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Advancing decarbonization through 3D printed concrete formworks: Life cycle analysis of technologies, materials, and processes[☆]

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ABSTRACT

3D printing technologies are innovating several industrial fields for their ability to produce complex shapes, reduce material use and obtain high-performance structures. Among the possible applications of 3D printing in the civil construction sector, manufacturing formwork for concrete casting is a promising solution for producing thin-walled and complex structures. Given the increasing interest and numerous applications being developed, comprehensive studies on the sustainability of 3D-printed concrete formwork are required to improve the processes and drive low-carbon construction practices. In this context, the present study provides for the first time an evaluation of the environmental and economic sustainability of concrete structures achieved using 3D printed formwork. The research investigates the influence of various factors such as: i) geometry complexity, ii) printing technology (Fused Deposition Modelling and Material Jetting), iii) process parameters, iv) raw materials (PLA, ABS, PVA, Geopolymers, Cements, Clay) v) machines kinematic systems and vi) End of Life alternatives. To perform such an investigation, a parametric CAD model was developed to define structure geometry; furthermore, Life Cycle Assessment and Life Cycle Costing methodologies were applied to calculate the impacts and cost of the different alternatives. The results showed that a proper choice of the combination of geometry, technology, material, and process parameters is crucial for reducing the carbonization-related impacts associated with 3D-printed formwork production. In addition, reuse and recycling of the formworks cut overall impacts, making 3D printing a sustainable alternative to traditional production processes while allowing greater design freedom.

1. Introduction

3D printing is a digital manufacturing technology that enables the fabrication of three-dimensional objects by creating successive layers of material in a controlled manner. Widely acknowledged in both academic and technical circles, this technology is considered one of the disruptive innovations that could significantly influence the future [1]. One of the sectors destined for significant change owing to additive manufacturing is the construction industry [2]. Indeed, in recent years, 3D printing technology has been widely utilized in various applications within civil engineering [3]. Due to the several advantages offered by this technology, its adoption is expected to continue growing significantly in the coming years, as acknowledged by McKinsey & Company [4]. Recent reports estimate that the 3D printing market in construction will transition from a value in the billions to several hundred billion euros within the next 10 years [5,6]. As extensively discussed and studied in recent studies [7], there are three main production approaches gaining prominence in 3D printing: 1) fabrication of monolithic structures through on-site printing [8]; 2) prefabrication of 3D printed components off-site [9]; and 3) utilisation of 3D printed formwork to fabricate components [10].

Monolithic 3D printing or prefabrication still carries many uncertainties in terms of performance and lacks a standardized process for quality control [11]. Monolithic 3D printing or prefabrication still carries many uncertainties in terms of performance and lacks a standardized process for quality control [11]. Indeed, as recent review articles discuss [1], in general, 3D construction printing is affected by uncertainty regarding the performance of printed materials due to limited scientific knowledge. An effective method for inserting reinforcement is still under investigation [12]. The seismic performance of these structures is still unknown, as no comprehensive dynamic tests have been conducted on a shake table to simulate behavior under dynamic horizontal loads [1]. Furthermore, 3D printing is also typically influenced by numerous printing defects [13] which result in the printed product differing from the designed model, and the impact of these defects on performance remains an open question.

Additionally, regulations are still in the development phase. In contrast, the technique of 3D printed formworks offers the possibility to achieve building components by casting concrete with the inclusion of reinforcements [14,74]. More in detail, it offers the advantage of

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innovating the construction process through a disruptive technology, while maintaining all the structural performance of a traditional component. Consequently, even regulatory assessments of components made with 3D printed formworks can be conducted following traditional procedures. According to Bos et al. [15], the primary applications of 3D printed structures were formwork for traditional reinforced concrete elements such as walls, columns, and beams. These formworks can be created through either on-site or off-site 3D printing.

From a sustainability standpoint, a recent study demonstrates that 3D printed formworks have significant advantages as they are compared to other concrete construction techniques [7]. The 3D printed formworks can be obtained using different 3D printing technologies, including Fused Deposition Modelling (FDM) and Material Jetting (MJ), and various types of 3D printer kinematic systems such as robotic arms, delta printers, and gantry cranes [16,15]. Additionally, a range of 3D printing materials can be employed, such as raw clays, ceramic materials, geopolymers, and cementitious mortars. The potential in terms of environmental sustainability and economic viability for all these possible solutions to obtain 3D printed formworks for building components is still unknown. Even though these technologies are widely used and have significant growth potential, there is no study investigating their environmental and economic impacts and potential contribution to advancing decarbonization.

In this context, the present study focuses on evaluating the environmental and economic sustainability of 3D printed formworks for construction sector applications. The analysis incorporates different additive manufacturing (AM) technologies for formwork fabrication, machine kinematic systems, materials for 3D printing, and the moulds use typology (reusable, recyclable, or sacrificial).

The main goal is to identify the best alternatives for producing components (such as beams, columns, or partitions) with a specified cross-sectional area and height to enhance decarbonization. This analysis presents a high level of complexity, as it encompasses a multitude of variables contingent upon technology, machinery configuration, printable materials and formwork end-of-life. Furthermore, it explores the extensive adaptability inherent in 3D printing with formworks, aiming to achieve complex geometric shapes. The study addresses the complex interactions among these factors, considering their collective impact on the outcomes of the analysis. Indeed, depending on the identified geometric complexity in terms of the perimeter-to-cross-sectional area ratio, different analysis results can be obtained.

To reach the defined goal, a three-step methodology is proposed: 1) a literature review on 3D printed formworks to identify commonly used parameters; 2) a parametric model to investigate the flexibility of the achievable geometry; 3) a Life Cycle Assessment (LCA) and a Life Cycle Costing (LCC) analyses to assess all involved parameters (e.g., geometry, technologies, machines kinematic systems, materials for 3D printing, and geometric complexity).

The novelty of the proposed research is threefold:

i) Advancing scientific knowledge on the economic and environmental sustainability of 3D-printed formworks. A sustainability analysis (LCA and LCC) is conducted on 3D-printed formworks for building components, encompassing potential technologies, printer types, materials, the complexity of the mould form and end-of-life considerations. This analysis provides valuable insights for both the academic and technical fields, facilitating the application of existing technologies and the development of new machines or materials to improve processes;

ii) Contributing to the scientific understanding of CO2 emissions in relation to geometric parameters and machine configurations.

iii) Proposing a three-step methodological approach. This approach integrates the capabilities of a parametric model (with parameters identified through a literature review) with LCA and LCC analyses. It addresses the complexity of analysing 3D-printed formwork production, enabling the automatic generation of complex geometries and calculation of data relevant to the analysis.

The findings of this study enhance the understanding of the sustainability aspects and decarbonisation associated with these technologies. The proposed approach opens up new possibilities for the effective application of 3D printing technologies to achieve sustainable and high-performing 3D printed formworks. Additionally, it provides valuable insights to guide future technology and printing material developments, steering the construction industry toward more sustainable and innovative practices.

2. Materials and methods

As previously mentioned, the proposed approach is based on three steps, shown in Fig. 1 and listed below:

1) Literature review and classification are conducted to identify the most commonly used technologies, machinery configurations, and materials or those with significant potential for obtaining formworks for construction.

2) A parametric model is developed to generate 3D models of different formworks with the same cross-sectional area but varying parameters such as formwork thickness (including number of wall lines) and surface rippling which increases the perimeter-to-cross-sectional area ratio.

3) An LCA and LCC are conducted by analyzing all parameters related to technologies, machinery configuration, printing materials, and geometric complexity.

2.1. Literature review: 3D printed formworks technologies, machine kinematics, configurations and production techniques

The first step proposes a brief review useful to identify all the parameters influencing the 3D printed formworks production, encompassing both literature and major applications of 3D printed formworks in the entrepreneurial world. The approach adheres to the four principles outlined by Snyder for scientific reviews (Snyder 2019), including purpose definition, article selection, data extraction analysis, and writing the review. In particular, firstly, the review defines its specific purpose, aiming to explore the usage of 3D printed formworks to identify the primary and most prevalent technologies, machine kinematic systems, materials, and end-of-life aspects.

Secondly, scientific articles and practical applications of 3D printed formworks are selected. In the proposed work, the focus has been on the use of 3D printed formworks involving the casting of concrete or reinforced concrete for building components (such as beams, columns, walls, slabs, and arches), while excluding papers that contemplate complex treatments or post-processes before their use as formwork. Thirdly, useful data are extracted from these works such as used technology, machine kinematic system, configuration, material, mould wall thickness and end-of-life aspects.

The proposed brief review allows to achieve the following conclusions.

The most used technologies for concrete formworks manufacturing are considered:

- FDM in which a thermoplastic material in the form of filament or pellets is extruded through a heated nozzle and deposited layer by layer.
- MJ in which viscous materials such as concrete or clay are pumped and selectively deposited through a nozzle layer by layer.

For both technologies, three different machine kinematic systems, including a robotic arm, a cartesian system, or a delta system, can be used [17].

The most commonly used materials are cement and PLA or ABS filaments. However, PVA [18]and clay [19]are materials that, at an experimental level, have shown interesting results. Regarding the printed mould wall thicknesses, they vary considerably depending on the technology used. As far as the FDM technology is concerned, thickness

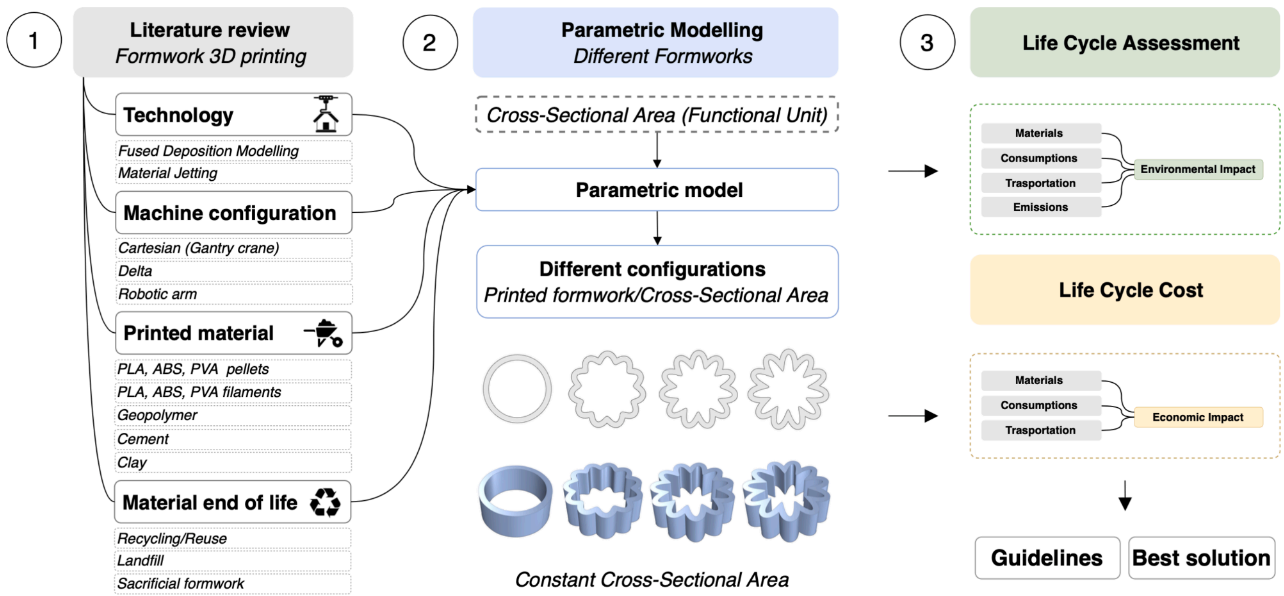

Fig. 1. The three steps of the proposed methodological approach.

ranges from 0.8 mm for ultra-thin formworks to 40 mm for robust ones. By using the MJ technology, wall thickness can vary from about 4 mm (in prefabrication) to more than 50 mm in on-site 3D printing moulds embedded in monolithic construction [20]. The final applications of the structure cast within the printed formwork are diverse, ranging from a simple structural role to a combination of both structural and aesthetic functions. In all cases, the objective of the formwork is to enable the creation of a component with a sufficient cross-sectional area for use within the building. Fig. 2 shows different 3D printed formworks dedicated to various components such as pillars, walls, and arches. Table 1 summarizes the most important formworks that emerged from the synthetic review.

It is worth noting that the results obtained from the brief literature review have been fundamental in defining both the aspects to be further explored in the subsequent investigation, such as technologies, materials, and machine configurations, and the boundaries of the variability of the parameters involved (thicknesses and geometries).

Furthermore, beyond materials that have already been extensively used, the research in the subsequent subsections aims to analyze emerging and underutilized materials for formworks with significant potential, such as clay or geopolymers.

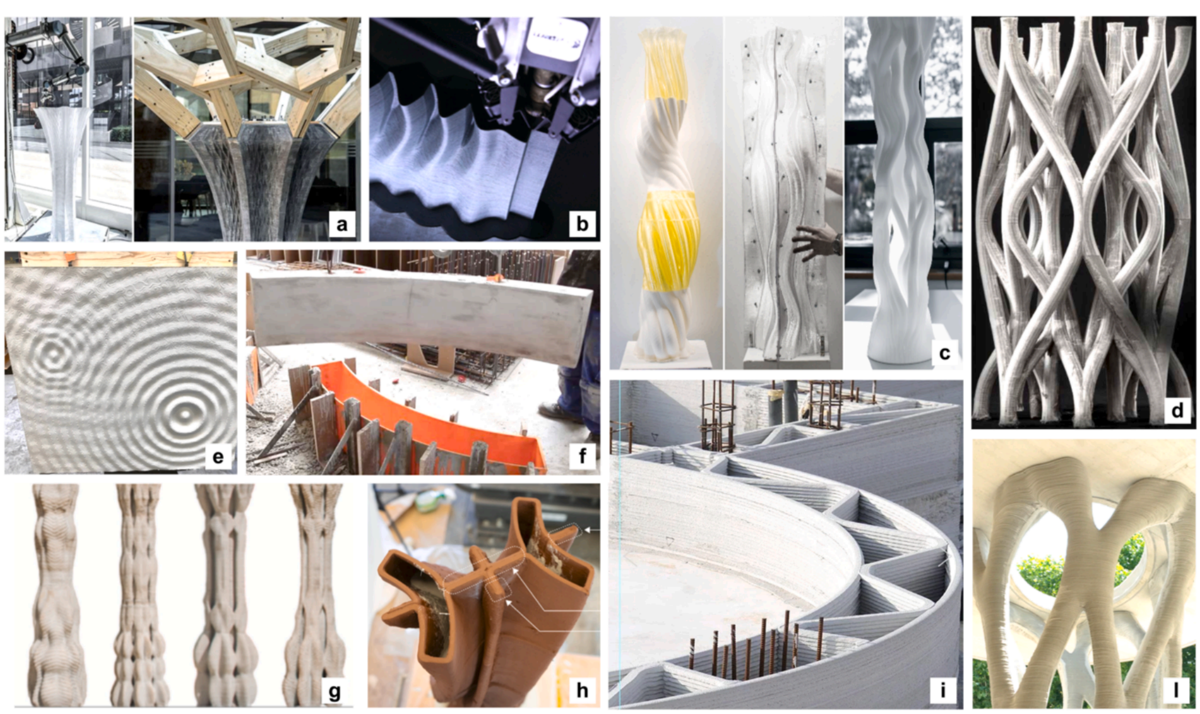

Fig. 2. A) column from the project future tree pavilion [47], b) High-Resolution PanelNaboni and Breseghello [48], c) Additive thermoplastic formwork for casted columns [70], d) Submillimeter formwork for complex columns or truss [49], e) Water drop facade wall from the company BigRep[50], f) Concrete arch from the company BigRep [51], g) Bespoke columns [75], h) clay formwork to cast concrete column [19], i) embedded column in 3d printed two-storey office in Dubai [20], l) Truss-shaped pillarsGaudillière et al. [52].

Table 1
Most important research works and formwork applications that emerged from the achieved brief review.

Cite	Projet	Component	Printing technology	Machine Configuration	3D printing material	3D printing material EoL	Formwork wall thickness (mm)
[75]	Bespoke columns	Column	Material Jetting	Robotic arm	Cement	Sacrificial formwork	10.0
[20]	Two-storey office in Dubai	Column	Material Jetting	Cartesian	Cement	Sacrificial formwork	50.0/100.0
[76]	Eggshell (material-informed formwork geometry)	Column	FDM	Robotic arm	PLA filaments	Landfill	1.5
[47]	Eggshell (three branches column and Future three)	Column	FDM	Robotic arm	PLA filaments	Landfill	1.5
[53]	Earthen formworks	Column	Material Jetting	Robotic arm	Raw earth	Sacrificial formwork	25.0
[18]	Dissolvable 3D printed formwork	Column	FDM	Cartesian	PVA	Landfill	1.5
[50]	Water drop facade	Wall	FDM	Cartesian	PLA filaments	Reuse	15.0
[54]	FreeFab Wax formwork	Column	FDM	Robotic arm	PLA filaments	Reuse	more than 50.0
[52]	Truss-shaped pillars	Column	Material Jetting	Robotic arm	Cement	Sacrificial formwork	20.0
[32]	Ultra-thin 3D printed formwork	Beam	FDM	Robotic arm	PLA filaments	Landfill	2.0
[55]	YRYS Concept House	Column/Walls	Material Jetting	Robotic arm	Cement	Sacrificial formwork	20.0
[56]	WinSun 3D prints 6-story	Column/Walls	Material Jetting	Cartesian	Cement	Sacrificial formwork	40.0
[49]	Submillimeter formwork	Column	FDM	Robotic arm	PLA filaments	Landfill	0.8
[58]	Concrete canoe	Truss	FDM	Robotic arm	PLA filaments	Sacrificial formwork	0.8
[57]	Funicular slab	Slab	FDM	Robotic arm	PLA filaments	Landfill	0.8
[59]	3D printed formworks which substitute reinforcement	Beam	FDM	Cartesian	ABS	Sacrificial formwork	1.4
[60]	Dissolvable 3DP formwork	Column	FDM	Robotic arm	PVA	Landfill	1.2
[70]	Additive thermoplastic formwork	Column	FDM	Robotic arm	PLA filaments	Recycling	0.8
[19]	Clay formwork	Column	Material Jetting	Robotic arm	Clay	Reuse/Recycling	6.0 / 3.3
[77]	Formworks for complex concrete constructions	Column	FDM	Cartesian	PLA filaments	Reuse	0.8
[48]	High resolution panel	Wall	FDM	Delta	PLA filaments/ pellet/ABS	Recycling	40.0
[61]	Germany's first printed home	Walls	Material Jetting	Cartesian	Cement	Sacrificial formwork	50.0 / 100.0
[62]	Aditive formwork	Wall	FDM	Robotic arm	PLA filaments	Reuse	0.8
[51]	Modular formwork	Column / Arch	FDM	Cartesian	PLA filaments	Reuse	15.0
[63]	Domino sugar factory	Column and Beam	FDM	Cartesian	PLA filaments	Reuse	25.0
[64]	Counter Pressure Casting	Column	FDM	Robotic arm	PLA filaments	Landfill	0.8
[65]	NowLab Wall	Wall	FDM	Cartesian	PLA filaments	Reuse	50.0
[66]	Properties of 3D printed permanent formwork	Column	Material Jetting	Robotic arm	Cement	Sacrificial formwork	18.0 / 30.0 / 38.0
[67]	Concrete column construction	Column	Material Jetting	Cartesian	Cement	Sacrificial formwork	25.0

2.2. Parametric model

As emerges from the literature analysis, geometric complexity is extremely variable due to the great freedom provided by new 3D printing technologies [21]. To this aim, the second step of the methodological approach leverages the power of parametric modelling to quickly generate several geometric configurations of formwork with different levels of complexity measured as the perimeter-to-area ratio of the section. Furthermore, the parametric model takes into account the varying fundamental parameters identified in the brief literature review (Subsection 2.1) such as the shell thickness.

There are several software tools for creating parametric models (Table 2), among the most widely used are Rhino + Grasshopper [25], Dynamo for Revit [22], Blender + Sverchok [23] and Fusion 360 [24]. Typically, Dynamo is used to achieve complete BIM modeling, enabling the automation of tasks, the creation of complex parametric geometries, and the manipulation of data within the BIM environment. Blender + Sverchok is a powerful software typically used for rendering and animations, while Fusion 360 is less flexible and is mainly used in mechanical engineering environments. Among all these, the choice falls on Rhino + Grasshopper because, although not the only software capable of generating the required type of geometry, it is the one that, offers the greatest flexibility and works well for complex architectural and building components. More in detail, the modelling is performed using the Grasshopper software (Version 7.28.23058.03002, 2023–02-27). It is a visual programming language operating as an extension of the 3D computer-aided design (CAD) application Rhinoceros [25]. The analysis is carried out by developing an algorithm to create configurations based

Table 2
Software for parametric modeling and key features.

Software	Reference	Architecture	Complex geometries	BIM Modeling	Rendering	Animations	Mechanical Engineering
Grasshopper (Rhinoceros)	rhino3d.com	×	×		×		
Dynamo (Revit)	dynamobim.org	×		×			
Sverchok (Blender)	github.com	×	×		×	×	
Fusion 360	autodesk.com						×

on the provided parameters. By adjusting these parameters, the geometry can vary accordingly. The role of this parametric modeling is of fundamental importance. Through this tool, it is possible to quickly generate various geometric configurations and automatically calculate, in real time, several parameters such as the perimeter of the formwork, the cross-sectional area of the formwork, and the volume of the printed material. Furthermore, the synergy between the parametric model and LCA and LCC analyses becomes essential to achieving the desired results, as parameters such as the quantity of printed material and the length of the printing path are essential inputs for the Life Cycle analyses.

Given the considerable geometric freedom afforded by parametric modelling and 3D printing, it becomes crucial to comprehend how geometric complexity can impact the sustainability of the production process. To achieve an effective Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) analysis, the functional unit needs to be defined. In this approach, the functional unit is already defined in this phase to enable the development of a parametric model using visual scripting programming that allows for the variation of various geometric characteristics while keeping the functional unit constant. Specifically, the functional unit is defined as the production of a structure with a defined cross-sectional area and height. Consequently, beyond a constant cross-sectional area, the parametric model is achieved to consider the possibility of undulating the surface to simulate printing with complex geometry. Such undulation is achieved by introducing a surface perturbation through a sine wave. Geometric size values, such as the number and amplitude of the sinusoids (which affect the perimeters of the cross-section), as well as the thickness of the formwork wall, are parametrized using visual scripting components well-established in the literature [26]. These include 'number sliders' and a combination of curve generation, mathematical operations, and geometric transformations.

More in detail, a radius slider feeds a '*circle*' component to generate a circumference. This circumference is then divided into points using the '*divide curve*' component and subsequently reconstructed with a spline. In parallel, an '*expression*' component contains the equation of a sine wave, which is fed by a domain linked to the slider for the number of sine waves and a slider controlling the sine wave's amplitude. This expression is connected to the discretized points on the curve via a 'move' and 'cross product' component to impart a sinusoidal undulation through a set of displacement vectors. Finally, an additional number slider governs the wall thickness, connected to the visual script through an '*offset curve*' component and a series of '*surface*' and '*solid difference*' commands to define various regions (e.g., the cross-sectional area of the 3D-printed formwork and the cross-sectional area of cast concrete). The final part focuses on extrusion and the automatic calculation of various geometric parameters using '*area*' and '*volume*' components. This part is useful to verify the consistency of the functional unit and for accurately estimating the perimeter-to-cross-sectional area ratio of the formwork, the area of the formwork wall thickness (surface depending on the perimeter and the wall thickness), or the volume of the printed material. Additionally, it involves a comparison of these values with the circular form that minimizes the perimeter-to-cross-sectional area ratio. All these values are calculated to be included in the LCA and LCC assessments presented in the next section 2.3.

The only assumption/approximation involves the decomposition of the circumference into points and its reconstruction with a spline. However, by increasing the number of points, the error from this approximation becomes largely negligible. Indeed, for the number of

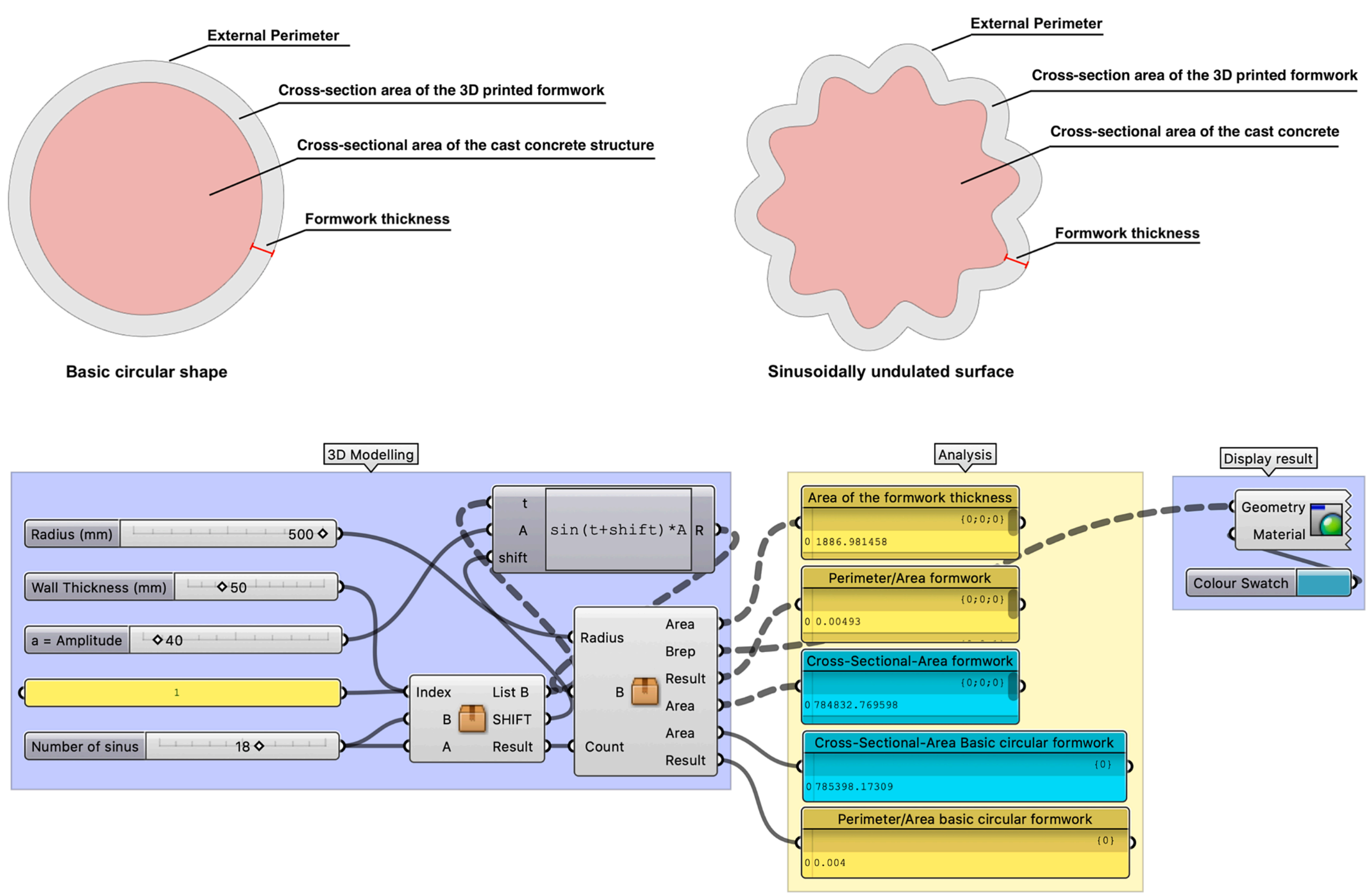

Fig. 3. Comparison of sections of the formwork achieved for a basic circular configuration and for an undulated configuration (upper part). Excerpt of the script that displays parameters and the results of the automatic calculation of the perimeter-to-cross-sectional area ratio of the formwork and the area of the printed material in a single layer (bottom part).

points used (over 1000), the relative error of the area of achieved geometry is approximately 0.00048 % (comparing the results before and after the division into points and the subsequent reconstruction of the circumference).

The upper part of Fig. 3 shows two sections of the formwork: the basic circular configuration and an undulated one. In addition, the most important parameters, such as the external perimeter, formwork thickness, the cross-section area of the 3D printed formwork and cross-sectional area of the cast concrete structure within the formwork, are shown. The bottom part of Fig. 3 displays an excerpt of the visual script created to generate the shape of the formwork. Again, in this case, the most important parameters (number sliders) are shown.

2.3. Life Cycle Assessment

The analysis of the third step was conducted following the standardised methodologies of Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) according to ISO standards 14040–14044.

These methodologies follow four iterative phases: 1) goal and scope definition, in which the objective of the study, the system boundaries and the functional unit (FU) are defined; 2) Life Cycle Inventory (LCI) in which all data required forthe sustainability model are gathered; 3) Life Cycle Impact Assessment (LCIA) which LCI data are translated into potential environmental and economic costs; 4) Results discussion in which the obtained impacts are critically reviewed to ensure analysis reliability and direct sustainable practices.

2.3.1. Life Cycle goal and scope definition

The proposed analyses aim to provide an evaluation of the environmental and economic impacts associated with concrete structures realized by means of 3D printed formworks. Different technologies, formwork geometries, materials, machine kinematic systems and process parameters were included to create a complete model for concrete structure production.

The functional unit is defined as the production of a concrete structure using a 3D printed formwork; the structure has a concrete-resistant cross-section area equal to 7854 cm^2, and a height of 100 cm. This cross-section value corresponds to an equivalent circular cross-section with 100 cm diameter. The developed parametric CAD model was used to provide data related to different geometries (with constant cross-section area but increasing perimeter) to assess the overall structure impacts as the geometric complexity increases. The same functional unit was considered for both the sustainability and economic analyses. The functional unit was chosen to be general and ensure comparability with other studies; in this way, the results can be extended to any other concrete structure.

The analysis includes different alternatives for the 3D printing process to assess how the overall structure impacts can vary depending on the used technology and specific parameters and design choices. More specifically, the following alternatives were considered for the 3D-printed formwork:

- 3D printing technology.

FDM of plastic materials and MJ of viscous materials. Indeed, the technology choice also determines which kind of feedstock can be used;

- Raw material (type and feedstock form).

For the FDM technology, PLA, ABS and PVA thermoplastic materials were taken into account. It was considered that they can be provided and used both in the form of filaments (as for most commercial 3D printers [27]or granulate pellets. On the other hand, clay, concrete or geopolymers were considered for the MJ technology;

- Printer kinematic type.

Different machine configurations were considered, namely cartesian, delta and robotic arm kinematic systems;

- Formwork End of Life (EoL) route.

In sustainability and cost assessment, EoL options could strongly contribute to the life cycle impacts. Three possible options were hence included: recycling of the formwork material (i.e. for plastics to obtain recycled feedstock), landfill disposal of formwork material, and sacrificial formwork (i.e. the 3D printed formwork remains within the final cast structure). In addition, the possibility of reusing the formwork after the first casting cycle was considered for non-sacrificial formworks [28],

- 3D printing process parameters.

As demonstrated in previous studies, process parameters can strongly influence the overall sustainability of 3D printing processes [29,30,31]. Printing speed was considered in this study as it can strongly affect both environmental impacts and costs.

In addition, different nozzle diameters ranging from 0.4 to 50 mm were taken into account. Since the FU is defined by considering the cast concrete cross-section area, a 3D-printed structure with varying thicknesses of the formwork can be investigated. As reported in the literature, formwork with thin walls can be used for concrete casting [32]; hence, in most cases, the nozzle diameter can also determine the wall thickness (i.e. the wall thickness coincides with the width of extruded material). Therefore, nozzle dimensions could determine material use and be relevant for the component sustainability.

It should be noted that, on a practical level, not all alternative combinations are possible; for example, nozzle diameter is typically smaller for filament FDM while it can reach higher values for viscous material extrusion. Fig. 4 summarizes all the scenarios considered within the proposed model.

A “from cradle to gate” approach was selected to include all impacts from the extraction of raw materials to the production of the final concrete structure. More specifically, the following phases were included within the system boundaries:

- Extraction and processing of materials used in 3D printing. This includes, for plastic materials, material production and feedstock preparation (i.e. pellets or filament production), whilst, for viscous materials, raw materials extraction and mix preparation (e.g. for concrete and geopolymer);
- Raw materials transport to the construction site or the printing company;
- Transport for machines and concrete structures for production in situ. In the case of production of the parts directly at the building sites, 3D printing machine transport was considered. Otherwise, concrete structure transport was taken into account;
- 3D printing phase. This includes energy consumption during the printing process. In addition, for viscous materials, the use of mixing and pumping systems was included;
- Traditional concrete casting within the printed formwork. This phase includes concrete mixing and pumping;
- 3D printed component EoL, either recycling or landfill disposal for non-sacrificial formworks.

Impacts related to the service life of the components were not included (e.g. energy consumption, maintenance, etc.). These impacts could strongly depend on specific construction typology and application; hence, to obtain generalizable results, they were excluded from the analysis. Furthermore, in the construction sector, these energy use and maintenance phenomena are primarily linked to non-structural components or systems. However, in the developed research, the focus is on structural elements of a known resistant section.

Finally, a sensitivity analysis was conducted to evaluate the potential

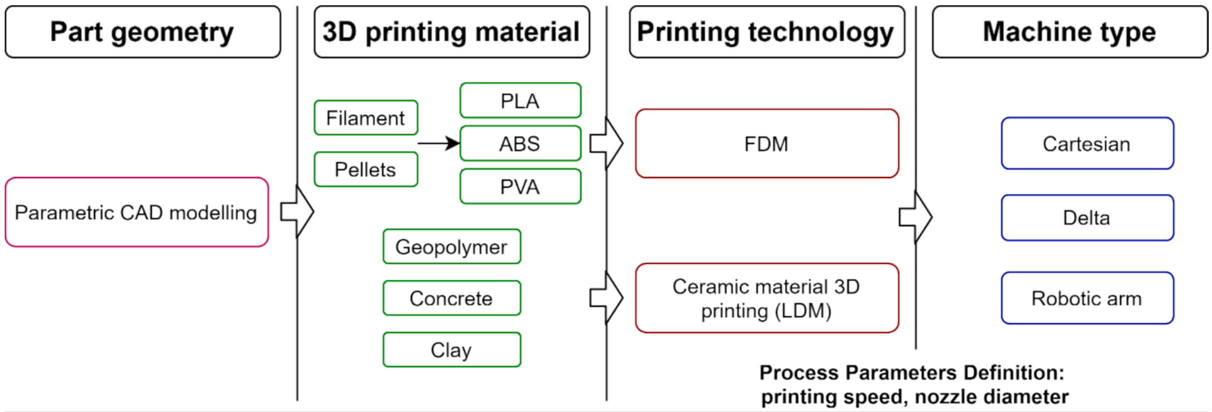

Fig. 4. 3D printing process alternatives considered in the proposed model.

variations in the impact of the component production when different cross-sectional areas were considered (i.e. different functional units). This can broaden the validity of the study results by integrating evaluation related to structures with different dimensions and weights.

2.3.2. Life Cycle Inventory

The Life Cycle Inventory phase for LCA and LCC cost was carried out by considering both primary and secondary data. Literature studies, mathematical relationships and the Ecoinvent 3.1 database were employed as secondary data sources. The latter is provided by default within the LCA-dedicated software SimaPro [33] that was used for this study. The software allows to model the life cycle phases included within the analysis and translate the inventory data into possible effects on the environment (LCIA phase). In order to investigate several alternatives and compare them, a parametric approach was undertaken. Unitary impacts (e.g. per kg of material or energy use) were obtained in SimaPro software by modelling all the system boundary phases. Hence, by means of a spreadsheet, mathematical relationships were found between input (the specific structure design and process configuration) and output (the final structure impacts). For each structure configuration, the input data (e.g. material weight, energy consumption…) were calculated starting from the structure design and parametric model; hence, environmental impacts of each life cycle phase were calculated by multiplying unitary impacts and input values. This allowed to calculate the impacts of all possible configurations.

Details related to LCI data are reported as follows.

Structure design.

Data related to the structure design were obtained from the Grasshopper parametric model. The investigated structures are characterized by the same cross-sectional area (i.e. the cast concrete area) and different perimeter and formwork wall thickness. The CAD model results were used to determine the 3D printed component volume and the 3D printing perimeter. In turn, these values were employed to quantify material weight considering material density and 3D printing energy use.

It is worth noting that, in the case of sacrificial formwork, the structural contribution of the 3D printed component was not considered; hence, all structures are characterized by the same cast concrete cross-section area. Since the structure section is constant for each configuration, no support material was considered to be required for the 3D printing phase.

Raw materials and transport.

Impacts related to PLA and ABS plastic pellets for FDM printing were retrieved from Ecoinvent 3.1. PVA impacts were obtained from the literature [34]. Plastic filaments were considered to be obtained starting from pellets subjected to an extrusion process (modelled according to Ecoinvent 3.1).

A concrete mixture specifically developed for 3D printing applications was modelled according to the literature [7]. The mixture is constituted by cement, fly ash, micro silica fume, fine aggregate, water and additives to adjust material viscosity and workability (i.e. superplasticizer, viscosity modifying admixture and PP fibres). Traditional concrete mixture for casting was considered to be constituted of the same elements except the additives required only for the 3D printing process. A geopolymer for 3D printing applications was modelled according to Bong et al. [35]. It is constituted by fly ash, slag, silica sand, water, sodium silicate (solid activator) and sucrose (retarder). Clay impacts were obtained through Ecoinvent 3.1. Proportions for the 3D printing mix between clay and water were taken from recent literatureMadrid and Sotorrío Ortega [36].

Material weight was calculated by multiplying the 3D printed component volume for each design configuration (i.e. obtained starting from the grasshopper parametric model) and the material density.

Raw material transport was estimated considering possible supplier distances and a company located in the centre of Italy. Road transport was considered in all cases and it was modelled using the Ecoinvent 3.1 database (transport, freight lorry).

Table 3 reports the LCI data related to raw materials.

Energy consumption.

For what concerns the 3D printing process, the volumetric flow rate was calculated according to the following Eq. (1) [37]:

$$\dot{V} = v_e t \frac{\pi d^2}{4} \tag{1}$$

where $\dot{V}$ is the volumetric flow rate (m^2/h), v_e the extrusion speed, t the time, d the nozzle diameter. The volumetric flow rate can be calculated as a function of the two process parameters considered in this study (printing speed and nozzle diameter). Hence, by considering the formwork volume obtained in the parametric model, printing time for each structure can be calculated.

The energy consumption of the printing phase (i.e. associated with kinematic systems, extruders and pumps) was calculated by multiplying the machine energy absorption and the printing time. To define the average energy absorption, cartesian, delta and robotic arm kinematic systems with a build volume of about 1 m x 1 m x 1 m were considered (i.e. BigRep Pro for cartesian, Wasp 3MT HDP for delta and KUKA KR60 HA for robotic arm [71–73]). According to the literature, if directly measured data for the energy absorption of the kinematic system were not available, it was calculated by considering nominal power divided by 2 [38]. This assumption was discussed in the results section. As reported in the literature [39], 3D printing machine's power absorption does not significantly vary depending on the moving speed. Hence, power absorption was considered constant irrespective of the printing speed. Similar estimations were carried out for the extruder's energy consumption and the pumping system (required only for material jetting

Table 3
LCI data related to raw materials.

Raw materials	Density [g/cm^3]	Cost per kg [€/kg]	LCA model / comments
Plastic material		**Pellets / filament**	
PLA	1.24	8.5 / 15	Ecoinvent 3.1
ABS	1.05	9.5 / 15	Ecoinvent 3.1
PVA	1.26	10 / 65	Production was modelled according to literature [34] and using Ecoivnent datasets
Filament production			Ecoinvent 3.1. Modelled as an extrusion process
Viscous material	**Constituent weight [kg/m^3]**	**Cost per kg [€/kg]**	**LCA model / comments**
Clay	1760	0.013	Ecoinvent 3.1. Water and clay content in the mixture (27.4 %/72.6 %) retrieved from literature (Madrid et al., 2023)
Geopolymer	2156	0.067	Geopolymer constituents weight was taken from literature [35] and they were modelled with Ecoinvent datasets
– Fly ash	363.6	0.036	
– Slag	363.6	0.2	
– Silica sand	1090	0.018	
– Water	261.8	0.002	
– Solid activator (sodium silicate)	72.7	0.5	
– Retarder (sucrose)	3.6	0.55	
Concrete	2176.55	0.086 Traditional concrete 0.129 3D printing concrete	
– Cement	~50 %	0.280	Due to confidentiality reason, the exact amount of each constituent cannot be disclosed.
– Durapozz fly ash		0.036	
– Micro Silica Fume	~40 %	0.050	
– Fine aggregate		0.018	
– Water:	~10 %	0.002	
3D printing concrete additives			
– Superplasticizer.	/	1.700	Due to confidentiality reasons, the exact amount of 3D printing concrete additive cannot be disclosed. The total weight of additives is lower than 1.5 % of the total mixture. VMA: Modelled as polylactive [68] PP fibers: modelled according to literature [69]
– VMA (viscosity modifying admixture)	/	2.760	
– 6 mm HM-PP Microfibres	/	6.000	

Table 4
LCI inventory data related to machines use impacts and cost.

Machines	Purchase cost [€]	Nominal Power [kW]	Weight [kg]	Comments
3D printer kinematic				
Cartesian	40,000	1.8	285	Datasheet data
Delta	53,000	5	250	
Robotic arm	30,000	16.8	665	
Other machines	**Purchase cost [€]**	**Nominal Power [kW]**	**Productivity [kg/h]**	
Pump	8000	4	2600	Datasheets data
Mixing machine	2000	2.2	5200	
Other assumption for 3D printing machine machine cost evaluation				
3D printing machines				
Lifetime [yrs]		8	Data based on manufacturing experience and employed to calculate machine depreciation cost.	
Infrastructure cost [% machine cost]		0.01		
Maintenance [% machine cost]		0.03		
Machine uptime [%]		80 %		
Hours/day [h]		18.00		
Days/week [d]		5.00		
Labour cost				
3D printing build time,setup, operator [h] h		0.2	build setup, operator	
build removal	h	0.1	build removal	
Labour cost	Labour time (h/m3)			
Labour time for concrete casting	0.4		[40]	
Labour cost	€/h	30		
Additional data	**Cost (€)**			
Transport (kg*km)	0.15		Evaluated considering industrial quoted	
Electric energy (kWh)	0.5			
Landfill (kg)	0.5			
Plastic recycling (kg)	0.45			

technology) for the 3D printing phase. Machine weights were retrieved from their databases; these data are relevant in the case of production in situ of the 3D printed and final concrete structures.

Pump and mixing system energy consumptions were evaluated by considering the machine's rated power and their productivity. Primary data were provided by industrial partners.

Impacts related to electric energy use were retrieved from the Ecoinvent database considering low voltage energy mix (Italy).

Table 4 reports the data related to machine use and energy consumption.

EoL.

Landfill disposal was modelled in SimaPro using the Ecoinvent 3.1 database. For what concerns the recycling scenarios (i.e. possible for plastic formworks), transport, shredding and pelletizing of the waste were considered. Energy consumption for shredding was calculated by considering the nominal power of a commercial plastic shredding machine and its hourly productivity. Pelletizing was modelled by taking into account an extrusion process modelled within the Ecoinvent database. Credits for the recycling process were considered, hence negative impacts are associated with this phase. It was assumed that the use of recovered material prevents virgin material production so negative impacts equal to those of virgin pellet production were considered. In the case of sacrificial formwork (i.e. ceramic formwork included within the final cast part), no impact related to its disposal was included. If the formwork was considered to be used for more than one moulding cycle, the impacts related to its production and disposal were allocated to the functional unit by dividing them by the number of use cycles.

2.3.3. *Life Cycle Costing data*

The LCC analysis was conducted using a parametric approach to evaluate the economic impact associated with the different 3D printed concrete structures.

Life Cycle Costing data were obtained by considering costs of commercial products and using LCI data from the sustainability assessment. Data related to structure design are derived from the grasshopper parametric model. Weight, material use, transport and energy consumption are the same considered for the LCA analysis and are detailed in the previous section. Market research and simple mathematical relationships were employed to calculate costs related to all the phases included within the system boundaries. In general, cost of raw materials, transport and labour were calculated based on unitary cost data and multiplied by the corresponding quantity needed for each structure. This allowed to calculate the cost of the different cost contributors (materials, labour, transport, machines use, etc.) for all the investigated concrete structures. Inventory data employed in the LCC analysis are reported in tables 3 and 4. As a general simplification, no unforeseen cost and other inefficiencies were included within the model.

Costs per kg plastic materials (both pellets and filaments) and clay were retrieved from the market and quote requests. Material costs strongly depend on the order quantity due to the price discount offered to buyers who purchase in large quantities; hence, a constant order quantity equal to 100 kg was considered to assess the unit cost (cost per kg of the materials). Geopolymer and concrete costs were calculated considering the cost and quantity of each constituent material; premixed products are also available on the market but they are typically more expensive than the sum of constituents.

Most of the cost items were calculated by considering their unit cost and by multiplying it for the actual use in each scenario; this was applied to transport, electric energy, landfill disposal and possible recycling costs. For the latter, revenues for recycled products sold were also included.

Depreciation and maintenance costs of the 3D printing machines were included in the analysis. Commercial products for cartesian, delta and robotic arm kinematic systems were identified. The same machine costs were considered irrespective of the specific technology since end effectors, such as pellet or filament extruders, have purchase costs considerably lower than those of kinematic systems. Hence, they were not included in the analysis.

Depreciation costs per hour were calculated by diving the machine purchase cost by its uptime during the service life. A 10 years life span and a 80 % uptime corresponding to 18 h per day of use were considered for all the 3D printers. Hence, depreciation cost for each machine was allocated to the functional unit by multiplying machine processing time (calculated, as for the printing energy consumption, as a function of the component weights and printing speed) and the hourly depreciation cost. The costs of pumping and mixing machines for concrete were allocated by similar calculations.

Labour costs were considered for both 3D printing and concrete casting. For the former, set up and demolding time were evaluated according to industrial experience. Concrete casting costs were calculated by considering labour cost per hour, concrete cast weight and a required labour time equal to 0.4 person-hour per m^3 of concrete [40].

All these cost items were added to quantify the total cost of each structure investigated.

2.3.4. Life Cycle Impact Assessment

For each impact category, the ReCiPe methodology defines a set of characterization factors that quantify the contribution of specific emissions (e.g., CO2, CH4) or resource consumption (e.g., energy, water) to the corresponding environmental impact [41]. During the Life Cycle Inventory (LCI) phase, data on materials, emissions, resource use, and waste were collected and modeled for each impact item using the SimaPro software, which incorporates the Ecoinvent commercial database. The software then applies the characterization factors to automatically convert the inventory data into potential environmental impacts for each category. In this way, the unitary impacts (e.g. per kg, per kWh…) for each input and output included in the study were calculated; hence, total structure impacts were calculated via a parametric approach as described in section 2.3.2.

Given the large number of formwork production alternatives included in the study, this methodology and the use of multiple categories can provide a complete overview of the scenario effects on the environment.

The same methodology was employed in several previous LCA analyses focused on concrete structures [42,43].

3. Results and discussion

3.1. GWP of concrete structures

Fig. 5 shows the LCA results in terms of GWP for formworks with circular cross section structure (i.e. characterized by the lowest perimeter-area ratio investigated) based on MJ and FDM 3D printing using nozzles with different diameters.

Fig. 5 a, b and c concern FDM structures realized using PLA, ABS and PVA pellets as feedstocks respectively, whilst Fig. 5 d, e, f refer to MJ structures realized using geopolymer, concrete and clay feedstocks respectively. In all cases, a cartesian moving system with a printing speed equal to 80 mm/s was considered. For each graph, the hatched region highlights nozzle diameters that are not commonly used for that specific printing technology. However, these results show that future developments could allow their adoption.

3.2. Influence of raw materials

Irrespective of printing technology, the most relevant input contributors are formwork raw material, 3D printing energy consumption and casting concrete use. Since the FU was defined by considering a fixed resistant cross-section area, cast concrete impact is equal to 474.76 kg CO_2 eq and it is independent of the 3D printing technology and nozzle diameter. However, its percentage contribution strongly varies depending on process parameters. As far as the nozzle diameter is concerned, cast concrete accounts for up to 88 % of GWP in MJ scenarios whilst its contribution can be as low as 7 % of GWP for FDM cases. It can be also noted that, with a proper selection of the process parameters, technology and raw material, the contribution of the 3D printed formwork to the overall structure impact is small; the overall structure GWP would be mostly influenced by concrete casting. This suggests that 3D-printed formwork can be a sustainable production tool for concrete structures.

As a general result, MJ technology (Fig. 5 d, e, f) shows much lower impacts than the FDM one (Fig. 5 a, b, c), hence the former is preferable as impact reduction is a requirement. This is mainly related to the lower unitary impacts of viscous materials, such as concrete, geopolymer and clay, with respect to polymeric ones. More specifically, geopolymer, concrete for 3D printing and clay have unitary impacts equal to 0.11, 0.30 and 0.01 kg CO_2 eq per kg, respectively. On the other hand, plastic materials have much higher unitary impacts with respect to the previous one, with unitary impacts equal to 3.12, 4.72 and 6.48 CO_2 eq per kg, for PLA pellets, ABS pellets and PVA pellets respectively. In addition, if plastic filaments are used as feedstock instead of pellets, unitary impacts for plastic material increase by about 0.5 kg CO_2 eq per kg.

3.3. Influence of nozzle diameter

By considering the formwork printed by MJ technology (Fig. 5 d, e, f), the environmental impact decreases with increasing nozzle diameter until a minimum is reached. Such minimum is obtained for nozzle diameter values depending on the formwork material. Then, the GWP increases with diameter with an effect less pronounced as clay is concerned. An increase in nozzle diameter implies a higher volumetric flow rate of the 3D printing material and higher layer thickness. Therefore, a lower number of layers would be required to complete the printing process, resulting in a lower printing time and energy consumption. For low nozzle diameters, a high number of layers is required to reach the desired structure height; this implies high electric energy consumption to carry out the process. As the nozzle diameter increases, the energy consumption decreases and material use increases. Even if it was possible to use very small nozzles for MJ (i.e. 0.4 mm), that would not be recommended from a sustainability perspective; in fact, the reduction in material use and wall thickness would not compensate for the increase in energy consumption.

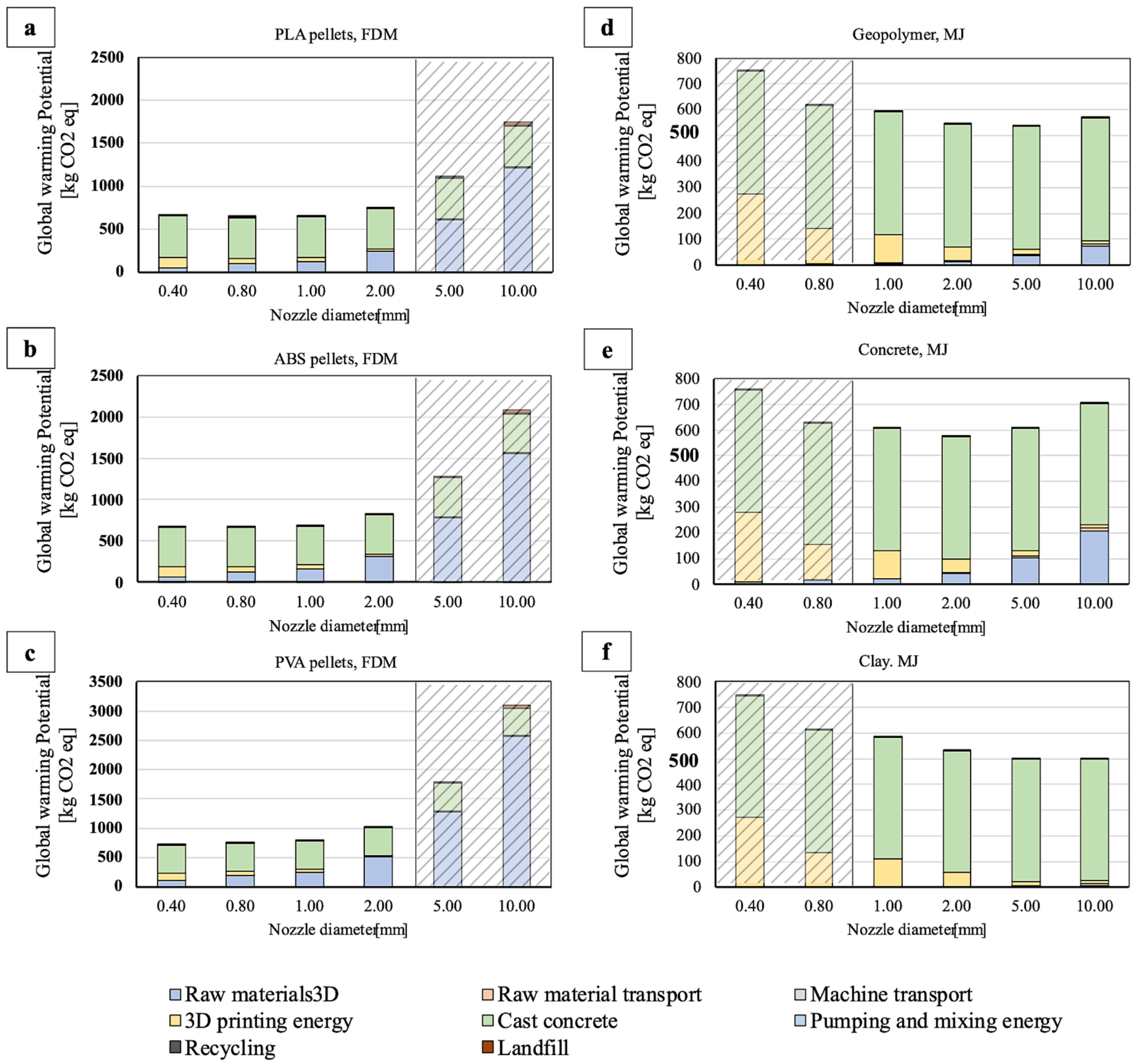

Fig. 5. GWP results vs nozzle diameter for structures, realized in a cartesia moving system and a printing speed equal to 80 mm/s, with FDM technologyusing PLA (a), ABS (b) and PVA (c) feedstock and structures manufactured using geopolymer (d), concrete (e) and clay (f) as feedstock with MJ technology.

As far as the FDM technology is concerned, irrespective of the formwork material, the GWP value monotonically increases with nozzle diameter, with a more marked effect for higher nozzle diameters. Materials used in the FDM technology are characterized by much higher unitary impacts and material use reduction is crucial to guarantee a low carbon footprint. Also in this case, a reduction in the energy consumption is obtained as nozzle diameter increases; however, the contribution to impacts caused by the energy use is almost negligible with respect to that provided by raw materials. The reduced effect of nozzle diameter on the overall impacts for nozzle diameter ranging from 0.4 to 1 mm is due to energy–material trade-off. For these nozzle diameters, the impacts of FDM formworks are similar to those obtained for the MJ technology, with most of the impacts associated with cast concrete (72–74 %) and 3D printing material (7–18 %). Larger nozzle diameters would strongly increase material use and its impact, by making FDM formworks impactful solutions (i.e. up to 10 times more impactful than MJ formworks).

This result suggests that the proper definition of process parameters for environmental impact reduction also depends on the type of raw material and the trade-off between material use and energy consumption.

Energy consumption during 3D printing can also be reduced by increasing the printing speed; the increase in material flow with no effect on material use, leads to lower energy consumption and impacts (Fig. 6).

As the kinematic systems are taken into account, among the considered ones, the cartesian system is characterized by the lowest nominal power whilst delta and robotic arm configurations require higher power. These results are related to specific machine choices; hence, strong variability can be expected for different commercial products characterized by different technical specifications. Other sources of energy consumption, such as extruders are characterized by negligible energy absorption with respect to the kinematic system (0.007 kW in the present study). Hence, the 3D printing machine energy consumption mostly depends on the kinematic configuration rather than the specific technology. For MJ, higher energy consumption occurs due to the material pump.

Energy consumption concerning material transport, concrete pumping and mixing machines, is usually negligible.

3.4. End of life

EoL can be a relevant phase, in particular as the plastic formworks are concerned (Fig. 5 a, b, c). Landfill disposal is generally associated

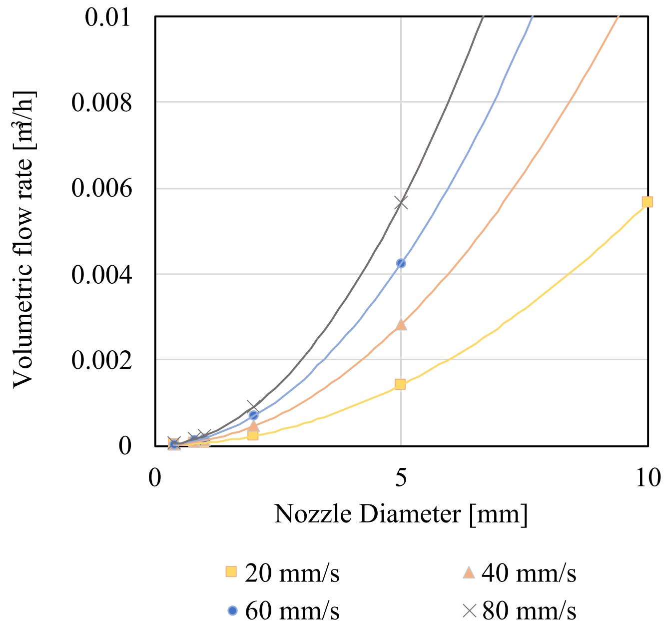

Fig. 6. Volume flow rate as a function of nozzle diameter for different printing speeds.

with low-impact contribution due to the relatively reduced use of plastic materials for thin-walled formworks. Some exceptions can be found for impact categories related to water pollution (e.g. freshwater eutrophication and marine eutrophication) for which landfill disposal can be the most relevant impact item, with a percentage contributions higher than 50 %. Plastic material recycling is an ideal solution to reduce the impacts associated with raw material extraction. The recycling process, which includes material transport, grinding and extrusion, has low unitary impacts (0.66 kg CO_2 eq per kg) and the credits associated with waste material reuse contribute to counterbalance the high impacts of virgin material extraction. This solution makes FDM technology impacts closer to those of MJ.

A further relevant improvement for FDM formwork is represented by the multiple uses of the same 3D printed structure. In this way, all impacts related to the 3D printed structure are allocated to the FU by dividing the total impacts by the number of possible reuse. This strongly reduces formwork impacts and makes the use of plastic more sustainable than the other alternatives. On the other hand, MJ formwork is embedded in the final structure with no immediate disposal of the raw material (Fig. 5 d, e, f).

3.5. Geometry complexity

Fig. 7 shows the results in terms of GWP of 3D printed formworks in concrete obtained using the MJ technology as a function of the cross section perimeter. Data related to the printed formwork geometry were derived by means of the Grasshopper parametric model by considering different formwork cross-sections obtained with an increasing number of sinusoid perturbations (0–5-10–15) and amplitude (from 100 to 200 mm). The section perimeter increases with the number and amplitude of the sinusoids, resulting in a cross-section characterized by higher perimeter-area ratio (i.e. more complex geometries).

In the 3D printing phase, higher values of the formwork perimeter imply higher quantities of material use and energy consumption, resulting in higher impacts. This leads to an increase in carbon footprint associated with the formwork production with an almost linear trend with the component perimeter. Impacts related to concrete casting remain unchanged (FU with constant resistant cross-section area) and therefore, 3D printing phase becomes more relevant in terms of total impact contributions. At least for smaller nozzle diameters, formwork

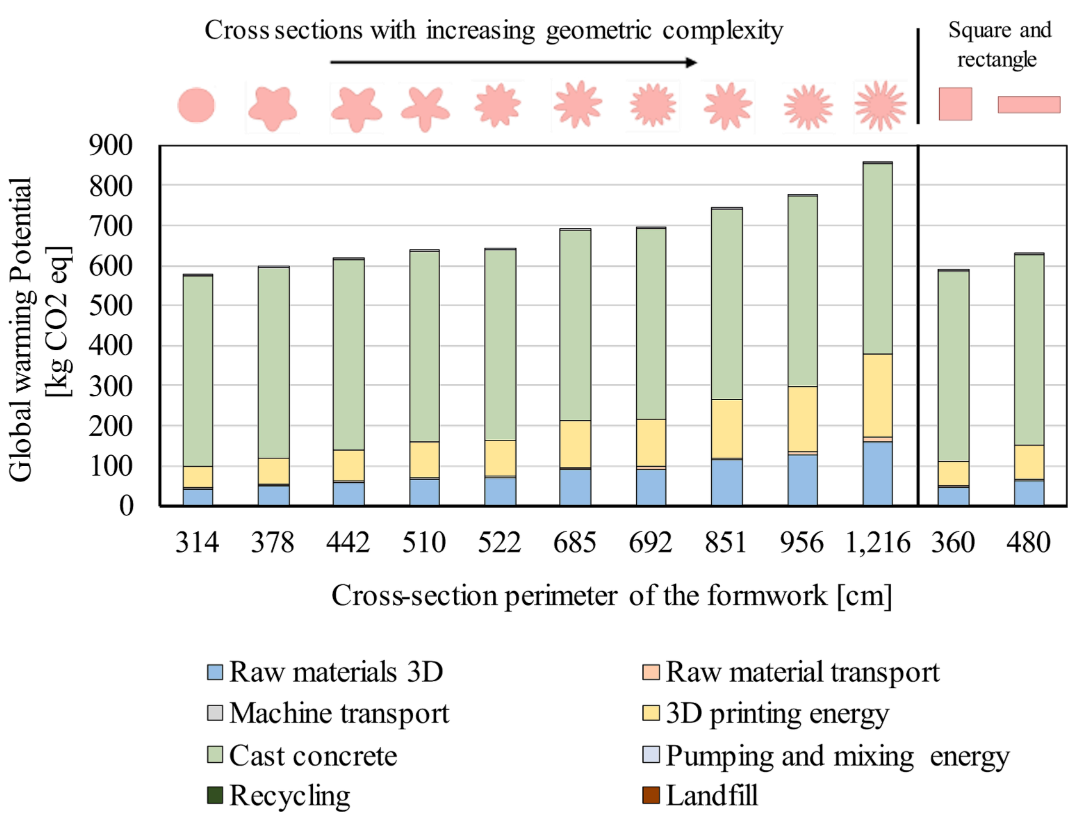

Fig. 7. GWP results for formworks characterized by increasing geometrical complexity (section perimeter). Concrete 3D printed structure and nozzle diameter equal to 2 mm were considered.

impacts are still less relevant than those of the other phases such as concrete casting (Fig. 5). For larger nozzle diameters, the dependency between 3D printed formwork impacts and component perimeter is even more noticeable (Fig. 8). In fact, higher values of nozzle diameter correspond to higher material use and, therefore, a higher percentage contribution to the 3D printing phase. For this reason, an increase in the component perimeter leads to a relevant increase in impacts. This further highlights the advantages related to thin-walled structures: complex geometries can be produced while still keeping low formwork impacts.

These results are also true for formworks produced via FDM (i.e. with plastic material feedstock), with the impact of the 3D printing phase (including both energy use and materials) that increases as the structure complexity increases. In that case, the contribution of 3D printing materials is more relevant due to the higher unitary impacts of the polymers with respect to the viscous materials.

In addition to the sections defined by means of the grasshopper model, square and rectangular cross sections were investigated to represent more common structures in standard construction. In fact, despite design freedom and parts complexity being a great advantage of 3D printing, this technique also allows to produce simple and standard structures. The same cross section area defined for the previous structures was considered. This led to a large square column of about 90 cm x 90 cm. For the rectangle a concrete wall approximately 40 cm x 200 cm is considered. LCA results were calculated analogously to the other sections and are reported in Fig. 7. These two cross sections show impacts similar to those of the circular section and the shapes characterised by the lowest degree of geometric complexity. This is true both in terms of final impacts and cost contributions. This similarity arises because these shapes have low perimeter-to-area ratios, resulting in minimal material usage during the printing process. Similar results are also expected for compact and simple traditional shapes.

This highlights that the perimeter of the cross-section is the key factor influencing impacts in 3D printing. In fact, the determining factors are the extrusion path length and material consumption whilst the specific shape has lower significance. Hence, the model and the results here presented can be easily generalized to any shape.

These results were confirmed for all the investigated impact categories (i.e. GWP and all ReCiPe midpoint categories).

3.6. Sensitivity analysis on cross-section area

Since the previous results are referred to a given FU characterized by a concrete-resistant cross-section area equal to 7854 cm^2 and a height of 100 cm, it is worth to assess the environmental impact contributions as a function of the resistant cross-section area. This is useful to evaluate the industrial applicability of 3D printed formworks. Fig. 9 shows a sensitivity analysis that quantifies the total impacts for structures with variable diameter with a circular cross-section. A variation of the cross-section diameter equal to ± 50 % with respect to the initial value (100 cm) was considered for the sensitivity analysis. It can be seen that impacts related to the 3D printed formwork linearly increase with the diameter and, consequently, the perimeter of the component cross-section.

By considering simple geometric relationships, the volume and weight of the 3D printed formwork are directly proportional to the component diameter. Similarly, according to the proposed model, energy use is proportional to component volume. On the other hand, cast concrete impacts are proportional to the cross-section area or the diameter squared of the component. Hence, the impact contribution of cast concrete increases with the structure cross-section area. This confirms the previous results: by increasing the cross-section area of a concrete structure produced using a 3D printed formwork, for a given shape, the ratio between perimeter and area decreases (less complex geometry), and the contribution of the 3D printed formwork decreases.

The dashed line in Fig. 9 also reports the structure specific impacts, calculated as the total impacts of the structure divided by its concrete weight (kg CO_2 eq per kg). As structures with higher cross section area (and lower perimeter to area ratio) are considered, unitary impacts decrease. Impacts per kg range between 0.39 kg CO_2 eq per kg for the smaller diameter to 0.32 kg CO_2 eq per kg per the largest diameter.

3D printing is a relatively energy-intensive process, and the raw materials used during this phase, such as the plastics employed in FDM, generally have significantly higher unitary impacts compared to traditional cast concrete (e.g., the unitary impacts of plastic materials can be an order of magnitude higher than those of cast concrete). Hence, as the structure area increases and the percentage contribution of 3D printing decreases, the unitary impacts of the final structure decrease. To sum up, the analysis highlights that the use of formwork can also be a sustainable option, potentially resulting in very low environmental impacts. In particular, this potential could be realized by utilizing a sustainable 3D printing material for the formwork or the filling cast, which play a significant role in CO2 production.

The same considerations can be made as formworks produced via MJ are considered with the main difference that, as observed in Figs. 5, 3D printing material would have an even lower impact contribution to the total GWP.

3.7. Life Cycle Costing

Fig. 10 shows the concrete structure cost vs nozzle diameter. As far as the FDM structures realized using PLA pellets as feedstock is concerned (Fig. 10 a), the overall cost decreases with increasing nozzle diameter until a minimum is reached for a nozzle diameter equal to 1 mm; then, it increases with nozzle diameter. By considering the MJ structure produced using geopolymer (Fig. 10 b), the overall cost decreases with increasing nozzle diameter with a more pronounced slope with respect to the FDM technology; for a nozzle diameter equal to 5 mm the minimum is reached and then the cost slightly increases with nozzle diameter. In both cases, the economic impact of 3D printing raw materials increases with the nozzle diameter and wall thickness; for the FDM technology, raw material is the main cost contributor as the nozzle diameter is equal to or larger than 2 mm. This is related to the high unitary cost of PLA pellets (8.5 €/kg) that makes the economic impact of raw material more relevant with respect to the other cost items as large amount of material is used. On the other hand, geopolymer used in the MJ technology is much cheaper (0.07 €/kg), and its contribution to the total cost is almost negligible also for larger nozzle diameters.

The impact of electric energy in LCC analysis is not as relevant as in the LCA one due to the relatively low unitary cost. Cost of electric energy

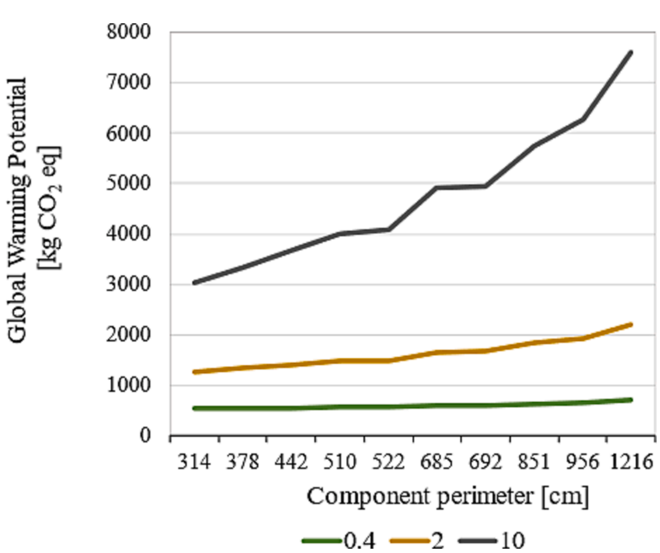

Fig. 8. GWP as a function of component perimeter and nozzle diameter.

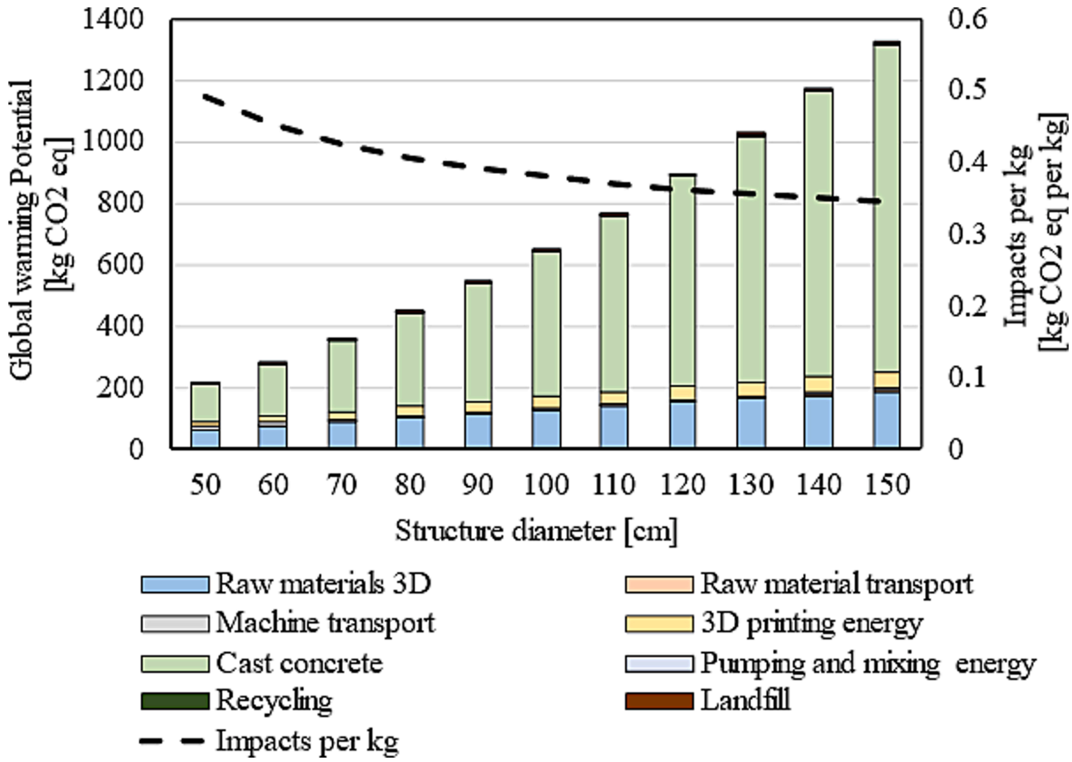

Fig. 9. GWP vs Structure diameter, FDM, ABS, 0.8 mm.

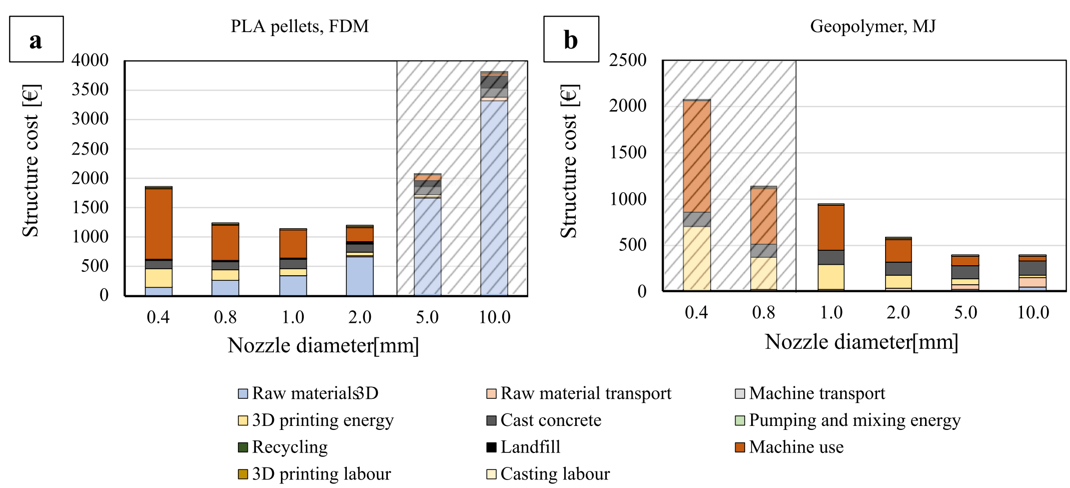

Fig. 10. Cost assessment results vs nozzle diameter for structures realized with the. FDM technology and PLA feedstock (a) and the MJ technology and geopolymer feedstock (b).

is higher for small nozzle diameter due to longer printing time which leads to higher electric energy consumption. A further significant contributor is represented by the machine depreciation cost; as for energy consumption, the lower the structure printing time, the lower the cost associated with machine use. Hence, it decreases with increasing nozzle diameter and accounts for up to 65 % with nozzle diameter equal to 0.4 mm, while it is almost negligible for larger diameters.

The trade-off between the cost of machine use and electric energy consumption, which decreases with increasing nozzle diameter, and the cost of 3D printing raw material, which increases with nozzle diameter, allows us to identify the nozzle diameter associated with the lowest cost. Due to the lower cost of feedstock materials used in the MJ technology with respect to those used in the FDM technology, in the former, the lowest cost is obtained at nozzle diameter (5 mm) higher than the latter (1 mm).

Labour time was considered independent of nozzle diameter (i.e. the same set-up time is required). 3D printing labour is an almost negligible cost contributor due to the high degree of process automation. Similarly, concrete casting determines labour costs typically lower than 1 % of total costs.

3.8. *Considerations for Low-Carbon 3D-Printed formworks and traditional solutions*

As shown in Fig. 5 a, b, c, if formworks are produced via FDM, the environmental impacts due to raw material can be reduced by correctly selecting the nozzle diameter which is responsible for wall thickness and raw material use. On the other hand, for formwork produced via MJ

(Fig. 5 d, e, f), wall thickness in the range of to 2–5 mm is the best compromise between 3D printing energy use and raw material impacts. For both cases, 3D printing energy consumption can be reduced by increasing the printing speed. Cast concrete is a relevant impact contributor and its quantity has to be minimised in order to reduce overall impacts. Such result is consistent with previous studies focused on the use of 3D printing technologies for concrete structures. To this purpose, as reported in Liu et al. [44], cast concrete can be responsible for the largest share of 3D printed structure impacts (up to 95 %); Bianchi et al reported that plastic materials used in formwork production can determine up to 60 % of the concrete structure impacts [7]. However, this work also investigated the correlation between design and process choices and structure sustainability, showing how specific results can be obtained and how environmental impacts can be reduced.

In traditional concrete casting processes, the formwork is usually reused several times, resulting in low impact contribution over the total footprint of the concrete structure [44,45,46]. Other phases are independent of the formwork production process (traditional of 3D printing), and lead to the same environmental impacts. The results show that, by properly choosing design and process parameters, manufacturing of 3D printed formwork leads to low environmental impacts with respect to the other production phases of concrete structures, as for the traditional casting processes. Hence, also for simple geometries, 3D printed formworks can match the impacts of conventional solutions. This proves the sustainability of 3D printing in the construction sector also for simple geometries. In addition, 3D-printed thin formworks allow the production of complex structures and customized designs that are difficult to obtain with traditional technologies. In these cases, traditional formworks would be more complex to produce, more expensive and impactful, with impact contribution equal to up to 90 % of the concrete structure [44]; on the other hand, 3D printed formworks can have limited impacts also for complex geometries, leading to a reduction of environmental impacts reduction with respect to traditional alternatives.

For what concerns the LCC analysis, formworks produced via FDM are associated with higher economic impacts mainly due to material cost; on the other hand, the cost of formworks produced via MJ is mainly related to machine use and energy consumption, whilst the material cost is almost negligible. However, with a proper selection of nozzle diameter, FDM technology allows the production of formworks with similar costs to those of the MJ ones. This highlights the need for a proper selection of technology and process parameters to make 3D printing a valuable solution for concrete structure production.

4. Conclusions

The present study investigated the environmental and economic impacts of cast concrete structures produced using 3D-printed formworks. To this end, LCA and LCC methodologies were used. Different technologies (Fused Deposition Modelling and Material Jetting), materials for 3D printing, component geometries, machine kinematic systems and process parameters were investigated to provide an overall picture of the application of 3D printing in the manufacturing of formworks for concrete components. A parametric model was developed by means of the Grasshopper software to provide primary data concerning formworks with different concrete structure geometries. This has enabled the analysis of the contribution of various production phases to the environmental impact of concrete structures and allowed the identification of strategies for reducing these impacts. These strategies involve the selection of the appropriate combination of design choices, technology, materials, and process parameters (e.g. nozzle size and printing speed).

The main results can be summarized as follows:

- Proper selection of formwork material and process parameters is crucial to increase environmental sustainability and reduce carbonization-related impact.
- Viscous materials (concrete, geopolymer and clay) have lower unitary impacts (up to 0.3 kg CO_2 eq) than plastic counterparts (up to 7 kg CO_2 eq); this makes the MJ technology an alternative more sustainable than FDM.
- For formworks manufactured via MJ, a nozzle diameter in the range of 2–5 mm is the best compromise between material and electric energy impacts. Smaller nozzles are associated with a strong increase in energy consumption and environmental impacts.
- For the FDM process, plastic material accounts for the largest part of the impacts; hence, small nozzle diameter in the range of 0.4–1 mm and minimization of material use are sustainable practices. Printing energy is not as relevant as raw materials in terms of environmental impacts; hence, to minimize the concrete structures impacts, thin formwork walls are recommended.
- The increase in the printing speed can reduce energy consumption. The cartesian kinematic system showed energy use lower than half of those of delta and robotic arm alternatives.
- The reuse of formwork, as an alternative approach to the use of sacrificial formwork or to disposing them to landfill, can strongly contribute to environmental improvements. Similar advantages are obtained if plastic recycling is considered.
- The increase in the component complexity, in terms of a higher perimeter-area ratio, leads to higher environmental impacts related to formwork production due to higher material use and energy consumption.
- From an economic perspective, material can be a relevant contributor that increases with component complexity and nozzle diameter. Its contribution is much higher for FDM technology with respect to the MJ one due to higher unitary plastic material cost. Machine use accounts for up to 65 % of the total costs; printing time minimization strategies are required to reduce printed component costs (e.g. via optimal selection of printing parameters).

This study could have a significant industrial impact as it provides sustainability and cost models applicable in the construction sector as decision-making tools. It can be employed as a guideline for sustainable practices in the production of concrete structures since it allows to selection of process parameters and design alternatives for environmental impact reduction.

On the other hand, from a scientific perspective, it provides an overview of the environmental and economic sustainability of 3D printed formworks. These results have the potential to guide future studies and developments in the construction sector towards the use of 3D printing in the manufacturing of complex-shaped formworks that cannot be obtained via conventional techniques to achieve more sustainable and efficient production.

CRediT authorship contribution statement

Valentino Sangiorgio: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Iacopo Bianchi:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Archimede Forcellese:** Writing – review & editing, Validation, Supervision, Methodology, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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