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# Comparative life cycle assessment of ornamental stone processing waste recycling, sand, clay and limestone filler

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**Abstract**

Owing to the cost of destination and transportation of ornamental stone processing waste, many studies focused on the reuse and recycling of this product. However, there is a scarcity of articles addressing the environmental viability of the recycling of ornamental stone. In this context, this study comprehends a comparative life cycle assessment of ornamental stone processing waste and conventional materials: sand, clay and limestone filler. The modelling software used was SimaPro 8.3.0.0 with Ecoinvent 3.2 database, employing the ReCiPe H/H methodology for impact assessment. The results show that the recycling of ornamental stone processing waste is environmentally preferable, and the artificial drying alternatives, such as flash dryer and rotary dryer, have lower environmental impact than extracting and processing clay through atomisation methods and limestone filler production. The sensitivity analysis indicated that it is possible to transport the ornamental stone processing waste 37 km after processing, so it reaches the same environmental impact as sand extracted by dredging. On the other hand, an increase of 25% in the energy consumption incremented only 7% of the environmental impact owing to the Brazilian energy mix.

**Keywords**

Life cycle assessment, environmental impact assessment, ornamental stone processing waste, clay, sand, limestone filler

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## Introduction

According to Montani (2014; cited in ABIROCHAS, 2014), the world ornamental stone production in 2014 corresponded to 130 million tonnes and it is estimated to rise up to 170 million tonnes by the year of 2020 (ABIROCHAS, 2014). As the production increases, the waste generation, which represents 25%–30% of the ornamental stone production, is expected to rise (Gonçalves, 2000).

Uliana et al. (2015) argue that owing to the cost of destination and transportation of the ornamental stone processing waste (OSPW), many researches study the reuse or recycling of ornamental stone waste. Some studies show that OSPW can be used for soil acidity correcting (Raymundo et al., 2013), manufacturing concrete (Degen et al., 2013), tiles (Souza et al., 2010), porcelain (Silva et al., 2011), and producing fibres for acoustic insulation (Alves et al., 2015). The OSPW may be used in cementitious matrices, filling the spaces between the pastes and positively influencing the stability. Nevertheless, if high quantities are inserted, the filler effect may be reduced (Galetakis and Soultana, 2016). Corinaldesi et al. (2010) discovered that a 10% substitution of sand with the use of additives contributed with the axial compression resistance to the same workability. Almeida et al. (2007) analysed different quantities of sand substitution from 5%–100% and have discovered that the 5% substitution presents improvement to the mechanical properties and durability of high performance concrete. At last, Calmon et al. (2005) showed that self-compacting concrete with high slag content combined with 31% of OSPW may create a concrete with high resistance. On the other hand, the OSPW may also substitute clay in ceramic materials, such as soil-cement bricks (Calmon et al., 1998), roof tiles (Monteiro et al., 2004) and ceramic bricks with good technical viability proved by different studies. However, one must stress that reuse and recycling options might affect the environment more than producing a new product, depending on the processes utilised. To conclude, if reusing or recycling are better alternatives for a product or system, a detailed environmental impact study is required, that can be effectively achieved using the life cycle assessment (LCA) methodology, which can be product or system oriented (UNEP, 1996).

García et al. (2007) conducted an initial evaluation of building material incorporating ornamental stone sludge utilising the life cycle assessment (LCA) with the software SimaPro 7.0 and

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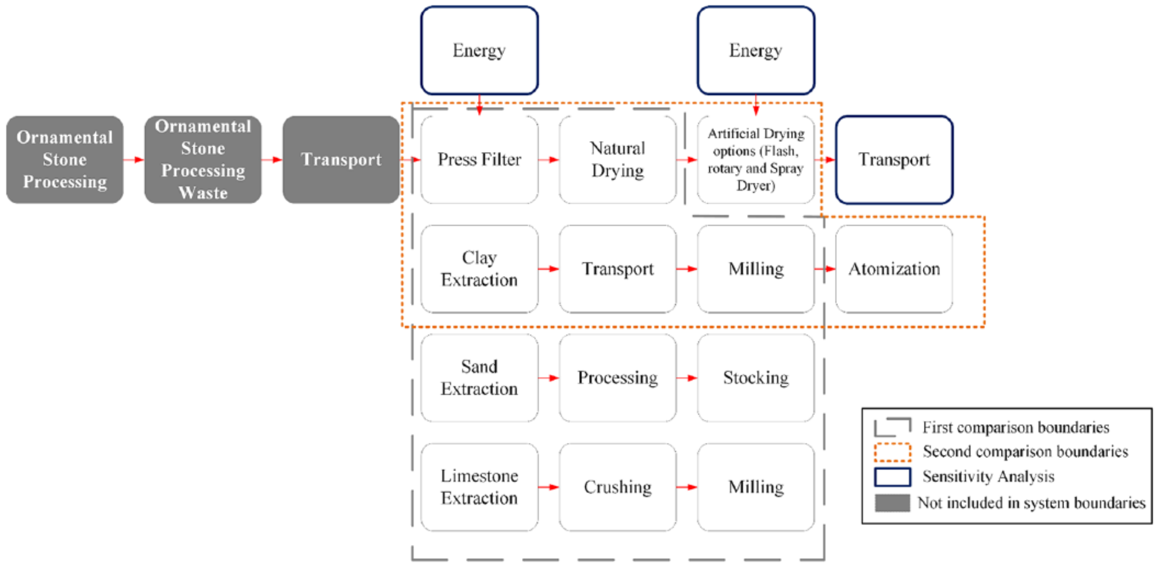


**Figure 1.** System boundaries.

Ecoinvent database. For the impact analysis, the study used Eco-Indicator 99. The authors compared natural limestone with artificial stones produced with ornamental stone sludge. They concluded that the artificial stone is preferable owing to a lower environmental impact from emission of inorganic fine particulate matter (<2.5 µm), originated in the extraction phase of the natural stone. Furthermore, Napolano et al. (2016) made a comparison of artificial lightweight aggregates (LWAs), produced with ornamental stone waste and clay, and its posterior use in concrete. For this study, they used SimaPro 7.3 with the Ecoinvent database. For the impact evaluation, the authors used Impact 2002+. They concluded that the incorporation of the ornamental stone waste was environmentally preferable. Singh et al. (2017) and Khodabakhshian et al. (2018) evaluated the environmental impact of the introduction of marble powder in concrete. The authors displayed an environmental impact comparison of normal concrete with the use of marble powder as cement and sand replacement. They used UMBERTO NXT and ReCiPe midpoint and endpoint methods and found that the use of marble slurry reduces the environmental impact of concrete. On the other hand, Khodabakhshian et al. (2018) describes the environmental impact of 16 concrete mixes containing marble waste powder and silica fume as a partial replacement to Portland cement. The environmental impact analysis consisted of global warming potential, acidification and fossil depletion. As a result, the authors found that the 20% rate of cement substitution results in a 14% to 20% reduction in environmental indicators.

To our best knowledge, few studies in the literature are available to categorise the recycling of OSPW environmental impacts through the LCA tool and no detailed study was found in that matter. In this context, this work aims to evaluate the environmental impacts of recycling the OSPW in comparison with the products it may replace in the production of cement and ceramic-based building materials, such as sand, clay and filler, by using a cradle-to-gate approach. Furthermore, this work evaluates the environmental impact of different transportation distances and energy consumption.

## Methodology

The methodology of LCA is defined by ISO 14040 (2006) and ISO 14044 (2006). The first describes the principles and framework and the second provides guidelines for LCA, including: (1) goal and scope definition; (2) the life cycle inventory (LCI) analysis and; (3) the life cycle impact assessment (LCIA).

### *Goal and scope definition*

According to ISO 14040 (2006), the goal includes the intended application, the reasons for carrying out the study, the intended audience and whether the results are intended to be used in comparative assertions. For this study, the goal is to compare the environmental impact of OSPW, clay, sand and filler in order to understand if it is environmentally viable to recycle the OSPW, reaching the scientific community and enterprises interested in the recycling process of OSPW.

This study includes four products that will be evaluated: (1) sand; (2) clay; (3) limestone filler; and (4) OSPW (Figure 1). All the analysis were carried out considering 1 kg of product as the functional unit. Only the production process of all products was considered, since the information of the infrastructure and maintenance was scarce and did not fulfil the requirements of this research. In addition, the authors excluded emissions of particulate matter in the drying patio for the analysis for all the products, because there was not data available for this impact. Regarding the OSPW, the authors considered the economic allocation. Therefore, the waste entered the recycling process without impact.

## LCI

The data collection consisted in background and foreground data (Table 1), the first composed by the available literature and the latter using a questionnaire sent by email to the enterprises visited (one that recycles OSPW and one that produces limestone filler). The database used in this work was Ecoinvent 3.2. In order to assert that the LCI data was enough to assess the goal and scope defined in this work, this article has used Data Quality Goals, considering the temporal (TC), geographic (GC), further technological correlation (FTC), reliability (RE) and completeness (CO). The research was carried out in 2016 and the technology representativeness are the machines and operations available in Espírito Santo, Brazil. In order to assess the data quality, this work used the methodology stablished by Weidema et al., 2013 and Weidema and Wesnaes (1996) (Table 1).

For the sand, this work considered two cases: Sand extracted by dredging and by submerged cave. The sand processing for both cases takes place in the site of extraction. According to Souza (2012), for the sand extracted with the dredging technique there is a consumption, per kilo of sand, of 1.11E-06 $m^3$ of water, 4.33E-02 MJ of diesel and an output of 2.38-04 $m^3$ of water. Since the processing and the extraction use the same types of motors, it made it possible to apply the same data for the processing stage. Finally, at the storage stage, a consumption of 6.50E-03 MJ of diesel per kilo of sand was considered. On the other hand, for the submerged cave, Castro et al. (2015) listed a consumption of 7.41E-02 MJ of diesel and 1.30E-04 kWh of electricity, both per kilo of sand.

This research considered three case scenarios for clay: (1) captive mine, (2) medium size mine, (3) average of (1) and (2) scenarios with the atomisation using natural gas instead of coal. According to the Mines and Energy Ministry (MME, 2009) the clay extraction on captive mine and on medium production mine consumed 0.029104 MJ diesel and 0.014552 MJ diesel per kilo of clay, respectively. Additionally, for the atomisation and milling process, the coal consumption were 2.09 MJ and 1.8424 MJ per kilo of clay for the first and second case of extraction (Pereira, 2004). In the last case studied, the milling had a consumption of 0.01180 kWh $kg^{-1}$ of clay and 0.0002 $m^3$ of water $kg^{-1}$ of clay and the atomisation process had an input of 1.7740 MJ of natural gas $kg^{-1}$ of clay, which represents the national thermal energy consumption average (Alves et al., 2007). The transportation between the extraction site and the processing site, for all three cases considered, was 6.6 kg $km^{-1}$, utilising the coordinates given by Ferreira et al. (2012).

Since it was not possible to find or collect data for the extraction and the crushing phases of limestone filler production, the library *Limestone, unprocessed {CA-QC}| limestone quarry operation | Alloc Def, U* and *Limestone, crushed, for mill {CA-QC}| production | Alloc Def, U*, were utilised. Moreover, the water source and the energy source were adapted to the Brazilian reality. For the milling of filler, the enterprise visited provided the energy used by the six mills and the bag house, which sums 1635 kW. The enterprise also provided that the mills are working 3036 hours per year and according to the Mineral Production National Department (DNPM, 2010), the production of limestone miller is estimated to be 78370 t of filler per year, which results in a consumption of 0.06334 kWh $kg^{-1}$.

For the process of ornamental stone waste, this research considered a humidity of 50% on the entry of the system. The press filter consumes 0.723E-03 kWh of electricity $kg^{-1}$ of waste and –0.304E-03 $m^3$ of avoided water consumption per kilo of waste, calculated with the data provided by the enterprise visited. In the subsequent phases, natural drying and crushing, the consumptions were: 0.000156 kWh of electricity $kg^{-1}$ of waste, 1.06 kg of the waste, 1.31E-05 h of machine operation and 1.5E-03 transportation of 1 ton per 1 km (tkm) of transportation to move the product inside the factory. It was also considered an output of 0.106E-3 $m^3$ of evaporating water. Nonetheless, it was assumed three different artificial drying scenarios, two of them after the crushing and with the impact of the previous phases added (rotary and flash dryer), and one after the press filter (spray dryer). The rotary dryer energy consumption estimation was 0.276 MJ $kg^{-1}$ of heat and an output of 0.04E-03 $m^3$ of water, while the flash dryer had a consumption of 0.270 MJ $kg^{-1}$ of heat and 0.04E-03 $m^3$ of water as an output. On the other hand, the consumption of natural gas in the spray dryer is much higher than both previous alternatives: it comes to 1.2 MJ $kg^{-1}$ and the output of water is 0.04E-03 $m^3$ (Mujumdar, 2015).

## LCIA

The assessment tool applied was SimaPro Faculty 8.3.0.0. For the impact analysis, the methodology utilised was ReCiPe 2008 v1.3. The midpoint categories analysed in this study were: (i) climate change (CC), (ii) ozone depletion (OD), (iii) terrestrial acidification (TA), (iv) freshwater eutrophication (FEU), (v) marine eutrophication (MEU), (vi) human toxicity (HT), (vii) photochemical oxidation (PO), (viii) particulate matter (PM), (ix) terrestrial ecotoxicity (TE), (x) freshwater ecotoxicity (FE), (xi) marine ecotoxicity (ME), (xii) ionising radiation (IR), (xiii) agricultural land occupation (ALO), (xiv) urban land occupation (ULO), (xv) natural land transformation (NLT), (xvi) water depletion (WD), (xvii) metal depletion (MD) and (xviii) fossil depletion (FD). For the endpoint categories, this study used human health, resources and ecosystem. The standard scenario consisted of two comparisons: (1) Comparison between sand, clay without the atomisation process, limestone filler and the recycling process of ornamental stone waste with natural drying; and (2) clay with atomisation process and the OSPW artificial drying. The standard scenario was conducted from cradle-to-gate and two sensitivity analyses were carried out: (1) Energy sensibility, in which the energy used in the OSPW standard scenario was increased in 25% or decreased 25%; and (2) transportation sensibility, in which the distance of 1 kgkm was performed in the SimaPro 8.3.0.0 to equalise the environmental impact of OSPW with sand, clay and limestone filler.

**Table 1.** Data used in SimaPro and quality data.

| Product | Stage | Input | Value | Unit | Source | Quality data[a] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | RE | CO | TC | GC | FTC |
| Sand (dredging) | Extraction | Sand, quartz | 1 | Kg | — | No loss assumed in the process | | | | |
| | | Water, unspecified natural origin, BR | 1.11E-06 | $m^3$ | Souza, 2012 | 3 | 5 | 2 | 3 | 2 |
| | | Diesel, burned in building machine {GLO}\| market for \| Alloc Def, U | 4.33E-02 | MJ | Souza, 2012 | 3 | 5 | 2 | 3 | 2 |
| | Processing | Sand Extraction – dredging | 1 | Kg | — | No loss assumed in the process | | | | |
| | | Water, unspecified natural origin, BR | 1.11E-06 | $m^3$ | Souza, 2012 | 3 | 5 | 2 | 3 | 2 |
| | | Diesel, burned in building machine {GLO}\| market for \| Alloc Def, U | 4.33E-02 | MJ | Souza, 2012 | 3 | 5 | 2 | 3 | 2 |
| | Storage | Sand Processing (dredging) | 1 | Kg | — | - | - | - | - | - |
| | | Diesel, burned in building machine {GLO}\| market for \| Alloc Def, U | 6.50E-03 | MJ | Souza, 2012 | 3 | 5 | 2 | 3 | 2 |
| Sand (submerse extraction) | All Stages | Sand, quartz | 1 | Kg | — | No loss assumed in the process | | | | |
| | | Diesel, burned in building machine {GLO}\| market for \| Alloc Def, U | 7.41E-02 | MJ | Castro et al., 2015 | 3 | 5 | 1 | 3 | 2 |
| | | Electricity, medium voltage {BR}\| market for \| Alloc Def, U | 1.30E-04 | kWh | Castro et al., 2015 | 3 | 5 | 1 | 3 | 2 |
| Clay (captive mine) | Extraction | Clay, unspecified | 1 | Kg | — | No loss assumed in the process | | | | |
| | | Diesel, burned in building machine {GLO}\| market for \| Alloc Def, U | 0.02904 | MJ | MME, 2009 | 3 | 5 | 3 | 2 | 2 |
| | Transportation to processing site | Transport, freight, lorry 3.5–7.5 t, EURO3 {RoW}\| transport, freight, lorry 3.5–7.5 t, EURO3 \| Alloc Def, U | 6.60E-03 | Tkm | Google Maps | 2 | 5 | 1 | 1 | 5 |
| | | Clay extraction (case A) | 1 | Kg | — | No loss assumed in the process | | | | |
| | Processing | Water, unspecified natural origin, BR | 5.33E-04 | $m^3$ | Pereira, 2004 | 3 | 5 | 4 | 3 | 2 |
| | | Clay transport (case A) | 1 | Kg | — | - | - | - | - | - |
| | | Lignite briquettes {RoW}\| production \| Alloc Def, U | 2.09 | MJ | Pereira, 2004 | 3 | 5 | 4 | 3 | 2 |

**Table 1.** (Continued)

| Product | Stage | Input | Value | Unit | Source | Quality data[a] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | RE | CO | TC | GC | FTC |
| Clay (medium size extraction) | Extraction | Clay, unspecified | 1 | Kg | — | No loss assumed in the process | | | | |
| | | Diesel, burned in building machine {GLO}\| market for \| Alloc Def, U | 0.01455 | MJ | MME, 2009 | 3 | 5 | 3 | 2 | 2 |
| | Transportation to processing site | Transport, freight, lorry 3.5–7.5 t, EURO3 {RoW}\| transport, freight, lorry 3.5–7.5 t, EURO3 \| Alloc Def, U | 6.60E-03 | Tkm | Google Maps | 2 | 5 | 1 | 1 | 5 |
| | | Clay extraction (case B) | 1 | Kg | — | No loss assumed in the process | | | | |
| | Processing | Water, unspecified natural origin, BR | 2.00E-04 | $m^3$ | Pereira, 2004 | 3 | 5 | 4 | 3 | 2 |
| | | Clay transport (case B) | 1 | Kg | — | | | | | |
| | | Lignite briquettes {RoW}\| production \| Alloc Def, U | 1.84242 | MJ | Pereira, 2004 | 3 | 5 | 4 | 3 | 2 |
| Clay (intermediate extraction) | Extraction | Clay, unspecified | 1 | Kg | — | No loss assumed in the process | | | | |
| | | Diesel, burned in building machine {GLO}\| market for \| Alloc Def, U | 0.02157 | MJ | MME, 2009 | 3 | 5 | 3 | 2 | 2 |
| | Transportation to processing site | Transport, freight, lorry 3.5–7.5 t, EURO3 {RoW}\| transport, freight, lorry 3.5–7.5 t, EURO3 \| Alloc Def, U | 6.6 E-03 | Tkm | Google Maps | 2 | 5 | 1 | 1 | 5 |
| | | Clay extraction (case C) | 1 | Kg | — | — | — | — | — | — |
| | Milling | Water, unspecified natural origin, BR | 0.0002 | $m^3$ | Pereira, 2004 | 3 | 5 | 4 | 3 | 2 |
| | | Clay transport (case C) | 1 | Kg | — | — | — | — | — | — |
| | | Electricity, medium voltage {BR}\| market for \| Alloc Def, U | 0.0118 | kWh | Alves et al., (2007) | 5 | 3 | 3 | 3 | 2 |
| | Atomisation | Clay processing (case C – moagem) | 1 | Kg | — | — | — | — | — | — |
| | | Heat, district or industrial, natural gas {RoW}\| heat production, natural gas, at boiler condensing modulating >100 kW \| Alloc Def, U | 1.77402 | MJ | Alves et al., (2007) | 5 | 3 | 3 | 3 | 2 |
| OSPW | Press filter | Electricity, medium voltage {BR}\| market for \| Alloc Def, U | 7.23E-04 | kWh | Enterprise visited | 3 | 4 | 1 | 1 | 1 |
| | | Water, BR | −3.04E-04 | $m^3$ | Enterprise visited | 3 | 4 | 1 | 1 | 1 |
| | Natural drying | Electricity, medium voltage {BR}\| market for \| Alloc Def, U | 1.56E-04 | kWh | Enterprise visited | 3 | 4 | 1 | 1 | 1 |
| | | Transport, freight, lorry 7.5–16 t, EURO3 {RER}\| transport, freight, lorry 7.5–16 t, EURO3 \| Alloc Def, U | 1.5 | kgkm | Enterprise visited | 3 | 4 | 1 | 1 | 1 |
| | | LBRO – press filter 15% | 1.106 | kg | — | — | — | — | — | — |
| | | Machine operation, diesel, ⩾18.64 kW and <74.57 kW, steady-state {GLO}\| market for \| Alloc Def, U | 1.31E-05 | hr | Enterprise visited | 3 | 4 | 1 | 1 | 1 |
| | | Water $m^{-3}$ | 1.06E-04 | $m^3$ | Enterprise visited | 3 | 4 | 1 | 1 | 1 |

*(Continued)*

**Table 1.** (Continued)

| Product | Stage | Input | Value | Unit | Source | Quality data[a] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | RE | CO | TC | GC | FTC |
| OSPW | Rotary dryer | LBRO – press filter and natural drying | 1.04 | kg | — | — | — | — | — | — |
| | | Heat, district or industrial, natural gas {RoW}\| heat production, natural gas, at boiler condensing modulating >100 kW \| Alloc Def, U | 0.276 | MJ | Mujumdar, 2015 | 5 | 4 | 5 | 5 | 2 |
| | | Water $m^{-3}$ | 4.00E-05 | $m^3$ | Mujumdar, 2015 | 5 | 4 | 5 | 5 | 2 |
| OSPW | Flash dryer | LBRO – press filter and natural drying | 1.04 | kg | — | — | — | — | — | — |
| | | Heat, district or industrial, natural gas {RoW}\| heat production, natural gas, at boiler condensing modulating >100 kW \| Alloc Def, U | 0.27 | MJ | Mujumdar, 2015 | 5 | 4 | 5 | 5 | 2 |
| | | Water $m^{-3}$ | 4.00E-05 | $m^3$ | Mujumdar, 2015 | 5 | 4 | 5 | 5 | 2 |
| OSPW | Spray dryer | Heat, district or industrial, natural gas {RoW}\| heat production, natural gas, at boiler condensing modulating >100 kW \| Alloc Def, U | 1.2 | MJ | Mujumdar, 2015 | 5 | 4 | 5 | 5 | 2 |
| | | LBRO – press filter 15% | 1.15 | kg | — | — | — | — | — | — |
| | | Water $m^{-3}$ | 1.50E-04 | $m^3$ | Mujumdar, 2015 | 5 | 4 | 5 | 5 | 2 |
| Limestone filler | Milling | Limestone, crushed | 1 | kg | — | — | — | — | — | — |
| | | Electricity, medium voltage {BR}\| market for \| Alloc Def, U | 6.33E-02 | kWh | Enterprise visited | 3 | 4 | 1 | 1 | 1 |

[a]The data quality is described in scores from 1 to 5, where 1 represents the best mark and 5 the worst. The scores were given according to the methodology described by Weidema and Wesnaes (1996) and Weidema et al. (2013).

RE: reliability; CO: completeness; TC: temporal; GC: geographic; FTC: further technological correlation; BR: Brazil; GLO: Global; Alloc Def: Allocation Default; RoW: rest of the world.

**Table 2.** Characterisation results of midpoint category for sand, clay, filler and OSPW.

| Impact category | Unit | Sand (submerged cave) | Sand – dredging | Limestone filler | OSPW | Cay – (milling – intermediate extraction) |
|---|---|---|---|---|---|---|
| CC | kg CO2 eq | 0.00685 | 0.008575 | 0.01573 | 0.000764 | 0.007699 |
| OD | kg CFC-11 eq | 1.25E-09 | 1.57E-09 | 1.9E-09 | 1.26E-10 | 1.2E-09 |
| TA | kg SO2 eq | 5.51E-05 | 6.91E-05 | 8.31E-05 | 3.39E-06 | 4.22E-05 |
| FEU | kg P eq | 3.11E-07 | 3.82E-07 | 3.88E-06 | 9.41E-08 | 1.15E-06 |
| MEU | kg N eq | 3.24E-06 | 4.07E-06 | 5.07E-06 | 1.89E-07 | 2.42E-06 |
| HT | kg 1,4-DB eq | 0.000386 | 0.000477 | 0.003648 | 0.000157 | 0.001664 |
| PO | kg NMVOC | 9.41E-05 | 0.000118 | 8.81E-05 | 4.44E-06 | 5.75E-05 |
| PM | kg PM10 eq | 2.84E-05 | 3.56E-05 | 0.000192 | 1.64E-06 | 2.12E-05 |
| TE | kg 1,4-DB eq | 2.79E-07 | 3.17E-07 | 1.32E-05 | 3.25E-07 | 3.49E-06 |
| FE | kg 1,4-DB eq | 1.34E-05 | 1.63E-05 | 0.000231 | 5.17E-06 | 5.94E-05 |
| ME | kg 1,4-DB eq | 1.28E-05 | 1.55E-05 | 0.000205 | 5.38E-06 | 5.94E-05 |
| IR | kBq U235 eq | 0.000473 | 0.00059 | 0.001802 | 6.81E-05 | 0.000675 |
| ALO | m2a | 4.56E-05 | 3.16E-05 | 0.010005 | 0.000155 | 0.001908 |
| ULO | m2a | 1.53E-05 | 1.9E-05 | 7.87E-05 | 1.58E-05 | 0.000134 |
| NLT | m2 | 2.64E-06 | 3.26E-06 | 2.19E-05 | 5.32E-07 | 5.85E-06 |
| WD | m3 | 1.69E-05 | −0.00046 | 0.001639 | 0.000362 | 0.000513 |
| MD | kg Fe eq | 0.000227 | 0.000283 | 0.000649 | 2.95E-05 | 0.000337 |
| FD | kg oil eq | 0.002385 | 0.00299 | 0.003737 | 0.000243 | 0.002371 |

OSPW: ornamental stone processing waste; CC: climate change; OD: ozone depletion; TA: terrestrial acidification; FEU: freshwater eutrophication; MEU: marine eutrophication; HT: human toxicity; PO: photochemical oxidation; PM: particulate matter; TE: terrestrial ecotoxicity; FE: freshwater ecotoxicity; ME: marine ecotoxicity; IR: ionising radiation; ALO: agricultural land occupation; ULO: urban land occupation; NLT: natural land transformation; WD: water depletion; MD: metal depletion; FD: fossil depletion.

## Results and discussion

Limestone filler presented the largest environmental impact of all products for most categories, except (Table 2) photochemical oxidation and urban land occupation that had sand (dredging) and clay – intermediate case with bigger impacts, respectively. This is owing to the use of diesel in the extraction, processing and stocking of sand. Moreover, for the clay with intermediate extraction and only milling, the impact of urban land occupation was mostly owing to the transportation phase. The filler presented the bigger impacts owing to the consumption of energy in the milling process.

Regarding the comparisons of the products with the OSPW recycling process, the OSPW had an overall better performance than the other products. However, in the categories of TE, ALO, ULO and WD the OSPW had a bigger impact than sand extracted by submerged cave for TE and ULO and ALO and WD for dredging sand. For the TE, WD and ALO, most of the impact of OSPW is owing to the energy use on the press filter. On the other hand, ULO is caused mostly by the transportation in the site of recycling the OSPW. Finally, the most important category in all products was climate change, because of the use of energy and diesel in the processes evaluated.

Regarding the clay with atomisation and the further drying of the OSPW scenarios, the scenario with captive mine presented a bigger impact in most of the categories except CC, OD, TA, TE and NLT. All those categories had the clay intermediate case with the bigger impact owing to the use of natural gas to dry the clay (Table 3). Nevertheless, the clay with captive mine presents a bigger impact also owing to the larger use of coal in the atomisation process than for the medium size extraction clay. The categories with more importance were climate change and human toxicity owing to the energy, gas and coal use for the drying process.

Despite the high energy consumption in the spray dryer, this alternative presented an average reduction of 50% in all midpoint categories when compared with the best-case scenario for clay, intermediate extraction. The best alternative, when only the environmental impact was analysed through SimaPro 8.3, was the flash dryer, which is directly associated with the energy consumption for this alternative.

In the first comparison (Figure 2(a)), around 50% of the total impact was owing to the resources categories, except for limestone filler, which had most of the impact in the human health category owing to the emissions of particulate matter at the stage of crushing and the extraction phase. For the cases of sand extraction, the majority of the impacts is owing to diesel consumption. Moreover, most of the clay impact is owing to the transportation from the extraction site to the processing enterprise. Furthermore, the comparison of the products shows that the recycling of ornamental stone with natural open air-drying (D) has a lower environmental impact to all the other materials. The total impacts of sand submerged cava sand (A), dredging sand (B), filler (C) and clay (E) were 896%, 1148%, 2727% and 927% higher, respectively, than the impact of naturally drying the waste (Figure 3(a)).

For the comparison of the artificial drying technologies and the clay with atomisation (Figure 2(b)), the best alternative found was the flash dryer (H) alternative. The total impacts of rotary

**Table 3.** Results obtained in the midpoint category for Clay and OSPW.

| Impact category | Unit | OSPW – spray dryer | OSPW – rotary dryer | OSPW – flash dryer | Clay (average extraction – atomisation) | Clay – medium size extraction | Clay – captive mine |
|---|---|---|---|---|---|---|---|
| CC | kg CO2 eq | 0.07547966 | 0.018119 | 0.017742 | 0.119047 | 0.044325 | 0.050973 |
| OD | kg CFC-11 eq | 5.50493E-09 | 1.39E-09 | 1.37E-09 | 9.32E-09 | 2.99E-09 | 3.53E-09 |
| TA | kg SO2 eq | 0.000211499 | 5.2E-05 | 5.1E-05 | 0.000354 | 0.000213 | 0.000249 |
| FEU | kg P eq | 1.59683E-06 | 4.54E-07 | 4.46E-07 | 3.44E-06 | 0.000493 | 0.00056 |
| MEU | kg N eq | 1.95152E-06 | 6.36E-07 | 6.27E-07 | 5.25E-06 | 0.000108 | 0.000123 |
| HT | kg 1,4-DB eq | 0.004586598 | 0.001208 | 0.001185 | 0.008378 | 0.280452 | 0.318081 |
| PO | kg NMVOC | 7.81444E-05 | 2.25E-05 | 2.21E-05 | 0.000172 | 0.000148 | 0.00018 |
| PM | kg PM10 eq | 5.23369E-05 | 1.37E-05 | 1.34E-05 | 9.81E-05 | 0.000157 | 0.000182 |
| TE | kg 1,4-DB eq | 3.88379E-06 | 1.19E-06 | 1.17E-06 | 8.98E-06 | 2.75E-06 | 3.03E-06 |
| FE | kg 1,4-DB eq | 0.000279367 | 6.9E-05 | 6.76E-05 | 0.000468 | 0.006897 | 0.007824 |
| ME | kg 1,4-DB eq | 0.000108641 | 3E-05 | 2.95E-05 | 0.000216 | 0.006588 | 0.007472 |
| IR | kBq U235 eq | 0.000418759 | 0.000162 | 0.00016 | 0.001263 | 0.005653 | 0.006459 |
| ALO | m2a | 0.000256947 | 0.00019 | 0.00019 | 0.002095 | 0.002014 | 0.002282 |
| ULO | m2a | 3.34726E-05 | 2.39E-05 | 2.37E-05 | 0.000182 | 0.000594 | 0.00066 |
| NLT | m2 | 1.0707E-05 | 2.95E-06 | 2.9E-06 | 2.13E-05 | 1E-05 | 1.16E-05 |
| WD | m3 | 0.000393289 | 0.000382 | 0.000381 | 0.000546 | 0.000614 | 0.001003 |
| MD | kg Fe eq | 0.000299086 | 9.79E-05 | 9.64E-05 | 0.000769 | 0.000758 | 0.000875 |
| FD | kg oil eq | 0.027030454 | 0.006462 | 0.006327 | 0.042283 | 0.0575 | 0.065467 |

OSPW: ornamental stone processing waste; CC: climate change; OD: ozone depletion; TA: terrestrial acidification; FEU: freshwater eutrophication; MEU: marine eutrophication; HT: human toxicity; PO: photochemical oxidation; PM: particulate matter; TE: terrestrial ecotoxicity; FE: freshwater ecotoxicity; ME: marine ecotoxicity; IR: ionising radiation; ALO: agricultural land occupation; ULO: urban land occupation; NLT: natural land transformation; WD: water depletion; MD: metal depletion; FD: fossil depletion.

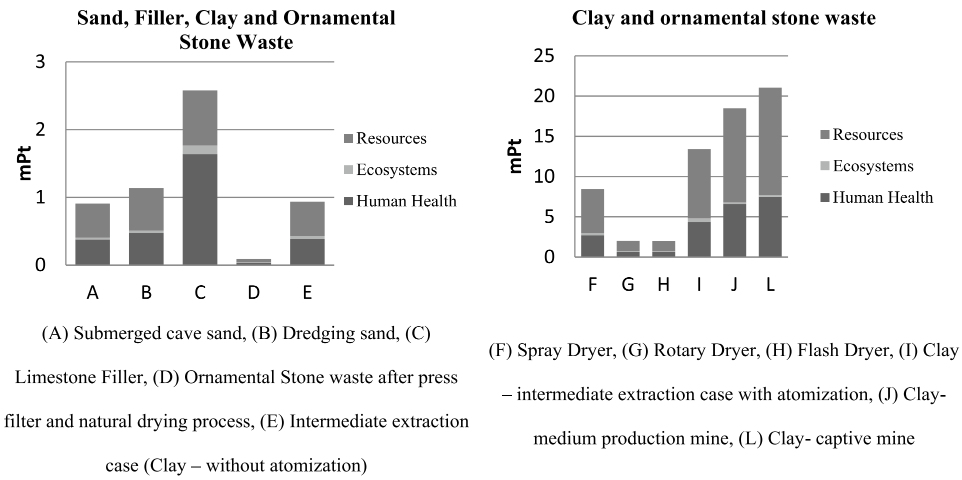


**Figure 2.** Single score categories results.

dryer (G), spray dryer (F), clay with intermediate extraction (I), clay medium production (J) and clay captive mine (L) were 2%, 324%, 573%, 826% and 955% higher than that of flash drying the waste. Despite the large amount of energy consumed by the spray dryer, which represented 99.81% of its total impact, it is still a better alternative than any scenario of the clay atomisation process.

The sensitivity analysis for the energy input showed that the increase of 25% of the energy input in the system only increased 6% of the total impact evaluated in the single score analysis, which results directly from the small energy input utilised in the standard scenario. Nevertheless, this result accrues from the Brazilian energy mix. Besides, with further research on the natural drying process, it was noticed that 3% of the impact for the solid waste treatment plant process is from crushing, 45% is from the transport in the site, 17% from the energy used in the press filter and 34% from the machine operation.

Considering the data from 1 kgkm Transport, freight, lorry 16–32 t, *EURO3 {GLO}| market for | Alloc Def, U*, the distances verified varied from 37.31 km to sand submerged cave and 956.92 km for clay extracted in captive mine for the OSPW dried naturally (Figure 3). On the other hand, for the rotary dryer

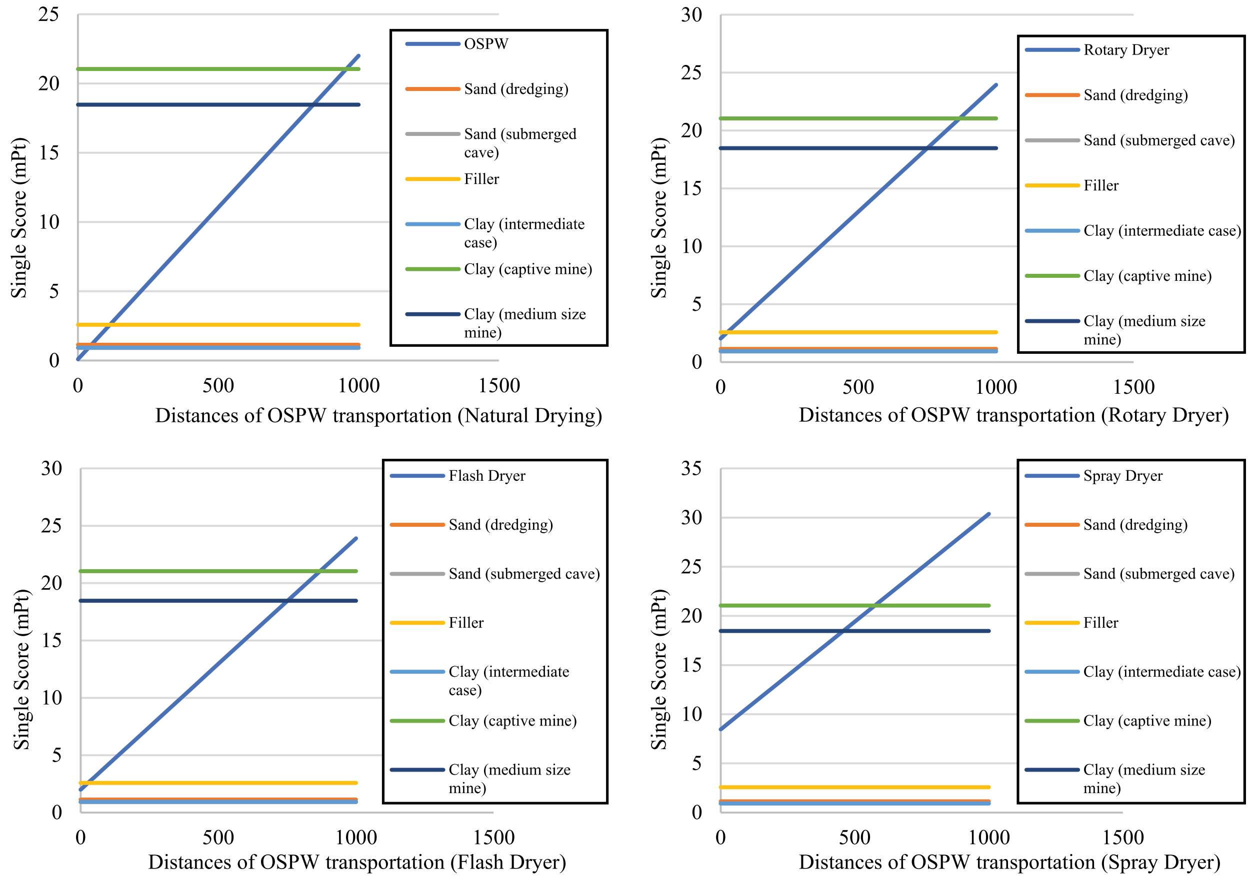


**Figure 3.** Distances of OSPW.

comparison and the flash dryer, it varied from around 25 km for filler and 870 km for clay extracted in captive mine. The spray dryer presented advantage only when compared with clay captive size and medium size extraction mine, presenting 574 and 457 km, respectively.

## Conclusion

In conclusion, for the parameters analysed and the case scenarios studied, the processing of ornamental stone waste is environmentally preferable when compared with clay, filler and sand. The second environmentally preferable option, sand extracted by submerged cava, presented a total impact 896% higher than the use of the naturally dried OSPW.

As for the hypothetical scenarios of spray dryer, flash dryer and rotary dryer, compared with three cases of clay atomisation, the study found that the processing of ornamental stone waste is environmentally preferable, even in its worst-case scenario, using spray dryer for its drying, than all the clay alternatives.

For the sensibility analysis, it was observed that the OSPW may be transported for at least 37 km when comparing the OSPW with natural drying to the sand with submerged cave. As for the input of energy in the treatment, it was noticed that the process with natural drying at the end does not present a large sensibility to the variation of 25% of the energy input, since the total environmental impact assessed was 6% higher than the medium input category.

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