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DOI

[10.1111/jiec.12930](https://doi.org/10.1111/jiec.12930)

Publication date

2019

Document Version

Final published version

Published in

Journal of Industrial Ecology

Citation (APA)

Yao, Y., Hu, M., Di Maio, F., & Cucurachi, S. (2019). Life Cycle Assessment of 3D Printing Geo-polymer Concrete: An Ex-ante Study. *Journal of Industrial Ecology*, 24 (2020)(1), 116-127. Article JIEC12930. <https://doi.org/10.1111/jiec.12930>

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Life cycle assessment of 3D printing geo-polymer concrete

An ex-ante study

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Funding information

The corresponding author Mingming Hu is grateful to the support of European Union's Horizon 2020 research and innovation programme (Grant Agreement No 723582).

Editor Managing Review: Thomas Seager

Abstract

Three-dimensional (3D) printing and geo-polymers are two environmentally oriented innovations in concrete manufacturing. The 3D printing of concrete components aims to reduce raw material consumption and waste generation. Geo-polymer is being developed to replace ordinary Portland cement and reduce the carbon footprint of the binder in the concrete. The environmental performance of the combined use of the two innovations is evaluated through an ex-ante life cycle assessment (LCA). First, an attributional LCA was implemented, using data collected from the manufacturer to identify the hotspots for environmental improvements. Then, scaled-up scenarios were built in collaboration with the company stakeholder. These scenarios were compared with the existing production system to understand the potential advantages/disadvantages of the innovative system and to identify the potential directions for improvement.

The results indicate that 3D printing can potentially lead to waste reduction. However, depending on its recipe, geo-polymer likely has higher environmental impacts than ordinary concrete. The ex-ante LCA suggests that after step-by-step improvements in the production and transportation of raw materials, 3D printing geo-polymer concrete is able to reduce the carbon footprint of concrete components, while it does still perform worse on impact categories, such as depletion of abiotic resources and stratospheric ozone depletion. We found that the most effective way to lower the environmental impacts of 3D concrete is to reduce silicate in the recipe of the geo-polymer. This approach is, however, challenging to realize by the company due to the locked-in effect of the previous innovation investment. The case study shows that to support technological innovation ex-ante LCA has to be implemented as early as possible in innovation to allow for maintaining technical flexibility and improving on the identified hotspots.

KEYWORDS

3D printing, concrete, emerging technologies, ex-ante LCA, geo-polymer, industrial ecology

1 | INTRODUCTION

Concrete is the most used construction material, thanks to its good physical and chemical performances and long durability (Valipour, Yekkalar, Shekarchi, & Panahi, 2014). Due to the mass application even a small improvement in the environmental performance of concrete would have a significant effect on greening the built environment. It has been suggested that the environmental performance of concrete can be improved by incrementing the use of raw materials with an improved environmental profile, and by investing on new manufacturing technologies that maintain the competitive advantage of concrete in the construction market, while limiting avoidable environmental impacts (Prospe, Hainer, Rezvani, & Graubner, 2013).

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Three-dimensional (3D) printing technologies may offer opportunities for the traditional construction industry toward an improved resource-efficiency (Hager, Golonka, & Putanowicz, 2016). 3D printing is an additive manufacturing technology, in which material is added in small portion until the whole desired product is realized (Conner et al., 2014; Kietzmann, Pitt, & Berthon, 2015). The technology allows producing pieces by depositing material layer-by-layer, thus reducing raw materials consumption and waste generation in the production phase. 3D printing technologies can be applied to manufacture concrete pieces to be used in the construction industry (Delgado Camacho et al., 2018). Kafara, Süchting, Kemnitz, Westermann, and Steinhilper (2017) conducted a comparative life cycle assessment (LCA) of conventional and additive manufacturing (3D printing) of mold cores. In the study, four types of mold cores from conventional and additive manufacturing processes of concrete were compared. The results indicate that mold cores made from additive manufacturing show better environmental performance compared to those made from traditional manufacturing on a small production scale. Craveiro, Bartolo, Gale, Duarte, and Bartolo (2017) and Hager et al. (2016) studied several examples of 3D printing buildings. According to these studies, 3D printing buildings show higher resource-efficiency, lower emissions, waste generation, and resource consumption in construction processes when compared with traditional manufacturing.

Further potential to improve the environmental performance of construction could come from the use of geo-polymers (GP) as a substitute of ordinary Portland cement (OPC) in the manufacturing of concrete (Singh, Ishwarya, Gupta, & Bhattacharyya, 2015). In the manufacturing of ordinary concrete, Portland cement is used as the binding material. Due to the energy intensive processing and the chemical reaction in the production, the use of OPC is the key driver for the CO₂ footprint of concrete. While GP concrete utilizes wastes to substitute the OPC binder, and has superior mechanical properties (e.g., compression, flexural, and tensile bond strength) and durability as compared to traditional OPC concrete (Panda & Tan, 2018). The chemical mechanism of GP concrete is a geo-synthetics process, in which silicon- and aluminum-rich products are reacted in an alkaline solution (Panda, Paul, Mohamed, Tay, & Tan, 2018). Industries wastes (e.g., fly ash and slag) that contain silicon and aluminum ingredients can be used as raw materials of GP concrete (Panda et al., 2018). Due to the use of wastes and the avoided cement, GP concrete is expected to have less embodied CO₂. Habert, d'Espinose de Lacaillerie, and Roussel (2011) show that GP concrete has a similar impact on climate change, but performs worse on other impact categories compared to OPC concrete, in particular due to the impacts of sodium silicate manufacturing. More recent work by Turner and Collins (2013) and Petrillo, Cioffi, Ferone, Colangelo, and Borrelli (2016) compared the CO₂ footprint of GP concrete and 100% OPC concrete. Results of the two research suggest that the CO₂ footprints of GP concrete are approximately 9% and 16% lower. The authors highlight that the production of the alkali activators is the key driver of the life cycle impacts of GP concrete. As the 3D manufacturing and GP technologies only start penetrating in the construction market, it is interesting to analyze if the expected environmental improvement would be achievable in a real market context. In this study, ex-ante LCA is used to assess the potential environmental impacts of a GP concrete object manufactured by powder bed and inkjet 3D printing. Through the application of a three-phase approach we demonstrated how ex-ante LCA can be applied in practice to a real-world emerging technology. Using data directly provided by a powder bed and inkjet 3D printing geo-polymer concrete (3DGP) manufacturer, the environmental performance of the 3DGP concrete was evaluated at lab scale. The lab scale results were then scaled up through scenarios analysis, and then compared with ordinary concrete commonly used in the construction industry.

Aiming at combining environmental management and technology development, in close-collaboration with technology developers, the study shows that ex-ante LCA can not only estimate the potential environmental impacts, but, more importantly, provide directions for the future deployment of 3DPG technology from the current lab-scale experiment. The study is the results of multiple iterations of the analysis and regular interactions with the developers of the technology over a period of 6 months. While the technology developers welcomed with interest the results of this study, still some of the suggested improvements in the developed scenarios face implementation challenges in the short term. The technology readiness level (TRL; Moorhouse, 2002) of the 3DGP concrete technology in this research is estimated to be 6, which is already on technology demonstration stage. This would suggest to use LCA even at an earlier stage of the TRL trajectory to guarantee a greater support of technological innovation, when the core components of a technology are more flexible to change. While the technology under assessment can be defined as emerging, yet it does exist at a well-defined level of complexity. A further assessment of the market in which the technology will be introduced, which is also an emerging one, should be added to future studies dealing with emerging technologies to guarantee for the full consideration of the potential for a technology to be successful.

In this research, scenarios for environmental systems analysis were generated in accordance with previous literature on the topic, since no specific guidelines are currently available in the ex-ante LCA framework to develop and quantify scenarios. We involved technology developers in the research process and discussed with them the potential future technological landscape, potential market penetration, and thus the future commercial data and the feasibility of the scenarios.

We additionally followed Börjesson, Höjer, K.Dreborg, Ekvall, and Finnveden (2006), which identify three scenario categories to conduct LCA studies of emerging technologies. These include predictive scenarios, explorative scenarios, and normative scenarios based on different aims and starting points. In the second step of this research, forecasts on the condition of several specific improvements in the short term are made. "What-if" scenarios involved in predictive scenarios are chosen to respond to this question. To generate "what-if" scenarios, hotspots analysis is performed and then four scenarios are developed on the basis of improved hotspots, using the hotspots as building blocks. Thus, hotspots analysis can be seen as a structured method to develop scaled-up scenarios in ex-ante LCA studies. For the application of the framework of the ex-ante LCA methodology to other technological systems, additional scenario types and generating methods need to be considered as additional case studies and methodological contributions become available.

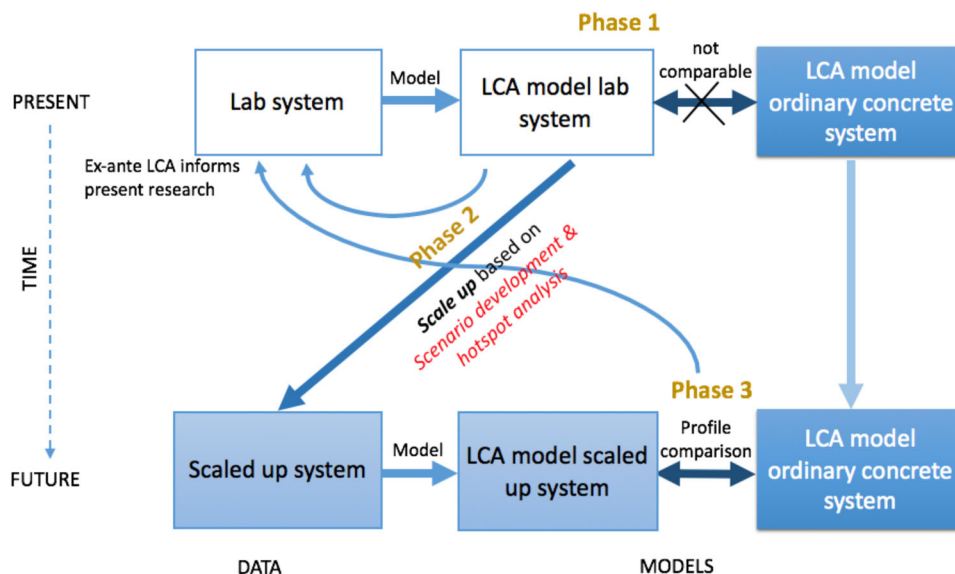


FIGURE 1 The summary of research processes (Adapted from Villares et al., 2017)

The remainder of the paper is organized as follows. First, we present the ex-ante framework under which the study is conducted. Following it, we present the specific powder bed and binding liquid jet 3D printing technology and GP concrete, assess the related lab scale technological setup, and identify the related environmental hotspots. Focusing on the identified hotspots, we then present four viable upscaling commercial scenarios. These were developed in collaboration with technology developers with the objective of improving the performance of the lab-scale technology following the results of the hotspots lab-scale assessment. The scenarios represent alternative realistic commercial developments of the lab-scale technology. We then compare the most promising of the commercial scenarios from an LCA perspective with a commercial scale system performing a similar function, to highlight the potential advantages and disadvantages of the innovative system. The basis for the comparison is the production of a standard concrete panel. Using the results of this scenario analysis we provide recommendations on the use of 3DGP concrete in the construction industry.

2 | METHODS AND SETUP OF THE STUDY

2.1 | Ex-ante LCA framework

LCA is one of the standard methods to evaluate the environmental impacts associated with product or service systems. Traditionally, LCA has been applied to existing and established product systems, with the consequence that results have always had a limited impact on decision-making, due to the cost of implementing needed changes, for example, in established manufacturing processes (Cucurachi, van der Giesen, & Guinée, 2018). Ex-ante LCA is regarded as the application of LCA on a novel product system before its full commercial deployment. The early application of LCA can help gain an insight into the environmental performances and potential challenges at an early stage (Cucurachi et al., 2018). It can be used as an environmental screening tool to assess research proposals or design concepts in the research and industry, thus contributing directly to the improvement of the design or the technology, thus fostering the transition to a circular economy (Villares, Işıldar, van der Giesen, & Guinée, 2017).

To operationalize the ex-ante LCA methodology, we follow the guidelines of Villares et al. (2017). The authors propose a cumulative research approach under the ISO technical framework for LCA (ISO 2006). The proposed approach involves three phases (see Figure 1).

First, an attributional LCA on the lab product system is conducted to preliminarily identify the potential hotspots. Second, the lab product system is scaled-up to commercial scale to allow for a comparison with an incumbent commercial system that is taken as a reference of business-as-usual performance. To achieve this goal, several scenarios are developed to establish several plausible and realistic commercial scale systems. Third, an attributional comparative LCA can be conducted to compare the environmental profiles of the scaled-up system with the reference incumbent system.

2.2 | The 3D printing geo-polymer concrete (3DGP) technology

3D printing has an advantage of manufacturing customized products, while maintaining similar performance and functions as ordinary concrete. In the 3DGP technology system, the powder and a binding material are two key materials for concrete manufacturing. To produce the powder, three

raw materials including slag, fly ash, and sand are first collected and mixed in a certain ratio in the mixer. Then, the powder is spread in thin layers. Meanwhile, silicate, water, and additives are gathered also in a certain ratio and mixed by hand to produce the binding liquid. Finally, the binding liquid is sprayed through a printer head to deposit the powder, layer by layer, in the desired shape. This 3DGP technology system under assessment in this contribution is created by a start-up manufacturing 3D printing concrete in the Netherlands. The 3D company (real name hidden at request of the company) is now setting up a large scale inkjet 3D printer that uses the 3DGP technology system to create custom, highly precise GP concrete to manufacture components used in the constructions industry.

We collected inventory data for foreground processes from measurements conducted in the company during direct on-site visits. The detailed recipe for 3DGP concrete (including the ratio of raw materials) was provided by the manufacturer. The upstream and background data are sourced from Ecoinvent v2.2 and relevant literature (see e.g., Chen, Habert, Bouzidi, Jullien, & Ventura, 2010). The 3D company contributed to the development of the commercial scenarios for the 3DGP technology system, using technical feasibility as primary criterion to develop the scenarios. The detailed information can be found in the section of scaled-up scenarios (Phase 2). The detailed data related to the unit processes in these two cases are reported in the Appendix in Supporting Information S4 available on the Journal's website. Each unit process of the product system is modeled using the CMLCA software (Guinée, 2006).

2.3 | Description of the incumbent reference system: Ordinary concrete production processes

Information on the manufacturing processes was obtained from the manufacturer. Several steps are introduced to produce one customized panel using ordinary concrete. In the beginning, a mold is needed to hold the shape of the panel. Expanded polystyrene (EPS) is used for the fabrication of the mold. To produce the mold, a block of EPS foam is milled to the shape of the panel in it by a large CNC mill. Then, the milled mold is sanded and coated to make it smooth and strong using epoxy. Next, a releasing agent is put on the coated mold to ensure that the concrete does not stick to the mold in the following steps. After that, a preprocessed mold is prepared. Then, the mixed concrete including glass fiber is poured into the preprocesses mold. Finally, the shaped concrete panel can be separated after rest.

For this system, the background data are extracted from Ecoinvent v2.2, while the foreground data are collected from relevant literature (see e.g., Chen et al., 2010). The detailed data related to the unit processes are included in Supporting Information S4. Each unit process of the product system is modeled by CMLCA software (Guinée, 2006).

3 | PHASE 1: LAB-SCALE LCA STUDY

3.1 | Goal and scope definition

The first phase of the ex-ante LCA study is the assessment of the lab system. This phase aims to identify the environmental hotspots in the current 3D printing technology system according to specifications provided by the 3D company. The analysis refers to 2017 technological development. At the lab-scale, we consider as a functional unit the production of a small 3DGP concrete product of 0.307 kg (i.e., standard specifics for use in the construction industry). In phase 1, we use a *declared* unit, and do not further specify what the use of this prototype will be. We focus on the physical output of the technology, to better assess the components of the system that are under the control of the technology developers. The scope of this LCA study is defined as “cradle-to-gate.”

3.2 | Inventory analysis

Within the boundaries of the lab system technology at the lab scale, we considered the stages of raw materials production and transport (dried slag, fly ash, sand, silicate, ultrapure water), and 3DGP concrete manufacturing. The production and transportation of the additive are cutoff due to the small amount of use and the lack of relevant data. The related flowchart of the 3DGP concrete technology is visualized in Figure 2.

We defined slag and fly ash in the system as by-products of iron and electricity productions according to EU end-of-waste criteria (European Union directive; EU, 2008), in which a waste may be considered as a by-product if several conditions are fulfilled (Chen et al., 2010). To accurately partition the upstream environmental burdens of iron and slag, electricity and fly ash, we apply an economic allocation method based on shares in proceeds. The allocation details of iron production and coal fired power generation processes are shown in Table S1-1 and S1-2 in Supporting Information. The inventory table can be found in the spreadsheet in Supporting Information S2.

3.3 | Results and interpretation of the lab-scale impact assessment

Nine impact categories from the CML-2001 (Oers, 2015) method are analyzed including eutrophication, depletion of abiotic resources, acidification, photochemical oxidation, climate change, terrestrial ecotoxicity, freshwater aquatic ecotoxicity, stratospheric ozone depletion, and human

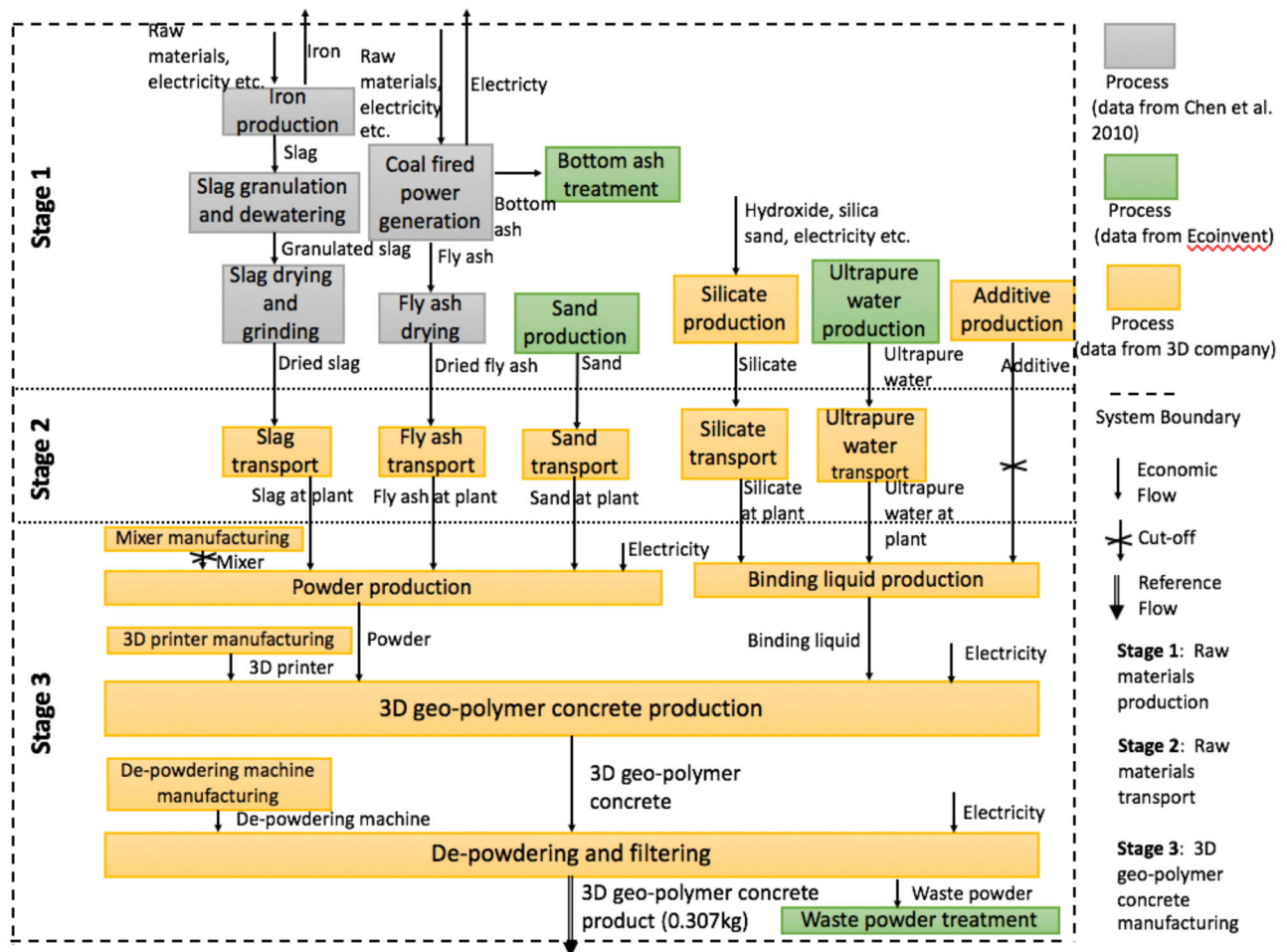


FIGURE 2 The flowchart of 3D printing geo-polymer (3DGP) concrete

toxicity (Frischknecht et al., 2007). The environmental interventions are automatically classified into nine impact categories using the CMLCA software.

We performed a contribution analysis on three stages of the 3DGP concrete system: raw materials production, raw materials transport, and 3DGP concrete manufacturing. The analysis is based on the impact scores after characterization for all of the impact categories considered in the assessment.

It found that the 3DGP manufacturing stage dominates the total environmental impacts in each category, as can be seen from the Figure "Contribution analysis on three stages" in Supporting Information S5. The raw materials production stage accounts for approximately 5% of the results, while the raw materials transport stage shows less than 5% of the results in each category.

Figure 3 shows a detailed contribution analysis on three stages on the basis of the sole climate change impact category. At the raw materials production stage (stage 1), the silicate production shows significant contribution compared to other materials, due to the use of a substantial amount of steam and heat in the production process. Dried fly ash and slag productions account for the remainder of the impacts, since a small part of upstream environmental burdens are allocated to them. The production of sand and ultrapure water show almost no contribution to the environmental impacts at this stage.

At the raw materials transport stage (stage 2), the transportation of all five raw materials is taken into account. Sand and silicate transports make up about 50% and 20% of the total climate change impacts, respectively, due to the impact of transportation of the imported materials. Dried fly ash transport accounts for another 20%, due to the sheer amount used at this stage. However, dried slag and ultrapure water transports show relatively lower contributions by reason of the short transportation distances and the small amounts used.

At the 3DGP concrete manufacturing stage (stage 3), the electricity use from the 3D printer, to power the de-powdering and filtering machine is the key driver of the impact. Furthermore, the machines consumption accounts for approximately 10% of the result. On the other hand, waste powder treatment did not show a contribution at this stage due to the small amount of waste powder generation.

To conclude, electricity consumption is the first significant hotspot for 3DGP concrete on the lab scale. The electricity may be used efficiently through the large scale production, which may be achieved on the commercial scale in the future. Second, long transport distances of several raw

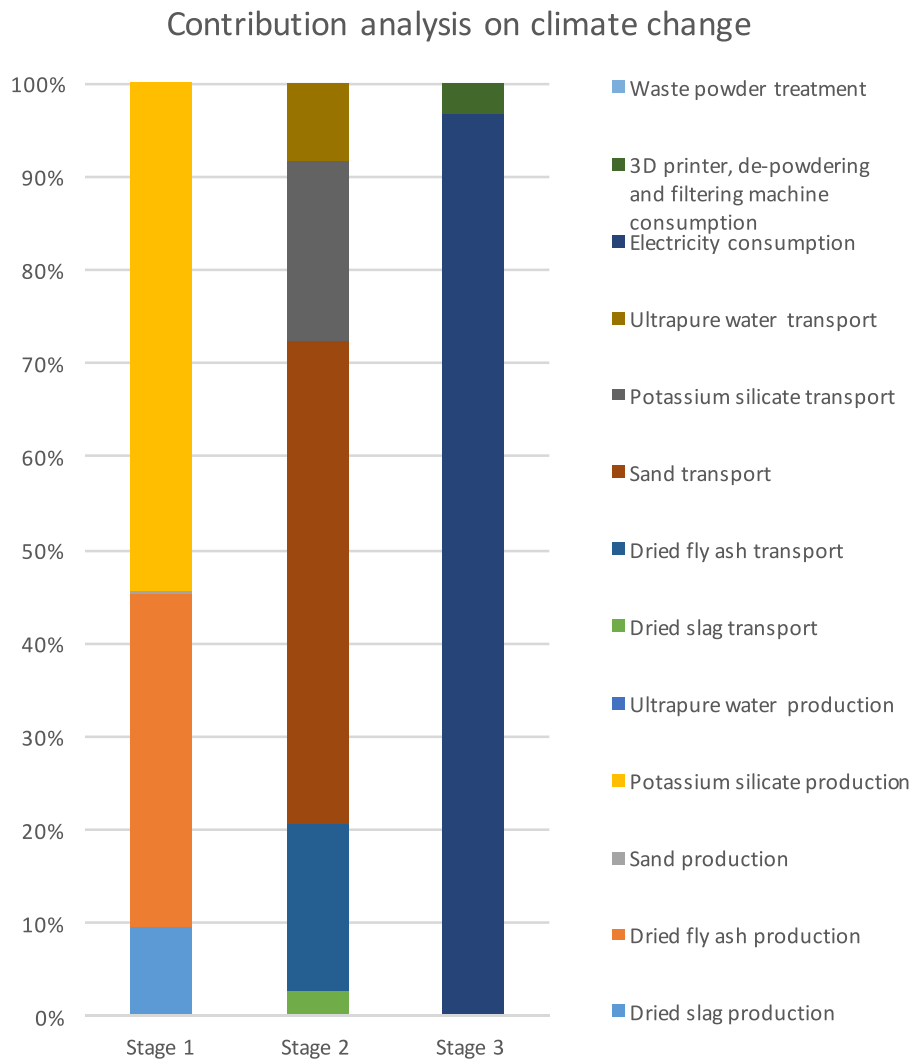


FIGURE 3 Contribution analysis on climate change. Underlying data used to create this figure can be found in supporting information S3

materials is another hotspot, which can be improved by changing the raw material suppliers. Third, the manufacturing of silicate has heavy impacts. Thus, reducing the use of silicate in the recipe is an effective way to cut down the impacts. Besides, slag and fly ash also show significant impacts due to the upstream environmental burdens. Therefore, substituting them with industrial wastes can largely decrease the relevant impacts.

3.4 | Phase 2: Development of scaled-up scenarios based on the hotspots LCA

The results of the hotspots analysis are passed on to the following phases of the ex-ante assessment (see Figure 1), and used as a modeling basis for the development of scenarios. To scale up and generate future scenarios, forecasts on the condition of several specific improvements in the short term are made with the company stakeholder and technology developers. Four “what-if” scenarios are built upon improved hotspots identified from the laboratory case, and are assessed in ascending order of feasibility. Table 1 illustrates the details of four future scenarios. The scenarios represent the possible step-wise developments to scale up the lab-scale system that was assessed in the hotspot LCA analysis. The four scenarios are technical evolution of the technology over time all the way to the best performing scenario from an environmental perspective. The scenarios are presented in decreasing order of ease of implementation.

Scenario 1 is considered by the company as the one with the highest viability and likelihood at commercial scale. In this scenario, a large scale 3D printer and machines are used. Furthermore, the processes of the 3DGP technology system are not changed, as well as the recipe and transportation of raw materials. Efficient electricity consumption can be achieved at scale in scenario 1. In scenario 2, the transportation of materials is seen as the most feasible aspect to improve in the next step on the basis of scenario 1. The transportation distances of sand and silicate are both reduced to 100 km, assuming local sourcing of materials. Next, in scenario 3, further adaptation of the sources of slag and fly ash provide a possible viable supply of materials. All the slag and fly ash are replaced by industrial wastes, leading to zero upstream environmental burdens. Finally, the reduction

TABLE 1 The details of four scenarios

Scenario 1	Efficient electricity consumption (Business feasible)	<ul style="list-style-type: none"> No change in the production processes, materials, and transportation distances. Use a bigger 3D printer, powder mixing machine, and de-powdering and filtering machine.
Scenario 2	Reduce transport distances based on scenario 1	<ul style="list-style-type: none"> Sand and silicate are bought in domestic and the transport distance of both of them is assumed to be 100 km.
Scenario 3	Replace all the slag and fly ash (by-products) with industrial wastes based on scenario 2	<ul style="list-style-type: none"> No upstream environmental burdens of slag and fly ash.
Scenario 4	Improve the recipe based on scenario 3	<ul style="list-style-type: none"> The use of silicate is reduced by 2%.

of the amount of silicate in the recipe was included in scenario 4. The recipe is improved by reducing the use of silicate by 2% with respect to the silicate content in scenario 3. The reduction of the silicate content was seen by the technology developers as the most challenging technological development from the current lab-scale setup.

4 | PHASE 3: COMPARATIVE ASSESSMENT AT SCALE

4.1 | Goal and scope definition

The goal of the third phase of the ex-ante LCA study is to define the environmental profiles of the 3DGP technology system on the potential commercial scale. The results are, then, compared with that of the traditional concrete technology system to understand the potential advantages and disadvantages of the innovative system and its improving directions.

At this phase of the ex-ante assessment, the comparative LCA study developed focuses on the comparison of post-2000 ordinary concrete technology and the novel 3DGP technology. Given the location of the 3D company in Rotterdam, the Netherlands, we focus the assessment on technology development in the construction sector in the Netherlands.

To set up a fair comparison between the novel technology and the incumbent, we considered, in agreement with the technology developers, a standard case study on which the company had already collected data. In particular, we consider the coverage of the customized façade of an existing building with the following technical specifications:

- The size of the façade is 3.6 m (height) * 62 m (length) * 0.6 m (thickness).
- It is assumed that 30 panels make up the whole façade.
- We consider that for each panel 3.6 m (height) * 2.07 m (length) * 0.6 m (thickness) = 4.46m³ concrete is needed.
- We evaluate and compare the environmental impacts of one panel (4.46m³).

4.2 | Inventory analysis

We maintained the same system boundaries for the 3DGP technology system. For the case of the ordinary concrete technology system, we also included in the assessment raw materials production and transport (i.e., of cement, gravel, glass fiber, additives, and water), mold production, and ordinary concrete manufacturing. The transportation of additives and water was neglected. The functional unit is defined as 4.46m³ concrete panel production. The scope of this LCA study is defined as “cradle-to-gate” as well. The flowcharts of 3DGP concrete panel and ordinary concrete panel are visualized in Figures 4 and 5.

4.3 | Impact assessment results and interpretation for incremental scenarios at scale

The same classification in the CML-2001 method applied for the lab scale system has been maintained in the commercial scale system.

Using the scenarios described earlier, we assessed whether the 3DGP concrete panel has environmental benefits compared to ordinary concrete panel in an evolutionary way. We assumed that the technological improvements necessary to meet the conditions of the four defined

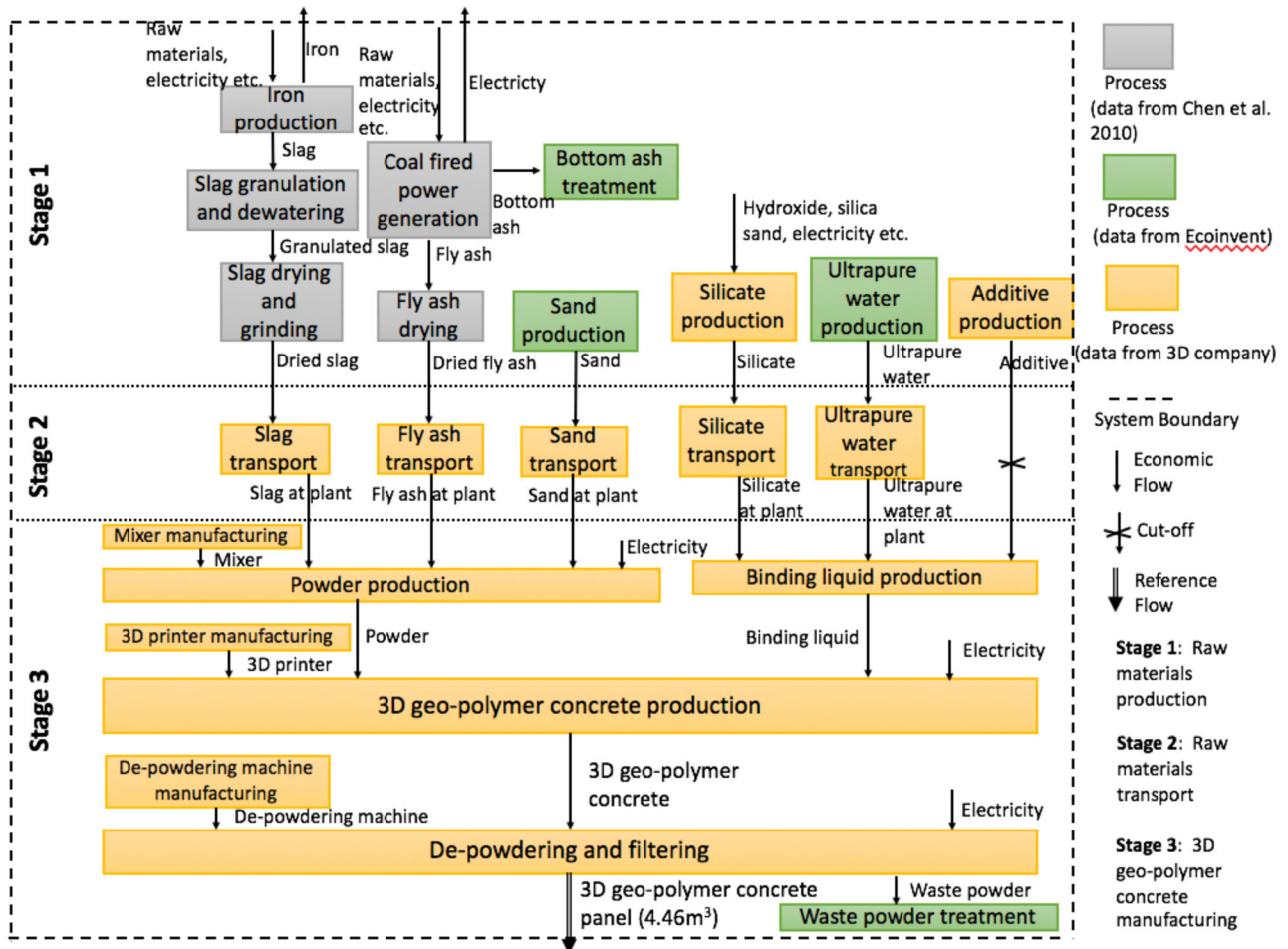


FIGURE 4 The flowchart of 3D printing geo-polymer (3DGP) concrete panel

scenarios would potentially happen without interference with the background processes obtained from standard LCA databases and the literature. Therefore, the impact of changes on the lab scale 3DGP technology would only influence the foreground system.

First, we quantified the impacts of the upscaling scenario 1 against business-as-usual ordinary concrete. The comparative characterization results are shown in the graph in Supporting Information S6. The results show that ordinary concrete panel has a better performance across all impact categories. A comparative contribution analysis on climate change category is performed on scenario 1 and ordinary concrete technology on the basis of the impact scores to identify major contributors to the difference in impacts.

Figure 6 shows the comparative contribution of raw materials production (stage 1), raw materials transport (stage 2), and concrete panel manufacturing (stage 3) to the Global Warming Potential impact between 3DGP concrete panel and ordinary concrete panel. It appears that ordinary concrete panel shows better environmental performance on stage 1 and 2, while 3DGP concrete panel outperforms ordinary concrete panel on stage 3.

On stage 1, though the cement shows the most significant impact in ordinary concrete, the total impact of the productions of dried slag, dried fly ash, and silicate in 3DGP concrete panel overtake that of the productions of all raw materials in ordinary concrete panel. This is due to the heavy effect of silicate manufacturing and the upstream environmental burdens of dried slag and fly ash productions. On stage 2, 3DGP concrete panel has a higher impact since the transportation distances of several raw materials are long. For example, no qualified sand supply nearby can meet the quality requirement for GP production. Therefore, these materials have to be bought from far places outside the Netherlands, leading to a higher impact than ordinary concrete panel on transportation aspect. However, on stage 3, 3DGP concrete panel has an advantage over ordinary concrete panel since no mold is used for manufacturing 3DGP concrete panel.

We further assessed the evolution of the technology over time across the following three incremental scenarios, to identify areas for improvement. Figure 7 summarizes characterization results comparison among four scenarios and ordinary concrete panel, among which the results of ordinary concrete panel are considered as a base.

As shown, 3DGP concrete panel still does not show environmental benefits after improving transportation on scenario 2. While after further replacing slag and fly ash on scenario 3, 3DGP concrete panel has a lower impact on climate change but still has higher impacts on other categories

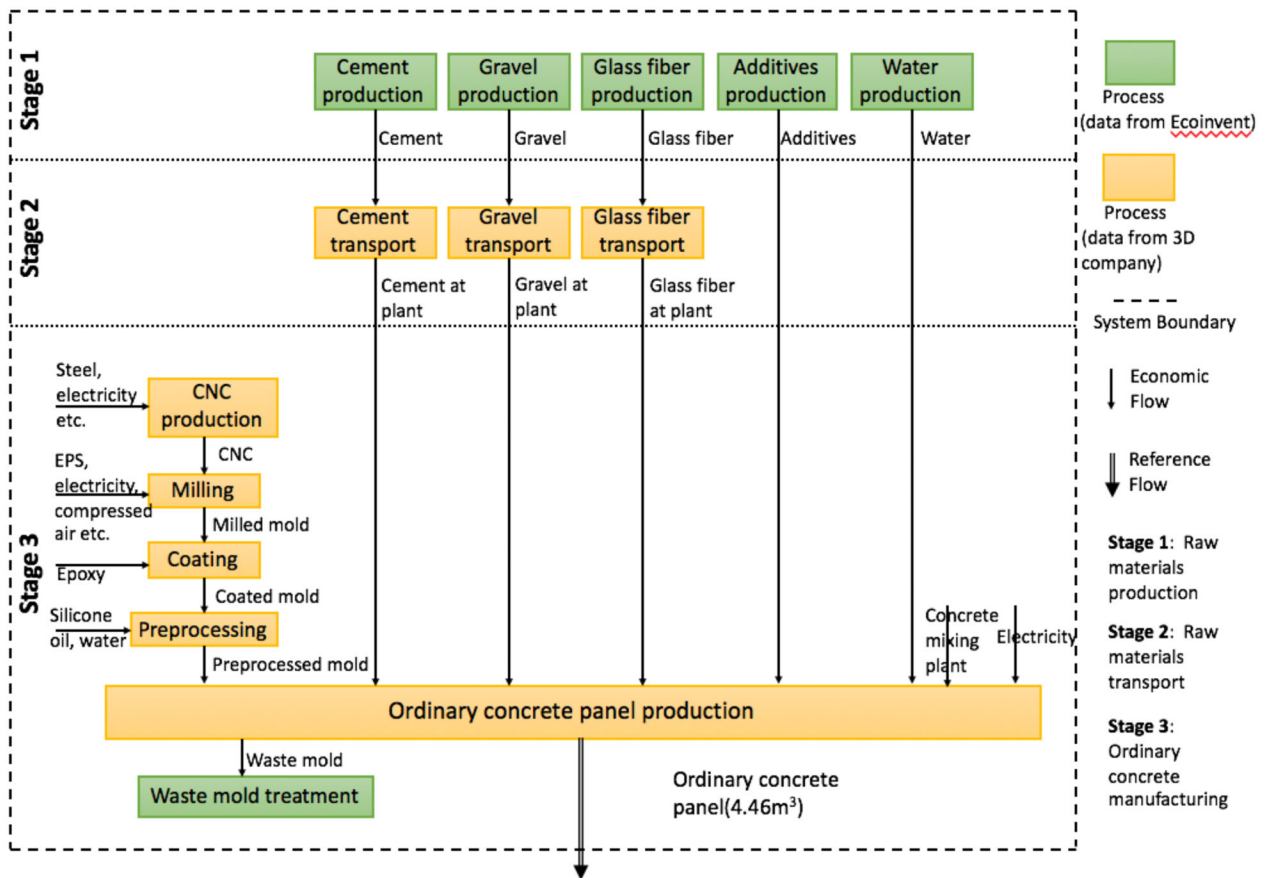


FIGURE 5 The flowchart of ordinary concrete panel

when compared to ordinary concrete panel. For scenario 4, 3DGP concrete panel shows an obvious environmental advantage on climate change, which is almost 60% of that of ordinary concrete panel. Meanwhile, the results on terrestrial eco-toxicity and human toxicity indicate a slight advantage, while the results on other categories are still higher. Thus, a small reduction of silicate use can further decrease the overall results, among which the result of climate change shows evident benefits while others still need further improvement.

5 | DISCUSSION

5.1 | Interpretation of results and limitations

The results of the ex-ante LCA study here presented show some discrepancies with previous 3D printing studies. This is mainly due to the different raw materials assessed in combination with 3D printing technologies. In the case here presented, one raw material in the recipe, namely the silicate, has considerable impacts on the manufacturing processes, leading to higher results compared to that of the ordinary raw materials in 3D printing. Additionally, available LCA studies on GP (see e.g., Petrillo et al., 2016; Turner & Collins, 2013), often exclude the upstream environmental burdens of fly ash and slag. In addition, these studies do not include the transportation phase of raw materials for the GP component of the life cycle. In the case here presented, the transportation distances of raw materials for the GP are obviously higher compared to that considered for the case of traditional concrete. Thus, the CO₂ emissions of GP concrete are higher than that of ordinary concrete in this research.

Additional modeling limitations may be identified. The temporal and geographical scope of background data and foreground data for both technology systems are not homogenous. Most of the upstream or background data are extracted from Ecoinvent v2.2 database, in which the data are aged and several data are not specific to the study area, the Netherlands. To our knowledge, more recent versions of the Ecoinvent database do not include relevant updates for the inventory processes of interest for the current study. In addition, the degree of foreground data accuracies between ordinary concrete technology and 3DGP technology are different when comparing two systems.

The current study setup excludes the use-phase and end-of-life phase for both technology systems. While the environmental impacts of 3DGP concrete and ordinary concrete in the use phase are similar, the collection, treatment, and potential recycling ratio of these two alternatives may be different after utilization. Further research is needed to assess whether the exclusion of the use-phase and end-of-life phase would affect the comparison result of the two alternatives.

Comparative contribution analysis on climate change

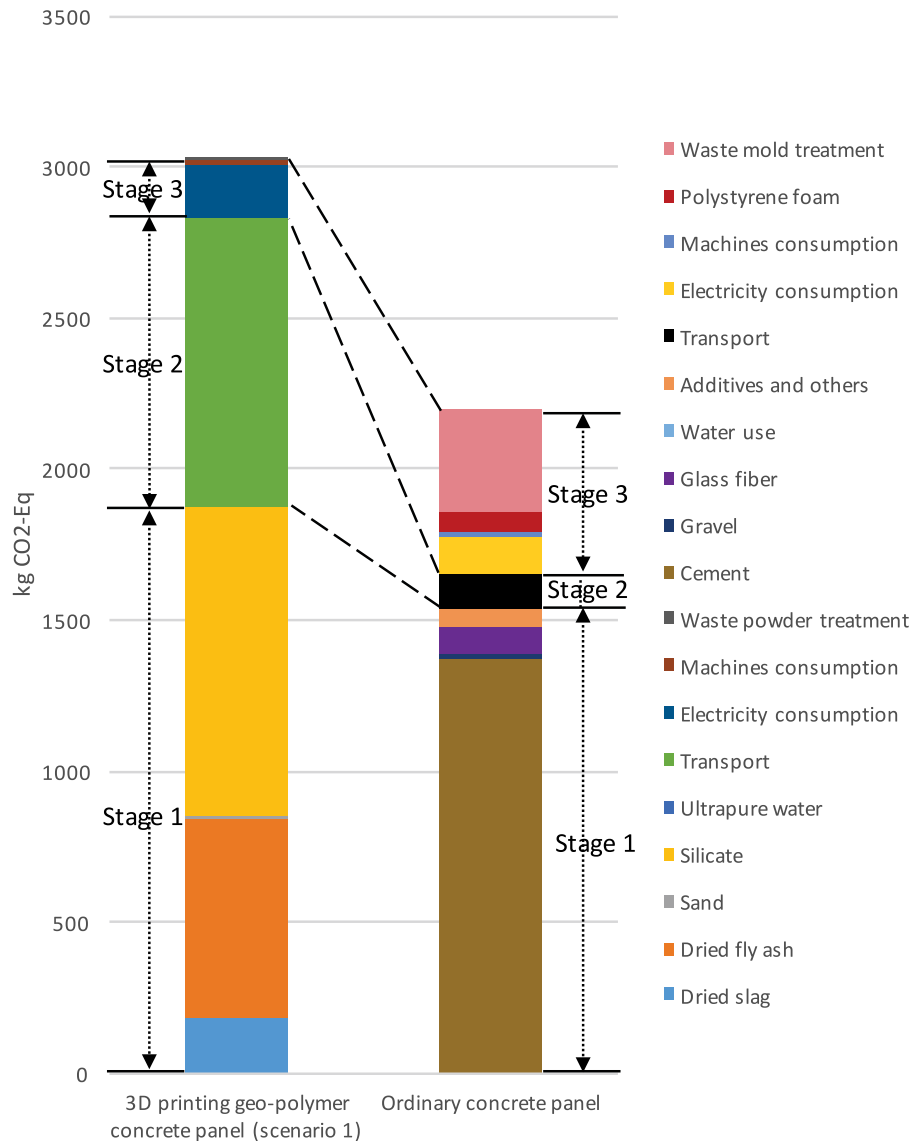


FIGURE 6 Contribution analysis between two panels on climate change. Underlying data used to create this figure can be found in supporting information S3

The combined use of 3D printing and geo-polymer innovations is superior to the ordinary concrete especially on realizing special shapes. It is due to the avoided use of mold, like in this case study, a complex customized facade. Using ordinary concrete, it means large amount of EPS foam would be consumed for the creation of the mold. However, if the object is a simpler design such as a flat wall, the comparison of two alternatives on concrete panel manufacturing stage would be different since the mold is reusable and EPS foam for mold production could be saved for ordinary concrete.

In this research, the economic allocation method was applied to two multifunctional processes in the 3DGP technology system. We acknowledge that the method may lead to unstable results due to potential price fluctuations in the market of by-products. The alternative use of mass allocation method was considered at first, but excluded due to the large upstream environmental burdens of by-products (Chen et al., 2010).

Finally, several limitations exist in the scenarios development. To build up “what-if” scenarios, both external factors and/or internal factors are taken into account to make up forecasts (Höjer et al., 2008). We were able to include specific internal factors such as raw materials transportation, the substitutes of raw materials, and the improvement of GP concrete recipe that are controlled by the decision-makers. However, due to lack of data we were not able to adequately model external factors that influence the development of an emerging technology, such as social aspects (e.g., acceptance) and additional aspects related to the visual appeal of the final products developed using the 3DGP innovation.

Characterization results comparison on 4 scenarios

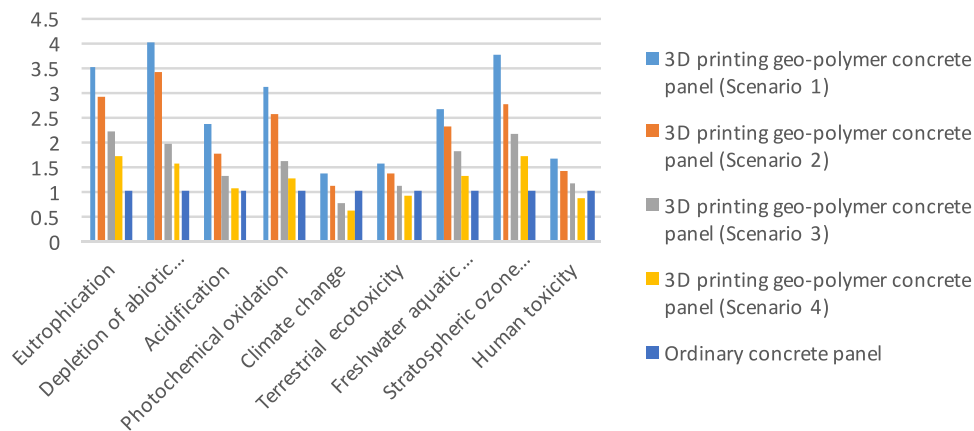


FIGURE 7 Comparative characterization results on four scenarios. Underlying data used to create this figure can be found in supporting information S3

5.2 | 3D printing geo-polymer (3DGP) concrete in the construction industry

As can be seen from the comparative contribution analysis, 3DGP concrete has a lower waste generation in the manufacturing processes since almost all waste powder can be reused and no mold is consumed. For ordinary concrete, the environmental impact of the mold production and the waste mold treatment still accounts for a major part of the environmental impacts. Therefore, the environmental impact of the waste treatment in 3D printing manufacturing processes is significantly lower than that of in ordinary manufacturing processes.

However, 3DGP concrete has higher impacts when it comes to the production of raw materials. First, the use of supplementary cementitious materials, such as fly ash and slag, may represent a limitation to reduce environmental impacts. In the current modeling setup, the fly ash and slag have economic values and are defined as by-products. Therefore, a part of upstream environmental burdens is appropriately allocated to them since the manufacturing processes involved still use up resources. However, if the slag and fly ash come from other industrial production processes and their use is seen as waste treatment, no upstream environmental burdens would be allocated to them. Then these supplementary cementitious materials could bring a significant advantage from an LCA perspective. This condition may be achieved by industrial symbiosis, in which the wastes generated from one industrial process may be the raw materials input for another industrial process. Second, the use of silicate in GP concrete may bring significant environmental impacts, due to the high energy requirements of the manufacturing of the material. Alternative materials to silicate should be considered, but do present functionality and design limitations.

3DGP concrete does not have an advantage over ordinary concrete from the perspective of the transportation of raw materials. For ordinary concrete, the supply of raw materials operates at full commercial scale, due to the mature nature of the market. The transportation distances of raw materials are not long for ordinary concrete. These aspects do leave still little room for improvements and rationalization in the use of resources.

On the other hand, it is still a challenge for the GP concrete industry to obtain raw materials nearby due to the high-quality requirement and immature supply chain for these raw materials. If the demand of these raw materials is well matched with the supply nearby, the transportation distance would be largely cut down and the relevant impacts would be significantly lower. With the development of the 3DGP technology, raw materials supply market for GP concrete would likely gradually mature, thus limiting transportation costs. Besides, GP concrete manufacturers can try to use alternative materials nearby or in situ resources. Alternative technologies using recycled concrete are emerging, in which the organic sand made from discarded concrete can be used as an alternative to the fine sand used in GP concrete manufacturing. Considering the scenario analysis, current 3DGP concrete on a potential commercial scale based on scenarios 1 and 2 does not show environmental benefits when compared to ordinary concrete. However, in scenarios 3 and 4, an obvious environmental advantage is shown for 3DGP concrete on climate change after updating the raw materials, *de facto* improving the transportation and the recipe. Therefore, 3DGP concrete still has a potential to cut greenhouse gas emissions after the step-by-step improvement, but the environmental impacts on other impact categories are still higher mainly due to the heavy impacts of the silicate. Changes in the formulation recipe to further reduce the silicate content is advisable.

CONFLICT OF INTEREST

The authors have no conflict to declare.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Yao Y, Hu M, Maio FD, Cucurachi S. Life cycle assessment of 3D printing geo-polymer concrete: An ex-ante study. *J Ind Ecol*. 2020;24:116–127. <https://doi.org/10.1111/jiec.12930>