Life cycle assessment and life cycle costing of sanitary ware manufacturing: a case study in China

Jingxiang LV [a,b], Fu GU [c,d] *, Wujie ZHANG [c,d], Jianfeng GUO [e,f]

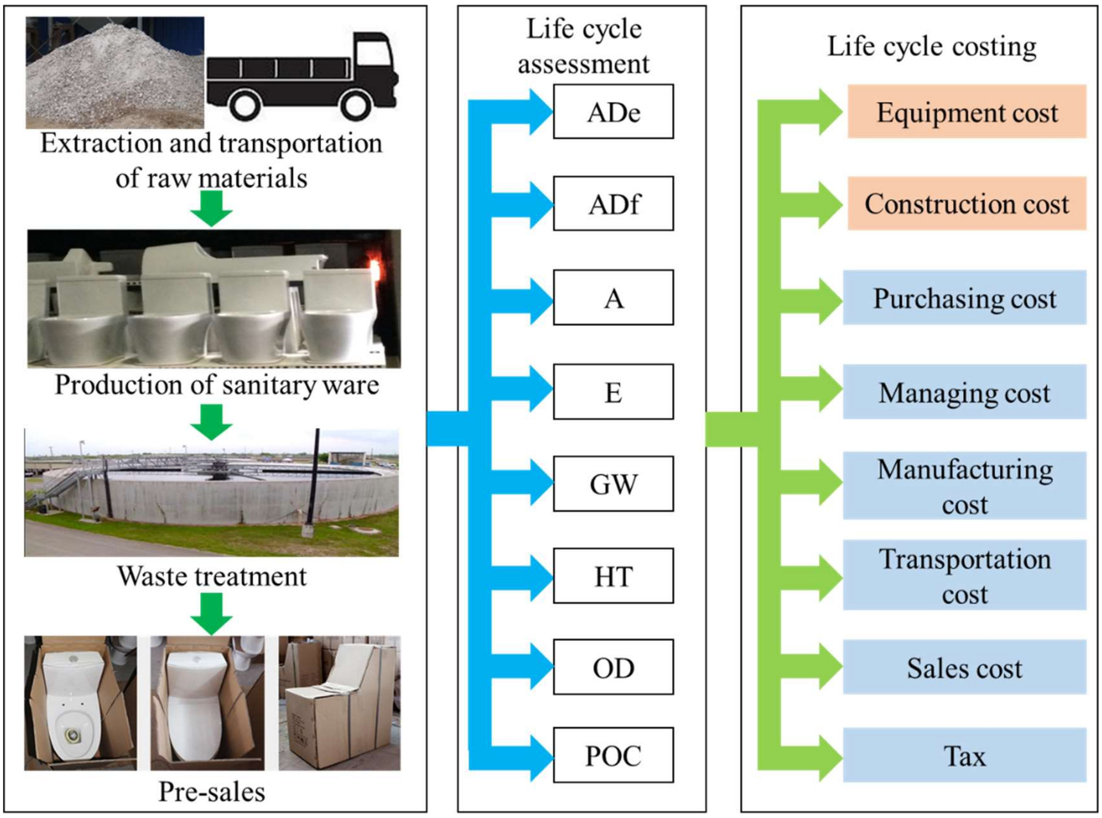
[a] *Key Laboratory of Road Construction Technology and Equipment, Ministry of Education, School of Construction Machinery, Chang'an University, Xi'an 710064, Shaanxi, China.*
[b] *Institute of Energy, School of Engineering, Cardiff University, Cardiff CF24 3AA, United Kingdom.*
[c] *Department of Industrial and System Engineering, Zhejiang University, Hangzhou 310027, China.*
[d] *National Institute of Innovation Management, Zhejiang University, Hangzhou 310027, China.*
[e] *Institutes of Science and Development, Chinese Academy of Sciences, Beijing 100190, China.*
[f] *School of Public Policy and Management, University of Chinese Academy of Sciences, Beijing 100049, China.*

Abstract

Sanitary ware industry consumes vast amounts of energy and materials; however, little is known about the environmental impacts and economic costs associated with the production of sanitary ware. Selecting a factory of a leading Chinese sanitary ware company, Huida Co. Ltd., this paper employs a combined "cradle-to-gate" life cycle assessment (LCA) and life cycle costing (LCC) methodology to evaluate the environmental impacts and economic costs related to the production of one tonne of sanitary ware. The LCA results indicate firing and drying are the processes with the greatest environmental impacts, attributing to the combustion of coke oven gas. The LCC results show that casting, body preparation and firing are the greatest contributors to the total equipment, material and energy costs, respectively. The results of sensitivity analysis confirm that increasing fuel efficiency, natural gas usage and recycling rates can reduce the overall environmental impacts, but the total costs would be increased by 13.8% if coke oven gas is fully replaced by natural gas, even considering carbon tax. Based on the findings, recommendations such as using green materials and improving energy efficiency, are provided to promote both the environmental and economic sustainability of sanitary ware production.

* **Corresponding to**: Dr. Fu GU, Zhejiang University, gufu@zju.edu.cn.

Graphical abstract



Keywords

Ceramic industry; LCA; LCC; Material flow analysis; Material efficiency

1. Introduction

The sanitary ware industry plays an important role in sustaining human well-being and economy growth, and its global market is expected to reach 59.17 billion USD by 2022 with a compound annual growth rate (CAGR) of 7.8% (Research and Markets, 2018). According to Grand View Research (2019), the market value of the sanitary ware industry is comparable to that of the ceramic tile industry (56.21 billion USD by the end of 2018). Meanwhile, the sanitary ware industry is a highly energy- and material-intensive sector, releasing a great amount of emissions to the environment (EC, 2007). Rigorous legislations on carbon emission reduction (Guo et al., 2018a; Wang et al., 2019) and increasing energy costs (Zhang et al., 2018) pose a serious threat to the sustainability of all ceramic sectors including the sanitary ware industry. Thus, it is urgent to improve the understanding of the environmental impacts and economic costs that are associated with the production of sanitary ware.

Extensive studies have been carried out on examining the relevant environmental impacts of ceramic products, including the life cycle environmental impacts and/or emissions of ceramic tiles (Bovea et al., 2010; Ibáñez-Forés et al., 2011; Ibáñez-Forés et al., 2013; Almeida et al., 2016) or other closely-related products such as ceramic bricks (Souza et al., 2015; Souza et al., 2016), ceramic tableware (Chuenwong et al., 2017) and red clay (Bovea et al., 2007), and adoption of innovations in manufacturing ceramic tiles (Ros-Dosdá et al., 2018; Vieira et al., 2016). In particular, life cycle assessment (LCA) has widely been applied on ceramic tile production, with the goal to identify the processes or components with great environmental impacts (Bovea et al., 2010; Ibáñez-Forés et al., 2013; Almeida et al., 2016), or to compare ceramic tile with other construction materials (Souza et al., 2015; Souza et al., 2016). However, when it comes to the environmental impacts of the sanitary ware industry, an industrial sector with the market size comparable to the ceramic tile industry (Grand View Research, 2019), only few articles can be found. Cuviella-Suárez et al. (2018) propose a model to manage the energy and water consumption in sanitary ware production, yet other environmental impacts such as human toxicity have not yet been included. Similarly, limited attention has been paid on analysing the costs related to these ceramic products; only Ye et al. (2018) estimated the costs of ceramic tile production. Detailed cost breakdown (calculating equipment cost, material cost and energy cost for each process) is absent in the extant literature.

A brief literature review suggests that there exist two major research gaps. Firstly, to the best of our knowledge, no attention has been paid on identifying the environmental impacts of sanitary ware production, as most articles focus only on ceramic tiles. Considering the huge market (Research and Markets, 2018), intensive energy and material consumption of the sanitary ware industry (Cerame-Unie, 2016; Cuviella-Suárez et al., 2018), and the rigorous environmental legislations such as carbon tax (Liu and Lu, 2015) or carbon markets (Guo et al., 2018b; Wang et al., 2019), the environmental impacts and economic costs of sanitary ware production are severely under-examined. Secondly, joint analysis of LCA and LCC has seldomly been applied on the sanitary ware production. Usually, LCA or LCC is applied separately (Ye et al., 2018), while only few studies employed integrated LCA and LCC methodology. Most works simply used LCC to calculate the total cost rather than the cost of each process (Geng et al., 2017; Zhang et al., 2018a), thereby losing the opportunities to improve economic sustainability at process-level.

To address the knowledge gaps, this paper employs a combined LCA and LCC methodology to assess the environmental impacts and economic costs of sanitary ware production. Typically, LCA is used to identify the environmental impacts in different life cycle stages of a product based on International Standardization Organization (ISO) 14040 (ISO, 2006a) and ISO 14044 standards (ISO, 2006b), and LCC focuses on determining all costs occurred during life cycle stages of a product (Zhang et al., 2018a). A factory of a leading Chinese sanitary ware manufacturer, Huida Group Co. Ltd., is selected as the case study. Huida is a public company listed on Shanghai Stock Exchange (Stock Code: 603385), and achieved 1.37 billion CNY sales revenue with 141,024 tonnes of sanitary ware products in 2017. The factory is in Tangshan, Hebei Province, China. As "ceramic capital of northern China", Tangshan is in urgent need of green economic transformation (Tangshan Municipal Government, 2018). Material flow analysis (MFA) is performed based on the data provided by the operation managers. The CML2001 method evaluates the environmental impacts, and the traditional LCC estimates the total cost associated with the production of one tonne sanitary ware, as well as the costs of each process. Sensitivity analysis is conducted to investigate the variations of LCA and LCC results caused by changes of fuel inputs and waste recycling. Further, recommendations to reduce the environmental impacts and economic costs are proposed.

2. Methodology

In this study, the LCA method follows the ISO 14040 standard (ISO, 2006a), as four major stages are included, namely, goal and scope definition, inventory analysis, impact assessment, and final interpretation. The analysis is carried out with the support of the GaBi Professional Academy (version 8.6.0) software; the choice of LCA software is influenced by our previous research (Gu et al., 2017; Gu et al., 2019), as this tool is applicable to model industrialized processes. The LCC method follows the ISO 15686 standard (ISO, 2008), in which the total cost and the cost of each process are identified, and both capital investment and operational expenditure are included.

2.1. Goal and scope

The primary goal of the combined LCA and LCC methodology includes:
(1) To evaluate the environmental impacts and economic costs that are associated with the production of one tonne of sanitary ware.
(2) To identify the processes and/or materials with high environmental burdens and economic costs.
(3) To provide potentially feasible measures to support sustainable development of the selected factory.

The product categories of sanitary ware are highly diversified, as typical products include bidets, pedestals, sinks, showers, tanks, flush toilets and wash basins. According to the production managers of the plant, the weights of these products range from 7.6 kg to 39.5 kg per piece. Due to the data availability and the great product variety, the functional unit (FU) is defined as one tonne of sanitary ware produced by the studied factory.

According to the ISO 14040 standard (ISO, 2006a), the study scope should include the system boundary and the defined level of detail. To achieve the defined objective of evaluating the environmental impacts of sanitary ware production, the "cradle-to-gate" strategy is adopted; the system boundaries include the life cycle stages of one FU of sanitary ware that are prior to delivery. Studying the life cycle stages after delivery is deviated from our primary objective because this paper aims to promote the sustainability of sanitary ware production. According to Cuviella-Suárez et al., (2018), the energy and water consumption of sanitary ware mainly occur in its production phase. Besides, the great product variety leads to great difficulty in data acquisition and modelling of the use and disposal processes.

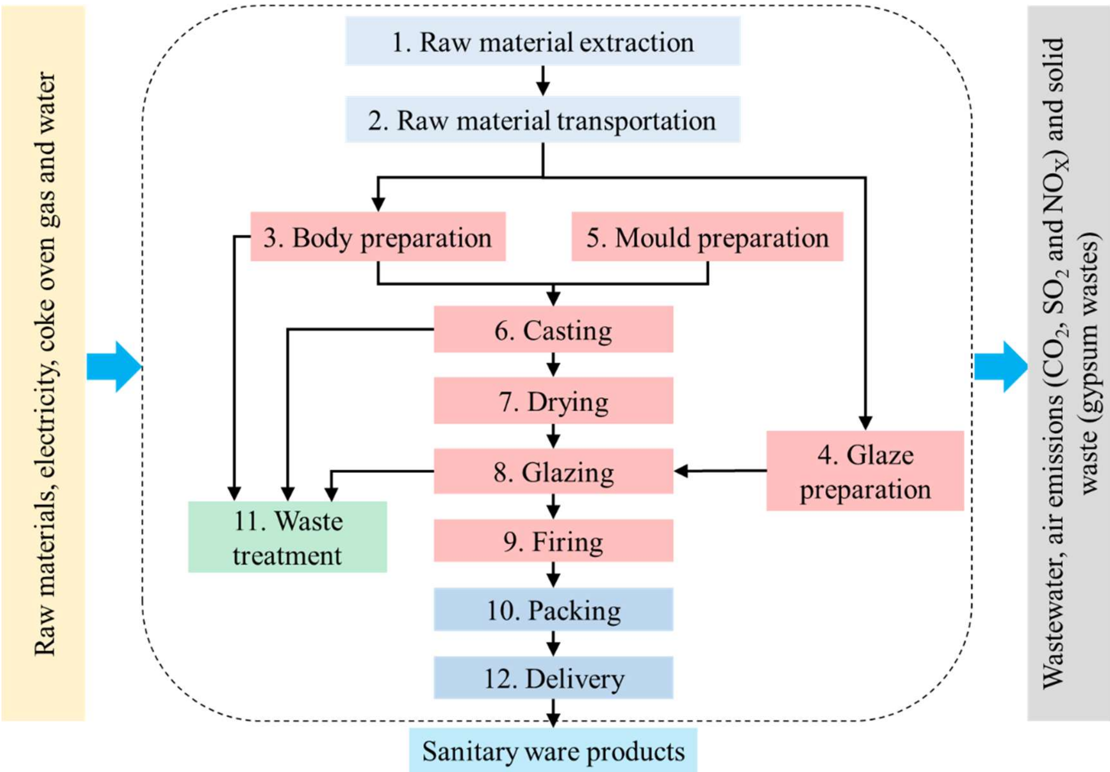


Fig. 1. System boundary of one FU (1 tonne) of sanitary ware production.

The system boundary of the production of one FU of sanitary ware is shown in Fig. 1, and the included life cycle processes are described as follows:
(1) **Raw material extraction**, raw materials are extracted from the earth via mining.
(2) **Raw material transportation**, raw materials are then transported to the plant using big trucks.
(3) **Body preparation**, slurry for body is prepared by grinding the raw materials with water in ball mills.
(4) **Glaze preparation**, glaze is also prepared by wet grinding.
(5) **Mould preparation**, mould is made from Plaster of Paris.
(6) **Casting**, the slurry is poured into the mould to form sanitary ware body.
(7) **Drying**, the casted body is dried using hot air flow.
(8) **Glazing**, the glaze is sprayed onto the dried sanitary ware body.
(9) **Firing**, the sanitary ware is then sent to kiln for firing at a high temperature.
(10) **Packing**, the sanitary ware is packed and stored in warehouse.

(11) **Waste treatment**, wastewater, solid wastes and air pollutants (i.e., CO_2, SO_2 and NO_X) from the production processes are treated, and part of the wastewater and solid wastes are recycled and reused.
(12) **Delivery**, the products are distributed to domestic and overseas markets.
Notably, the system boundary is applicable for both LCA and LCC, and detailed data is elaborated in the next subsection.

The major difference between sanitary ware production and ceramic tile production lies in the processes in body formation: slip casting is used to form the body of sanitary ware, while the body of ceramic tiles is prepared by dry pressing. Moreover, the plaster mould is manufactured for slip casting of sanitary ware, while in ceramic tile production, free-flowing powder for dry pressing is prepared by atomization.

2.2. Inventory analysis

In this study, both primary and secondary data are used. The primary data is provided by the operation managers of the studied plant; the data refers to the average values of all the operational data in 2017, most of which is directly acquired from the plant's management information systems such as enterprise resource planning (ERP). Interviews with the operation managers are used as supplements. Average amounts of energy, coke oven gas and water that are consumed in the production of one FU of sanitary ware products are shown in Table S1 in the Supporting Information (SI). The secondary data refers to life cycle inventory (LCI) datasets of Gabi and Eco-Invent (EI) version 3.4.

(a) Extraction and transportation of raw materials (life cycle stage 1 and 2)

The raw materials are acquired from various suppliers, and the locations of the suppliers and the distances between the suppliers and the plant are shown in Table S2 in SI, as well as the amounts of raw materials used in producing one FU sanitary ware. Datasets and assumptions for the modelling of the extraction and transportation of raw materials are shown in Table S3 and S4 in SI. The Gabi dataset "*CN Transport, truck-trailer (40 t total cap., 24.7t payload)*" is used to calculate the environmental impacts of raw material transportation.

(b) Production of sanitary ware (life cycle stage 3 to 9)

Information of the raw material consumptions for preparing bodies and glazes used in the production of one FU of the sanitary ware products is shown in Table S5 in SI. Raw materials for the bodies and glazes are ground with water in ball mills to form slurry and glaze, and iron contents in slurry and coarse particles in glaze are removed. The glazes are further mixed to diminish bubbles during firing (Li *et al.*, 2014).

In the mould preparation process, the moulds are produced by casting by mixing water with plaster of Paris. 154.2 kg of plaster of Paris is required to produce one FU of the sanitary ware products. The ratio of plaster to water is kept at 4:3. The moulds are dried and hardened through a drying process, which consumes electricity and coke oven gas. There are 192.1 kg moulds for manufacturing one FU of the sanitary ware products. The means of transportation is assumed to be heavy-load trucks, described by the Gabi dataset "*CN Transport, truck-trailer (40 t total cap., 24.7t payload)*", and the average distances are assumed to be 200 km.

In the casting process, the mixed slurry is poured into the moulds to form the bodies of products. Water is used to keep the insides of the moulds wet. Once the bodies are shaped, the so-called "green ware" dry in the ambient condition for several days. Later, a drying process is employed to further remove moisture contents with continuous feeding of hot air for 10 h. The drying temperature is retained at 110 to 120 °C, and the resulting moisture contents are restricted below 1.5 wt.%. The fuel is coke oven gas, which is generated from coal and has a calorific value of 17.0 MJ m^{-3}.

In the glazing process, glazes are sprayed in the dry ware bodies. Later, the sprayed ware is fed into kilns by conveyers, and are then baked in a long firing cycle ranging from 10 to 17 h. In the firing process, chemo-physical reactions are occurred to make the bodies and the glazes fused. The coke oven gas is used in the firing process. Data and assumptions for the modelling of the primary materials, energy and manufacturing processes are shown in Table S3 and S6 in SI.

Besides, the Gabi dataset "*CN: Storage*" is used to present the potential environmental impacts of storage, and the dataset has no environmental impacts.

(c) Pre-sales (life cycle stage 10 and 12)

After the firing process, all the products are transported to the packing area, where they are visually inspected. The products with minor defects such as pin holes are repaired or sent to a re-fire section. If serious defects such as crack are found, the defective products are rejected and can be recycled as raw materials of sanitary ware or ceramic tiles. Qualified products are packed with cardboard boxes and straps. The packing process is labour-intensive. Lighting and heating are used, and electricity and coke oven gas are consumed.

The packed sanitary ware products are distributed to domestic markets (69.12%) and oversea markets (30.88%) (Huida, 2018) (see Table S7 and S8 in SI). Based on the annual report, the average transportation distances are calculated to be 978.6 km (domestic markets) and 10,622 km (oversea markets), respectively. The Gabi dataset "*CN Transport, truck-trailer (40 t total cap., 24.7t payload)*" is used in the calculation of the potential environmental impacts related to the domestic transportation, while the Gabi dataset "*EU28: Bulk carrier ocean incl. fuel, 100,000-200,000 dwt, ocean going*" is employed for the oversea transportation. Data and assumptions for the modelling of the pre-sales processes is shown in Table S9 in SI.

(d) Waste treatment (life cycle stage 11)

With dissolved minerals removed, most of wastewater is reclaimed and reused in the production, and the rest effluent is discharged into municipal sewage. The solids from the wastewater are recycled to produce new sanitary ware products. It is a common measure to dispose wastewater from sanitary ware production (Cuviella-Suárez et al., 2018).

The solid wastes mainly include unqualified sanitary ware, sediment glazes and gypsum wastes produced during the production process. The unqualified ware is recycled to produce raw materials for producing ceramic tiles, the precipitated glaze is recovered for glaze production, and the waste gypsums are sold to cement factories to replace virgin gypsum as cement retarder.

The air pollutants include dusts generated in the material warehouse, exhaust gases generated by combustion of coke oven gas in the hot air furnaces, kilns and boilers. Dusts in the material warehouse is contained by sprinkling water and covering the raw materials. H_2S and soot in the exhaust gases from combustion are monitored and treated by a water-bath-based collector; only the exhaust gases that reach the emission standards will be discharged. Data and assumptions that model the waste treatment are shown in Table S10 in SI.

2.3. Impact assessment

The CML2001 method, a method has been widely used to quantify the environmental burdens of ceramic products, such as ceramic tiles (Bovea et al., 2010; Ibáñez-Forés et al., 2013; Ros-Dosdá et al., 2018), ceramic bricks (Almeida et al., 2015; Garcia-Ceballos et al., 2018) and ceramic facade materials (Han et al., 2015), is selected to assess the environmental impacts of the sanitary ware production. Based on reviewing the related literature, the following characterization factors are included to evaluate the potential environmental impacts: abiotic depletion elements (ADe), abiotic depletion fossil (ADf), acidification (A), eutrophication (E), global warming (GW), human toxicity (HT), ozone-layer depletion (OD) and photochemical ozone creation (POC). It worth mentioning that particulate formulation is not included, because the plant has installed dust removal system to collect the particles in the air, and the collected particles are sent to production. No weighting of indicators nor normalisation is performed, as the CML2001 method is not applicable for weighting and aggregation of scores (Dreyer et al., 2003).

2.4. Life cycle costing

In this study, LCC and LCA share the same system boundary, see Fig. 1. The traditional LCC is adopted, and its structure is shown in Fig. 2. Two types of costs are included, namely capital investment and operational expenditure (Auer et al., 2017): the former category includes equipment and construction costs; the latter one contains purchasing and manufacturing expenses, management costs, transportation and sales expenses, as well as taxes (Ye et al., 2018). Specifically, the purchasing expenses include the costs of raw materials and energy, and the manufacturing expense consists of the costs of labour and maintenance. Purchasing cost of each process is calculated based on the material and energy consumptions, as depicted in Table S11 in SI.

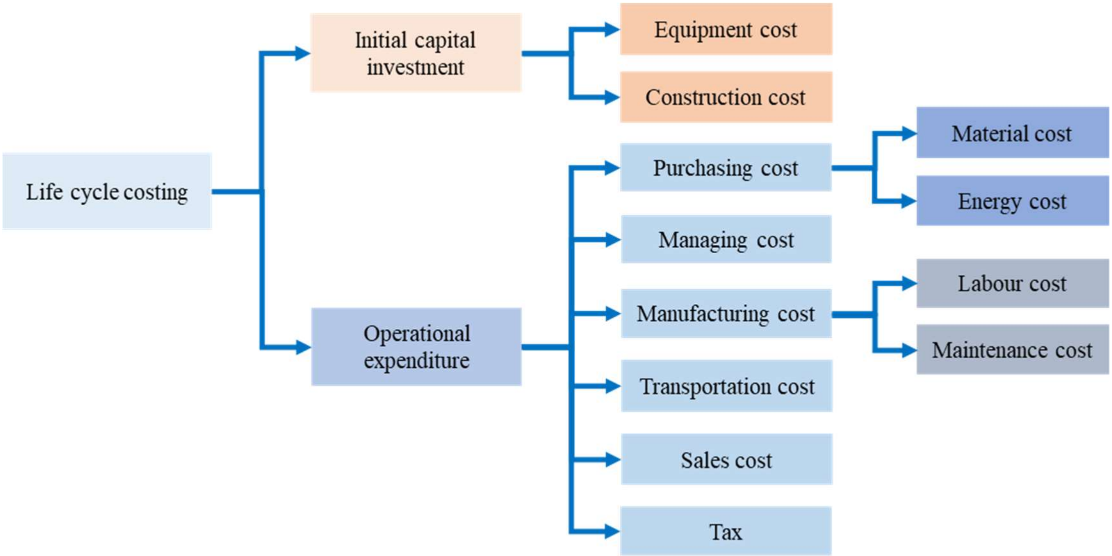


Fig. 2 The structure of LCC.

Depreciation of the initial capital investment is calculated using a compound interest method, which is a deceleerated depreciation method and widely used in engineering, shown as follows (Kim et al., 2016):

$$DC_{\mathrm{t}} = \left[PC_{\mathrm{A}} - \frac{RV_{\mathrm{A}}}{(1+r)^N}\right] \times \frac{r \cdot (1+r)^N}{(1+r)^N - 1} \tag{1}$$

where DC_t is the depreciation cost at year t, PC_A and RV_A are the original cost and residual value of tangible assets A, N is the durable period, r is the interest rate. the residual value is assumed to be 0.1% of the original cost (Kim et al., 2016). The lifespans of production equipment, construction and transportation equipment are set to 10, 20 and 5 years, respectively. Interest rate is assumed to be 3%, referring to that of China's one-year government bonds. Details of equipment costs of each process are shown in Table S12 and S13 in SI. The construction costs are evenly allocated to the processes other than raw material extraction, transportation and delivery.

2.5. Sensitivity analysis

Here our attention focuses on the drying and firing processes, which are highly energy- and material-intensive (Cuviella-Suárez et al., 2018). According to the LCA studies on ceramic tiles (Ibáñez-Forés et al., 2011; Ibáñez-Forés et al., 2013; Almeida et al., 2016), these stages are also associated with great emissions. Additionally, the recycling rates for scrapped ware and gypsums are considered. We denote the initial setting as ***Base Scenario***, and the sensitivity analysis is carried out to investigate the varied inputs of the following three aspects:

(1) Rates of fuel saved due to technology innovation or equipment renovation. i.e., more fuel is saved in alternative scenarios when compared to that of ***Base Scenario***.

(2) Rates of natural gas used to replace coke oven gas, i.e., instead of coke oven gas,

natural gas is used as fuel in alternative scenarios.
(3) Recycling rates for unqualified ware and gypsum wastes, i.e., raw materials are recovered from unqualified ware and gypsum wastes in alternative scenarios.

(a) Rates of fuel saved

Technological advances not only reduce emissions, but also save costs (Song and Wang, 2018), particularly in the ceramic industry (Mezquita et al., 2014; Milani et al., 2017; Cuviella-Suárez et al., 2019). In the past two decades, Huida Group Co. Ltd. has upgraded its facilities such as kilns and stoves to improve the energy efficiency. Measures to renovate the kilns and stoves include using thermal insulating materials, heat recovery and installation of air preheater. As a result, the amount of coke oven gas used to produce one tonne of sanitary ware has been reduced by 21.1% (from 973.91 m^3 in 2008 to 768.23 m^3 in 2017). Recently, over 50% of carbon emissions are reported to be reduced in a new plant in Ibstock, the UK's largest brick manufacturer (British Ceramic Confederation, 2017). The energy efficiency of the studied company is expected to further increase, as new technologies are continuously implemented. Therefore, we expect that the fuel usage will be reduced in the future and vary the rates of fuel saved to be 5, 10 and 15 vol.%, according to anticipated technological progress in Huida Group Co. Ltd.

(b) Rates of natural gas used

Using natural gas as an energy source is encouraged by the Chinese government (Wan *et al.*, 2016), because it is cleaner. The ceramic industry is in this energy transition, including Huida Group Co. Ltd. Here, according to the energy replacement scheme of the selected plant, we expect 40%, 70% and 100% of the required heat is generated by the combustion of natural gas, which has a calorific value of 34.3 MJ m^{-3} (Yang et al., 2016), while the rest is still supplied by the coke oven gas, which is generated from coal and has a calorific value of 17.0 MJ m^{-3}. Then the environmental impacts and economic costs are analysed regarding the different usage rates of natural gas.

(c) Recycling rates for waste ware and waste gypsum

As illustrated previously, the sanitary ware with minor defects is repaired by cold fill or sent to the re-firing section, while the ware with major defects is rejected. Waste gypsums are mainly generated from the casting process of sanitary ware production. Rejected sanitary ware can be grounded as raw materials of slurry, and gypsum wastes can be used as cement retarder to replace virgin gypsum. Recycling is encouraged by the management of Huida Group Co. Ltd, with recycling goals set. Here, according to the designated objectives of the company, we expect 40%, 70% and 100% of the unqualified ware or gypsum wastes are recovered as secondary materials, while the rest is sent to landfill. The transportation distance for gypsum recycling is assumed to be 100 km and the Gabi dataset "*CN Transport, truck-trailer (40 t total cap., 24.7t payload)*" is used to calculate the environmental impacts of this transportation. The electricity consumed in the crushing of rejected ware and gypsum wastes is assumed to be 14.55 and 15 kWh t^{-1}, respectively. The Gabi dataset "*CN Electricity grid mix*

3.6MJ” is used to model the environmental impacts of the crushing processes, and the Gabi dataset “*EU28 Municipal solid waste on landfill*” is employed to acquire the environmental impacts of landfill.

3. Results

3.1. Overall material and energy balance

The material and energy flows of manufacturing one FU of the sanitary ware products are calculated and depicted in Fig. 3, and the use of recycled (or reclaimed) materials are included. Firing (life cycle stage 9) is the greatest consumer of coke oven gas, followed by drying (life cycle stage 8). This observation confirms that these processes are the hotspots for energy management in sanitary ware production (Cuviella-Suárez et al., 2018). Massive electricity is used in casting (life cycle stage 6) and body preparation (life cycle stage 3), mainly attributed to the use of equipment that grinds, mixes and injects the raw materials, followed by firing and glazing due to the energy consumed by kilns and robotics. Casting (life cycle stage 6) consumes the largest amount of water, 35.8% of which is reclaimed water, followed by glaze and body preparation.

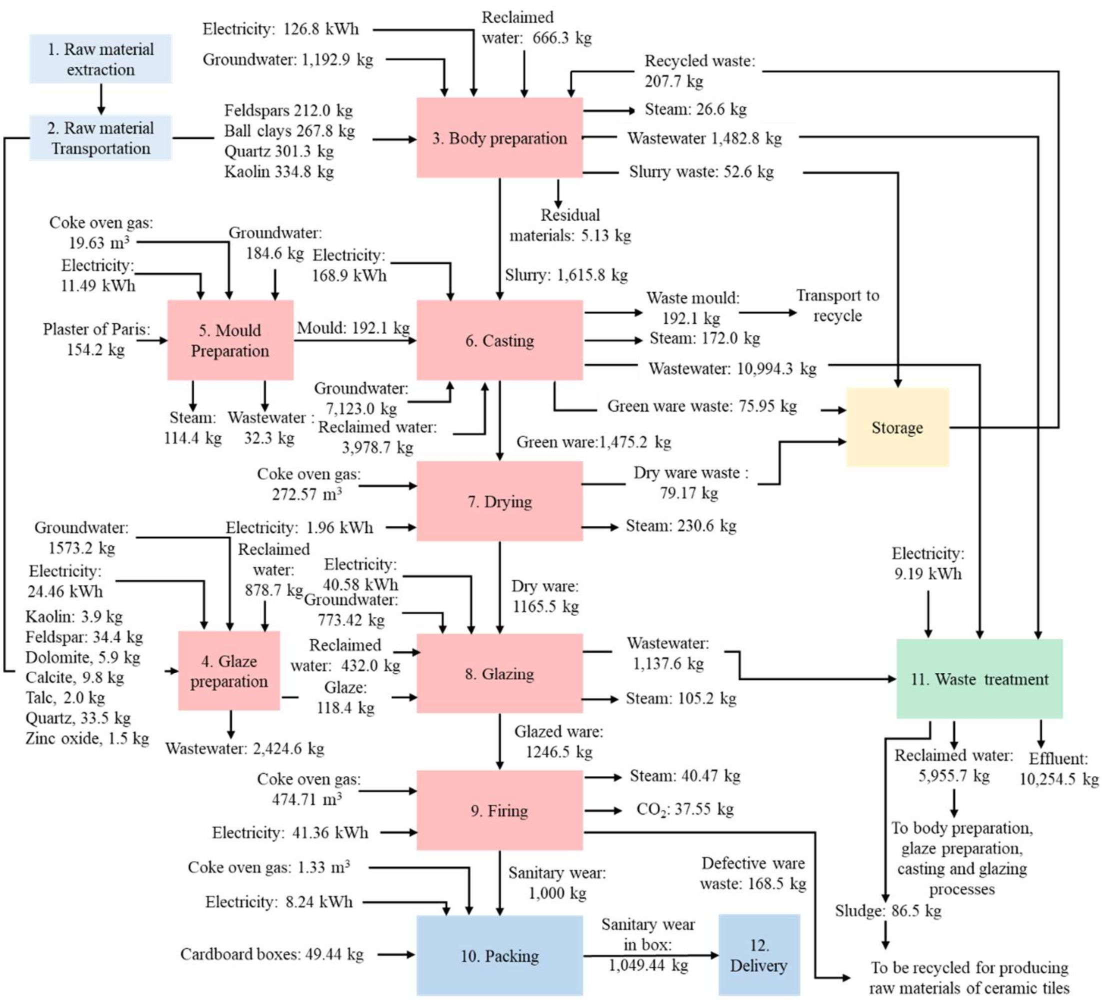


Fig. 3. Material and energy flows during the production of one FU of sanitary ware products.

Using the data of mass balance in Fig. 3, the material efficiency (ME), which is defined as the ratio of the output mass to the input mass (Shahbazi, 2015), of each production process is summarized in Table 1. Low ME (< 0.12) is observed in glaze preparation and casting, probably resulted from massive water consumption. Body preparation, mould preparation and glazing have medium ME values between 0.50 and 0.57, because the weights of their water consumptions are close to their outputs. Drying and firing have the highest ME values (around 0.80), as only vapour and defective items are removed during these processes.

Table 1. ME of processes in sanitary ware production.

Process	Body preparation	Glaze preparation	Mould preparation	Casting	Drying	Glazing	Firing
ME	0.5076	0.0465	0.5670	0.1143	0.7900	0.5008	0.8022

3.2. Overall environmental and economic performance

Table 2 presents the overall environmental impacts associated with the production of one FU sanitary ware. The total economic cost is estimated to be 3,823.4 CNY t^{-1}, including the construction cost, equipment cost, purchasing cost, managing cost, manufacturing cost, transportation cost, sales cost and taxes. The breakdown of life cycle costs for the production of 1 tonne of sanitary wares are shown in Fig. 4 and Table S14 in SI. The primary contributors that account for over 20% of the overall cost are the managing cost and sales cost. Materials and energy also account for 16.30% and 13.26% of the total cost, respectively, while the proportions of the equipment, construction, labour, maintenance, transport and tax costs to the total cost are less than 10%.

Table 2. LCA results of the production of one FU of sanitary ware products.

Category	Value	Unit of measurement (UoM)
ADe	2.70E+01	kg Sb eq
ADf	2.49E+04	MJ
A	5.09E+00	kg SO_2 eq
E	7.82E-01	kg Phosphate eq
GW	1.35E+03	kg CO_2 eq
HT	4.26E+02	kg DCB eq
OD	6.11E-06	kg R11 eq
POC	1.30E+00	kg Ethene eq

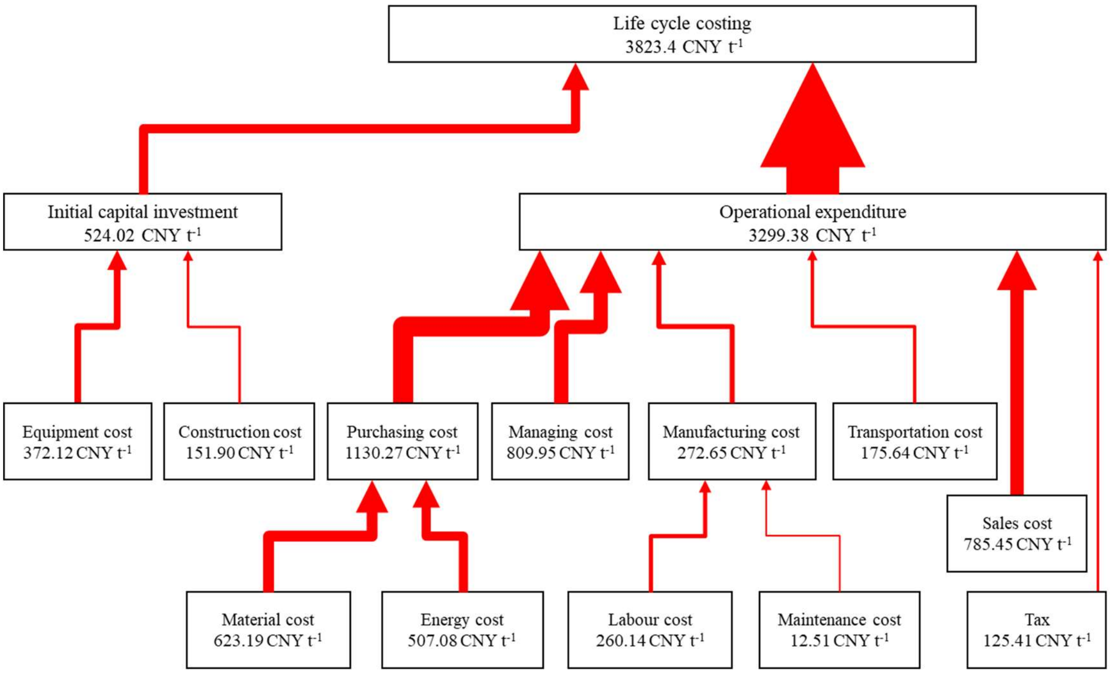


Fig. 4. LCC analysis results for contribution of each category.

3.3. Contributions of processes

A detailed contribution analysis, a method that is frequently used in the previous LCA studies (Gu et al., 2017; Gu et al., 2018; Zhao et al., 2018), is performed to identify the contributions of each involving process, as shown in Fig. 5. The equipment, construction, materials and energy costs of each process are calculated and shown in Table 3. The firing process makes the greatest contribution to all the selected impact categories, and accounts for 17.82% of the total equipment cost and 37.25% of the energy cost. The high environmental impacts and energy cost can be attributed to the use of coke oven gas.

Table 3. The equipment, construction and purchasing cost of each process [CNY t^{-1}].

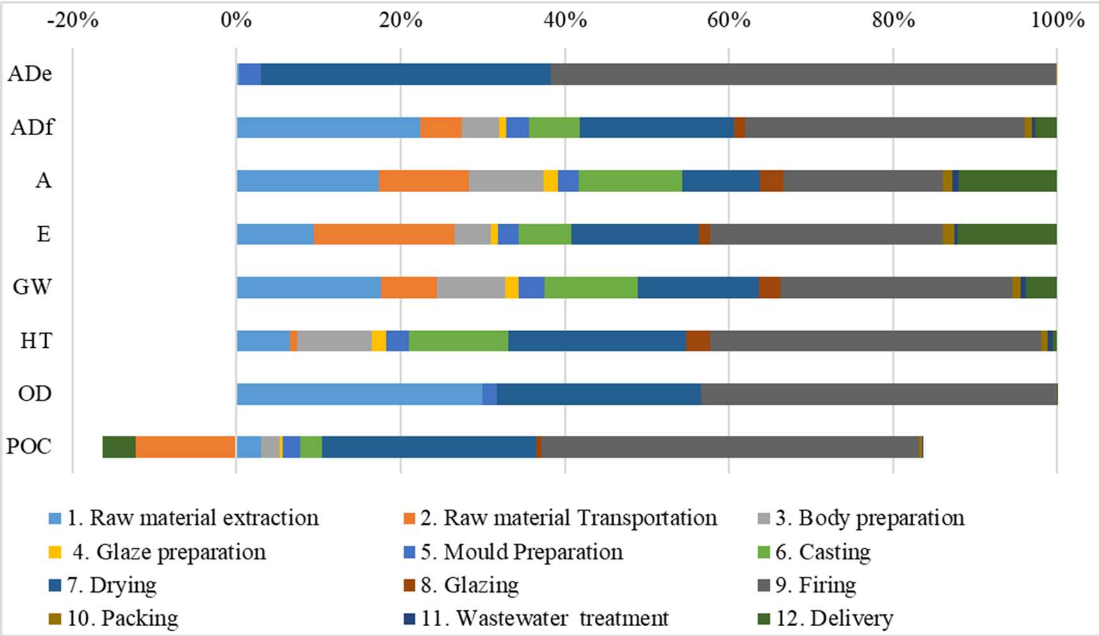
Process	Equipment cost	Construction cost	Material cost	Energy cost
1. Raw material extraction	0	0	0	0
2. Raw material transportation	11.14	0	0	0
3. Body preparation	18.49	16.88 [1]	381.43	69.74
4. Glaze preparation	5.57	16.88 [1]	40.21	13.45
5. Mould Preparation	13.88	16.88 [1]	78.17	13.19
6. Casting	132.10	16.88 [1]	10.54	92.92
7. Drying	37.93	16.88 [1]	0.00	96.48
8. Glazing	44.48	16.88 [1]	1.14	22.32
9. Firing	66.64	16.88 [1]	0.00	188.90
10. Packing	14.48	16.88 [1]	111.82	5.00
11. Wastewater treatment	13.50	16.88 [1]	0.00	5.05
12. Delivery	13.92	0	0	0
Total	372.12	151.90	623.31	507.05

1. Total construction cost is evenly allocated to processes.

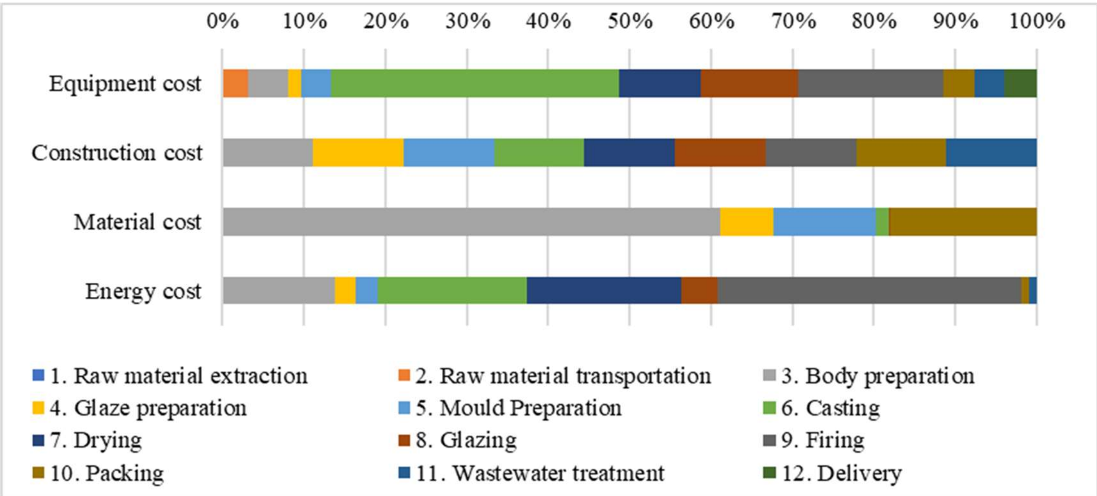
Drying is the second greatest contributor to the environmental impacts of ADe (35.3%), HT (21.6%) and POC (38.6%), and the process is the third most significant contributor to the environmental impacts of ADf (18.7%), E (15.5%), GW (14.7%) and OD (24.9%). From the economic perspective, drying accounts for 10.14% of the total equipment cost and 19.03% of the energy cost, due to the use of hot air oven and coke oven gas. Raw material extraction is the second greatest contributor to several categories such as ADf (22.4%), A (17.4%), GW (17.6%) and OD (29.9%), and is the third greatest contributor of POC (4.5%). A detailed contribution analysis of raw materials is carried out in the next subsection.

Casting is the third greatest contributor to the environmental impacts belong to A (12.5%) and HT (12.1%), and is taking the fourth place in the categorised impacts of ADf (6.2%) and GW (11.4%). According to the material and energy flows (see Fig. 3), the environmental impacts and energy cost of the casting process are largely determined by its high electricity and water consumptions. From the economic point of view, casting makes the highest contribution to the equipment cost (35.32%) due to expensive casting lines, and accounts for 18.33% of the energy cost. Body preparation is ranked as the fourth contributor to the environmental impacts of HT (9.0%) and POC (3.3%), owning to the huge amount of electricity consumed by ball mills. As for cost, it accounts for 61.19% of the material cost and 13.75% of the energy cost. The two processes involve with long-distance transportation, i.e., raw material transportation and delivery. These processes are mainly responsible for the environmental impacts of A, E and GW, due to the combustion of fossil fuels. The other processes contribute limited impacts to all the categories.

Glazing accounts for more than 10% of the total equipment cost, attributing to robotics used. Other processes, including raw material transportation, body preparation, glaze preparation, mould preparation, packing, wastewater treatment and delivery, together contribute to 24.82% of the equipment cost. The expenses of these processes consist of purchase costs of trucks, ball mills, testing equipment, wastewater treatment system and other jigs. For the material cost, packing, mould and glaze preparation are the second, third and fourth largest contributors for the procurement costs of cardboard boxes, plaster of Paris and glaze raw materials.



(a)

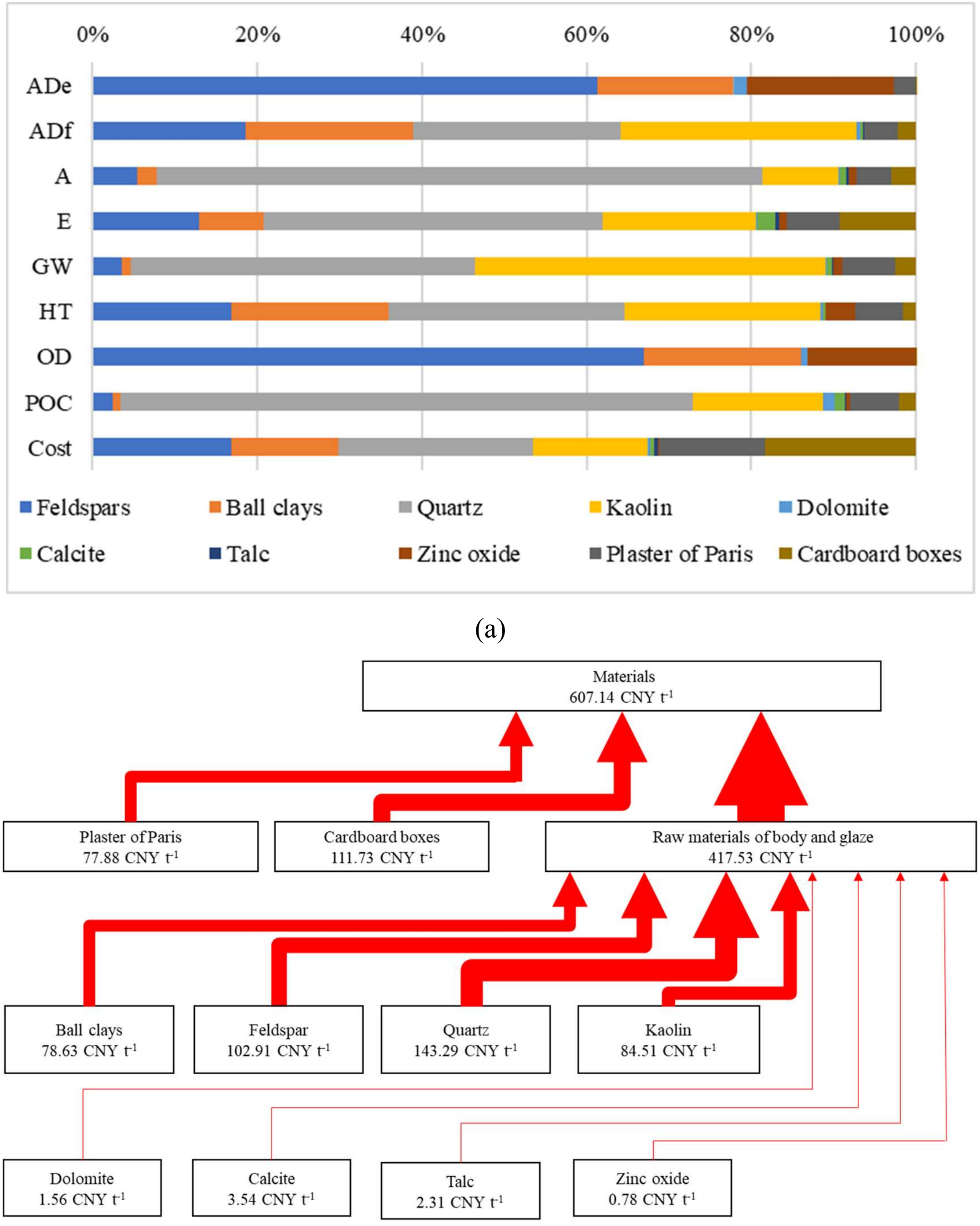


(b)

Fig. 5. Contribution of each process to the (a) environmental impacts and (b) the costs associated with the production of one FU sanitary ware products.

3.4. Contributions of materials

Fig. 6 shows the environmental impact and economic cost contribution of each raw material used to produce one FU of sanitary ware.



(b)

Fig. 6. Contribution of each type of material to (a) the environmental impacts and (b) the material costs in the production of one FU of sanitary ware products.

From Fig. 6 (a), the acquisition of quartz has the highest environmental impacts in the indicators of A, E, HT and POC, and exhibits the second greatest environmental impacts in the categories of ADf and GW. The quartz extraction also accounts for the largest proportion of total material cost (23.6%), due to the vast consumption of quartz. Similarly, due to the high consumption of feldspars, the extraction of the material dominates the environmental impacts of ADe and OD and accounts for 18.7% of the values of ADf, 12.9% of the values of E, 16.9% of the values of HT and 17.0% of the total material cost. The extraction of ball clays has the second highest environmental impacts on OD and the third highest environmental impacts in the indicators of ADe, ADf and HT, as well as accounts for 13.0% of the total material cost.

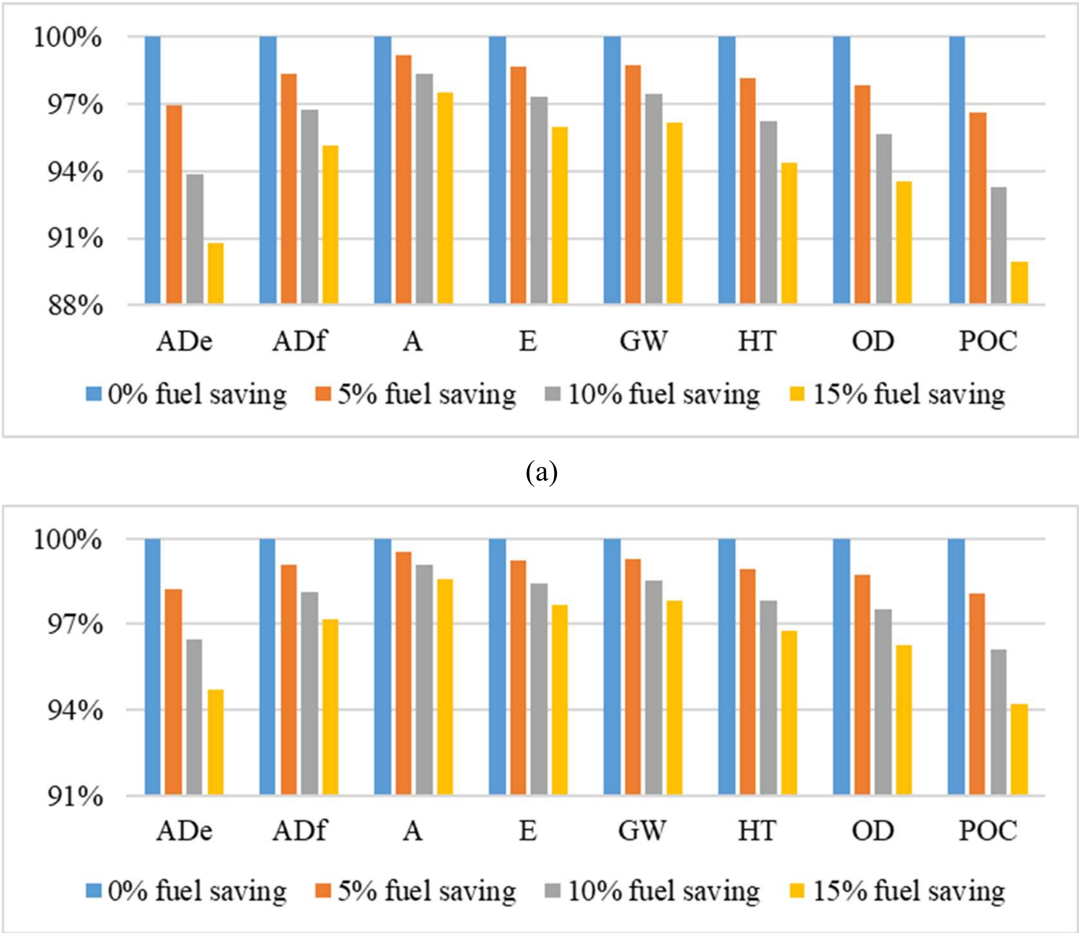
Kaolin is the most significant contributor to the environmental impacts of ADf (30.5%) and GW (46.8%). Moreover, the material is also responsible for the second largest proportion of the environmental impacts of A (9.8%), E (22.0%), HT (25.8%) and POC (17.0%) and accounts for 13.9% of the total material cost. This could be attributed to the large amount of kaolin used and the high energy consumed by the equipment and treatments involved in the extraction of kaolin (Almeida et al., 2016).

The plaster of Paris and cardboard boxes lead to 12.8% and 18.4% of the total material cost, while their environmental burdens are relatively low (their contributions to all the impact categories are lower than 10%). The remaining materials, including dolomite, calcite, talc and zinc oxide, have much smaller contributions to all the selected impact categories as well as to the material costs. There is only one exception: the zinc oxide production has a significant contribution of 18.4% to the impacts of ADe. This indicates that the ADe value for extraction of one kg of zinc oxide is higher than that of other materials, possibly resulting from limited natural reserve of zinc (USGS, 2018).

3.5. Results of sensitivity analysis

(a) Effects of fuel saving rates

With varied fuel saving rates (5, 10 and 15 vol.%), the environmental impacts of firing and drying are assessed and compared to those of the base scenario (0 vol.%), as shown in Fig. 7. As it is evident from Fig. 7, the environmental impacts of both processes are negatively correlated to the fuel saving rates. In the firing process, when the consumption of the coke oven gas is reduced by 5 vol.%, the environmental burdens are decreased by around 3% for the indicators of ADe and POC. For the indicators of ADf, A, E, GW, HT and OD, their scores are roughly decreased by 1-2%. In other words, the use of coke oven gas leads to depletion of non-renewable natural sources and formation of photochemical emissions. In the drying process, a similar pattern is observed: when the consumption of the coke oven gas is saved by 5 vol.%, the environmental impacts of ADe and POC are decreased by around 2%, and the environmental impacts of other categories including ADf, A, E, GW, HT and OD are reduced by 0.5-1.3%.



(b)

Fig. 7. The life cycle environmental impacts of one FU of the sanitary ware products with different fuel saving rates in (a) firing and (b) drying. The fuel saving rates varies from 0 vol.% (Base Scenario) to 15 vol.%.

(b) Effects of natural gas usages

Adopting the predetermined rates (40%, 70% and 100%) of heat generated by the combustion of natural gas, the potential life cycle environmental impacts and economic cost associated with the production of one FU sanitary ware are assessed and compared to those of the base scenario (no natural gas), as plotted in Fig. 8. In this calculation, carbon tax is assumed to be 100 CNY t^{-1}, according to Zhao et al. (2019). With the increasing use of natural gas, the environmental burdens of all indicators except for ADf are decreased. The most significant decrements in the environmental burdens are observed in the categories of ADe and POC; the decreases are up to 100%, when coke oven gas is completely replaced by natural gas. The values of the indicators of OD and HT are also significantly reduced, as around 70% and 50% savings are realised at using 100% of thermal energy from natural gas. The value of ADf is kept the same, because the same amount of thermal energy is required to be produced by either coke oven gas or natural gas. The environmental savings of the other impact categories are over 20%, provided that natural gas fully replaces coke oven gas in providing thermal energy. However, the cost is increased with the increasing usage of natural gas. If coke oven gas is fully replaced by natural gas, the fuel cost would be increased from 268.88 to 856.44 CNY to produce one FU of sanitary ware, and the carbon tax would be decreased from 133.97 to 90.47 CNY. When the carbon tax is considered, the total cost would be increased by 13.8%, from 3,957.37 to 4,501.42 CNY per FU.

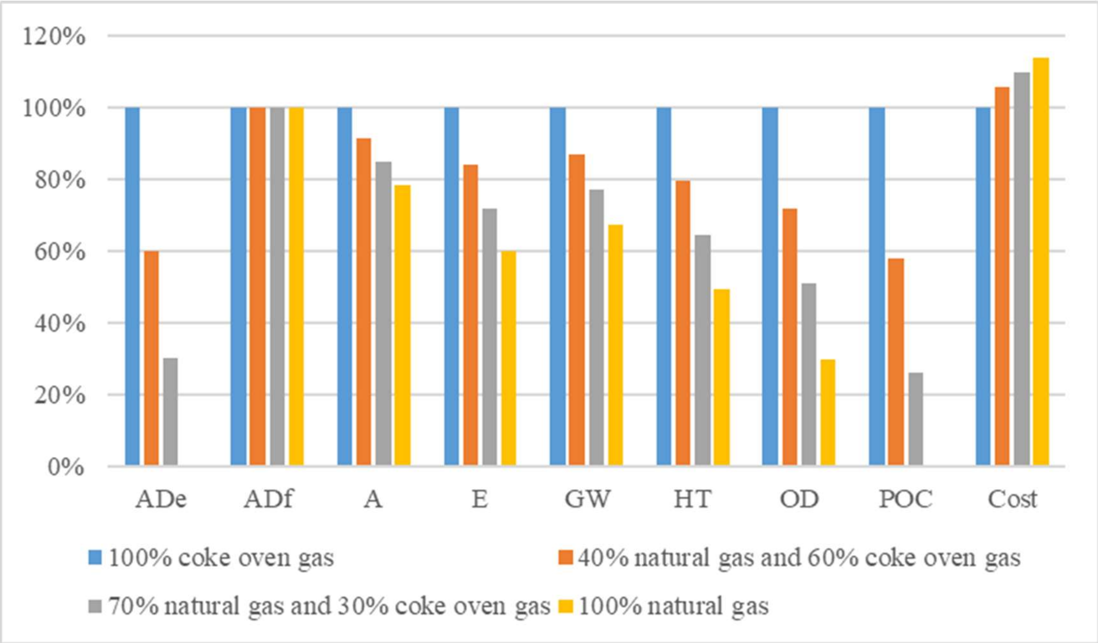
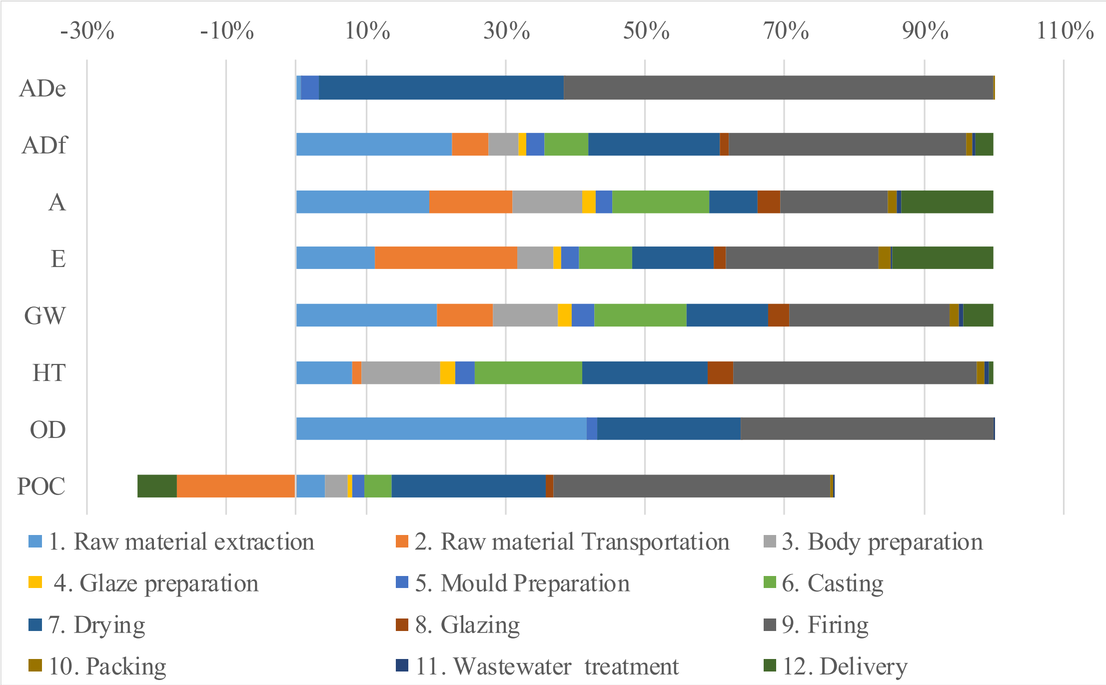


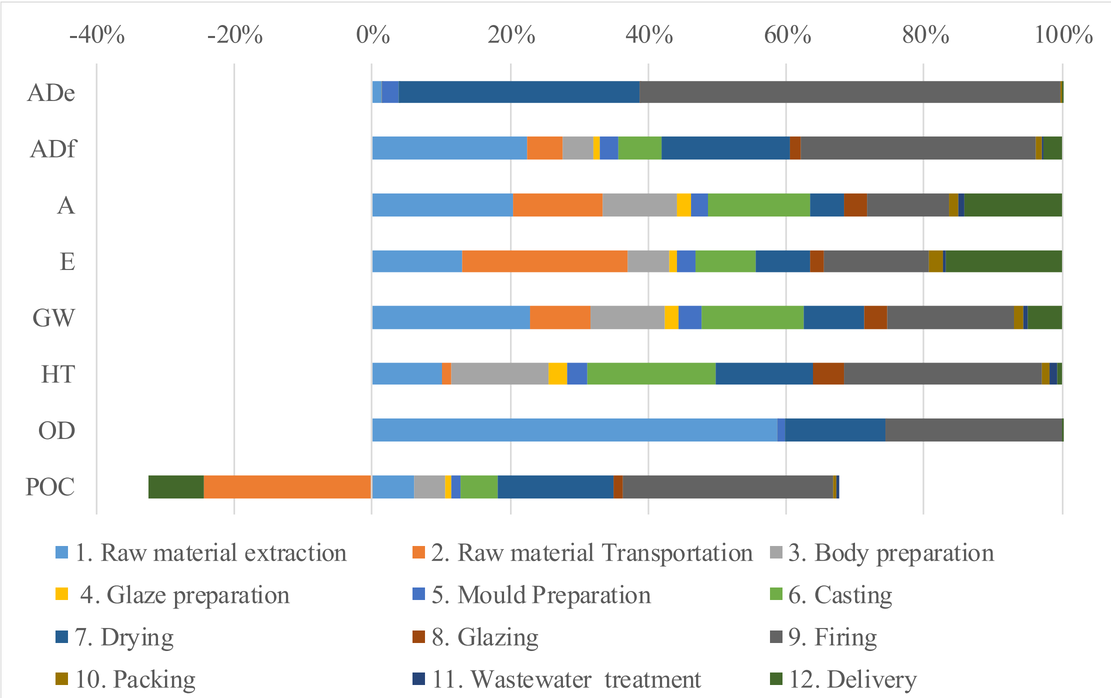
Fig. 8. Life cycle environmental impacts and economic cost associated with the production of one FU of sanitary ware products with different rates of natural gas usage.

Using different combinations of energy, the contribution of each process is shown in Fig. 9. Due to the increase use of natural gas, the potential environmental impacts of the firing and drying processes are reduced noticeably, especially in the values of the indicators of ADe and OD. Therefore, the environmental impacts of the sanitary ware production in the studied plant could be largely reduced by replacing coke oven gas with natural gas.



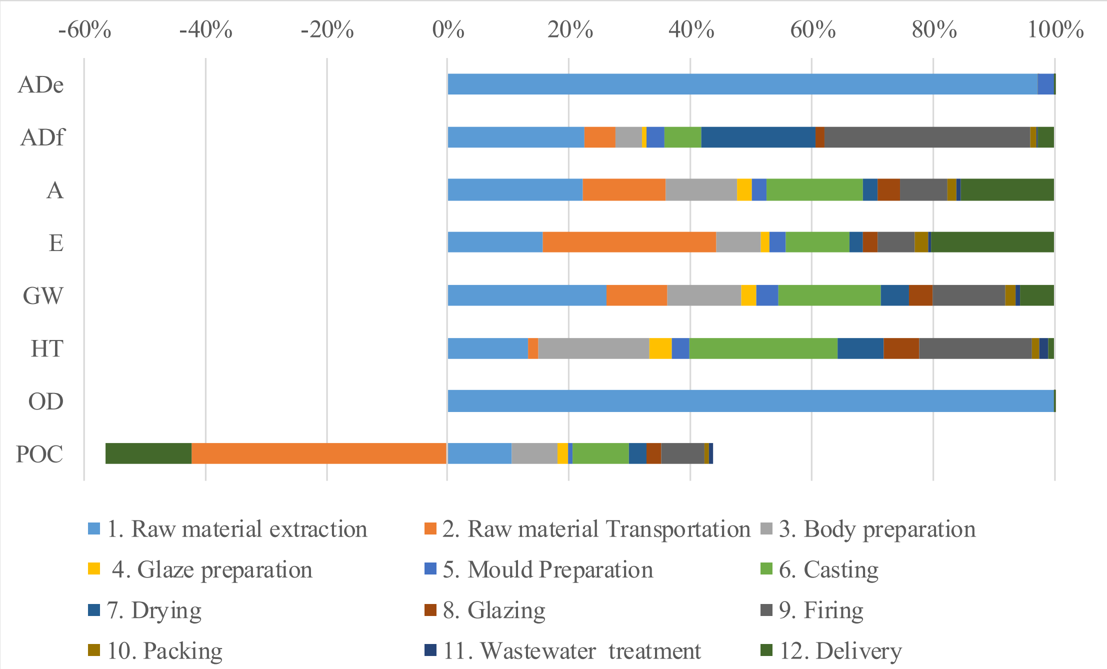
-30%
-10%
10%
30%
50%
70%
90%
110%
ADe
ADf
A
E
GW
HT
OD
POC
1. Raw material extraction
2. Raw material Transportation
3. Body preparation
4. Glaze preparation
5. Mould Preparation
6. Casting
7. Drying
8. Glazing
9. Firing
10. Packing
11. Wastewater treatment
12. Delivery

(a)



-40%
-20%
0%
20%
40%
60%
80%
100%
ADe
ADf
A
E
GW
HT
OD
POC
1. Raw material extraction
2. Raw material Transportation
3. Body preparation
4. Glaze preparation
5. Mould Preparation
6. Casting
7. Drying
8. Glazing
9. Firing
10. Packing
11. Wastewater treatment
12. Delivery

(b)



(c)

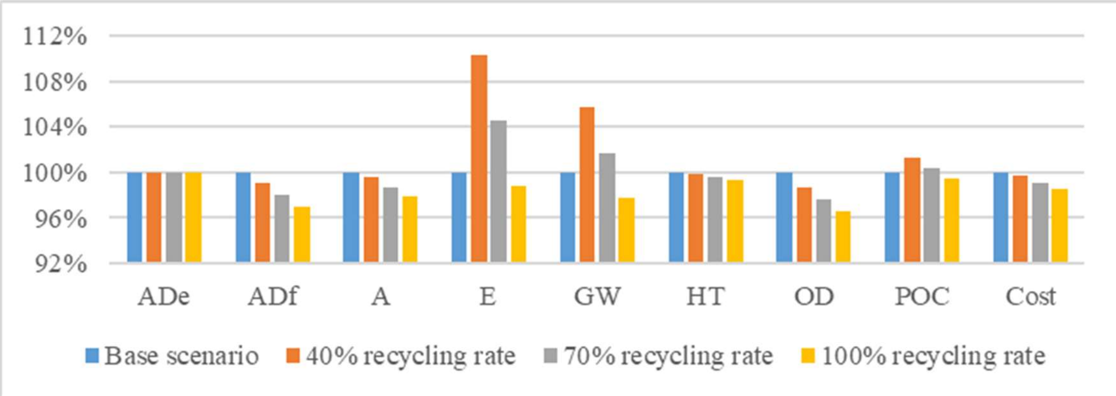
Fig. 9. Contribution of each process to the environmental impacts for producing one FU of sanitary ware products using different combinations of coke oven gas and natural gas. (a) 40% natural gas and 60% coke oven gas, (b) 70% natural gas and 30% coke oven gas and (c) 100% natural gas.

Fuel pellets from agroindustrial residues can be another possible candidate to substitute coke oven gas. Take wood pellets as an example, the environmental impacts of this resource for generating 1 MJ of heat are far lower than those of coke oven gas in all impact categories, and even lower than those of natural gas in most impact categories such as ADe, ADf, GW, HT and POC. In sanitary ware production, the fuel might be applicable for drying, as the required drying temperature is 110 to 120 °C. However, this fuel cannot be used for firing, because the temperature of firing needs to be 1,160 °C while the combustion temperature of wood pellets can only reach 700 °C (Cardozo et al., 2014).

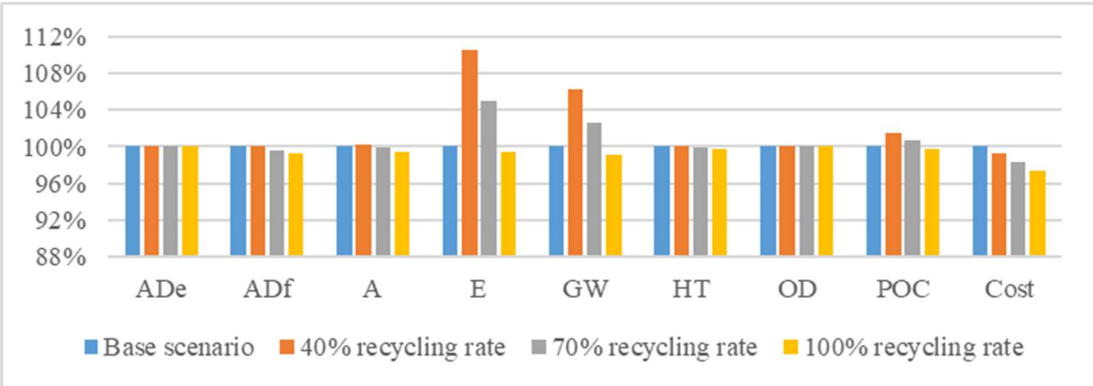
(c) Effects of recycling rates

With varied waste recycling rates (40%, 70% and 100%), the environmental impacts and economic costs of the sanitary ware production are assessed and compared to those of the base scenario, as shown in Fig. 10. The total environmental impacts are negatively correlated to both waste wares and gypsum recycling rates; with increasing recycling rates, the environmental burdens of all indicators decreased. When the recycling rate is increased from 40% to 70%, the most noticeable decrements are observed in the categories of E and GW, as around 6% and 4% of E and GW savings are realised. In this case, the environmental impacts of ADf, A, OD and POC are reduced by around 1%, while the environmental savings of the other impact categories are limited (0.00-0.39%). Provided that the recycling rate reaches 100%, the total costs would be reduced by 1.52% and 2.58%. Thus, waste recycling is proved to be able to bring great environmental and economic benefits.

When the recycling rates are 40% and 70%, the values of some indicators (E, GW and POC) exceed 100% compared to those of the base scenario. This is because the waste ware and gypsum are assumed to be landfilled instead of recycling, while in the base scenario, the waste ware and gypsum are not landfilled and their environmental impacts are not considered.



(a)



(b)

Fig. 10. The life cycle environmental impacts of one FU of the sanitary ware products with the different recycling rates of (a) waste sanitary ware and (b) waste gypsum. The waste recycling rates varies from 40% to 100%.

4. Discussion

4.1. Literature comparison

Here we compare the results of this work against the results from the previous LCA studies on ceramic tile production, with the objective to examine the similarities and differences in the environmental impacts of ceramic products. Production of sanitary ware and ceramic tiles shares some same processes, including raw material extraction and transportation, body preparation, glaze preparation, drying, glazing, firing, packing, delivery and wastewater treatment. Notably, there are some differences: the production of sanitary ware includes mould preparation and casting, while ceramic tile production involves atomization, pressing and subsequent treatments such as polishing, chamfering and waxing, as shown in Fig. 11.

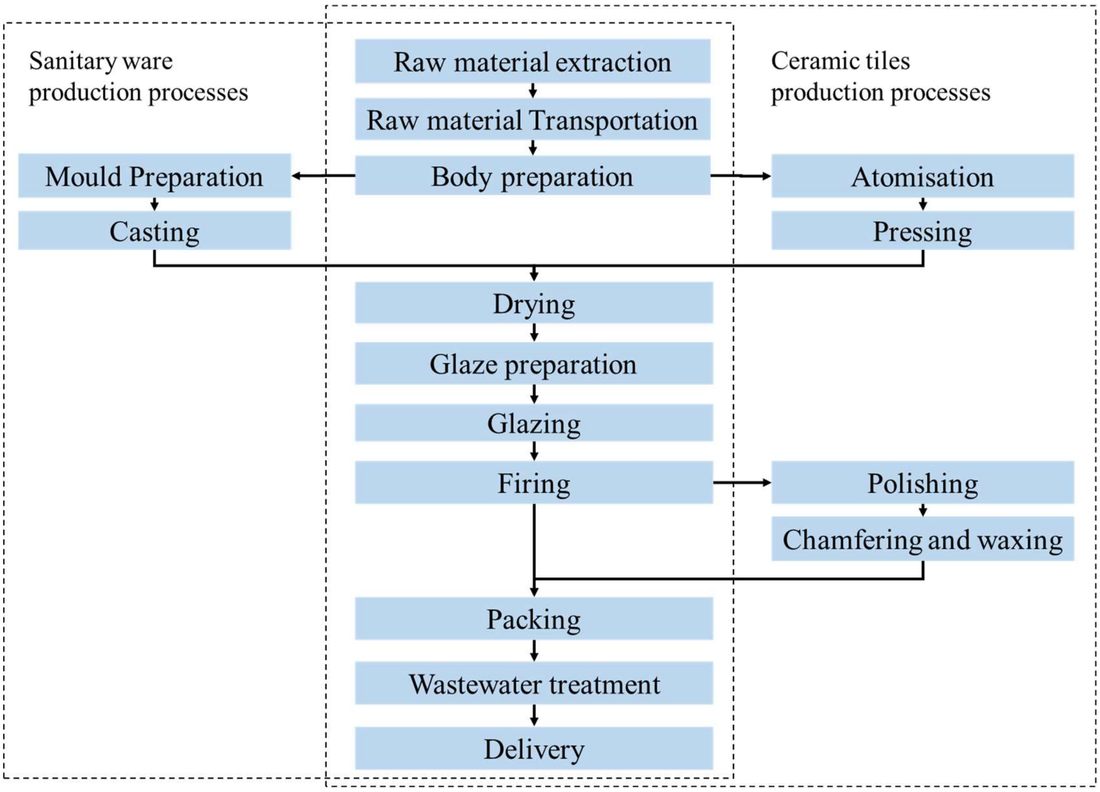


Fig. 11. Processes for producing sanitary ware and ceramic tiles

Information of the selected LCA studies on ceramic products is shown in Table 4, including articles, strategies and methods of LCA, studied sites, products and FUs. Since most of the studies employ the FU of 1 m^2 of ceramic tiles, the obtained results are converted to the environmental impacts of one tonne of ceramic products. Here we assume that the density of ceramic tiles is 17.2 kg m^{-2}, according to the work of Ibáñez-Forés et al. (2011). According to Souza et al. (2015), the density of ceramic roof tiles is 38.4 kg m^{-2}.

Table 4. Selection of LCA studies on ceramic products.

Source	Strategy	Method	Location	Product	FU
Almeida et al. (2016)	Cradle-to-grave	CML 2001	Portugal	Ceramic tiles	1 m^2
Bovea et al. (2010)	Cradle to gate	CML 2001	Castellon, Spain	Ceramic tiles	1 m^2
Souza et al. (2015)	Cradle-to-grave	IMPACT 2002+	Brazil	Ceramic roof tiles	1 m^2
Ibáñez-Forés et al. (2011)	Cradle-to-grave	CML 2001	Spain	Ceramic tiles	1 m^2
Ye et al., (2018)	Cradle-to-gate	ReCiPe method	Jiangxi, China	Ceramic tiles	1 m^2
Tikul and Srichandr (2010)	Cradle-to-gate	EDIP method[1]	Bangkok, Thailand	Ceramic tiles	1 ton
Gabi[2]	-	-	European	Sanitary ware	1 kg
This study (coke oven gas)	Cradle to gate	CML 2001	Tangshan, China	Sanitary ware	1 ton
This study (natural gas)	Cradle to gate	CML 2001	Tangshan, China	Sanitary ware	1 ton

[1] EDIP: Environmental Design of Industrial Products.

[2] Obtained from GABI database: "*EU-28 Sanitary ware (EN15804 A1-A3)*".

Adopting the same set of impact categories and the same UoM as Table 2, the comparison of the environmental impacts of one tonne of ceramic products is shown in Table 5. From Table 5, the values of ADe, ADf, GW and OD are in different orders of magnitude, possibly can be attributed to different production processes and fuel being used, while the values of A, E, HT and POC remain in the same order of magnitude. Natural gas is used to provide energy in European countries such as Portugal (Almeida et al., 2016) and Spain (Bovea et al., 2010; Ibáñez-Forés et al., 2011), while wood chips, water gas (i.e., carbon monoxide and hydrogen mixtures) and liquefied petroleum gas (i.e., propane and butane) are used as fuel in Brazil (Souza et al., 2015), China (Ye et al., 2018) and Thailand (Tikul and Srichandr, 2010).

The environmental impacts in sanitary ware production in this study are greater than those obtained in other studies on ceramic tile production, even when natural gas is used as fuel. For instance, the values of ADe and ADf are greater than those of a Portuguese plant (Almeida et al., 2016) and the values of A, E, GW and HT are higher than those of the Spanish ceramic manufacturers (Bovea et al., 2010; Ibáñez-Forés et al., 2011). This could be explained by the fact that more fuel is being consumed in the firing process of sanitary ware than that of ceramic tiles, due to longer cycle time and higher firing temperature.

Table 5. Comparison of environmental impacts of one ton of ceramic products.

Source\Indicators	ADe	ADf	A	E	GW	HT	OD	POC
Almeida *et al.* (2016)	1.80E-04	1.64E+04	4.15E+00	1.01E+00	1.26E+03	-	1.08E-04	2.40E-01
Bovea *et al.* (2010)	2.60E+00	-	3.09E+00	1.33E-01	4.92E+02	-	1.45E-05	2.18E-01
Souza *et al.* (2015)	-	2.03E+03	7.37E+00	-	1.29E+02	-	1.88E-05	1.17E-01
Ibáñez-Forés *et al.* (2011)	-	-	2.55E+00	3.45E-01	7.67E+02	9.42E+01	8.69E-05	1.08E-01
Ye *et al.*, (2018)	-	5.73E+03	1.63E+00	-	8.40E+02	4.65E+01	6.05E-06	-
Tikul and Srichandr (2010)	-	-	1.03E+01	-	3.73E+03	-	2.86E-04	1.08E+00
Gabi	2.12E-04	3.71E+04	1.83E+00	2.84E-01	2.31E+03	1.38E+02	8.53E-10	2.03E-01
This study (coke oven gas)	2.70E+01	2.48E+04	5.04E+00	7.70E-01	1.34E+03	4.26E+02	6.11E-06	1.32E+00
This study (natural gas)	1.11E-01	2.48E+04	3.96E+00	4.61E-01	9.05E+02	2.11E+02	1.83E-06	-7.18E-02

Comparing to the average levels of European sanitary ware manufacturers (Gabi), the environmental impacts of the studied plant (using coke oven gas) are higher in terms of ADe, A, E, HT, OD and POC, while lower for ADf and GW. the values of ADe, OD and POC are five, four and one orders of magnitude higher than those obtained from the Gabi database, respectively. The values of A, E and HT are around triple values of the Gabi data. This could also be attributed to the consumption of coke oven gas, as well as the energy efficiency. When natural gas is used, the environmental impacts of this study are much closer to those provided by the Gabi database, such as the values of ADe, A, E, HT, OD and POC. This could be explained by that the Gabi data is obtained in Europe, where the natural gas is used in sanitary ware production.

4.2. Recommendations

This work can be regarded as an exploratory study to examine the environmental impacts and economic costs associated with sanitary ware production. Based on the results and the comparison, recommendations are provided for practitioners and administrators to improve the environmental and economical sustainability.

4.2.1. For industrial practitioners

Firstly, the use of green and sustainable materials should be encouraged, because the environmental burdens associated with the raw materials, more precisely, their extraction processes, cannot be mitigated by improving processes and equipment or switching to more cleaner energy sources (Sun et al., 2018a). A potential candidate is to use recycled materials, such as the replacement of feldspar with waste glass (Kim et al., 2015), because substituting primary materials with recycled counterparts is proved to be an environmentally-friendly and economically-viable practice (Gu et al., 2017; Gu et al., 2019).

Secondly, the results confirm that improving the energy efficiency is a potential route to minimise the environmental impacts of the key processes in sanitary ware production, namely, firing and drying. This is a common measure to promote the environmental sustainability of the ceramic industry (Milani et al., 2017; Cuviella-Suárez et al., 2018), and this study provides quantitative evidence of how fuel saving could reduce the environmental impacts of the related processes. To this end, it might be helpful to introduce state-of-art information and communication technologies such as Big Data analytics (Sun et al., 2018b; Zhang et al., 2018b; Zhu et al., 2018) and artificial intelligence (Ren *et al.*, 2019) to save energy consumption in production, and to develop energy prediction models (Jia et al., 2018; Jia et al., 2019), energy-saving and emission-reduction strategy (Cai et al., 2019a) and energy performance certification (Cai et al., 2019b).

Thirdly, improving the recycled rates of waste ware and gypsum can be another viable option to reduce the environmental impacts and economic costs. This is a common measure to promote the environmental sustainability of the ceramic industry (Milani et al., 2017; Cuviella-Suárez et al., 2018). The findings of this study provide quantitative evidence of how the increasing recycling rates reduce the environmental impacts of the related processes.

Fourthly, using natural gas to replace coke oven gas is proved to be an effective measure to diminish the environmental impacts, and the results of the sensitivity analysis prove that it might be more effective than fuel saving. However, considering the current limited supply and high cost of natural gas in China (Wan et al., 2016; Chen et al., 2018; Dong et al., 2018), this alternative remains the last option.

4.2.2. For administrators

Firstly, environmental impacts can be reduced by increasing energy efficiency (Sun et al., 2019a). The government shall encourage the ceramic manufacturers to improve their energy efficiency by reducing tax or providing subsidies to facilitate the installation of production equipment with high energy efficiency.

Secondly, the results suggest that replacing coke oven gas with natural gas can greatly reduce environmental impacts but increase cost by 13.8% even considering the carbon tax. This may impede the use of natural gas. The government shall make policies to guide sanitary ware manufacturers to expand the use of natural gas, and measures such as increasing pollution tax for the ones still consume coke oven gas and providing subsidies to those use natural gas can be considered.

Thirdly, due to limited natural gas supply in China (Wan et al., 2016), another possible solution is to install environmental protection equipment, which aims at constraining emissions from the combustion of coke oven gas such as sulphur dioxide, nitrogen oxides and particulate matter generated (Sun et al., 2019b). Policy instruments such as taxes and subsidies can be considered to encourage sanitary ware manufacturers to adopt such equipment.

4.3. Shortcomings

Admittedly, this work suffers from two major limitations. The first limitation is the selected case, as the selected plant in Tangshan cannot represent the average technological level of the global sanitary ware industry. Yet still, the selected case is meaningful, because (1) China is the world's largest sanitary ware producer, (2) the selected case is a leading sanitary ware manufacture in China. Thus, the plant represents the technological level of Chinese sanitary ware industry.

The other limitation lies in the limited data availability of raw materials. As the raw materials are supplied by various suppliers, and their production processes might not be readily obtainable. Instead, in this study we employ the data of Europe and the world, which could lead to deviations in the results. However, the deviations can be minimal, due to (1) globalisation of supply networks of raw materials (Liu and Zhang, 2011) and (2) rapid development of mining technologies in China (Lei et al., 2016). Besides, materials only account for part of environmental impacts of sanitary ware production.

5. Conclusion

In this study, based on the data acquired from a leading sanitary ware factory in China, the material and energy flows, and the environmental impacts and economic cost of the production of the sanitary ware are evaluated. Based on the results, the following conclusive remarks can be derived:
(a) Firing and drying consume most of coke oven gas, casting and body preparation are electricity-intensive, and casting is also the largest consumer of water.
(b) Managing cost and sales cost are the primary contributors of the overall cost (over 20%), followed by material cost (16.30%) and energy cost (13.26%).
(c) Firing, drying and raw material extraction are the processes with the greatest environmental impacts, and the environmental burdens of the previous two processes can be attributed to the combustion of coke oven gas.
(d) Casting, body preparation and firing are the greatest contributors to the equipment, material and energy costs, respectively.
(e) Quartz, feldspars and Kaolin are the materials with the greatest environmental impacts, and quartz accounts for the largest proportion of total material cost (23.6%), followed by cardboard boxes (18.4%) and feldspars (17.0%).
(f) Saving fuel, increasing recycling rates of waste wares and gypsum, and using more environmentally-friendlier fuels such as natural gas can reduce the environmental burdens of sanitary ware production, yet the use of natural gas requires additional cost, even carbon tax is considered.

This research makes two major contributions. Our first contribution is to provide a comprehensive evaluation of the environmental impacts associated with the production of sanitary ware, an important sector of the ceramic industry, which has been neglected in the current research. The second contribution is within the methodology of this study, that is, the joint analysis of LCA and LCC on process-level, by which the potentials of reducing the environmental burdens and economical costs of sanitary ware production have been identified in detail. Further, recommendations are provided to reduce environmental impacts, including using green materials to substitute the original ones, improving production yield and energy efficiency, increasing the waste recycling rates, and replacing coke oven gas with natural gas. A possible direction of future research can be considered: to analyse the environmental impacts and costs for adopting advanced manufacturing technologies and paradigms.

Acknowledgements

We would like to thank the operation managers of the selected sanitary ware factory, Mr. Chao Wang and Mr. Hongwu Han, for providing the detailed descriptions and data about the production processes of sanitary ware.

This work is financially supported by National Natural Science Foundation of China (no. 51705428 & 71671180), Fundamental Research Funds for the Central Universities (no. 2018QNA4007) and International Clean Energy Talent Program (iCET) of China Scholarship Council (Liujinfa [2017] 5047 and Liujinfa [2018] 5023).

Nomenclature

DC_t	Depreciation cost at year t
N	Durable period
PC_A	Original cost of tangible assets A
RV_A	Residual value of tangible assets A
r	interest rate

Abbreviations

ADe	Abiotic depletion elements
ADf	Abiotic depletion fossil
A	Acidification
CAGR	Compound annual growth rate
E	Eutrophication
EC	European Commission
EI	EcoInvent
ERP	Enterprise resource planning
FU	Functional unit
GG	Green growth
GW	Global warming
HT	Human toxicity
ISO	International Standardization Organization

LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
ME	Material efficiency
MFA	Material flow analysis
OD	Ozone-layer depletion
POC	Photochemical ozone creation
SI	Supporting information
UoM	Unit of measurement
USGS	Unites States Geological Survey

References

Almeida, M.I., Dias, A.C., Demertzi, M., Arroja, L., 2015. Contribution to the development of product category rules for ceramic bricks. J. Clean. Prod. 92, 206-215.

Almeida, M.I., Dias, A.C., Demertzi, M., Arroja, L., 2016. Environmental profile of ceramic tiles and their potential for improvement. J. Clean. Prod. 131, 583-593.

Auer, J., Bey, N., Schäfer, J.-M., 2017. Combined Life Cycle Assessment and Life Cycle Costing in the Eco-Care-Matrix: A case study on the performance of a modernized manufacturing system for glass containers. J. Clean. Prod. 141, 99-109.

Bovea, M.D., Saura, Ú., Ferrero, J.L., Giner, J., 2007. Cradle-to-gate study of red clay for use in the ceramic industry. Int. J. Life Cycle Ass. 12(6), 439-447.

Bovea, M.D., Díaz-Albo, E., Gallardo, A., Colomer, F.J., Serrano, J., 2010. Environmental performance of ceramic tiles: Improvement proposals. Mater. Des. 31(1), 35-41.

British Ceramic Confederation, 2017. Ceramic sector: industrial decarbonisation and energy efficiency roadmap action plan. Available from: https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-action-plans (Assessed on 28th March 2019).

Cai, W., Lai, K.H., Liu, C., Wei, F., Ma, M., Jia, S., Jiang, Z., Lv, L., 2019a. Promoting sustainability of manufacturing industry through the lean energy-saving and emission-reduction strategy. Sci. Total Environ. 665, 23-32.

Cai, W., Liu, C., Lai, K., Li, L., Cunha, J., Hu, L., 2019b. Energy performance certification in mechanical manufacturing industry: A review and analysis. Energy Convers. Manag.186, 415-432.

Cardozo, E., Erlich, C., Alejo, L., Fransson, T.H., 2014. Combustion of agricultural residues: An experimental study for small-scale applications. Fuel 115, 778-787.

Chuenwong, K., Chiarakorn, S., Sajjakulnukit, B., 2017. Specific energy consumption and carbon intensity of ceramic tablewares: Small enterprises (SEs) in Thailand. J. Clean. Prod. 147, 395-405.

Cuviella-Suárez, C., Colmenar-Santos, A., Borge-Diez, D., López-Rey, Á., 2018.

Management tool to optimize energy and water consumption in the sanitary-ware industry. J. Clean. Prod. 197, 280-296.
Cuviella-Suárez, C., Colmenar-Santos, A., Borge-Diez, D., López-Rey, Á., 2019. Heat recovery in sanitary-ware industry applied to water and energy saving by multi-effect distillation. J. Clean. Prod. 213, 1322-1336.
Cerame-Unie, 2016. The European Ceramic Industry Association. Available from: http://cerameunie.eu/topics/climate-energy/ (accessed on 28th Dec 2018).
Dreyer, L.C., Niemann, A.L., Hauschild, M.Z., 2003. Comparison of Three Different LCIA Methods: EDIP97, CML2001 and Eco-indicator 99. Int. J. Life Cycle Ass. 8(4), 191-200.
EC, 2007. Reference document on best available techniques in the ceramic manufacturing industry. Institute for Prospective Technological Studies, European Commission, Sevilla, Spain. Available from: http://eippcb.jrc.ec.europa.eu /reference/BREF/cer_bref_0807.pdf (accessed on 28th Dec 2018).
Garcia-Ceballos, L., de Andres-Díaz, J.R., Contreras-Lopez, M.A., 2018. Life cycle study of different constructive solutions for building enclosures. Sci. Total Environ. 626, 1167-1174.
Geng, A., Zhang, H., Yang, H., 2017. Greenhouse gas reduction and cost efficiency of using wood flooring as an alternative to ceramic tile: A case study in China. J. Clean. Prod. 166, 438-448.
Gu, F., Guo, J., Zhang, W., Summers, P.A., Hall, P., 2017. From waste plastics to industrial raw materials: A life cycle assessment of mechanical plastic recycling practice based on a real-world case study. Sci. Total Environ. 601-602, 1192-1207.
Gu, F., Zheng, Y., Zhang, W., Yao, X., Pan, D., Wong, A.S.M., Guo, J., Hall, P., Sharmin, N., 2018. Can bamboo fibres be an alternative to flax fibres as materials for plastic reinforcement? A comparative life cycle study on polypropylene/flax/bamboo laminates. Ind. Crops Prod. 121, 372-387.
Gu, F., Zhang, W., Guo, J., Hall, P., 2019. Exploring “Internet+Recycling”: Mass balance and life cycle assessment of a waste management system associated with a mobile application. Sci. Total Environ. 649, 172-185.
Guo, L., Qu, Y., Wu, C., Wang, X., 2018a. Identifying a pathway towards green growth of Chinese industrial regions based on a system dynamics approach. Resour. Conserv. Recy. 128, 143-154.
Guo, J., Su, B., Yang, G., Feng, L., Liu, Y., Gu, F., 2018b. How do verified emissions announcements affect the comoves between trading behaviors and carbon prices? Evidence from EU ETS. Sustainability 10(9), 1-17.
Grand View Research, 2019. Ceramic tiles market size, research, industry trend report 2019-2025. Available from: https://www.grandviewresearch.com /industry-analysis/ceramic-tiles-market (Assessed on 28th March 2019).
Han, B., Wang, R., Yao, L., Liu, H., Wang, Z., 2015. Life cycle assessment of ceramic façade material and its comparative analysis with three other common façade materials. J. Clean. Prod. 99, 86-93.

Huida, 2018. The 2017 annual report of Huida Group Co. Ltd (in Chinese). Available from: http://vip.stock.finance.sina.com.cn/corp/view/vCB_AllBulletinDetail.php?stockid=603385&id=4186582 (accessed on 28th Dec 2018).
Ibanez-Fores, V., Bovea, M.D., Simo, A., 2011. Life cycle assessment of ceramic tiles. Environmental and statistical analysis. Int. J. Life Cycle Ass. 16(9), 916-928.
Ibáñez-Forés, V., Bovea, M.D., Azapagic, A., 2013. Assessing the sustainability of Best Available Techniques (BAT): methodology and application in the ceramic tiles industry. J. Clean. Prod. 51, 162-176.
ISO, 2006a. ISO 14040. Environmental Management - Life Cycle Assessment - Principles and Frameworks. Geneva, Switzerland.
ISO, 2006b. ISO 14044. Environmental Management - Life Cycle Assessment - Requirements and Guidelines. British Standards Institution, London, UK.
ISO, 2008. ISO 15686-5:2008. Buildings and Constructed Assets e Service-life Planning e Part 5: Life-cycle Costing. Available from: https://www.iso.org/standard/39843.html (Accessed on 28th Dec 2018).
Jia, S., Yuan, Q., Cai, W., Li, M., Li, Z., 2018. Energy modeling method of machine-operator system for sustainable machining. Energy Conv. Manag. 172, 265-276.
Jia, S., Yuan, Q., Cai, W., Lv, J., Hu, L., 2019. Establishing prediction models for feeding power and material drilling power to support sustainable machining. Int. J. Adv. Manuf. Tech. 100(9-12), 2243-2253.
Kim, K., Kim, K., Hwang, J., 2015. LCD waste glass as a substitute for feldspar in the porcelain sanitary ware production. Ceram. Int. 41(5), 7097-7102.
Kim, S., Ko, W., Youn, S., Gao, R., Chung, Y., Bang, S., 2016. Advanced depreciation cost analysis for a commercial pyroprocess facility in Korea. Nuclear Eng. Technol. 48(3), 733-743.
Lei, K., Pan, H.Y., Lin, C.Y., 2016. A landscape approach towards ecological restoration and sustainable development of mining areas. Ecological Engineering 90, 320-325.
Li, J., Liang, J., Wang, F., Wang, L., 2014. The role of firing process on bubble formation in a glaze layer of sanitary ware. Thermochimica Acta 588, 75-80.
Liu, P.D., Zhang, X., 2011. Research on the supplier selection of a supply chain based on entropy weight and improved ELECTRE-III method. Int J Prod Res 49(3), 637-646.
Liu, Y., Lu, Y., 2015. The economic impact of different carbon tax revenue recycling schemes in China: A model-based scenario analysis. Appl. Energy 141, 96-105.
Mezquita, A., Boix, J., Monfort, E., Mallol, G., 2014. Energy saving in ceramic tile kilns: Cooling gas heat recovery. Appl. Therm. Eng. 65(1–2), 102-110.
Milani, M., Montorsi, L., Stefani, M., Saponelli, R., Lizzano, M., 2017. Numerical analysis of an entire ceramic kiln under actual operating conditions for the energy efficiency improvement. J. Environ. Manage. 203, 1026-1037.
Ren, S., Zhang, Y., Liu, Y., Sakao, T., Huisingh, D., Almeida, C.M.V.B., 2019. A comprehensive review of big data analytics throughout product lifecycle to support sustainable smart manufacturing: A framework, challenges and future research directions. J. Clean. Prod. 210, 1343-1365.

Research and Markets, 2018. Global ceramic sanitary ware market 2018-2022. Available from: https://www.researchandmarkets.com/research/kpnkzj/global_ceramic?w=5 (accessed on 28th March 2019).
Ros-Dosdá, T., Fullana-i-Palmer, P., Mezquita, A., Masoni, P., Monfort, E., 2018. How can the European ceramic tile industry meet the EU's low-carbon targets? A life cycle perspective. J. Clean. Prod. 199, 554-564.
Shahbazi, S., 2015. Material Efficiency Management in Manufacturing. Mälardalen University, Sweden.
Souza, D.M.D., Lafontaine, M., Charron-Doucet, F., Bengoa, X., Chappert, B., Duarte, F., Lima, L., 2015. Comparative Life Cycle Assessment of ceramic versus concrete roof tiles in the Brazilian context. J. Clean. Prod. 89, 165-173.
Souza, D.M.D., Lafontaine, M., Charron-Doucet, F., Chappert, B., Kicak, K., Duarte, F., Lima, L., 2016. Comparative life cycle assessment of ceramic brick, concrete brick and cast-in-place reinforced concrete exterior walls. J. Clean. Prod. 137, 70-82.
Song, M., Wang, S., 2018. Market competition, green technology progress and comparative advantages in China. Manage. Decis. 56(1), 188-203.
Sun, W., Wang, Y., Zhang, F., Zhao, Y., 2018a. Dynamic allocation of surplus by-product gas in a steel plant by dynamic programming with a reduced state space algorithm. Eng. Opt. 50(9), 1578-1592.
Sun, W., Yue, X., Wang, Y., Cai, J., 2018b. Energy and exergy recovery from exhaust hot water using organic Rankine cycle and a retrofitted configuration. J. Central South Univ. 25(6), 1464-1474.
Sun, W., Xu, X., Lv, Z., Mao, H., Wu, J., 2019a. Environmental impact assessment of wastewater discharge with multi-pollutants from iron and steel Industry. J. Environ. Manag. 245: 210-215.
Sun, W., Zhou, Y., Lv, J., Wu, J., 2019b. Assessment of multi-air emissions: Case of particulate matter (dust), SO2, NOx and CO2 from iron and steel industry of China. J. Clean. Prod. 232: 350-358.
Tangshan Municipal Government, 2018. Our city held the ceramic industry transformation and upgrading mobilization meeting (in Chinese). Available from: http://www.tangshan.gov.cn/zhuzhan/zhengwuxinwen/20180913/640970.html (accessed on 28th Dec 2018).
Tikul, N., Srichandr, P., 2010. Assessing the environmental impact of ceramic tile production in Thailand. J Ceram. Soc. Jpn. 118(1382), 887-894.
USGS, 2018. Mineral Commodity Summaries 2017 – USGS – Zinc. Available from: http://www.tangshan.gov.cn/zhuzhan/zhengwuxinwen/20180913/640970.html (accessed on 28th Dec 2018).
Vieira, D.R., Calmon, J.L., Coelho, F.Z., 2016. Life cycle assessment (LCA) applied to the manufacturing of common and ecological concrete: A review. Constr. Build. Mater. 124, 656-666.
Wan, A., Gu, F., Jin, J., Gu, X., Ji, Y., 2016. Modeling and optimization of shutdown process of combined cycle gas turbine under limited residual natural gas. Appl.

Therm. Eng. 101, 337-349.
Wang, J., Gu, F., Liu, Y., Fan, Y., Guo, J., 2019. Bidirectional interactions between trading behaviors and carbon prices in European Union emission trading scheme. J. Clean. Prod. 224, 435-443.
Yang, J., Wu, J., He, T., Li, L., Han, D., Wang, Z., Wu, J., 2016. Energy gases and related carbon emissions in China. Resources, Conservation and Recycling 113, 140-148.
Ye, L., Hong, J., Ma, X., Qi, C., Yang, D., 2018. Life cycle environmental and economic assessment of ceramic tile production: A case study in China. J. Clean. Prod. 189, 432-441.
Zhang, W., Guo, J., Gu, F., Gu, X., 2018a. Coupling life cycle assessment and life cycle costing as an evaluation tool for developing product service system of high energy-consuming equipment. J. Clean. Prod. 183, 1043-1053.
Zhang, Y., Ma, S., Yang, H., Lv, J., Liu, Y., 2018b. A big data driven analytical framework for energy-intensive manufacturing industries. J. Clean. Prod. 197, 57-72.
Zhao, P., Rao, C., Gu, F., Sharmin, N., Fu, J., 2018. Close-looped recycling of polylactic acid used in 3D printing: An experimental investigation and life cycle assessment. J. Clean. Prod. 197, 1046-1055.
Zhao, X., Yao, J., Sun, C., Pan, W., 2019. Impacts of carbon tax and tradable permits on wind power investment in China. Renew. Energy 135, 1386-1399.
Zhu, Q., Wu, J., Song, M., 2018. Efficiency evaluation based on data envelopment analysis in the big data context. Comput. Oper. Res. 98, 291-300.