Can digital fabrication meet low-carbon materials?

ETH zürich

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Drives innovation to overcome complexity and stagnation
In our current cities we observe disruption and innovation at an always increasing pace[1]

Cost Savings
By optimizing material usage, minimizing errors, and shortening construction timelines

Why Digital Fabrication?

Enables customized and tailored production
Personalized mass production, where products are adapted to the preferences and specific requirements of each individual

Improved Efficiency
Computer-controlled fabrication tools enable construction processes to be streamlined and automated, resulting in increased efficiency

[1] *Bettencourt L.M.A. et al. 2007. 2013. Growth, innovation, scaling, and the pace of life in cities. Proceedings of the National Academy of Science*

Historical Development - Additive manufacturing

The Winsun apartment block. Sce: Winsun Global

2015

WinSun, has achieved a significant milestone by successfully printing the tallest-ever five-story building

Project Milestone. Eindhoven University

2018

First habitable 3D-printed cement houses set to appear in Eindhoven, Netherlands

2014

The first prototypes are produced by the Center for Rapid Automated Fabrication Technologies (CRAFT).

Contour Crafting Corporation, Behrokh Khoshnevis.
University of Southern California (USC)

3D-printed concrete bike bridge in Gemert.
Photograph: Bart Maat/EPA

2017

World's first 3D-printed bridge opens to cyclists in Netherlands

2023

Construction is underway on the largest community of 3D-printed homes, Texas, USA

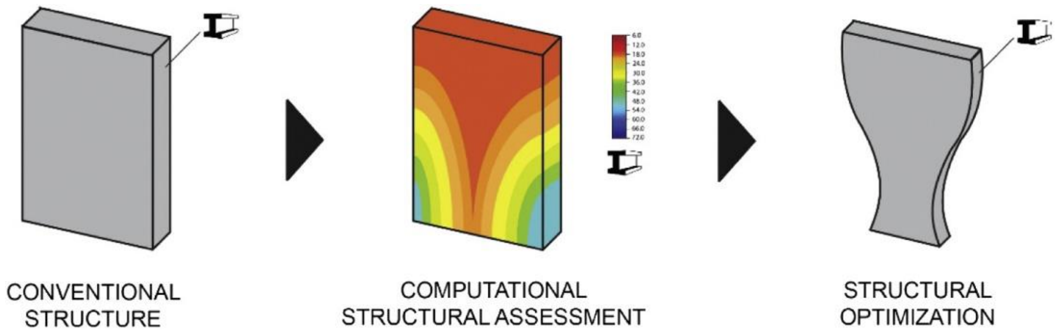
Sce: BIG and ICON

Is Additive Manufacturing better for climate than conventional technique?

For 3dP with concrete:
Impact of deposition process is much more important than in conventional construction
(it could account for 70% of impacts)[1]

Impact of 3dP material is almost twice bigger than conventionally casted concrete[2]
(more cement per m^3 is usually needed in 3dP concrete)

→ Structural optimization has to compensate
for higher impact of material AND higher impact of processing



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1. Saade M. et al. 2020. How has LCA been applied to 3D printing? A systematic literature review and recommendations for future studies. *Journal of Cleaner Production*
2. Roux C. et al. 2023. Life cycle assessment of a concrete 3D printing process. *The International Journal of Life Cycle Assessment*
3. Agustí-Juan & Habert G. 2017. Environmental design guidelines for Digital Fabrication. *Journal of Cleaner Production*.

3dP of low carbon materials

What else can we do to reduce this impact?


Casa Covida, Emerging Objects

2020

Experimental case-study house sited in the high alpine desert


Itaca Project, WASP

2023

The first habitable house with coupled subsystems.


Gaia Project, WASP

2018

WASP achieve the milestone of printing the first large scale structure with earth

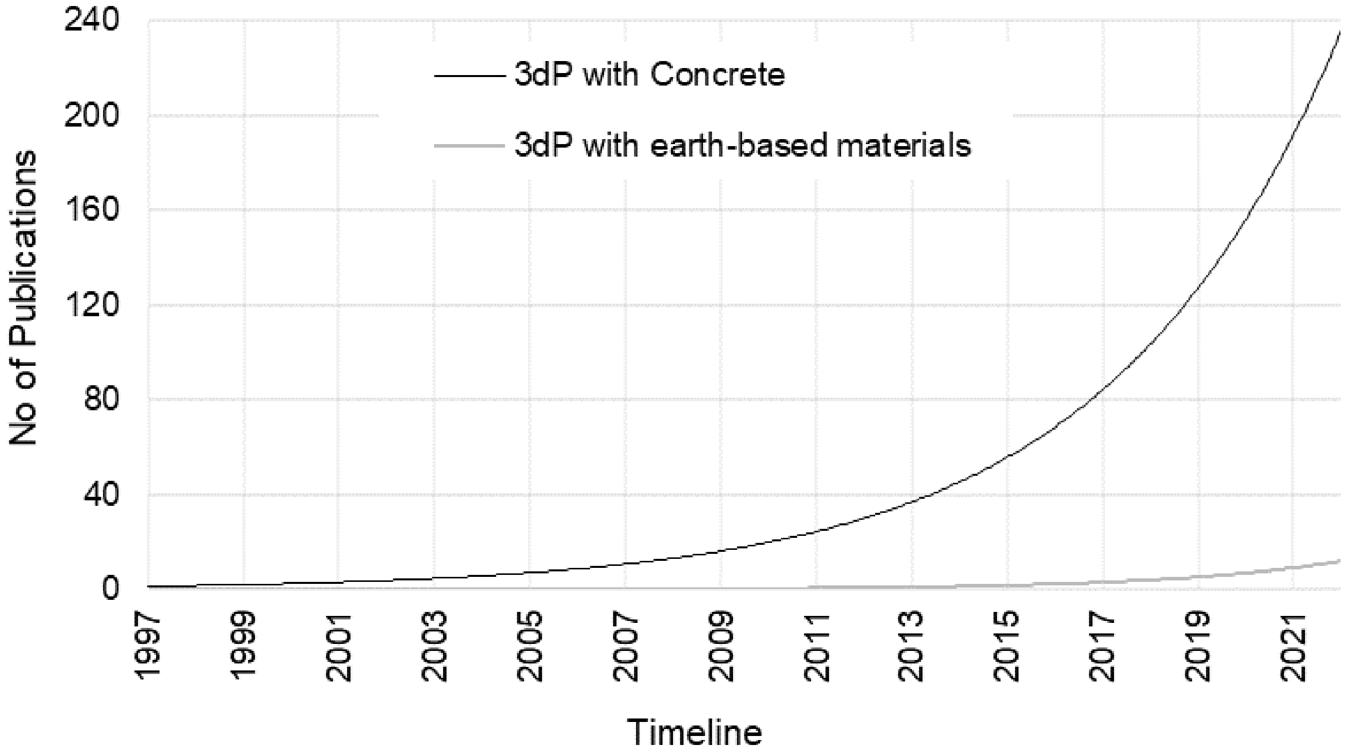

Tecla House, WASP

2021

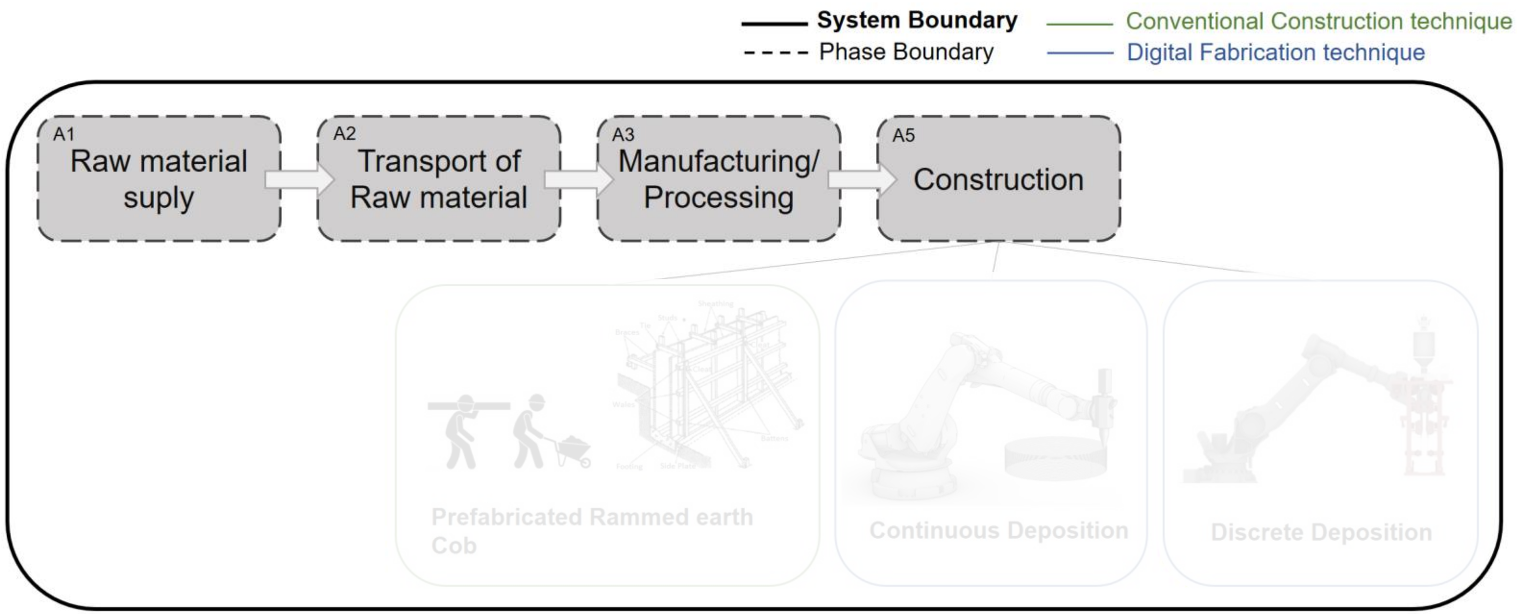
Tecla House, by WASP, $60m^2$ surface and 4.2m in height

3dP of low carbon materials

Very few studies related to earth based digitally fabricated…



Study Goal



Conventional

Ricola Kräuterzentrum, 2014

Mud Dauber School of Natural Building

Digital fabrication techniques

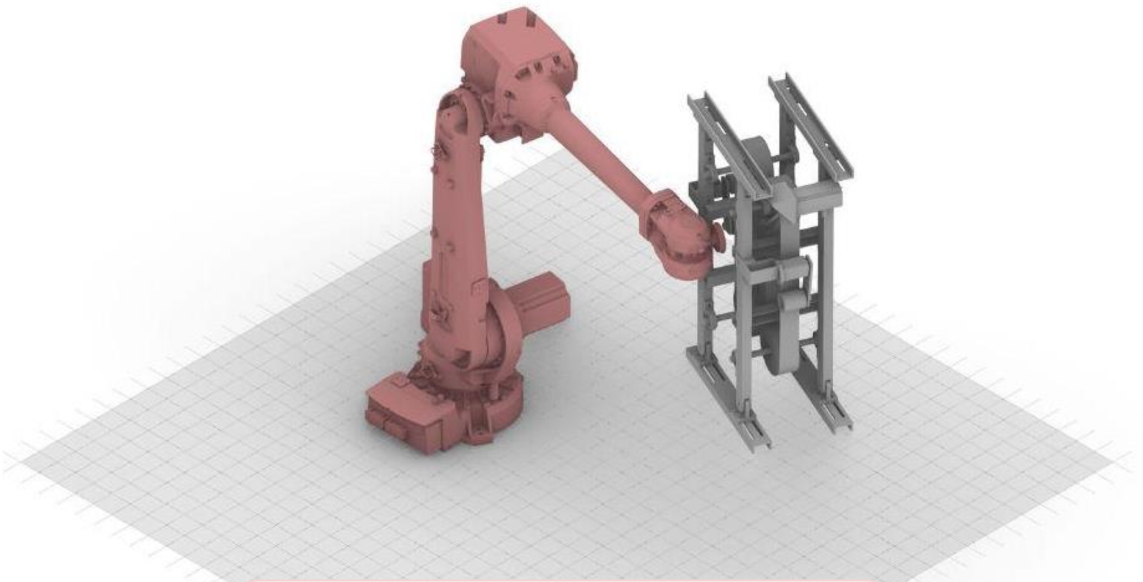
Gomaa M. et al., 2018

Perrot A. et al., 2018

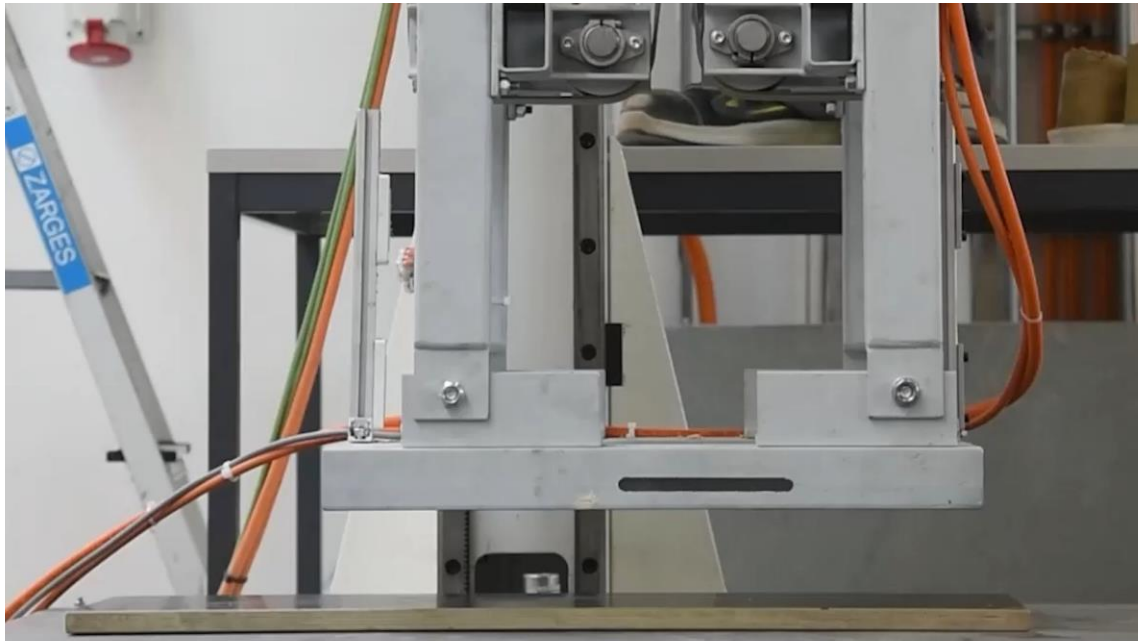
ETH Zürich, 2023

Discrete deposition

A custom additive manufacturing method based on high-velocity discrete deposition



6-axis industrial robot
+
Customized end-effector



Chadha K. et al., ETH Zürich, 2021. Video of preliminary tests of 500 x 300 x 120mm wall using Impact Printing process

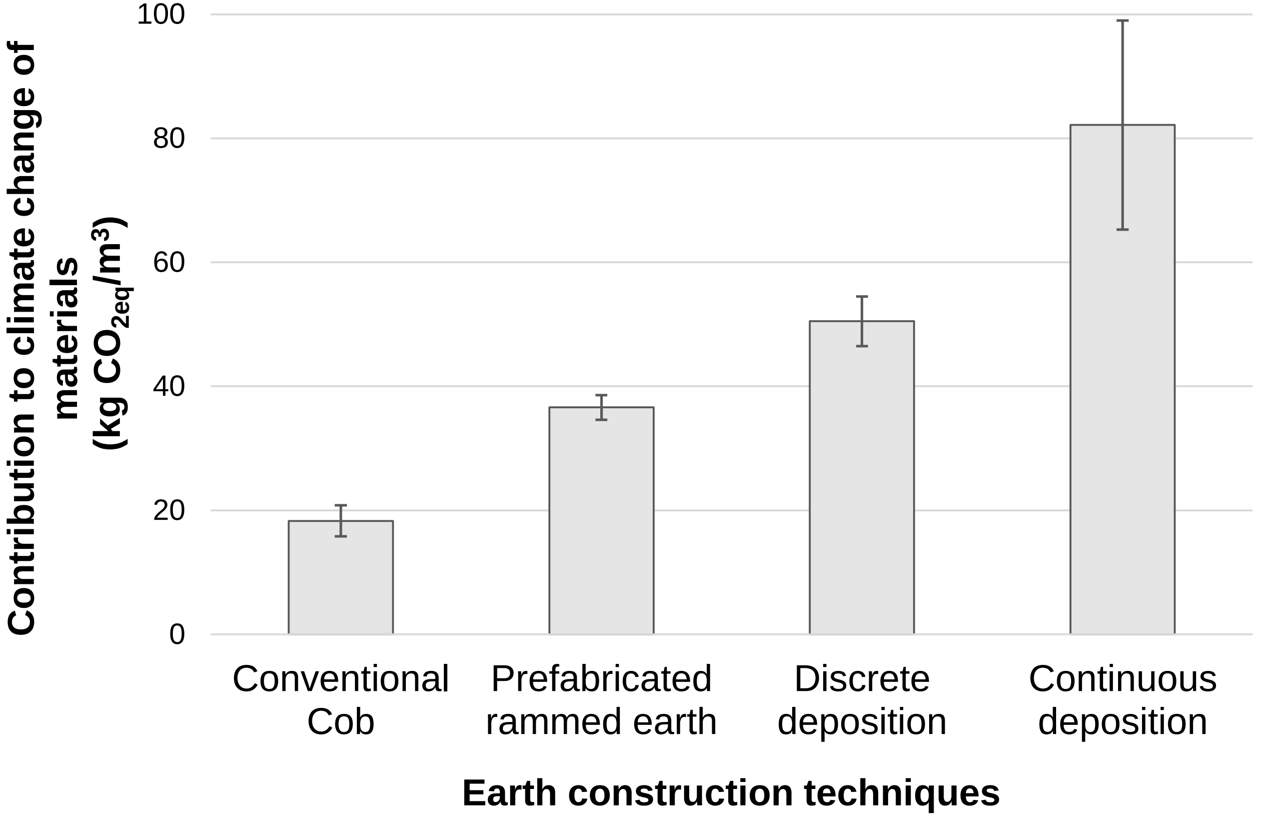
Model of environmental impact

- Simple drivers:

- Impact of material production (embodied emissions) → **$kgCO_2$ eq./m^3**
- Impact of construction process → **$kgCO_2$ eq./m^3**
- Volume of material used → **m^3/m^2**

$$(I_{mat}^{Con} + I_{pro}^{Con}) \times Vol^{Con} \quad \text{vs} \quad (\underline{I_{mat}^{AM}} + I_{pro}^{AM}) \times Vol^{AM}$$

Environmental Impact of material mix



Due to buildability constraints, environmental impact of digitally fabricated material is higher than conventional

Model of environmental impact

- **Simple drivers:**
  - Impact of material production (embodied emissions) → **$kgCO_2$ eq./m^3**
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  - Volume of material used → **m^3/m^2**

$$\boxed{(I_{mat}^{Con} + I_{pro}^{Con}) \times Vol^{Con}} \quad \text{vs} \quad \boxed{(I_{mat}^{AM} + I_{pro}^{AM}) \times Vol^{AM}}$$

Machine's Outlay + Energy consumption

Contribution of deposition process

Robot + Controler
Preparation unit
Printing Head
…

Machinery Embodied Impact

$$\frac{\text{Embodied carbon}}{\text{Lifespan}} \rightarrow kgCO_2eq/h$$

+

Market for electricity

Printing process Consumption

Energy Consumption Impact

$kgCO_2eq/kWh \rightarrow kgCO_2eq/h$

X

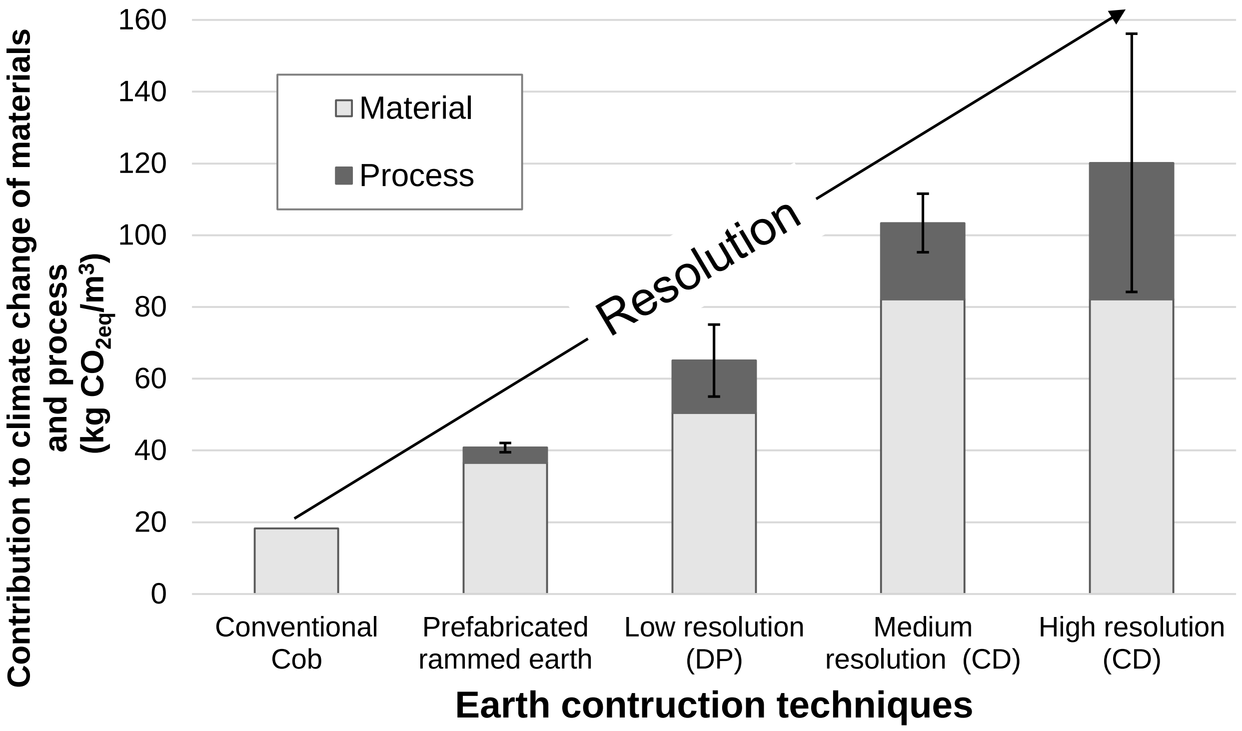
Printed Volume

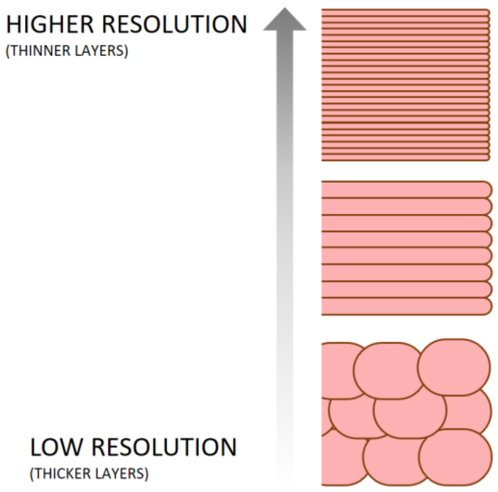
h/m^3

Resolution/Nozzle Size

Printing speed

Contribution of deposition process

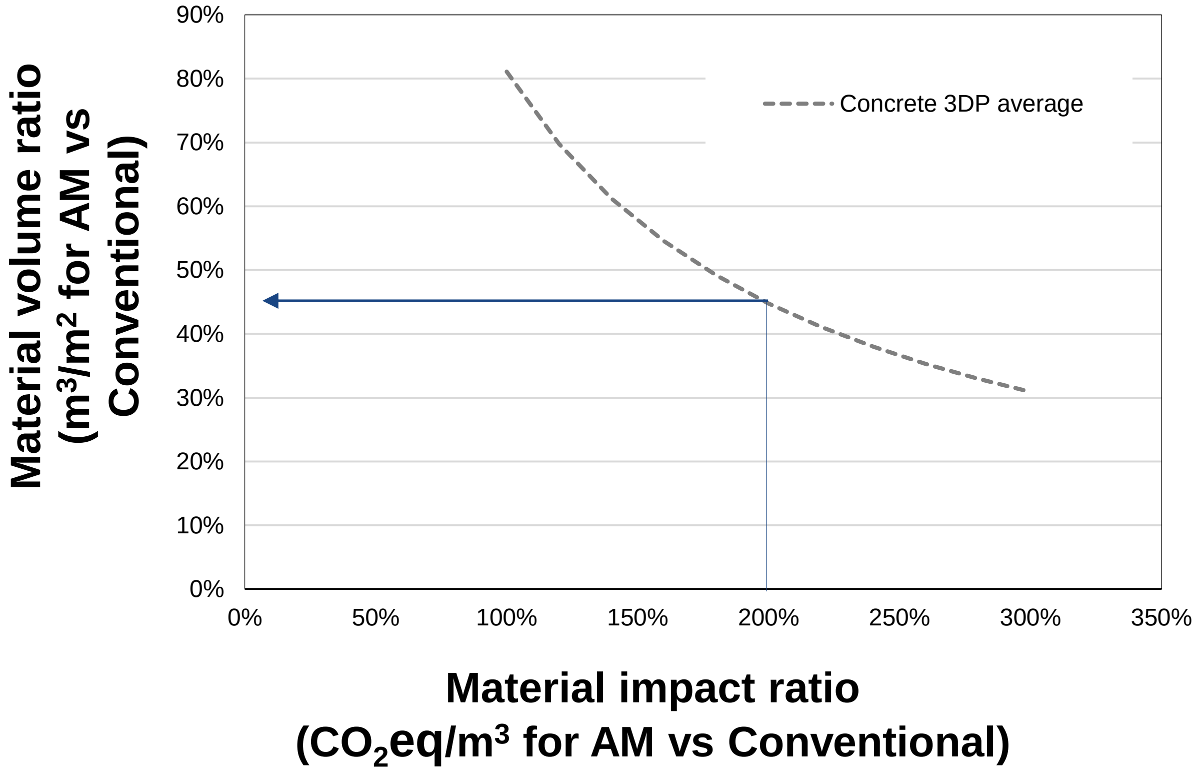




Digital fabrication increases both embodied emission from material and process

→ Need to save material through structural optimization

Conventional vs 3dP considering environmental impact



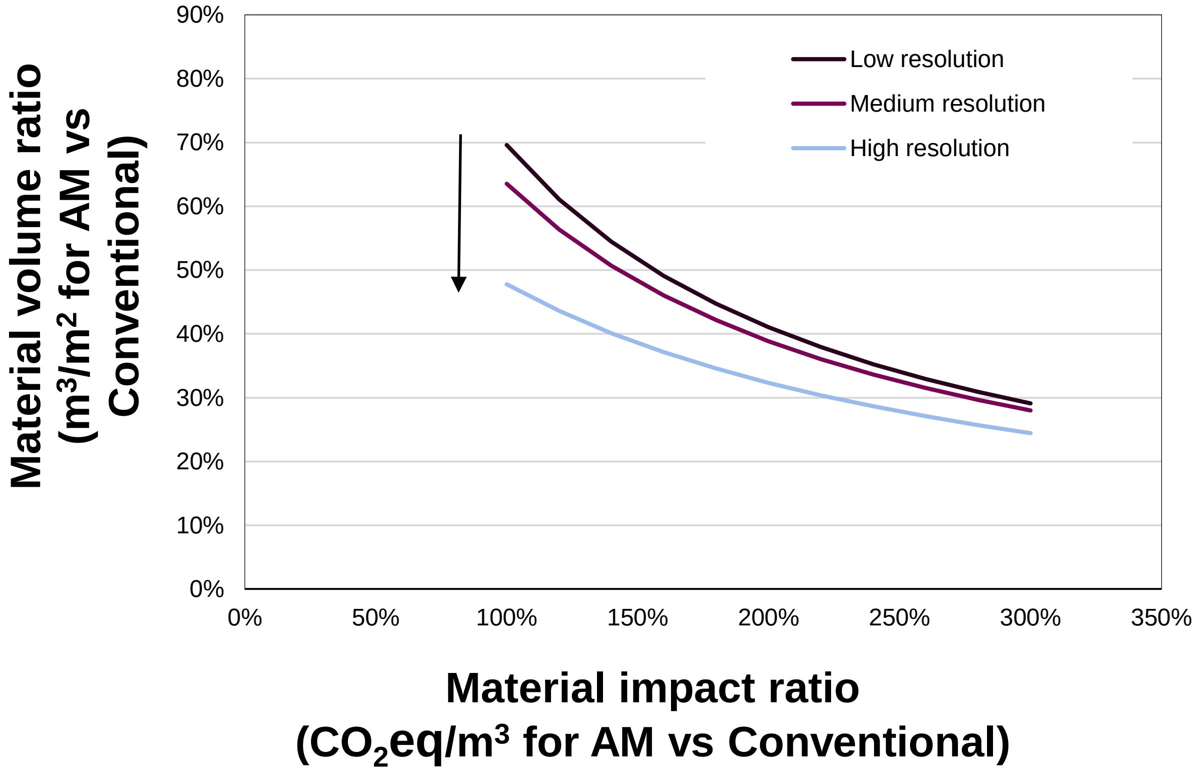
Material Impact Ratio between 3DP Concrete vs Conventional equal to **200% means twice higher** impact per m^3

So the Material volume ratio indicates how much material should be save to balance this extra impact

45% means 3DP Concrete uses **55% less material per m^2** to mitigate the impact

Data from Kuzmenko K. et al. 2022. Environmental impact of extrusion-based additive manufacturing: generic model, power measurements and influence of printing resolution. *Cement and Concrete Research*

Conventional vs 3dP considering environmental impact

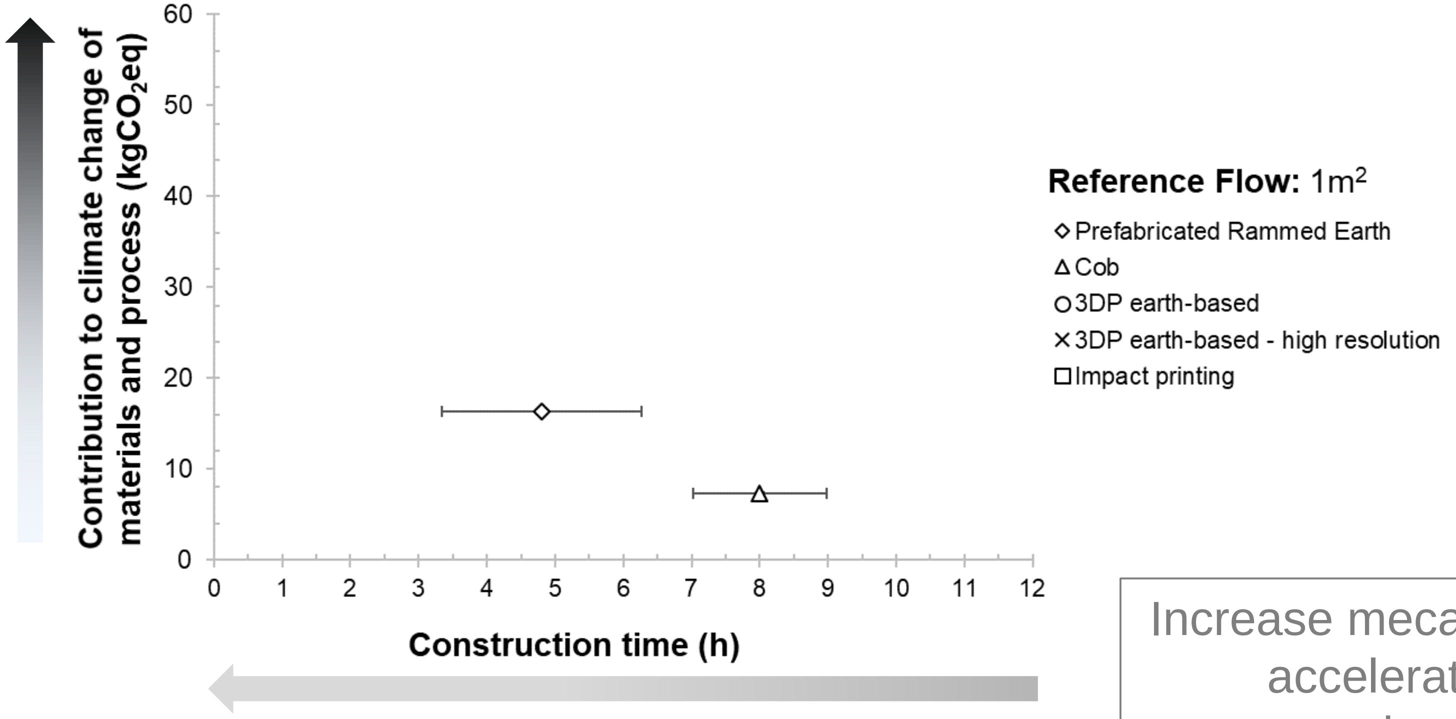


AM vs Prefabricated Rammed earth

– such processes have the same economic viability considering time and cost of construction

Conventional vs 3dP: Productivity and Environmental Impact

higher resolution increases the environmental impact



Increase mecanisation accelerates construction speed

Key Take-away

Earth-based materials are a great candidate for applications in digital fabrication

Increase the embodied emission and make the final impact of the building element higher

High resolution exhibit a disproportionately high environmental impact while not necessarily being more efficient in terms of construction time

Low resolution allows to provide both a high productivity while maintaining low environmental impact of construction

THANK YOU FOR YOUR ATTENTION

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