Visions and Strategies for Reinforcing Additively Manufactured Constructions 2025
Contribution to the symposium
https://doi.org/10.52825/ocp.v7i.2795

Published: 12 Dec. 2025

A Critical Materials Perspective on 3DCP

Extractive Practices and Environmental Scalability in AM for Construction

Nadja Gaudillière-Jami[1,*]

[1]CITA, Institute for Architecture and Technologies, Royal Danish Academy, Denmark.

*Correspondence: Nadja Gaudillière-Jami, ngau@kglakademi.dk

Abstract. The current state of the art in assessing the environmental impact of 3D Concrete Printing (3DCP) technologies has focused especially on the material impacts, given the known issues posed by concrete. By contrast, 3DCP machinery impacts remain mostly unknown, with only few studies examining the equipment necessary to additive manufacturing and evaluating their impact with Life-Cycle Assessment (LCA) techniques. Taking point of departure in 3DCP as a case study, the research examines the usual assumption in the construction industry that materials impacts outweigh significantly machine impacts and that the latter can therefore remain out of scope of standard LCAs of buildings and building products. Assessing different concrete additive manufacturing (3DCP) wall typologies and focusing on the amounts of critical materials present in the system, the research compares the presence of such resources in the material and the set-up as well as the consequences for abiotic depletion and the scaling up of AM practices in the AEC industry (Architecture, Engineering and Construction). Highlighting the risk of significant impact transfer in some of the evaluated scenarios, the research advocates for a systematic impact of machinery impacts in 3DCP.

Keywords: 3DCP, LCA, Abiotic Depletion Potential

1. Introduction

1.1 Studying abiotic depletion in 3DCP technologies

Alongside a larger range of digital manufacturing technologies for the construction industry, 3D Concrete Printing (3DCP) has gained attention in recent years for the materials savings it allows, and for the potential improvement of environmental impacts associated with it. The awareness of the very high environmental costs of concrete at large, and especially of 3D-printing concrete formulations [1] [2], has put further focus on the environmental impacts of 3DCP. Research on lower impact formulations and manufacturing strategies has been increasingly developed [3] [4], with a strong focus on lowering the carbon footprint of 3DCP.

However, environmental costs also touch upon other types of impacts, as the complete list of Life-Cycle Assessment (LCA) impacts evaluated in standardized methodologies demonstrate [5]. Greenhouse gas emissions are part of a larger set of measures framing the effects of human activities on ecosystems, such as eutrophication and ecotoxicity. This set of measures also includes assessing the resource depletion entailed by the transformation of part of it. As part of this, Abiotic Depletion Potential (ADP) measures the use of non-renewable resources and includes the two sub-categories of Abiotic Depletion Potential for fossil resources (ADP-f) and of Abiotic Depletion Potential for mineral resources (ADP-m).

The latter is of particular relevance for the assessment of 3DCP environmental impacts. Evaluating ADP-m is a key insight into our use of critical materials. Critical materials are materials that have a significant risk of supply disruption, in part because of the essential role they play in the manufacturing of various products in the digital chain [6]. Amongst critical materials, the “electric eighteen” - materials such as aluminum, cobalt, copper, lithium, neodymium, silicon or platinum - are of particular note given the variety of components they are integrated in: batteries, alloys, magnets or circuitry all requires some of these to function. While a strong focus is placed on their role in energy production, these materials are also highly relevant to 3DCP given their presence in all digital infrastructure. As representative of scarcity stakes for critical materials, ADP-m is a precious economic indicator. However, as extractive practices in particular for minerals also yield strong damage to ecosystems, with high human and ecological costs, it is also a key environmental indicator. ADP-m is calculated by evaluating the scarcity of a given resource [7] and is a time-sensitive indicator as the rarity of resource is also evaluated according to yearly extraction rates [8].

1.2 Aims

Given its expected potential in decreasing environmental impacts of construction, 3DCP has been evaluated accordingly [9] [10]. However existing assessments focus mostly on the material itself [11], as concrete is known to have high impacts and as the high amount of cement in early formulations for 3DCP has driven associated carbon emissions up [12]. The associated greenhouse gas emissions indicator (GHG) is therefore the most present in performed assessments, with a handful of LCA also performed over the complete board of MidPoint ReCiPe indicators [13].

Yet almost none of the existing studies takes into account the machinery employed to perform the printing, which is consuming a large amount of critical materials, and the exact ADP-m of 3DCP remains to be evaluated. This is especially the case given that the few studies having taken into account machinery [1] [14] display results highlighting the risk of impact transfer. Changes in a production process can result in a diminution of the environmental impacts in a given indicator. However, the same changes can also result in the increase of impacts in other indicators across the board. This transfer of impacts from one indicator to the other triggers a shift in environmental issues, which can go unnoticed in case of limited assessments. Due to this impact transfer risk, changes that could initially be considered as leading to a more sustainable solution do not always constitute a progress. It is potentially the case with 3DCP, with impacts that could shift from GHG emissions to ADP-m.

This research therefore aims at understanding the environmental impacts of 3DCP through a critical materials lens, studying the impact transfers at play in 3DCP and what it might entail for future developments of 3DCP technologies for the AEC industry. The paper first presents an overview of critical materials in construction and 3DCP. It then details the methodological approach adopted to perform the LCA and presents numerical results for GHG and ADP-m indicators for four wall typologies. Finally the demonstrated impact transfer is discussed as well as strategies to limit ADP-m impacts in future 3DCP for construction applications.

2. The ore rush: critical materials in construction

2.1 Critical materials conventional construction

Critical materials and ADP-m represent a significant issue in conventional construction itself, as this industry is the second most consuming of critical materials [15]. This is due to the very high amounts of iron ore used in the fabrication of steel for concrete reinforcement.

Both concrete research and 3DCP have allowed for alternatives for reinforcements to be explored, including glass fibers that could allow lowering ADP-m impacts. However, reinforcement still accounts for 42% of the ADP-m in 3DCP LCAs [9], a significant amount when only accounting for the materials environmental bill.

2.2 Machinery assessments in construction

While research mostly assesses materials only when evaluating the impact of 3DCP, the state of the art has shown the importance of machinery when it comes to ADP-m. One LCA of large-scale 3DCP has shown the weight of the 3D-printing cell in the ADP-m score [1]. Other studies focusing on AM equipment for polymers and metals have also shown the weight of the machinery in this indicator, where it accounts for 82 to 85% of the total depending on the type of printer evaluated [16]. Furthermore, a great variability in impacts has been underlined when it comes to additive manufacturing in construction, due to the differences in set-ups [17]. This renders the prediction of the environmental weight of machinery difficult.

Traditionally, LCA of construction products and of buildings disregards construction machinery, as studies have shown early on the low impacts of it in comparison to the material impacts [18] [19]. This entails that the balance between material and machinery in conventional construction weights so much towards material that machinery becomes negligible in assessments. However, the existing studies on AM equipment including 3DCP equipment hint towards a potential impact spike for ADP-m, due to the high-tech machinery employed. This entails the need for more specific studies to be conducted on a range of set-ups, in order to reassess the balance between material and machinery in this technology.

2.3 ADP-m in 3DCP for construction

Figure 1 presents a 3DCP robotic set-up, detailing the presence of critical materials in it and providing an illustration of the critical materials density of 3DCP, the reason for its potentially high ADP-m. While the set-up presented is specific [12] and does not account for all 3DCP set-ups, many of the components it features are present in some version in all set-ups. A broader study of 3DCP set-ups has been performed in [17], discussing the weight of the different components, overall machine designs and providing further insights on their role in ADP-m impacts.

Present in the set-up are both highly on demand materials such as steel and copper, and rare materials such as platinum and gold. Table 1 illustrates the variability of ADP-m impacts for each of these materials, showcasing the relation between rarity and demand in calculating the indicator. Scale-up strategies in 3DCP for AEC include increasing the size of the set-ups, causing need for longer cables and larger counterweights, which increases the amount of copper, steel or other highly on demand materials in the system. Modelling and computing operations also request equipment which includes further critical materials, such as silicon [20].

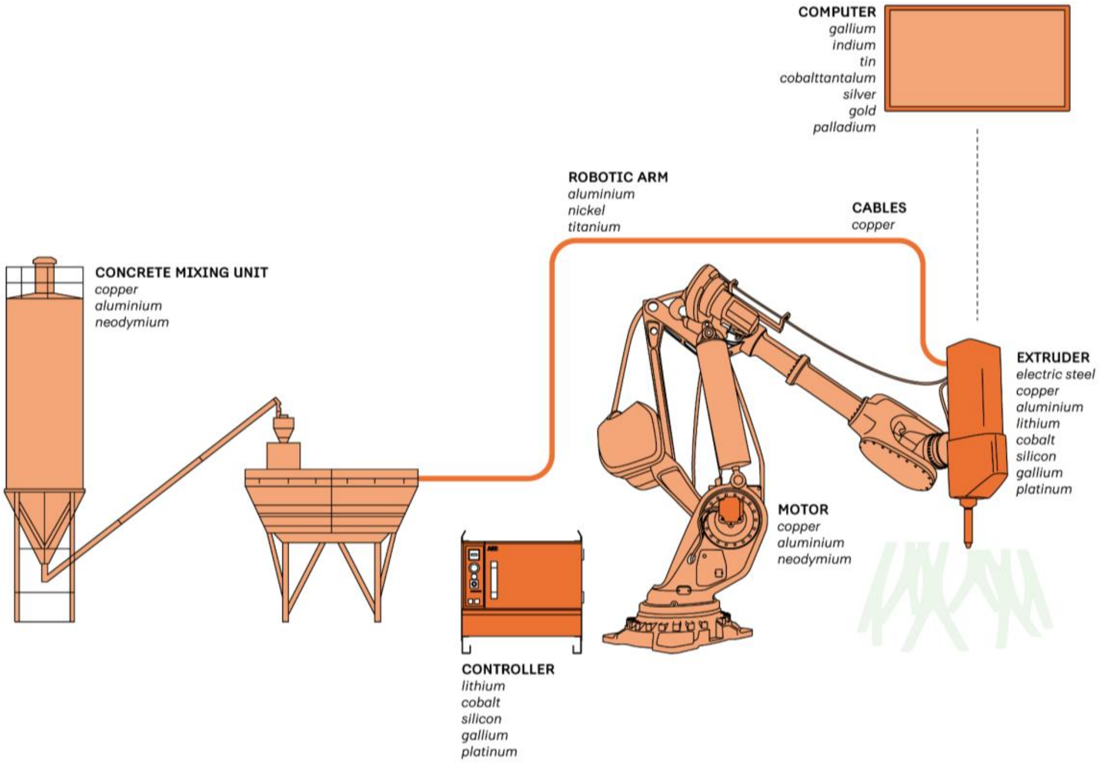

Figure 1. *Critical materials presence in 3DCP set-up*

Table 1*. Critical materials present in 3DCP machinery and their ADP-m (source: USGS Mineral Commodity Summary)*

Material	ADP-m (kg SB eq./kg)
Platinum	9,71E+02
Copper	2,13E-02
Steel	2,20E-03
Nickel	8,15E-04
Cobalt	2,51E-04
Lithium	2,57E-05
Neodymium	2,16E-05
Gallium	4,21E-07
Titanium	3,79E-07
Aluminium	2,54E-08
Silicon	8,20E-10

3. Methods

3.1 Methodology and typologies assessed

The present research calculates both the ADP-m and the GHG impact scores for four different wall typologies, presented in Figure 2. The first is a rebar cast concrete wall, serving as a point of reference to compare 3DCP and its set-up to conventional construction methods. The three other walls present variations in the reinforcement method: use of Ultra-High-Performance

Concrete (UHPC) for the first, integration of cast rebar for the second and mixing in of steel fibers for the third.

The functional unit adopted is 1 sqm of wall with identical mechanical properties and varying mass. Indicators have been assessed according to the MidPoint ReCiPe method [13], only considering A1-A3 phases of the wall fabrication but including all phases for the manufacturing of the materials and machines. Both materials and machinery have been considered in the four scenarios, with an identical 3D-printing system in scenarios 2 to 4, This system has been assessed prior to this study in [1]. The outlay of machinery has been considered for every scenario, spreading the ADP-m impacts of the equipment across their service life and production capacity. Details for the outlays considered here are detailed in the study previously conducted [1]. The outlay is based on the service life of the different components of the 3D-printing cell, with the longest being the robotic arm’s service life of 12 years. The 3D-printing cell is considered to be producing wall segments throughout its service life during working hours, minus servicing and recalibration periods. Data on concrete formulations GHG impacts has been extracted from EPDs published by Weber for conventional and 3D-printable concrete [2] [21] [22].

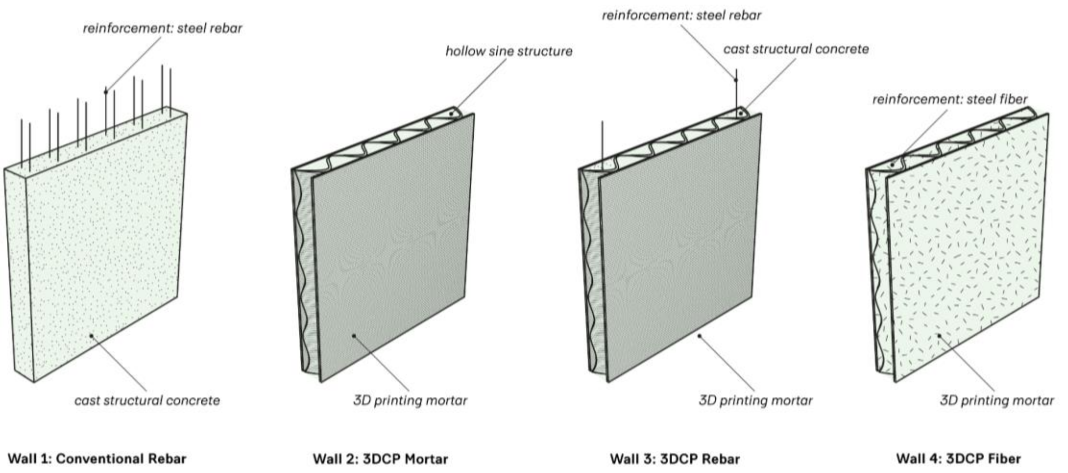

Figure 2. *Schematic illustration of the four wall typologies assessed*

3.2 Life-Cycle Inventory

Figure 3 displays the Life-Cycle Inventory for each of the wall typologies assessed, presenting on one hand the machinery taken into account and on the other hand the material recipes taken into account. As the third typology integrates cast concrete and traditional rebar, it is of note that its Life-Cycle Inventory combines the different equipment and material sets together.

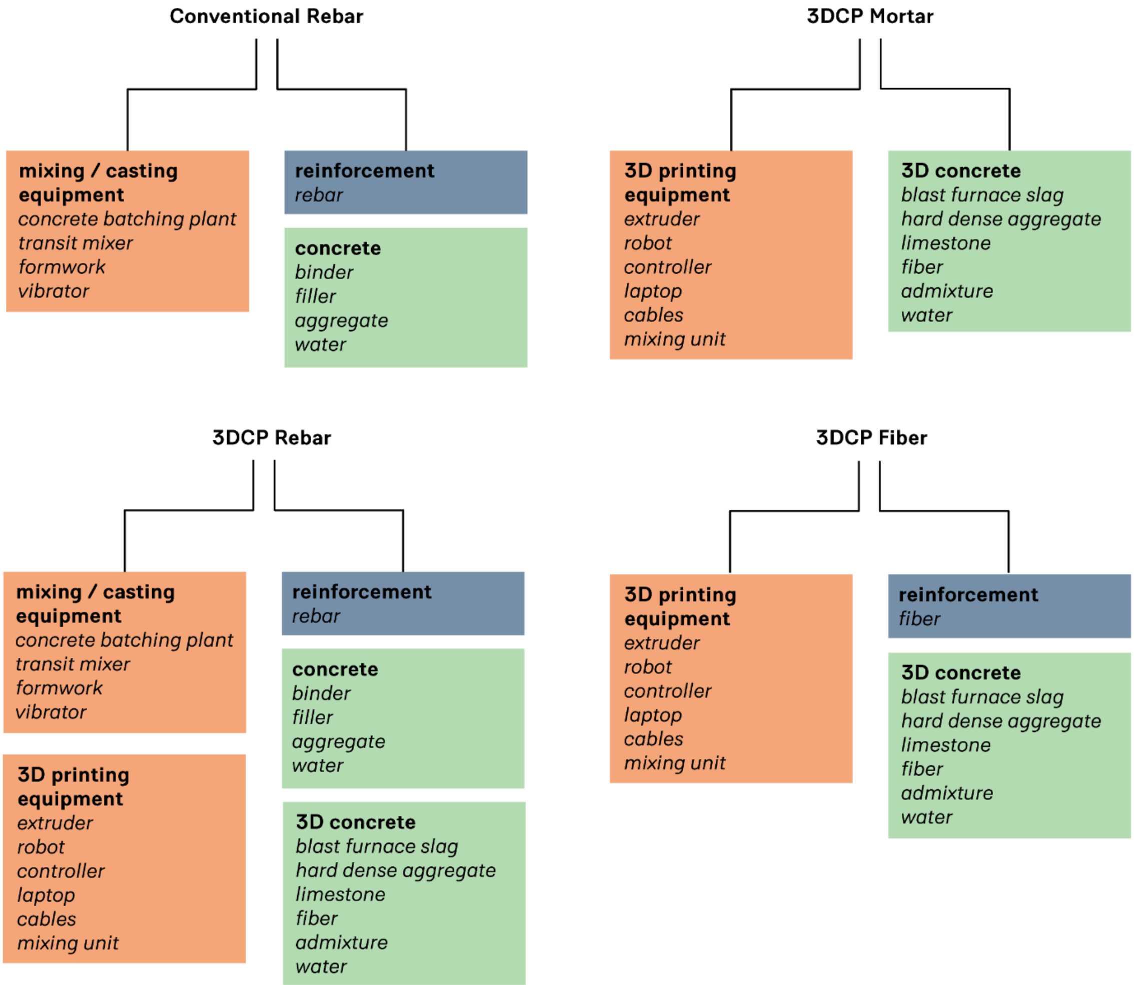

Figure 3. *Life-Cycle Inventory for each wall typology assessed*

4. Results

4.1 Numerical results

Table 2 presents a breakdown of the assessment results for the ADP-m indicator across all four typologies. Table 3 presents a breakdown of the assessment results for the GHG indicator across all four typologies.

Table 2. *ADP-m breakdown for the four wall typologies*

	Conventional Rebar	**3DCP Mortar**	**3DCP Rebar**	**3DCP Fiber**
Steel	*4,82E-02*	*0,00E+00*	*4,82E-02*	*3,02E-02*
Concrete	*2,16E-05*	*3,45E-04*	*3,54E-04*	*3,45E-04*
Materials	4,82E-02	3,45E-04	4,86E-02	3,05E-02
Set-Up	1,86E-05	2,36E+00	2,36E+00	2,36E+00
Total	**4,83E-02**	**2,36E+00**	**2,41E+00**	**3,39E+00**

Table 3. *GHG breakdown for the four wall typologies*

	Conventional Rebar	3DCP Mortar	3DCP Rebar	3DCP Fiber
Steel	4,36E+01	0,00E+00	4,36E+01	1,73E+01
Concrete	5,32E+01	3,44E+01	5,57E+01	3,44E+01
Total	**9,69E+01**	**3,44E+01**	**9,93E+01**	**3,61E+01**

4.2 Material/machinery balance

Figure 4 shows the material/machinery balance in all four scenarios. While in the conventional scenario the materials make up for almost all the ADP-m impact, in the three 3DCP scenarios it is the set-up that makes up for most of the ADP-m impact. While the impact of the reinforcement is visible in scenarios 3 and 4, it is still very significantly lower than the set-up impact. These results demonstrate the strength of the impact transfer at play in 3DCP, as well as the need to evaluate the impact of machinery in certain indicators within an LCA.

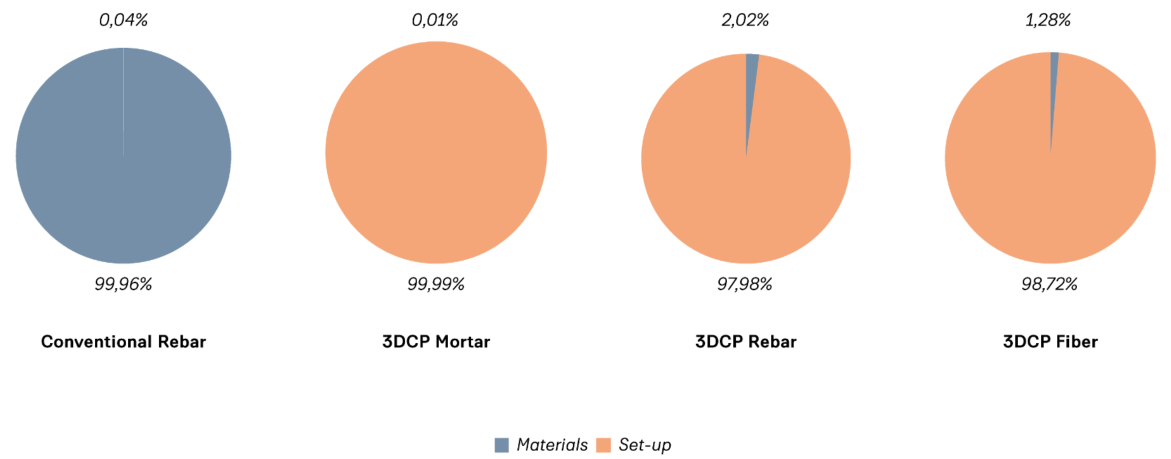

Figure 4. *Material/machinery balance for the four typologies assessed*

Figure 5 complements these results and observations by providing a breakdown of the ADP-m impact across the set-up as well as the different materials. Figure 6 provides a breakdown of the GHG impact between materials. The GHG impact associated with the reinforcement significantly diminishes depending on the type of reinforcements and the design of the wall. While fibers have a higher GHG impact in themselves, the rebar wall combines cast and printed concrete, driving its impacts up significantly.

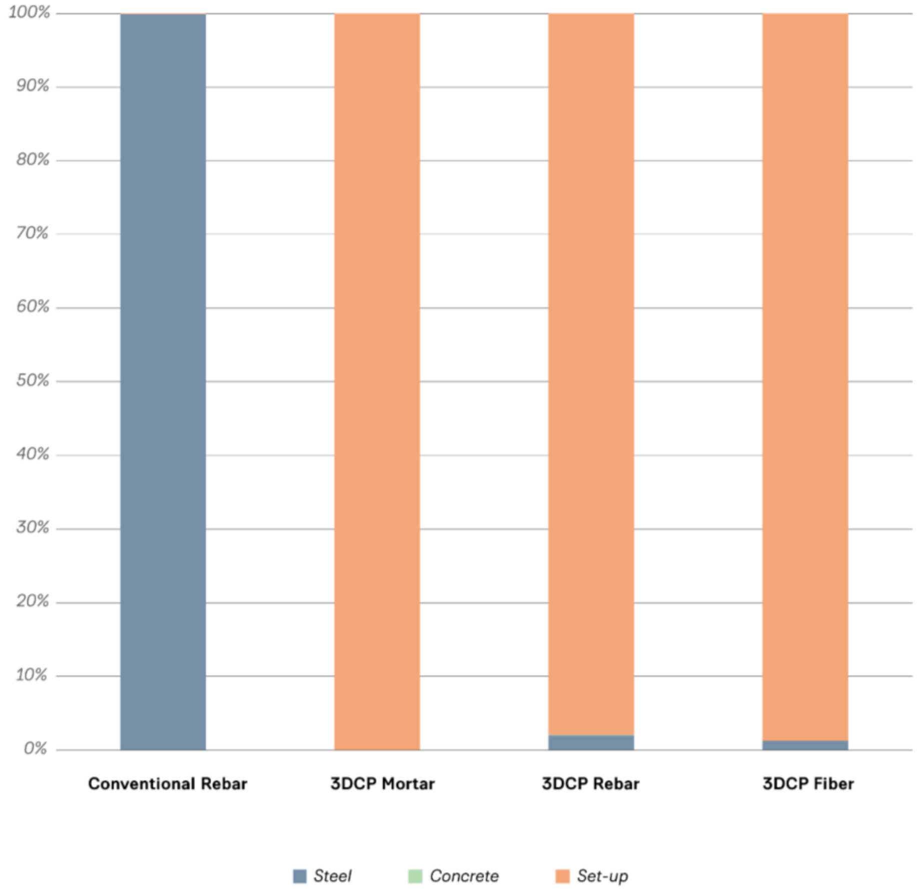

Figure 5. *ADP-m breakdown for the four wall typologies*

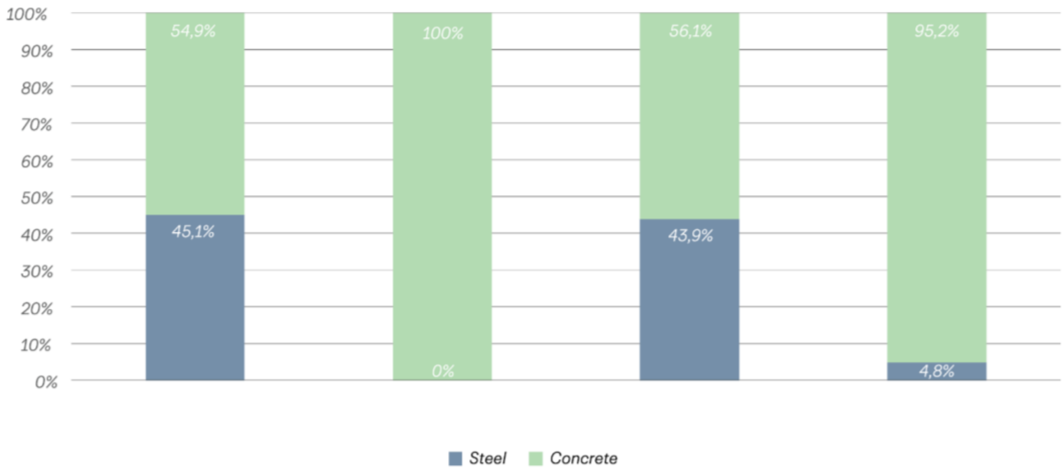

Figure 6. *GHG breakdown for the four wall typologies*

4.3 Impact transfer

Figure 7 presents an overview of all walls and their ADP-m and GHG impacts, putting the impact transfer in perspective across all typologies assessed. While ADP-m impacts are very close to one another in the different 3DCP scenarios given the predominance of set-up impacts - from 2,36 to 2,41 kg Sb eq. - the impact is on average 50 times higher than in the conventional rebar scenario. GHG impacts are more variable, with the 3DCP rebar scenario close to the conventional rebar scenario and the 3DCP mortar and fiber scenarios also close to one another. Despite this variability, it can be observed that in some cases the impact transfer is significant: between conventional rebar and 3DCP fiber it is especially noteworthy.

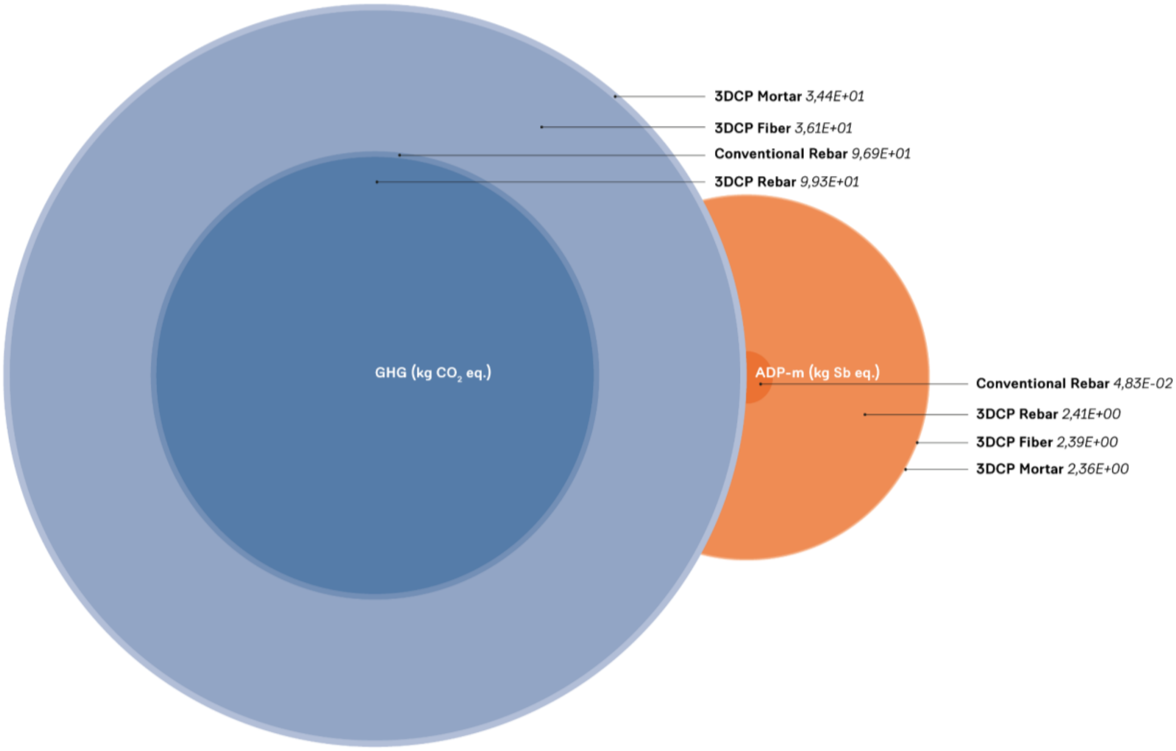

Figure 7. *Impact transfer between the conventional and 3DCP typologies*

5. Conclusion

The present study provides a closer look at critical materials presence in 3DCP technologies, detailing their presence within additive manufacturing systems and examining their consequences on the assessment of abiotic depletion. The assessed 3DCP wall typologies present significant increases in ADP-m across the board - up to 50 times the impact for conventional casting walls, while in some cases presenting significantly lower GHG emissions. This bidirectional change in impacts demonstrates the suspected transfer at play in 3DCP technologies. However, the study also demonstrates the variability of this impact transfer. While the chosen set-up can have a significant role in ADP-m increases, the geometry and design choices can also alter the impacts, which advocates for systematic assessment of both GHG emissions and ADP-m when developing construction applications for 3DCP.

This reasoning is furthered by the balancing of 3DCP in construction with other available AEC methods as well as with other uses of the digital in other sectors. Given the increasing scarcity of critical materials present in AM infrastructure at large, efforts must be put on the recycling of such materials. In addition to this, a complementary issue is that of priorities to establish in a limited resource framework. As part of this, modelling availability and productivity of 3DCP set-ups is key, alongside the exploration of new machinery models and new regulations guiding the use of critical materials in 3DCP and in AEC. While a systematic assessment of ADP-m and of critical materials presence is necessary, this also entails an understanding of 3DCP geographies of productions: origin, manufacturing and use locations as well as scales of production for sustainable 3DCP landscapes. As part of this larger enquiry, investigating prefabrication VS on-site construction methods and the associated methods of transport and assembly. As these different production paradigms could have significantly different end-of-life scenarios, dismantling and reuse opportunities could also be integrated in this larger assessment.

Further investigations should also be conducted regarding the role played by geometry and the extent to which it can be leveraged to lower environmental impacts. 3DCP technologies are of relevance when producing complex and multifunctional geometries rather than simpler ones for which traditional construction methods are much more optimized. The wall geometry assessed here, while leveraging 3DCP for its internal structure, remains straightforward, a choice made to remain consistent in the functional unit and allow comparison of the ADP-m potential in machines and materials. While the results presented here show that impact transfer is dependent on the geometry adopted, prior research on biopolymer additive manufacturing shows much higher levels of variation [23]. The correlation between printability and sustainability observed opens research venues for graded materials with a high potential for lowering impacts by adjusting geometries depending on their assigned formulations and resulting impacts. Studies remain to be conducted to assess whether similar correlations exist in 3DCP and whether they can become the basis for sustainability related geometry optimizations.

Author contributions

Conceptualization, Investigation, Methodology, Validation, Visualization, Writing (original draft, review & editing) have all been performed by the author Nadja Gaudillière-Jami.

Competing interests

The author declares that they have no competing interests.

References

[1] Kuzmenko, K., Gaudillière, N., Feraille, A., Dirrenberger, J. & Baverel, O. (2020). Assessing the environmental viability of 3D concrete printing technology. In Impact: Design With All Senses: Proceedings of the Design Modelling Symposium, Berlin 2019 (pp. 517-528). Springer International Publishing. https://doi.org/10.1007/978-3-030-29829-6_40

[2] Saint-Gobain Weber Benelux (2025) Environmental Product Declaration Weber 3D ECO (BB EIH), ReTHiNK-97631. https://www.3d.weber/media/pages/news/now-available-epds-for-our-3d-concrete-mortars/5573ec75ca-1748248755/epd_weber-3d-eco_-bb-eindhoven.pdf

[3] Heywood, K. (2025). Additive Manufacturing Processes for Architectural Design: Rethinking 3DCP through a lens of Sustainability. Doctoral Thesis, Royal Danish Academy.https://adk.elsevierpure.com/en/publications/additive-manufacturing-processes-for-architectural-design-rethink

[4] Heywood, K., & Nicholas, P. (2024, April). 3D Concrete Printing in a Circular Economy: What we can learn from a 3DCP slab designed for dissassembly. In CAADRIA 2024-ACCELERATED DESIGN: he 29th Annual Conference for Computer-Aided Architectural Design Research in Asia (CAADRIA) (pp. 271-280). https://doi.org/10.52842/conf.caadria.2024.3.271

[5] International Organization for Standardization: ISO 14040-14044. https://www.iso.org/standard/38498.html

[6] Center for Sustainable Systems, University of Michigan (2024). “Critical Materials Factsheet.” Pub. No. CSS14-15. https://css.umich.edu/sites/default/files/2024-10/Critical%20Materials_CSS14-15.pdf

[7] Ibrahim Dincer, Azzam Abu-Rayash, Chapter 6 - Sustainability modeling, Editor(s): Ibrahim Dincer, Azzam Abu-Rayash, Energy Sustainability, Academic Press, 2020, Pages 119-164, ISBN 9780128195567. https://doi.org/10.1016/B978-0-12-819556-7.00006-1.

[8] van Oers, L., Guinée, J. B., & Heijungs, R. (2020). Abiotic resource depletion potentials (ADPs) for elements revisited—updating ultimate reserve estimates and introducing time series for production data. The International Journal of Life Cycle Assessment, 25(2), 294-308. https://doi.org/10.1007/s11367-019-01683-x

[9] Arash Motalebi, Mohammad Abu Hasan Khondoker, Golam Kabir, A systematic review of life cycle assessments of 3D concrete printing, Sustainable Operations and Computers, Volume 5, 2024, Pages 41-50, ISSN 2666-4127. https://doi.org/10.1016/j.susoc.2023.08.003.

[10] Matheus Pimentel Tinoco, Érica Martinho de Mendonça, Letícia Ikeda Castrillon Fernandez, Lucas Rosse Caldas, Oscar Aurelio Mendoza Reales, Romildo Dias Toledo Filho, Life cycle assessment (LCA) and environmental sustainability of cementitious materials for 3D concrete printing: A systematic literature review, Journal of Building Engineering, Volume 52, 2022, 104456, ISSN 2352-7102. https://doi.org/10.1016/j.jobe.2022.104456

[11] Khan, S. A., Koç, M., & Al-Ghamdi, S. G. (2021). Sustainability assessment, potentials and challenges of 3D printed concrete structures: A systematic review for built environmental applications. Journal of Cleaner Production, 303, 127027. https://doi.org/10.1016/j.jclepro.2021.127027

[12] Gosselin, C., Duballet, R., Roux, P., Gaudillière, N., Dirrenberger, J., & Morel, P. (2016). Large-scale 3D printing of ultra-high performance concrete–a new processing route for architects and builders. Materials & Design, 100, 102-109. https://doi.org/10.1016/j.matdes.2016.03.097

[13] Huijbregts, M. A., Steinmann, Z. J., Elshout, P. M., Stam, G., Verones, F., Vieira, M., Zijp, M. Hollander, A. & Van Zelm, R. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. The international journal of life cycle assessment, 22(2), 138-147. https://doi.org/10.1007/s11367-016-1246-y

[14] De Soto, B. G., Agustí-Juan, I., Hunhevicz, J., Joss, S., Graser, K., Habert, G., & Adey, B. T. (2018). Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall. Automation in construction, 92, 297-311. https://doi.org/10.1016/j.autcon.2018.04.004

[15] U.S. Geological Survey, 2025, Mineral commodity summaries 2025 (ver. 1.2, March 2025): U.S. Geological Survey, 212 p., https://doi.org/10.3133/mcs2025.

[16] Faludi, J., Baumers, M., Maskery, I. & Hague, R. (2017). Environmental Impacts of Selective Laser Melting: Do Printer,vPowder, Or Power Dominate?. Journal of Industrial Ecology, 21: S144-S156. https://doi.org/10.1111/jiec.12528

[17] Gaudillière-Jami, N. (2025). AM in construction. Taking environmental scalability into consideration. In Iurio, O., Wolf, A., Figueiredo, B., Knaack, U., Cruz, P.J.S. (eds.) AM Perspectives 2. Research in Advanced Manufacturing for Architecture and Construction, pp. 26-36. https://doi.org/10.47982/eqdj0367

[18] Ozcan-Deniz, G., & Zhu, Y. (2013). Analyzing the effect of equipment selection on the global warming potential of construction projects. In ICCREM 2013: Construction and Operation in the Context of Sustainability (pp. 247-257). https://doi.org/10.1061/9780784413135.023

[19] Rakhmawati, A. N., Devia, Y. P., & Wijatmiko, I. (2020). Life cycle assessment (LCA) analysis of concrete slab construction for estimating the environmental impact. Rekayasa Sipil, 14(3), 232-237. https://doi.org/10.21776/ub.rekayasasipil.2020.014.03.10

[20] Roussilhe, G., Ligozat, A. L., & Quinton, S. (2023). A long road ahead: a review of the state of knowledge of the environmental effects of digitization. Current Opinion in Environmental Sustainability, 62, 101296. https://doi.org/10.1016/j.cosust.2023.101296
[21] Weber (2024) Environmental Product Declaration weber REP 38 Cast concrete SR C35/45-8, EPD-IES-0017505. https://www.fi.weber/files/fi/2025-01/weber-REP-38-Valubetoni-SR-C35-45-8-EPD-ymparistoseloste-EN.pdf
[22] KrampeHarex (2023). Environmental Production Declaration Steel fibre with hooked ends, NEPD-4605-3859-EN. https://www.environdec.com/library/epd8154
[23] Galluccio, G., Tamke, M., Nicholas, P., Svilans, T., Gaudillière-Jami, N., & Thomsen, M. R. (2024, June). Material Stories: Assessing Sustainability of Digital Fabrication with Bio-Based Materials through LCA. In The International Conference on Net-Zero Civil Infrastructures: Innovations in Materials, Structures, and Management Practices (NTZR) (pp. 25-37). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-69626-8_3