A life cycle assessment of the cradle-to-gate phases of clay brick production in South Africa

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Abstract

Quantified environmental impacts associated with clay brick production are not very well researched for the South African context. This paper, based on a study undertaken for the Clay Brick Association of South Africa, where clay bricks are still the predominant wall construction material, identifies processes within the various clay brick firing techniques, where environmental impacts are the most severe, with the intention to make producers aware of where they may improve production processes and reduce adverse environmental impacts. The paper will focus on the research results of the cradle-to-gate phase of the life cycle of clay bricks. The data collected from the full population survey were used to identify and model the environmental impacts using SimaPro software and the EcoInvent database. The results for the full industry (averaged across firing technologies) per kg of fired clay brick for the impact categories assessed are: carcinogens 0.007315 kg C_2H_3Cl eq, non-carcinogens 0.031052 kg C_2H_3Cl eq, respiratory inorganics 0.000426 kg PM2.5 eq, ionizing radiation 1.070064 Bq C-14 eq, ozone layer depletion <0.0000 kg CFC-11 eq, respiratory organics 0.000076 kg C_2H_4 eq, aquatic ecotoxicity 77.239 kg TEG water, terrestrial ecotoxicity 21.27 kg TEG soil, terrestrial acidification/nitrification 0.0088 kg SO_2 eq, land occupation 0.001759 m^2org.arable, aquatic acidification 0.004045 kg SO_2 eq, aquatic eutrophication 0.000150 kg PO_4 P-lim, global warming 0.853033kg CO_2 eq, non-renewable energy 8.99914 MJ primary and mineral extraction 0.000558 MJ surplus. Overall, the findings suggest that there is great potential to improve the clay brick manufacturing industry in terms of its environmental impacts.
Keywords: life cycle assessment, cradle-to-gate, clay brick, environmental impact, SimaPro.

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1 Introduction

The issue of sustainability has become increasingly critical in the current climatic and economic environment. In the 1987 Bruntland Report, the UN's World Commission on Environment and Development defined sustainability as meeting the needs of the present generation without compromising the ability of future generations to meet their needs [1].

Sustainability can also be defined as the balance needed between the gratification of present needs and the concern for the well-being of future generations [2]. This definition also alludes to the fact that although we deplete natural resources at the expense of future generations, we also generate capital and knowledge which raise the well-being of future generations.

The greatest contributor to achieve sustainability will be to reduce the global environmental changes earth is experiencing due to anthropogenic climate change. Man has evolved in such a way that little consideration is placed on earth's finite resources and the impacts development has had on the environment.

Construction is a major source of global greenhouse gas emissions, both during the manufacturing stages of building materials and in the operational phase of the building [3]. The building sector consumes between 30% and 45% of global energy production, with about 20% of that on the construction of the building and 80% during the operational phase of the building [4].

1.1 Scope of the study

The developing South African construction industry is dominated by two construction typologies: concrete frame and brick infill construction and load bearing brick construction. Other technologies such as light steel frame construction, timber construction and combination construction have traditionally been less used.

South Africa produced 450 million tonnes of CO_2 in 2009, placing it as the 12th greatest CO_2 emitter globally [5]. South Africa's CO_2 emission breakdown is dominated by transport at 16% and manufacturing at 40% [6]. Manufacturing includes the production of building materials, which contributes 18 million tonnes CO_2 per year to South Africa's emissions, 40% of this CO_2 is attributed to the manufacture of clay bricks [6].

1.2 Problem statement

The environmental impacts from the production and manufacture of clay bricks for the South African industry are not known; there is currently no published comprehensive research on the clay brick manufacturing industry's environmental impacts and this study attempted to fill this knowledge gap through the implementation of a life cycle assessment (LCA).

2 Research methodology

The research employed a quantitative methodology through a field survey of the total population and modelling using an internationally recognised and accepted LCA software model.

2.1 Population

The field survey targeted the full population of South African clay brick manufacturers that implement all the various clay brick firing technologies. Primary data were obtained from over 84% of the population.

The full population is made up of 102 manufacturers using six different firing technologies; all of which use very much the same production processes with the only difference being in the firing stage. Clamp kilns fire bricks in open air pyramid like structures of stacked green bricks. Tunnel kilns fire bricks in a closed natural gas/refined oil fired kiln. Transverse Arch (TVA) kilns are characterized by a continual insertion and removal of green and fired bricks in a continually coal-fired system of adjacent arched brick kilns. The Hoffman kiln is a circular tunnel constructed out of refractory brick with a continual coal supply shifting the fire along the tunnel. The Vertical Shaft Brick Kiln (VSBK) is a continually coal-fired shaft structure into which green bricks are hoisted at the top and removed once fired at the base. A Zigzag kiln is a continually coal-fired tunnel-like structure; the fire is moved through the zigzag shaped tunnel using fans. A breakdown of the population's firing technologies is shown in Table 1.

Table 1: Breakdown of the clay brick manufacturers' firing technologies.

Technology	Clamp	Tunnel	TVA	Hoffman	VSBK	Zigzag
Percentage of population	68%	20%	6%	2%	2%	2%

2.2 Research strategy

The data collection phase followed a literature review which revealed pertinent aspects of similar projects and consisted of the questionnaire design, ethical clearance, pre-testing followed by the field survey. The collected data were allocated to a predetermined set of manufacturing processes to better group the stages of production, which facilitated the process of LCA modelling. Preliminary statistical analyses were done to configure the collected data into the format required for LCA modelling in the SimaPro software.

2.3 Research delimitations

The study was delimited to the processes involved from raw material extraction to the gate of the manufacturing plant. Environmental impacts associated with the transport to site, construction, operational and end of life stages were not modelled. The format of the study is based on the LCA guidelines suggested in ISO 14040:2006 [7].

3 Life cycle assessment

3.1 Goal and scope definition

The purpose of the study was to assess the environmental impacts associated with the production of clay bricks in South Africa and is intended to be used as a baseline project for the subsequent stages of the life cycle of clay bricks, i.e. the use, demolition, waste and recycle phases.

The intended audience of the study includes LCA consultants, professions in the building industry, with particular reference to architects, specification writers as well as the clay brick manufacturers.

3.2 Product system description

The product system for this study started with raw material extraction and ended with bricks at the production plant gate which covered the following stages: raw material extraction, raw material processing, clay preparation, extrusion and forming, brick drying, brick firing and off packing.

The primary function of a clay brick is to provide a construction component with a defined set of thermal and structural principles which may be used in conjunction with other bricks and building materials to construct a wall or barrier between indoor and outdoor environments.

3.3 Reference flow and functional unit

The reference flow for this product system is one kilogram of fired clay brick. The functional unit for the product system is one standard brick equivalent (SBE) which is defined as a unit of 2,75kg of fired clay with a compressive strength between 12.5 and 17 MPa.

3.4 System boundary

The system boundary for this study is shown in Figure 1 and is defined by ISO 14040:2006 as the definition of the unit processes to be included in the system.

3.5 Allocation approach

Minimal allocation needed to be applied in this study as per ISO 14040:2006. Very few respondents in the study perform multi-output operations; therefore an allocation definition was not deemed necessary. Production plants which produce more than one product already provided a mass breakdown of all elementary flows to and from the different outputs. The data from these plants were treated as a single output plant as the data did not need to be allocated.

3.6 Data requirements and data quality

Data which were not available from the clay brick manufacturers' responses were sourced from the EcoInvent v2.2 database via SimaPro. Whereas the data obtained

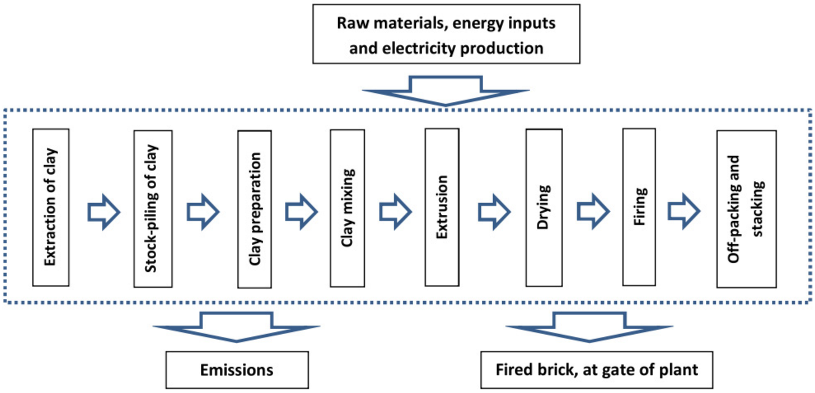

Figure 1: System boundary of the study.

from the field survey questionnaires were considered of the highest quality, data obtained from the EcoInvent were assumed to be of acceptable quality; it being peer reviewed before being incorporated in the database.

3.7 Impact assessment method

The inventory, developed from the data collection and subsequent modelling, identified certain environmental impacts through an assessment process within SimaPro. The impact assessment method selected for this study is Impact 2002+ which was selected as it proposes a feasible implementation of a combined midpoint/damage-orientated approach. Impact 2002+ assesses the following environmental impacts: carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, aquatic eco-toxicity, terrestrial eco-toxicity, terrestrial acidification, land occupation, global warming, non-renewable energy and mineral extraction.

3.8 Interpretation of the identified impacts

An interpretation of the main contributors to the environmental impacts was performed to identify the source of the greatest environmental impact from the assessed production processes.

3.9 Life cycle inventory (LCI)

The main data categories surveyed were land use, water use, energy use and waste creation, the latter included emissions, landfill and pollution. It was found feasible to use one questionnaire for all manufacturers, and even though their firing technologies differ, environmental inputs and outputs to and from all technologies are very similar. Selected aspects from the collected inventory for the life cycle model are presented in Table 2 below.

Table 2: Data collected used to compile LCI. (Quantities are expressed per kg fired clay brick.)

	Land	Water	Fuel burnt	Electricity	Transport (Diesel)
Clamp Kiln	0.0032 m^2	0.126 l	0.3067 kg Coal	0.00925142 kWh	0.00076 l
Tunnel Kiln	0.00000059 m^2	0.2150 l	0.14255 kg Coal 0.00203 GJ gas 0.0323 l fuel oil	0.042432838 kWh	0.00026 l
TVA Kiln	0.00000090 m^2	0.2022 l	0.25769 kg Coal	0.080068801 kWh	0.00054 l
Hoffman Kiln	0.00000155 m^2	0.1420 l	0.3062 kg Coal	0.022933906 kWh	0.00032 l
VSBK Kiln	0.00000023 m^2	0.1147 l	0.22913 kg Coal	0.018409449 kWh	0.00076 l
Zigzag Kiln	0.00000047 m^2	0.1926 l	0.182484 kg Coal	0.011293055 kWh	0.00131 l
Average	0.0005340 m^2	0.1655 l	0.237459 kg Coal	0.030689675 kWh	0.00066 l

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3.10 Life cycle impact assessment

The emissions of the modelled system are grouped into 15 environmental impacts according to Impact 2002+. The averaged environmental impacts associated with the production of clay bricks in South Africa are presented in Table 3 below.

Table 3: Environmental impact contributions averaged across all firing technologies.

Impact category		Unit	Quantity (emitted per kg fired clay brick)
1	Carcinogens	kg C_2H_3Cl eq	0.007315
2	Non-carcinogens	kg C_2H_3Cl eq	0.031052
3	Respiratory inorganics	kg PM 2.5 eq	0.000426
4	Ionizing radiation	Bq C-14 eq	1.070064
5	Ozone layer depletion	kg CFC-11 eq	0.000000
6	Respiratory organics	kg C_2H_4 eq	0.000076
7	Aquatic ecotoxicity	kg TEG water	77.239618
8	Terrestrial ecotoxicity	kg TEG soil	21.268101
9	Terrestrial acidification	kg SO_2 eq	0.008790
10	Land occupation	m^2 org.arable	0.001759
11	Aquatic acidification	kg SO_2 eq	0.004045
12	Aquatic eutrophication	kg PO_4 P-lim	0.000150
13	Global warming	kg CO_2 eq	0.853033
14	Non-renewable energy	MJ primary	8.999114
15	Mineral extraction	MJ surplus	0.000558

3.11 Normalization of results for comparison

Figure 2 below shows the normalization results for selected impact categories across all firing technologies. Normalization allows interpretation of results by comparing the different categories with the same units on the same graph. Normalization is performed by dividing the impact by the respective normalization factor. The normalization is a ratio of the total impact of a specific category and the total European population [8]. It was deemed satisfactory to use these normalization factors as there are currently no geographically specific factors for South Africa. The normalization of results is expressed as the impact caused by a Unitarian emission that is equivalent to the impact generated by the given number of persons per year (person. year/Unitarian$_{emission}$).

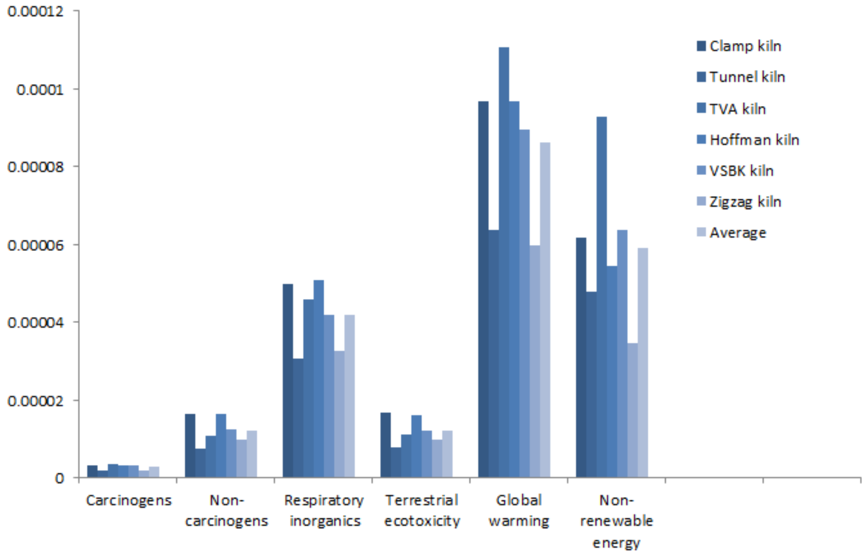

Figure 2: Normalization results for selected environmental impact categories.

3.12 Characterization of results

Table 4 shows the characterization results for all firing technologies in the clay brick production industry in South Africa. The total impact from the industry for the annual production of 9 611 178 Tons fired clay brick is reported in Table 4.

3.13 Interpretation

3.13.1 Significant issues

The results from the impact assessment show the impact each firing technology has on the assessed impact categories. Table 5 shows the severity of firing technologies on all impact categories. An assessment of the severity results show that the TVA kiln has the greatest environmental impact across most impact categories while the Tunnel kiln poses the least environmental impacts across the impact categories. These results should be read with an understanding of the population breakdown in order to evaluate the impacts.

The impact assessment reveals the unit processes or stages within the cradle-to-gate life cycle of clay bricks in South Africa which has the greatest impact on the environment. For all the firing technologies using coal as the firing fuel, the most severe impacts come from the firing stage unit process, where internal body fuel and external burning fuel release the following emissions into the atmosphere per kg of fired clay brick, refer to Table 6.

Table 4: Numerical characterization for all impact categories and for all firing technologies using Impact 2002+ calculation in SimaPro.

Impact category Unit	Clamp kiln	Tunnel kiln	TVA kiln	Hoffman kiln	VSBK kiln	Zigzag kiln	Total for industry
Carcinogens kg C_2H_3Cl eq	54 061 513.75	9 016 694.73	8 763 114.74	501 303.11	1 392 205.05	175 291.85	73 910 123.24
Non-carcinogens kg C_2H_3Cl eq	277 515 792.72	33 668 662.43	26 085 687.08	2 583 394.78	5 199 313.02	883 231.99	345 936 082.01
Respiratory inorganics kg PM2.5 eq	3 360 282.85	545 139.05	446 862.65	31 966.98	70 072.32	11 724.03	4 466 047.88
Ionizing radiation Bq C-14 eq	6 359 658 692.50	1 532 351 028.60	1 416 251 247.20	58 953 760.56	240 468 424.16	24 985 697.40	9 632 668 850.41
Ozone layer depletion kg CFC-11 eq	15.36	44.85	60.43	0.13	4.77	0.16	125.70
Respiratory organics kg C_2H_4 eq	433 239.52	110 918.70	114 739.25	3 861.05	15 739.14	1 803.36	680 301.02
Aquatic ecotoxicity kg TEG water	703 703 397 088.03	86 930 461 374.48	68 530 756 496.05	6 192 283 271.13	12 651 563 454.87	2 120 344 022.74	880 128 805 707.30
Terrestrial ecotoxicity kg TEG soil	192 615 116 299.31	23 829 918 642.52	18 617 667 571.56	1 711 476 326.18	3 483 118 627.42	597 907 045.18	240 855 204 512.17
Terrestrial acid/nutri kg SO_2 eq	67 081 018.35	11 722 246.63	9 856 363.76	630 209.99	1 425 117.76	243 393.54	90 958 350.04
Land occupation m^2 org.arable	15 299 307.51	1 797 799.42	1 303 711.12	173 867.33	282 863.85	47 621.08	18 905 170.30
Aquatic acidification kg SO_2 eq	32 917 420.26	5 025 664.30	4 139 883.43	310 854.27	662 583.84	109 785.45	43 166 191.55
Aquatic eutrophication kg PO_4 P-lim	1 473 738.97	161 798.71	122 496.17	11 942.96	24 651.05	4 132.92	1 798 760.77
Global warming kg CO_2 eq	6 358 877 310.30	1 101 882 500.55	1 049 650 165.80	59 380 429.44	146 811 623.48	20 901 533.47	8 737 503 563.04
Non-renewable energy MJ primary	62 234 562 910.54	12 737 162 457.34	13 503 328 363.55	513 486 856.15	1 608 284 737.18	185 965 002.06	90 782 790 326.82
Mineral extraction MJ surplus	3 641 788.83	677 644.44	594 055.22	31 544.95	139 132.60	15 765.05	5 099 931.08

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Table 5: Highest and lowest severity of all firing technologies for all impact categories per kg fired clay brick.

Impact category		Most severe contributing firing technology	Least severe contributing firing technology
1	Carcinogens	TVA	Zigzag
2	Non-carcinogens	Clamp	Tunnel
3	Respiratory inorganics	Hoffman	Tunnel
4	Ionizing radiation	TVA	Zigzag
5	Ozone layer depletion	TVA	Hoffman
6	Respiratory organics	TVA	Zigzag
7	Aquatic ecotoxicity	Clamp	Tunnel
8	Terrestrial ecotoxicity	Clamp	Tunnel
9	Terrestrial acidification	TVA	Tunnel
10	Land occupation	Hoffman	Tunnel
11	Aquatic acidification	Hoffman	Tunnel
12	Aquatic eutrophication	Clamp	Tunnel
13	Global warming	TVA	Zigzag
14	Non-renewable energy	TVA	Zigzag
15	Mineral extraction	VSBK	Tunnel

Table 6: Emissions data from coal combustion for 1 kg of fired clay brick*.

Substance	Quantity
Carbon dioxide	0.095 kg
Carbon monoxide	0.005 kg
Sulphur dioxide	0.00044 kg
Polonium-210	0.000085 kg
Radium-228	0.000065 kg
Nitrogen oxides	0.000060 kg
Lead-210	0.000046 kg
Particulates > 10 µm	0.000035 kg
Silicon	0.0000158 kg
Hydrogen chloride	0.0000152 kg
Methane	0.000015 kg

*Proxy data was used as a basis for developing the emissions data used in the model (highest 10 contributors to emissions shown here).

3.13.2 Sensitivity, consistency and completeness checks

Sensitivity analyses were carried out on the model to assess the impact of emissions data, water use, mass of clay, electricity consumption split between unit processes and transport of firing fuel to manufacturing plant. Data obtained from literature are estimates for the South African context; this includes emissions from burning coal. Analyses showed little variation, this is due to the fact that the full population was surveyed and actual figures were recorded in the field survey. It can therefore be concluded that the data represented in the LCA model are accurate and a true reflection of the clay brick industry in South Africa.

Consistency and completeness checks were carried to ensure complete data was utilized in the LCA model. Consistency was achieved through invariable questionnaires being utilized in the field survey process as well as the disregarding incomplete questionnaires. Infrastructure processes were excluded from data collected. Literature data were sourced from a single database to ensure consistent reviewing. Geographically specific data was used where possible.

4 Conclusions

The research shows that the production of clay bricks in South Africa is heavily energy intensive. Most of the emissions generated from the cradle-to-gate stages are attributed to burning fuel during the firing process on the production site where coal is combusted in order to vitrify the clay bricks. The greatest environmental impact is the use of non-renewable energy sources; in this case from the high use of fossil fuels for firing bricks or electricity which is sourced from the South African electricity grid, which in turn is generated almost entirely by coal powered power stations.

The research shows that continually fired kilns have lower environmental impacts. It is advisable for manufacturers that currently utilise kilns that require start up for each batch of bricks to investigate and eventually invest in continually fired kiln technologies such as Zigzag kilns and Tunnel kilns.

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