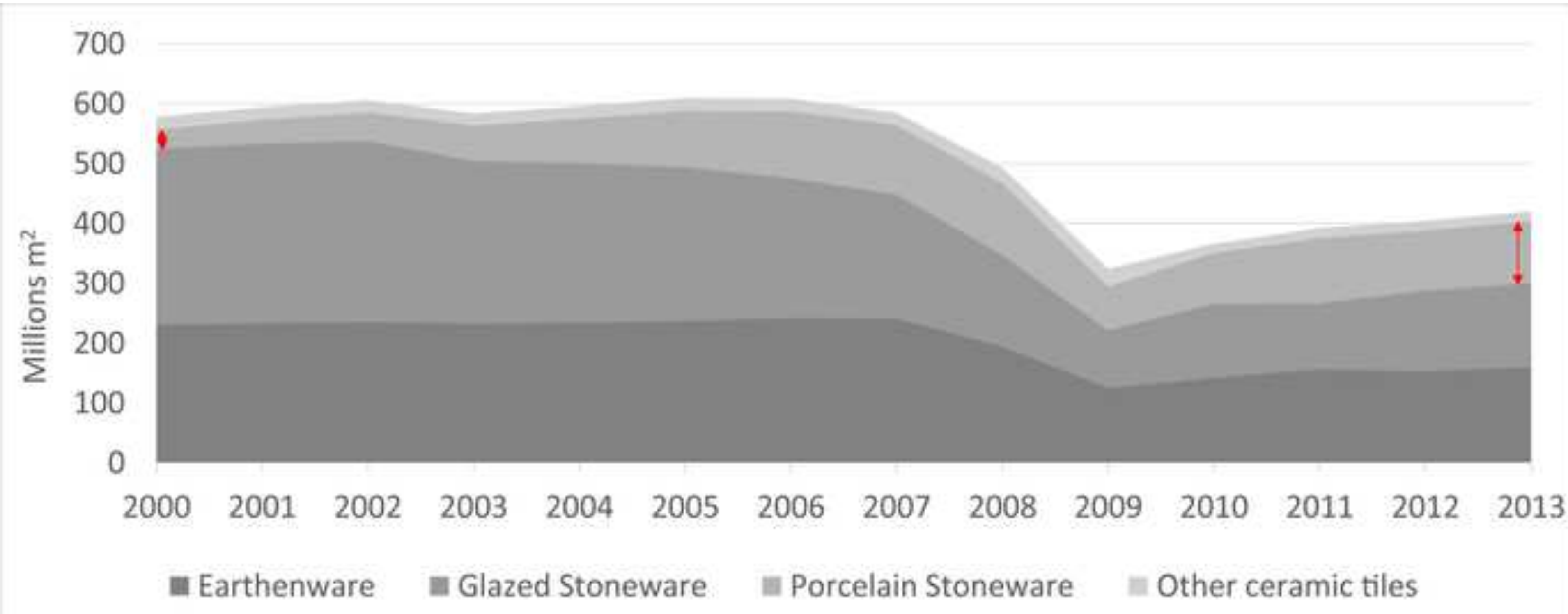

700
600
500
400
300
200
100
0
Millions m²
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
Earthenware
Glazed Stoneware
Porcelain Stoneware
Other ceramic tiles

Figure 2

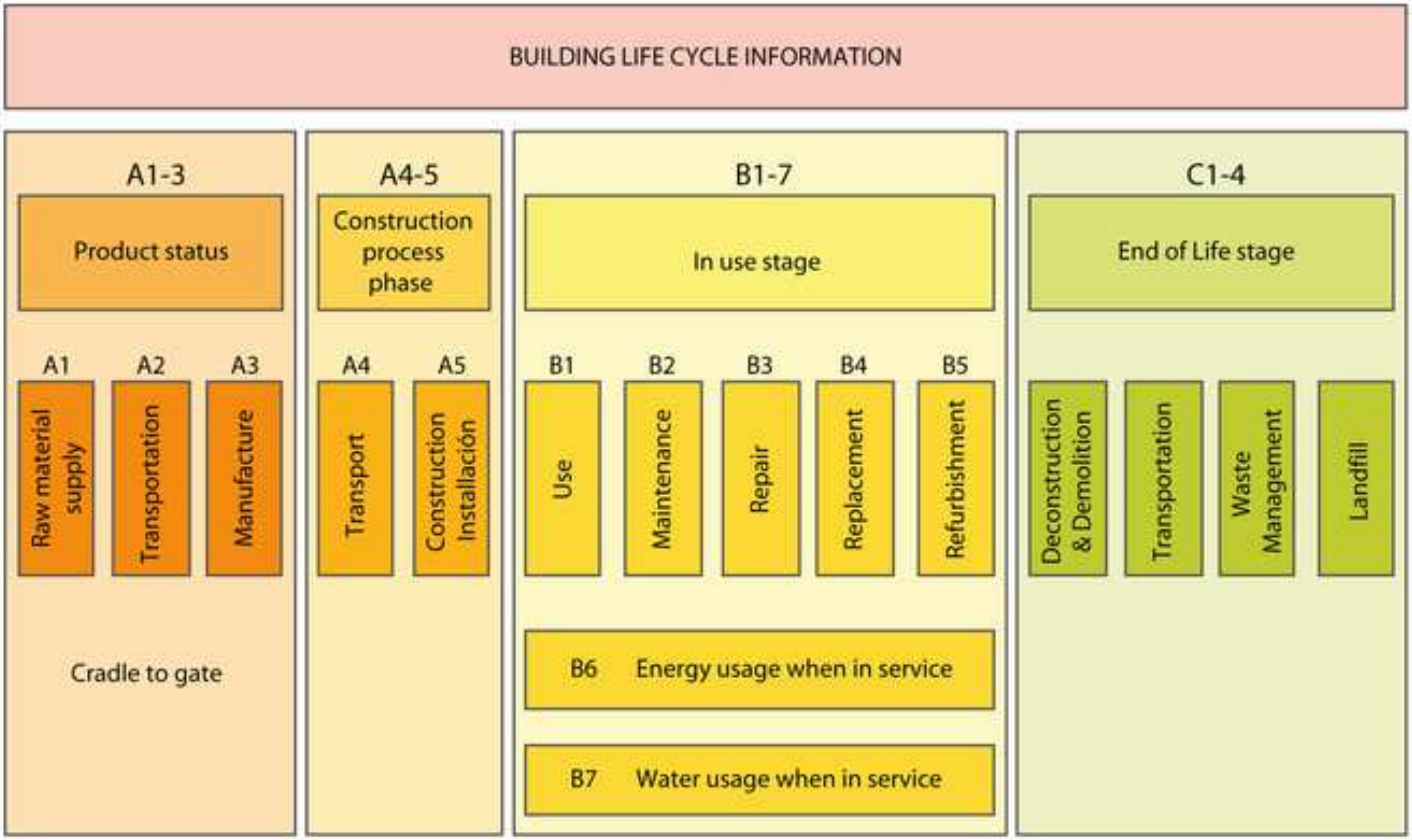
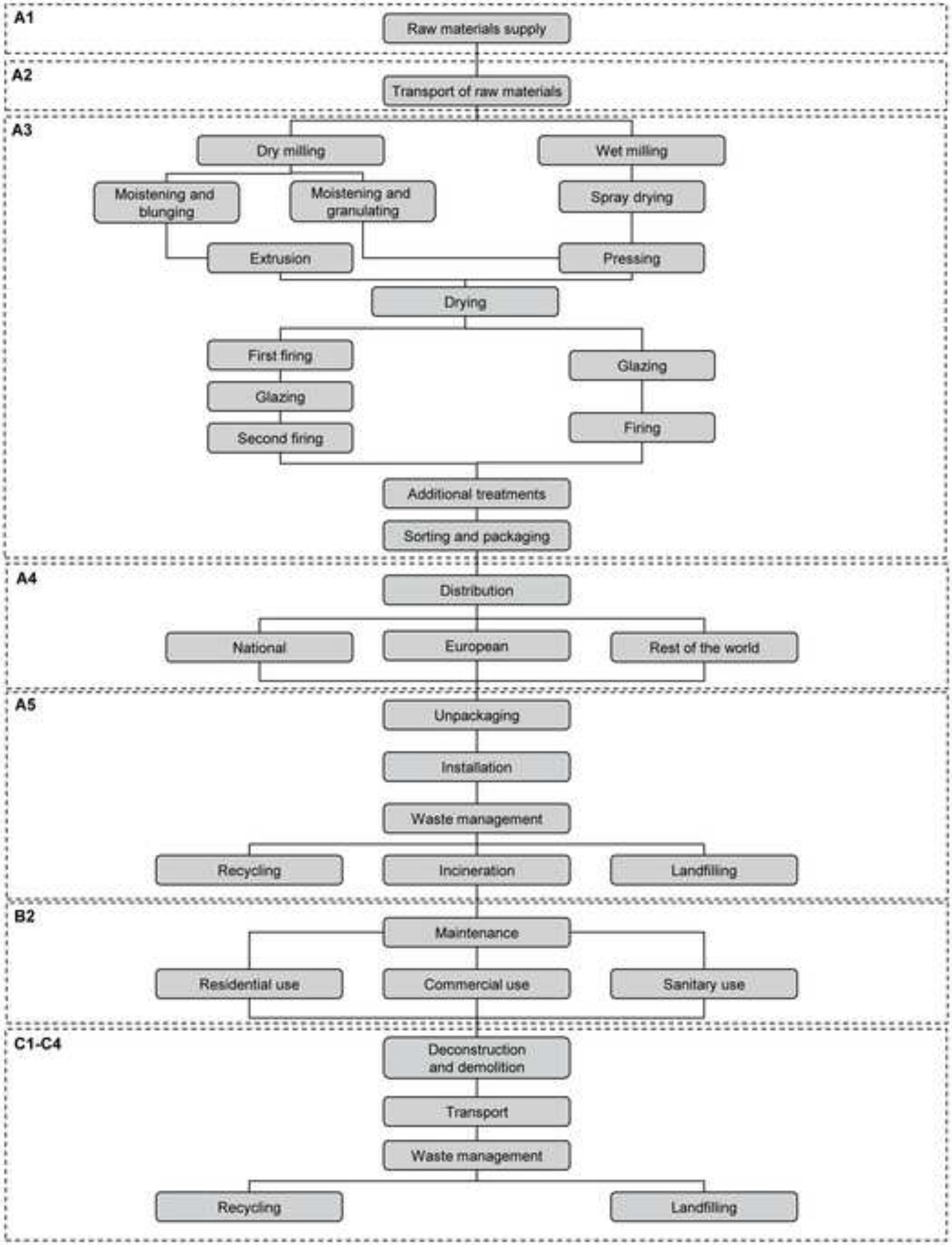

BUILDING LIFE CYCLE INFORMATION
A1-3
Product status
A1
Raw material supply
A2
Transportation
A3
Manufacture
Cradle to gate
A4-5
Construction process phase
A4
Transport
A5
Construction Installación
B1-7
In use stage
B1
Use
B2
Maintenance
B3
Repair
B4
Replacement
B5
Refurbishment
B6 Energy usage when in service
B7 Water usage when in service
C1-4
End of Life stage
Deconstruction & Demolition
Transportation
Waste Management
Landfill

Figure 3



A1
Raw materials supply
A2
Transport of raw materials
A3
Dry milling
Wet milling
Moistening and blunging
Moistening and granulating
Spray drying
Extrusion
Pressing
Drying
First firing
Glazing
Second firing
Glazing
Firing
Additional treatments
Sorting and packaging
A4
Distribution
National
European
Rest of the world
A5
Unpackaging
Installation
Waste management
Recycling
Incineration
Landfilling
B2
Maintenance
Residential use
Commercial use
Sanitary use
C1-C4
Deconstruction and demolition
Transport
Waste management
Recycling
Landfilling

Figure 4

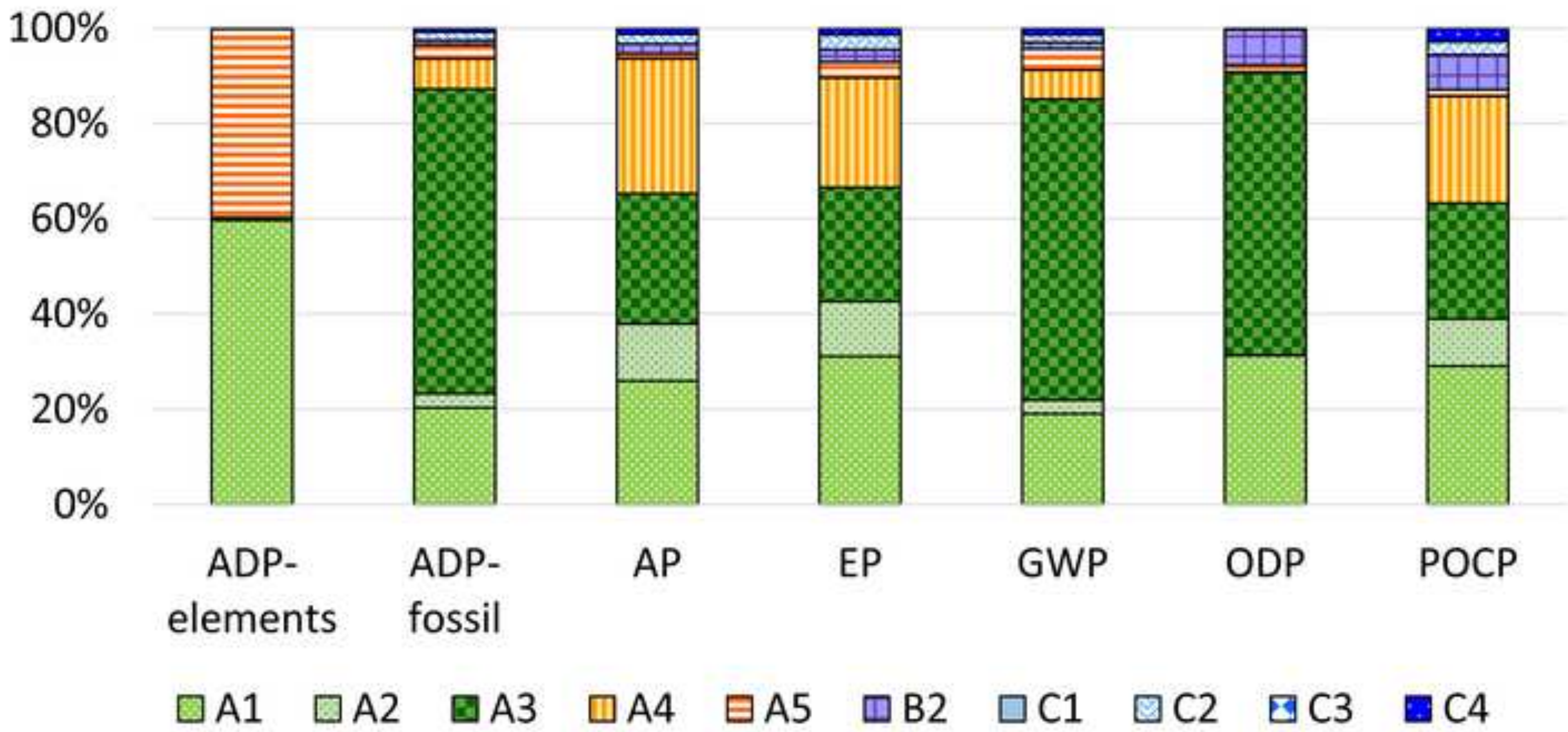

100%
80%
60%
40%
20%
0%
ADP-elements
ADP-fossil
AP
EP
GWP
ODP
POCP
A1
A2
A3
A4
A5
B2
C1
C2
C3
C4

Figure 5

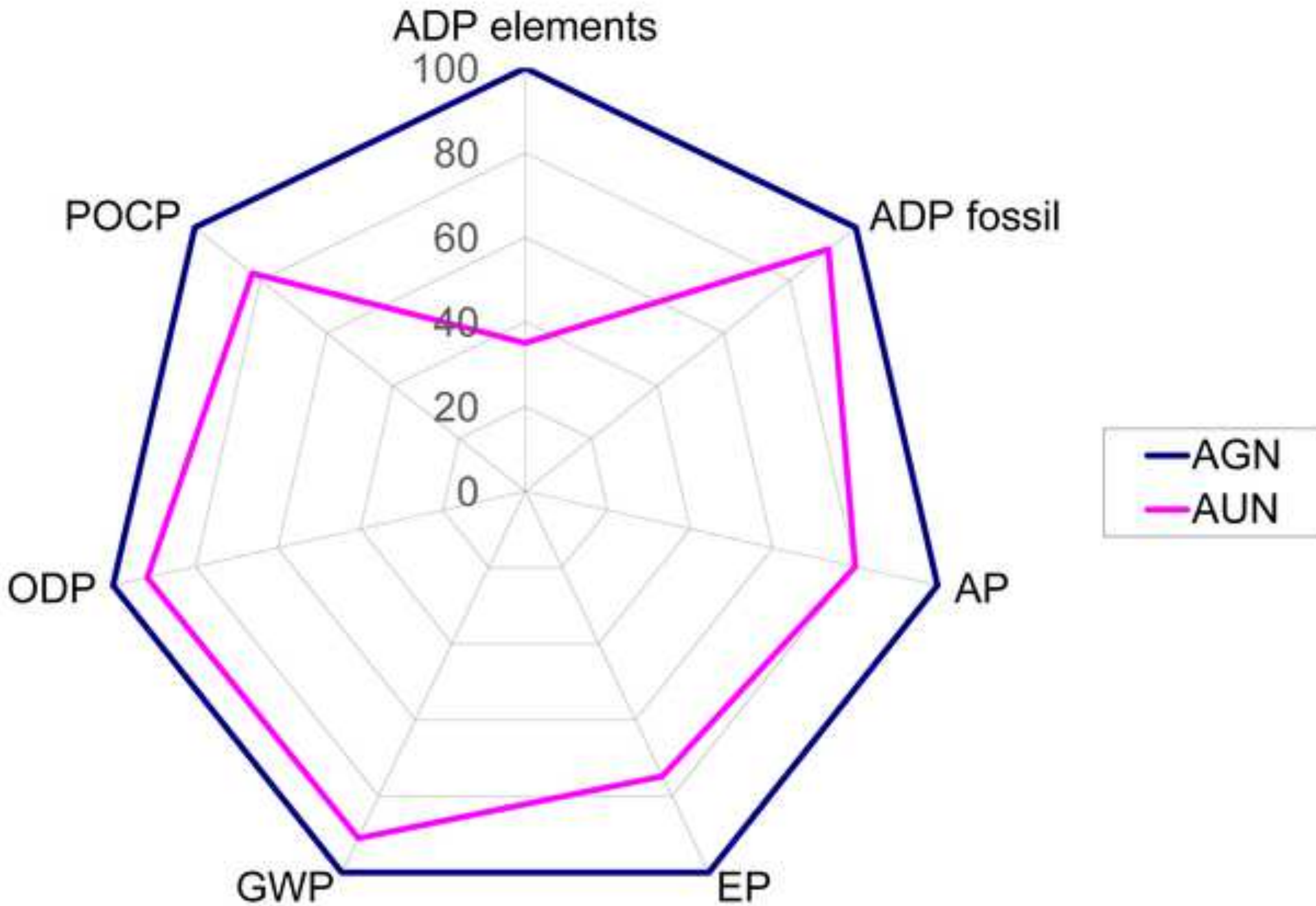

ADP elements
100
80
60
40
20
0
ADP fossil
AP
EP
GWP
ODP
POCP
AGN
AUN

Figure 6

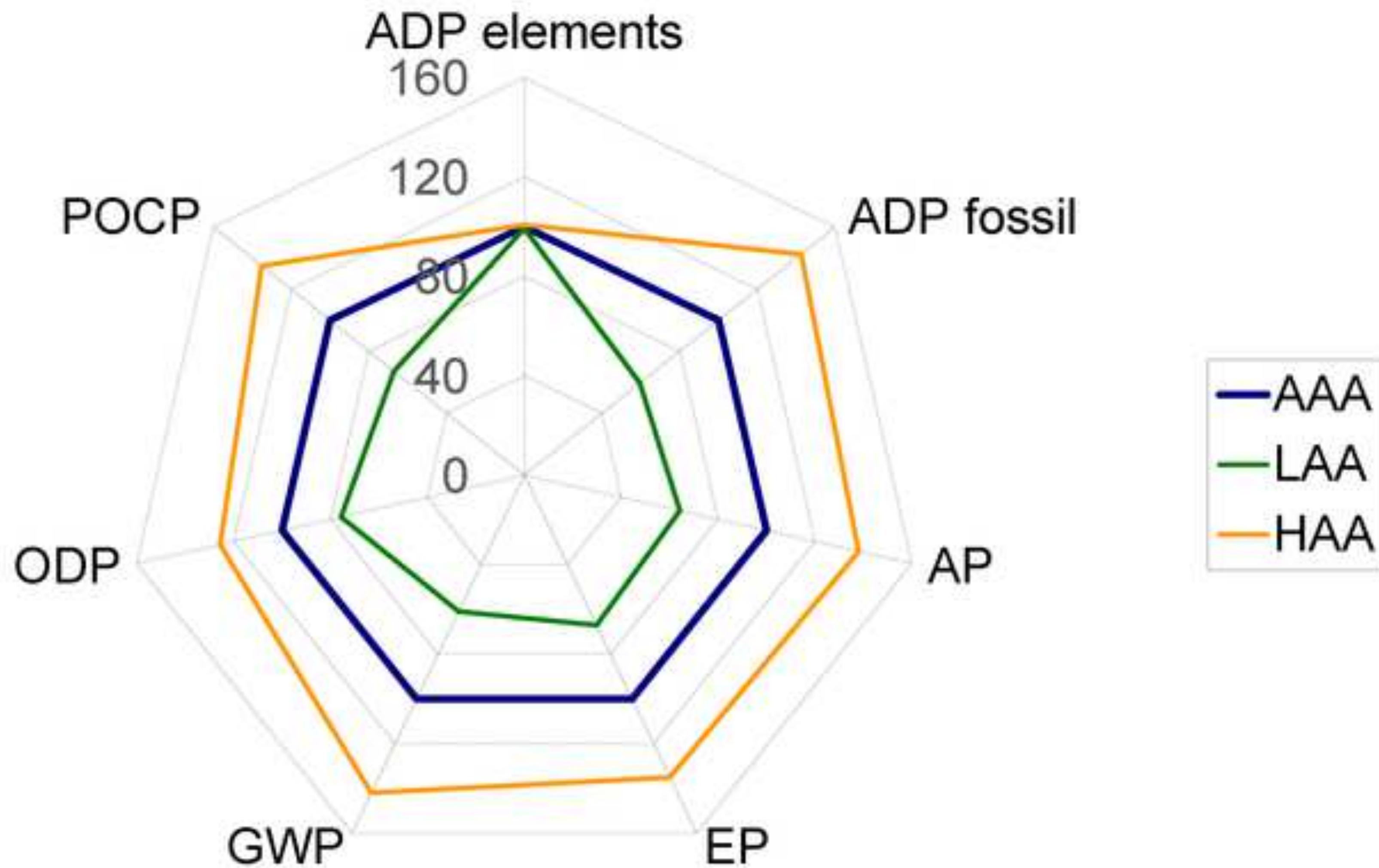

ADP elements
160
120
80
40
0
ADP fossil
AP
EP
GWP
ODP
POCP
AAA
LAA
HAA

Figure 7

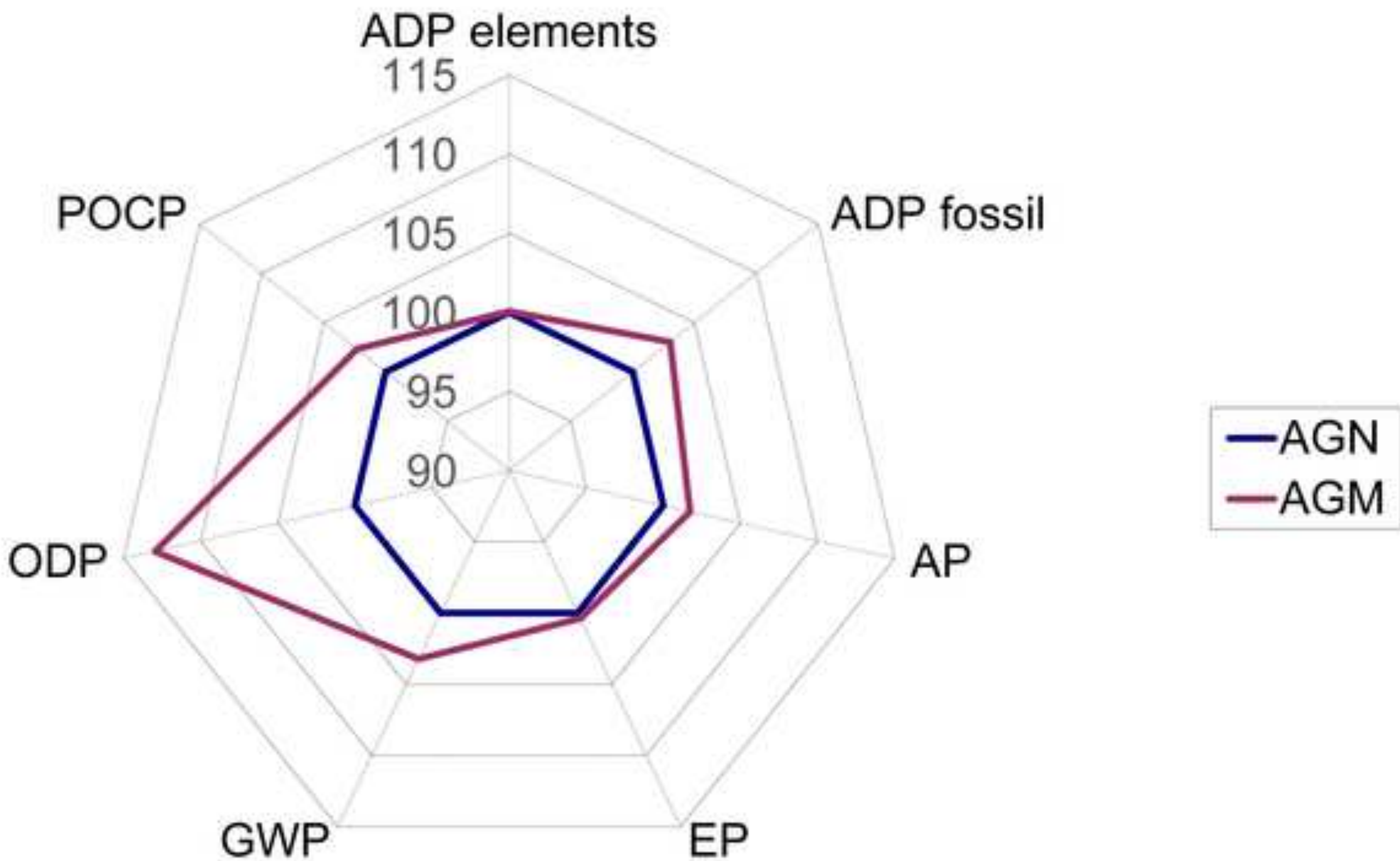
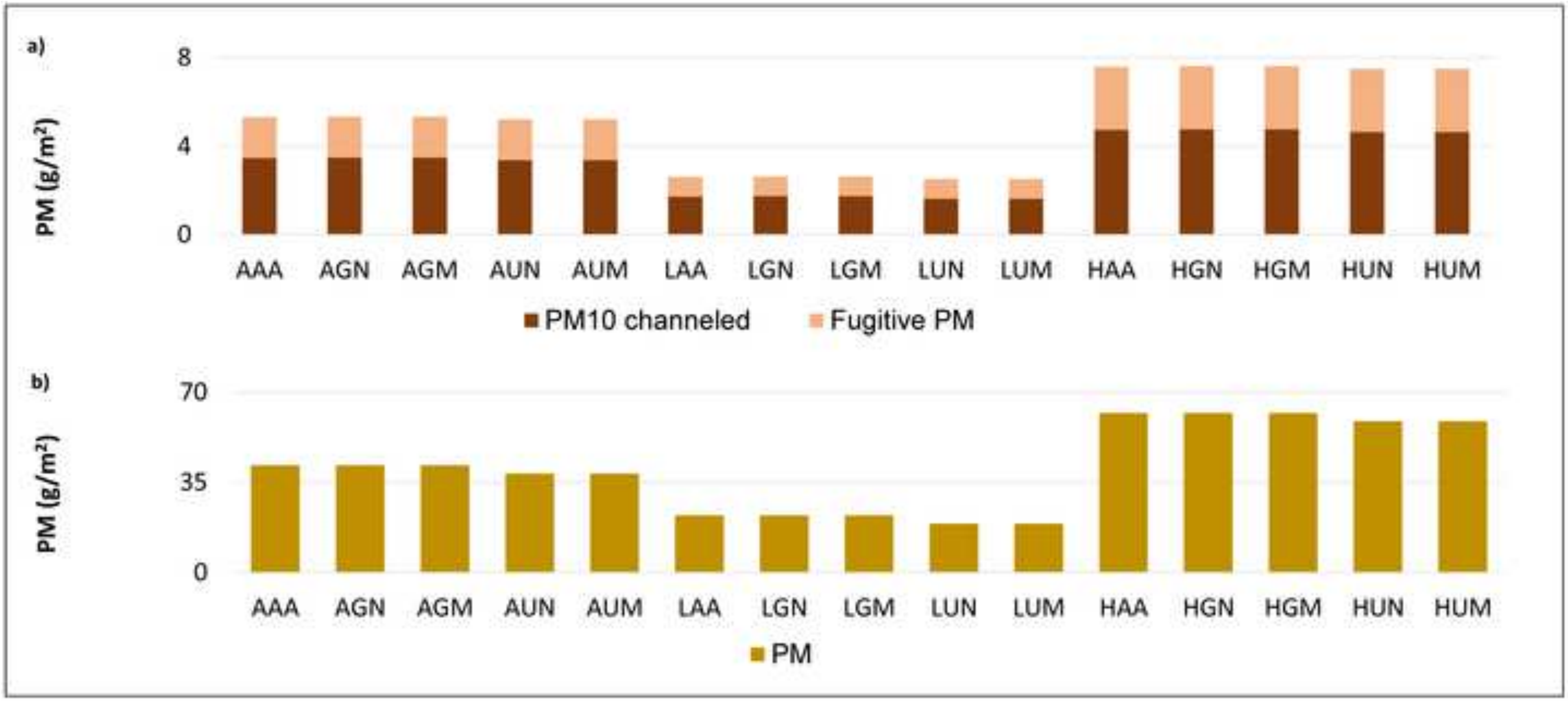
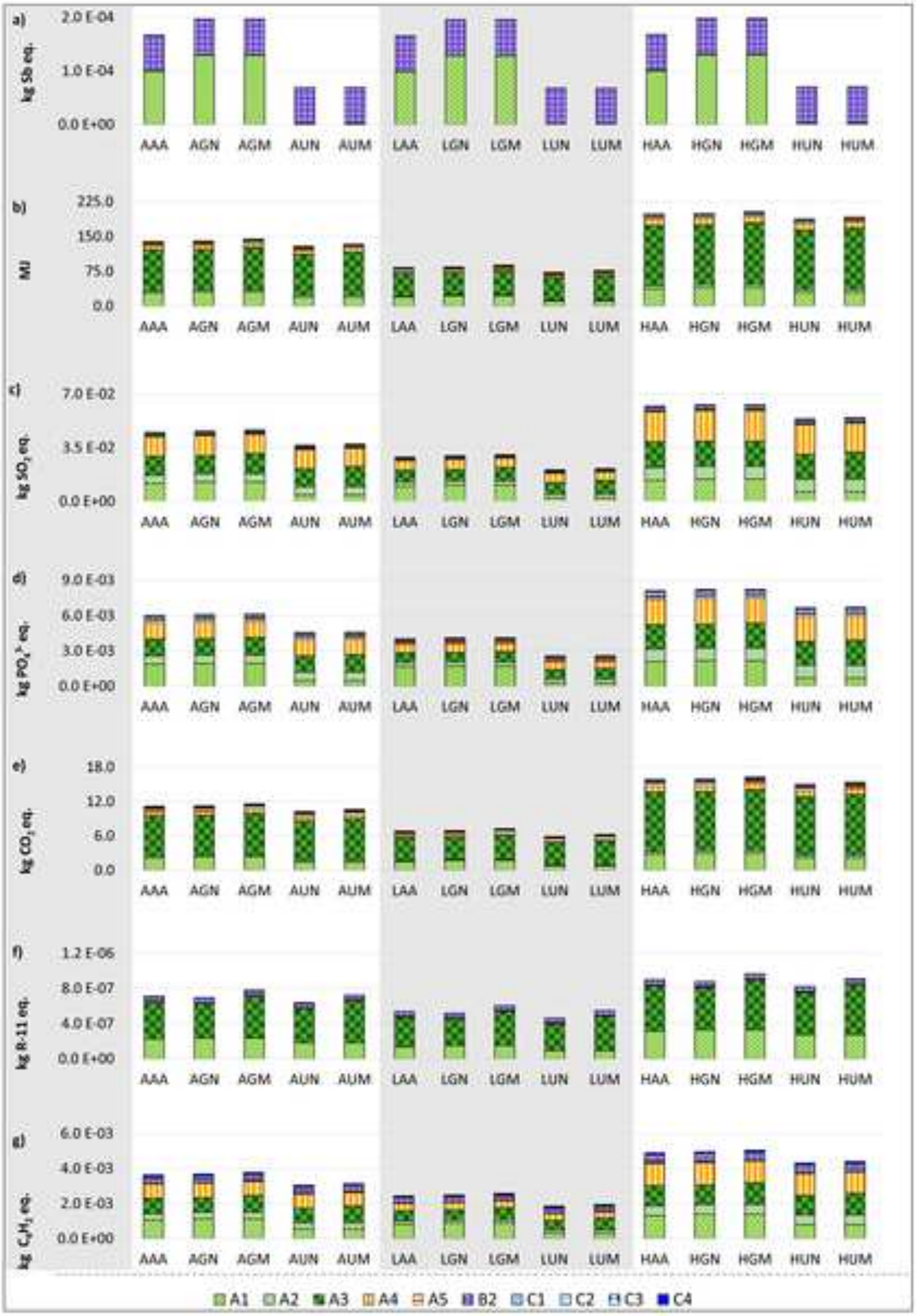

ADP elements
115
110
105
100
95
90
ADP fossil
AP
EP
GWP
ODP
POCP
AGN
AGM

Figure 9



a)
8
4
0
PM (g/m²)
AAA
AGN
AGM
AUN
AUM
LAA
LGN
LGM
LUN
LUM
HAA
HGN
HGM
HUN
HUM
PM10 channeled
Fugitive PM
b)
70
35
0
PM (g/m²)
AAA
AGN
AGM
AUN
AUM
LAA
LGN
LGM
LUN
LUM
HAA
HGN
HGM
HUN
HUM
PM

Figure 8



a)
kg Sb eq.
2.0 E-04
1.0 E-04
0.0 E+00
b)
MJ
225.0
150.0
75.0
0.0
c)
kg SO_2 eq.
7.0 E-02
3.5 E-02
0.0 E+00
d)
kg PO_4^{3-} eq.
9.0 E-03
6.0 E-03
3.0 E-03
0.0 E+00
e)
kg CO_2 eq.
18.0
12.0
6.0
0.0
f)
kg R-11 eq.
1.2 E-06
8.0 E-07
4.0 E-07
0.0 E+00
g)
kg C_2H_4 eq.
6.0 E-03
4.0 E-03
2.0 E-03
0.0 E+00
AAA AGN AGM AUN AUM LAA LGN LGM LUN LUM HAA HGN HGM HUN HUM
A1 A2 A3 A4 A5 B2 C1 C2 C3 C4

Table 1 Classification and features of the most common ceramic tiles manufactured in Spain (ISO 13006:2012 and ASCER 2011)

ISO 13006 classification		Glaze	Common name	Abbreviation	Production (% in m^2)
Types	Water absorption (E_b)				
BIa-AIa	≤0.5%	No–Yes	Porcelain stoneware tile	PST	25
BIb-BIIa	0.5–10%	Yes	Glazed stoneware tile	GST	33
BIII	>10%	Yes	Earthenware tile	ET	38

Table 2 Summary of the considerations made in declaring the average environmental results of a number of products

Programme/standard (product category)	Considerations when an average environmental performance for a number of products is declared
EN 15804:2012+A1:2013 (Construction products)	Grouping criteria and description of the range/variability of the LCIA results if significant.
International EPD® System (Construction products and construction services)	Differences in the LCIA results below ±10% (concerning A1–A3) could be presented using the impacts of a representative product. A variation range description shall be presented in the declaration. Differences above ±10% (concerning A1–A3) could be presented in the same EPD, but using separate columns or tables. An alternative is to select a product within the product group but stating that the span exceeds 10% or the exact figure valid for the product.
CET 2014 and Thurning et al. 2013 (Construction clay products)	Always weighted averages. In addition, depending on the number of sites and manufacturers, declaration of the maximum and minimum values.
FDE&S (Construction products)	Idem to EN 15804:2012+A1:2013 (Standard XP P 01-064/CN) The product with the highest impact (Standard XP P 01-064/CN)
IBU EPD programme (ceramic tiles and panels)	If averages are declared across various products, the average breakdown must be explained.
DAPcons® system (ceramic coverings)	Grouping criteria according to water absorption group. The average can be declared only if the differences between impacts are below ±10%, indicating the degree of deviation
GlobalEPD (ceramic coverings)	Grouping criteria according to water absorption group. Declaration of the weighted average, declaring the individual product with the highest and the lowest impact
NSF USA (Flooring: carpet, resilient, laminate, ceramic, wood)	The variation shall be described and the minimum and maximum level for the product group's environmental performance shall be given

Table 3 Literature review

LCA study	Year of data collection	Final ceramic product	Country of origin	Functional Unit	Scope	Representativeness	Environmental impact assessment
Almeida et al. 2016	2012	- Glazed tiles - Unglazed tiles - Glazed PST	Portugal	1 m^2 of ceramic tile with a lifespan of 50 years	Cradle to grave	Four factories	**CML2001**: ADP – elements; ADP – fossil; AP; EP; GWP; ODP; POCP **ILCD:** Human toxicity particulate matter, land use, water depletion and ecotoxicity
Islam et al. 2015a	2009	Interior flooring. No specific ceramic product	Australia	House over its 50-year lifetime	Raw material extraction and processing, transportation and distribution, use/operation, maintenance, and final disposal.	Integrated in a house	**Australian Impact Method with Normalization:** Greenhouse gases (tCO_2-eq); Cumulative Energy Demand (GJ);Solid waste (tonne); Life cycle cost ($)
Islam et al. 2015b	2006–2009	Interior flooring. No specific ceramic product	Australia	House over its 50-year lifetime	Raw material extraction and processing, transportation and distribution, use/operation, maintenance, and final disposal.	Integrated in a house	**Australian Impact Method with Normalization:** Greenhouse gases (tCO_2-eq); Cumulative Energy Demand (GJ);Solid waste (tonne); Life cycle cost ($)
Han et al. 2015	Not specified	Façades of extruded ceramic tile	China	1 m^2 of ceramic façade panels	Cradle to grave	One typical ceramic tile manufacturing company in China	**CML2001:** ADP, POCO, GWP, AP, EP, ODP, Human toxicity
Belusi et al. 2015	2012 for the prototype and <2002 for the ceramic tile	Photovoltaic ceramic tile prototype	Italy	1 m^2 laminate	Cradle to grave	Prototype scale	**CML 2001**: ADP, POCP, GWP, AP, EP, ODP
Souza et al. 2015	2010–2011	Roof tiles	Brazil	Coverage of 1 m^2 roof with tile for a duration of 20 years in Brazil	Cradle to grave	Average conditions of the country	**IMPACT 2002+VQ2.2**. climate change, human health, ecosystem quality, resources depletion, water withdrawal
Minne and Crittenden 2015	Not specified	Generic ceramic tile with recycled glass	USA	1 m^2 of flooring in residential scenario for 61 years	Raw materials, manufacturing, installation, use phase and end-of life management of the flooring products.	From BEES database for products, 2010	**World ReCiPe midpoint hierarchist and endpoint:** Climate change; Fossil depletion; Photochemical oxidant formation; Water depletion; Freshwater eutrophication; Land occupation; Human toxicity

LCA study	Year of data collection	Final ceramic product	Country of origin	Functional Unit	Scope	Representativeness	Environmental impact assessment
Pini et al. 2014	2008	Ceramic stoneware slab reinforced with a fibreglass (PST) backing (3.5 mm thick, 8.2 kg/m^2 and Eb=0.1%)	Italy	1 m^2 of a black, large, thin ceramic tile (3.5mm) reinforced with fibreglass backing	Raw materials supply, transport of raw materials, manufacturing, distribution and end of life	One manufacturing company	**IMPACT 2002+:** Human health; Ecosystem quality; Climate change; Resources; Single score (Pt)
Ruschi Mendes Saade et al. 2014	Not specified	Generic ceramic tile	Brazil	1 m^2 of gross floor area (GFA)	Cradle to gate. For reinforced concrete, steel rebar and formwork quantification, only the superstructure was considered, in order to isolate the effects of the soil's carrying capacity on the sizing – and, consequently, on material consumption – of the foundation elements. External and urbanisation elements were also disregarded	Ecoinvent v.2.2	**Method unknown:** embodied energy; embodied CO2e; blue water footprint; non-renewable minerals; volatile organic compound emissions of building materials
Ibañez-Forés et al. 2013	2009	Glazed stoneware tile	Spain	1 m^2 of tile	Cradle to gate	35 Spanish companies	**CML 2001:** ADP; GWP; ODP; AP; EP; POCP; human toxicity
Benveniste et al. 2011	2008	PST: $E_b \leq 0.5\%$; GST $0.5\% < E_b \leq 10\%$ ET: Eb>10%	Spain	1 m^2 covering of a (floor/wall) surface inside a home for 50 years with different types of ceramic tiles	Cradle to grave, excluding repair, replacement, and refurbishment	56 Spanish manufacturing companies (encompassing over 50% of Spanish production)	**CML 2001:** ADP; GWP; ODP;EP;AP; POCP; primary energy consumption and water consumption
Ibañez-Forés et al. 2011	2009	Glazed stoneware tile	Spain	1 m^2 of ceramic tile over a period of 20 years	Cradle to grave except use stage	35 Spanish companies	**CML 2001:** ADP; GWP; ODP; AP; EP; POCP; human toxicity
Tikul and Srichand 2010	March 2008 to February 2009	Not specified	Thailand	1 megagram (Mg) of double-fired glazed plain white and pink ceramic	Raw material transportation, manufacturing, and packing of final products, including glaze production	One ceramic plant	**EDIP:** fossil fuel impact; global warming; ozone depletion; ecotoxicity; human toxicity. **Eco-indicator 99**:

LCA study	Year of data collection	Final ceramic product	Country of origin	Functional Unit	Scope	Representativeness	Environmental impact assessment
				tile, (5 mm thick, 10.57 kg/m^2 weight).			
Bovea et al. 2010	2004–2006	Wall and floor tiles	Spain	1 m^2 of manufactured and classified ceramic tile, ready for sale	Extraction of red clay and glaze raw materials, transport, production of the tiles and glazes, and delivery to customer.	Several Spanish companies	**CML 2001:** ADP; GWP; ODP; AP; EP; POCP. Noise dBA
Nicoletti et al. 2002	<2002	Single-fired ceramic tile (18 kg/m^2). Lifespan of ceramic tile 20 years	Italy	1 m^2 of floor tile over a period of 40 years.	Extraction of raw materials for body and glazes, transport, manufacturing, packaging, and end of life	Several Italian companies	**Method unknown:** ADP; GWP; ODP; HT; ECA; AP; POCP; NP
Present study	2010–2015	15 varieties of porcelain stoneware tile: $E_b \leq 0.5\%$;	Spain	Covering 1 m^2 of household floor surface for 50 years with different varieties of PST.	Cradle to grave	26 Spanish companies	**CML2001:** ADP – elements; ADP – fossil; AP; EP; GWP; ODP; POCP

Table 4 Variations of PST characteristics according to PST thickness, glaze content, and mechanical finishes

Parameter	Designation	Values
Thickness	Low (L) Average (A)[1] High (H)	5 mm (11 kg/m^2 weight unfired) 10.4 mm (24.5 kg/m^2 weight unfired) 16 mm (34 kg/m^2 weight unfired)
Glaze content	Unglazed (U) Average (A)[1] Glazed (G)	0 kg/m^2 0.76 kg/m^2 1 kg/m^2
Mechanical treatment	Non-mechanised (N) Average (A)[1] Mechanised (M)	0% 32% 100%
[1] Average performance, weighted by the production of all formats, patterns, and mechanical finishes		

Table 5 Nomenclature used in this study

Letter	Parameter			
1st	Thickness	L	A	H
2nd	Glaze content	U	A	G
3rd	Mechanical treatment	N	A	M
Example: AUN → PST with Average thickness, Unglazed, and No mechanical treatments				

Table 6 Environmental impact categories

Impact category	**Acronym**	**Units**
Abiotic Depletion – elements	ADP-elements	kg Sb Equivalent
Abiotic Depletion - fossil fuels	ADP-fossil	MJ
Acidification Potential	AP	kg SO_2 Equivalent
Eutrophication Potential	EP	kg PO_3^4 Equivalent
Global Warming Potential (100 years)	GWP	kg CO_2 Equivalent
Ozone Layer Depletion Potential (steady state)	ODP	kg R11 Equivalent
Photochemical. Ozone Creation Potential	POCP	kg C_2H_4 Equivalent

Table 7 Studied PST body and glaze compositions

Body raw materials	**Composition (wt%)**
Feldspars	43.53%
Clays	41.16%
Sands	10.91%
Unfired ceramic tile scrap	2.09%
Kaolin	1.23%
Fired ceramic tile scrap	0.53%
Pigments	0.32%
Deflocculants	0.23%
Glaze and decorative raw materials	**Composition (%)**
Frit content	33%
Feldspars	26.02%
Quartz	21.04%
Carbonates	19.73%
Boron-introducing raw materials	7.35%
Clays	6.54%
Silicates	5.16%
Zinc oxide	4.29%
Zirconium	4.27%
Kaolin	3.12%
Alumina	2.48%

Table 8 Material and energy inputs and outputs of the PST AAA life cycle relative to the FU (including glaze life cycle from cradle to gate)

	Product stage	Construction process stage	Use stage	End of life stage
	A1-A3	**A4-A5**	**B1-B7**	**C1-C4**
INPUTS				
Body raw materials[(1)] (kg/m^2)	2.39E+01			
Glaze raw materials[(1)] (kg/m^2)	7.85E-01			
Auxiliary inputs (kg/m^2)		3.50E+00	4.94E-02	
Electric energy from the grid (MJ/m^2)	1.68E+01			negligible
Thermal energy from natural gas (MJ/m^2)	1.31E+02			
Groundwater (l/m^2)	1.55E+01			
Tap water (l/m^2)	2.36E+00	8.80E-01	2.60E+02	
Recycled water from other industries (l/m^2)	1.83E+00			
Packaging (kg/m^2)	8.13E-01			
OUTPUTS				
PST (kg/m^2)	2.15E+01			
Electric energy sold to the grid (MJ/m^2)	1.46E+01			
Air emissions of particulate matter[(2)] (mg/m^2)	6.00E+03			
Air emissions of NO_x from the process (mg/m^2)	3.36E+03			
Air emissions of SO_2 from the process (mg/m^2)	2.79E+03			
Air emissions of HF (mg/m^2)	1.36E+03			
Air emissions of HCl (mg/m^2)	1.43E+01			
Air emissions of heavy metals (mg/m^2)	1.88E+00			
Non-hazardous wastes (kg/m^2)	4.91E+00			2.50E+01
Hazardous wastes (kg/m^2)	1.54E-03	8.13E-01		
Wastewater discharge (l/m^2)	3.39E-01		2.60E+02	

NOTE:

1. Composition detailed in Table 7
2. Channelled and fugitive particle matter emissions into the air

Table 9 Specific data from mechanical treatments

Mechanical treatments	**Q2**	**SD**
Electricity consumption (MJ/m^2)	3.5	2.5
Water consumption (l/m^2)	3.8	1.7
Waste generation (kg/m^2)	1.8	2.2

Table 10 Direct particulate matter emissions in the manufacturing stage

Type of emission	Manufacturing Stage	mg PM/m^2	PM_{10}/PM(1)	mg PM_{10}/m^2
Channelled	Milling	399	74.80%	298
	Spray drying	1136	91.45%	1039
	Drying	768	84.50%	649
	Glazing	121	74.50%	90
	Firing	874	99.40%	868
	General ventilation	678	75.30%	511
Fugitive	Bulk solids handling(2)			1850

(1) PM_{10}/PM ratio from Celades 2013.
(2) Fugitive emissions factor in the ceramic industry from Monfort et al. 2011b

Table 11 Management of the wastes generated by the FU of PST AAA

Waste generated in the life cycle		Quantity (kg)	Treatment
A3	Fired ceramic tile scrap	0.13	Landfilling
		0.38	Recycling in other industries
	Waste from mechanical treatments	0.34	Landfilling
A5	Cardboard waste	0.01	Incineration
		0.11	Recycling
		0.04	Landfilling
	Plastic	0.002	Incineration
		0.01	Recycling
		0.01	Landfilling
	Wood	0.11	Incineration
		0.24	Recycling
		0.04	Landfilling
C3	Ceramic tiles and adhesive	17.50	Recycling
		7.50	Landfilling

Table 12 Characteristics of the extra-plant transports associated with the life cycle of 1 m^2 of PST AAA

Life Cycle Stage	Type of load	Quantity	Distance (km)	Means of transport
A2	Body raw materials	3.22 kg	150	27 t truck
		1.96 kg	500	27 t truck
		0.80 kg	900	27 t truck
		0.56 kg	1300	27 t truck
		1.94 kg	1000	105,000 dwt(2) cargo ship
		9.91 kg	3000	105,000 dwt(2) cargo ship
		4.10 kg	3500	105,000 dwt(2) cargo ship
		1.42 kg	4200	105,000 dwt(2) cargo ship
	Decoration raw materials	0.28 kg	500	27 t truck
		0.18 kg	2000	27 t truck
		0.18 kg	3500	105,000 dwt(2) cargo ship
		0.12 kg	10000	105,000 dwt(2) cargo ship
	Glaze packaging	0.25 kg	140	27 t truck
A3	Spray-dried granulates	23.90 kg	10	27 t truck
	Glazes and inks Packages	0.81 kg	28	27 t truck
	PST packaging	0.56 kg	94	27 t truck
	Mechanical treatment[1]	37%	3	27 t truck
	Waste management	5.25 kg	93	27 t truck
A4	PST for distribution	22%	500	27 t truck
		15%	2000	27 t truck
		63%	10000	105,000 dwt(2) cargo ship
	Packaging waste management(3)	0.56 kg	100	27 t truck
A5	Fast-setting mortars(3)	3.50 kg	100	27 t truck
B2	Detergent(3)	0.05 kg	100	27 t truck
C2	Ceramic tile end of life(3)	25 kg	100	27 t truck

NOTE:
(1) 37% of the sample was mechanised
(2) dwt: dead weight tonnage
(3) Assuming a round trip of 50 km

Table 13 Environmental impact assessment of 1 FU of PST AAA

	ADP-elements	**ADP-fossil**	**AP**	**EP**	**GWP**	**ODP**	**POCP**
	kg Sb Eq.	**MJ**	**kg SO_2 Eq.**	**kg PO_3^{4-}Eq.**	**kg CO_2 Eq.**	**kg R11 Eq.**	**kg C_2H_4 Eq.**
A1	9.93E-05	2.82E+01	1.17E-02	1.87E-03	2.12E+00	2.23E-07	1.05E-03
A2	6.45E-09	4.19E+00	5.37E-03	6.94E-04	3.16E-01	5.93E-10	3.59E-04
A3	9.74E-07	8.90E+01	1.23E-02	1.44E-03	7.04E+00	4.22E-07	8.81E-04
A4	1.44E-08	8.79E+00	1.27E-02	1.38E-03	6.75E-01	1.24E-09	8.12E-04
A5	6.60E-05	4.05E+00	4.82E-04	2.00E-04	5.01E-01	1.06E-08	5.32E-05
B2	2.19E-07	1.32E+00	9.12E-04	1.57E-04	1.52E-01	5.36E-08	2.64E-04
C1	0	0	0	0	0	0	0
C2	4.23E-09	2.45E+00	9.11E-04	1.84E-04	1.79E-01	3.63E-10	1.01E-04
C3	0	0	0	0	0	0	0
C4	9.93E-10	1.13E+00	5.79E-04	8.50E-05	1.56E-01	1.38E-09	1.02E-04
D	2.37E-08	-1.70E+00	-1.24E-04	-3.87E-05	-1.78E-01	-1.72E-08	-1.61E-05

NOTE:
Eq.: Equivalent

Table 14 Main relative contributions (in %) of the inputs/outputs in the FU of PST AAA to the environmental impact categories studied

Module life cycle	Input/output	ADP-elements	ADP-fossil	AP	EP	GWP	ODP	POCP
A1	Body raw materials		14.4	9.2	8.1	12.5	25.8	15.0
	Glazes (from cradle to gate)	59.6	6.1	16.8	23.2	6.8	6.2	14.2
A3 Granulate manufacture	Electricity sold to the grid		-28.3	-19.0	-9.0	-28.1	<-1.0	-25.8
	Electricity bought from the grid		6.3	6.0	3.0	6.7	23.3	6.7
	Thermal energy from natural gas		32.3	7.6	9.3	31.1	<1.0	11.8
A3 PST manufacture	Thermal energy from natural gas		44.7	10.5	12.6	43.1		16.3
	Electricity bought from the grid		10.0	9.3	4.7	10.5	36.5	7.5
	Emissions from raw materials decomposition			12.8	2.6	1.1		4.6
A2	Transport			12.0	11.6	2.9	<1.0	10.0
A4	Transport		6.4	28.4	23.2	6.2	<1.0	22.5
A5	Adhesive	40.0						
B2	Detergent						7.1	6.3
D	Benefits and loads beyond the product system boundary						-2.5	
Rest of processes			≤3.0	<2.5	≤3.5	<3.0	<2.0	<3.0