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LCA Case Study of Ceramic Tableware: Ecodesign Aspects of Ceramics Production from Ancient Technology to Present Factory

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Abstract: Ceramic tableware, as one of the products of daily use, can be produced in multiple ways. However, they all consume primary raw materials for manufacturing and energy for firing and generate emissions and waste. To assess how different types of production cause an environmental impact, five scenarios were compared using the Life Cycle Assessment (LCA). In the first step, the energy and material flows from the following scenarios were analysed: factory (FAC), slip casting (PSC), pottery wheel (PW), high energy rate formation technique (HERF) and experimental reconstruction of the ancient technique (ANC). The results related to 1 kg of ceramics were interpreted using the perspective of ecodesign to discuss key parameters that affect environmental impacts. Considering the results in the Climate Change category, the FAC production of 1 kg of ceramics reached 3.64 kg CO_2 eq. but the highest impact in this category was caused by low energy efficiency in the specific case of the PSC scenario (8.93 kg CO_2 eq.). On the one hand, this paper contributes to the discussion of environmentally friendly tableware, but also serves as a case study that describes the implementation of ecodesign in the ceramic tableware industry as an important field of industrial production in the specific context of the Czech Republic, as a state, which has significant deposits of kaolin.

Keywords: ceramic; tableware; LCA; ecodesign; climate change

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1. Introduction

The production of ceramic tableware represents only a small part of the ceramic industry. Nevertheless, utility ceramics have been used for millennia with the demand for them is constantly increasing, and the market is flooded with countless new shapes and designs reflecting current trends and needs. The increased number of ceramics produced results in an increased environmental impact. Specifically, in the context of the Czech Republic, which has, relatively to its size, significant deposits of kaolin and so represents an important exporter of ceramic tableware, of which potential environmental impacts should be analysed. To assess key parameters that affect the environmental performance of ceramic tableware, this paper compares several techniques using the Life Cycle Assessment method [1].

Among the potential environmental impacts, it can be assumed that the depletion of mineral raw materials is the main effect of the mass production of ceramics, which is related to the consumption of not only clay, but also critical raw materials [2,3]. Furthermore, although the clay material from which utility ceramics are made is nontoxic and potential ceramic waste is inert and does not cause a significant toxic impact on the environment, the ceramic production process is associated with high energy consumption [4–6]. Although

production technologies are constantly improving, and their efficiency has advanced significantly since the days of firing in primitive kilns, they still cause a significant environmental impact (e.g., particulate matter) as an effect of combustion [7].

Some of the key parameters that affect the environmental performance of ceramic production are outlined in the BREF document for the ceramics industry, which describes the potential sources of emissions and suggests measures that can be taken to reduce the impact of ceramic production [8]. However, since it addresses only the ceramic production phase, the use of this document is insufficient to reduce the environmental impacts of the entire ceramics life cycle.

An approach to find a truly sustainable solution is called ecodesign [9]. It is a systematic process that considers the environmental impacts caused during the entire life cycle of a proposed product, along with other considerations such as affordability, functionality, ergonomics, and aesthetics. Therefore, the product is designed taking into account, for example, emissions from production, the use of packaging material, the recyclability of the product or its likely disposal [10]. An important starting parameter is also the degree of fulfilment of the function for which the product is designed. However, two basic issues arise in an ecodesign study: (1) what indicators should be implemented in an ecodesign-based study and (2) how to measure and evaluate the performance of compared products.

In 2010, the issue of ecodesign and optimisation in ceramic production was investigated in Portugal, Spain, and Greece [11]. The result of the questionnaire pointed to a lack of systematic information and education on the necessary adaptations in the sector. Furthermore, even though the question of sustainability in ceramic production is in an early stage, ecodesign strategies are considered an important factor for competitiveness, and so manufacturing companies are asking their associations for more information about eco-efficient materials and production techniques [12].

To support ecodesign strategies, the environmental performance of the product must be analysed throughout the life cycle of the product. The potential environmental impacts associated with a ceramic product can be compared using the Life Cycle Assessment (LCA) method [1]. This method, which is standardised by ISO 14040 and ISO 14044 [13,14], is a suitable analytical tool to assess the potential environmental impacts of a product, technology, or service from the perspective of the entire life cycle, including the acquisition of the primary raw material, the production of the material and subsequently the product, the use of the product, and its disposal.

In this study, five different scenarios of ceramic production are considered, which allows us to form a holistic view of the production of utility ceramics in the Czech Republic under different conditions. The production of ceramics was modelled in the following scenarios: Ceramics from an automatized factory (FAC), ceramics from a small ceramic studio produced by either pottery wheel (PW) or using slip casting (PSC), experimental reconstruction of ceramics making with ancient technology (ANC), and ceramics made in a small studio using an alternative technique of high energy rate formation (HERF).

The scenarios were modelled using GaBi v2022.2 software and based on inventory analysis combining information from industry, small producers, and experiments. For the process that describes tableware production, manufacturer-specific data or, where appropriate, generic data taken from the Gabi database and the Ecoinvent database, version 3.6, were used [15,16].

This study helps identify key parameters that affect the environmental impacts of utility ceramic production and serves as a basis for improving production technology or corporate strategy. Moreover, it identifies which of the scenarios for the production of utility ceramics has the lowest environmental impact.

2. Materials and Methods

Ceramics can be considered one of the first artificial materials with the oldest ceramic utility vessels dating back to 20,000 years ago [17,18]. Although technology has been developed, the basic approach is the same. After the creation of a ceramic product from

plastic material, the shaped products are dried and then fired at a temperature higher than 800 °C [19].

The basic resource for ceramic production is clay, and various mineral compounds (e.g., feldspar, quartz). The mixture can also obtain organic, inorganic, or synthetic admixtures, which affect the properties of ceramic after its firing.

The properties of the ceramics can differ according to the field of use. In addition to utility ceramics (tableware), ceramic materials are used in the construction industry, refractory applications, military or space industry, and many others. The development of the production technology for utility ceramics has two main segments. The first is handmade pottery that focusses on the quality and originality of the product. The second one is the mass production in factories, which produce a huge number of products with high efficiency in the use of sources.

This study compares ceramic vessels produced using the following five technologies with different production scales: mass production in a factory (FAC), handmade production using slip casting (PSC), handmade production in a factory using a pottery wheel (PW), an alternative production using high energy rate formation (HERF), and production using the experimental reconstruction of ancient technology of firing in a pit (ANC). The compared technologies are described in the following sections.

2.1. Mass Production of Tableware in Automatized Factory

The first compared scenario (FAC) is based on data from the factory in the Czech Republic, which represents the mass production of porcelain tableware and reaches 3500 tons of ceramics produced annually.

The main resources such as kaolinite, feldspar, dolomite, and wollastonite are milled and used to produce casting and plastic matter. Additionally, an external producer supplies a granulate for isostatic casting.

The operation uses automatic lines to produce hollow products (cups, mugs, cups, vases, jugs, milk jugs, sugar bowls, saltines, dippers, soup, and vegetable bowls, etc.) and flat products (saucers, plates, round bowls, oval bowls, side dishes, compote bowls, etc.). The whole process is described in Figure 1.

The hollow product range is produced by gravity casting into plaster moulds and pressure casting into polymer moulds (approx. 15% of production), as well as by plastic moulding, which is carried out on a turning line (approx. 25% of production). The isostatic dry granulate moulding technique is used to create the flat range (approx. 60% of production).

After drying the products, which takes place first in the open air at a temperature of 25 °C and then in chamber dryers at 60 °C, products are fired to a temperature of 1000 °C. The reheated goods are glazed with a transparent glaze and then fired at a temperature of 1380–1400 °C. After sorting, the products proceed to decoration (painting, decals, stamps, spraying) and then a third, decorative firing is carried out at temperatures of 650 °C in the case of glaze paints and 1200 °C in the case of fusible paints. The products that meet the quality grades are then packed and shipped. According to the internal standards of this producer, there are four quality categories. However, more than 15% of production does not meet the standards of the lowest quality and so these products with insufficient quality are disposed.

2.2. Manufactory Production Using Slip Casting

The second scenario (PSC) was based on data from a manufactory with an annual production of about 180 kg. The main production material is soft porcelain of the French type. In the form of a dry ready-mix, it is delivered by a transport company directly to the workshop, where it is mixed with water in a floatation plant. Additionally, the production of beverage pottery and bowls is carried out by gravity casting into plaster moulds.

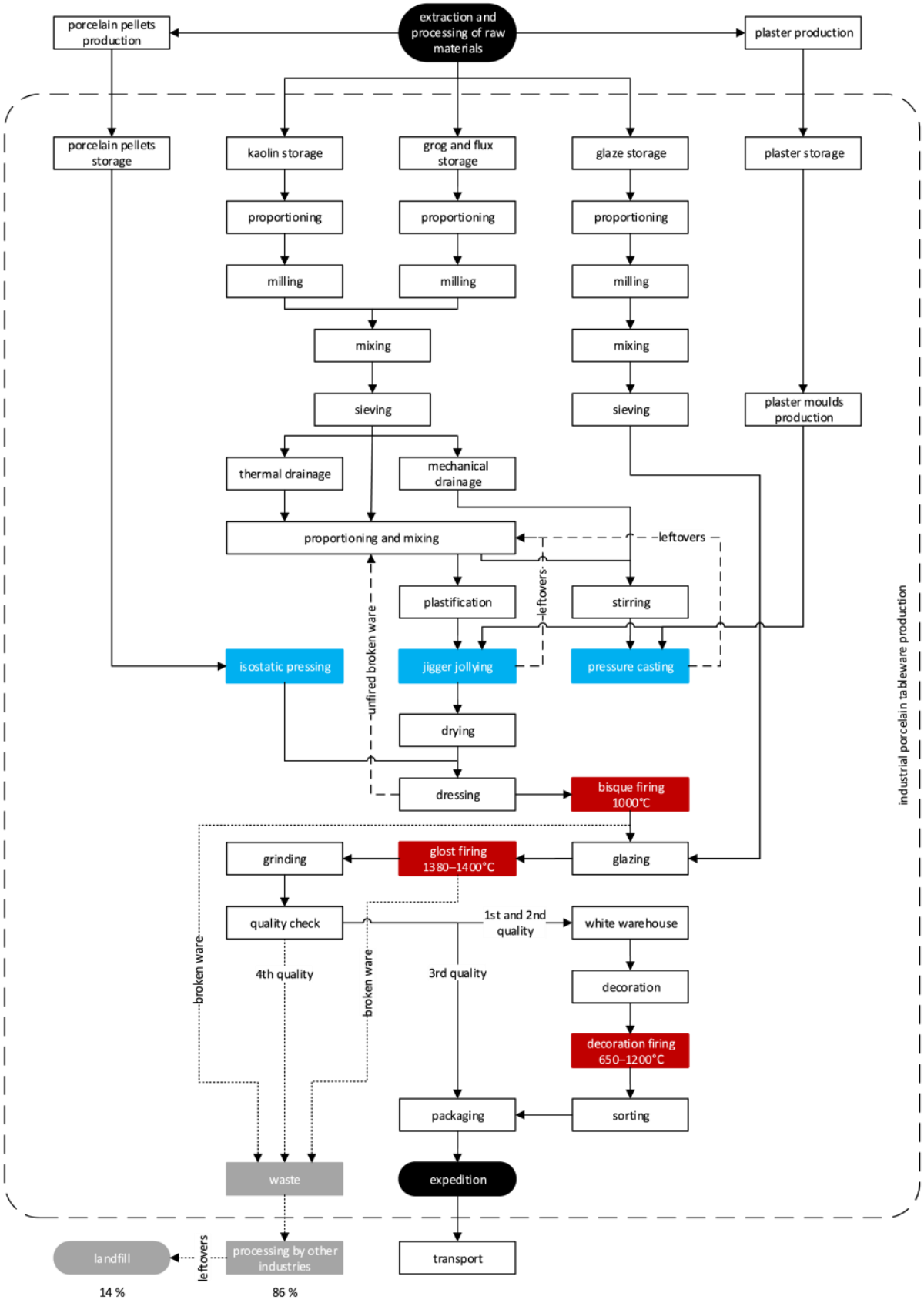


Figure 1. Process map of tableware production in automatized factory.

The moulded products are free-dried and then decorated with underglaze paints. After firing at 900 °C, the products are glazed with a transparent glaze and fired at 1240 °C in an electric kiln with an oxidising atmosphere. The products are then inspected and ready for dispatch.

2.3. Manufacture Production Using a Pottery Wheel

The traditional method of producing tableware on the pottery wheel in the factory was compared with another scenario (PW). The considered studio with two employees reaches a production of 5 tons per year. Part of the production, especially the flat products, is shaped on a turning machine and a small part of the range is produced by casting in plaster moulds. The free-dried products are glazed with different types of glazes after drying and fired in an electric kiln at 1280 °C. A part of the range is decorated with glaze paints which are fired in a third at 650–800 °C.

The factory uses a single composition of ceramic mass in the form of finished turning and casting mass. These masses are delivered by the manufacturer directly to the plant. The total production of table ceramics in this studio with two employees is about 5 tons per year.

2.4. Experimental Production Using High Energy Rate Forming Technique

In this experimental technique of shaping ceramic vessels, conventional methods of shaping, such as casting or turning, are not used. However, the shaping of the product is in this scenario (HERF) performed using pressure caused by the forces of rapid energy transformations induced by the pyrotechnic composition [20].

Two variants of the pyrotechnic composition with different properties are used for moulding. For a slower reaction and a smaller volume of gas produced, it is a mixture of powdered aluminium with copper oxide, whereas for a more violent reaction with a larger volume of gas, it is a mixture with potassium chlorate. The products are moulded from a porcelain plastic mass, fired at 900 °C after free drying, are glazed with a transparent glaze, and finally fired in a gas furnace with a reduction atmosphere at 1340 °C. Due to the experimental nature of this method of production, only one batch of the kiln was again considered. The process of production using HERF is described in Figure 2.

2.5. Experimental Production Using Reconstruction of the Ancient Technique

To fulfil the spectrum of methods for firing ceramics, a reconstruction of a prehistoric pottery firing plant was carried out as another scenario (ANC). The scenario represents the technique of production of utilitarian pottery from the Linear Pottery culture period, or corded pottery (Bronze Age), where a simple kiln construction—a pit—was used to fire the hand-shaped products [21]. The process is described in Figure 3.

In this type of kiln, where freely collected wood is used as an energy source, temperatures of around 900 °C were achieved [22,23]. The progress of the temperature increase was measured using a thermocouple with a temperature probe (type S) and the results are summarised in Figure 4. To estimate the consumed materials, the hanging weight (accuracy 10 g) was used to measure the weight of wood and straw. Also, the humidity meter (Trotec T510 manufactured by Trotec GmbH in Heinsberg, Germany) was used to measure the humidity in the used wood.

In contrast to previous production scenarios where the annual operation was analysed, in this case, it was a measurement of the input and output flows of a single firing. The untreated plastic clay was used as the only material input. The fired ceramics were not glazed and so the shard was significantly moisture-absorbing.

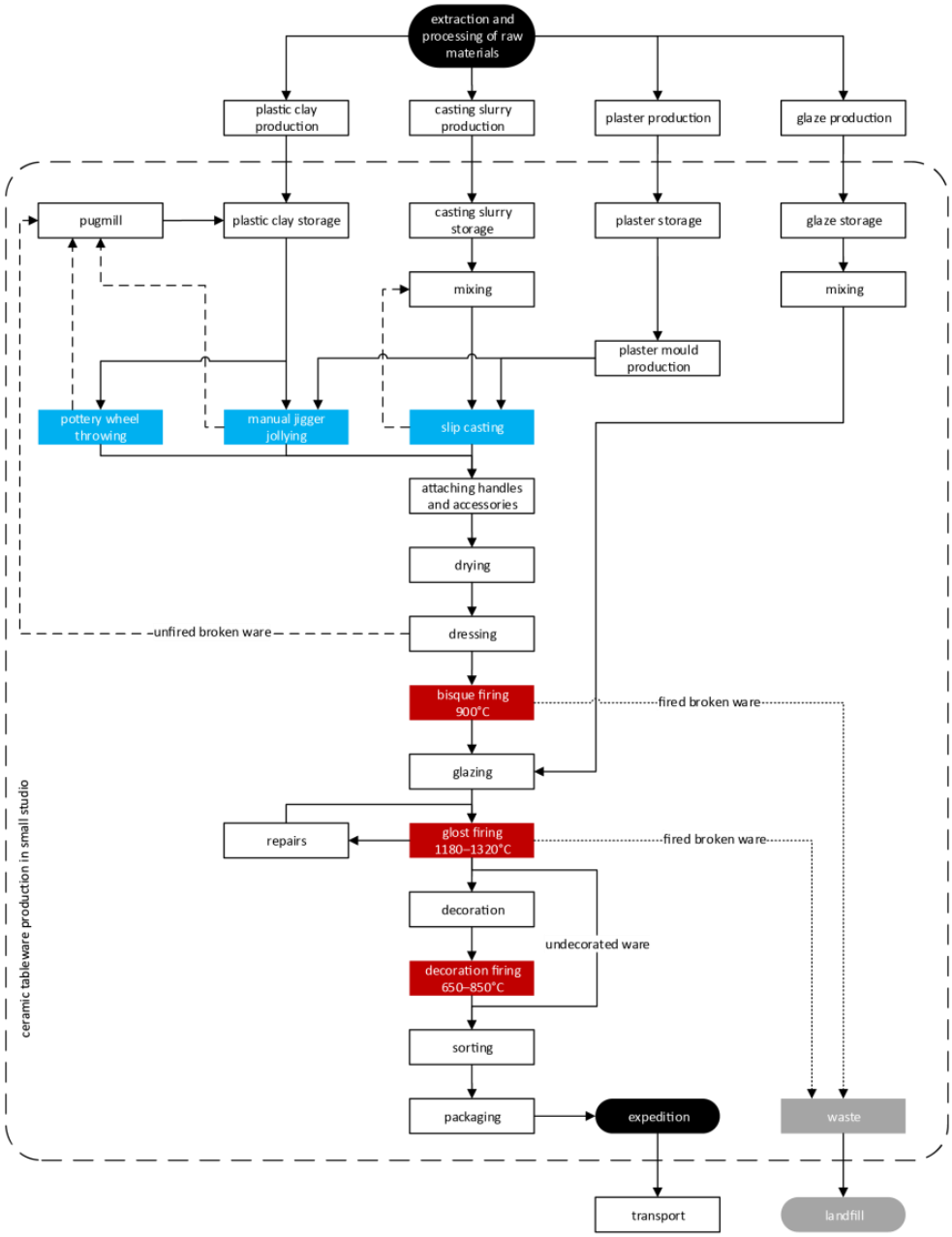


Figure 2. Process map of Manufacture Production Using a Pottery Wheel.

2.6. Life Cycle Assessment

The environmental assessment was performed using the Life Cycle Assessment (LCA) method in compliance with standards ISO 14040 and ISO 14044. LCA is an analytical tool for the assessment of potential environmental impacts related to the life cycle of the product or service [13,14]. The conducting of the LCA study consists of four steps: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation [24].

The purpose of this study is to compare the potential environmental impacts caused by ceramic tableware produced in various technologies and scales. The environmental impacts were related to the 1 kg of fired ceramic tableware. The considered system boundaries can be described as cradle-to-gate and include excavation of raw materials, transport of materials to the production plant, preparation of the mixture, moulding, glazing, and firing of the ceramic vessel.

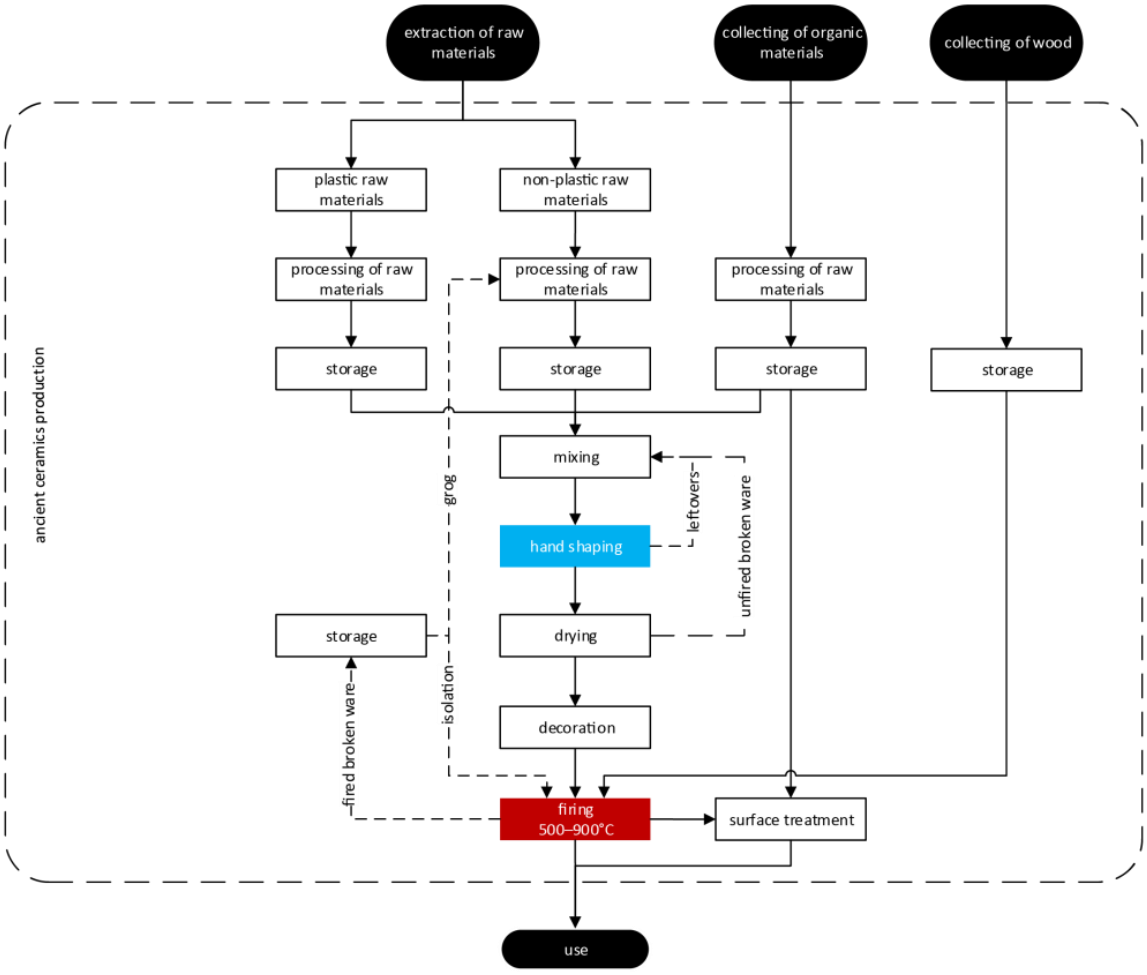


Figure 3. Process map of experimental production using reconstruction of the ancient technique.

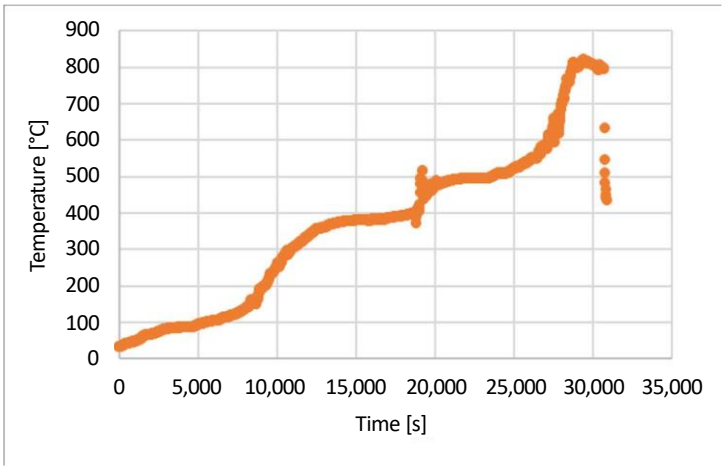


Figure 4. Temperature measured in the centre of the fireplace (pit).

Material and energy flows were inventoried in cooperation with ceramic producers in the Czech Republic. The material and energy inventory for the ANC scenario was conducted based on the measurement of the experimental replication of the ancient approach. The overview of inventories is in Table 1. Based on the inventories, the specific process in models for each scenario was created in the Gabi software [25]. The background processes were modelled using generic processes from the Gabi database [15].

Table 1. Overview of inputs and outputs for considered scenarios.

Life Cycle Stage	Inputs and Outputs	FAC	PSC	PW	HERF	ANC
Production	Products, total (kg)	3.0×10^6	180	5.0×10^3	113	9
	Secondary products	8.3×10^5	0	0	0	0
	Ceramic waste (kg)	1.4×10^5	5	60	4	0.4
	Loss (%)	4.5	2.8	1.2	3.5	4.0
Porcelain + Glaze	Kaolin (kg)	3.3×10^6	91	3.0×10^3	59	10
	Spar (kg)	2.3×10^5	48	1.0×10^3	31	0
	Dolomite	5.4×10^4	1	8	0	0
	Silica (kg)	3.6×10^5	48	1.0×10^3	31	0
	Gypsum (kg)	4.6×10^4	180	80	4	0
	Water (L)	2.6×10^7	49	3.5×10^4	20	0
	Titanium dioxide (kg)	0	0	3.75	0	0
Specials	Aluminium (g)	0	0	0	340	0
	Perchlorate (g)	0	0	0	225	0
	Copper (g)	0	0	0	85	0
	Kaolinite (kg)	0	0	150	0	0
Firing	Wood (m^3)	0	0	0	0	91
	Straw (kg)	0	0	0	0	45
	Natural gas (m^3)	2.9×10^6	0	0	60	0
	Electricity (kWh)	4.5×10^6	2.5×10^3	2.2×10^4	180	0
Transport	Oil fuel (L)	4.1×10^4	13	277	46	0
	LPG (L)	2.5×10^3	0	0	0	0
	Gasoline (L)	1.2×10^4	0	0	0	0
Waste	Gypsum (kg)	4.6×10^4	90	80	4	0
	Polypropylene packaging(kg)	3.5×10^3	5	10	0	0
	Inert (kg)	1.4×10^5	5	60	4	0

To assess potential environmental impacts, the elementary flows were characterised using the Product Environmental Footprint methodology, version EF 3.0 [26,27].

2.7. Assumption Accepted in the Study

In this study, the following assumptions were established:

- Material and energy inventories were based on specific data of producers related to the year 2019. The inventory for the ANC scenario is based on one batch of ceramic products fired during the replication of the ancient approach.
- To model emissions from open-pit burning of wood, the generic process from the Gabi database was used (Process name: GLO: Open biomass burning—garbage burning of 1 kg dry matter, 40% C).
- The general composition of the dry mixture for glazing was considered in scenarios PW, PSC, and HERF. The considered percentage of kaolin, quartz, and feldspar was 50%, 25%, and 25%, respectively.
- In the PSC scenario, the consumption of gypsum was measured as 180 kg per year. However, the waste flow of gypsum was estimated to be 90 kg, because the producer stated that the life expectancy of the gypsum forms will last longer than one year.
- Packaging materials for ceramic products were excluded from the inventories and the phase of transport of the product to a customer was also not considered.
- Environmental impacts are allocated to 1 kg of fired ceramic without considering the volume or design of the vessel.

3. Results

Based on the calculation performed using the LCA method (see Table 2), the scenario defined as production using a pottery wheel (PW) has the lowest overall environmental

impacts. Together with the second small-scale operation in the ceramic studio (PSC), both operations have high efficiency in the use of raw materials production and low scrap rates (1.2 and 2.7%). However, in the PSC scenario, the use of electricity for firing and running the whole studio is very inefficient (more than double that of the other scenarios), causing a significant impact in the climate change impact category, which is closely linked to the consumption of fossil resources for electricity generation.

Table 2. Results of environmental indicators of different types of ceramic production, according to EF 3.0.

Indicator	FAC	HERF	ANC	PW	PSC
Acidification [Mole of H^+ eq.]	3.71×10^{-3}	6.03×10^{-3}	1.24×10^{-1}	6.95×10^{-3}	2.08×10^{-2}
Climate Change—total [kg CO_2 eq.]	3.64	3.78	4.03	3.1	8.93
Climate Change, biogenic [kg CO_2 eq.]	1.60×10^{-2}	1.66×10^{-2}	1.85×10^{0}	1.94×10^{-2}	5.77×10^{-2}
Climate Change, fossil [kg CO_2 eq.]	3.63	3.75	2.17	3.08	8.87
Climate Change, land use and land use change [kg CO_2 eq.]	5.48×10^{-4}	8.54×10^{-3}	8.01×10^{-3}	1.61×10^{-3}	2.94×10^{-3}
Ecotoxicity, freshwater—total [CTUe]	6.72	22.7	31.8	17.9	52.8
Ecotoxicity, freshwater inorganics [CTUe]	3.39	14.9	7.18	8.81	24.4
Ecotoxicity, freshwater metals [CTUe]	3.3	7.67	0.87	9.07	28.3
Ecotoxicity, freshwater organics [CTUe]	2.48×10^{-2}	1.72×10^{-1}	2.37×10^{1}	4.97×10^{-2}	1.15×10^{-1}
Eutrophication, freshwater [kg P eq.]	3.96×10^{-6}	1.43×10^{-5}	0.000241	7.76×10^{-6}	2.24×10^{-5}
Eutrophication, marine [kg N eq.]	1.08×10^{-3}	1.92×10^{-3}	0.0406	1.45×10^{-3}	0.00412
Eutrophication, terrestrial [Mole of N eq.]	1.16×10^{-2}	2.12×10^{-2}	5.95×10^{-1}	1.53×10^{-2}	4.31×10^{-2}
Human toxicity, cancer—total [CTUh]	4.83×10^{-10}	5.84×10^{-10}	1.21×10^{-7}	3.55×10^{-10}	9.87×10^{-10}
Human toxicity, cancer inorganics [CTUh]	5.44×10^{-21}	2.04×10^{-20}	1.55×10^{-20}	6.93×10^{-21}	1.01×10^{-20}
Human toxicity, cancer metals [CTUh]	2.90×10^{-10}	4.22×10^{-10}	3.12×10^{-10}	1.58×10^{-10}	4.14×10^{-10}
Human toxicity, cancer organics [CTUh]	1.93×10^{-10}	1.63×10^{-10}	1.21×10^{-7}	1.97×10^{-10}	5.73×10^{-10}
Human toxicity, non-cancer—total [CTUh]	3.68×10^{-8}	3.83×10^{-8}	7.43×10^{-7}	2.54×10^{-8}	7.31×10^{-8}
Human toxicity, non-cancer inorganics [CTUh]	4.47×10^{-9}	7.05×10^{-9}	6.26×10^{-7}	1.10×10^{-8}	3.33×10^{-8}
Human toxicity, non-cancer metals [CTUh]	3.23×10^{-8}	3.12×10^{-8}	3.36×10^{-8}	1.44×10^{-8}	3.97×10^{-8}
Human toxicity, non-cancer organics [CTUh]	2.89×10^{-10}	2.99×10^{-10}	8.40×10^{-8}	2.11×10^{-10}	6.02×10^{-10}
Ionising radiation, human health [kBq U_{235} eq.]	1.46×10^{-1}	1.67×10^{-1}	1.60×10^{-2}	4.10×10^{-1}	1.28
Land Use [Pt]	5.26	12.3	932	14.5	43.3
Ozone depletion [kg CFC-11 eq.]	5.18×10^{-11}	6.67×10^{-10}	2.32×10^{-12}	2.90×10^{-11}	7.16×10^{-11}
Particulate matter [Disease incidences]	4.23×10^{-8}	4.97×10^{-8}	3.51×10^{-5}	6.02×10^{-8}	1.76×10^{-7}
Photochemical ozone formation, human health [kg NMVOC eq.]	3.07×10^{-3}	4.71×10^{-3}	3.94×10^{-1}	3.94×10^{-3}	1.13×10^{-2}
Resource use, fossils [MJ]	6.07×10^{1}	5.80×10^{1}	1.44×10^{1}	4.86×10^{1}	1.40×10^{2}
Resource use, mineral and metals [kg Sb eq.]	3.56×10^{-7}	3.67×10^{-6}	1.03×10^{-6}	3.55×10^{-7}	1.01×10^{-6}
Water use [m^3 world equiv.]	4.00×10^{-1}	6.90×10^{-2}	5.16×10^{-2}	3.51×10^{-1}	1.48×10^{-1}

However, the highest potential environmental impact is related to the experimental scenario of the reconstruction of the ancient technique (ANC), mainly due to particulates released into the air as a result of the burning of biomass during the firing of goods. This process accounts for 81% of the total environmental impacts for the ANC scenario. On the other hand, this experimental replication was performed only once, and the excessive temperature was reached. Thus, with a larger number of experiments, the average consumption of wood could be decreased due to the target of lower temperatures. Also, the amount of fired ceramic could be changed.

Although the factory consumes fossil fuels and energy generated in the Czech energy grid mix, the total impact in the Climate Change category is the second lowest. The ANC scenario has a total impact in this category of 4.03 kg CO_2 eq., but more than 1.85 kg CO_2 eq. is produced from biogenic sources (process of burning biomass). Similarly, the PSC scenario has the highest impact in this category due to its low energy efficiency.

Normalisation and Weighting

To assess the overall environmental impact, normalisation and weighting of the impact indicators' results were carried out according to EF 3.0 (person equivalents) [26]. The results

are presented in Table 3. The most significant results were reached in the category of Climate Change and Resource use, fossils. On the other hand, the results of the Ozone depletion category contribute the least to the overall impact.

Table 3. Normalized and weighted results, EF 3.0 (person equivalents).

Indicator	FAC	HERF	ANC	PW	PSC
Acidification	4.14×10^{-4}	6.73×10^{-4}	1.39×10^{-2}	7.76×10^{-4}	2.32×10^{-3}
Climate Change—total	9.48×10^{-3}	9.82×10^{-3}	1.05×10^{-2}	8.06×10^{-3}	2.32×10^{-2}
Ecotoxicity, freshwater—total	3.02×10^{-4}	1.02×10^{-3}	1.43×10^{-3}	8.07×10^{-4}	2.37×10^{-3}
Eutrophication, freshwater	6.91×10^{-6}	2.50×10^{-5}	4.19×10^{-4}	1.35×10^{-5}	3.91×10^{-5}
Eutrophication, marine	1.64×10^{-4}	2.91×10^{-4}	6.15×10^{-3}	2.20×10^{-4}	6.24×10^{-4}
Eutrophication, terrestrial	2.44×10^{-4}	4.46×10^{-4}	1.25×10^{-2}	3.20×10^{-4}	9.04×10^{-4}
Human toxicity, cancer—total	6.08×10^{-5}	7.37×10^{-5}	1.53×10^{-2}	4.47×10^{-5}	1.24×10^{-4}
Human toxicity, non-cancer—total	2.95×10^{-4}	3.07×10^{-4}	5.96×10^{-3}	2.04×10^{-4}	5.86×10^{-4}
Ionising radiation, human health	1.73×10^{-4}	1.98×10^{-4}	1.90×10^{-5}	4.86×10^{-4}	1.51×10^{-3}
Land Use	5.09×10^{-5}	1.19×10^{-4}	9.03×10^{-3}	1.41×10^{-4}	4.19×10^{-4}
Ozone depletion	6.10×10^{-9}	7.85×10^{-8}	2.73×10^{-10}	3.41×10^{-9}	8.42×10^{-9}
Particulate matter	6.37×10^{-4}	7.47×10^{-4}	5.28×10^{-1}	9.06×10^{-4}	2.64×10^{-3}
Photochemical ozone formation, human health	3.62×10^{-4}	5.55×10^{-4}	4.64×10^{-2}	4.64×10^{-4}	1.34×10^{-3}
Resource use, fossils	7.76×10^{-3}	7.42×10^{-3}	1.84×10^{-3}	6.22×10^{-3}	1.80×10^{-2}
Resource use, mineral and metals	4.22×10^{-5}	4.35×10^{-4}	1.22×10^{-4}	4.21×10^{-5}	1.20×10^{-4}
Water use	2.97×10^{-4}	5.12×10^{-5}	3.83×10^{-5}	2.60×10^{-4}	1.10×10^{-4}

The overall environmental impact can be calculated as a sum of normalized and weighted results. The comparison of the overall impact is presented in Figure 5.

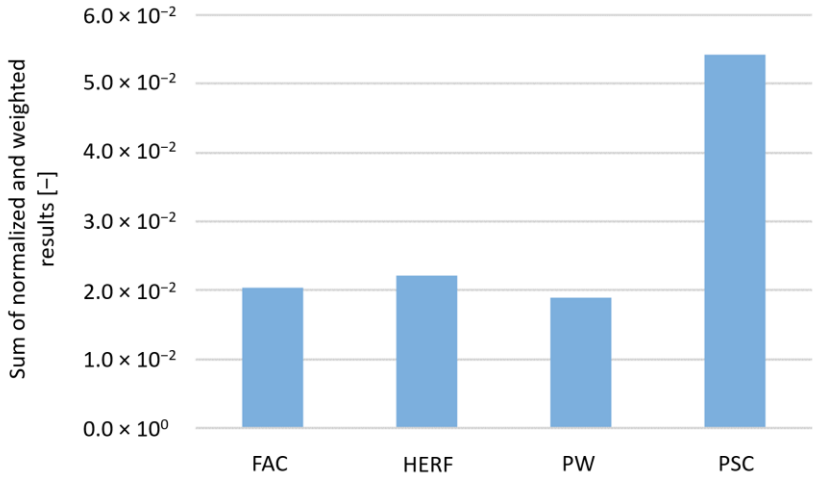


Figure 5. Normalized and weighted results of different types of ceramic production (without ancient production), EF 3.0 (person equivalents).

4. Discussion

Based on the environmental assessment of the scenarios considered, key parameters that influence the environmental impacts of tableware were identified. Similar to other studies, the key parameters are material and energy efficiency. These parameters affect the environmental impact of ceramic production regardless of the scale of production. However, the difference in the scale of production is reflected in the quality of systematisation and management of the production. For example, the low quality of the available input and output data of the production process was identified during the inventory analysis performed in the manufacturing production (small-scale studios). Although ceramics manufacturing does not reach the production capacity as high as a well-systematized factory, their overall number (in the Czech Republic more than 800) results in a regionally significant environmental impact. Therefore, the management of the production and

competence for an inventory analysis should be considered as an opportunity to reduce the environmental impact of this industry. Moreover, higher production in a factory can result in an increased impact related to transport and distribution [28].

4.1. Material Efficiency

In terms of material efficiency, manufacturers reach lower material losses than production in the factory. Due to the small production capacity, which allows more focus on each product, the rate of flaws is reduced. Moreover, the simplified space for production supports additional corrections, which decreases the number of damaged goods.

Considering overall production capacity, if one large industrial producer produces approx. 5000 tonnes and a small manufactory next to it produces 5 tonnes of ceramic tableware per year, the large number of these small producers makes their input of raw materials non-negligible. Assuming, that there are three large producers in the Czech Republic with a total capacity of 15,000 tonnes per year and approx. 800 small producers, then the production of ceramics and porcelain per year by manufacturers can be estimated as up to a quarter of the total production of ceramics and porcelain per year.

If we focus on waste generation, in the case of industrial production, this represents 30% of the total production (assuming the fourth quality grade as unsalable products), but in the case of a small studio, it is only 1–3%. Therefore, increasing material efficiency as one of the circular principles can be a way to prepare this industry for the reduced availability of primary raw materials in the future [29].

4.2. Energy Efficiency

The industrial production of ceramics is subject to environmental standards, and so the advanced technology used must enable a highly efficient use of energy in its operation [8]. For example, residual heat from the continuous tunnel kiln is used in further production processes (e.g., heat recovery). Due to systematisation and advanced technology, the industrial production of 1 kg of goods has a lower consumption of energy and therefore lower environmental impact than in the case of production in small ceramic workshops. This is in accordance with Cerame-Unie, which declared a roadmap to increase efficiency and rapidly decrease environmental impact [30].

Consequently, production in manufactories, specifically their firing process, often has lower efficiency. This may be due to an outdated kiln, which, for example, has a higher energy consumption due to inefficient thermal insulation. Furthermore, the energy requirements can also be negatively affected by the low density of the goods in the kiln—representing an insufficient use of space in the kiln chamber. As a result of these factors, the differences in energy consumption can range from 4 to 14 kWh per kg of fired goods. Similarly, the design of goods can influence not only the energy consumption but also the demand for water in the production of ceramic tiles and sanitaryware [31]. The energy intensity of each production scenario is expressed in kWh in Section 2.

4.3. Demanded Quality of a Product and Scrap Rate

The FAC scenario has the highest efficiency in terms of energy consumed and amount of fuel burnt. However, due to the relatively large number of discarded products (11%) that do not meet the customer quality criteria and the losses during bisque firing (7%), the environmental impact is allocated to a smaller amount of mass than the actual fired goods. However, in the overall comparison, the lowest environmental impact is allocated per kilogram of industrially produced ceramics (scenario FAC).

The significant potential for reducing impact can be reached by imparting not-so-strict criteria for the quality of the product (e.g., visual flaws) or by recycling this material in a closed loop. Unfortunately, closed-loop recycling in this technology is limited by the above-mentioned strict criteria, which do not allow any visual flaws. These strict criteria were previously criticized by designer David Sila, who suggested a concept developing

visual flaws on the surface as an intended design, which reduced the amount of discarded goods [32].

Similar to energy efficiency, the scrap rate of the fired product in the open pit (ANC scenario) could be reduced with a higher number of experiments. The evolving experience with the HERF technique could also be improved with a higher number of experiments, and so the quality of the product in this scenario could be improved.

The experimental method of ceramics production by pyrotechnics (HERF) lags behind the other scenarios in raw material consumption and uses pyrotechnic means containing potassium chlorate ($KClO_4$) during the process. The production of this raw chemical substance has an increased impact in the category of ozone depletion.

4.4. Limitation of the Inventory Analysis

In all cases, the input data for inventory analysis were obtained in collaboration with the ceramic producers, but each producer provided data with a different level of confidence. The inventory data of the industrial production scenario (FAC) was based on raw material purchase and white warehouse intake reports (warehouse for the 1st and 2nd Qty. grade products), energy and waste management reports, and emission measurement reports, and therefore a high level of confidence in the data obtained can be assumed. In the case of the scenarios for small ceramic studios (PW, PSC), the data were determined in part based on energy bills, invoices, and raw material purchases, and in part by expert estimation. In the Inventory of the Experimental Production Scenario (HERF), the data was obtained in part by measurement and in part by expert estimation. Another limitation of the study is the determination of the (ANC) scenario data. Considering a single-fire operation, the variability in the results can be assumed based on the amount of wood consumed. In terms of the impacts of the different process groups (material extraction, material preparation, product creation, firing, packaging, etc.), the firing phase, which is associated with high energy consumption, has the most significant negative impact on the environment in all scenarios considered. For example, in the (FAC) scenario, the amount of energy consumed during firing is 87% of the total energy used to produce 1 kg of goods.

4.5. Limitation of LCA Study

In this LCA case study, potential environmental impacts were related to the functional unit, which was characterised as 1 kg of fired ceramic tableware. However, the function of ceramic tableware can be more developed in future work. Although the calculation considering the amount of material is a possible option, future research can develop the functional unit, which will be characterised by considering esthetical properties, which are technical properties of a fired product or material properties of a green body.

In this study, the difference in properties of ceramic matter was neglected because it does not affect the outputs of the inventory analysis or the results of potential environmental impacts. Also, the outputs of the inventory analysis are not affected by the time of production or the number of calories per unit of product. These parameters are optimised by producers to reach energy consumption as low as possible and so the differences among technologies are covered by the overall consumption of electricity or heat.

Technical properties (e.g., mechanical hardness) of the fired product were assumed to be the same because they should meet the requirements of ISO 6486-2:1999 which describes the limit values for the use of tableware in contact with food [33], which represents the main function of the compared tableware.

Moreover, future research can be focused also on the definition of a function using the maximal reachable inner volume of tableware or even an esthetical evaluation of its appearance (considering properties such as shape, size, or user-friendliness). Nevertheless, these properties are rather influenced by the design of tableware and not by the production technology. Therefore, these properties were not considered in this study.

4.6. Alternative Production of Ceramic Tableware

Current ceramic production is limited by processes, of which environmental impacts are described in this study. Therefore, future research should be focused on new alternative ways of production. A possible way to reduce environmental impact can be the use of a hydrogen furnace for firing [34]. This is conditional on the use of so-called green hydrogen produced using renewable sources of electricity. Outside the conditions of the Czech Republic, the possible alternative to fossil-based firing can be solar furnaces or firing using geothermal energy [35,36].

Another alternative way of production can be the use of ecodesign to redefine limited technical values or limit the acceptable change of the esthetical properties of the product. Both these aspects must be developed and be transparently communicated with customers. Because this communication can be useful in the principles of environmental, social, and corporate governance (ESG), and the technology changes must be developed in compliance with the Do No Significant Harm (DNSH) principle [37,38]. An example of such a change can be the project which was focused on upcycling the 4th-grade of ceramic tableware. To increase the value of this low-quality ceramic, the plates were painted in cooperation with retirees, who could tell their life stories using paintings, which were printed on plates [39].

In general, the implementation of ecodesign leads to a reduction of potential environmental impacts. However, the most important step is the proper inventory analysis, which can kickstart the optimization of energy and material consumption. Consequently, this can bring changes such as the transfer to non-fossil sources, the use of residual heat, and the reduction of shapes, which have a more demanding technological process.

5. Conclusions

Based on the calculation performed using the LCA method, the PW production produced the lowest results of the overall environmental impact allocated to 1 kg of ceramic tableware. On the other hand, experimental prehistoric firing (ANC) has the highest environmental impact, mainly due to the particles released into the air during biomass combustion, which in this case account for 81% of the total environmental impact. However, if we compare only current ceramics production methods, the worst scenario is the PSC due to its low energy efficiency in the whole manufacturing process. Thus, the impact of PSC in the Climate Change category is 8.32 kg CO_2 eq. Furthermore, because of the high dependency of the Czech energy mix on fossil fuels, this scenario caused the highest impact in the Resource use category (fossils) (140 MJ). The experimental method of producing ceramics by explosion (HERF) lags behind the other scenarios in raw material consumption, using extra compounds (pyrotechnical aids) during the process. The use of these raw materials leads to an increased impact in the Ozone depletion category (6.67×10^{-10} kg CFC-11 eq.). The scenario (FAC) has the highest efficiency in the ratio of energy consumed to the amount of produced goods, however, due to the relatively large number of discarded products that do not meet strict quality criteria (more than 15%), the environmental impact is allocated to a smaller amount of material than the actual production. Among parameters such as material and energy efficiency, the key parameter for the ecodesign of ceramic tableware is the reduction of loss in production. Therefore, future research will focus on investigating ways to increase the circularity of secondary products and waste. Additionally, it was found that there is a need to educate producers on life cycle thinking and inventory analyses and support them in the preparation of fact-based communication in compliance with the principles of ESG.

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Abbreviations

ANC (Ancient ceramics technology), BREF (Best available techniques reference document), EF (Environmental footprint), FAC (Industrial production of ceramic tableware), ISO (International Organization for Standardization), LCA (Life Cycle Assessment), HERF (High energy rate forming), PSC (Manufacturing using slip casting), PW (Manufacturing using pottery wheel).

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