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CAN DIGITAL FABRICATION MEET LOW-CARBON MATERIALS? A CLOSER LOOK AT THE ENVIRONMENTAL IMPACT OF 3D PRINTING WITH EARTH

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ABSTRACT

This paper compares conventional earth construction techniques (rammed earth and cob) with additive manufacturing techniques, specifically 3D printing (3DP) with earth. The goal is to analyze the degree to which using 3DP to build with earth is still considered "sustainable," based on the analysis of global warming potential (GWP), and how parameters such as printing resolution and stabilizer content in the mix can influence these impacts. The method used to conduct the analysis was based on a Life cycle assessment (LCA) model Cradle-to-Gate. Additionally, a case study is presented in which a custom deposition tool/end effector is integrated with an extrusion system, which allows a frequent high velocity deposition of extruded discrete earth elements. This technique is called Impact Printing and is still in the early stages of development, but first results show it could allow a more efficient deposition of material per time with lower process intensive energy, and could enable the use of less stabilizers than classic 3DP technology. Overall, this paper highlights the risks of combining digitalization with low-carbon materials, such as earth, and the need for further investigation and optimization of additive manufacturing techniques for sustainable construction practices.

KEYWORDS

Life cycle assessment (LCA); Robotic Fabrication; Earth Construction; 3D Printing (3DP); Environmental impact.

INTRODUCTION

The modern era was built based on what we call 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) (Global Alliance for Buildings and Construction, 2021). In this context, the emergence of additive manufacturing technologies, such as 3DP, has been mainly driven by the need of higher productivity, as well as the potential for mass customization in architecture (Besklubova et al., 2023; García de Soto et al., 2018).

However, digital fabrication using concrete can result in elements that have higher carbon footprints than those used in standard construction (Flatt and Wangler, 2022). According to a study conducted by Kuzmenko et al., 2020, the impact of 1m^3 of printed concrete is almost twice as large as that of 1m^3 of cast concrete. Such result is due to both the fact that the 3D printed material has a much higher impact than conventional one and second that the process for depositing the material is more energy intensive. Therefore environmental benefits of using additive manufacturing in construction occurs when significant material savings can be done and when deposition process is not too energy intensive (De Schutter et al., 2018).

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 (Voney et al., 2021) or the use of low carbon concrete in 3DP (Bos-caro et al., 2022) and more recently in the use of clay based matrix (earth) with robotic fabrication (Perrot et al., 2018a). However, most studies focus on carbon footprint reduction of the material and rarely consider the embodied emissions linked with the process. Systematic literature review has shown that such emissions can not 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, while for additive manufacturing technique, we observe the opposite (Saade et al., 2020).

In the current study, we want to include processing in environmental impact calculation and question the very idea of combining additive manufacturing with low carbon material considering that the embodied emission related with the process will control the final impact. Our question is to be able to understand how much material saving has to be achieved through complex deposition thanks to additive manufacturing in order to compensate for the additional emission related with the process itself. We will limit our study to 3dP with earth and with cement based concrete. Some of these methods include automated extrusion (Perrot et al., 2018b), robotic rammed earth (Gomaa et al., 2023), and also some digital inspiration from the cob technique (Gramazio Kohler Research, 2021), which hold promise for advancing the field of earthen digital fabrication.

MATERIALS AND METHODS

Study Goal and Scope

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. The conventional techniques selected comprise rammed earth and cob, while digital fabrication techniques will be primarily centered on 3DP employing earth as the principal construction material.

The study's scope is focused on the carbon footprint of the aforementioned construction techniques and does not take into account other environmental aspects, such as waste generation. Additionally, the study is con-fined to the context of Switzerland, and the findings may not be universally applicable due to regional variations in energy and material resources. Variations in 3DP with earth-based materials were explored and several factors being varied, such as mix design proportions, presence of stabilizers and printing resolution. The printing resolution is directly related to the amount of energy required to print $1m^2$ standard wall. According to the literature, earth-based 3DP is generally slower than concrete-based printing, with speeds ranging from 20-50mm/s (Perrot et al., 2018; Alhumayani et al., 2020) and the layer thickness can vary from 0.01 to 0.04m. The aforementioned dissimilarities in the set up can be attributed to the different physical and rheological characteristics of earth and concrete (Gomaa et al., 2021). Finally, a case study was conducted in which a custom end-effector and robotic printing cell was modified to deposit a greater amount of material per time than that of a contour crafting method. This method implements high velocity (~8-10 m/s) deposition of discrete elements at a high yield stress (~26-29 kPa). This new technology will be referred to as Impact Printing (IP) in this study.

System boundaries

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, Figure 1). For scenarios that include manufacturing with the aid of robots, embodied emissions were also considered based on the same principle, with the same 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. We used SimaPro 9.5 software to implement the LCA method together with Ecoin-vent v3.9.1 Cut-off database (Ecoinvent, 2022). The impact assessment method was IPCC 2013 GWP 100a V1.03, which assesses a single impact category, the GWP (kg CO^2 eq.).

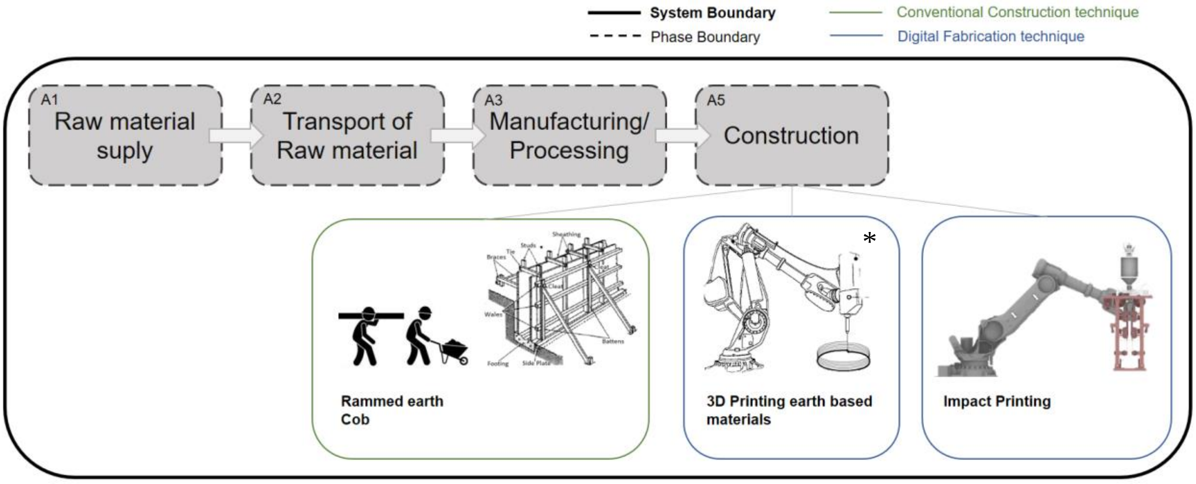

Figure 1 - System boundaries considered for the life cycle assessment (*fig. from Kuzmenko, 2021)

Model of environmental impact

Various environmental impact are calculated separately. We first calculate the environmental impact of material (I_{mat}) for both conventional and 3DP technologies. This impact is expressed per cubic meter. We also calculate the environmental impact of depositing one cubic meter of material (I_{proc}) for both conventional and 3DP. This leads us to the environmental impact of one building element, usually a m^2 wall expressed as ($I_{mat}^{3dp} + I_{proc}^{3dp}$)* Vol^{3dP} and this has to be compared with the production of the same element through conventional technique. The results can then be expressed in a volume saving needed (Vol^{3dP}/Vol^{Conv}) depending on the 3DP process intensity and the environmental material ratio ($I_{mat}^{3dp}/I_{mat}^{conv}$).

As environmental impact of process is highly depending on the speed and resolution, we have taken extreme cases to cover the full range of possibilities (Alhumayani et al., 2020; Kuzmenko et al., 2020; Perrot et al., 2018c; Roux et al., 2023). The environmental impact of a robot can be calculated by taking the mass of the robot and its components, determining the embodied carbon footprint of these components, and then dividing by the robot's lifespan. 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 Kuzmenko. 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 some studies have provided valuable estimates (Alhumayani et al., 2020).

RESULTS AND DISCUSSION

Environmental impact of material

The first scenario to be analysed in this study will focus on rammed earth, cob, and 3DP as construction methods. Figigure 2 summarizes the initial comparisons between material used in conventional construction techniques (rammed earth and cob) and material used in digital construction techniques, notably 3DP. Consistent with what is already present in the literature, material used conventional construction techniques have a lower environmental impact than materials used for digital fabrication.

Furthermore, the percentage of stabilizer in the mix also significantly affects the GWP. The mixes with 5% lime in the composition presented the highest GWP values. The study also analyzed the 3DP of earth-based materials without straw. It was found that reducing the stabilizer amount by 2% and excluding straw from the mix resulted in a considerable decrease in GWP.

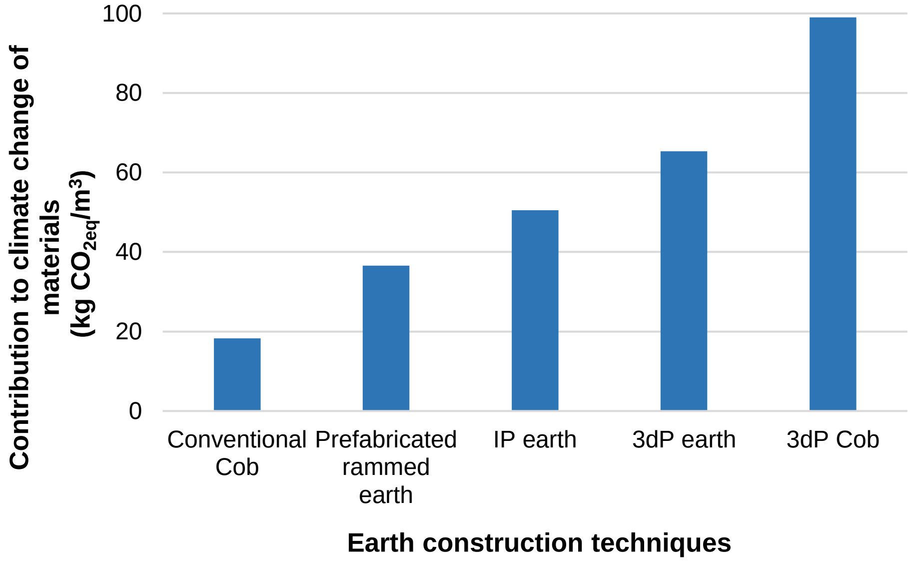

Figure 2 - Environmental impact assessment of earth materials using different techniques

Contribution of deposition process

The evaluation results (see Figure 3) indicate that the GWP impact of the Impact Printing process is lower than that of 3DP whatever the resolution of the 3DP. The only scenarios that showed a lower GWP impact were the ones with prefabricated rammed earth.

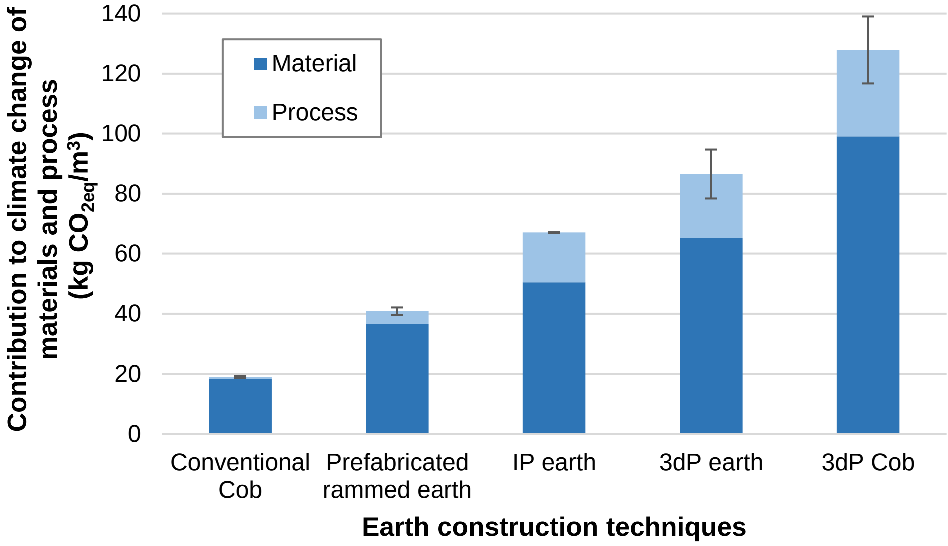

Figure 3 - Environmental impact assessment of earth constructions (material and process) using different techniques

Material saving needed

Considering the average impact of the process for each additive manufacturing technique (IP and 3DP), one can relatively easily infer the material saving required to compete with the conventional technique. We compared digital earth construction with prefabricated rammed earth as such processes have the same economic viability considering time and cost of construction. Additionally, we considered classic concrete construction and compared with 3dP of concrete. The objective is to be able to compare strategies used for earth with those used for materials with higher environmental impact.

Results presented in Figure 4 show the ambitious material reduction which are needed. For 3DP concrete reduction of 50% when low carbon cement is used would provide an environmental benefit for digital fabrication technologies. For impact printing technique, 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 earth 3DP technologies, it seems that higher reduction would be needed. 60 to 70% reduction should be achieved which would mean deposing 12 to 15 cm thick walls compared to the conventional 40cm walls of rammed earth. Our literature survey do not evidence such cases and rather stay to a 50% material saving for both earth and concrete (Alhumayani et al., 2020).

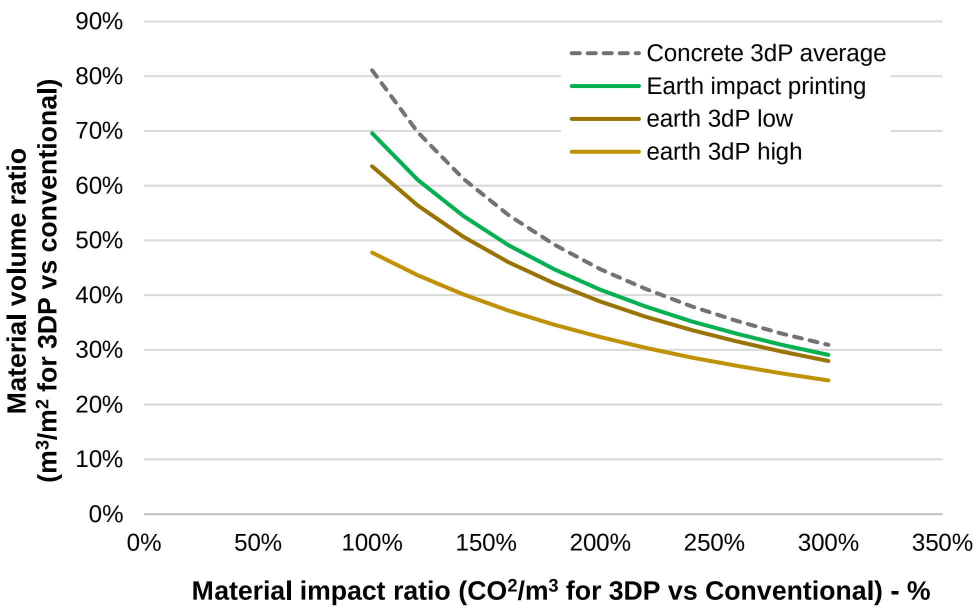

Figure 4 - Synthesis of the material saving requirement depending on additional impact of material and intensity of the process

Environmental Impact and Construction Efficiency

Figure 5 highlights the trade-off between the environmental impact and the construction time required for the different building techniques analysed in this study. The construction time considered in this analysis is solely the time during which the robotic system (both for 3DP and Impact Printing) are actively working, and does not include any downtime or interruptions.

As illustrated in the figure below, enhancing the resolution of 3D printing with earth material inadvertently extends the duration of robotic operations, resulting in increased energy consumption and, consequently, a heightened environmental impact.

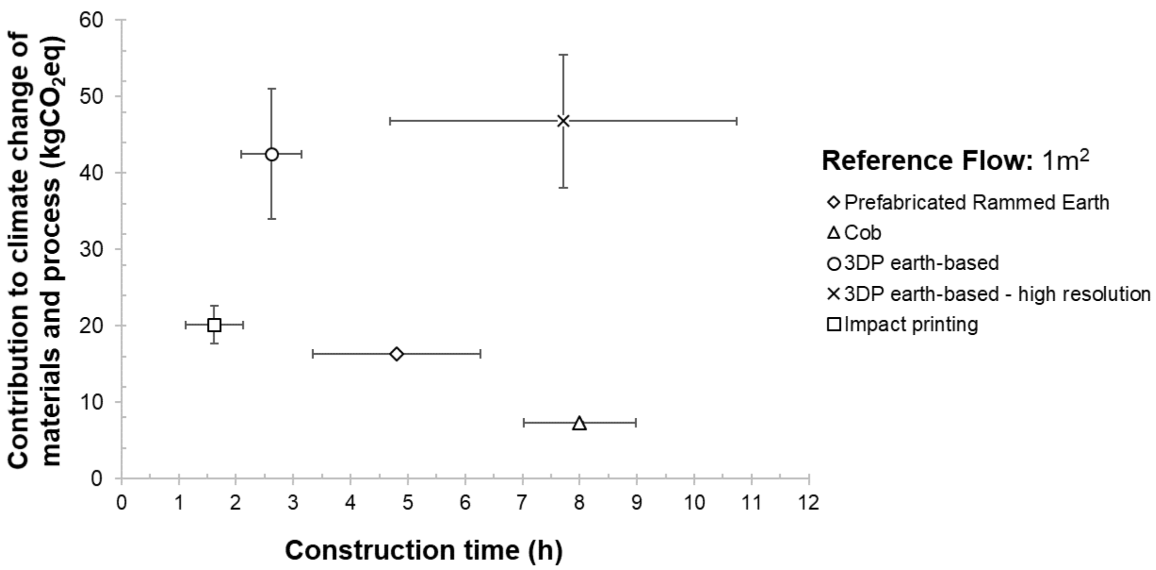

Figure 5 – Construction time for different techniques and their respective environmental impact in terms of GWP for a reference flow of $1m^2$

CONCLUSIONS

This study aimed to compare the environmental impact of conventional rammed earth and cob techniques with digital fabrication techniques, focusing on 3DP with earth. 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. This higher impact can be compensated by a smart design allowing material reduction. 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

We observed that when 3DP using earth-based materials is performed at high resolution (i.e., with small layer thickness), this construction technique starts to exhibit a disproportionately high environmental impact while not necessarily being more efficient in terms of construction time. On the other hand, the studied technology of impact printing, when integrated with the aforementioned process, offers a promising alternative. By leveraging this combination, it becomes possible to achieve building elements with significantly lower environmental impact compared to conventional methods, while still maintaining competitive construction timelines and allowing for greater design complexity.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest associated with the work presented in this paper.

DATA AVAILABILITY

Data on which this paper is based is available from the authors upon reasonable request.

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