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Review Article

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Publication date:
2024-09

Permanent link:
https://doi.org/10.3929/ethz-b-000679851

Originally published in:
Automation in Construction 165, https://doi.org/10.1016/j.autcon.2024.105545

Funding acknowledgement:
ETH-01 20-2 - Impact Printed Structures (ETHZ)

Automation in Construction 165 (2024) 105545

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Review

Contribution of production processes in environmental impact of low carbon materials made by additive manufacturing

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A R T I C L E I N F O

Keywords:
Life cycle assessment (LCA)
Robotic fabrication
Earth construction
3D printing (3DP)
Environmental impact

A B S T R A C T

This paper compares conventional earth construction with innovative additive techniques. The goal is to assess the sustainability of employing digital fabrication in earth construction, with a particular emphasis on analyzing the Global Warming Potential. The research also investigates how printing speed and resolution impact environmental outcomes. Using a Cradle-to-Gate Life Cycle Assessment model, the analysis reveals that integrating digital fabrication leads to an overall increase in environmental impact across all cases studied. The environmental impact of $1m^3$ of digitally fabricated earth-based material is nearly double that of conventional earth techniques, ranging from 65 to 20 $kgCO_2eq/m^3$ compared to 20–40 $kgCO_2eq/m^3$. This emphasizes the urgent need to reduce material usage in digitally fabricated structures. Higher system resolution leads to increased environmental impacts and may require the same construction time as conventional methods. These findings underscore the importance of carefully weighing the trade-offs between the benefits of digital fabrication and its potential environmental drawbacks.

1. Introduction

The modern era has been built upon what is commonly known as a “growth model”, where one of the most important pillars is productivity. The relentless pursuit of process optimization in response to the imminent explosive growth of the population has also reached the construction sector, responsible for almost 40% of the annual anthropogenic greenhouse gases (GHG) [1].

In the current context, the exponential progress of digital fabrication technologies, specifically additive manufacturing and its layer-by-layer process known as 3D printing, has revolutionized the manufacturing industry and has been primarily fueled by the pressing need for higher productivity [2] and the remarkable potential for mass customization [3]. Moreover, these innovative technologies offer significant cost-saving benefits by optimizing material utilization, reducing waste, and streamlining the construction process [4]. Unlike traditional methods that rely on single formwork, additive manufacturing could provide greater flexibility in terms of construction design [5].

Furthermore, as emphasized in the research conducted by Helbing et al. [6] on growth, innovation, scaling, and the pace of life in cities, the integration of new technologies has emerged as a vital solution to overcome stagnation within post-modern society. In the face of increasingly intricate urban environments, it becomes imperative to introduce innovative approaches that drive societal progress. By embracing additive manufacturing, cities can unlock its transformative potential, resulting in significant enhancements in architectural design and construction methods, all while avoiding additional costs. This pioneering approach not only expands the realm of possibilities but also streamlines processes, ultimately enabling cost savings within the construction industry.

Among the various techniques encompassing digital fabrication, it is undeniable that 3D concrete printing has stood out prominently. Its historical evolution can be traced back to the construction of the first large-scale prototypes in 2014 at the University of Southern California (USC) in the Center for Rapid Automated Fabrication Technologies (CRAFT). Subsequently, in 2015, WinSun, Chinese company specialized in 3D printing with concrete, achieved a groundbreaking milestone by using this technology to construct the world’s tallest 3D-printed building

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https://doi.org/10.1016/j.autcon.2024.105545
Received 19 September 2023; Received in revised form 7 June 2024; Accepted 7 June 2024

with five stories [7]. Notable recent cases include the opening of the world's first 3D-printed bridge for cyclists in the Netherlands in 2017 [8]. Additionally, in 2023, construction began on the largest community of a hundred 3D-printed homes in Texas, USA, led by the collaboration of Lennar and ICON, pioneers in large-scale 3D printing [9].

The growing interest in 3D printing within the construction sector, evident by the emergence of numerous startups and established companies dedicating specialized divisions to this technology, is also reflected in the scientific community. A large number of papers have been published with the objective of analyzing and comprehending the various aspects that surround this technology. Researchers are actively investigating and exploring the intricacies of 3D concrete printing, seeking to gain insights into its potential applications [10,11], technical challenges [12–14], material properties [15–17], structural performance [18–20] and sustainability aspects [21–25].

However, digital fabrication using concrete can result in elements that have higher carbon footprints than those used in standard construction [23]. According to a study conducted by Kuzmenko et al. [26], the impact of $1m^3$ of printed concrete is almost twice as large as that of $1m^3$ of cast concrete. This result is attributed to both the higher environmental impact of 3D-printed material compared to conventional material, as well as the more energy-intensive process for depositing the material.

The industry's current strategy and the most compelling argument for validating the use of these technologies lie in the potential to achieve material savings through structural optimization [21,27]. Structural optimization involves analyzing the forces acting on structural elements, identifying where material is truly necessary, and thereby reducing volume while maintaining the same structural function. Therefore, the environmental benefits of utilizing additive manufacturing in construction are realized when significant material savings can be achieved, coupled with a deposition process that is not excessively energy-intensive.

In order to combine digitalization and environmental sustainability, one has seen emerging recent work related with the use of low carbon material for additive manufacturing. This has been illustrated by the use of geopolymer instead of epoxy based resins in binder jetting [28] or the use of low carbon concrete in 3DP [29] and more recently in the use of clay based matrix with robotic fabrication support [30].

In contrast, the exploration of large-scale applications using less carbon-intensive materials has seen more limited progress. When compared to the remarkable growth and widespread adoption of concrete-based 3D printing technologies, the development in this particular domain has not experienced the same level of exponential expansion and broad acceptance. This is due to the inherent complexities associated with earth-based materials, such as their diverse compositions and regional variations, making standardization and scalability more intricate [31]. Consequently, the digitalization of earth-based construction faces obstacles related to both material characteristics and the intricacies of translating traditional building methods into digital workflows. However, the primary emphasis in research has been on exploring the design potential enabled by these emerging technologies, often overlooking advancements in constructability aspects [32].

Regarding large-scale prototypes developed by the industry, the work of Emerging Objects is of particular interest; they have explored the usage of many natural materials such as salt, saw dust, coffee waste or tires rubber and more specifically earthen materials [33]. With the Tecla House by WASP and Mario Cucinella Architects [34], a full-scale structure was built with a custom earth material mix coupled with a digitally-controlled polar-coordinate gantry machine system. The significance of this project was that the material for 3D printing was excavated from the site, paving the way for onsite construction with local materials.

However, the sustainability of using additive manufacturing techniques for construction with low-carbon materials requires further investigation. While many studies have focused on reducing the carbon footprint of the materials themselves, there is a significant gap in considering the embodied emissions associated with the additive manufacturing process. Systematic literature review has shown that such emissions cannot be neglected. Indeed it seems that in conventional techniques, relative contribution of material over the full life cycle is on average equal to 80% and 20% is related with processing, additive manufacturing techniques exhibit the opposite trend [35].

In the current study, the aim is to evaluate the environmental impact of combining additive manufacturing with low-carbon materials, with a particular focus on earth-based materials and on the emissions generated during the manufacturing process. Our objective is to critically analyze the feasibility of this combination and determine the extent of material savings required through complex deposition techniques to offset the additional emissions associated with the process. The resolution aspect of the structures to be printed is also investigated. Traditional vernacular techniques like Cob, considered in this study as a low-resolution process, as well as partially automated techniques such as pre-fabricated rammed earth. However, when it comes to digitally fabricated objects, particular emphasis is placed on 3D printing with earth-based materials. In this context, high resolution is achieved through thinner layers, allowing for significantly more detailed elements. As the amount of material deposited increases, the resolution decreases. Understanding the relationship between resolution and material deposition is crucial for evaluating the trade-offs involved in achieving desired levels of detail in additive manufacturing with low-carbon materials. By comprehensively considering processing-related factors and resolution aspects, the goal is to gain a deeper understanding of the environmental trade-offs involved.

2. Materials and methods

2.1. Materials

2.1.1. Conventional techniques

2.1.1.1. Cob. Hamard et al. [36] proposed four key features to collectively define the distinctive nature of the Cob construction technique; 1) the formation of earth elements in a plastic state, 2) implementation of a wet mixture, 3) construction of monolithic walls, and 4) the ability to create load-bearing or freestanding walls.

The composition of the material used in Cob elements typically consists of a mixture of straw, sand, and clay-rich soil in a ratio of 20%, 40%, and 40% by volume, respectively [37]. Straw provides tensile strength and helps prevent cracking, while sand acts as an aggregate, enhancing stability and workability. The cohesive properties of the clay-rich soil facilitate binding and adhesion within the mixture. This balanced combination of materials contributes to the overall strength of Cob structures. Cob load-bearing walls have thickness ranging from 20 cm to 120 cm [38]. The thickness is based on factors such as expected load, wall height, and wall section. This study focuses on straight Cob walls with a thickness of 60 cm.

In conventional techniques such as cob (Fig. 1 right), manual labor is required for executing all steps, from extracting raw materials to building. However, in environmental analysis, it is common practice to overlook the energy demands and emissions associated with human activity [4,38].

Ben-Alon et al. [39], conducted several studies to assess the environmental impact of structural elements built with cob. The results showed that this vernacular technique presents an impact ranging from 15 to 20 $kgCO_2eq./m^2$. The study evaluated a tapered wall with a base width of 61 cm and a top width of 30.5 cm, which is a commonly used structure in the construction industry.

In terms of construction time, defining this parameter for Cob constructions is extremely complex. This is because it heavily relies on factors such as the quantity of labor involved, the skills and knowledge of the workers, the composition of the mix design used (including the use of hydraulic stabilizers, for example), and so on. Hamard et al. [36] also address this issue in their research, concluding that the estimated time required to construct a Cob wall could range from 2 to 20 weeks, depending on the region's climate. In this study, the time required to construct a volume of $1m^3$ of Cob is assumed around 20 h, solely for the construction process, excluding the waiting time for the final drying period of the building elements.

2.1.1.2. Pre-fabricated rammed Earth. Rammed earth (Fig. 1 left) is considered as a dry vernacular construction method where the water content in the mix design is approximately the same as the optimum Proctor water content. The optimum Proctor refers to a concept used in civil engineering to determine the ideal moisture content of soil during the compaction process. The Proctor test is a technique used to measure the maximum dry density that a soil can achieve at various moisture contents [40]. By conducting the Proctor test, engineers and contractors can determine the moisture content at which the soil achieves its maximum compaction and, as a result, its highest dry density. This process ultimately maximizes the compressive strength of the material applied [41]. According to the literature, the water content in the mix design should never exceed 10% of the total mass [42].

According to Gomaa et al. [43], the production of rammed earth walls typically involves five steps: 1) formwork assembly, 2) material deposition, 3) robotic ramming, 4) demolding, and 5) transportation of completed elements to storage. The duration of this entire process can range from approximately 8 to 12 h per cubic meter [44], and it heavily relies on the expertise and proficiency of the individuals involved. Furthermore, it is worth noting that the thickness of rammed earth walls, on average, is approximately 40 cm.

To assess the life cycle impact of pre-fabricated rammed earth walls, Fernandes et al. [45] conducted a research specifically focused on context of Portugal, revealing a value of 47 $kgCO_2eq./m^3$. However, when considering other databases such as KBOB [46], focuses on the environmental and energy aspects of building materials and construction techniques used in Switzerland, values ranging from 36 to 40 $kgCO_2eq./m^3$ are observed. These variations in LCA results can be attributed to various factors, including divergent construction practices, material sourcing, transportation distances, energy sources, and region-specific considerations.

2.1.2. Digital fabricated techniques

This study explores two branches of digital fabrication techniques: continuous and discrete deposition. In continuous deposition, the printing process proceeds smoothly without any internal breaks to the layering process, creating a seamless and cohesive structure. On the other hand, discrete deposition generates separate extruded blocks resembling individual units that can be assembled independently. Although both techniques involve extrusion processes, the main distinction lies in the continuity of the structure. Continuous deposition forms a seamless object, while discrete deposition results in individual blocks that can be arranged freely.

2.1.2.1. Continuous deposition (CD). In this study, the continuous deposition method is considered to be essentially 3D printing with earth-based materials. Fig. 2 highlights some examples encompassing both scientific projects focused on comprehending the mechanisms of earth-based printing and large-scale projects implementing this technology. In 2018, Perrot et al. [30] published the first scientific paper addressing rheological issues for the processing of earth in 3D printing. In subsequent research, Gomaa et al. [49] delved into the incorporation of fibers into the mix design and the adaptation of the cob mix for digital fabrication. Both studies emphasized the importance of parameters such as yield stress, viscosity, and particle size distribution, as the material undergoes pumping and extrusion processes.

In contrast to 3D printing with concrete, there is a noticeable lack of documented and scientifically proven information regarding the processing of earth in the context of digital fabrication. Perrot's research has significantly contributed to the exploration of an important aspect that the concrete printing sector has been actively pursuing: achieving a delicate equilibrium between buildability capacity and the prevention of cold joint formation. The concept of buildability in 3D printing with concrete extends beyond simply constructing objects or structures; it encompasses the capacity to do so efficiently and effectively. Key factors that influence buildability include the speed of construction, the ability to maintain the integrity of printed layers, and the overall stability of the completed structure. The structural stability of the printed object is of paramount importance, encompassing resistance to deformation, prevention buckling failures during the printing process, and the ability to withstand external loads or stresses upon completion [50]. To achieve the desired buildability, the industry has been employing strategies such as "setting on demand" to control the early strength development of the material [15]. By carefully managing the curing process, the industry aims to strike a balance between rapid construction and maintaining the structural integrity of the printed layers [51]. The formation of cold joints poses a notable obstacle within the 3D printing industry. Cold joints arise when freshly printed layers interface with partially cured or

Fig. 1. Prefabricated Rammed earth wall for Ricola Kräuterzentrum by Herzog & de Meuron with Martin Rauch [47] (left) and an example of a Cob house construction [48] (right).

Fig. 2. Robotic 3DP cob with wheat straw by [54] (left), 3DP earth based material with alginate as a bio-stabilizer by [30] (middle) and Gaia Project (right) first large scale earth printed house [55].

hardened layers. These junctions have the potential to compromise the overall structural integrity of the printed object, resulting in diminished buildability and increased vulnerability to failure under load [52,53].

Considering the case of using earth-based materials instead of printing concrete, a parallel can be drawn. When an earth-mix is in a state close to the liquid limit, the process becomes significantly time-consuming if the mix design do not include any agent to accelerate the early-strength development process. It requires waiting for the earth to dry sufficiently before depositing the next layers. While this approach may potentially reduce the risk of cold joint formation, it can also result in an economically unappealing construction process in terms of construction speed. This contradicts the premise of digital fabrication, which aims to accelerate and automate construction processes. To address these challenges, researchers have explored the incorporation of bio-stabilizers based on alginate, as demonstrated in the work of Perrot et al. [30].

For the mix design, three distinct scenarios characterized by varying compositions: one comprising straw with 2% of the total, another containing 5% hydraulic lime stabilizer, and a third featuring 3% hydraulic lime content (Table 1).

According to the literature, earth-based 3DP is generally slower than concrete-based printing, with speeds ranging from 20 to 50 mm/s [30,38], both scenarios were taken into account in this study. The aforementioned dissimilarities in the set up can be attributed to the different physical and rheological characteristics of earth-based materials [54].

2.1.2.2. Discrete deposition (DD). Initially, there was a widespread belief that structures elements built using additive manufacturing would require a material close to its liquid limit state to prevent machine overload caused by increased friction and to enable pumpability. However, the Clay Rotunda project (Fig. 3), developed by the group Gramazio Kohler Research [56], has revealed an alternate approach based on discrete assembly of a workable material. It demonstrated that earth-based materials could be successfully processed in a stiffer state, exhibiting a considerably higher initial yield stress [57]. In the case of Clay Rotunda, an indoor mobile robot system procedurally placed compressed malleable prefabricated earth-based bricks (Fig. 3-middle).

A second related discrete deposition manufacturing method was developed on a prototypical scale: Ming et al. [58] observed that the cohesive bonding between the soft particles in a discrete deposition scenario could also originate from the conversion of kinetic energy into plastic deformation upon impact. As a result of this discovery, Ming et al. developed a pneumatic end-effector to "shoot" 2.2 g parts leading to the formation of bonded structures on a prototypical scale, and introduced the term "Impact Printing" to describe the process (Fig. 4- left and center). The scalability of this prototypical process was investigated in a further research step. A custom end-effector and robotic printing cell were adapted to deposit a greater amount of material per unit time in order to create full-scale structures (Fig. 4-right). This method involves high-velocity deposition of discrete 0.75 kg earth-based elements with a high yield stress (>26 kPa).

This deposition method does not include a pumping step, and allows for the processing of larger grains, including gravels, up to 4-6 mm. The addition of larger grains to the matrix of the earth mix design holds the potential to effectively mitigate shrinkage and crack formation. When incorporated into the material composition, these larger grains act as reinforcements within the matrix, imparting enhanced stability and strength to the final structure [59,60].

The yield stress of a material is directly associated with its resistance to flow. A higher yield stress suggests a greater ability to prevent elastic buckling in 3D printed elements. The hypothesis put forth is that by depositing the material at a higher yield stress such that the material exhibits a solid-like behavior, one could reduce the percentage of hydraulic stabilizers in the mix design necessary for green strength development.

To assess the environmental impact of a robot, a calculation can be performed by considering the mass of the robot and its components, determining the embodied carbon footprint associated with these components, and subsequently dividing it by the robot's lifespan. This approach provides an estimation of the environmental burden attributed to the manufacturing and use of robots in the construction sector. This calculation results in a value expressed in $kgCO_2eq./h$. For this model, the values of a high-payload 6-axis industrial robot ABB IRB 8700 were adopted, as in the study conducted by Kusmenko and Baverel [64].

The resulting value for the environmental impact of this robot's lifespan is estimated to be around 2.2 $kgCO_2eq/h$. Obtaining accurate energy consumption data is often challenging, but one can find some valuable estimations in literature. Kuzmenko [65] also provided a valuable estimation for the power consumption of all the individual process involved in the 3DP process with concrete. Therefore, this study is based on prior research conducted by Kuzmenko, and additional calculation details can be found in the supplementary information file.

Finally, within the context of our study, multiple scenarios have been considered, each employing different mix designs for the construction process. Table 1 contains all the essential details regarding the mix designs components and their proportions.

Table 1
Mass composition of each material for each scenario analyzed in the LCA model.

Earth Construction Technique		Composition (mass, %)				
		Clay rich soil	Water	Straw	Sand/ Gravels	Stabilizer
Conventional	Rammed earth	72.0	8.0	–	20.0	
	Cob	78.0	20.0	2.0	–	
Digital	Continuous	73.0	25.0	2.0	–	
		68.0	25.0	2.0	–	5.0
		67.0	30.0	–	–	3.0
	Discrete	63.06	24.18	–	10.12	2.64

Fig. 3. Scheme illustrating the operation of the discrete deposition method (adapted from [58]) (left) employed in the construction of the Clay Rotunda by Gramazio Kohler Research, in collaboration [56] (middle and right).

Fig. 4. (left) Visual representation of the high-speed discrete deposition method (adapted from [58]). The process convert kinetic energy into plastic deformation, enhancing adhesion between individual blocks (middle) [58]. The process was upscaled from the prototypical scale, enabling the production of large-scale prototypes fabricated at ETH, Zürich [61–63].

2.2. Methods

2.2.1. Study goal and system boundaries

The purpose of this paper is to conduct a comparative analysis of the environmental impact associated with a diverse set of construction methods that range from traditional to innovative digital techniques using Life Cycle Assessment (LCA). The conventional techniques selected comprise cob and pre-fabricated rammed earth, while digital fabrication techniques will be primarily centered on 3DP layer-by-layer process employing earth as the principal construction material. The purpose of the study is to investigate the Global Warming Potential (GWP) of these construction techniques. GWP is widely recognized as one of the most significant impact categories contributing to current global environmental concerns [66]. This focus aligns with the recommendations outlined in the Product Environmental Footprint Category Rules Guidance (PEFCR Guidance) [66]. Additionally, the study is confined to the context of Switzerland, and the findings may not be universally applicable due to regional variations in energy and material resources.

The system boundaries encompass environmental impacts from Cradle-to-gate, including raw material extraction and transport, building material production, and construction methods, with two options: robotic fabricated or conventional one (EN 15804 modules: A1-A3, A5, Fig. 5). The use phase and demolishing phase are not included in this study. In scenarios involving manufacturing with the assistance of

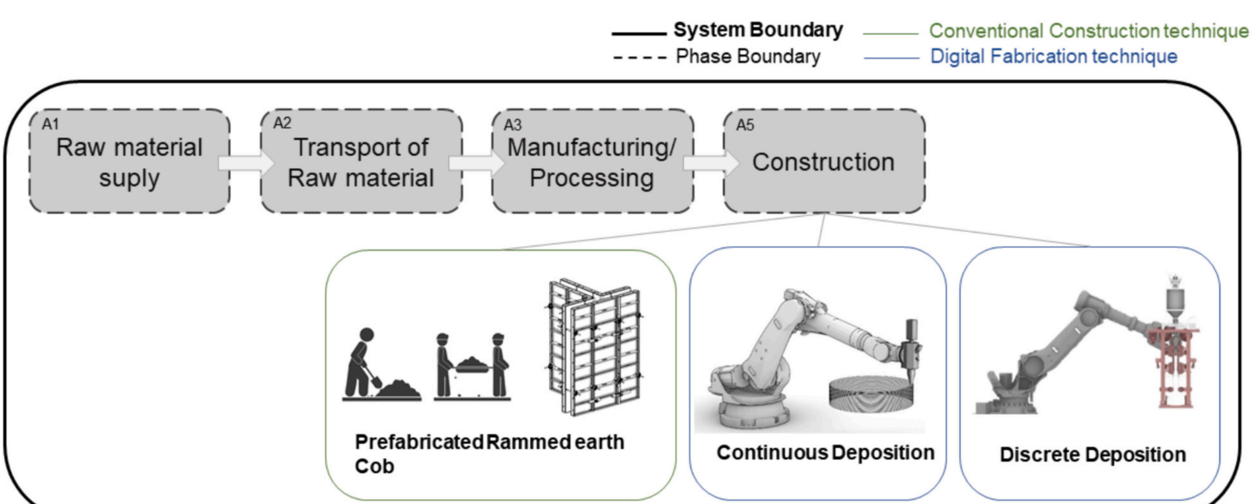

Fig. 5. Flowchart of the Life-Cycle Model with system boundaries and the different phase boundaries (Cradle-to-Gate).

robots, embodied emissions were also taken into account using the same principle and system boundary. The analysis primarily focuses on the construction phase of the life-cycle, and therefore, does not take into account the end-of-life scenario. SimaPro 9.5 software [67] was used to implement the LCA method together with Ecoinvent v3.9.1 Cut-off database [68]. The impact assessment method was IPCC 2013 GWP 100a V1.03, which assesses a single impact category, the GWP100a (kg CO_2 eq.).

2.2.2. Resolution of the system

In this study, "resolution" refers to the cross section of material that can be deposited based on the nozzle size of the printing head. Higher resolution implies thinner layers, resulting in more detailed and aesthetically homogeneous elements. Following this logic, traditional vernacular constructions like cob could be considered as having very low resolution. Kuzmenko et al. [26] has already studied the effect of resolution on 3D-printed concrete structures. The conclusion drawn was that there is a correlation between resolution and printing time. When robotic speeds along the printing path are similar, higher resolution implies a longer printing path and consequently, also requires a longer time for printing, which leads to increased energy consumption and a higher embodied impact of machinery usage. Fig. 6 provides a simplified visual representation of structures with high, medium, and low resolutions. This study followed a systematic approach that defined a correlation between the nozzle size and the resolution (Table 2). The deformation occurring during the printing process of the material was not taken into account, which could potentially influence the final height of the printed object [69].

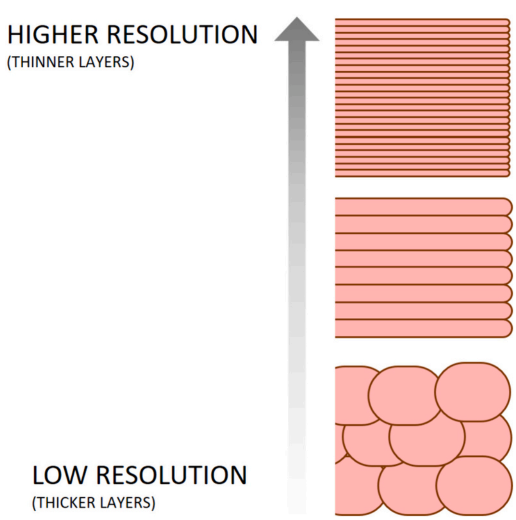

Fig. 6. Simplified schematic illustrating the concept of resolution, where resolution increases as the layers become thinner.

Table 2
Resolution classification, nozzle sizes, and printing speed for each method.

Method	Printing Parameters		
	Resolution	Noozle size (cm)	Speed (cm/s)
Discrete	Low	10	
Continuous	Medium	3.5–4.5	2–5
	High	1.5–3	2–5

2.2.3. Measuring printing-path complexity

The standard wall thicknesses of cob and rammed earth constructions are well-documented and have been extensively studied in previous research [36]. However, when it comes to 3D-printed structures, determining the optimum value of wall thickness is less straightforward due to the greater flexibility in design, allowing for unique and complex geometries that may not have a clear-cut optimal wall thickness. Gomaa et al. [70] conducted a study aiming to optimize 3D-printed cob structures for a two-story building, with the goal of determining the minimum material and optimized printing path required to achieve equivalent functionality as other construction earth construction techniques. Gomaa's study concluded that 3D-printed cob structures with specific inner gaps could maintain the same structural functionality while reducing the material volume.

However, the design freedom provided by innovative construction methods like 3D printing allows for the exploration of a multitude of shapes and forms, enabling a level of mass customization never seen before in the construction sector [71]. While there is already substantial research addressing this topic in concrete 3D printing [72], further investigations need to be conducted regarding additive manufacturing with earth-based materials to establish some boundaries. It is obvious that a load-bearing wall with a larger volume will have higher structural strength per unit area compared to a wall with a smaller volume. Nevertheless, the specific structural requirements dictate how the design of the wall section is adapted. This means that different specifications for the wall section may be necessary based on the unique demands and context, even though the primary structural function remains consistent, such as providing load-bearing support.

Therefore, one can observe a diverse range of printing paths in the most recent large-scale projects, each exhibiting distinct levels of "complexity" in their implementation (Fig. 7). The challenge in classifying a system as complex stems from the absence of a clear definition for complexity, particularly regarding how to measure it. Clark and Jacques [73] propose an energetic definition for classifying complexity and complex systems. A common observation is that complex systems typically process more energy than less complex ones. When trying to establish a correlation with this definition, two factors appear to be closely linked in practice: the size of the printing path and the energy expended to print it. Thus, extrapolating the complexity definition to distinguish what is more complex and what is less complex in terms of printing paths, the amount of material deposited per square meter can also be considered. A practical example would be comparing a completely straight wall to a wall with wavy patterns: the straight wall would be classified as less complex than the wavy wall. However, it is essential not to overlook that the curvature distributes external loads more effectively, reducing localized stress points and improving overall structural performance, which could make the more complex system perform better on some level.

Thus, a sensitivity test of the system concerning the indiscriminate increase of material volume per square meter should be carefully examined, and the evaluated scenarios are summarized in the Table 3.

2.2.4. Model of environmental impact

Various environmental impacts are calculated separately in our study. Firstly, the environmental impact of the material (I_{mat}) for both conventional and 3DP technologies were calculated. This impact is expressed per cubic meter of material used. Additionally, the environmental impact of depositing one cubic meter of material is analyzed (I_{proc}) for both conventional and digital construction technologies. Therefore, for the initial comparisons, the selected functional unit is kilograms of CO_2 equivalent per cubic meter (kg CO_2 eq./m^3).

Fig. 7. Different large-scale projects for two-story houses have adopted significantly different geometry and shapes of printing paths. On the left, Gaia Project by Wasp [55], Tova project by IAAC [74] (middle) and the Tecla House (right) [34].

Table 3
Volume per square meter for each load-bearing wall considered in this study, along with the corresponding construction technique.

Earth Construction Technique		Resolution	Area m^2	Complexity - Volume m^3
Conventional	Cob	Very low	1	0.60
	Prefabricated Rammed earth	Very low	1	0.40
Digital	Discrete deposition	Low	1	0.31–0.55
	Continuous deposition	Medium	1	0.31–0.55
		High	1	0.31–0.55

Next, the environmental impact of one building element is analyzed, which is a section of an external load-bearing wall in a two-storey house. To calculate this impact, the following relation was used:

$$\left(I_{mat} + I_{proc}\right) \text{ x Vol}$$

where I_{mat} and I_{proc} are the environmental impacts of the material and the process, respectively, and Vol represents the corresponding volume of material occupied in the section. As previously mentioned (Section 2.3), the value of I_{proc} is directly influenced by the chosen resolution level for the structural elements, whereas Vol is impacted by the complexity of the printing path.

The results are then expressed as the volume saving needed (Vol^{DF} / Vol^{Conv}), which is dependent on the digital fabrication (DF) process intensity and the environmental material ratio ($I^{DF}_{mat}/I^{Conv}_{mat}$).

In summary, our study analyzes the environmental impacts of different production methods for building elements, specifically comparing conventional and digital fabrication technologies. By breaking down the environmental impacts into different components allows for a better understand the benefits and drawbacks of each method.

3. Results

3.1. Environmental impact of material

In the initial phase of this study, our main objective was to analyze the environmental impact of the material mix design employed in three construction methods: prefabricated rammed earth, cob, and digital fabrication techniques (Continuous and Discrete deposition). Fig. 8 provides an overview of the initial comparisons, and, consistent with existing literature, our findings reinforce that materials used in conventional construction techniques generally exhibit a lower environmental impact compared to those used in digital fabrication.

The results indicate that stabilizing the mixture with a hydraulic binder can significantly increase the environmental impact of the elements, which is also consistent with the literature for stabilizing mixtures in conventional techniques [75]. Moreover, the environmental impact model is highly sensitive to changes in the stabilizer percentage. For materials applied in continuous deposition techniques, the values were significantly higher, suggesting that stabilizing at 5% of the dry mass might lead to an increase of up to 18% in the total impact when compared to scenarios with low stabilization percentages. These findings reveal the potential for optimizing the mix composition and refining the environmental performance of 3D-printed earth-based materials.

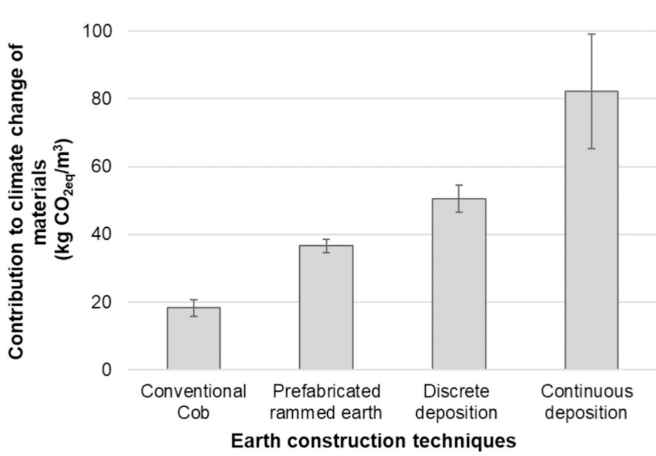

Fig. 8. Environmental embodied impact assessment of earth-based materials using different techniques.

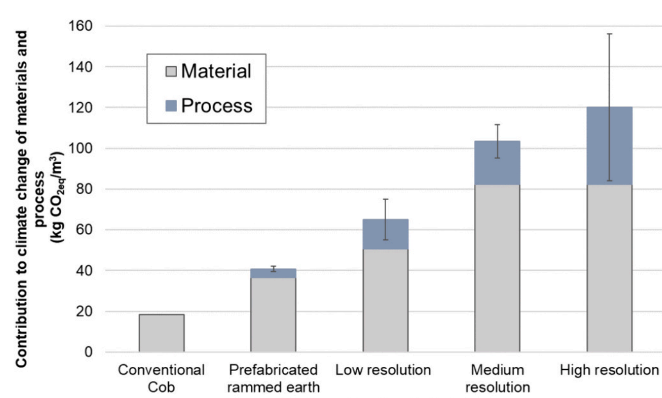

Fig. 9. Environmental impact assessment of earth constructions using four different techniques: Conventional ones - Prefabricated rammed earth and cob – and Digital fabricated ones – Low, medium and high resolution.

3.2. Contribution of deposition process

After evaluating the environmental impact of materials in both conventional and digital fabrication construction contexts, it is crucial to assess the contribution of the construction process itself to the overall environmental footprint. Fig. 9 summarizes the final impact per cubic meter.

In the scenarios of digital construction processes, an analysis was conducted to determine whether the deposition was performed continuously (CD) or discretely (DD). The system resolution was also varied, as shown in Table 2 of Section 2.2.2. Low resolution was associated with discrete deposition, while medium to high resolution was associated with the continuous deposition method.

As noted in the literature on digital fabrication with concrete, adopting these novel construction methods results in a notable escalation of the embodied impact of the materials used as well as an overall impact on the process itself. The same trend can be observed for the scenarios analyzed in this study, using low-carbon earth-based materials. The adoption of these new construction methods also leads to an increase in the embodied impact of the materials and the overall impact of the process. This increase can be linked to the criteria of construction speed imposed by this technology, transitioning from manual processes to energy-consuming methods for achieving the same outcome. As a result, the findings from the field of 3D concrete printing, which emphasize the importance of saving material through structural optimization to reduce additional environmental impact, are equally applicable when using low-carbon materials such as earth.

3.3. Material saving needed

Considering the average impact of the process for each digital fabrication technique (CC and DC), one can relatively easily infer the material saving required to achieve the same low values of environmental impact as the conventional techniques. Digital earth construction was compared with prefabricated rammed earth as such processes have the same economic viability considering time and cost of construction. To interpret the graph of Fig. 10, it is essential to grasp the information conveyed along the X-axis and Y-axis. The X-axis represents the material impact ratio, what means the incremental CO_2 emissions resulting from the use of a specific material in comparison to conventional materials. The Y-axis represents the material volume ratio, and it quantifies the amount of material that needs to be saved or reduced in order to mitigate the extra carbon emissions associated with the compared material and a more carbon-intensive one. The objective is to be able to compare strategies used for conventional earth construction with those used for materials with higher environmental impact.

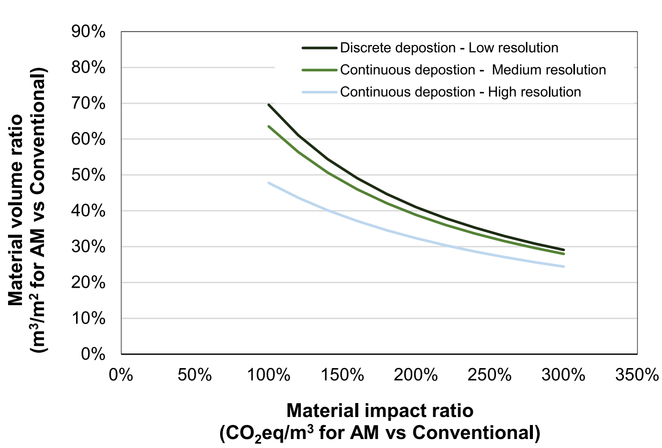

Fig. 10. Synthesis of the material saving requirement depending on additional impact of material and intensity of the process.

The results reveal a significant trend, indicating that higher resolution corresponds to reduced material usage needed to offset the additional impact. Consequently, printed elements must rely more heavily on structural optimization strategies to achieve a balance in the process. For the low resolution scenarios, 50% reduction is also compatible with lower environmental footprint due to both low carbon footprint of the material and low intensity of the deposition process. However, for medium and high resolution, it seems that higher reduction would be needed. Achieving a 60 to 70% reduction would entail depositing walls that are 12 to 15 cm thick, in contrast to the conventional 40 cm walls of rammed earth. Our literature survey do not evidence such cases and rather stay to a 50% material saving for earth 3DP [38].

3.4. Environmental impact x construction efficiency

Previously, in a historical review of the development of digital fabrication techniques, one could observed that the initial goal was not to address environmental issues but rather on enhancing productivity and process efficiency in the construction sector. However, as the field progressed, an increasing realization emerged regarding the potential environmental implications of these techniques.

Therefore, it is interesting to evaluate the economic competitiveness in terms of construction speed of these emerging technologies. The construction time considered in this analysis is the time during which the robotic systems (both for continuous and discrete deposition) are actively producing and does not include any downtime or eventual interruptions.

Fig. 11 summarize the results of an initial analysis that compared conventional construction techniques with innovative digital fabrication technologies. When considering scenarios involving digital fabrication processes, several parameters can affect construction time and, consequently, the final environmental impact of the printed elements. As demonstrated in Sections 2.2.2 and 2.2.3, the resolution and the complexity of the printing path used are two important parameters. Therefore, the nozzle size and the volume variations presented in Table 2 and Table 3, respectively, were applied in order to visualize the trend of the two evaluated parameters on the graph and establish some guidelines.

Although the final GWP increased in all the scenarios analyzed in this study, it is important to note that using low and medium resolutions significantly improved efficiency in terms of construction-time when compared to prefabricated rammed earth and cob techniques. This supports the idea of increased productivity, a cornerstone that aligns seamlessly with one of the fundamental premises of digital fabrication. However, it is also worth noting that using higher resolutions resulted in a substantial increase in the construction time, which makes them almost less efficient than conventional construction techniques. Additionally, it is important to highlight that these high-resolution scenarios did not necessarily result in a significant reduction in GWP. This indicates a crucial trade-off between construction efficiency and environmental impact.

4. Discussion

The presented study has provided valuable insights into the environmental impact and productivity aspects of digital fabrication with earth-based materials. However, several unanswered questions for further investigation warrant attention.

For example, the use of even lower carbon materials, such earth-based with alternative stabilizers, less carbon intensive. Delving into the investigation of incorporating bio additives or other sustainable materials into 3D printing holds the potential to notably mitigate the environmental impact, as the environmental impact of materials themselves represents the largest emissions in all scenarios, whether for conventional or digital fabrication techniques. Cicek et al. and Martins et al. [76,77] explored the feasibility of using a more sustainable binder

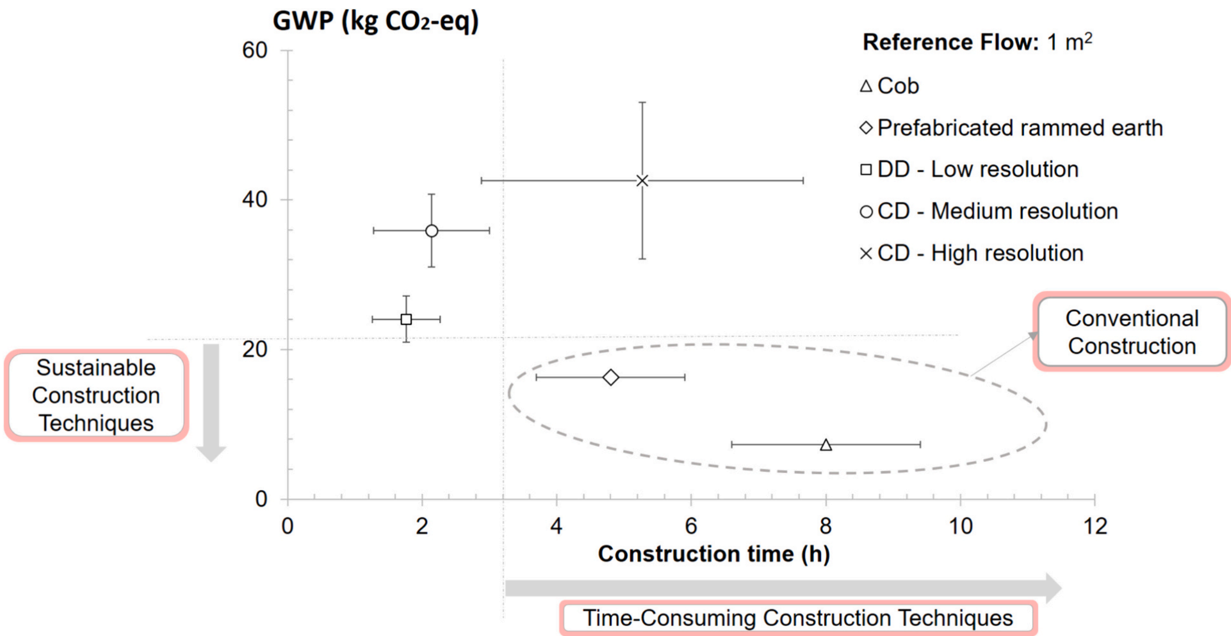

Fig. 11. Relationship between construction time of a reference flow of 1m^2, representing a load-bearing wall of a two-story. For the digital fabrication scenarios (CD and DD), the resolution of the printed and the complexity of the printing path was varied.

for earth stabilization, opening up a range of possibilities on how to control the early strength also offer a promising prospects for application in the realm of digital fabrication. Furthermore, hydraulic binders with a low amount of cement and a high proportion of Supplementary Cementitious Materials (SCM) indicated to be a possible sustainable alternative as well, when kept at low percentages [78]. Nevertheless, it is essential to acknowledge that this approach may not directly address the environmental implications inherent in the printing process itself or have a direct influence on overall productivity.

Another important consideration is whether the mass savings achieved with 3D printing for earth materials are truly advantageous. While it allows for mass reduction, it is crucial to evaluate the implications in terms of building physics and indoor comfort [49,79]. Buildings often require adequate mass for proper thermal regulation and comfort and exploring the trade-off between mass savings and building physics is worth investigating. While 3D printing with earth materials may reduce the required mass, alternative materials may need to be incorporated to ensure optimal building performance. Striking the right balance is pivotal to achieving both environmental sustainability and indoor comfort.

Ultimately, the question arises regarding the primary objective: saving mass for earth materials or focusing on improving productivity while minimizing environmental impact. This dilemma emphasizes the need for a comprehensive and holistic approach that considers various factors such as material choices, construction techniques, building physics, and overall sustainability goals.

Regarding the impact calculation for continuous deposition, a constant energy consumption of 1.5 kW was assumed (as detailed in the Supplementary Information), for the mixing and pumping unit, acting at a flow rate of 2.2 l per min, given by the study Kuzmenko et al. [26]. A mixing and pumping unit delivering material at a higher flow rate would have a higher energy consumption. Data given by Wangler et al. [80] shows that flow rates for commercially available concrete 3D printing systems can achieve a flowrates between 5 and 16 l per minute. Furthermore, previous work has been done to characterize the LCA of 3dP earth materials, unfortunately none of them looked at environmental impact of production process [81].

5. Conclusion

This paper compared the environmental impact of conventional rammed earth and cob techniques with digital fabrication techniques using earth-based materials. The results show that careful consideration of the mix design is required. Indeed, the contribution of the material processing increase the embodied emission and make the final impact of the building element higher. In terms of the Environmental Impact related to materials, an increase of up to threefold was observed when considering conventional earth-based constructions. Overall, this accounts for 77% of the total impact for low-resolution processes, 79% for medium-resolution processes, and 68% for high-resolution processes. This leads us to another conclusion: the higher the resolution of the process, the more significant the environmental impact related to the deposition process becomes.

This higher impact can be compensated by a smart design allowing material reduction. In terms of material savings to mitigate the impact of digitally constructed building elements through structural optimization, let us consider a scenario where the material itself is no longer a significant factor in any case, especially for a high-resolution system. In this case, a reduction of nearly 53% in the volume of elements (such as a straight wall) would be required. Conversely, for a low-resolution system, the reduction needed would be only about 31%. So far, projects seem to show saving with digitalization hardly higher than 50% which can be sufficient for high impact materials such as concrete but which is not sufficient for low carbon materials.

Upon thorough analysis of construction durations, it is evident that only the less intensive digital manufacturing processes (low and medium resolution) showed an acceleration in construction productivity, whereas the high-resolution process seems to display comparable total construction times to conventional methods.

Nevertheless, there are aspects that require further investigation in future research. For instance, further examination of the power consumption of various material delivery and pumping systems, and the relationship between the material flow rate and the power consumption. Additionally, as previously stated, the study is limited to the context of Switzerland, suggesting that the findings might not be universally applicable due to regional differences in energy and material resources. Moreover, within the presented discrete deposition setup, there is currently no material delivery system moving the material between a mixing unit and the hopper container, as this step is done manually. Hence, increasing the automation level of this system would also increase the energy consumption per unit of time.

In conclusion, our findings suggest that the resolution level used in the techniques is the most influential factor on the LCA model, affecting both construction time and the final impact of the printed elements. Techniques that use excessively high resolution, such as thin-layer 3D printing, result in a disproportionate environmental impact without necessarily offering an economic advantage in terms of construction time.

Funding

This work was funded by the ETH Grant ETH-01 20-2: “Impact Printed Structures”.

CRediT authorship contribution statement

Julie Assunção: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Kunaljit Chadha:** Data curation, Resources, Visualization. **Lauren Vasey:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Coralie Brumaud:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Edwin Zea Escamilla:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Fabio Gramazio:** Supervision, Funding acquisition. **Matthias Kohler:** Supervision, Funding acquisition. **Guillaume Habert:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.autcon.2024.105545.

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