Life cycle assessment to evaluate the environmental performance of new construction material from stainless steel slag

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List of Abbreviations

AA-block	Alkali Activated block
AOD	Argon Oxygen Decarburization
BFS	Blast Furnace Slag
FC-block	Fast-Carbonated block
GGBFS	Ground Granulated Blast Furnace Slag
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NA	Natural Aggregates
OPC	Ordinary Portland Cement
SC-block	Slow-Carbonated block
SCMs	Supplementary Cementitious Materials
SSS	Stainless Steel Slag
SSS-blocks	Stainless Steel Slag- blocks

Keywords:

Stainless steel slag; alkali activation; carbonation; sustainable building materials; hazardous waste management; industrial symbiosis; life cycle assessment;

Abstract

Purpose: Many new opportunities are explored to lower the CO_2 emissions of the cement industry. Academic and industrial research is currently focused on the possibility of recycling steel production residues in the cement industry, in order to produce new "low-carbon" binders for construction materials. The purpose of this paper is to assess the environmental benefits and costs of steel-residues valorization processes to produce a new binder for construction materials.

Methods: Among other stainless steel slag (SSS), argon oxygen decarburization (AOD) slag has the potential to be recovered as a binder during the production of new construction materials. Alkali-activation and carbonation processes can in fact activate the binding properties of the AOD-slag. However, AOD-slag is today only recycled as low-quality aggregate. For the present study, three different types of construction blocks (called SSS-blocks) were developed starting from the AOD-slag (one block through alkali-activation and two blocks through carbonation). The data from the production of the three construction blocks have been collected and used to perform a Life Cycle Assessment (LCA) study, comparing SSS-blocks production with the production of traditional paver OPC concrete.

Results: The analysis showed that SSS-blocks production through alkali activation and carbonation has the potential of lowering some of the environmental impact of OPC-concrete. The LCA results also show that the main bottleneck in the alkali-activation process is the production of the alkali activators required in the process, while the use of electricity and of pure CO_2 streams in carbonation lower the environmental performances of the entire process.

Conclusions: The valorisation of AOD-slag to produce new construction materials is a promising route to lower the environmental impacts of cement and concrete industries. This product-level analysis stresses the need of updating the LCI datasets for alkali activators and boric oxide, and of widening the scope of the environmental analysis up to system-level, including potential economic interactions and market exchanges between steel and construction sectors.

1. Introduction

Although Ordinary Portland Cement (OPC) is the most commonly used binder in concrete manufacturing, its highly energy intensive production is responsible for the 5-8 % of global anthropogenic CO_2 (Ammenberg et al., 2015). OPC production is also thought to contribute for in between 74 and 81% of the total carbon footprint of concrete (Blankendaal et al., 2014; De Schepper et al., 2014; Flower and Sanjayan, 2007; Turner and Collins, 2013). The causes of the high CO_2 emissions during OPC production are identified in (i) the calcination of limestone, which decomposes the $CaCO_3$ contained in the limestone into CaO and CO_2 (Worrell et al., 2001), and (ii) the high energy required to heat the raw materials at temperatures greater than 1400 °C (Huntzinger and Eatmon, 2009).

Academic and industrial research is currently committed to find alternatives to OPC, that can lower the environmental footprint of concrete (Ishak and Hashim, 2015). Among these alternatives, some industrial residues, called supplementary cementitious materials (SCMs)**,** can partially or completely substitute OPC in concrete production. Since SCMs are mostly residues coming from other industries, the use of SCMs can also enhance industrial symbiosis between the cement and the other industries (Ammenberg et al., 2015). One of the most commonly used SCMs is the ground granulated blast furnace slag (GGBFS), a by-product of pig iron produced during the manufacturing of steel in a blast furnace (Crossin, 2015). Thanks to its amorphous structure, which gives a latent hydraulic reactivity, GGBFS can be blended with OPC up to a certain ratio, producing the so-called “blended concrete”. It has been proved that the use of GGBFS mixed with OPC can improve concrete technical properties like strength, permeability and corrosion resistance (Shi and Qian, 2000; Song and Saraswathy, 2006; Yi et al., 2012).

Despite the successful implementation of symbiosis between steel and cement industries through GGBFS, the potential for the valorization of other residues from steel production is not fully explored at present. ***Stainless Steel Slag (SSS)***, for instance, a residue produced during the stainless steel making process, has the potential to be used in alternative cement production. However, since chromium is an essential constituent of stainless steel, a fraction of it appears also in the SSS, together with other heavy metals, posing environmental and health threats (Huaiwei and Xin, 2011). The chromium content has historically limited the valorisation of SSS. Consequently new processes are needed to reduce or mobilized the leachable chromium and to make SSS recyclable in new construction materials (Adegoloye et al., 2015).

In particular, ***AOD-slag*** is a SSS produced in the argon oxygen decarburisation (AOD) furnace, where stainless steel is commonly refined. AOD-slag occurs in a very fine texture (a few µm diameter), giving to the slag the shape of a fine powder. The fine texture is due to a process called “dusting”, in which the dicalcium silicate (C_2S) contained in the slag undergoes several polymorphic transformations that cause a volume expansion and a consequent pulverization of the slag (Kim et al., 1992). The powder shape makes the handling of the slag difficult due to the risk of heavy metals leaching. Considering that 270 kg of AOD-slag is produced per 1 t of stainless steel, the massive quantities and the powder shape make AOD-slag management problematic from an industrial and environmental point of view (Zhao et al., 2013).

In order to avoid the problem of dusting, boron oxide (B_2O_3) is commonly added during the cooling process of AOD-slag in a quantity equal to 2% of the total mass of the slag (Durinck et al., 2008). Boron oxide stabilizes the C_2S, thus preventing the formation of the fine particles. Stabilized AOD-slag grains present a bigger texture (few mm) and a more stable chemical status, which allows their disposal in hazardous waste landfills or their reuse as low quality aggregates, especially for roads construction. The valorization as low quality aggregates represents however a low-value application with respect to the high quality oxides (CaO, MgO, AlO_2) contained in the AOD-slag, whose chemical potential can be activated and exploited (Salman et al., 2014a). According to Faraone et al. (2009), the CaO content of AOD-slag is closer to the one of GGBFS and OPC than to the one of natural aggregates (NA). However, even if AOD-slag and GGBFS present a similar chemical composition, the main difference lies on the phase composition. GGBFS are vitreous/highly amorphous, while AOD-slag presents a highly crystalline structure that is mostly considered non-hydraulic. Therefore AOD-slag cannot be simply blended with OPC clinker, but further treatments are required in order to activate its binding properties.

Recent research investigates the potential of AOD-slag and other crystalline SSS to be used as binders (Baciocchi et al., 2010; Faraone et al., 2009; Iacobescu et al., 2016; Kriskova et al., 2012; Motz and Geiseler, 2001; Panda et al., 2013; Salman, 2014; Santos et al., 2013; Setién et al., 2009; Sheen et al., 2013). In particular, two different but equally promising routes are (i) the activation of AOD-slag as binder through alkali activation and (ii)the creation of solid carbonated blocks through the carbonation of the slag.

An alkali activated material is any binder system derived from the reaction between an alkali metal source (alkali hydroxides, silicates, carbonates, sulfates, aluminates or oxides) with a solid silicate powder, as for instance an aluminosilicate-rich precursor such as a metallurgical slag, natural pozzolan, fly ash or bottom ash (Provis and van Deventer, 2014). Carbonation refers to the reaction of CO_2 with alkaline divalent cations from natural ores or alkaline solid waste, such as steel slag and fly ashes, to produce stable carbonate minerals (Pan et al., 2016).

The valorization of AOD-slag through either alkali activation or carbonation raises many technical issues that have been described in the work of Salman et al. (2014; 2014a, 2014b, 2015, 2016). However, another prerequisite for the use of AOD-slag to substitute OPC binder is its environmental acceptability. As follow-up of the above cited work of Salman, the present paper uses **attributional life cycle assessment (LCA)** to assess the environmental impacts of newly developed construction blocks (called from now on *SSS-blocks)*, produced through alkali activation and carbonation of AOD-slag. More in detail, three different SSS-blocks are analyzed, one produced trough alkali activation and two produced through carbonation. To better understand the trade-off between the environmental costs of AOD-slag valorization and the environmental benefits of potential OPC substitution, the environmental performances of the SSS-blocks production are compared to the ones of traditional OPC concrete.

Although in Salman et al. (2016) LCA was already used as a first attempt to analyse the potential environmental performances of alkali activation and carbonation using SSS as precursor, the scope of the work of Salman was a more wide analysis on the technical, environmental and economic challenges in the development of the SSS-blocks technology. Therefore, the LCA presented in the current paper wants to deepen the environmental results of Salman et al. (2016), to analyse the environmental performances of SSS-blocks at various levels (midpoint and endpoint), and to highlight the environmental hotspots in the production process. In order to avoid reproduction with the above mentioned work of Salman, the present study only includes a concise description of the technical process that contains structural elements needed in the LCA analysis.

1.1 Literature review

Table 1 lists some of the most recent LCA studies analysing different alternative solutions to produce low carbon cement and concrete from industrial residues. A consistent number of studies focused on the partial or complete substitution of OPC with industrial SCMs (GGBFS or fly ashes), concluding that the OPC substitution with SCMs is a promising low-cost solution to radically decrease CO_2 emissions, but its development has been limited by standardization and availability of alternative materials. (Feiz et al., 2015; Habert et al., 2010a; Huntzinger and Eatmon, 2009; Van den Heede and De Belie, 2012). However, only a few studies are currently available on the environmental implications of the alkali activation and carbonation of metallurgic slags other than GGBFS.

Regarding previous LCA on alkali activation process, the few available LCA studies refer to alkali activation applied to different precursors (BFS, fly ash, metakaoline). It is worth to mention that a complete literature review on this field is hampered by the lack of a universally accepted terminology. Most of the available LCA studies refer to the alkali activated materials as geopolymers. According to the State-of-the-Art Report RILEM TC 224-AAM (Provis and van Deventer, 2014), geopolymers represent a subset of the broader category “alkali activated materials”, where the precursor is almost exclusively aluminosilicate with a low amount of available calcium. However, this definition is not universally accepted since, as stated by Davidovits (2008), alkali activated materials are not polymers, and therefore geopolymers are not a subset of alkali activated materials. Consequently, there exists a plethora of different names applied to very similar materials that may lead to confusion among the readers. In general, regardless their definition as geopolymer or alkali activated materials, the previous LCA studies focused only on some of the environmental aspects, as global warming potential (Duxson et al., 2007; Habert et al., 2011), abiotic resource depletion and cumulative energy demand (Weil et al., 2009). All studies agreed that alkali activated materials reduce the CO_2 emissions within a range of 40 to 70% compared to OPC, while similar impacts are caused in abiotic resource depletion and cumulative energy demand. However, this result is only valid if no impact is allocated to the industrial residue acting as precursor. If the impacts of the industrial process producing the residue are allocated by mass to the precursor, then the final results are completely reverse and geopolymers resulted to have higher impacts than OPC-concrete (Habert et al., 2011).

Regarding the carbonation process, many previous LCA studies focused on carbonation of minerals, but only a few studies are focused on carbonation of steel residues (Pan et al., 2016; Xiao et al., 2014). Results from these studies concluded that the higher is the CO_2 capture capacity of the carbonation process, the higher is the energy required. Therefore, depending on the efficiency of the process, the amount of electricity required could offset the environmental benefits deriving from the CO_2 uptake. However, the adverse impacts due to electricity consumption could be compensated by the utilization of the carbonated residue as supplementary construction material (Pan et al., 2016). Even when the environmental analysis is enlarged to other environmental categories (i.e. ecosystem quality and human health), the energy consumption remains the key factor affecting the environmental balance of the carbonation process (Xiao et al., 2014).

Table 1: Literature review of previous LCA studies on alkali activation and carbonation

	Technology	Residue (precursor)	Focus	Main findings
(Duxson et al., 2007)	Geopolymers	Coal fly ash and metakaolin	Global warming potential	Geoplymers can in general deliver 80% reduction in CO_2 emissions compared to OPC –based concrete.
(Habert et al., 2011)	Geopolymers	Fly ash, BFS and metakaolin	Global warming potential	If no allocation on the residue is considered, geopolymers can save 45% of CO_2 emissions compared to OPC-based concrete. However, this result is completely reversed if mass allocation is applied to the residue, and geopolymers resulted to have higher impacts than OPC-concrete.
(Weil et al., 2009)	Geopolymers	Slag, fly ash, metakaolin	Global warming potential Abiotic resource depletion potential Cumulative energy demand	Compared to OPC, geopolymers showed comparable environmental impacts in terms of ADP and CED, but 70% reduction in GWP.
(Pan et al., 2016)	Carbonation	Basic oxygen furnace slag		The capture of CO_2 could be offset by the increase of energy consumption due to both manufacturing and operation of high performance processes.
(Xiao et al., 2014)	Carbonation	Steelmaking slag	Global warming potential	The increase of the reaction temperature would

			Damage assessment	accelerate the carbonation rate, but it would also generate indirect CO_2 emissions that reduce the overall CO_2 capture capacity.

2. Materials and methods

2.1 AOD-slag valorisation in SSS-Blocks

The slag used for the development of the SSS-blocks is obtained from a Belgian stainless steel plant and it is sieved with a 500µm sieve for carbonation and 160µm for alkali-activation. The average oxide composition of the two fractions of the slag is similar and it is reported in Table 2.

Table 2: AOD-slag composition

Oxides	CaO	SiO_2	MgO	Al_2O_3	TiO_2	Cr_2O_3	Fe_2O_3	Others
wt%	57	29	8	2	1	0.6	0.6	1.8

2.2 Life Cycle Assessment

2.2.1 Goal of the study, functional unit and system boundaries

The goal of the LCA is to assess the environmental impacts of SSS-blocks, made through activation of AOD-slag from stainless steel production. This product-level analysis will help to identify possible hot spots and consequently to improve the environmental performance of the SSS-blocks production processes.

More specifically, the LCA assesses the environmental impacts during the production of three different types of SSS-blocks: (i) an **alkali activated block (AA-block)**, produced by mixing the AOD-slag with alkali activators (sodium silicate and sodium hydroxide), (ii) **a slow-carbonated block (SC-block)**, produced through the carbonation of AOD-slag with a pure CO_2 stream in a carbonation chamber, kept in standard condition (22°C, 1 atm) for 7 days, (iii) **a fast-carbonated block (FC-block)**, produced through the carbonation of AOD-slag with a pure CO_2 stream in a carbonation reactor, operating at 80°C and 8.3 atm for 2.5 hours in a 100 vol% CO_2 environment.

The produced blocks were tested for their properties related to compressive strength (as per EN 196-1:1994), thermal conductivity (as per ISO 8302:1991), freeze-thaw resistance (as per NBN B 27-009), and heavy metal and metalloid leaching (as per EA NEN 7345) on at least three samples. A more detailed analysis of the results of these tests is available in Salman et al. (2014a, 2014b, 2015).

The three SSS-blocks present a compressive strength between 15 and 25 MPa/m². This compressive strength is comparable to, or higher than, some of the commercially available OPC-concrete blocks. In particular, paver OPC concrete is used to form a segmented paver surface, and its compressive strength falls in the range than the one of the SSS-blocks (figure 1).

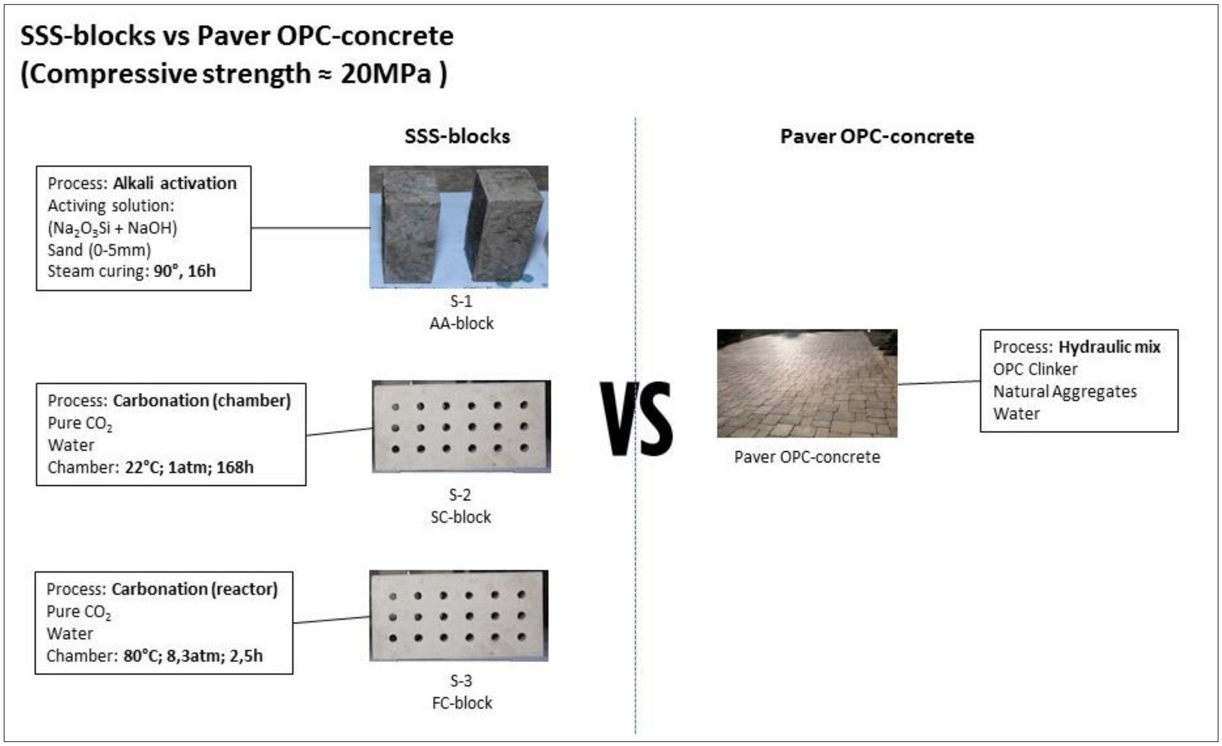

Figure 1: SSS-blocks vs paver OPC concrete)

The functional unit represents the product ability to perform a given function, and it provides a reference to which all the inputs and outputs are referred. When using LCA to compare different products, a common functional unit must ensure comparability among the analysed alternatives. As described before, the compressive strength of the SSS-blocks is comparable to the one of paver OPC-concrete. Therefore, the presented LCA compares 1 m² of SSS-blocks with 1 m² of OPC-concrete, able to provide the same compressive strength. The compared surface is made by 50 blocks, each measuring 20 cm (length), 10 cm (width) and 5 cm (thickness).

Three different scenarios are analysed, corresponding to three different valorisation routes:

- ***Scenario 1, alkali-activated-blocks (S-1, AA-blocks)***-AOD-slag is valorised through alkali activation to produce AA-blocks;
- ***Scenario 2, slow-carbonated-blocks (S-2, SC-blocks)***-AOD-slag is valorised through carbonation in a carbonation chamber, to produce SC-blocks;
- ***Scenario 3, fast-carbonated-blocks (S-3, FC-blocks)***-AOD-slag is valorised through carbonation in a carbonation reactor, to produce FC-blocks;

The system boundaries of the considered scenarios for SSS-blocks production and paver OPC-concrete are illustrated in figure 2. As the AOD valorisation routes avoid the stabilisation through boron and the consequent low quality recycling of the AOD-slag, the avoided use of boron and the avoided transport of stabilised AOD-slag to low quality applications are given as a credit (negative value) to the AOD-valorisation processes. At the same time, NA must replace the AOD-slag in low-quality applications. Therefore, the process of production and transport of NA to low-quality applications must be included in the study. In reality, other industrial waste is available to replace AOD-slag in low value applications (e.g. construction and demolition waste). However, to keep the simplicity of the study, NA is considered as the only alternative to AOD-slag in low value applications.

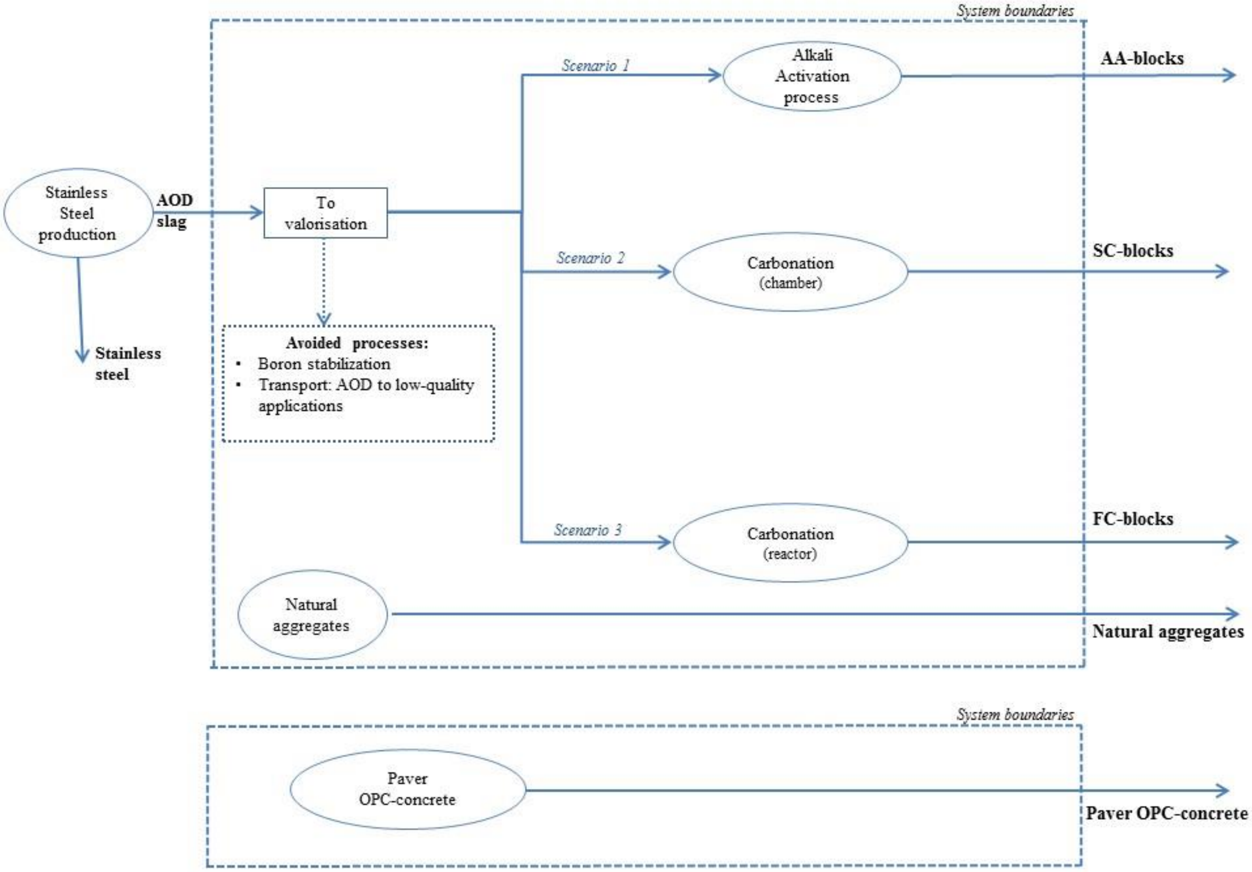

Figure 2: system boundaries for LCA analysis

The systems for both SSS-blocks and OPC-concrete consider a cradle-to-gate analysis, including only the production phase. The use phase and the end-of life phase of SSS-blocks are excluded from the analysis, since empirical data on possible long-life behaviour of SSS-blocks is still missing, due to the early stage of technology development. On top of that, a similar durability can be assumed between SSS-blocks and the OPC-concrete, and both materials can be considered as inert waste at their end-of life (Salman, 2014). To conclude, if the compared materials shows similar functional properties and durability during the use and the end-of-life phases, then the limitation of the study to a cradle to gate analysis is valid (Habert et al., 2011).

2.2.2 Life cycle inventory

The life cycle inventory (LCI) phase estimates the consumption of resources, the quantities of waste flows and emissions caused during a product's life cycle (Rebitzer et al., 2004). Therefore, the LCI phase creates a list of inputs and outputs related to the functional unit chosen, and it represents the basis for the calculation of the environmental impacts. The LCI for the presented study has been implemented on Gabi version 8.0.0.247, using Ecoinvent database v3.3 as the reference to model the background processes (materials, fuel and electricity sources). The electric mix used for all the process is referring to the Belgian electric mix 2017 (Elia, 2017), which mainly consists of 46.6% nuclear, 26.5% gas, 11% renewables, and 6.1% coal.

S-1: Alkali activated SSS-Blocks

The process to produce AA-blocks considered in this paper is described in details in (Salman et al., 2016, 2015,2014b). In the initial step of the process, AOD-slags are mixed with commercially available 0-5 mm river sand in a weight ratio of 1/6 (slag to sand) and with sodium silicate and sodium hydroxide. After mixing, the AA-blocks are cured in a steam-curing chamber at 90 °C for 16 hours. During the entire processing, the main electricity consumption is due to the energy needed for the mixer and the energy required to keep the stream curing chamber at high temperature.

Transport distances can vary greatly from case to case. However, some general assumptions can be made. These assumptions are common for both alkali activation and carbonation scenarios. When neighbouring industries start to exchange their secondary raw materials, transport distance reduction represents one of the main advantages. According to this prerequisite and considering a highly urbanised region, a distance of 10 km is assumed from the stainless steel plant producing the AOD slag to the concrete factory, where SSS-blocks are produced. The avoided transport of stabilised AOD-slag to low quality applications is assumed to be 50 km. Figure 3 summarises the input/output flows for the AA-blocks production.

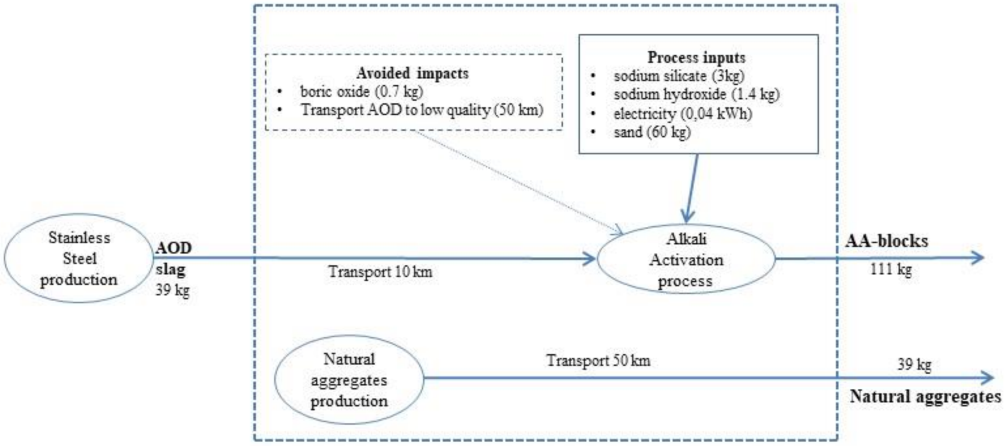

Figure 3: input/outputs flows for alkali activated blocks production

S-2 and S-3: Carbonated SSS-Blocks

Carbonation involves the reaction of carbon dioxide with alkaline materials, leading to the formation of stable carbonate products. Industrial carbonation simulates the natural weathering of silicates, in which natural occurring silicates fix atmospheric CO_2 through the following chemical reaction, where the element X generally represents calcium or magnesium:

Equation 1: carbonation reaction

$$\underbrace{X(OH)_2}_{\textit{Oxide}} + CO_2 = \underbrace{XCO_3}_{\textit{Carbonates}} + H_2O$$

The carbonation process producing the SC and FC blocks is better detailed in Salman et al. (2014a; 2016). To produce the SC-blocks, the AOD-slag reacts with a pure CO_2 stream in a carbonation chamber, kept in standard condition (22°C, 1 atm) for 7 days. To produce the FC-blocks, the AOD-slag reacts with a pure CO_2 stream in a carbonation reactor, operating at 80°C and 8.3 atm in a 100 vol% CO_2 environment. The higher values of temperature and pressure increase the kinetic of the carbonation process, allowing to complete the reaction in only 2.5 hours. In Salman et al. (2014a), the uptaken CO_2 is calculated to be the 15% of the mass of the slag. Within this 15%, the 2.25% of the total input of CO_2 is not uptaken, and it is lost as direct process emission. Therefore, the total CO_2 input of the process is calculated as the 17.25%, (15% uptaken plus the 2.25% lost in the process) of the mass of the slag.

The AOD-slag itself is used as aggregate; hence, the use of sand is avoided. For both SC and FC blocks, 18%wt (of the slag) of water was added to the slag. Figure 4 summarises the input/output flows for the SC and the FC blocks production.

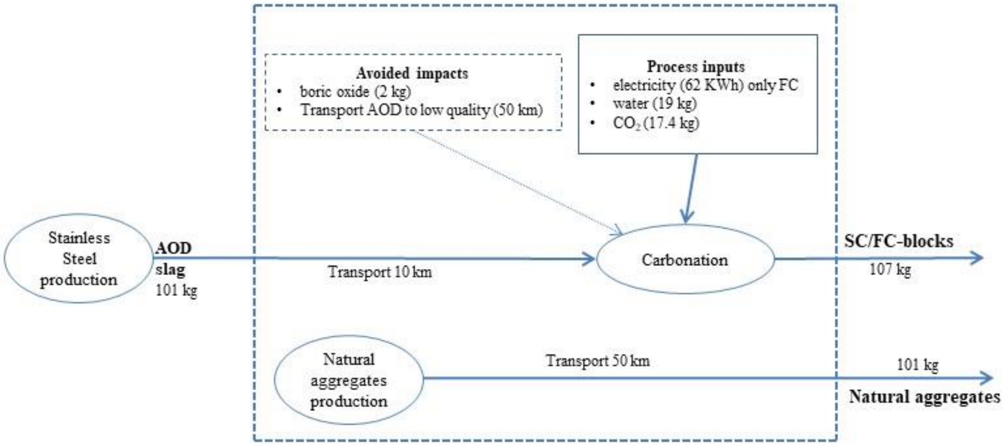

Figure 4: input/output flows for carbonated blocks production

Paver OPC-concrete

The concrete mixture (the share between binder, water and aggregates) of paver OPC-concrete is calculated based on the relation between the compressive strength and the cement content (Neville, 2012; Ollivier et al., 2012), and on information collected directly from local concrete producers in Belgium. The transport distances for the NA and for the OPC to produce OPC-concrete are assumed equal to 50 km (Habert et al., 2010b; Martaud, 2008; Mroueh et al., 2000). Figure 5 summarises the input/output flows for the paver OPC-concrete production.

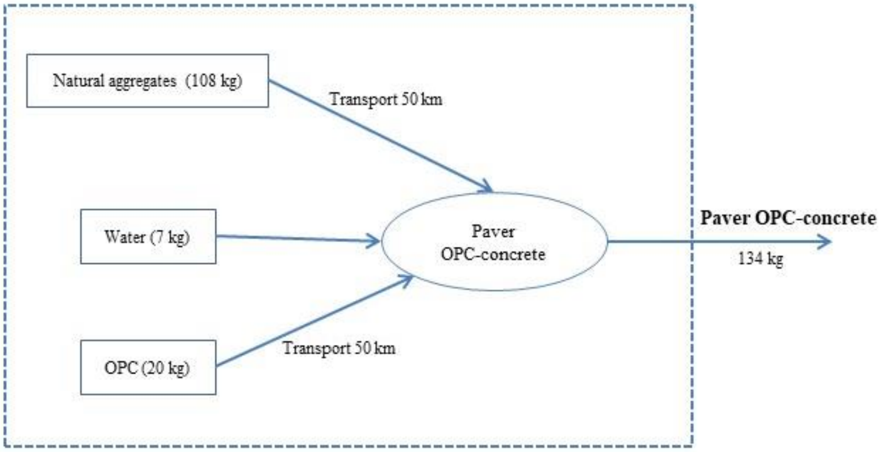

Figure 5: input/output flows for paver OPC-concrete production

Finally, table 3 summarises the inputs and outputs for all considered scenarios and the assumptions made for transport distances.

Table 3: life cycle inventory table

	S-1 (AA-blocks)	S-2 (SC-blocks)	S-3 (FC-blocks)	Paver OPC-concrete
Density (g/cm³)	2.22	2.14	2.14	2.6
Weight of FU (kg)	111	107	107	134

FU INPUTS

	S-1 (AA-blocks)	S-2 (SC-blocks)	S-3 (FC-blocks)	Paver OPC-concrete
Quantity of slag (kg)	39	101	101	/
NaOH (kg)	1.4	/	/	/
Na silicate (kg)	3	/	/	/
Aggregates (kg)	60	/	/	108
Electricity (kWh)	0.04	/	62	/
Avoided boron production (kg)	0.7	2	2	/
Water (kg)	/	19	19	7
CO_2_input (kg)	/	17.4	17.4	/
OPC (kg)	/	/	/	20

TRANSPORTS

	S-1 (AA-blocks)	S-2 (SC-blocks)	S-3 (FC-blocks)	Paver OPC-concrete
AOD-slag to valorisation (km) *(AOD-slag, from stainless steel plant to SSS-blocks production)*	10	10	10	/
NA to low quality (km) *(Natural aggregates to low-quality applications)*	50	50	50	/
Avoided_AOD slag to low quality (km) *(Avoided AOD slag recycled to low-quality applications)*	50	50	50	/
NA to OPC-concrete (km) *(Natural aggregates to OPC-concrete production)*	/	/	/	50
OPC to OPC-concrete (km) *(OPC to OPC-concrete production)*	/	/	/	50

2.2.3 Allocation

The allocation issue for the use of industrial residues to produce new materials is an ongoing discussion in scientific literature. Early LCA studies on SCMs, especially focusing on GGBFS or fly ashes, did not attribute any environmental impact to the process generating these industrial residues (Van den Heede et al. 2012). However, today the partial substitution of OPC with GGBFS or fly ashes became a common practice and those materials are no longer considered as waste but instead as a by-product (Habert 2013). The ISO provides different possible solutions to deal with allocation of industrial by-products. First, allocation should be avoided by dividing or expanding the system. However, Chen et al. (2010) showed that system expansion is highly dependent on the point of view of the LCA practitioner, and it can present inconsistency when the main product and the by-product are considered within the same system boundaries. Second, when system division or expansion is not possible, other physical or economical parameters should be used to allocate the environmental burden. However, mass or economical parameters are not applicable in the case of metallurgic slags used in cement production. As demonstrated by Van den Heede et al. (2012), an allocation by mass, poses an enormous environmental impact to the slags, which may discourage the concrete industry to use them as a cement replacement. An economic allocation allocates negligible impacts to the slags, due to the large differences in price between the main product and slags. Chen et al. (2010) and Habert (2012) proposed alternative allocation methods for GGBFS valorization in cement industry. These proposals are based on physical and economic empirical coefficients, as for instance the equivalent binding capacity, which is available for GGBFS and fly ashes, but still unknown for AOD-slag.

Following the Waste Framework Directive 2008/98/EC and the recommendations put forth in the ISO 14041, an allocation coefficient should be indeed applied only if the waste can be considered as a by-product, while no allocation is advised if the waste is considered as an unintended residue.

A waste can be in fact regarded as a by-product if the following conditions are met:

a) *further use of the substance or object is certain;*
b) *the substance or object is produced as an integral part of a production process;*
c) *the substance or object can be used directly without any further processing other than normal industrial practice;*
d) *further use is lawful, i.e. the substance or object fulfils all relevant product, environmental and health protection requirements for the specific use and will not lead to overall adverse environmental or human health impacts*

As reported in Iacobescu et al. (2016), SSS does not have the status of a by-product and it is today legally considered as waste material, since it does not meet all these conditions. Regarding the condition a), further use of AOD-slag is not certain because the research on AOD-slag valorisation is still in its early stage. Regarding condition d), the legislation regulating the use of AOD-slag is still missing and potential environmental and health consequences of AOD-slag valorisation are still under investigation. Therefore, for the LCA presented in this paper, the allocation procedure has been avoided and no impacts are attributed to the AOD-slag.

However, according to the level of desirability, a waste is considered as by-product if it is sold with revenues, or it is considered as an unintended residue if it is disposed with costs (Kronenberg et al. 2009). The desirability of waste therefore is not given only by its physicochemical nature, but it also depends on the economic circumstances, which are likely to change over time. Therefore, with future development of the AOD-slag valorisation technology, further research on allocation procedure may be needed. This will imply the need for empirical parameters applicable to AOD-slag. The determination of these empirical parameters for AOD-slag goes however beyond the scope of this paper.

2.2.4 Life cycle impact assessment

During the life cycle impact assessment (LCIA) phase, the potential impact from each inventory emission and material/resource flows is characterised and quantified, using specific characterisation models (Hauschild et al., 2013). Characterisation models can be grouped into two families: “problem-oriented” or midpoint, determining impact categories indicators at an intermediate position of the impact pathways, and “damage-oriented” or endpoint, aiming at more easily interpretable results in the form of damage indicators at the level of the ultimate societal concern (Jolliet et al., 2004).

The present study uses the CML 2016 method as characterisation model for the midpoint analysis. In order to confirm the findings of the CML midpoint analysis and to provide results that allow an easier comparison among scenarios, a further endpoint LCIA analysis is performed using Recipe endpoint as characterisation model.

In a LCA study, is also important to check the magnitude of uncertainty. Uncertainty of results can be caused by inaccuracy or unrepresentativeness of data or modelling assumptions (Björklund, 2002). Sensitivity analysis can reduce the LCA results uncertainty by evaluating the influence of input changes on the model’s results (Clavreul et al., 2012). Therefore, a sensitivity analysis is performed in chapter 3.3, to assess the influence of some assumptions on the final LCA findings. In particular, the sensitivity analysis is performed by varying the transport distances in each scenario, while keeping all other parameters constant.

3. Results

3.1 Midpoint analysis

The estimated midpoint environmental impacts are reported in table 4. As environmental impact categories are measured in different units, and to facilitate the comparison between the different scenarios, figure 6 shows the impacts relative to 100% for all categories.

Table 4: CML midpoint analysis

	S-1 (AA-blocks)	S-2 (SC-blocks)	S-3 (FC-blocks)	Paver OPC-concrete
Abiotic Depletion (elements) [kg Sb-Equiv.]	3.57E-05	1.21E-05	2.87E-05	4.23E-05
Abiotic Depletion (fossil) [MJ]	6.9	14.9	71.9	23.4
Acidification [kg SO2-Equiv.]	0.00628	-0.022	0.0124	0.0396
Eutrophication [kg Phosphate-Equiv.]	0.00473	0.00882	0.0162	0.0101
Freshwater Aquatic Ecotoxicity [kg DCB-Equiv.]	1.1	1.98	3.51	0.945
Global Warming Potential [kg CO2-Equiv.]	2.99	-3.23	12.5	19.1
Human Toxicity [kg DCB-Equiv.]	2	18.5	24.4	2.62
Marine Aquatic Ecotoxicity [kg DCB-Equiv.]	4.22E+03	6.44E+03	1.72E+04	3.54E+03
Ozone Layer Depletion [kg R11-Equiv.]	1.81E-06	2.66E-07	4.13E-06	7.65E-07
Photochem. Ozone Creation [kg Ethene-Equiv.]	6.45E-04	5.40E-04	3.40E-03	0.00389
Terrestric Ecotoxicity [kg DCB-Equiv.]	0.0357	0.0586	0.109	0.0402

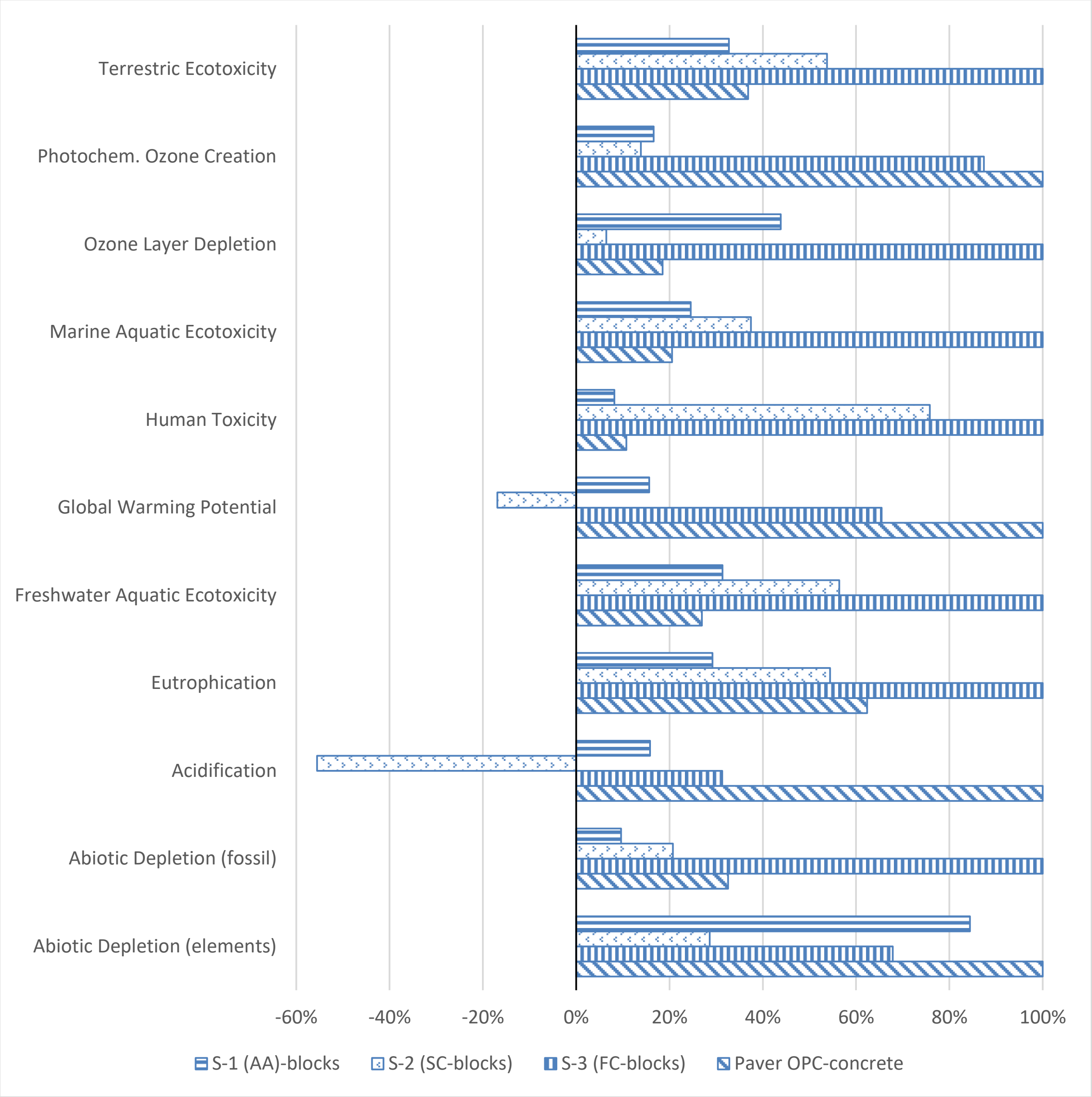

Figure 6: midpoint impact categories, as percentage of the largest impact

Compared to paver OPC-concrete, the AA-blocks (S-1) present higher impacts in the categories ozone layer depletion (+25%), marine aquatic ecotoxicity (+4%), and freshwater aquatic ecotoxicity (+4%), while they show lower impacts in all the other categories. The SC-blocks (S-3) show higher impacts than the paver OPC-concrete in the categories terrestrial ecotoxicity (+17%), marine aquatic ecotoxicity (+17%), human toxicity (+65%) and fresh water ecotoxicity (+29%). The SC-blocks have also negative impact in the categories global warming and acidification, meaning that the avoided impacts of CO_2 uptake, boric oxide production and AOD-slag transport to low-quality recycling are higher than the caused impacts from the production of the SC-blocks. The AA-blocks and the SC-blocks do not have the highest contribution in any of the considered categories. On the other hand, the FC-blocks (S-4) caused the highest impact in the categories terrestrial ecotoxicity, ozone layer depletion, marine aquatic ecotoxicity, human toxicity, freshwater aquatic ecotoxicity, eutrophication and abiotic depletion fossil. Finally, paver OPC-concrete presents the highest impact compared to all SSS-blocks in the categories photochemical ozone depletion, global warming, acidification and abiotic depletion (elements).

3.1.1 *Process contribution to midpoint results*

To understand better the results presented in table 4 and figure 6, it is also important to evaluate the contribution of the different processes to the final value for each category. Figures 7, 8, 9 and 10 show the relative contribution of different processes to the midpoint results for the AA-blocks, the SC-blocks the FC-blocks and the paver OPC-concrete respectively. The results for each impact categories are detailed in table 7 in the electronic supporting materials.

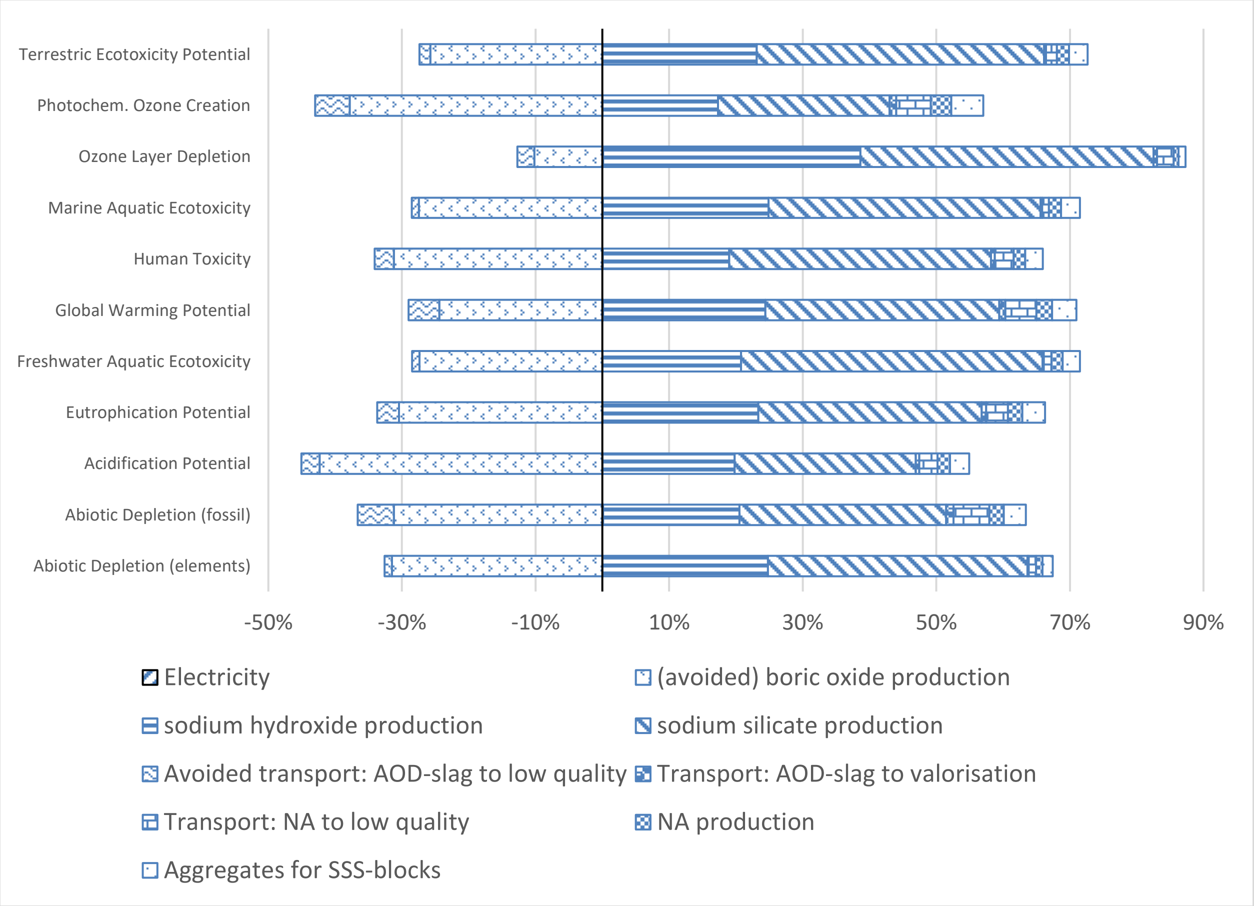

Figure 7: alkali activated blocks: relative contribution of the different process to the midpoint results

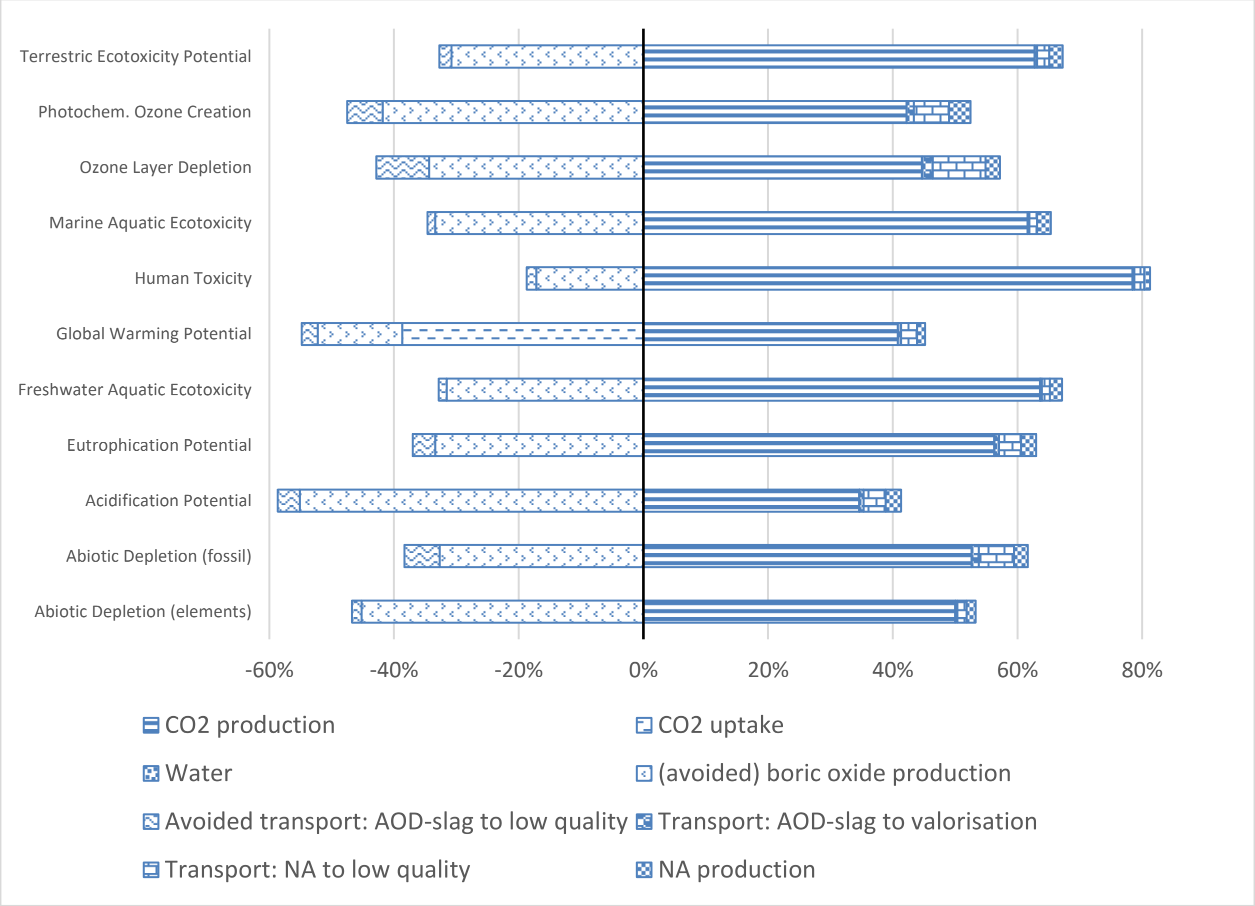

Figure 8: slow-carbonated blocks: relative contribution of the different process to the midpoint results

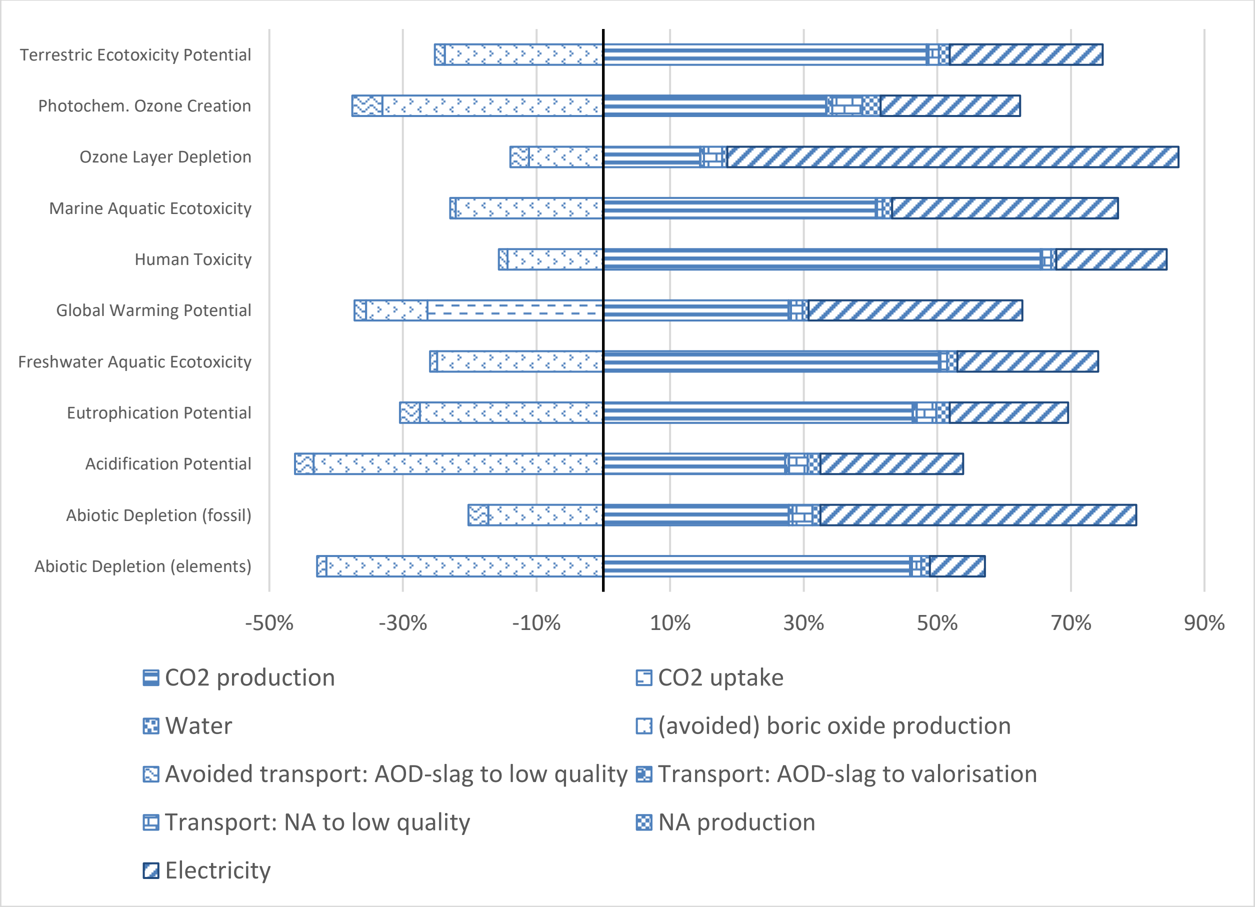

Figure 9: fast-carbonated blocks: relative contribution of the different process to the midpoint results

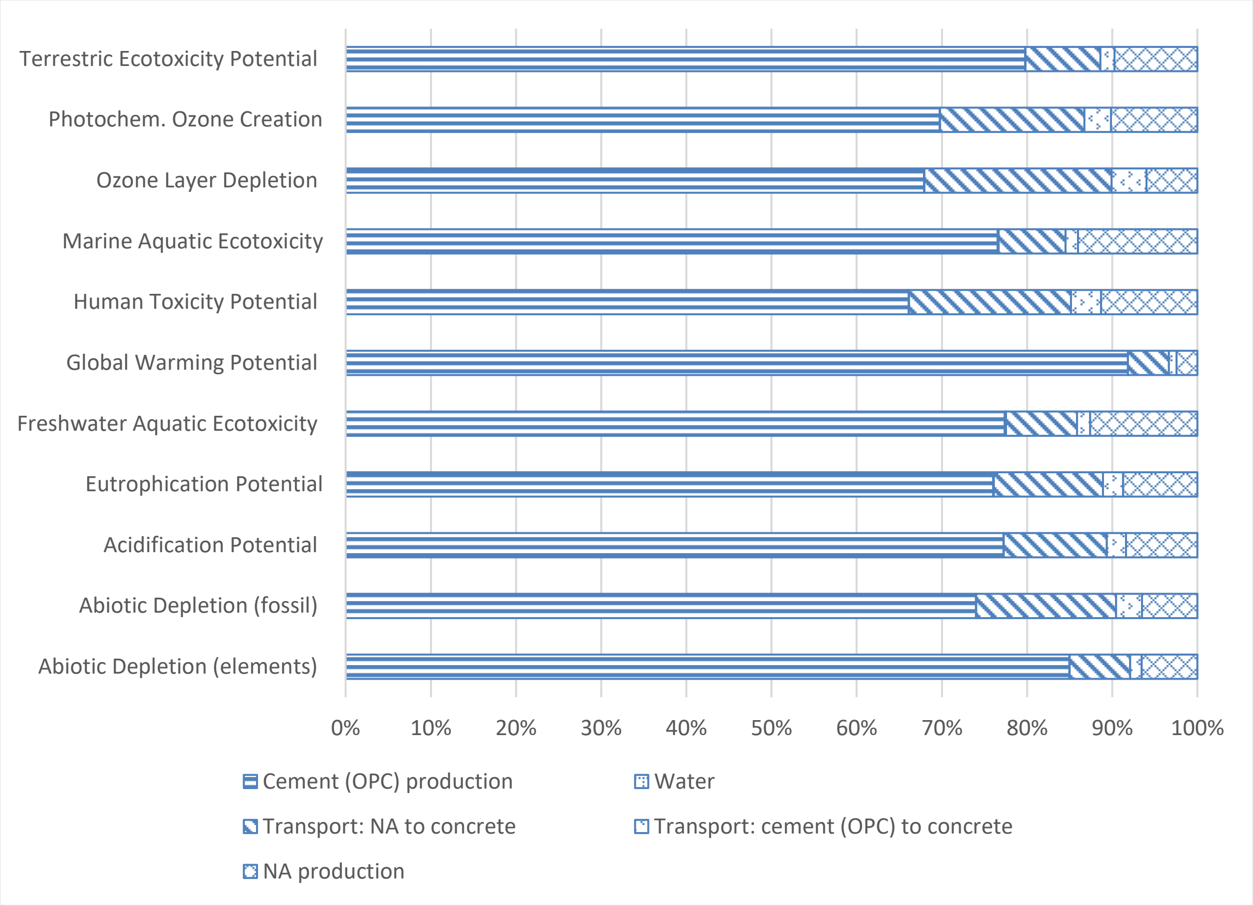

Figure 10: paver OPC-concrete: relative contribution of the different process to the midpoint results

Considering the results for AA-blocks in figure 7, the major contribution for all impact categories is given by the production of sodium hydroxide and sodium silicate, while minor contribution is given by the production and transport of the NA for low-quality applications. The left side of the graph in figure 7 represents the negative values, therefore the avoided impact. A major contribution to the avoided impact is given by the avoided production of boric oxide, despite the low quantity used (2 wt% of the AOD slag). However, for all impact categories, the sum of the positive impacts is always higher than the sum of the avoided impacts.

For the SC-blocks (figure 8), the major contribution to the different impact categories comes from the production of pure CO_2, with some minor contribution given by the NA production and transport. Among the avoided impacts, the avoided boric oxides production plays the major role in all categories, except for global warming potential, where the major avoided impact is given by the CO_2 uptake (-12 kg CO_2-eq).

Considering the process contribution in the FC-blocks production (figure 9), the electricity consumption and the CO_2 production give an important contribution to the final environmental impact, especially in the categories ozone layer depletion, global warming and abiotic depletion. Finally, as already proved by previous studies (see for instance Turner and Collins, 2013), for each of the analysed categories, the OPC production contributes the most to the final environmental impact of paver OPC concrete (figure 10).

The process contribution analysis for AA-blocks, SC-blocks and FC-blocks show consistency with previous LCA analyses on alkali activation and carbonation. Previous studies conducted on alkali activation of GGBFS and fly ashes showed in fact a similar performance in the midpoint category global warming, finding that concrete made with alkali-activated SCMs outperforms the OPC-concrete (Weil et al., 2009). In addition, Habert et al. (2011) and Duxson et al. (2007) identified also in the production of sodium silicate the main driving force in determining the environmental impacts of the alkali activation process, causing higher impacts than traditional OPC-concrete in midpoint categories other than global warming potential.

Regarding the carbonation, Kirchofer et al. (2012) proved that the carbonation of cement kiln dust, GGBFS and fly ashes, shows a negative CO_2 balance for a reaction at 25°C (meaning more CO_2 uptaken than emitted), while it becomes positive when increasing the temperature of the reactor. These results strengthen the importance of the trade-off between the additional reactivity gained with higher temperatures and pressures, and the increase of energy consumption to reach these conditions.

3.2 Endpoint analysis

Table 5 reports the result of the Recipe endpoint analysis, while figure 11 shows the same results relating the highest impact for each endpoint category to 100%.

Table 5: Recipe endpoint analysis

Endpoint category	S-1 (AA-blocks)	S-2 (SC-blocks)	S-3 (FC-blocks)	Paver OPC-concrete
Human health (DALY)	1.44E-05	1.99E-05	4.42E-04	4.36E-05
Ecosystems (species * y)	2.88E-08	-1.85E-08	1.35E-07	1.61E-07
Resources ($)	0.1137	0.2518	1.087	0.3485

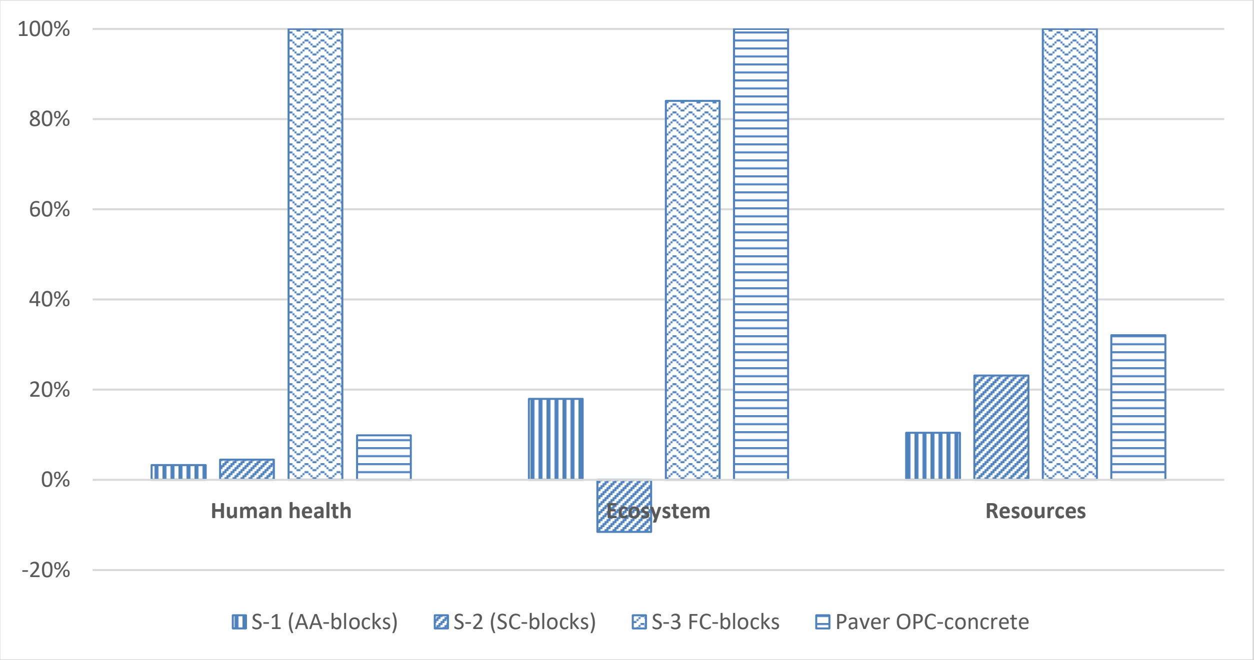

Figure 11: Recipe endpoint results

In the endpoint categories human health and resources, the FC-blocks have the highest contribution (4.42E-04 DALY and 1.087 $), followed by paver OPC-concrete (10% in human health and 32% in resources), SC-blocks (5% in human health and 23% in resources) and AA-blocks (3% in human health and 10% in resources). For the endpoint category ecosystems, the paver OPC-concrete is the material with the highest contribution, followed by the FC-blocks (84%) and the AA-blocks (18%). The SC-blocks is the only material presenting a negative value in the endpoint analysis, in the category ecosystems.

3.3 Sensitivity analysis

The sensitivity analysis tackles a possible source of uncertainty, represented by the assumption made on transport distances during the LCI phase.

One of the main advantages of circular economy is that materials exchange between two industries have normally a local or regional dimension and it enables a reduction of transport distances, compared to primary raw materials (Ghisellini et al., 2016). Nevertheless, transport distances can highly vary from one case to the other, and materials exchange between two industries might involve long transport distances. In order to assess the sensitivity of the LCA results to transport variation, a scenario (sensitivity scenario) with less favourable transport conditions for the AOD-slag valorisation is studied. In this scenario, the transport distance for the AOD-slag from the steel to the concrete factory producing the SSS-blocks is set at 100km, while all the other distances are kept equal to the base case. Table 6 shows the variation of the Recipe endpoint LCA results for the transport scenario.

Table 6: transport sensitivity analysis

	Human health (DALY)	Ecosystems (species * y)	Resources ($)
S-1 (AA-blocks)			
base case	1.44E-05	2.88E-08	1.14E-01
sensitivity scenario	1.60E-05	3.47E-08	1.51E-01
variation sensitivity scenario/ base case	+11%	+20%	+33%
S-2 (SC-blocks)			
base case	1.99E-05	-1.8E-08	0.2518
sensitivity scenario	2.41E-05	-3.1E-09	0.347144
variation sensitivity scenario/ base case	+21%	+17%	+38%
S-3 (FC-blocks)			
base case	4.42E-04	1.35E-07	1.087
sensitivity scenario	4.46E-04	1.5E-07	1.181368
variation sensitivity scenario/ base case	+1%	+11%	+9%

The endpoint category Resources is the most affected by the increased transport distances, showing increments between 38% (S-2) and 9% (S-3), while ecosystems show increments between 20% (S-1) and 11% (S-3). Human health is the endpoint category less affected by the distance increase, with increments between the 21% (S-2) and only 1% (S-3). SC-block is the material that presents the highest increments in two of the three endpoint categories (human health and resources), while the FC-blocks is the material that is less affected by the increase of transport distances. Therefore, when a high amount of electricity is consumed during the production process, the influence of transport variation becomes less relevant.

Figure 11 compares the Recipe endpoint results of the new transport scenario with the Recipe endpoint results of the paver OPC-concrete. It becomes evident that an increase of transport distances does not change the final ranking of the analysed materials. The only significant increment is reported in the damage Resources for the SC-blocks, where the increment of 38% compared to the base case brings the final value up to 0.34 species*year, which is equal to the value for paver OPC-concrete.

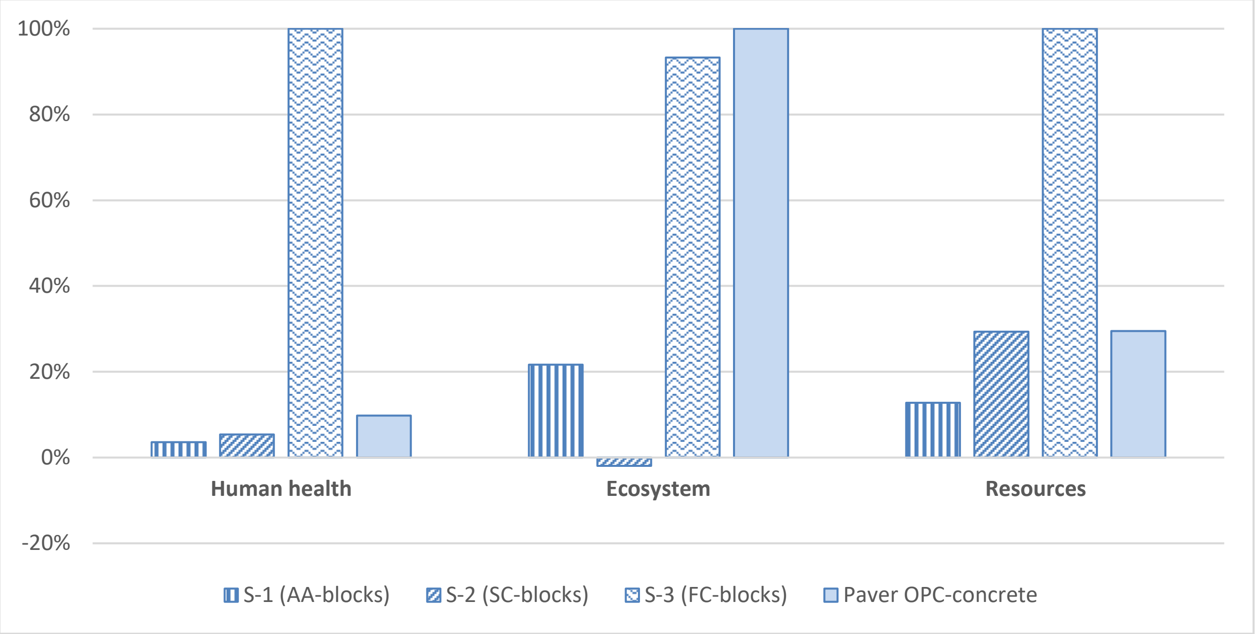

Figure 12: sensitivity analysis on transport variation. Comparison between sensitivity scenarios and base case paver OPC-concrete. Results for Recipe endpoint

4. Results interpretation and limitations

The LCA results presented in this study show the potential of AOD-valorisation to reduce the environmental impacts, compared to the traditional paver OPC-concrete.

In particular, the valorisation through slow carbonation seems the most promising option in terms of impact reduction. The major negative environmental effect, represented by the production of the pure CO_2, is offset by the environmental benefits due to the avoided boric oxide production, the CO_2 uptake and the low electricity consumption. On the other hand, however, the slow carbonation requires a long process time (7 days) that might be not cost-efficient for an industrial implementation of the process. Raising the temperature and the pressure can sensibly increase the kinetics of the carbonation, reducing the process time to only 2.5h. However, this hoists also environmental issues. The CML midpoint and Recipe endpoint analyses show that the electricity required to accelerate the process increases significantly the final environmental impacts. In some midpoint and endpoint categories, the final environmental impact of fast carbonation exceeds the one of the paver OPC-concrete, offsetting the environmental benefits of slag recovery and of the avoided boric oxide production. In view of a future industrial development of the carbonation process, it is therefore fundamental to optimise the trade-off between acceptable process time and sustainable electricity consumption. Lowering the impact coming from the production of CO_2 represents another valuable alternative solution to improve the environmental performances of the carbonation process. For instance, some studies have investigated the performances of the carbonation process by using CO_2 coming from flue gas directly from the steel industry (Tian et al., 2013). However, the results are not satisfying because of the presence of impurities that inhibit the performance of the processes.

The valorisation through alkali activation shows a promising environmental performance, thanks to the impact reduction in many midpoint and endpoint categories, compared to traditional paver OPC-concrete. While the traditional paver OPC-concrete production is energy intensive and produces high quantities of direct emissions, the alkali activation shows low energy requirements and no direct emissions. These factors, in combination with the avoided boric oxide production, make the alkali activation process environmentally attractive, especially in terms of CO_2 reduction. However, it should be noticed that the alkali activation requires a certain amount of chemicals (alkali activators). The results of the LCA show that the production of these chemicals can negatively affect the environmental profile of alkali activated materials, especially for some midpoint categories, where the impact of alkali activation is higher than the impact of paver OPC-concrete. Therefore, for a future industrial development, the quantity of alkali activators added to the process should be optimised and limited, in order to reduce its environmental impact. As an alternative, alkali activators could be recovered from glassy waste stream (Barbieri et al., 2000). However, at present, there is not an established procedure allowing the production of pure alkali compounds from waste streams.

The sensitivity analysis performed on transport distances shows how an increase of distances can have a negative effect on the final environmental performances of the SSS-blocks, but this negative effect does not influence the comparison with the environmental performances of the paver OPC-concrete.

It is also worth to highlight the limitations of the presented LCA results. First, the data used for the LCI are case-specific primary data collected from laboratory tests. However, the LCA results obtained at a laboratory scale might not be necessarily the same as the LCA results obtained at an industrial scale, since optimization and other learning effects may occur (Shibasaki et al., 2006). These improvements may lead to a more efficient use of material or an increased energy efficiency of individual process steps. On the other hand, a variation in the composition of the slag batches may affect the industrial production of SSS-blocks with a stable quality (Salman et al., 2016). As the economic value of the SSS-blocks is low compared to the value of the stainless steel, the metallurgic process will indeed focus on the properties of the stainless steel, rather than on the quality of the SSS.

Another limitation of the LCA results on SSS-blocks is represented by some old Ecoinvent datasets used during LCI phase. For instance, the dataset for boric oxide production refers to data collected during the period 2000-2006, while the dataset for CO_2, sodium hydroxide and sodium silicate production are valid until the year 2011. Even if these datasets are available in the most updated version of Ecoinvent (version 3.3, 2016), they might not be representative of today's technologies.

Finally, an additional limitation of the LCA results is represented by the intrinsic limitation of attributional LCA when it comes to industrial decision making and evaluation of industrial symbiosis applications. As clarified by Marvuglia et al. (2013) and Vázquez-Rowe et al. (2013), an attributional approach provides a good environmental reporting and understanding of the main environmental impacts within the analysed production system. On the other hand, it omits the analysis of potential indirect effect engendered in the markets by the underlying actions. Therefore, attributional LCA results provide a good environmental analysis at a product level, which enables a reliable comparison between alternative products. However, from attributional LCA results, no conclusions can be made on the environmental consequences of product substitution.

5. Conclusions and future work

The production of ordinary Portland cement (OPC), a widely used binder in concrete production, is thought to be responsible for 5-8% of the global CO_2 emissions. Therefore, the cement and concrete producers, together with the scientific community, is currently engaged in finding sustainable alternatives to OPC. Following the principle of industrial symbiosis, the present research has analysed the environmental performances of new construction materials using metallurgical slag as replacement of OPC. In particular, the AOD-slag, a residue from the stainless steel production, has been used to produce three different construction blocks, called SSS-blocks. The environmental performance of the SSS-blocks has been compared with the environmental performance of equivalent OPC-based construction blocks, used as paver concrete. The three SSS-blocks were produced separately by activating the AOD-slag through three different processes: alkali activation, slow carbonation and fast carbonation. From the results of the LCA, some conclusion can be drown:

- The valorisation of AOD-slag has the potential to lower some environmental impacts compared to paver OPC-concrete. For instance, the impact reduction can be significant in midpoint categories as global warming potential, where the analysis shows a reduction of

84% for alkali activated blocks, of 35% for fast carbonated blocks, and of 117% for slow carbonated blocks. At the same time, in some other midpoint and endpoint categories, the environmental impact of the SSS-blocks is higher than the one of paver OPC-concrete. For instance, the alkali activated blocks shows an increase of 58% in the midpoint impact category ozone layer depletion, the slow-carbonated block shows an increase of 45% in the midpoint category human toxicity, and the fast-carbonated block shows increases of 90% and 68% in the endpoint categories human health and resources.

- The production of alkali activators represents the environmental hotspot of the alkali activation process. Some effective solutions to lower the environmental impacts of alkali activated materials rely on a more efficient use of alkali activators during the process, or to a more sustainable alkali activators production process (as for instance the possibility of recovery the alkali activators from specific waste streams).
- The slow-carbonated blocks represent the materials with the lowest environmental impacts, both at a midpoint and endpoint analysis. However, the long process time required to complete the process makes the slow-carbonated blocks less attractive for possible industrial development. On the other hand, the possibility of increasing the kinetic of the process raises many environmental concerns, due to the electricity consumed to keep the high temperatures and pressures required. Therefore, it is fundamental to find the right balance between acceptable process time and electricity consumption. Another environmental hotspot for the carbonated blocks is represented by the use of pure CO_2 streams. The recovery of CO_2 from flue gas streams from other industries can represent an opportunity to reduce the overall environmental impacts of the process.
- The sensitivity analysis on transport distances shows how increments up to 10 times higher than the one assumed in the base case do influence the environmental profile of SSS-blocks. However, they do not affect the final comparison with paver OPC-concrete, showing that the benefits of AOD-slag valorisation are still valid even if high transport distances must be covered.

The LCA analysis highlights also important limitation on the data used as input, the database for chemicals and the LCA modelling:

- The input data used in the LCA model are based on a case-specific development in laboratory tests. The possible upscaling of the processes could have positive effects, as an increased efficiency in the use of alkali activators and a more efficient uptake of CO_2, but also it may presents some risks due to possible variation of slag batch composition.
- The database for chemicals used in the LCI phase is outdated and it may not represent the today’s technologies.
- Attributional LCA presents limitations when assessing the effect of product substitution into an economic system. Therefore, from the current analysis, no conclusions can be made on the environmental consequences for the steel and construction sectors when paver OPC-concrete is substituted with SSS-blocks.

A sustainable environmental profile and a promising economic plan are two fundamental pre-requisites for industrial and market development of new products. Economically, to upgrade research and lab-based innovation into industrial products, an attractive business case is key. The economic potential of SSS- blocks is promising since low-value or even costly (disposed) residues are transformed into valuable new products. Therefore, an in-depth analysis of the costs and revenues from bringing SSS-blocks to the market would further the understanding of the potential and would narrow the remaining distance to the market for these sustainable construction materials. Environmentally, as proved in the presented LCA-study, the SSS-blocks represent a good opportunity to lower the impact of cement industry. Consequently, industrial and scientific research should focus on increasing the efficiency of the processes. In addition, to make the environmental analysis more accurate, there is an urgent need for updated environmental life cycle inventory dataset for alkali activators, boric oxide and CO_2 production. Finally, the attributional approach should be integrated with a more systemic approach (e.g. consequential-LCA) able to widen the scope of LCA by assessing the possible environmental and economic consequences at a holistic system level.

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Table 7: Process contribution to the CML midpoint categories

	Abiotic Depletion (ADP elements) [kg Sb-Equiv.]	Abiotic Depletion (ADP fossil) [MJ]	Acidification Potential [kg SO2-Equiv.]	Eutrophication Potential [kg Phosphate-Equiv.]	Freshwater Aquatic Ecotoxicity [kg DCB-Equiv.]	Global Warming Potential [kg CO2-Equiv.]	Human Toxicity [kg DCB-Equiv.]	Marine Aquatic Ecotoxicity [kg DCB-Equiv.]	Ozone Layer Depletion [kg R11-Equiv.]	Photochem. Ozone Creation [kg Ethene-Equiv.]	Terrestric Ecotoxicity [kg DCB-Equiv.]
S-1 AA-blocks											
Electricity	1,07E-08	0,0368	2,22E-05	4,74E-06	0,000988	0,0102	0,00378	6,92	2,49E-09	1,85E-06	3,26E-05
(avoided) boric oxide production	-3,22E-05	-8,03	-0,027	-4,41E-03	-0,698	-1,74	-1,96E+00	-2,70E+03	-2,46E-07	-1,74E-03	-0,0203
sodium hydroxide production	2,53E-05	5,25	0,0126	3,38E-03	0,529	1,73	1,19E+00	2,44E+03	9,31E-07	7,96E-04	0,0182
sodium silicate production	3,97E-05	7,96	0,0173	4,84E-03	1,15	2,5	2,46E+00	4,00E+03	1,06E-06	1,18E-03	0,0339
Avoided transport: AOD-slag to low quality	-1,09E-06	-1,39	-0,00173	-4,71E-04	-0,0286	-0,33	-1,80E-01	-101	-6,08E-08	-2,38E-04	-0,00128
Transport: AOD-slag to valorisation	2,17E-07	0,277	0,000347	9,42E-05	0,00571	0,0661	3,59E-02	20,2	1,22E-08	4,75E-05	0,000256
Transport: NA to low quality	1,09E-06	1,39	0,00173	0,000471	0,0286	0,33	0,18	101	6,08E-08	0,000238	0,00128
NA production	1,00E-06	0,551	0,0012	0,000319	0,0429	0,169	0,107	179	1,65E-08	0,000142	0,00142
Aggregates for SSS-blocks	1,54E-06	0,847	0,00184	0,000491	0,066	0,26	0,165	275	2,54E-08	0,000219	0,00218
S-2 SC-blocks											
CO_2 production	9,22E-05	3,35E+01	0,0439	0,0192	3,65	1,36E+01	23,2	1,29E+04	8,28E-07	4,56E-03	0,107
CO_2 uptake						-12,9					
Water	1,29E-08	0,0196	3,27E-05	1,55E-05	0,00313	0,00607	0,00356	9,32	6,66E-10	2,36E-06	3,87E-05
(avoided) boric oxide production	-8,33E-05	-2,08E+01	-0,0699	-1,14E-02	-1,81E+00	-4,51	-5,08	-6,99E+03	-6,37E-07	-4,52E-03	-5,25E-02
Avoided transport: AOD-slag to low quality	-2,81E-06	-3,59E+00	-0,00449	-0,00122	-0,074	-8,56E-01	-0,465	-261	-1,57E-07	-6,15E-04	-3,31E-03
Transport: AOD-slag to valorisation	5,63E-07	7,18E-01	0,000898	0,000244	0,0148	0,171	0,0931	52,2	3,15E-08	1,23E-04	0,000663
Transport: NA to low quality	2,81E-06	3,59E+00	0,00449	0,00122	0,074	8,56E-01	0,465	261	1,57E-07	6,15E-04	3,31E-03
NA production	2,59E-06	1,43E+00	0,0031	0,000826	0,111	0,437	2,77E-01	463	4,28E-08	3,69E-04	0,00367
S-3 FC-blocks											
CO_2 production	9,22E-05	3,35E+01	4,39E-02	1,92E-02	3,65E+00	1,36E+01	23,2	1,29E+04	8,28E-07	4,56E-03	1,07E-01
CO_2 uptake						-1,29E+01					
Water	1,29E-08	1,96E-02	3,27E-05	1,55E-05	3,13E-03	6,07E-03	0,00356	9,32E+00	6,66E-10	2,36E-06	3,87E-05
(avoided) boric oxide production	-8,33E-05	-2,08E+01	-6,99E-02	-1,14E-02	-1,81E+00	-4,51E+00	-5,08	-6,99E+03	-6,37E-07	-4,52E-03	-5,25E-02
Avoided transport: AOD-slag to low quality	-2,81E-06	-3,59E+00	-4,49E-03	-1,22E-03	-7,40E-02	-8,56E-01	-0,465	-2,61E+02	-1,57E-07	-6,15E-04	-3,31E-03

Transport: AOD-slag to valorisation	5,63E-07	7,18E-01	8,98E-04	2,44E-04	1,48E-02	1,71E-01	0,0931	5,22E+01	3,15E-08	1,23E-04	6,63E-04
Transport: NA to low quality	2,81E-06	3,59E+00	4,49E-03	1,22E-03	7,40E-02	8,56E-01	0,465	2,61E+02	1,57E-07	6,15E-04	3,31E-03
NA production	2,59E-06	1,43	3,10E-03	8,26E-04	1,11E-01	4,37E-01	0,277	4,63E+02	4,28E-08	3,69E-04	3,67E-03
Electricity	1,66E-05	57,1	3,44E-02	7,35E-03	1,53E+00	1,57E+01	5,86	1,07E+04	3,86E-06	2,86E-03	5,06E-02
Paver OPC-blocks											
Cement (OPC) production	3,59E-05	17,3	0,0306	0,00771	0,732	17,5	1,73	2,71E+03	5,19E-07	0,00271	3,21E-02
Water	4,76E-09	0,00724	1,20E-05	5,70E-06	0,00115	0,00224	0,00131	3,43	2,45E-10	8,68E-07	1,42E-05
Transport: NA to concrete	3,01E-06	3,84	0,0048	0,0013	0,0791	0,915	0,498	279	1,68E-07	0,000658	0,00354
Transport: cement (OPC) to concrete	5,57E-07	0,71	0,000889	0,000241	1,46E-02	0,169	0,0922	51,7	3,12E-08	0,000122	6,56E-04
NA production	2,77E-06	1,52	0,00332	0,000883	1,19E-01	0,467	0,296	4,96E+02	4,58E-08	3,94E-04	3,92E-03