The International Journal of Advanced Manufacturing Technology (2021) 112:2149–2159
https://doi.org/10.1007/s00170-020-06487-0

ORIGINAL ARTICLE

Life cycle assessment of integrated additive–subtractive concrete 3D printing

Ivan Muñoz[1] · Javier Alonso-Madrid[2] · Manuel Menéndez-Muñiz[3] · Maylis Uhart[4] · Joseph Canou[4] · Christoph Martin[5] · Marc Fabritius[5] · Laura Calvo[6] · Louison Poudelet[6] · Roger Cardona[6] · Hélène Lombois-Burger[7] · Nikolaos Vlasopoulos[7] · Charles Bouyssou[8] · Justin Dirrenberger[8] · Alexios Papacharalampopoulos[9] · Panagiotis Stavropoulos[9]

Received: 3 June 2020 / Accepted: 9 December 2020 / Published online: 6 January 2021

Abstract

A life cycle assessment (LCA) was conducted on an innovative concrete 3D printing system, offering the following main advantages: (1) additive and subtractive capabilities, allowing for the automated post-processing of printed parts, including operations such as surface polishing, grooving and drilling and (2) the use of a cable robot, which is less expensive, lighter, more transportable, more energy-efficient and more easily reconfigurable than alternatives such as gantry-type systems. The production of a 4-m height structural pillar was assessed, comparing it to production with traditional methods, namely, using a mould. The study included the entire supply chain of the 3D printing equipment, operation and end-of-life, based on real data from the design and operation of a demonstration plant installed in Spain. Data for traditional construction was based on literature and expert judgement. The 3D production process included printing the pillar perimeter in four pieces with 3D printing concrete, transporting to the construction site and reinforcing and casting with conventional concrete. Traditional production involved reinforcing and casting with the mould on-site. The results show that when only one pillar needs to be produced, 3D printing has a lower environmental impact in all the environmental indicators assessed when compared to using a mould that is discarded after a single use. As an example, GHG emissions are lower by 38%. It was also found that the contribution of 3D printing to the environmental impact of producing a pillar is almost negligible, representing less than 1% of the pillar's total GHG emissions. However, when the same pillar needs to be produced in higher numbers, the results show that 3D printing and conventional production have a similar environmental impact, given that the mould used in conventional production can be reused, becoming a comparatively efficient option.

Keywords Additive manufacturing · LCA · Cable robot · Construction · 3D printing · Concrete

✉ Ivan Muñoz
ivan.munoz@lca-net.com

[1] 2.-0 LCA Consultants, Rendsburggade 14, Room 1.431, 9000 Aalborg, Denmark

[2] Atanga, C/ Valle del Tietar 10, Villanueva de la Cañada, 28692 Madrid, Spain

[3] Vías y Construcciones S.A., Avenida Camino de Santiago, 50, 28050 Madrid, Spain

[4] University of Bordeaux, ESTIA Institute of Technology, F-64210 Bidart, France

[5] Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Stuttgart, Germany

[6] Centre CIM, Llorens i Artigas 12, 08028 Barcelona, Spain

[7] LafargeHolcim, 95, Rue du Montmurier BP 15, 38291 Saint-Quentin Fallavier Cedex, France

[8] XtreeE, 18–20 Rue du Jura, CP 40502, 94623 Rungis, France

[9] Laboratory for Manufacturing Systems and Automation, Department of Mechanical Engineering and Aeronautics, University of Patras, 265 04 Patras, Greece

1 Introduction

3D printing, synonymous with additive manufacturing, has been defined as the fabrication of objects through the deposition of a material using a print head, nozzle or another printer technology [4]. It differs from traditional methods that are either subtractive, starting with a block and machining away material that is not required, or formative, shaping or casting material in a mould [6]. 3D printing originated as a rapid prototyping technology, but it is quickly developing into a fully developed manufacturing process [15]. According to Faludi [10], 3D-printed goods are already being sold in high-value, small-run niches such as aerospace, jewellery and medical devices. Although very few commercial products are 3D printed, many contain 3D-printed parts.

In the construction sector, the use of 3D printing techniques was, until a few years ago, confined to the production of affordable architectural models. However, more recently, attempts to 3D print complete houses have been the subject of much publicity [17]. The potential advantages of 3D printing in the construction sector are numerous, including, first of all, the ability to produce non-standard construction elements at a reasonable cost, which was virtually impossible earlier [24]. In this sense, Table 1 summarises the advantages and disadvantages of 3D printing in the production of complex concrete parts. Other advantages include reducing the dependence on labour, the risk of injuries and weather stoppages, as well as construction times and costs [23].

Advocates for 3D printing in the construction industry have also claimed potential advantages for this technology from a sustainability standpoint. The accurate nature of additive fabrication is expected to result in little or no material waste [16], mainly due to the lack of requirement of formwork and moulds [24] and because the highly optimised construction process reduces the amount of materials used [1]. However, it has been recognised that in order to determine the environmental performance of 3D printing in the construction context, a full life cycle assessment (LCA) must be performed [17], as it provides a comprehensive evaluation of the direct and indirect potential environmental impacts associated to any given product or service [11]. Saade et al. [28] performed a systematic review of the available peer-reviewed literature on the life cycle impacts of 3D printing, identifying 52 papers presenting quantitative LCA or other environmental results. The main industrial sectors addressed in these studies were the aircraft and automotive sectors, with construction featuring only three papers [2, 3, 9]. Two of these studies [2, 3] evaluated the life cycle impacts of several structures (concrete wall, concrete floor and timber roof), digitally designed and fabricated with a construction robot, but not 3D printed, while Esposito-Corcione et al. [9] assessed the environmental performance of using waste stone as a filler for production of 3D printing filaments used in fused deposition modelling (FDM). In more recent research, Yao et al. [34] assessed 3D printing of geo-polymer concrete; however, this was done based on a theoretical scale-up of lab-scale printing. To our knowledge, there are currently no peer-reviewed studies assessing actual 3D printing of concrete products, especially integrating both additive and subtractive capabilities. In this article, we present the results of assessing with LCA an innovative concrete 3D printing technology, developed in the framework of the EU-funded research project HINDCON[1], featuring additive and subtractive manufacturing capabilities and based on a cable robot. The goal of the LCA study was to determine whether or not production with this technology leads to an overall environmental benefit when compared with traditional construction methods, using as a case study the production of a structural pillar.

2 Methods

2.1 A demonstration plant for hybrid additive–subtractive manufacturing with concrete

The main innovations achieved by the HINDCON approach to 3D printing in construction can be boiled down to two key aspects: its hybrid additive–subtractive capabilities and the printer positioning system using a cable robot.

One of the common features of printed concrete is its characteristic ribbed finish. With current 3D printing technologies, achieving a smooth finish requires either trowelling the wet material or the printed finish needs to be ground to a smooth surface. Either way, this must be completed manually [19]. HINDCON aimed at designing and demonstrating a 3D printing machine incorporating subtractive capabilities, allowing automated post-processing of the printed parts, including operations such as surface polishing, grooving and drilling. Secondly, traditional 3D printing methods have relied on gantry-type positioning systems, which can be thought of as “giant” 3D printers and as such, these systems are expensive and bulky. Instead, HINDCON relied on the concept of cable-driven parallel robots [26], which are less expensive, lighter, more transportable, more energy-efficient and more easily reconfigurable [5].

The mechanical architecture of the demonstration plant designed and built in the framework of the HINDCON project was based on modular components. A cable robot structure was used to provide positioning in a given workspace. Interchangeable platforms provided the process functionality, either additive or subtractive. The demonstration plant system consisted of the following main elements:

[1] http://www.hindcon3d.com/

Table 1 Advantages and disadvantages of concrete 3D printing regarding traditional construciton (adapted from Papacharalampopoulos et al. [22])

Property	Advantage	Disadvantage (with current technology)
Non-standard walls	Aesthetics, load distribution	Need for motion control, potential need for support
Non-standard ceilings	Sunbathing, ventilation, load distribution	
Non-standard columns	Load distribution, aesthetics, extra functionalities	
Cavities in walls	Insulation, room for cabling	Potential need for extra structural analysis
Embedded furniture	Harmonised aesthetics, less cycle time (building + equipping)	Changes in the design phase

- A cable robot IPAnema 3 [25], with a working area of 17 × 12 × 4.5 m. This system included a steel frame, eight Bosch motors and gearboxes, 200 m of Dyneema LIROS D-PRO cable and control cabinet.
- A tool-changing platform suspended by the cable robot, used to manually switch between additive and subtractive end-effectors.
- The additive end-effector or extruder was designed and built by CIM UPC. This device was responsible for dosing additives to the concrete and carrying out the concrete addition. Its main components were a 150-L tank, progressive cavity pump and auxiliary pump, mixing chamber and print head. The average printing speed was 2.53 L/minute during demonstration tests.
- The subtractive end-effector, designed by ESTIA, consists of a robotic arm, model KUKA KR10 R1100 C-WP, to which different tools could be attached to polish, mill and engrave. The average processing speed for surface polishing was 9 m^2/hour.
- Different concrete formulations suitable for 3D printing were specifically developed by LafargeHolcim.
- A building constructed to house the plant and to serve as workshop/factory (231 m^2). A closed space was regarded as a necessity, since the machine would not be suitable for work in outdoor conditions.

The demonstration plant was built in a facility owned by Vías y Construcciones in Pancorbo, Spain, and was operational from May to October 2019. During these six months, operation tests of increasing complexity were carried out in order to validate the technology. Further information, including videos of the plant set up and demonstration tests, is available in the HINDCON website.

2.2 LCA methods and goal

LCA was carried out with the ISO 14040 and 14044 standards as methodological guidelines [13, 14]. The software used to model the life cycle was SimaPro version 8.5 [27]. The overall goal was to quantify the potential environmental benefits (or otherwise) associated to the implementation of the HINDCON concept for manufacturing, when compared to current practices in the construction sector.

2.3 Case study: a structural pillar

We assessed the production in Spain of a structural pillar designed by the company XtreeE (Fig. 1, left). This pillar is 4 m in height and weighs 1.5 tonnes, with diameters at the base and top of 1.52 m and 0.68 m, respectively. Its volume and area are 619 L and 6.8 m^2, respectively. A key aspect to consider is that this element needs to be printed in four independent pieces rather than in one single piece (Fig. 1, right). This was due to the fact that the extruder's storage capacity

Fig. 1 3D model of case-study pillar (left). The pillar broken down into four pieces that can be printed with the HINDCON demonstration plant (right)

was limited to 40 L of concrete. Also, it must be highlighted that the entire pillar was not printed during the plant's demonstration phase, but only one of its pieces, namely, the base. The reason for this was the time constraints during the HINDCON demonstration tests, which prioritised printing and processing construction elements with differing shapes, functions and applications, while the pillar pieces are very similar to one another. As a consequence, printing of the remaining pieces is assessed in this study on a theoretical basis, but based on real operational data gathered during the demonstration tests.

2.4 System boundaries and functional unit

The system under study is a 'cradle-to-gate' one, whereby we included all activities in the product system until the pillar is finished and placed in its position in the building or construction structure where it will be integrated. The use and end-of-life phases are excluded from the study, given that they are not affected by the technology used to produce the pillar.

The study includes the life cycle of all capital equipment, including the 3D printer, moulds, as well as of all raw materials (concrete, steel rebars, etc.) and disposal of waste, mainly concrete, originated during manufacturing.

The functional unit and reference flow for this analysis were the demand of one pillar.

2.5 Production process: 3D printing

Figure 2 shows a flow diagram for the 3D printing scenario, featuring those activities included as part of the foreground system, i.e., those activities for which primary data were collected with as much detail as possible. Production of the pillar is split into two stages, an on-site printing and polishing stage and an off-site casting and assembly stage, the latter taking place in the construction site where the pillar is ultimately installed. The pieces are not printed with a 100% infill rate, but rather only the outer perimeter is printed, representing approximately 21% of the pillar's volume, thus leaving a hollow interior. Stiffening of the concrete due to introduction of the secondary admixture to make it 3D printable takes typically less than a minute after mixing with the additives within the extruder. After the concrete has set, the pieces are subject to polishing using the subtractive system, in order to achieve a smooth surface finish. These finished parts are then transported from the workshop to the construction site where the pillar is assembled, reinforced with steel rebars and casted.

Concerning the types of concrete used, a C30 concrete formulation suitable for 3D printing is used to print the four individual hollow pieces; casting at the construction site is carried out using conventional C60 concrete.

2.6 Production process: conventional

The alternative to 3D printing was considered to be casting the pillar by means of formwork with the desired shape. We excluded the option of formwork in steel or wood, as this is only suitable for perfectly square or circular pillars and therefore do not offer the required design flexibility. The option considered is a reusable acrylonitrile butadiene styrene (ABS) mould.

Production of the pillar (Fig. 3) involves placing the formwork in position with the reinforcing steel bars and pouring the concrete. The concrete used is C60. As opposed to the 3D printing scenario, there are no transport steps involved, since the pillar is produced in the precise location where it will be integrated as part of the wider building/construction project. After use, the mould can be reused if more than one pillar needs to be produced. As a base case, a single mould use is considered in the study, although this particular aspect was subject to a sensitivity analysis.

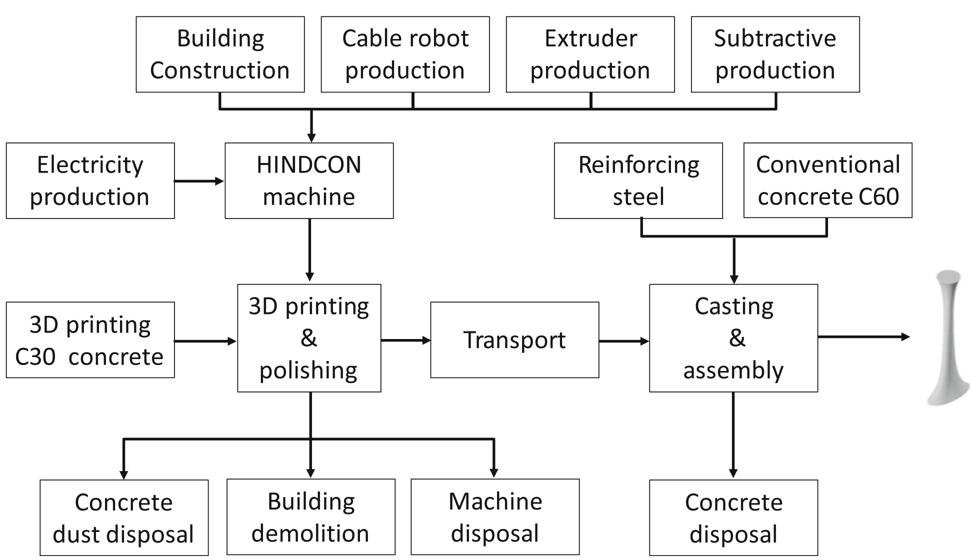


Fig. 2 Product system for the 3D printed pillar

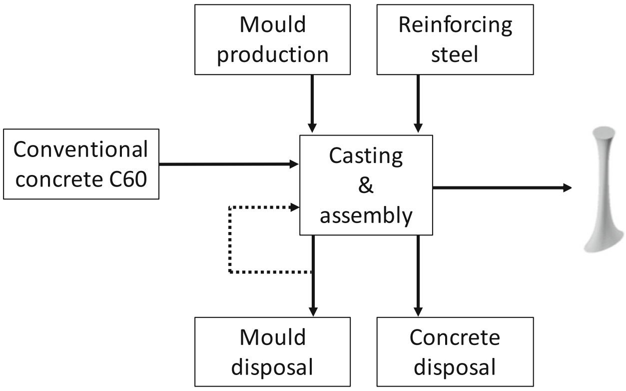


Fig. 3 Product system for the pillar constructed with traditional methods. The dashed line represents the potential reuse of the mould

2.7 Impact assessment methods

The method used for impact assessment in the LCA study is Stepwise2006, version 1.6. The method is described and documented in Annex II in Weidema et al. [33] and in Weidema [31]. Stepwise is capable of providing results at the level of midpoints (characterisation) and endpoints (damage). At the endpoint level, each impact category is expressed in monetary units (€2003) measuring environmental damage. In this study, we adjust the monetary units by inflation to €2019.

3 Inventory analysis

3.1 Background system

The life cycle model was built using the global hybrid environmentally extended multi-regional input–output database EXIOBASE (version 3.3.16) described in Merciai and Schmidt [20] and Stadler et al. [30].

3.2 Foreground system

Table 2 summarises the inventory for 3D printing and conventional production, the latter assuming the mould is only used once, i.e., only one pillar is produced. Further details regarding the inventory analysis, including how primary data were linked to EXIOBASE, can be found in the supplementary material (SM).

3.2.1 Concrete production

Two types of concrete were considered in the study. A confidential formulation for a 3D printing C30 concrete was shared by LafargeHolcim, containing CEM I cement, sand, a mineral filler, additives and water. The formulation for a conventional

Table 2 Inventory summary for production of 1 structural pillar according to 3D printing and conventional methods (functional unit: 1 pillar; see SM for further details)

Exchanges	Unit	3D printing	Conventional	Comments
Raw materials				
3D printing C30 concrete	L	139		Concrete to print pillar perimeter
C60 concrete	L	511	650	Concrete for casting
Printing				
3D printer equipment	kg	1.2		Depreciation of 3D printer equipment associated to 8.6 hours of operation
Electricity, Spain	kWh	31		3 kWh for printing, 6 kWh for polishing, 22 kWh for building lighting
Building	kg	3.6		Depreciation of building materials, safety fence and concrete silo associated to 8.6 hours of operation
Transports				
Road, Spain	tkm	30	6	100 km assumed
Road, China	tkm		6	100 km assumed
Maritime, China-Spain	tkm		1019	16,000 km assumed
Casting				
Mould production	kg		64	ABS mould used once
Steel rebar and tying wire	kg	74	74	Reinforcing steel and wire
Plastic separators	kg	0.07	0.07	Plastic supports for reinforcing steel
Post shores	kg	0.64	0.64	Depreciation of reusable post shores
Release agent	L		0.14	For removal of mould
Waste management				
Concrete to landfill	kg	74	76	Concrete dust from polishing, losses during casting

C60 concrete was obtained from Civil Engineering Portal [7], containing, on a per m^3 basis, 504 kg CEM I cement, 683 kg sand, 4.7 kg superplasticiser, 1108 kg gravel and 142 L water. The inventory includes the production of the individual ingredients and the transport of the product, although infrastructure for concrete production is excluded.

3.2.2 3D printer production and end-of-life

Production of the 3D printer was modelled based on a bill of materials for each of the machine modules, namely, the cable robot, additive system (extruder) and subtractive system. From a geographical point of view, each module was assumed to be produced in the country where it was developed, namely, Germany for the cable robot and subtractive robot and Spain for the additive system.

The inventory for the cable robot included the eight motors (188 kg), eight gearboxes (176 kg), 200 m of Dyneema cable (4.6 kg), a control cabinet (housing and electrical equipment, 250 kg), energy chain and spool (600 kg), and the tool changing platform mainly made in aluminium (77 kg) and the steel frame (8220 kg).

The additive system was constituted by a large number of elements. A bill of materials was produced with around 300 individual elements classified into groups (hydraulic system, transmission, pumping system, electronics, etc.). The total weight was 247 kg, most of which constituted by machinery (pumps, motors) and aluminium structures.

The subtractive system included, first of all, the KUKA robotic arm (56 kg), its controller (33 kg) and SmartPAD (1.1 kg), electrical cable estimated at 13.6 kg and a support platform made in steel, with an estimated weight of 92 kg. The subtractive system counts with a set of tools (milling tool, sanding tool, vacuum cleaner, among others), which amount to 23.4 kg.

Regarding the building/workshop, this was included in the inventory based on its expected construction cost, which was taken as 400 €/m^2 [29]. The total cost of construction was then linked to the EXIOBASE activity for construction in Spain, which is expressed in monetary units. In addition to the building itself, the inventory also included a safety fence to isolate the printer's working space (380 kg) and a silo to store concrete premix (2268 kg).

Besides accounting for the mass and type of materials and equipment, a key task in the inventory analysis was defining their expected service life. This was done on the basis of expert judgement, paying particular attention to the expected stress and rough environmental conditions (moisture, dust, wet concrete, etc.) to which the machine would be subject during operation. Useful lives were determined component by component, ranging from 6 months for the Dyneema cable, to 20 years for structural elements such as the cable robot frame. The building was given a longer service life, of 50 years.

In a hypothetical commercial deployment of the 3D printer, production would be expected to run 300 days per year in two 8-hour shifts, leading to 4800 operation hours per year. This was used to calculate the amortisation of the equipment, previously quantified in years.

Concerning the end-of-life stage, the fate of the different materials and equipment was determined based on plausible expectations. On the one hand, metallic components and the metal fraction of complex equipment, such as motors and pumps, were assumed to be sent for recycling. In EXIOBASE, recycling processes lead to a substitution of equivalent primary materials. Plastic components, on the other hand, were assumed to be disposed by landfilling. Construction materials embedded in the workshop building were also assumed to be sent to a landfill after demolition.

3.2.3 3D printer operation

Operation of the 3D printer involves electricity consumption by the machine and building. The average power consumption by the cable robot during printing is rather low, around 2 kW, since it is operating at low speeds. The average power consumption by the additive system is 1.1 kW. As for the subtractive system, the expected power consumption by the KUKA robot is 2 kW. The required power for the milling tools (sanding, drilling) and vacuum cleaner is 3.4 kW combined. With these data, we can establish that 1 hour of additive work uses 3.1 kWh, while 1 hour of subtractive work uses 7.4 kWh.

Concerning the building, we only include energy consumption for lighting, estimated as 54 kWh/m^2/year in Spain (European Communities 2002, p. 22). Based on 231 m^2 and 4800 operating hours/year, the energy consumption per hour of operation is 2.6 kWh.

The overall amount of time required to print the four pillar pieces is 8.6 hours. This includes 0.9 hours of printing and 0.8 hours of polishing using the subtractive system, while the remaining time is associated to manual tasks, such as setting up the machine for either printing or polishing, as well as cleaning activities at the end of the production process.

3.2.4 Plastic mould

The conventional method to produce the pillar is casting by means of formwork with the desired shape. In our study, we considered using a tailor-made formwork manufactured in ABS plastic, which is available from several Chinese manufacturers for similar construction elements such as decorative columns. However, we did not have access to a specific design for the targeted pillar. In Lcmolds [18], the weight of moulds for square pillars of 3- to 4-m height is given for several sizes, and this weight is well correlated to the volume of the pillar. For a pillar with a volume of 619 L, the estimated weight of the mould is 64 kg and this weight is assumed to remain constant even if the targeted pillar is not square. Production of the mould is modelled with the EXIOBASE data set for production of plastic and rubber products in China.

This kind of mould can be reused many times, although as a base case, we assume that only one pillar needs to be produced, after which the mould is discarded and sent to a landfill.

3.2.5 Transports

As it can be seen in Fig. 2, the four printed pillar parts require transport to the construction site. Given that this is a hypothetical analysis, we have taken as a starting point a road transport distance of 100 km.

For the plastic mould, we consider its shipping from China to Spain. This transport scenario assumes hypothetical distances of 100 km by road to the port in China, a maritime transport distance of 16,000 km and a final road transport distance to the construction site of 100 km.

For all other materials in the inventory analysis, the EXIOBASE data sets used include default transport services.

3.2.6 Casting

The inventory for reinforcing and casting the pillar, in both 3D printing and conventional scenarios was approximated by data for circular reinforced–concrete pillars of 4–5-m height published by CYPE ingenieros [8], where the reference flow is 1 m^3 casting. The inputs per m^3 casted pillar include steel rebar (120 kg), tying steel wire (0.6 kg), plastic separators (estimated at 10 g each), 0.24 L release agent and reusable post shores. The data set also establishes a concrete loss of 0.05 m^3 per casted m^3, which we model as disposed in landfill. All these aspects are included in the inventory for conventional casting, while for the 3D-printed pillar, the use of release agent is not necessary, due to the absence of moulds or formwork.

4 Results and discussion

4.1 Impact assessment: midpoint and endpoint levels

Table 3 shows the life cycle impact assessment results for the two scenarios, at both midpoint and endpoint levels. While at midpoint, each indicator has its own specific units, at endpoint level, they are all expressed in monetary units (€2019). We can see that the 3D printing scenario shows a lower environmental impact in all indicators, with a reduction in impact ranging from 24% in mineral extraction to 81% in aquatic eutrophication. The inclusion of results at endpoint level is useful to identify those impact indicators where the system has the highest contribution to environmental damages. In our case study, most of the damage corresponds to respiratory inorganics, closely followed by global warming, while the remaining indicators have a relatively minor contribution.

4.2 Contribution analysis

Figure 4 breaks down the global warming indicator into the different activities that have been described in the inventory analysis. Overall, greenhouse gas (GHG) emissions in the 3D printing scenario are lower by 385 kg CO_2-eq or 38%. On the one hand, we can see that the two production methods lead to a similar contribution to GHG emissions associated to concrete production, with 335 kg CO_2-eq for the 3D printing scenario vs. 353 kg CO_2-eq in the conventional scenario. On the other hand, the conventional scenario leads to a higher impact mainly due to the production of the mould (classified under 'Auxiliary materials, casting'). Last but not the least, it is worth mentioning that the 3D printing process (printing and polishing operations, including the entire life cycle of the machine) appears to be almost negligible, representing less than 1% of the total GHG emissions.

4.3 Sensitivity analysis: geographical variation

As a base case, we took Spain as the geographical context for the evaluation, given that this is the country where the demonstration plant was in operation. In order to check the robustness of the results regarding geographical scope, in Fig. 5, we show the results of a sensitivity analysis where we simulated the life cycle model in three alternative countries, namely, China, the United States and Denmark. This was done by linking the entire background system to the corresponding EXIOBASE supply activities in these countries.

In Fig. 5 we show only the impact assessment results for global warming, although a similar pattern is obtained in the remaining indicators (see SM). As it can be seen, the absolute CO_2-eq emissions vary substantially from one country to another; however, the key point of interest in these results is the fact that the 3D printing scenario consistently achieves a GHG reduction when compared to conventional construction, namely, 37% in the United States, 48% in China and 55% in Denmark.

Based on these results, our study seems to confidently point to a lower environmental for 3D-printed concrete products, when the alternative is to use a disposable mould, or a reusable mould that is used only once.

4.4 Sensitivity analysis: multiple pillars

As a base case, we assumed that only one pillar is ordered by a hypothetical customer. This is a reasonable scenario for 3D

Table 3 Life cycle impact assessment results at midpoint and endpoint levels (€2019) (functional unit: 1 pillar)

Impact category	Midpoint			Endpoint		
	Unit	Conventional	3D printing	Unit	Conventional	3D printing
Human toxicity, carcinogens	kg C_2H_3Cl-eq into air	39	26	€	13.2	8.9
Human toxicity, non-carcinogens	kg C_2H_3Cl-eq into air	13	7	€	4.5	2.5
Respiratory inorganics	kg $PM_{2.5}$-eq	1.6	1.1	€	136.5	91.4
Ecotoxicity, aquatic	kg triethylene glycol-eq into water	1960	1205	€	0.02	0.01
Ecotoxicity, terrestrial	kg triethylene glycol-eq into soil	5145	3263	€	7.3	4.6
Nature occupation	$PDFm^2a$	36	11	€	5.7	1.8
Global warming	kg CO_2-eq	1002	617	€	106.8	65.7
Acidification	m^2 unprotected ecosystem	79	44	€	0.8	0.4
Eutrophication, aquatic	kg NO_3-eq	2.5	0.5	€	0.3	0.1
Eutrophication, terrestrial	m^2 unprotected ecosystem	100	55	€	1.6	0.9
Respiratory organics	Person·ppm·h	0.8	0.4	€	0.3	0.1
Photochemical ozone, vegetation	m^2·ppm·hour	8261	3981	€	3.9	1.9
Non-renewable energy	MJ	10,448	4312	€	0.021	0.016
Mineral extraction	MJ	4.0	3.1	€	13.2	8.9

printing, which allows us to design and produce unique construction elements. However, a single building is likely to require more than one pillar. In a traditional construction scenario, these can be produced by few moulds reused many times. In this situation, the environmental impact of the conventional scenario is expected to decrease on a per pillar basis. Following this line of thought, we conducted a sensitivity analysis where we considered that more than one pillar needs to be produced, which in the conventional scenario is achieved by reusing the mould. This is approached as a break-even analysis, in order to find out if at a given point 3D printing appears to be less preferable than conventional construction methods.

Figure 6 shows the results of this break-even analysis for the global warming indicator. On the one hand, the graph shows a flat line at 617 kg CO_2-eq, corresponding to the GHG emissions for a 3D-printed pillar. On the other hand, GHG emissions for a traditionally produced pillar decrease exponentially as the number of mould reuse cycles increase. There is, however, no break-even point as such, but rather a convergence, as the value for the conventional pillar slowly approaches that of the 3D-printed pillar when multiple mould reuses are considered. In this way, 3D printing appears environmentally preferable when few pillars need to be produced, but there is no environmental benefit if the alternative is a

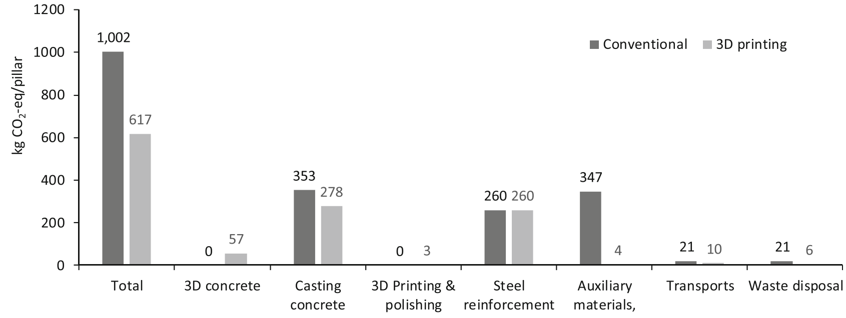


Fig. 4 Contribution analysis for global warming

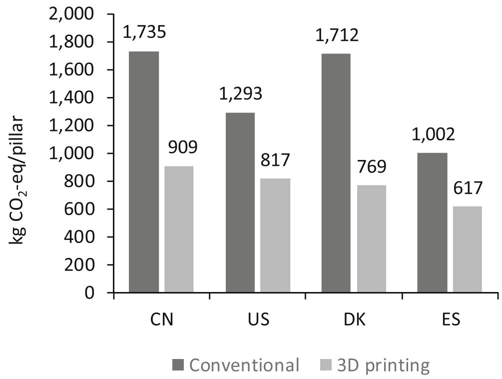


Fig. 5 Sensitivity analysis for global warming regarding geographical scope

conventional casting method with a mould withstanding multiple reuse cycles.

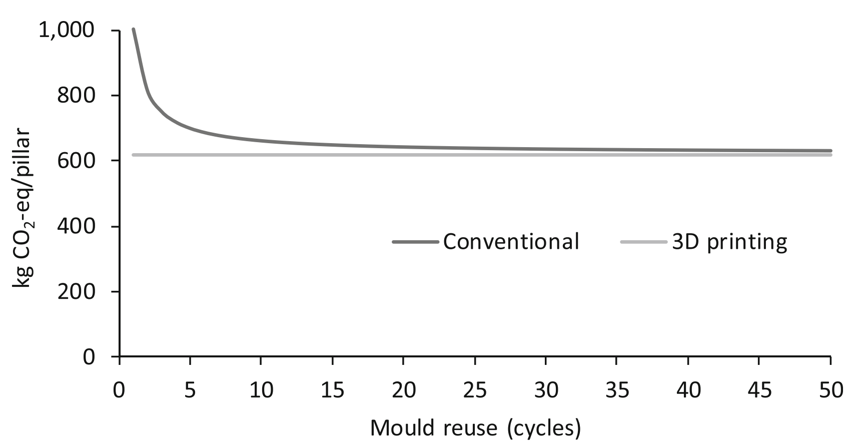
5 Discussion

Impact assessment results have shown that most of the environmental damage associated to the pillar's supply chain, when monetarised with the Stepwise2006 method, is caused by emissions of fine particulate matter (respiratory inorganics) and global warming. This is consistent with other studies applying the Stepwise2006 method, even in completely different sectors, such as soil and groundwater remediation [12], wastewater treatment [21] or meat and dairy products [32], where these two indicators dominate the environmental damage, together with nature occupation in the case of bio-based production systems.

When looking at the most and least important aspects in the life cycle of 3D printing, one of the most outstanding outcomes of this study is the relatively low contribution of the printing process (life cycle of the entire printing machine: production, energy consumption during use and end-of-life stage), when compared to, e.g., concrete production. This seems to be in agreement with the results of the meta-analysis carried out by Saade et al. [28], where GHG emissions for additive manufacturing case studies in the construction sector were consistently dominated by production of materials rather than by the manufacturing process itself, which contributed up to 10–12% of the total emissions in the worst case. This is in contrast to case studies in other industrial sectors, where the opposite was true, i.e., the additive manufacturing step had a dominant role in life cycle GHG emissions.

The comparison of 3D printing vs. traditional construction has shown that when a single unit of the pillar needs to be produced, 3D printing is preferable to using a mould that is discarded after a single use. This seems to support the claims made by Perkins and Skitmore [24] that concrete 3D printing is superior in environmental terms as it eliminates the need for moulds and formwork. A superiority in terms of raw material use and process waste, as claimed by other authors [1, 16], cannot be supported based on our case study, where both 3D printing and casting have a similar performance. In our opinion, a key result in our study is the finding that when many pillar units need to be printed, the preference for 3D printing rapidly decreases, since in this case the alternative is likely to be a reusable mould. As a consequence, in a context of mass production of construction elements so far produced by casting, 3D printing performs approximately the same as traditional construction, where the environmental impact is dominated by production of the required concrete and steel reinforcement. Further LCA studies with different and more complex construction elements should be conducted to get a wider view of the potential benefits (or otherwise) of this new manufacturing approach. In particular, an advantage that could not be explored in this research is that 3D printing, with its ability to deposit material where needed, rather than just pouring it—as it is done in casting—has a huge potential to save raw materials such as concrete, and therefore, environmental impacts. In our case study, designing and printing a 'hollow' pillar was not feasible, as it would not comply with European construction standards.

Fig. 6 Break-even analysis for 3D printing and conventional construction regarding the number of mould reuse cycles



Another interesting point of discussion is logistics. Our case study has shown that for a distance of 100 km to the construction project, transport of the hollow-printed pieces is not a major environmental concern. A completely different strategy would be to have a mobile 3D printer that would be set up at the construction site in some indoor space. As a rule of thumb, this would be justified from an environmental point of view only if the weight of the pieces to be produced at the construction site exceeds the weight of the 3D printer.

As for limitations of this study, we can mention that the printed pillar is expected to have a slightly lower strength than the traditional version. This is not because of 3D printing as such, but because the printed volume (21% of the total pillar volume) is constituted by C30 concrete, with the remainder being constituted by C60 concrete. The traditionally constructed pillar, on the other hand, used C60 concrete only. Better comparability in the LCA study could therefore be achieved by considering C60 concrete for printing.

Another limitation is that the inventory for casting did not include infrastructure, such as the use of a crane and skip to pour the concrete. Also, another limitation is that EXIOBASE does not currently allow to discriminate between different plastic products, and therefore, it was not possible to tell the difference between producing ABS and an average plastic product in China. Another limitation of our study is that it did not address potential rebound effects associated to differences in life cycle cost (Consequential LCA 2015). In the event that 3D printing shows a lower life cycle cost than traditional methods, this is expected to lead to additional disposable income that can be spent in other activities, which in turn have an environmental impact. Assessing life cycle costs, however, was not in the scope of this research.

Although not a limitation as such, this study has focused on comparing the HINDCON 3D printing approach to traditional construction methods, while its relative performance regarding other existing 3D printing approaches remains to be seen. From an environmental standpoint, on the one hand, the HINDCON approach could involve a lower environmental impact than gantry systems due to the use of a cable robot, with likely lower energy consumption during operation and a lower intensity in material infrastructure. On the other hand, the automation of post-processing by the HINDCON approach involves additional energy consumption as compared to manual work (polishing, drilling, etc.). A subsequent LCA study would be needed to confirm these assumptions.

6 Conclusions

LCA has been applied to an innovative concrete 3D printing system with both additive and subtractive capabilities and based on a cable robot. The production of a 4-m height structural pillar was assessed, comparing it to production with traditional methods, namely, using a mould.

The results show that when only one pillar needs to be produced, 3D printing has a lower environmental impact in all the environmental indicators assessed when compared to using a mould that is discarded after a single use. GHG emissions, for example, are lower by 38%. It was also found that the contribution of the 3D printing operation (printing and polishing, including the entire life cycle of the machine) appears to be almost negligible, representing less than 1% of the total GHG emissions. Most of the environmental impact appears to be associated to the supply chain of the materials embedded in the pillar, namely, concrete and steel.

However, when the same pillar needs to be produced in higher numbers, the results show that 3D printing and conventional production have a similar environmental impact, given that the mould used in conventional production can be reused, becoming a comparatively efficient option.

Based on these results, 3D printing appears to have a lower environmental impact as a method for production of unique architectural elements. In a context of mass production of construction elements, however, 3D printing performs approximately the same as traditional construction, where the environmental impact is dominated by production of the required materials.

An interesting feature of 3D printing that deserves further attention in future LCA studies is that this method, with its ability to deposit material where needed, rather than just pouring it—as it is done in casting—has a huge potential to save raw materials such as concrete, and therefore, environmental impacts.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00170-020-06487-0.

Authors' contributions Not applicable.

Funding This research has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 723611.

Data Availability Supplementary material includes the complete inventory analysis description, impact assessment results and sensitivity analysis results.

Compliance with ethical standards

Ethical approval This study complies with the ethical standards set out by Springer.

Competing interests The authors declare that they have no competing interests.

Code availability Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s00170-020-06487-0.

References

1. Achillas C, Aidonis D, Iakovou E, Thymianidis M, Tzetzis D (2015) A methodological framework for the inclusion of modern additive manufacturing into the production portfolio of a focused factory. J Manuf Syst 37(1):328–339
2. Agustí-Juan I, Habert G (2017) Environmental design guidelines for digital fabrication. J Clean Prod 142:2780–2791
3. Agustí-Juan I, Müller F, Hack N, Wangler T, Habert G (2017) Potential benefits of digital fabrication for complex structures: environmental assessment of a robotically fabricated concrete wall. J Clean Prod 154:330–340
4. ASTM (2009) Standard terminology for additive manufacturing technologies. The American Society for Material and Testing. West Consholhocken, United States, ASTM International. F2792 - 12a
5. Barnett E, Gosselin C (2015) Large-scale 3D printing with a cable-suspended robot. Addit Manuf 7:27–44
6. Buswell R (2007) Freeform construction: mega-scale rapid manufacturing for construction. Autom Constr 16(2):224231
7. Civil Engineering Portal (2018) Concrete mix design M-60. https://www.engineeringcivil.com/concrete-mix-design-m-60.html (accessed 02/03/2020).
8. CYPE (2019) Unidad de obra EHS011: Pilar circular de hormigón armado. http://www.generadordeprecios.info/obra_nueva/Estructuras/Hormigon_armado/Pilares/Pilar_circular_de_hormigon_armado.html (accessed 03/03/2020)
9. Esposito Corcione C, Palumbo E, Masciullo A, Montagna F, Torricelli MC (2018) Fused deposition modeling (FDM): an innovative technique aimed at reusing Lecce stone waste for industrial design and building applications. Constr Build Mater 158:276–284
10. Faludi J (2017) 3D printing and its environmental implications. In: OECD (2017), The next production revolution: implications for governments and business, OECD Publishing, Paris, Chapter 5
11. Finnveden, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S (2009) Recent developments in life cycle assessment. J Environ Manag 91(1):1–21
12. Huysegoms L, Rousseau S, Cappuyns V (2018) Friends or foes? Monetized life cycle assessment and cost-benefit analysis of the site remediation of a former gas plant. Sci Total Environ 619–620:258–271
13. ISO (2006a) Environmental management - life cycle assessment – principles and framework. International Standard Organization (ISO), Geneve
14. ISO (2006b) Environmental management - life cycle assessment – requirements and guidelines. International Standard Organization (ISO), Geneve
15. Kellens K, Baumers M, Gutowski TG, Flanagan W, Lifset R, Duflou JR (2017) Environmental dimensions of additive manufacturing: mapping application domains and their environmental implications. J Ind Ecol 21:S49–S68
16. Khoshnevis B (2003) Toward total automation of on-site construction an integrated approach based on contour crafting. Proceedings of the 20th ISARC, Eindhoven, Holland
17. Labonnote N, Rønnquist A, Manum B, Rüther P (2016) Additive construction: state-of-the-art, challenges and opportunities. Autom Constr 72(Part 3):347–366
18. Lcmolds (2019) Square type roman cement column molds. https://www.lcmolds.com/square-type-roman-cement-column-molds/ (accessed 03/03/2020)
19. Lim S (2012) Developments in construction-scale additive manufacturing processes. Autom Constr 21:262–268
20. Merciai S, Schmidt J (2017) Methodology for the construction of global multi-regional hybrid supply and use tables for the EXIOBASE v3 database. J Ind Ecol 22(3):516–531
21. Muñoz I, Rosiek S, Portillo F, Batlles FJ, Martínez-Del-Río J, Acasuso I, Piergrossi V, De Sanctis M, Chimienti S, Di Iaconi C (2019) Prospective environmental and economic assessment of solar-assisted thermal energy recovery from wastewater through a sequencing batch biofilter granular reactor. J Clean Prod 212(1):1300–1309
22. Papacharalampopoulos A, Bikas H, Foteinopoulos P, Stavropoulos P (2020) A path planning optimization framework for concrete based additive manufacturing processes, 30th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2020) 15-18 June 2020, Athens, Greece
23. Pegna J (1997) Exploratory investigation of solid freeform construction. Autom Constr 5(5):427–437
24. Perkins I, Skitmore M (2015) Three-dimensional printing in the construction industry: a review. Int J Constr Manag 15(1):1–9
25. Pott A (2018) Cable-driven parallel robots: theory and application. Springer
26. Pott A, Mütherich H, Kraus W, Schmidt V, Miermeister P, Verl A (2013) IPAnema: A family of cable-driven parallel robots for industrial applications. In: Bruckmann T, Pott A (eds) Cable-driven parallel robots. Mechanisms and machine science, vol 12. Springer, Berlin, Heidelberg
27. PRé (2016) SimaPro. https://simapro.com/. Accessed 10 Apr 2017
28. Saade MRM, Yahia A, Amor B (2020) How has LCA been applied to 3D printing? A systematic literature review and recommendations for future studies. J Clean Prod 244:118803
29. Soler, Durá (2014) Es el momento de comprar terreno industrial y construir su nave. http://www.solerdura.com/es-el-momento-de-comprar-terreno-y-construir-su-nave-industrial/ (accessed 4/09/2019)
30. Stadler K, Wood R, Bulavskaya T, Södersten CJ, Simas M, Schmidt S, Usubiaga A, Acosta-Fernández J, Kuenen J, Bruckner M, Giljum S, Lutter S, Merciai S, Schmidt J, Theurl MC, Plutzar C, Kastner T, Eisenmenger N, Erb KH, de Koning A, Tukker A (2018) EXIOBASE 3: Developing a time series of detailed environmentally extended multi-regional input-output tables. J Ind Ecol 22(3):502–515
31. Weidema BP (2009) Using the budget constraint to monetarise impact assessment results. Ecol Econ 68(6):1591–1598
32. Weidema BP, Wesnæs M (2008) Environmental improvement potentials of meat and dairy products. Joint research Centre, Insitute for Prospective Technological Studies, Seville, Spain
33. Weidema BP, Hauschild MZ, Jolliet O (2007) Preparing characterisation methods for endpoint impact assessment. In: BP Weidema, M Wesnæs, J Hermansen, T Kristensen, N Halberg, P Eder, L Delgado. Environmental improvement potentials of meat and dairy products. Sevilla: Institute for Prospective Technological Studies, 2008. (EUR 23491 EN). Annex II
34. Yao Y, Hu M, Di Maio F, Cucurachi S (2020) Life cycle assessment of 3D printing geo-polymer concrete - an ex-ante study. J Ind Ecol 24:116–127