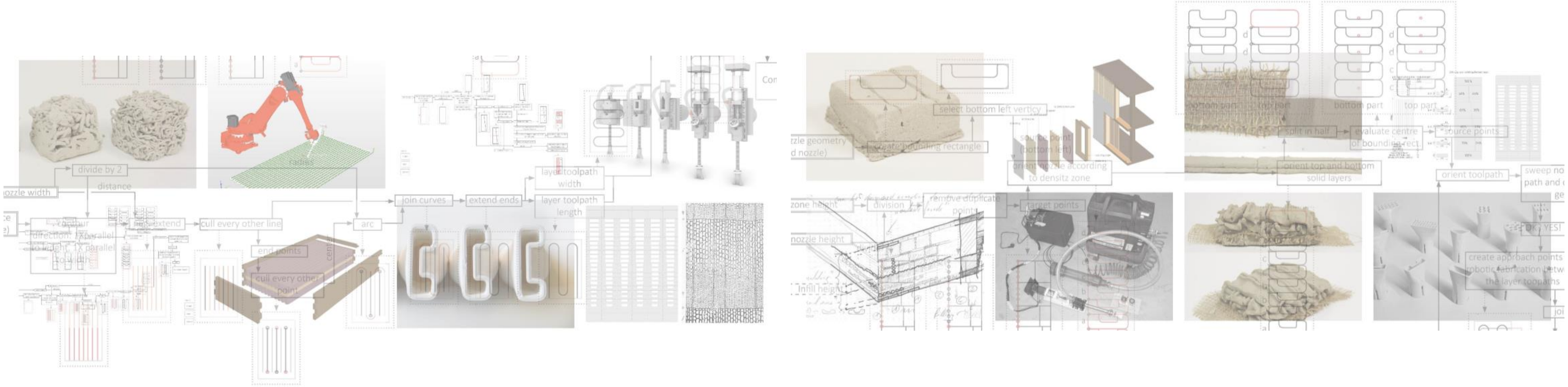
TU Delft
MSc Architecture, Urbanism & Building Sciences
Building Technology Track

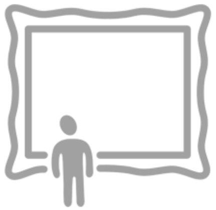
R obotic 3 D P rinting E arth

Robotic 3D Printing a Pre-Fab Wall Component With Earth

Student: Maximilian Mandat 4931068
1st Mentor: Dr. Serdar Aşut
2nd Mentor: Dr. Ing. Marcel Bilow
Delegate Examiner : Dr. Andrej Radman

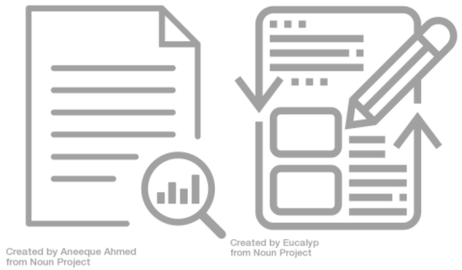


Content



Introduction

Background / Aim
Objectives
State of the Art
Hypothesis
Research Question



Research by Design

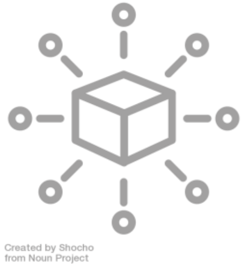
Experiments:
- Material
- Toolpath and Nozzles

Result Evaluation

Design

Gradient Material
Nozzle
Building Component

Conclusion



Outlook

Impact
Discussion
Reflection

Background

Current state

- Industrial Building Materials

  Pollution / emissions, difficult to recycle

- Large-Scale 3DPrinting

  Single nozzle on site, mostly concrete printing

- Robotic Fabrication

  Efficient, mass-customizable

  Prefabrication, possibly low carbon footprint

Background / Aim

- Material

  No waste, carbon neutral, bio-based, circular

- Building Environment

  Clay tradition + digitalisation = acknowledged culture

- 3D Printing

  Allows automated fabrication and new fabrication methods

Background / Aim

- Context, Location

    - Developed countries

    - Multi-storey buildings

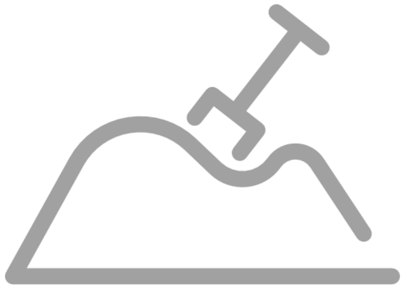
    - Dense urban areas

- Mainstreaming Clay

Developed countries

Area of traditional clay constructions

Problem Statement



Material

- Mixtures
- Properties (Wet/Dry)
- Interlayer Bonding
- Cracks (Production/drying)

Production

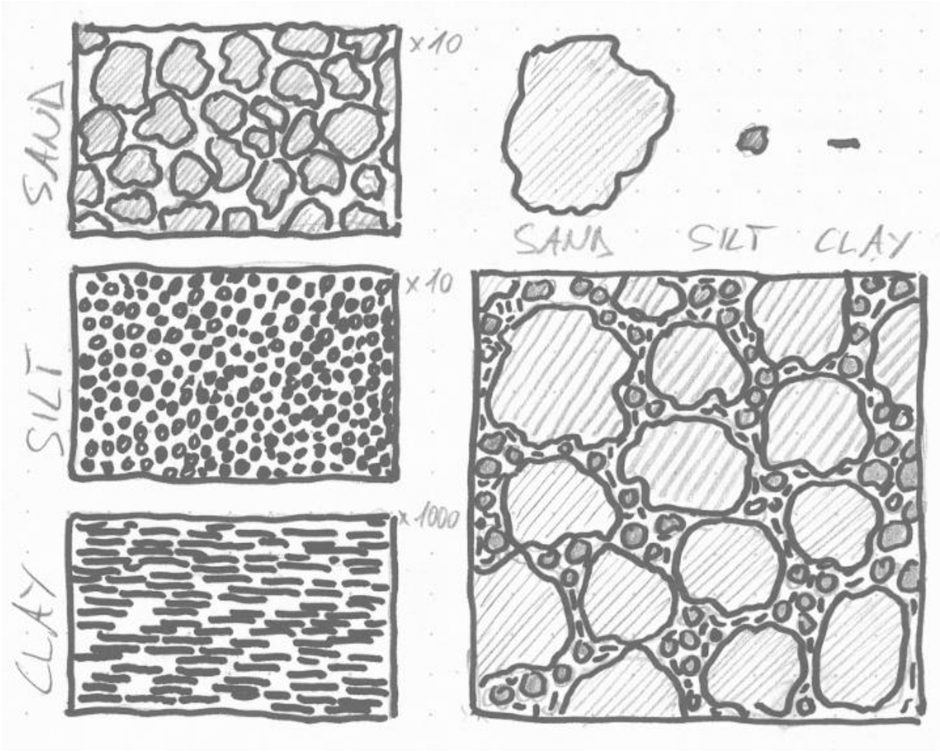
- Uniform Nozzle
- Large-Scale Extrusion
- Toolpath
- Long Cycle-Time

Component Design

- Market Niche
- Monofunctional
- Infill Design
- Size

- Pro’s of Earth
  - Circular
  - Low embodied energy
  - Highly available
  - Low material costs

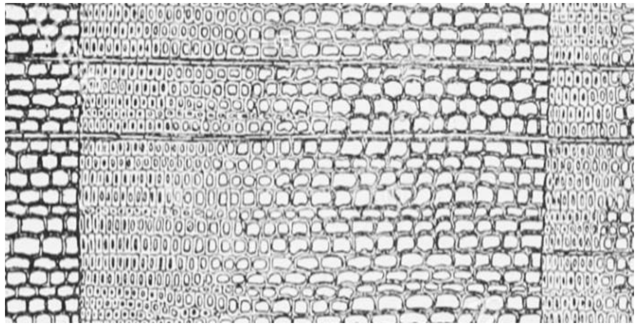
- Con’s of Earth
  - High labour costs
  - Limited building height
  - Low social status
  - Low structural strength



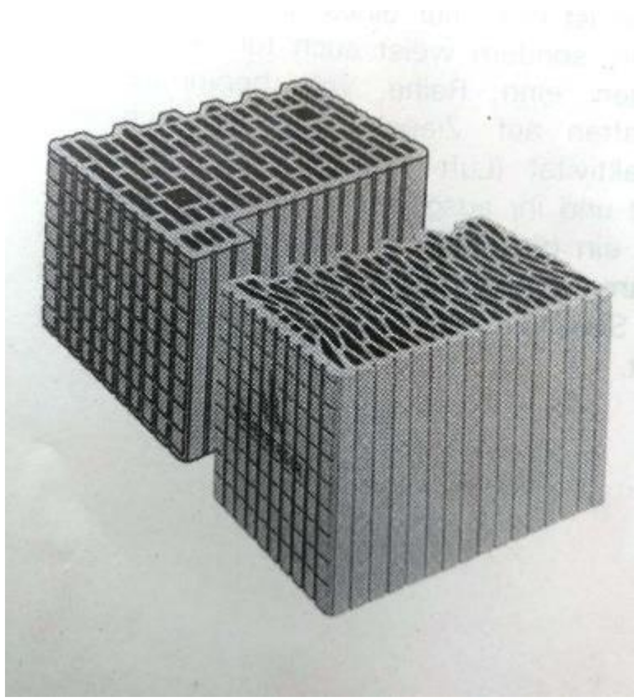
Grain size difference

State of the Art - Material, Production/3DPE, Building Component

- Gradient Material
  - Functionally Graded Material (FGM)
  - Possible on demand performance
- Porosity
  - Less weight
  - Higher insulation



Natural Gradient Material



Vertically Perforated Brick (VPB) to increase the insulation

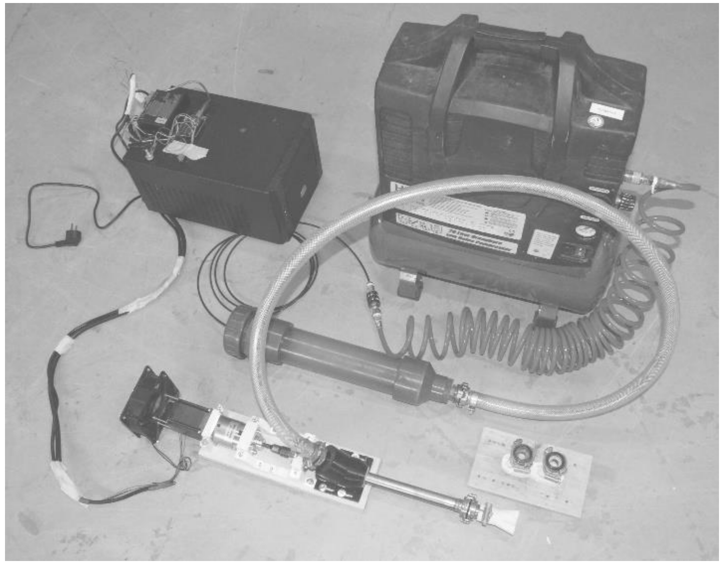
- Recyclability
  - No Energy
  - No Chemicals/Toxins
  - No Waste
  - Circular

Before 1 min. 24 h 36 h

State of the Art - Material, Production/3DPE, Building Component

- Single Nozzle Print
    - Inefficient for complex cross-section pattern
- In-Situ vs. Pre-Fab
- Printing Set-Up
    - Finite / Infinite
    - Clay / Concrete

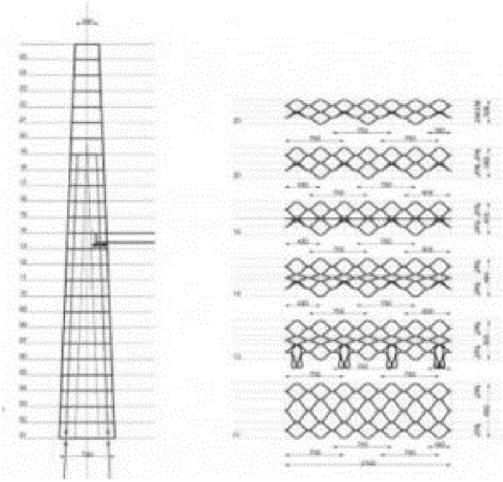
Delta WASP 3MT INDUSTRIAL 4.0 LDM



DIY Motorized Extruder Finite Set-Up

- Monolithic
  - Solid, massive, load-bearing construction
  - Height limited by material strength

Eden, Rammed Earth Pre-Fab Element



IAAC, Digital Adobe

- Hybrid
  - Skeleton carries “light” infills
  - Height limited by skeleton

Eden, Timber Skeleton

Traditional Clay-Timber Hybrid

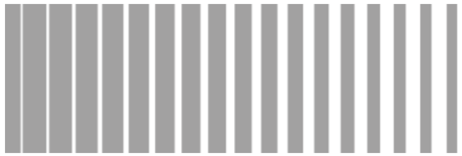
Research Question

- How can a gradient 3d printed clay wall be produced by customizing the nozzles within the limitations of the production process and the material?

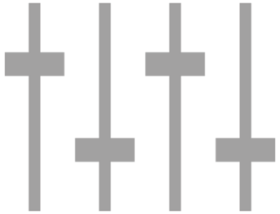
Hypothesis

- How can a gradient 3d printed clay wall be produced by customizing the nozzles?

- By designing a Functionally Gradient Material (FGM)
  - 3DPE allows the production of an earthen gradient material

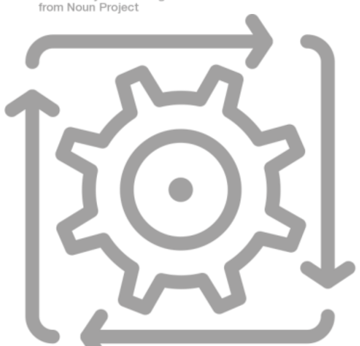


- By customizing the nozzles to print this FGM
  - Complex Nozzle = Simple Toolpath



Created by Alice Design
from Noun Project

- By establishing an informative workflow between:
  - Nozzle Design
  - Component Design
  - Production



Created by Flatart
from Noun Project

Objectives

- Material
  - Extrudable Material Mixture
  - Functionally Gradient Material (FGM)
- Production / 3DPE
  - Extruder
  - Nozzle Design
  - Informative Workflow for production limitations
- Component Design
  - FGM Material Infill
  - Building Component Design

Mainstreaming earth as a building material

Research by Design- Experiments

- Material Experiments:

  Manual extruder

- Toolpath and Nozzle Experiments:

  Robotic arm = INACCESIBLE due to lockdown

  - ADAPTATION : Manual Extruder = imprecise extrusion flow and movement

  - Manual experiments are valid but not repeatable

  - For consistent, repeatable results the experiments should be conducted with the robotic arm and the motorized extruder

- Three Soil Types: A,B,C - different clay and sand content
- Additive Materials: Cellulose Pulp, Straw, Milled Grain

Mixtures of soils and additive materials

	Mixture	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Soil Type	A	B	A	A	A	A-B	C	A	A	A	A	A	A	B
Earth	Clay	30	50	30	30	30	40	70	30	30	30	30	30	30	7,5
	Sand	70	50	70	70	70	60	30	70	70	70	70	70	70	7,5
Additives	Cellulose Pulp	-	-	-	-	-	-	-	-	30	-	-	-	-	-
	Straw	10	-	-	10	-	-	-	30	-	-	40	30	-	85
	Milled grain	-	-	-	-	-	-	-	-	-	20	-	-	20	-
	Water	25	20	30	25	20	20	20	25	-	45	35	35	60	3

Mix 1

Mix 6

Mix 2

Mix 7

Mix 14

Mixtures of soils and additive materials

Mixture		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Soil Type		A	B	A	A	A	A-B	C	A	A	A	A	A	A	B
Earth	Clay	30	50	30	30	30	40	70	30	30	30	30	30	30	7,5
	Sand	70	50	70	70	70	60	30	70	70	70	70	70	70	7,5
Additives	Cellulose Pulp	-	-	-	-	-	-	-	-	30	-	-	-	-	-
	Straw	10	-	-	10	-	-	-	30	-	-	40	30	-	85
	Milled grain	-	-	-	-	-	-	-	-	-	20	-	-	20	-
Water		25	20	30	25	20	20	20	25	-	45	35	35	60	3

Mix 1

Soil	A
Mixture:	1
Clay:	30
Sand:	70
Water:	25
Nozzle:	Rect.
Shrinkage:	1%
Production cracks:	Barely
Drying cracks:	No
Deformation:	Barely

Mix 6

Soil	A-B
Mixture:	6
Clay:	40
Sand:	60
Water:	20
Nozzle:	R=6mm
Shrinkage:	1%
Production cracks:	Yes
Drying cracks:	No
Deformation:	Barely

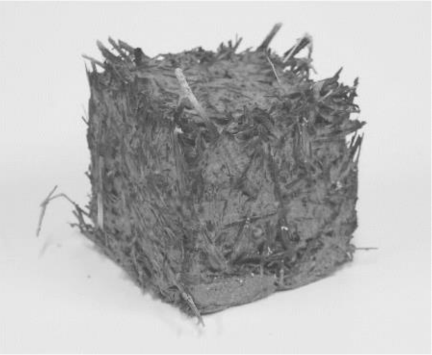
Mix 2

Soil	B
Mixture:	2
Clay:	50
Sand:	50
Water:	20
Nozzle:	R=6mm
Shrinkage:	1%
Production cracks:	No
Drying cracks:	No
Deformation:	Barely

Mix 7

Soil	C
Mixture:	7
Clay:	30
Sand:	70
Water:	20
Nozzle:	R=6mm
Shrinkage:	1%
Production cracks:	NO
Drying cracks:	No
Deformation:	Barely

Mix 14



Soil	B
Mixture:	14
Clay:	7,5
Sand:	7,5
Straw:	85
Water:	20
Mould:	Yes
Shrinkage:	1%
Production cracks:	No
Drying cracks:	No
Deformation:	No

Mix 1

Soil	A
Mixture:	1
Clay:	30
Sand:	70
Water:	25
Nozzle:	Rect.
Shrinkage:	1%
Production cracks:	Barely
Drying cracks:	No
Deformation:	Barely

Mix 6

Soil	A-B
Mixture:	6
Clay:	40
Sand:	60
Water:	20
Nozzle:	R=6mm
Shrinkage:	1%
Production cracks:	Yes
Drying cracks:	No
Deformation:	Barely

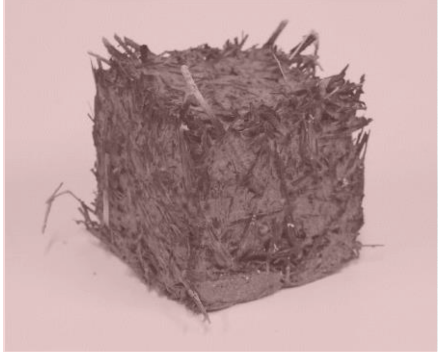
Mix 2

Soil	B
Mixture:	2
Clay:	50
Sand:	50
Water:	20
Nozzle:	R=6mm
Shrinkage:	1%
Production cracks:	No
Drying cracks:	No
Deformation:	Barely

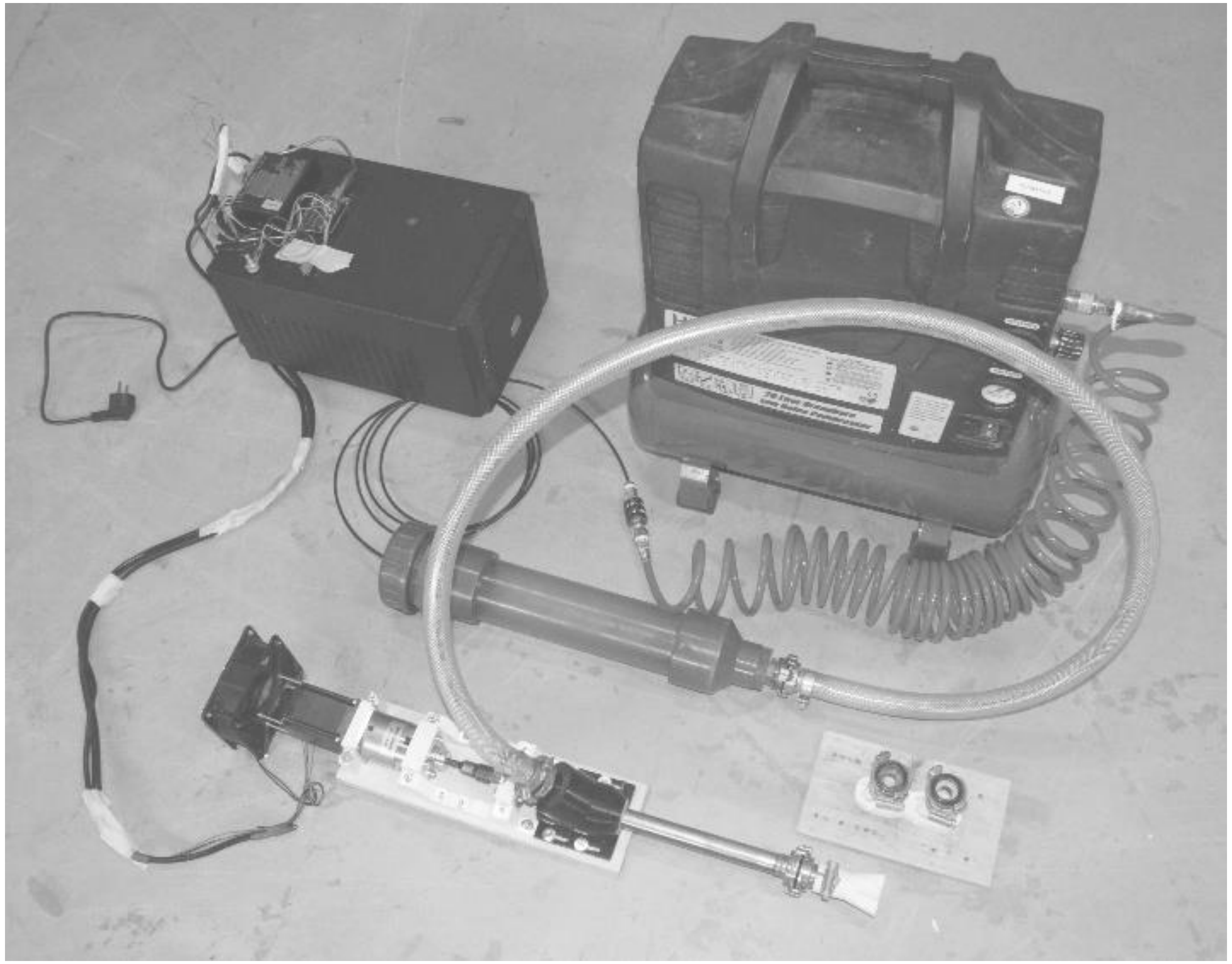
Mix 7

Soil	C
Mixture:	7
Clay:	30
Sand:	70
Water:	20
Nozzle:	R=6mm
Shrinkage:	1%
Production cracks:	NO
Drying cracks:	No
Deformation:	Barely

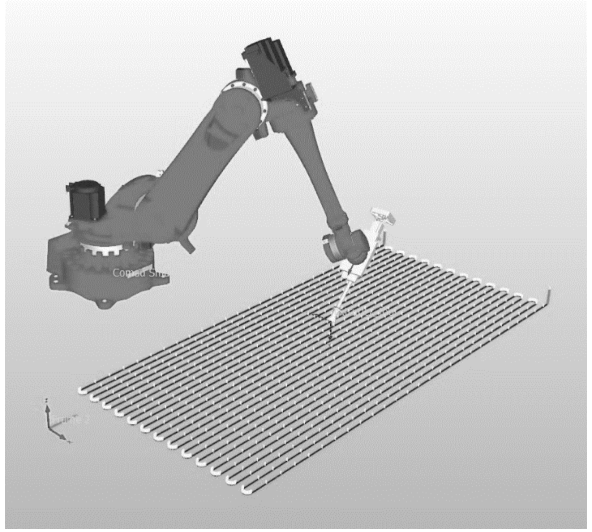
Mix 14



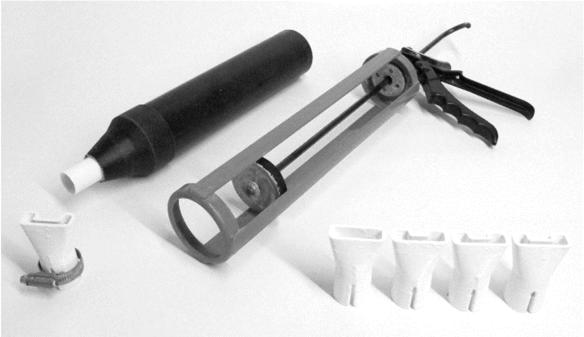
Soil	B
Mixture:	14
Clay:	7,5
Sand:	7,5
Straw:	85
Water:	20
Mould:	Yes
Shrinkage:	1%
Production cracks:	No
Drying cracks:	No
Deformation:	No



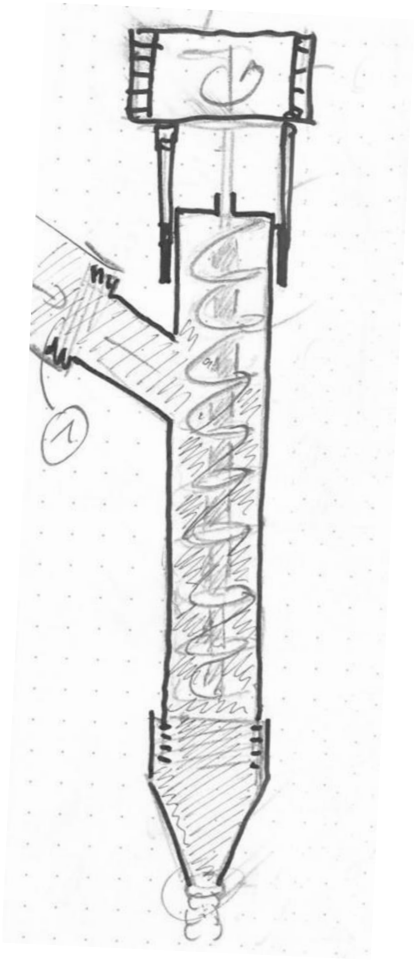
Finite printing Set-Up



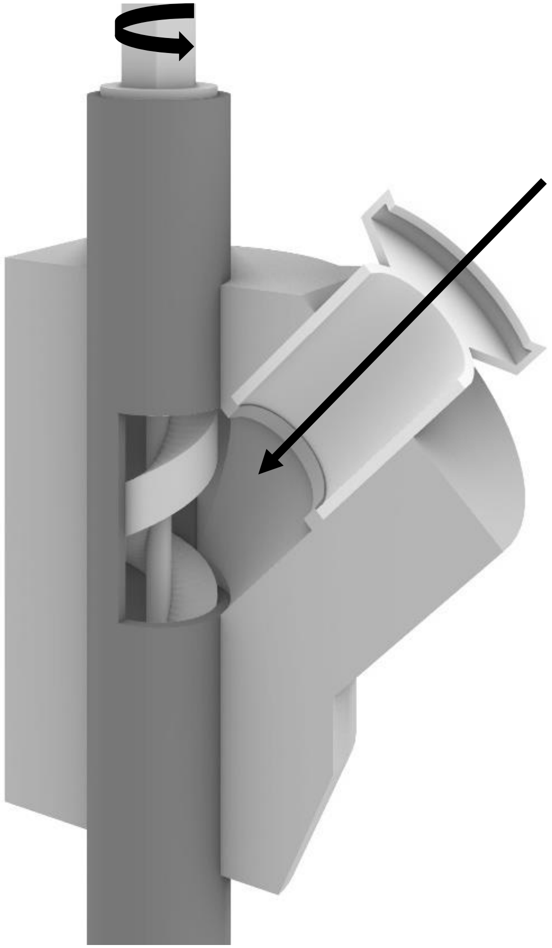
Comau NJ60 2.2



Manual Extruder



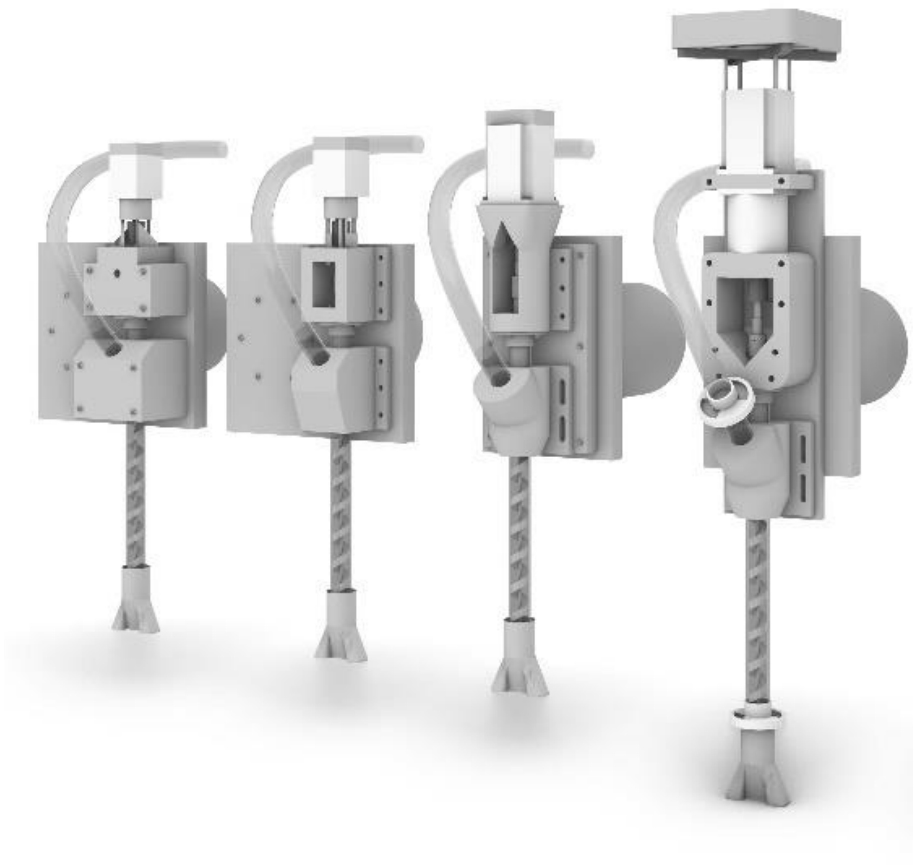
Extruder principle

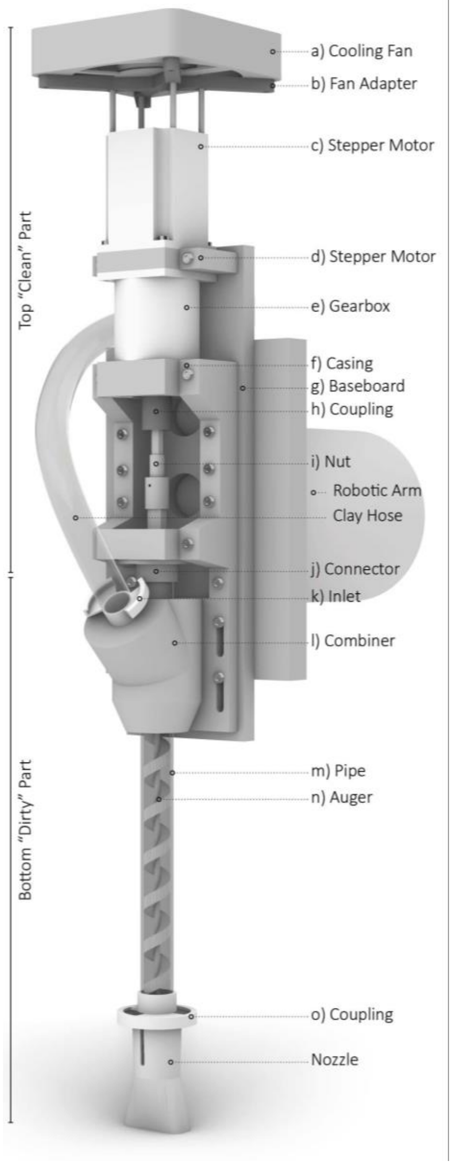


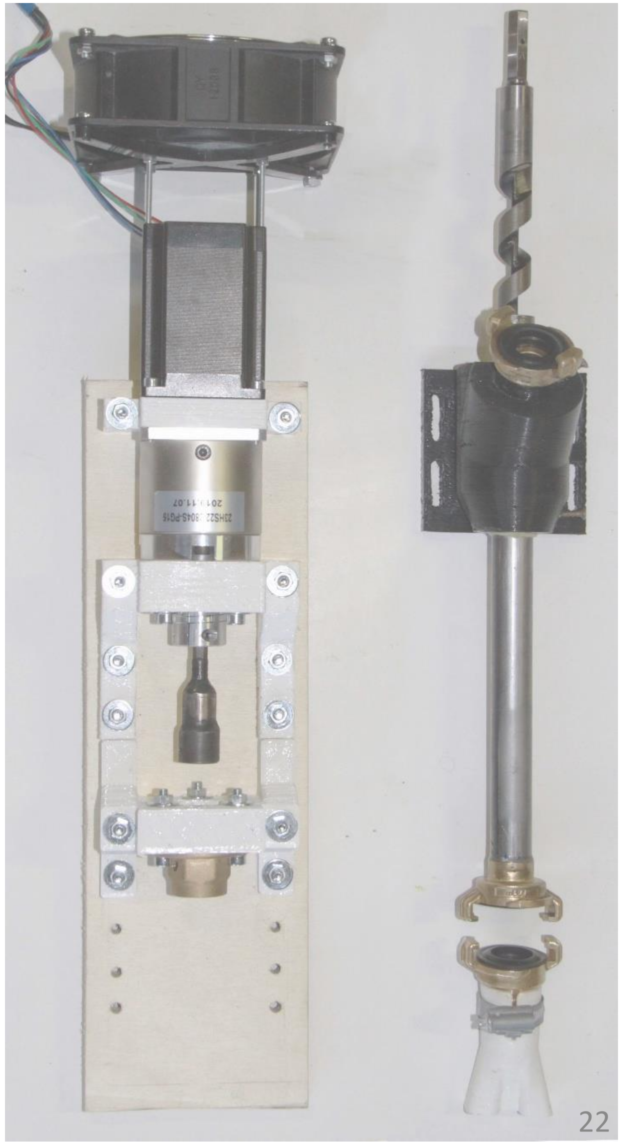
Realised Design

Research by Design- Experiments

Material, Production/3DPE – DIY Extruder



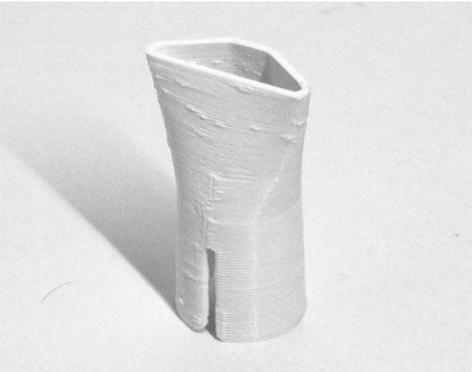




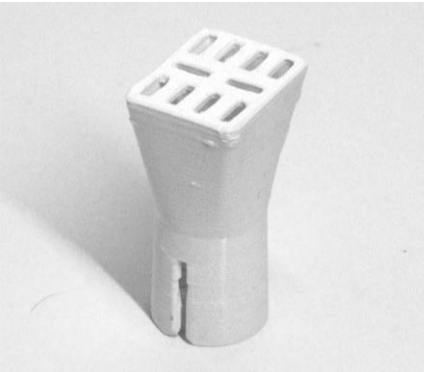
Rectangular

12x41mm

U-Shaped

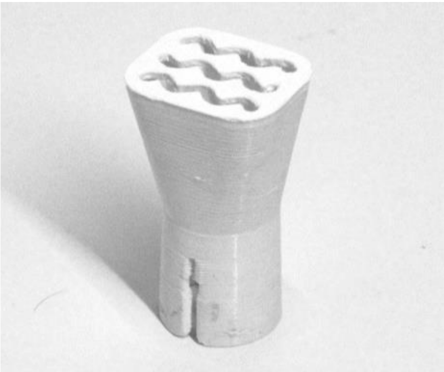


Triangular

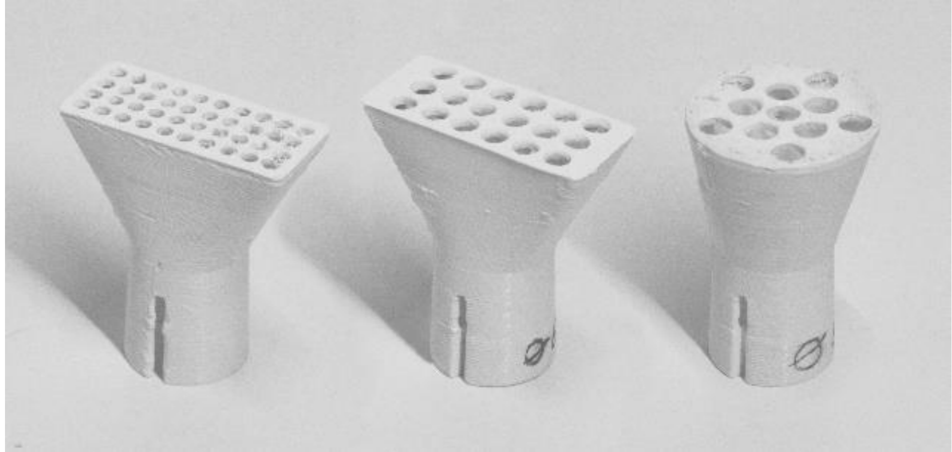


„Tagliatelle”

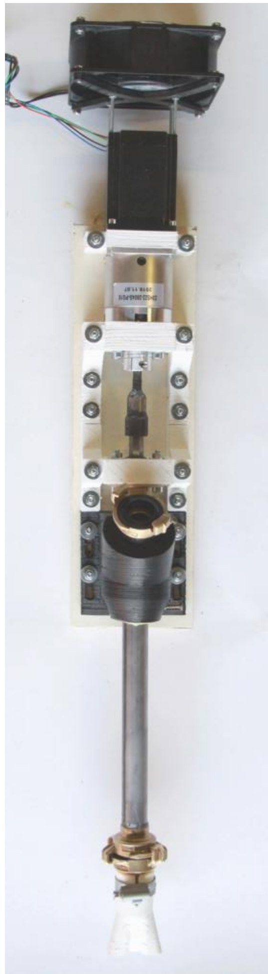
10x 3x12mm



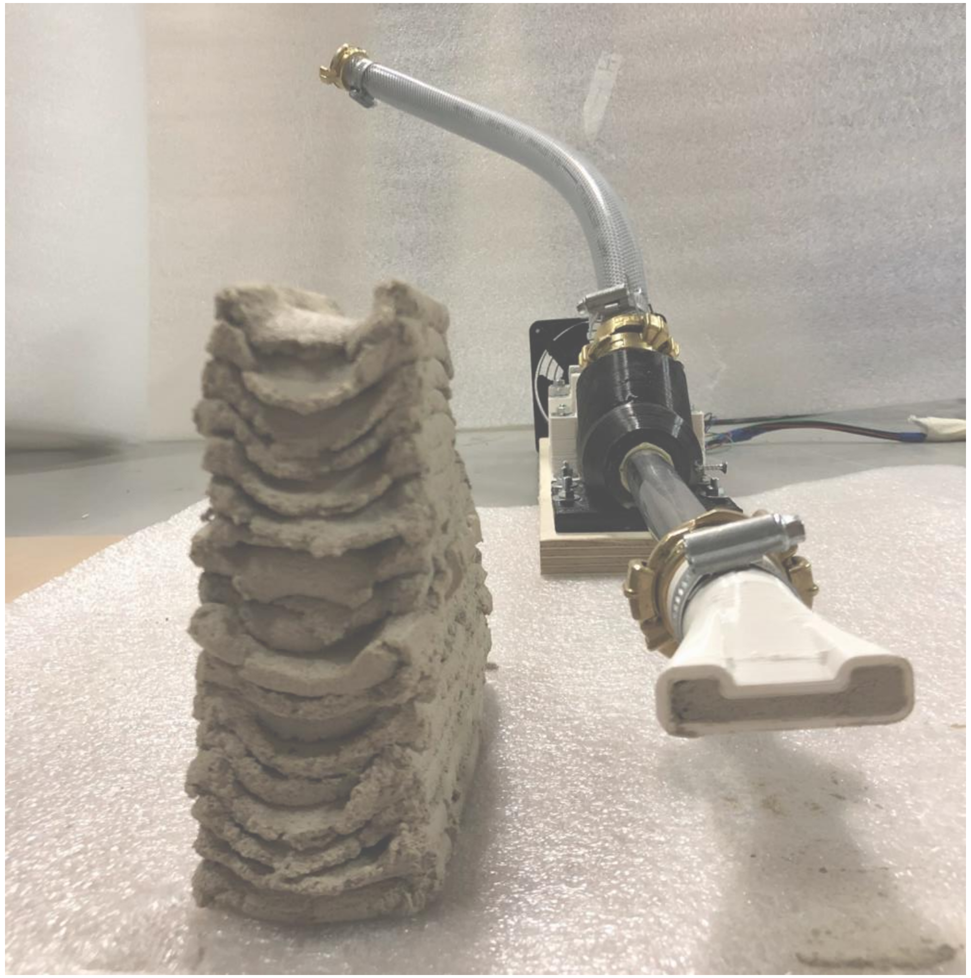
S-Shaped



“Spaghetti” 40x r=2mm,18x r=3mm,11x r=4mm



Assembled Extruder



First successful motorized extrusion

Constant material flow

Automated nozzle change between several production steps

a. Single layer extrusion

b. Stacked layer extrusion-
bridging

c. Stacked layer extrusion-
interlayer bonding, web bridging, compression

d. Chaotic snaking, waved extrusion

e. Interlayer Mesh

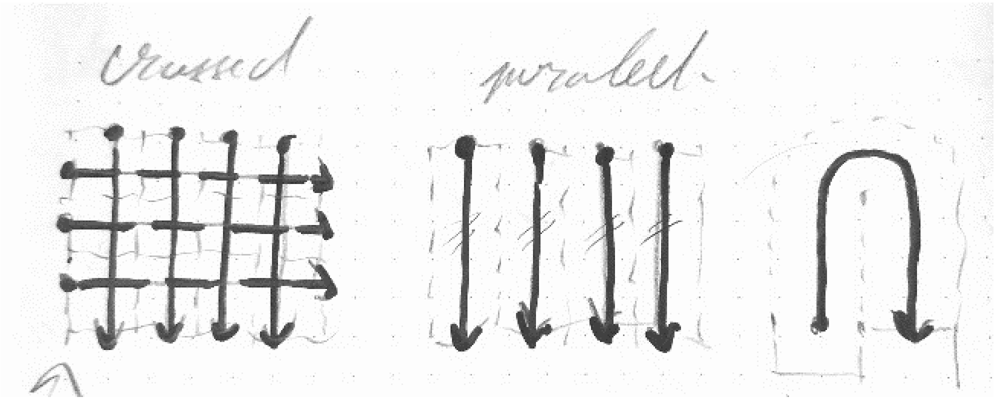
a. Single layer extrusion

b. Stacked layer extrusion- bridging

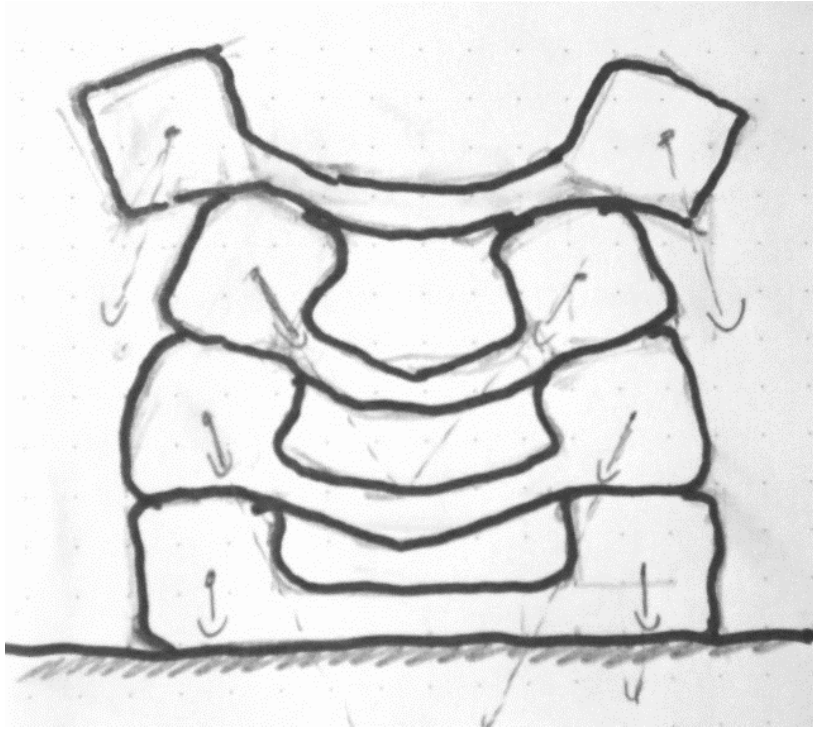
c. Stacked layer extrusion-
interlayer bonding, web bridging, compression

d. Chaotic snaking, waved extrusion

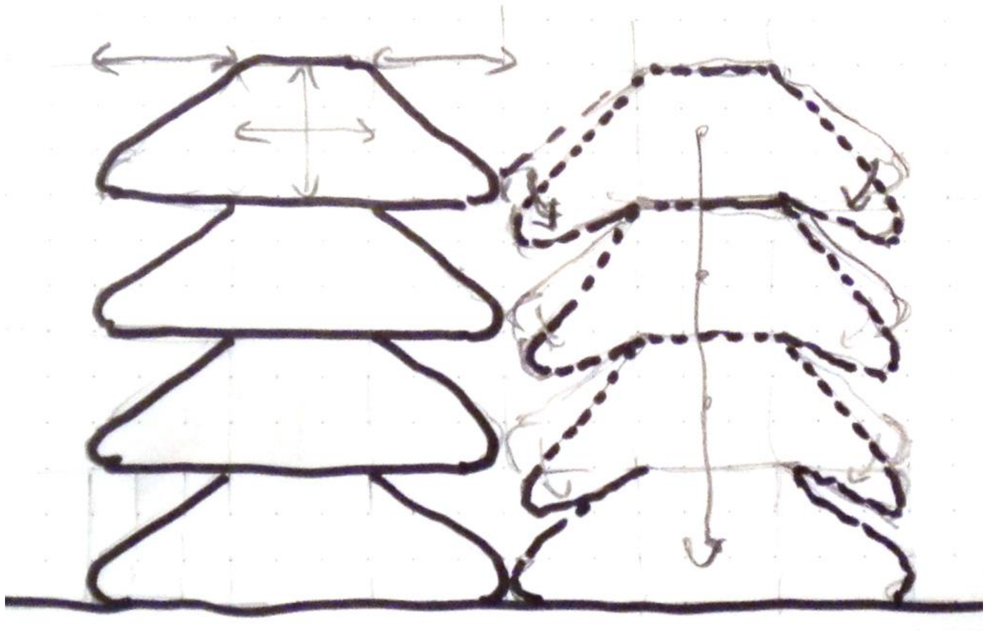
e. Interlayer Mesh



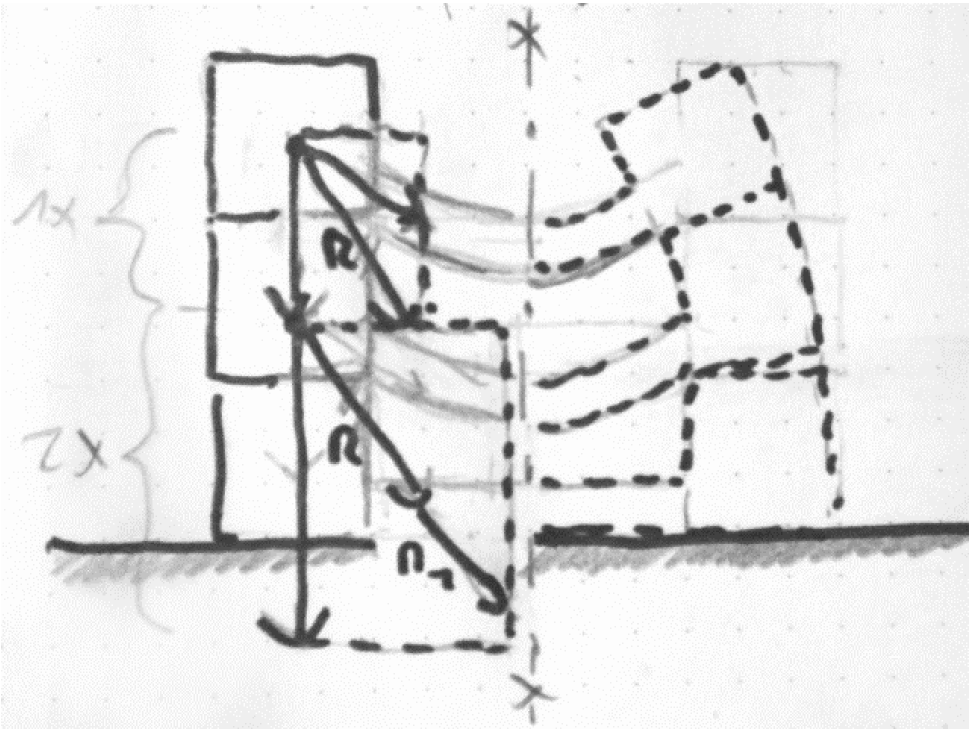
Toolpath c., crossed, parallel, curved



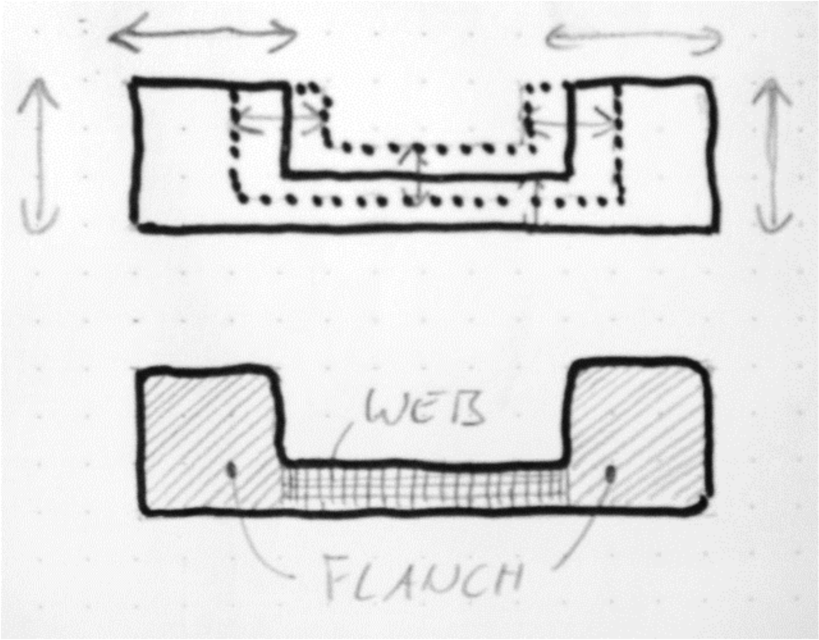
Deformation, collapsing extrusion



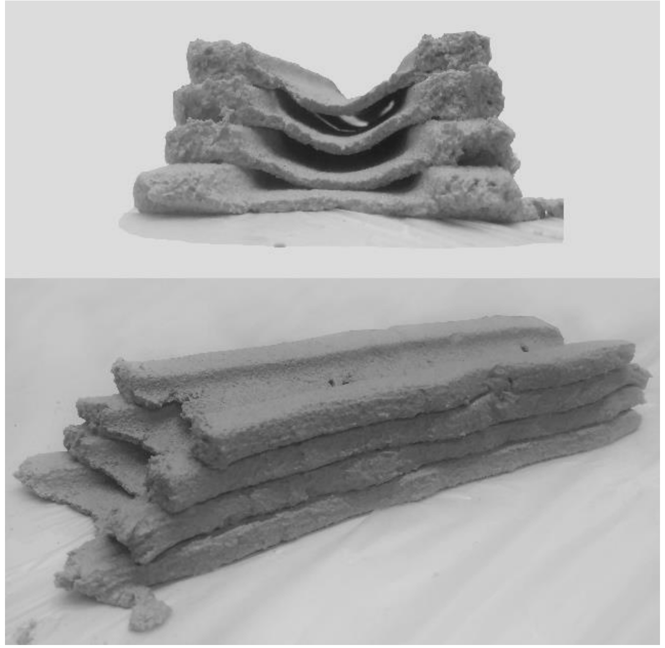
Centre is influencing the stability



Forces within the extrusion geometry



Flange dimension influences the stability

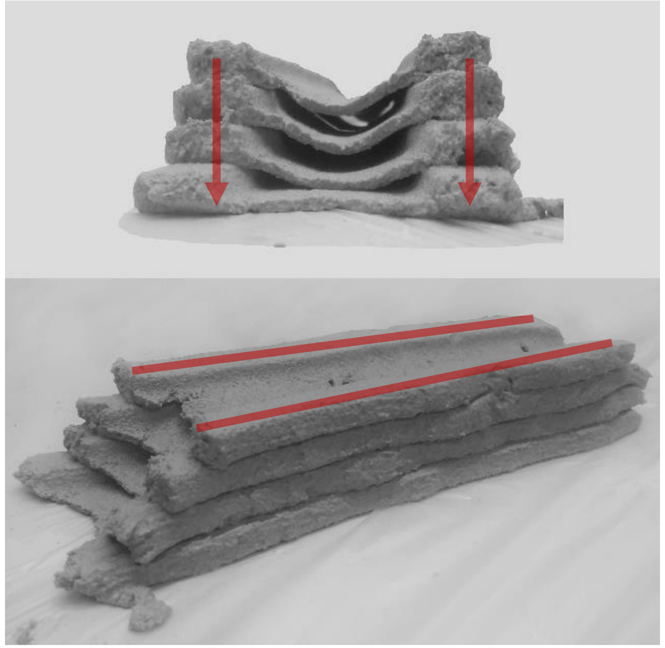


Wide flange = stable extrusion

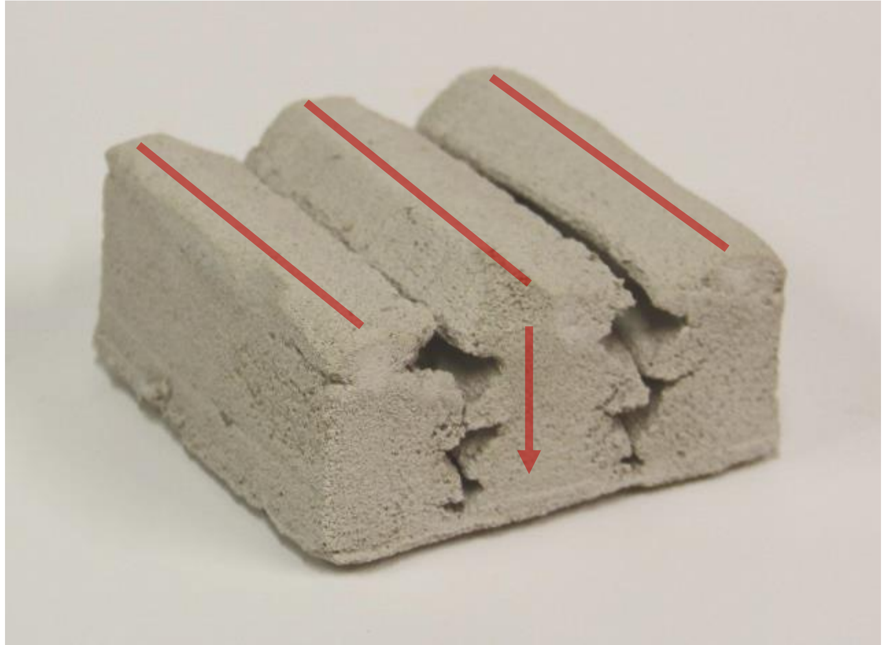
Narrow flange = unstable extrusion

Load distribution over centre = stable extrusion

- Parallel toolpath = line load


Wide flange = stable extrusion


Narrow flange = unstable extrusion


Load distribution over centre = stable extrusion


U-2


U-3


U-4

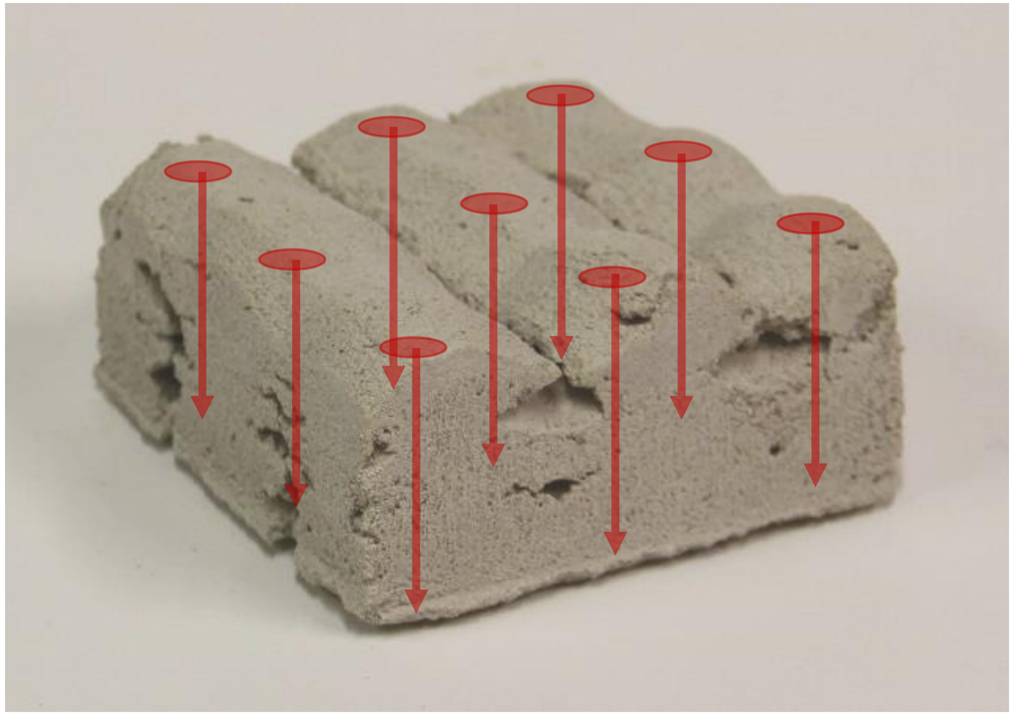

U-5

U-5 Nozzle , stacked, crossed-extrusion

Triangular Nozzle, stacked, crossed-extrusion

- Crossed toolpath = point load = higher load = higher compression

U-5 Nozzle , stacked, crossed extrusion



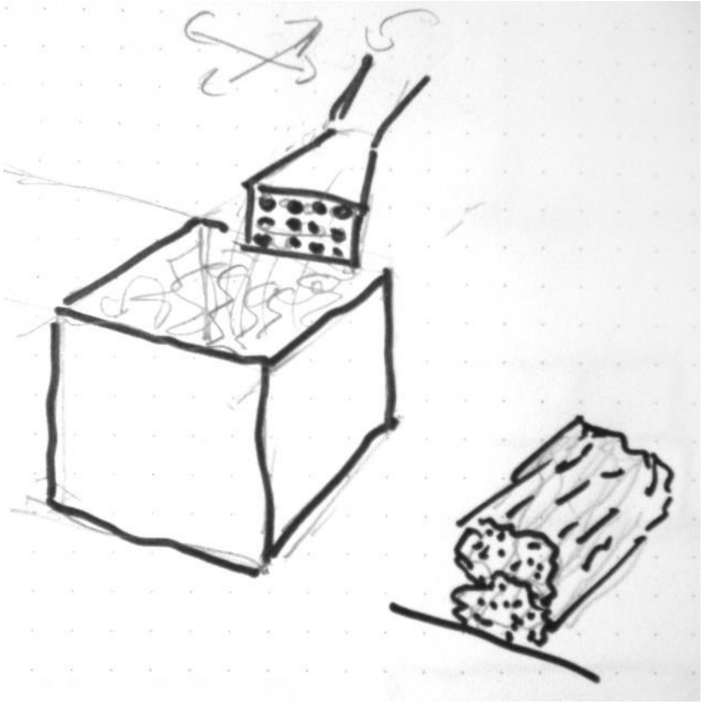
Triangular Nozzle, stacked, crossed extrusion

a. Single layer extrusion

b. Stacked layer extrusion- bridging

c. Stacked layer extrusion-
interlayer bonding, web bridging, compression

d. Chaotic snaking, waved extrusion



Toolpath d.

e. Interlayer Mesh

Compression due to self-weight is visible at the bottom

Enclosed air reduces the density

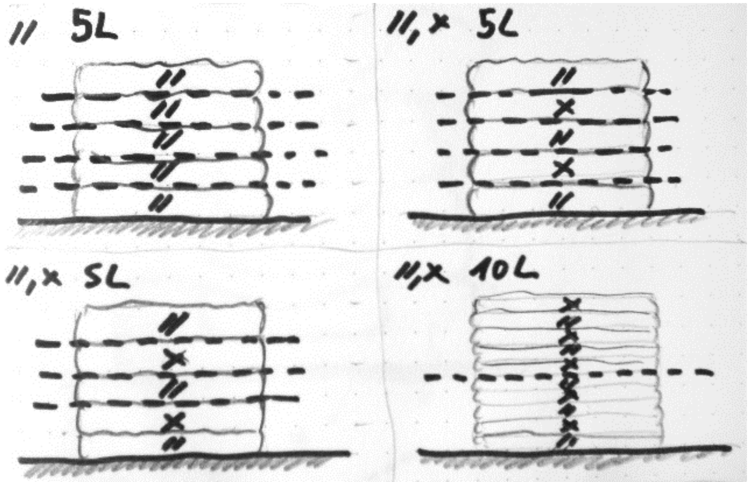
a. Single layer extrusion

b. Stacked layer extrusion- bridging

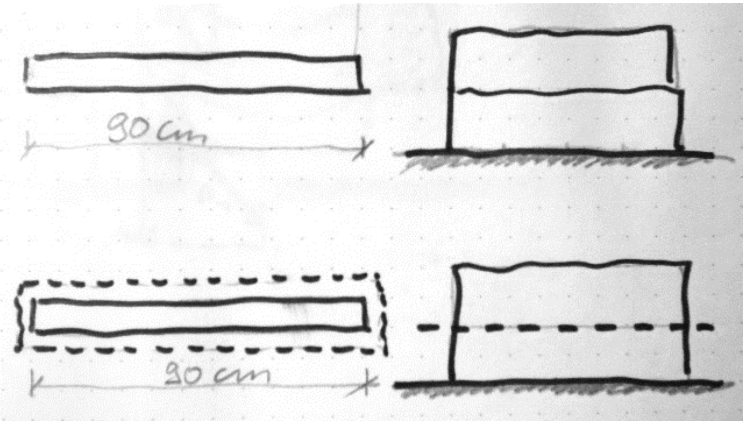
c. Stacked layer extrusion- interlayer bonding, web bridging, compression

d. Chaotic snaking, waved extrusion

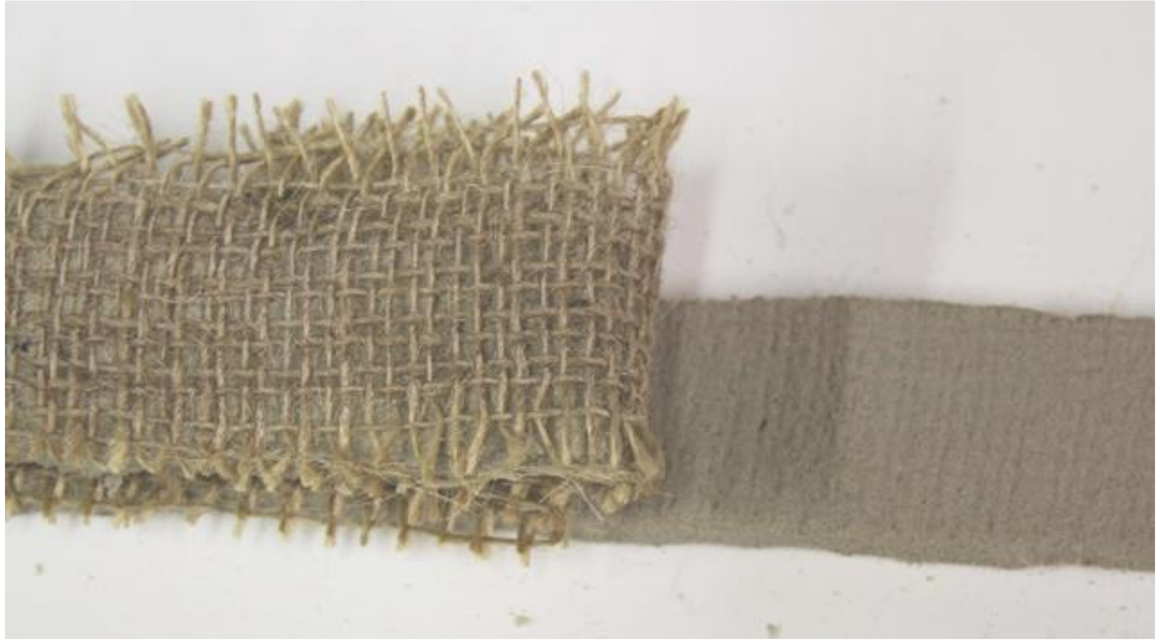
e. Interlayer Mesh



Toolpath e.



Toolpath e. – shrinkage



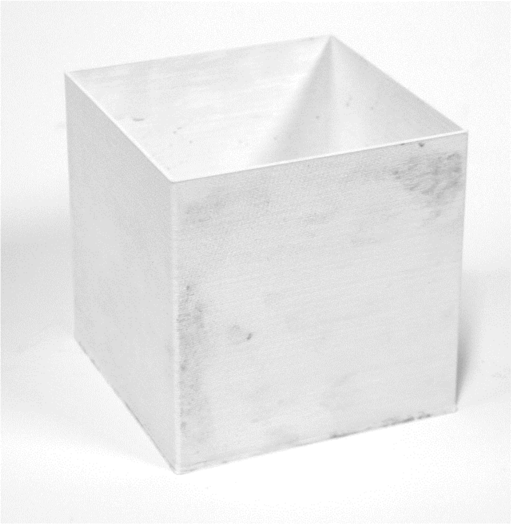
Rectangular, straight extrusion with interlayer mesh

= bad interlayer bonding

U-shaped straight extrusion with interlayer mesh

Research by Design- Experiments

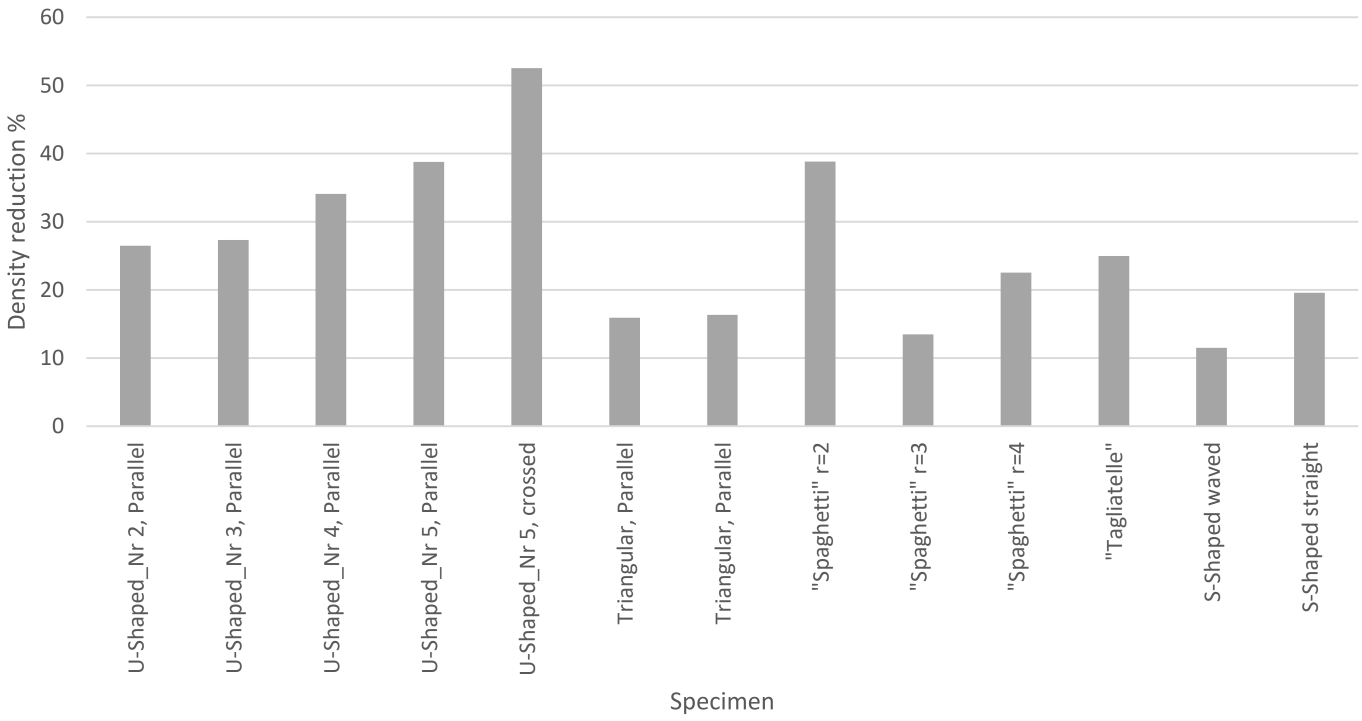
Material, Production/3DPE – Density evaluation



Density= Weight/Volume
d=W/V, V=a*a*a

NOZZLE / TOOLPATH	DENSITY[KG/M³]
VPB	650
STRAW CLAY (COMPRESSED)	970
STRAW CLAY (LOOSE)	600
CAST CUBE	1629
RECTANGULAR, PARALLEL	1747
U-SHAPED_NR. 2, PARALLEL	1197
U-SHAPED_NR. 3, PARALLEL	1184
U-SHAPED_NR. 4, PARALLEL	1073
U-SHAPED_NR. 5, PARALLEL	997
U-SHAPED_NR. 5, CROSSED	773
TRIANGULAR, PARALLEL	1369
TRIANGULAR, PARALLEL	1362
"SPAGHETTI" R=2, RANDOM	996
"SPAGHETTI" R=3, RANDOM	1410
"SPAGHETTI" R=4, RANDOM	1262
"TAGLIATELLE", RANDOM	1222
S-SHAPED, WAVED	1441
S-SHAPED, STRAIGHT	1310

Density reduction compared to solid rectangular extrusion [%]



Compression under self-weight with interlayer mesh

SPECIMEN	Height	Layers	Designed Height	Compression [%]
U-5, PARALLEL, MESH EVERY LAYER	58	5	60	3,33
U-5, CROSSED, MESH EVERY LAYER	45	5	60	25,00
U-5, CROSSED, MESH EVERY OTHER	45	5	60	25,00
U-5, CROSSED, MESH EVERY 5 LAYER	74	10	120	38,33
U-5, CROSSED, MESH EVERY OTHER	45	5	60	25,00
DRAFT U-NOZZLE, PARALLEL, DRY MIX	132	18	162	18,52

Compression due to self-weight and crossed toolpath induced point load

Dry mixture and wide flanges result in low compression

Research by Design- Experiments

Statements regarding:

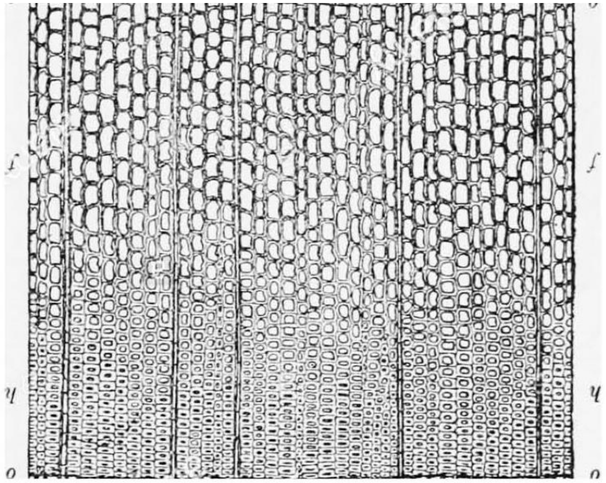
- Shrinkage
- Density
- Compression under self-weight
- Toolpath limitations
- Cracking during production
- Cracking during the drying process
- Interlayer bonding
- Nozzle influence on the extrusion geometry
- Extrusion angle and flow
- Material mixture
- Possible contour crafting
- Limitations of the production set up for a 1:1 prototype
- Productivity in relation to a conventional single nozzle production

Statements

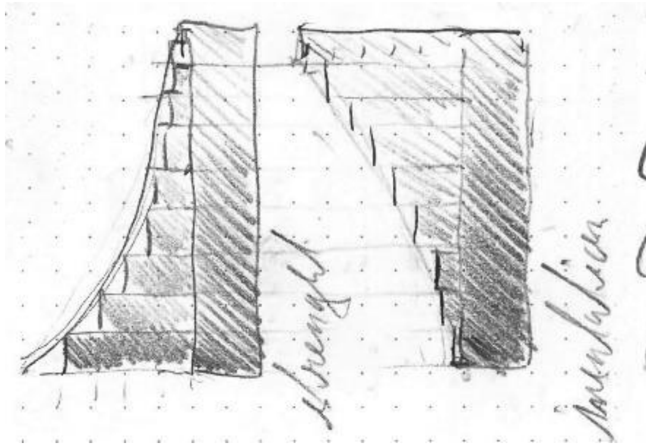
- Dry material mixture
- All nozzles have potential
- Parallel, crossed, chaotic toolpath is feasible
- Interlayer mesh: lower compression, lower interlayer bonding
- Drying process is crucial

Design- Goal : Nozzle, Gradient Material, Cross Section Pattern

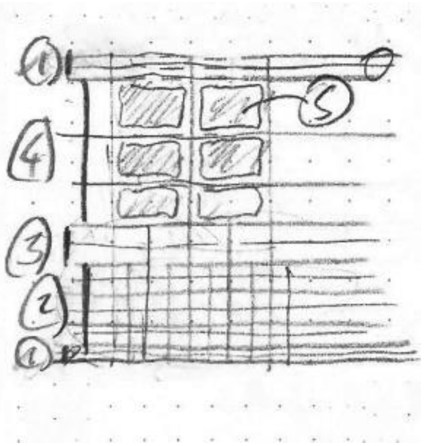
Gradient Material



Density shift within a wooden year ring

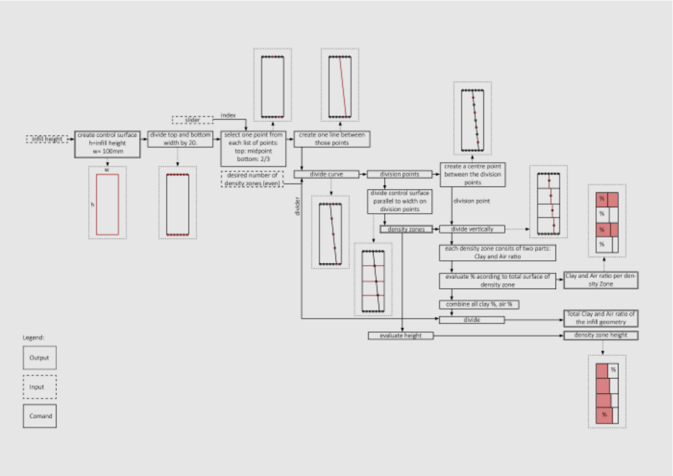


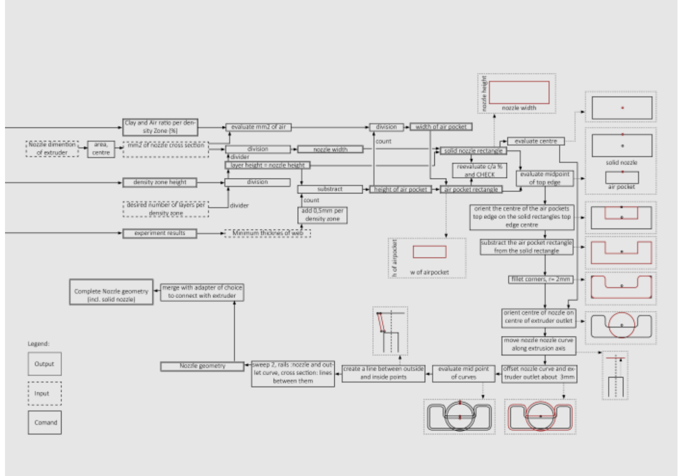
Stepwise functional shift

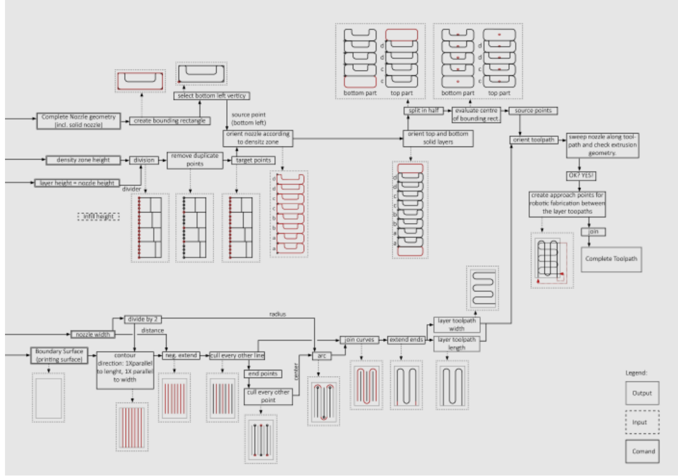


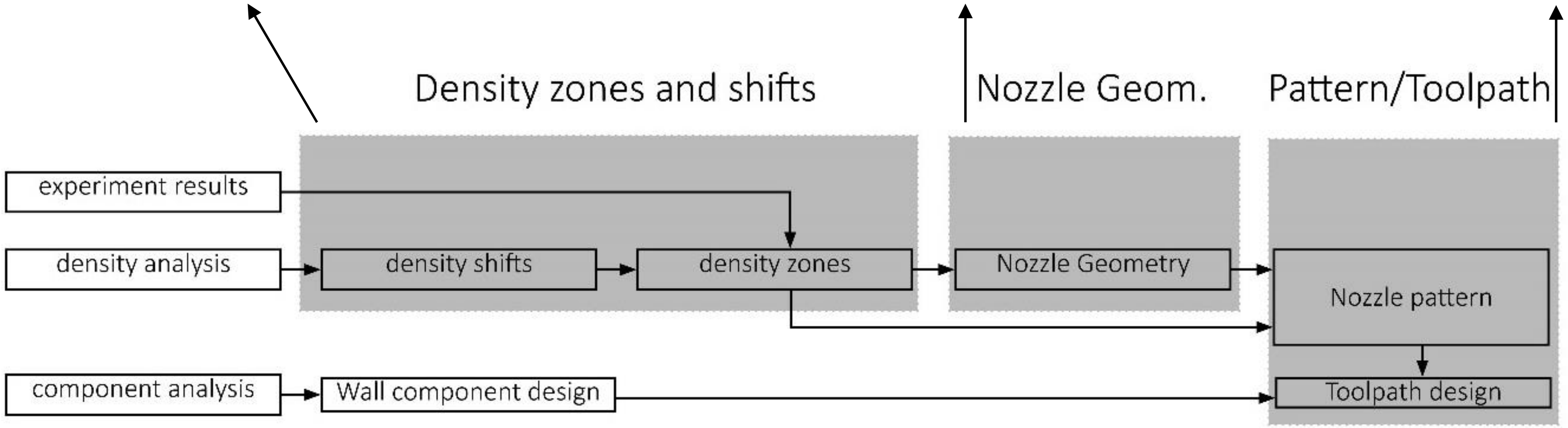
Idea of a stepwise gradation within the component

Design- Flowcharts

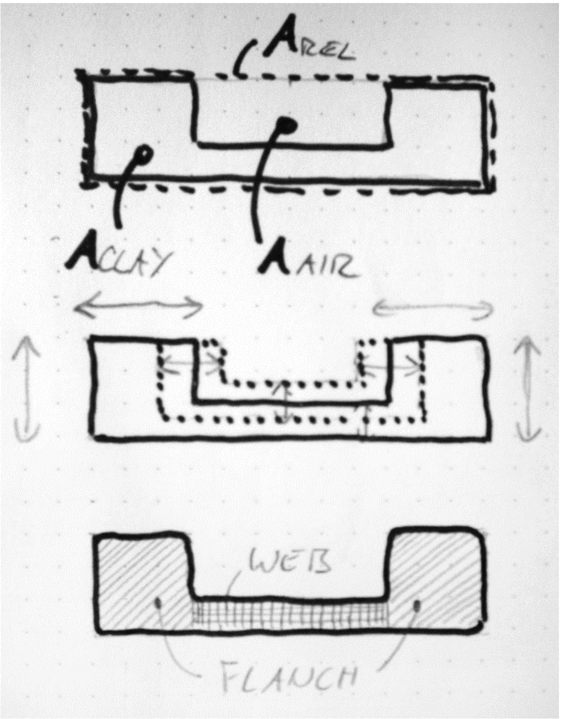




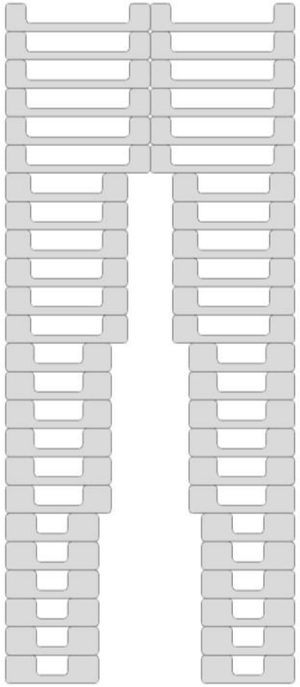




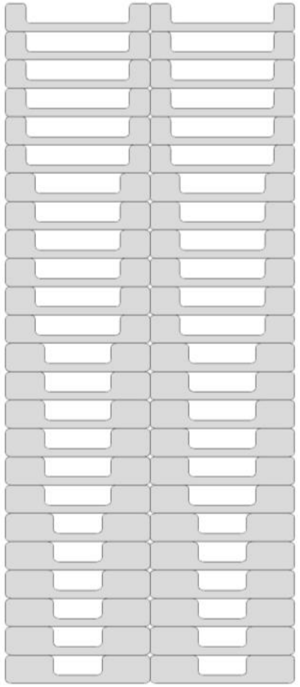
Design- Nozzle, Gradient Material, Cross Section Pattern



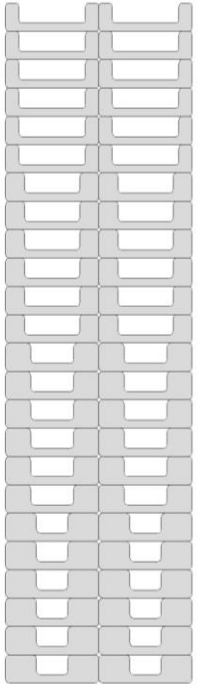
Clay and air ratio, adaptable proportions



Nozzle Area= 430mm²



Too much clay at the bottom



Faster printing on top

Design- Nozzle, Gradient Material, Cross Section Pattern

Toolpath length 2000-2300 m

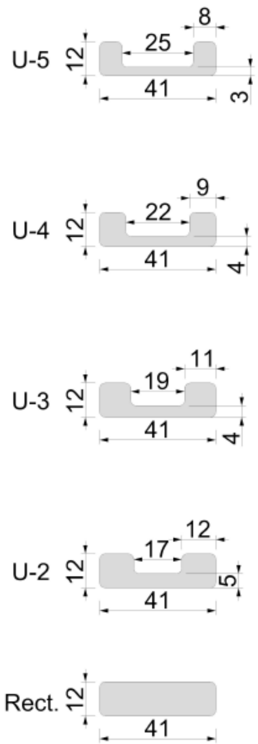
Design- Nozzle, Gradient Material, Cross Section Pattern

Toolpath length 2000-2300 m

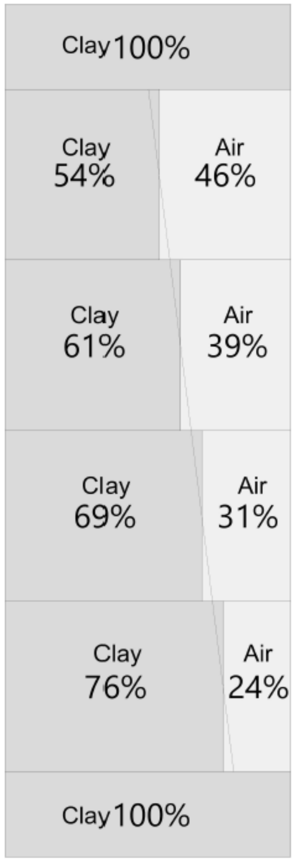
Design- Chosen settings for the gradient material infill

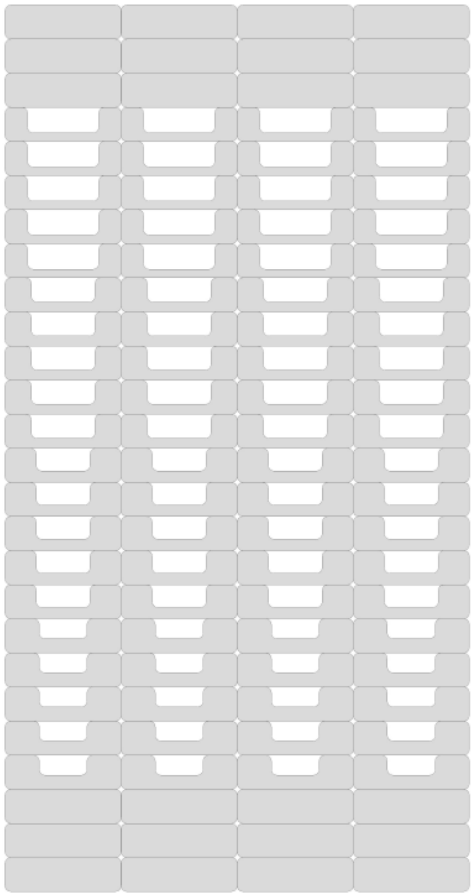
print speed [m/min]	printing time [h]	toolpath lenght [m]
2	18.3	2206
3	12.2	
4	9.1	
5	7.3	
6	6.1	
7	5.2	
8	4.5	

Density Zones	4
Layers/DZ	5
Solid Layers	3
Layers Total	26
Nozzle height Factor	7
density shift (index, top)	10
Density shift (index, bottom)	16



72% clay, excl. solid top/bottom layer

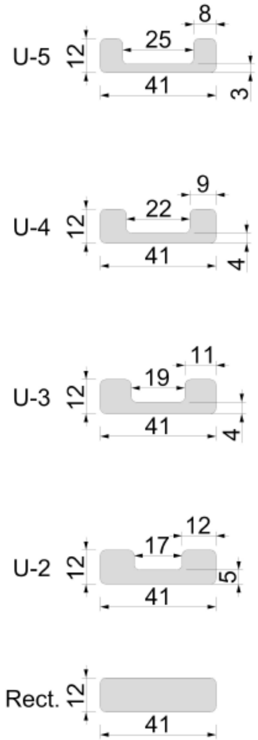




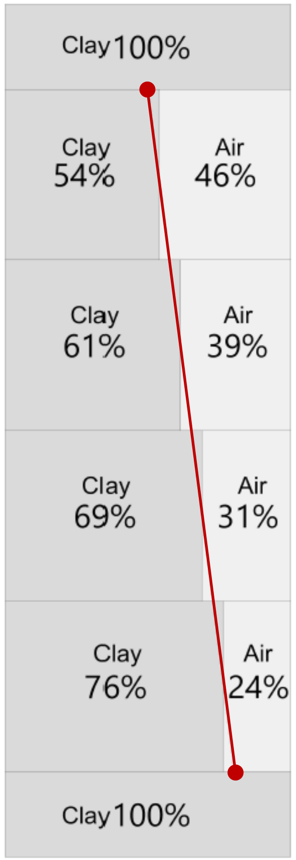
Design- Chosen settings for the gradient material infill

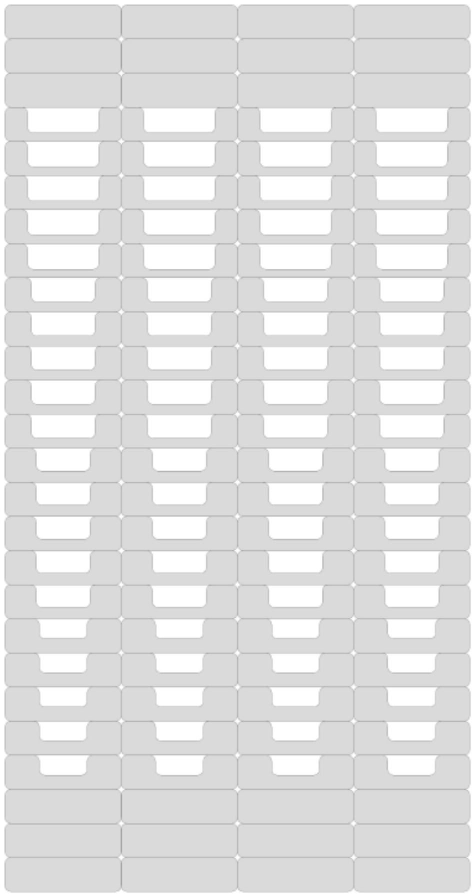
print speed [m/min]	printing time [h]	toolpath lenght [m]
2	18.3	2206
3	12.2	
4	9.1	
5	7.3	
6	6.1	
7	5.2	
8	4.5	

Density Zones	4
Layers/DZ	5
Solid Layers	3
Layers Total	26
Nozzle height Factor	7
density shift (index, top)	10
Density shift (index, bottom)	16

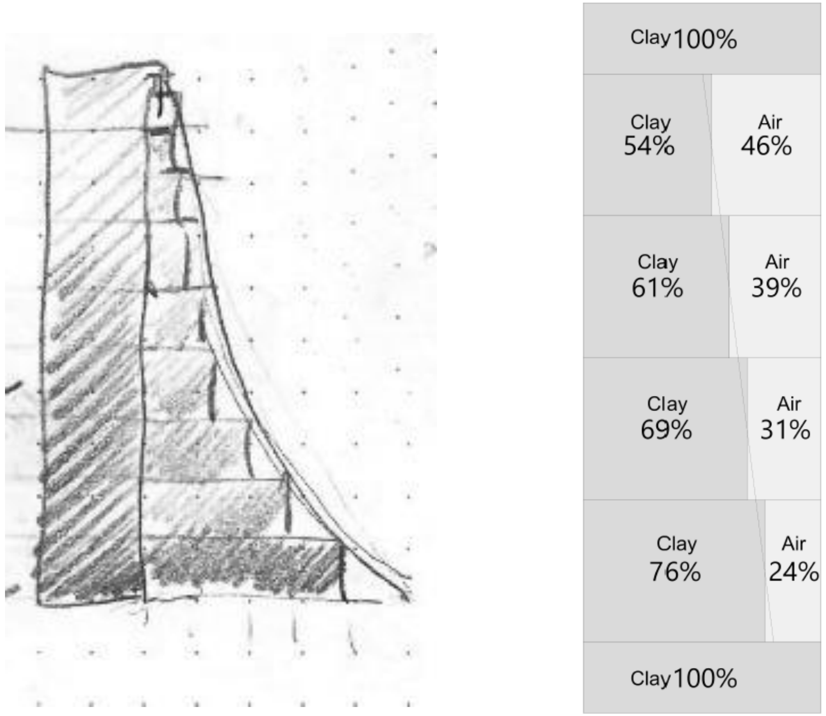


72% clay, excl. solid top/bottom layer

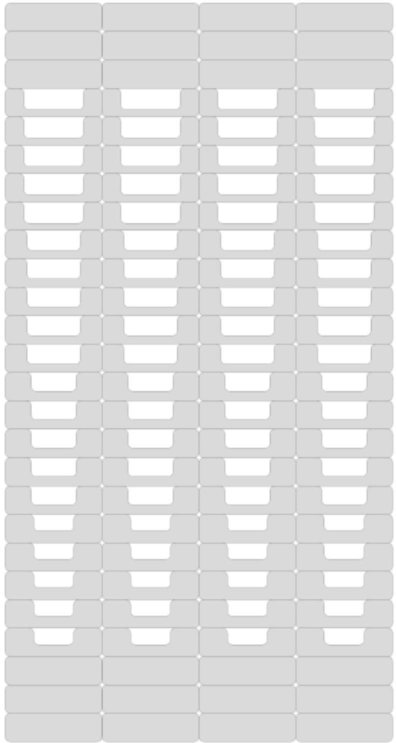




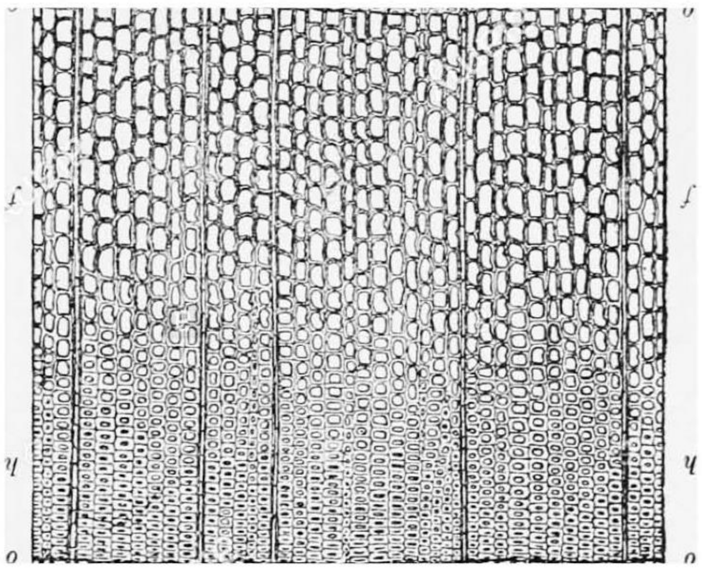
Design- Chosen settings for the gradient material infill



Stepwise gradation



Cross section pattern

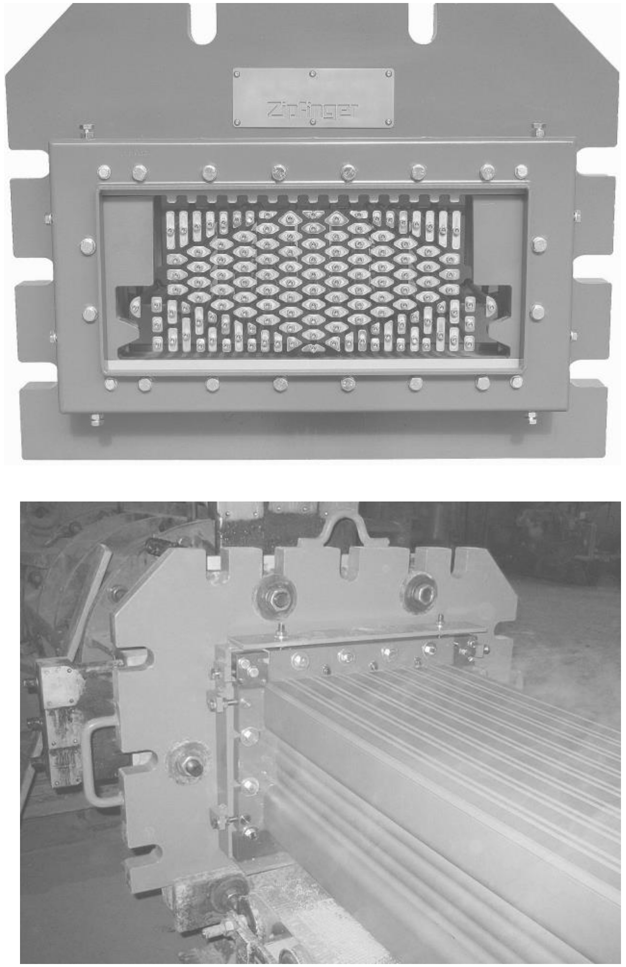


Concept idea of gradient shift

Extrusion

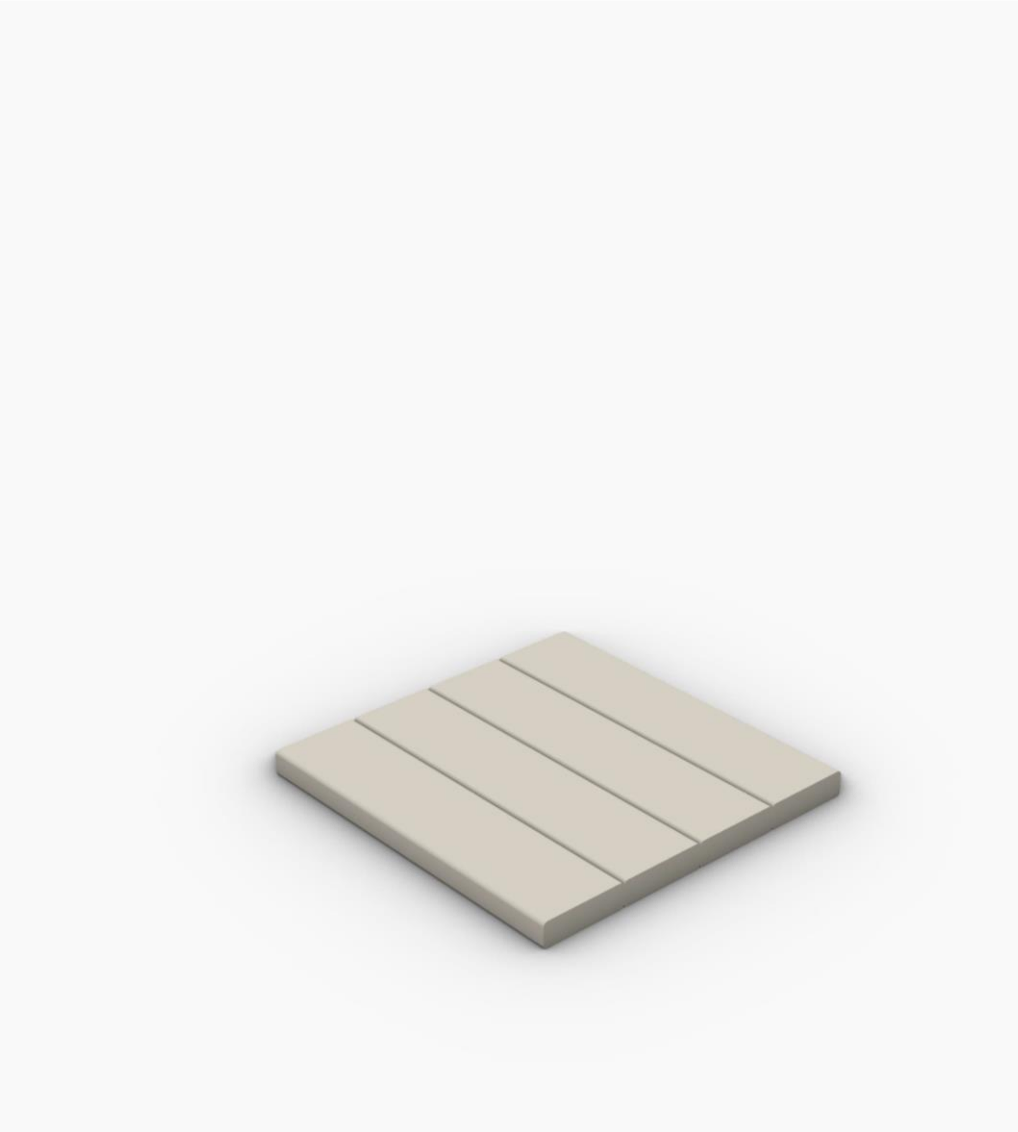
Conventional VPB production

Parallel toolpath gradient material

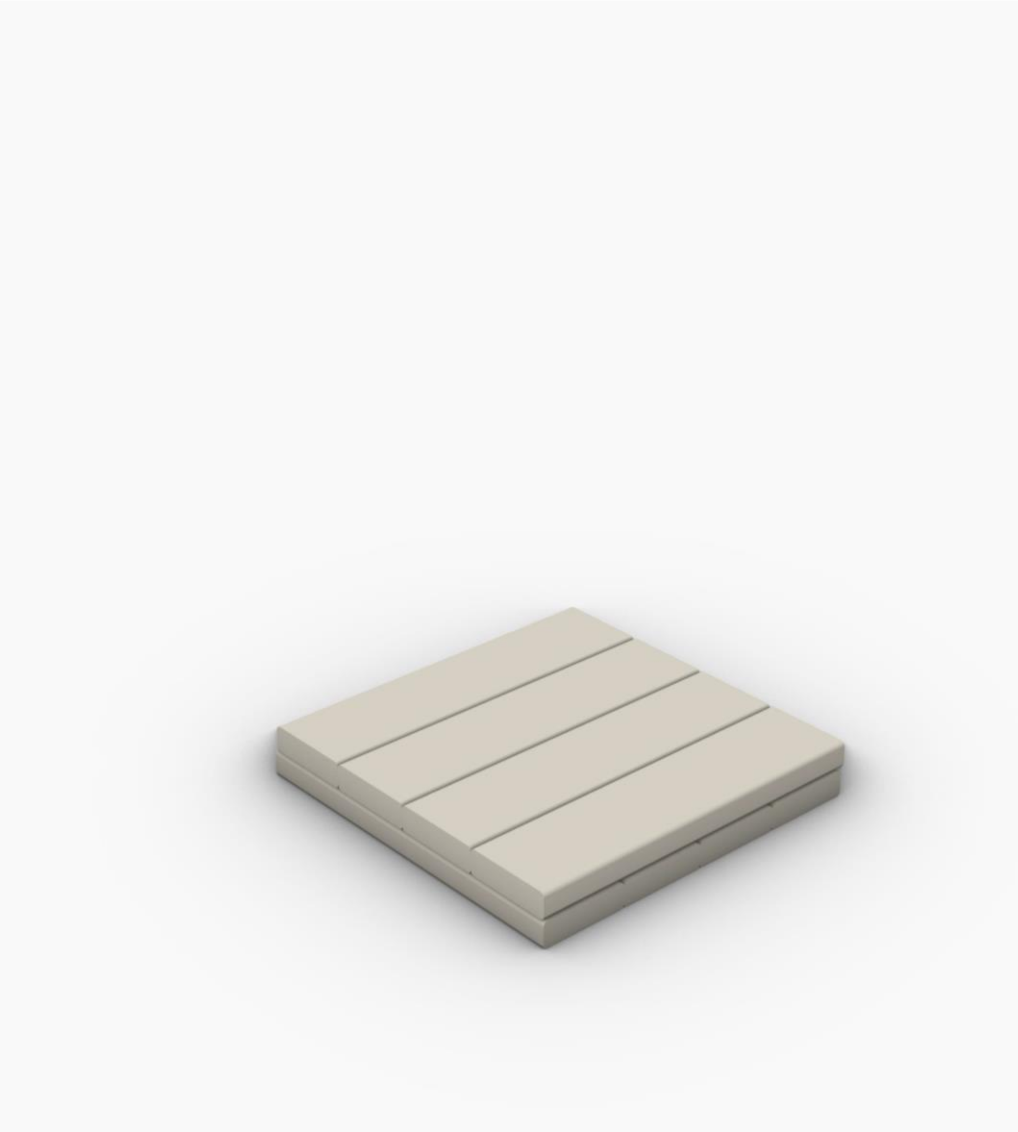


Conventional extrusion method for VPB

Design- Printing process



Design- Printing process

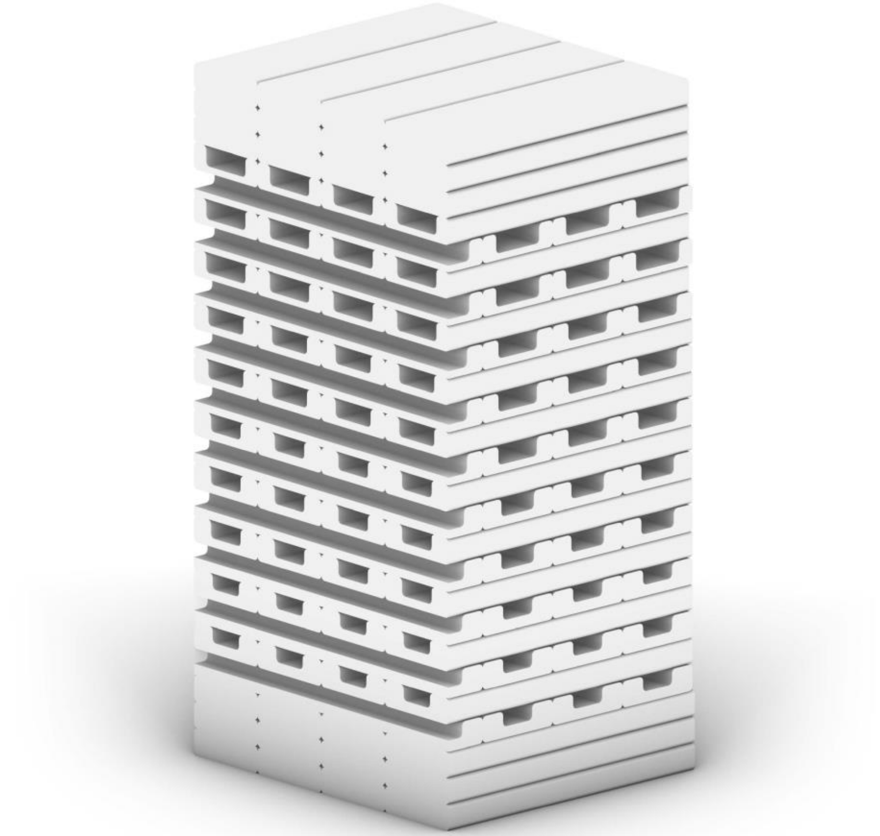


Design- Printing process

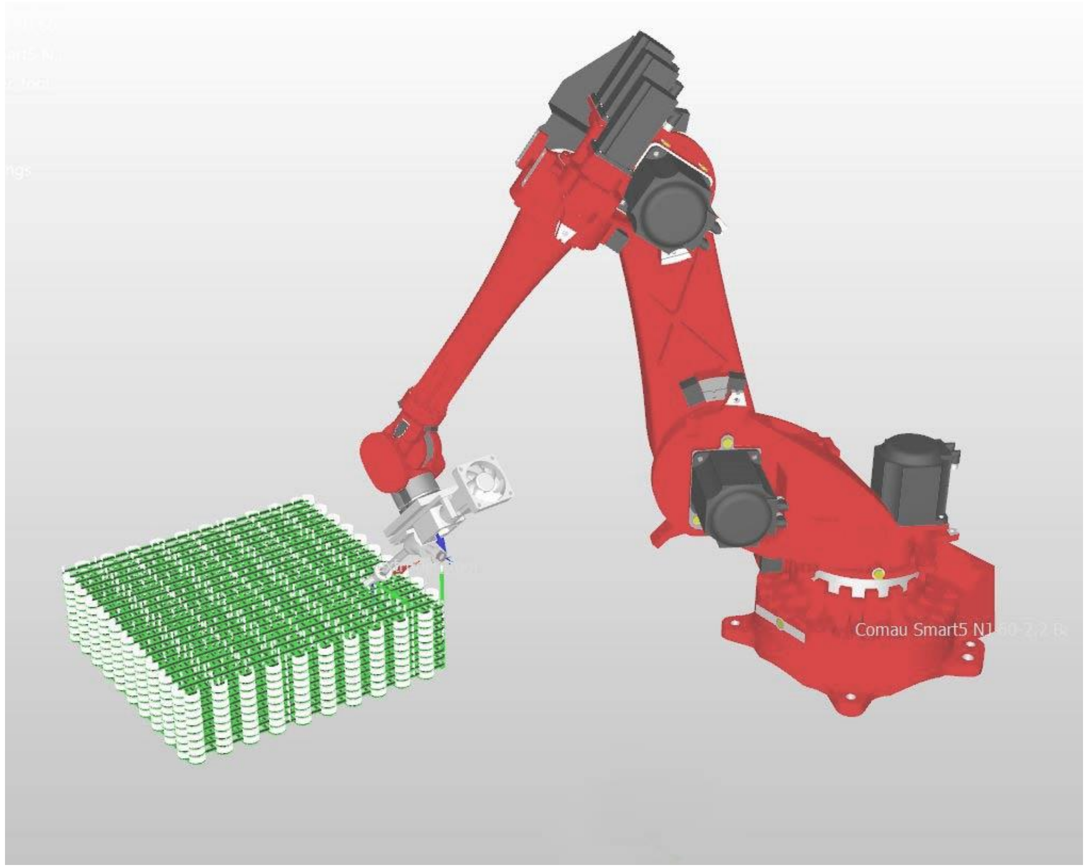
Design- Printing process

Design- Printing process

Design- Chosen settings for the gradient material infill



Crossed Toolpath Gradient Material



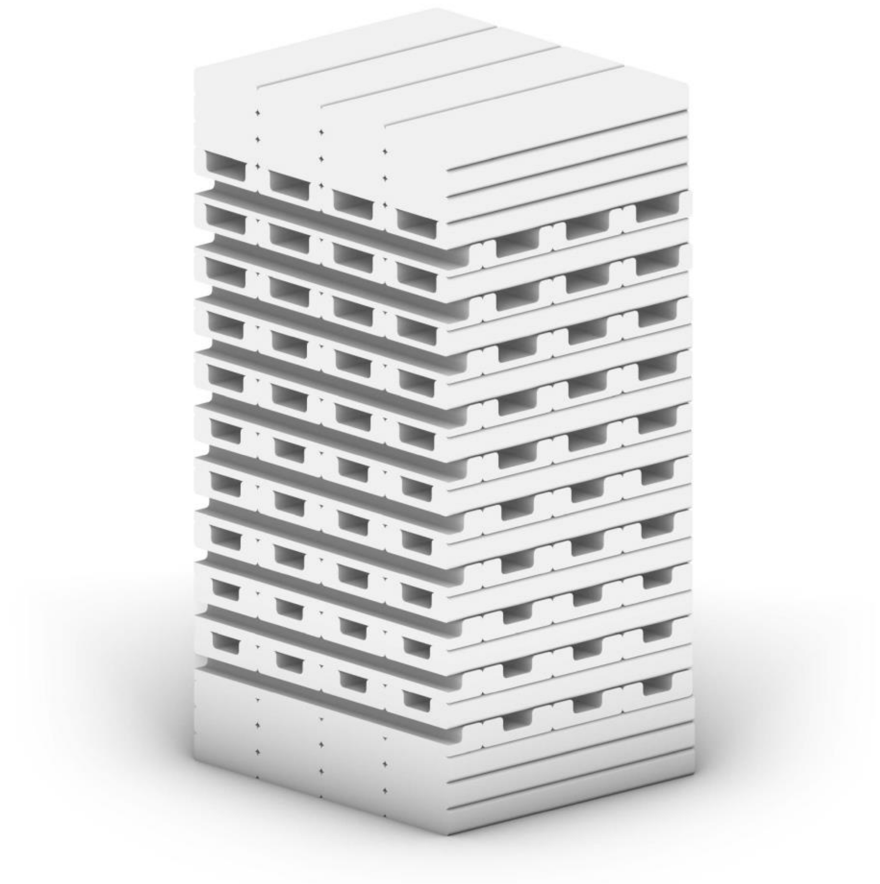
Cross Toolpath Gradient Material with spacer

Design- Chosen settings for the gradient material infill

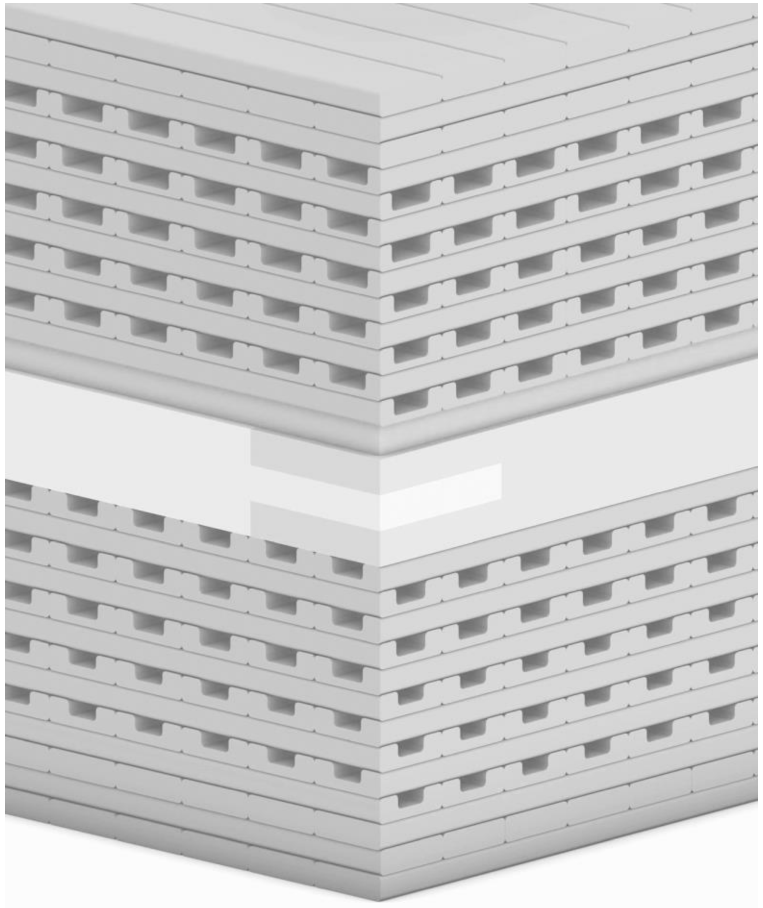
Point load = lower heat conduction

Linear load = higher heat conduction

Design- Chosen settings for the gradient material infill

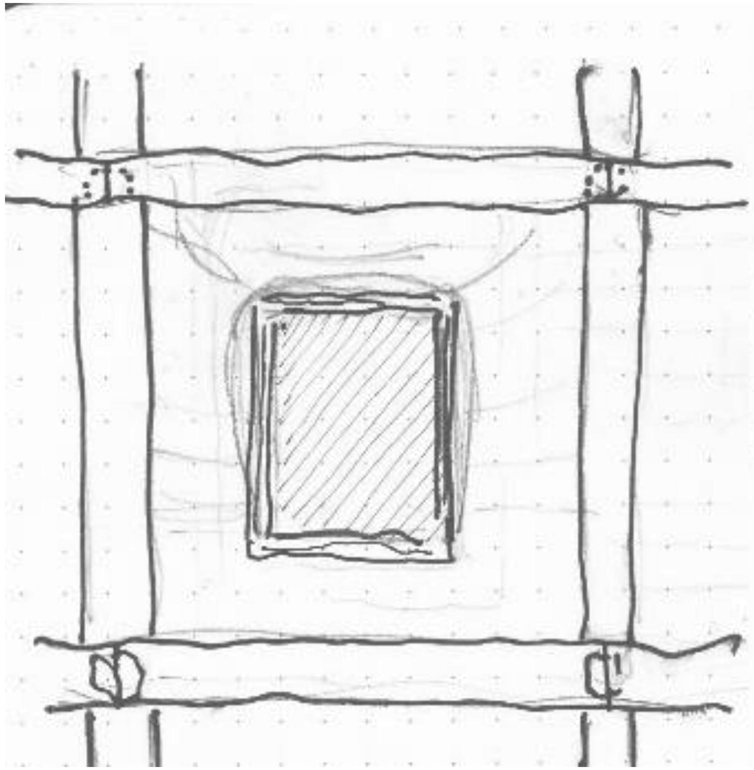


Crossed Toolpath Gradient Material

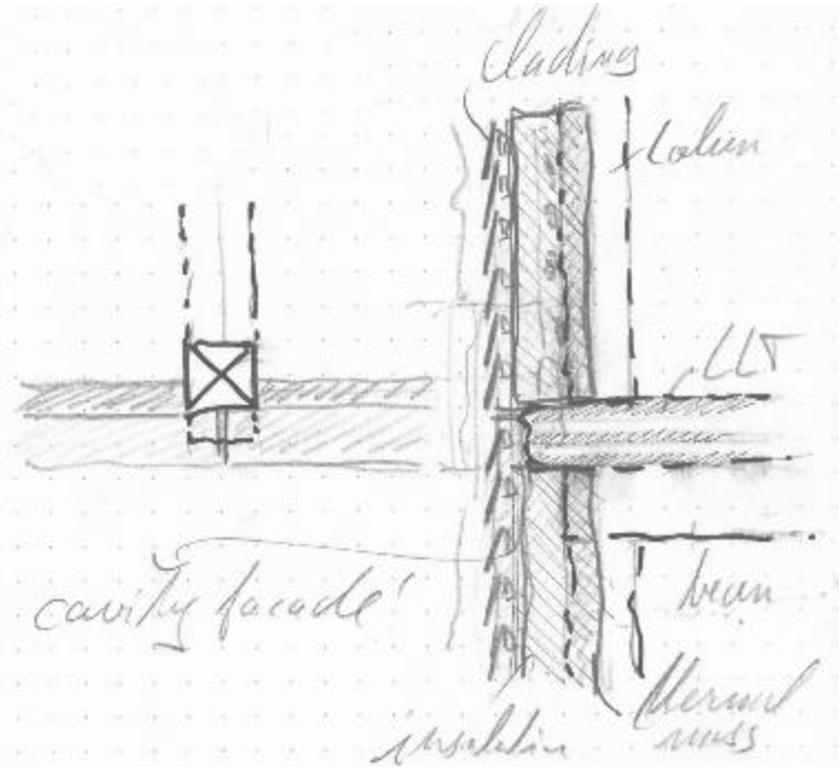


Cross Toolpath Gradient Material with spacer

Design- Component, Goal : Prefab wall element

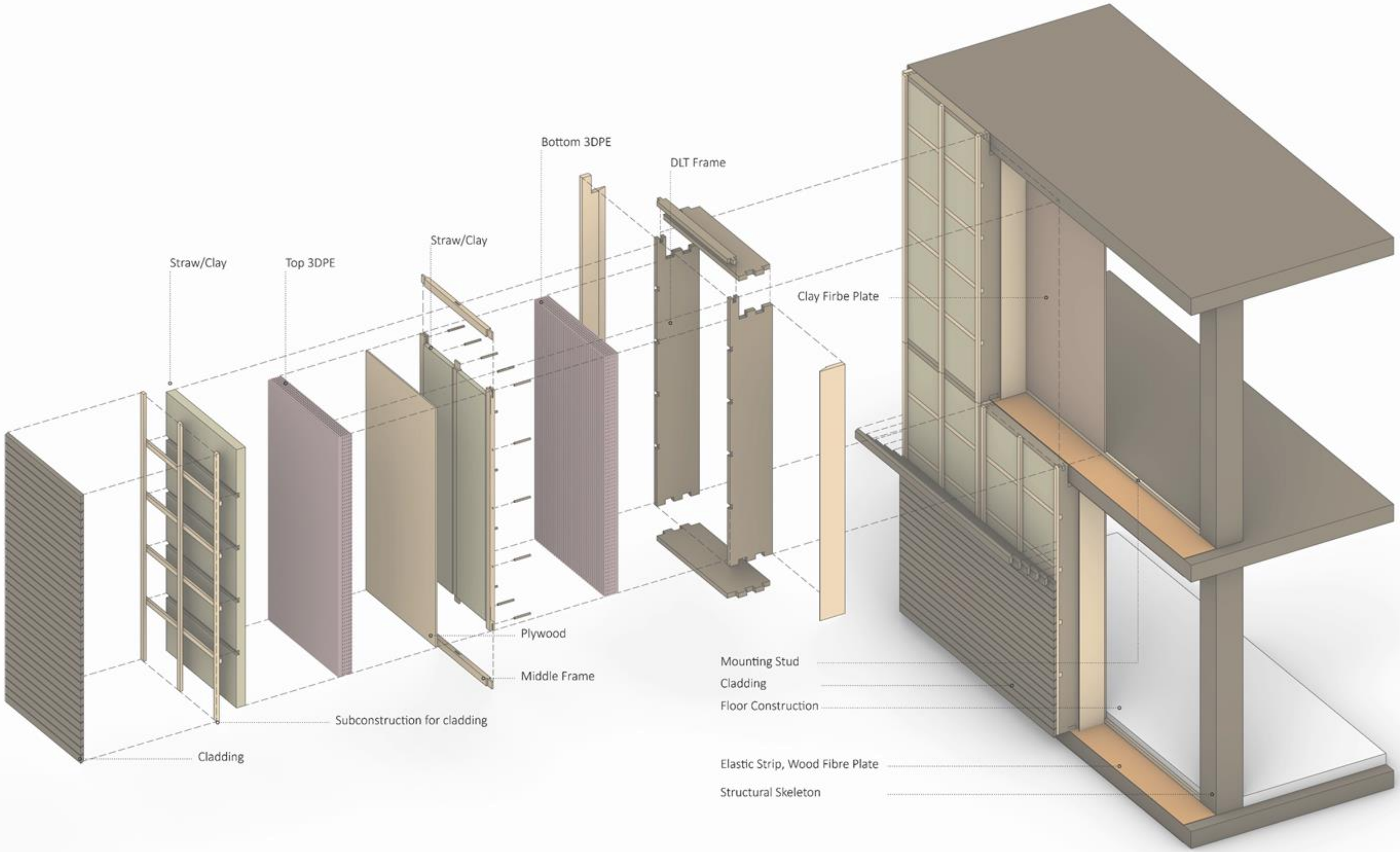


Timber Skeleton Structure

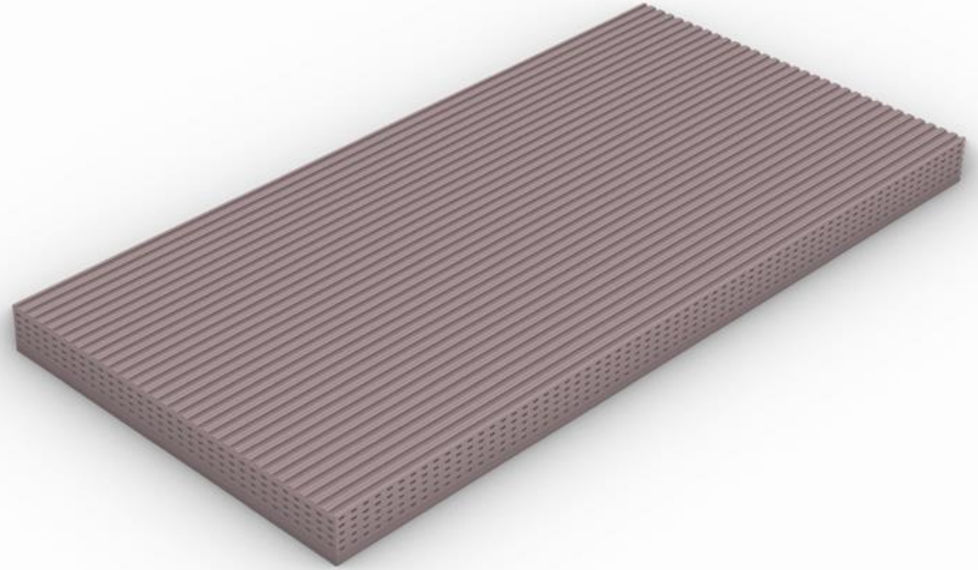


Clay-Timber Hybrid Wall Component

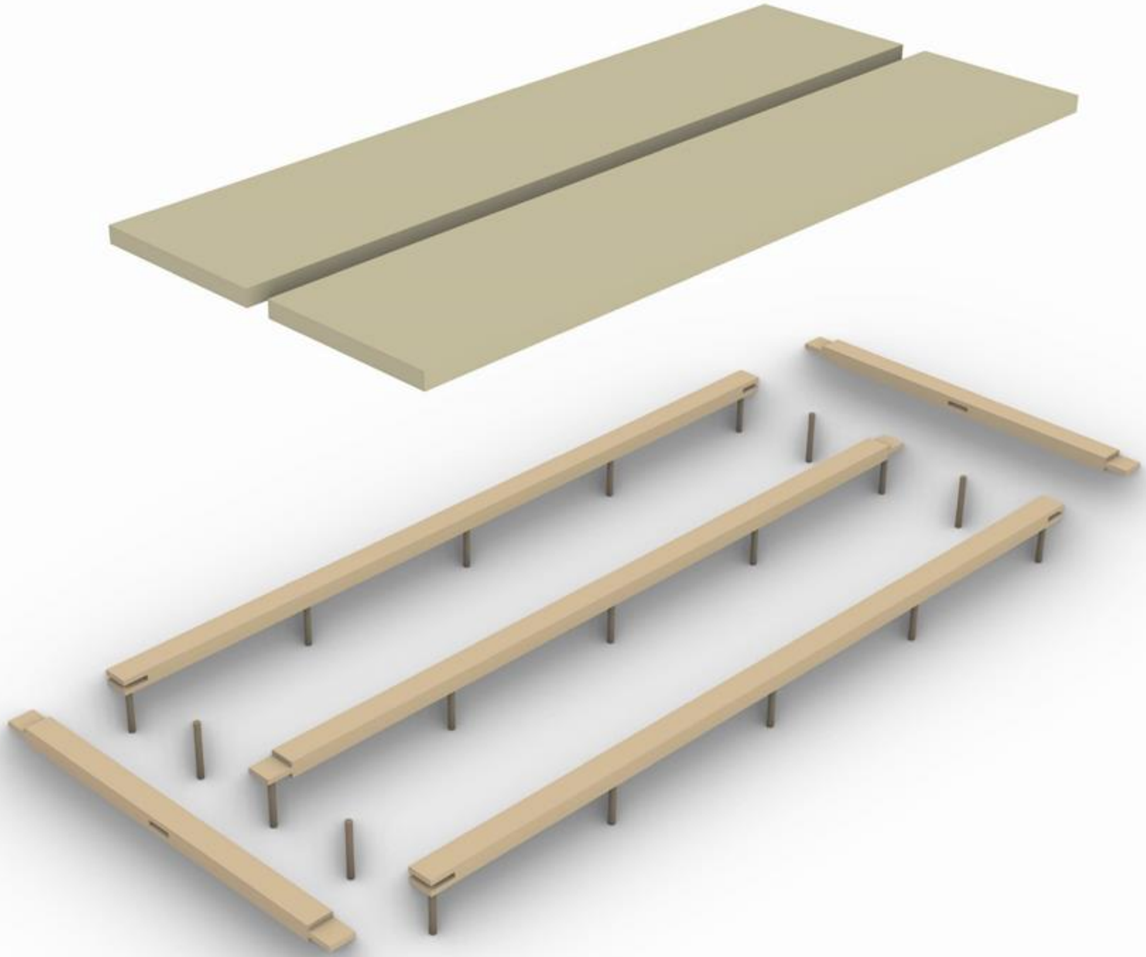
Design- Prefab Wall Component and Structure, Overview



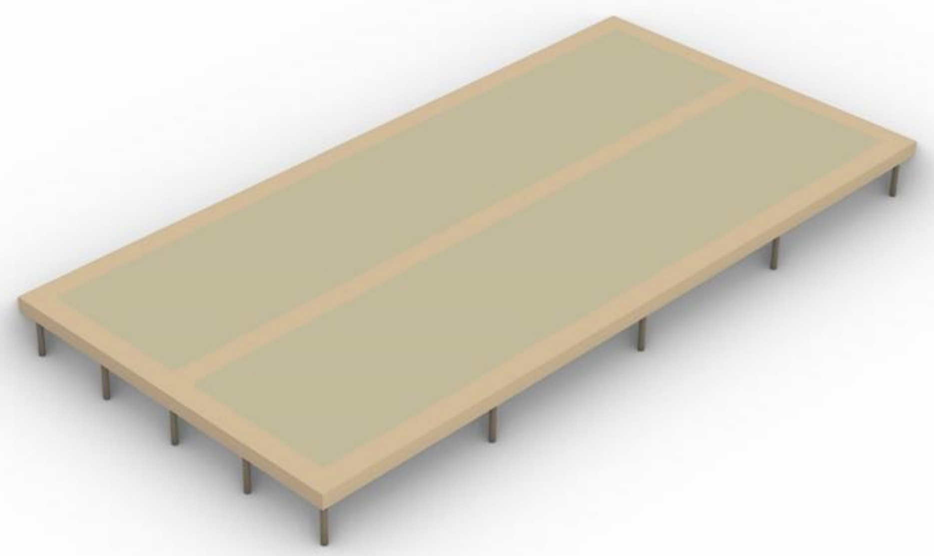
Design- Prefab Wall Component. Production – Bottom 3DPE Element



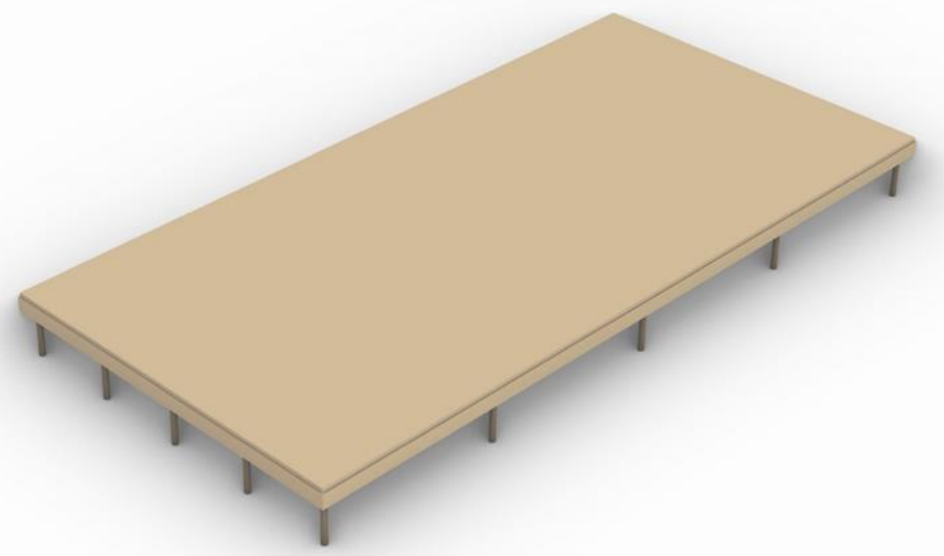
Design- Prefab Wall Component. Production – Middle Frame, Distance Legs, Straw Clay Infill



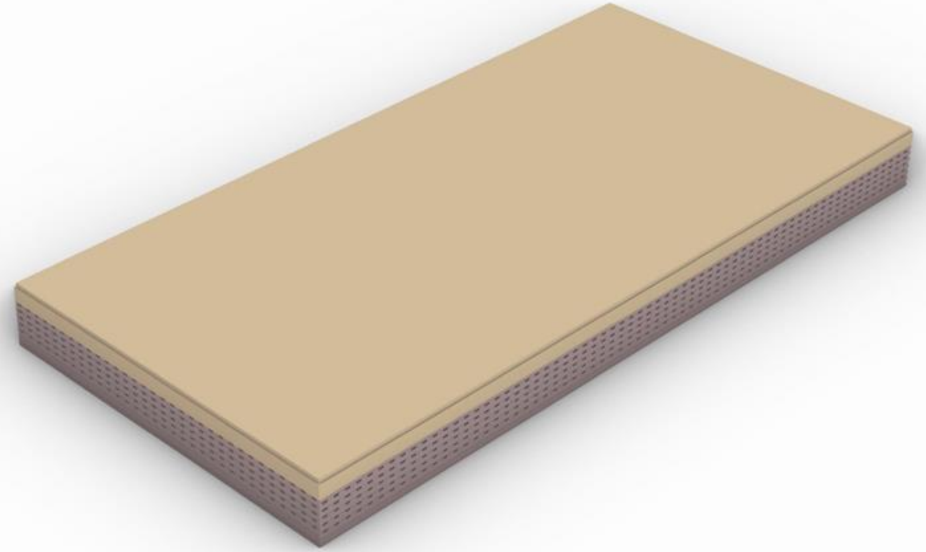
Design- Prefab Wall Component. Production – Middle Frame, Distance Legs, Straw Clay Infill



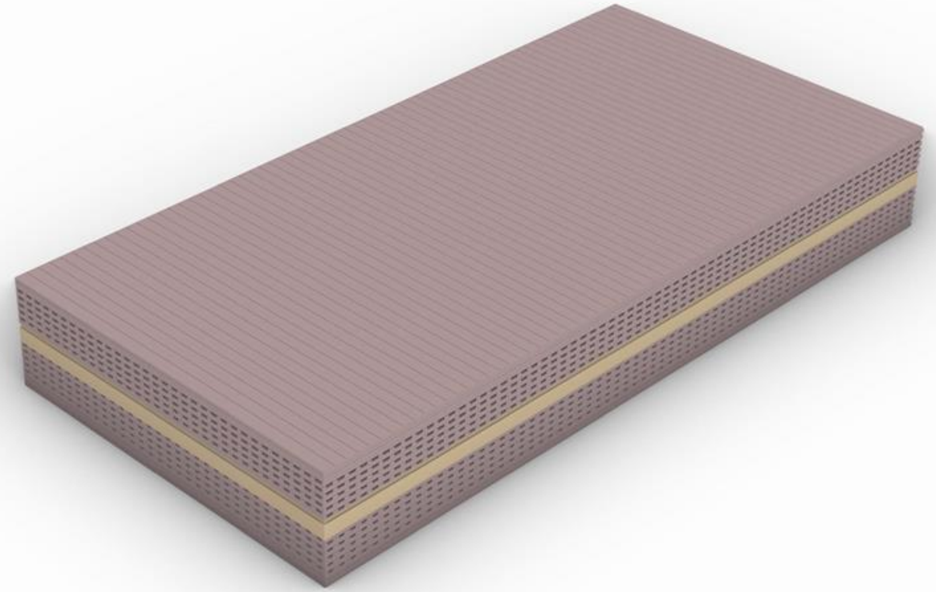
Design- Prefab Wall Component. Production – Plywood on middle frame functions as new printing surface and bracing



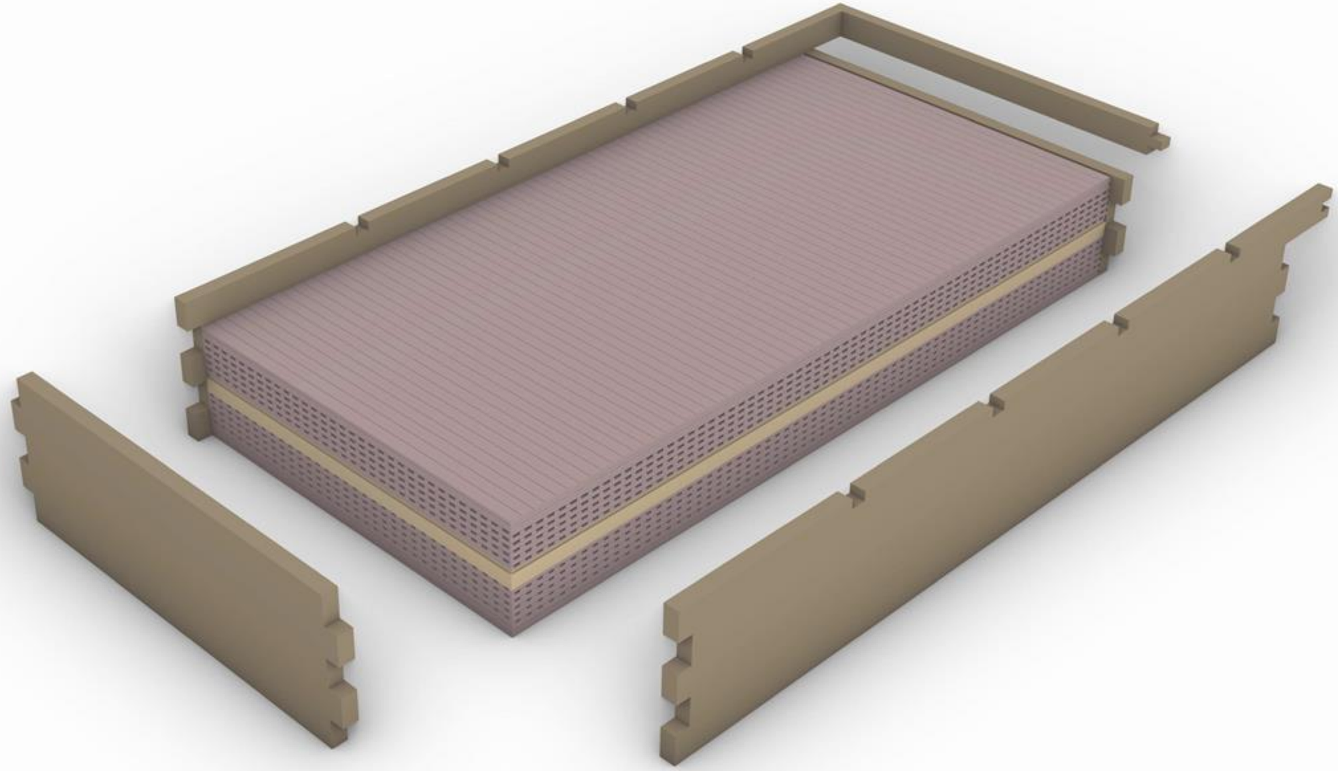
Design- Prefab Wall Component. Production – The spacer is standing on its legs in the bottom 3DPE element



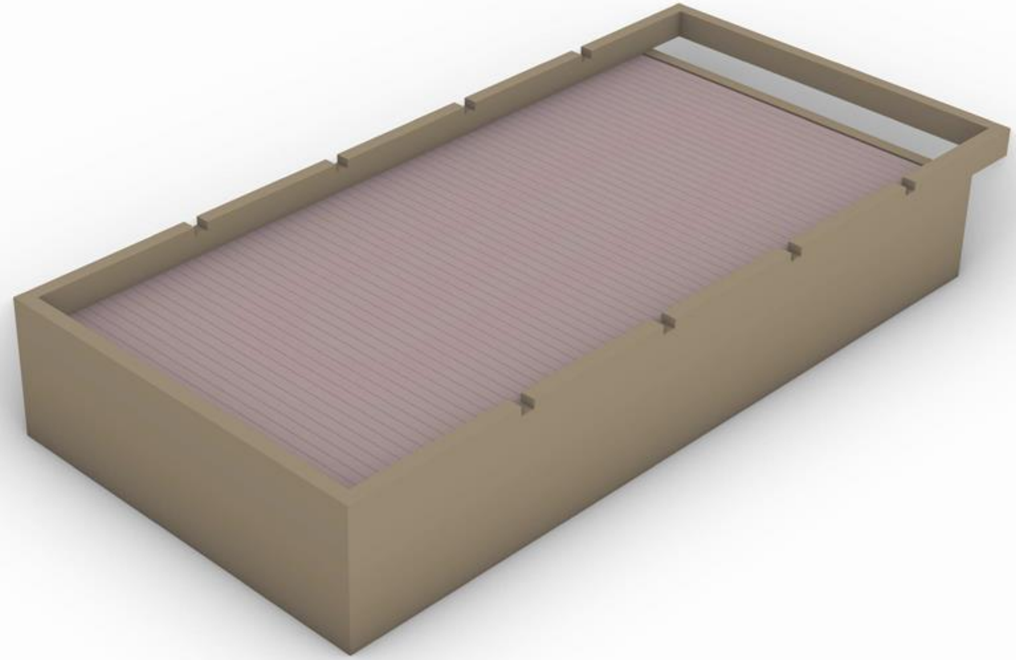
Design- Prefab Wall Component. Production – Top 3DPE element



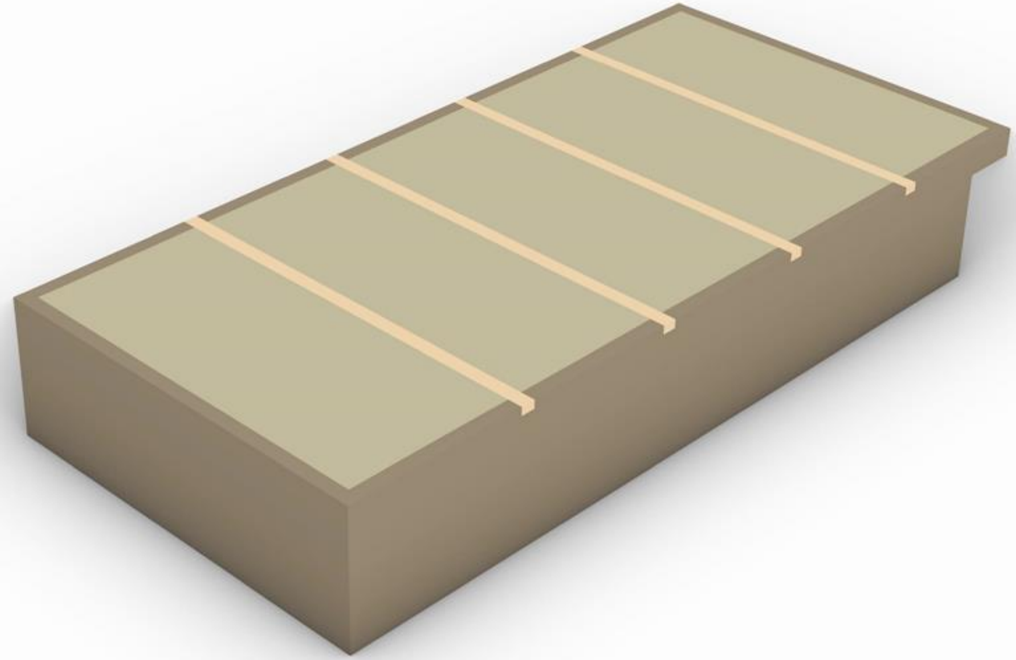
Design- Prefab Wall Component. Production – DLT Frame, Finger joints



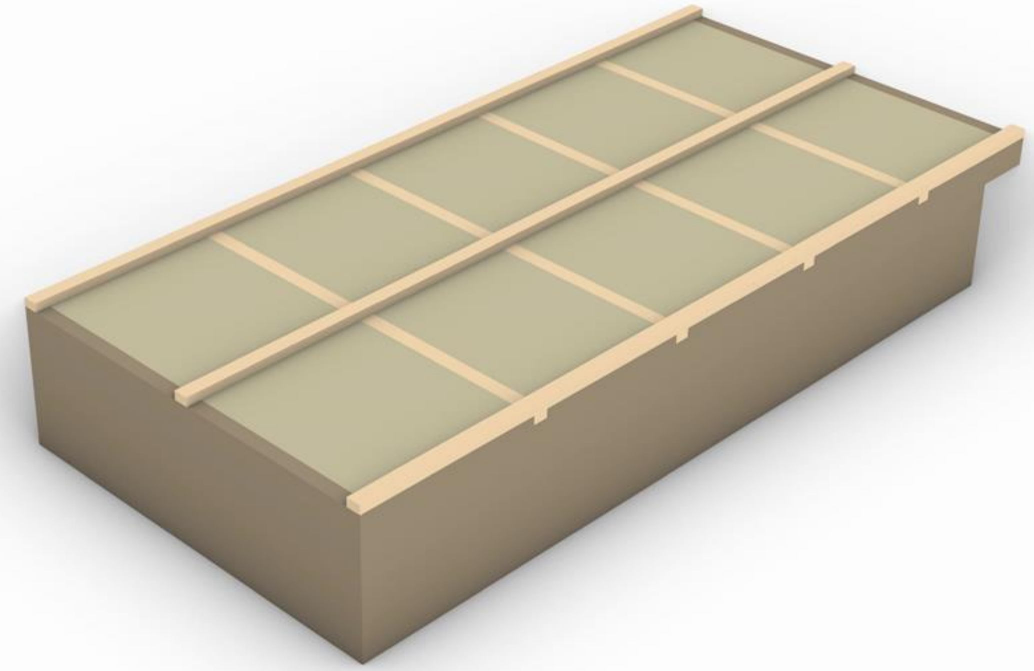
Design- Prefab Wall Component. Production – DLT Frame, Finger joints



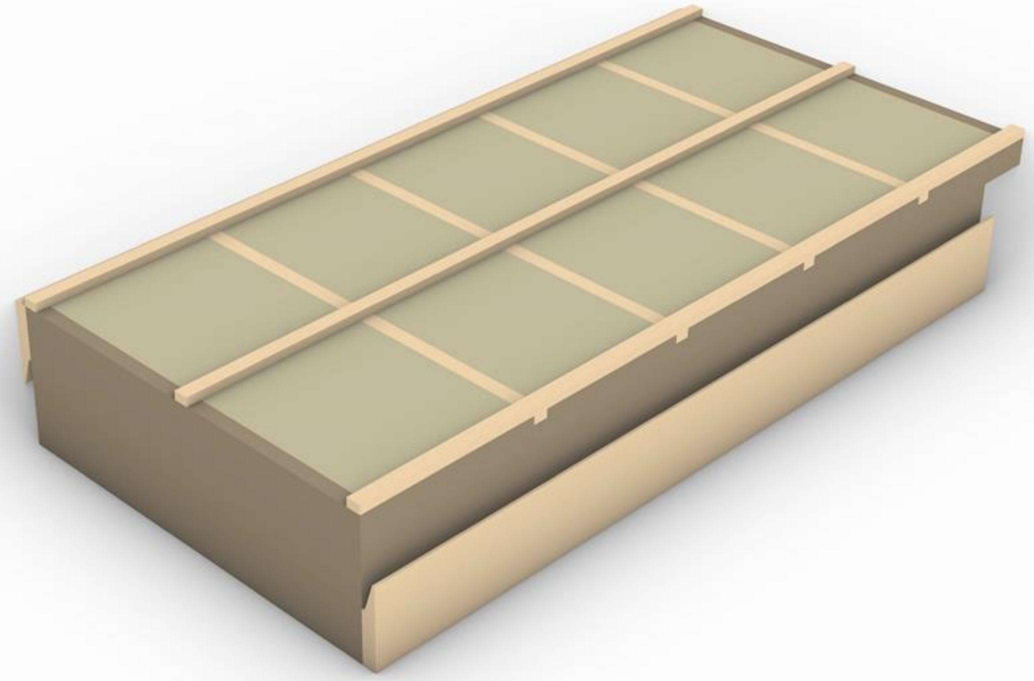
Design- Prefab Wall Component. Production – Straw-Clay insulation with sub-construction for cladding



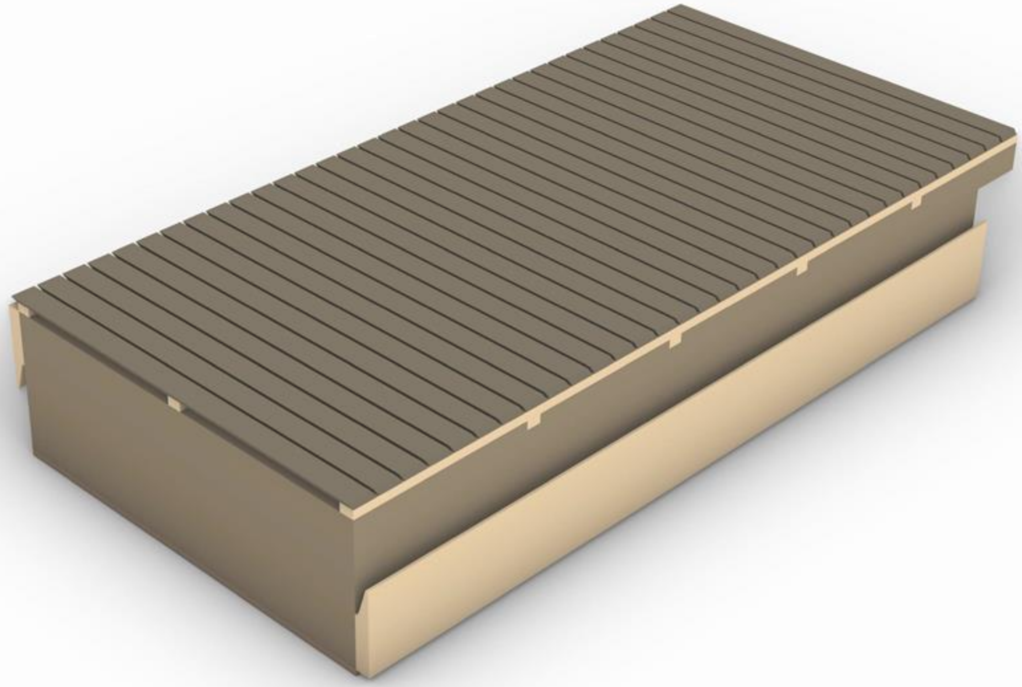
Design- Prefab Wall Component. Production – Sub-construction for cladding



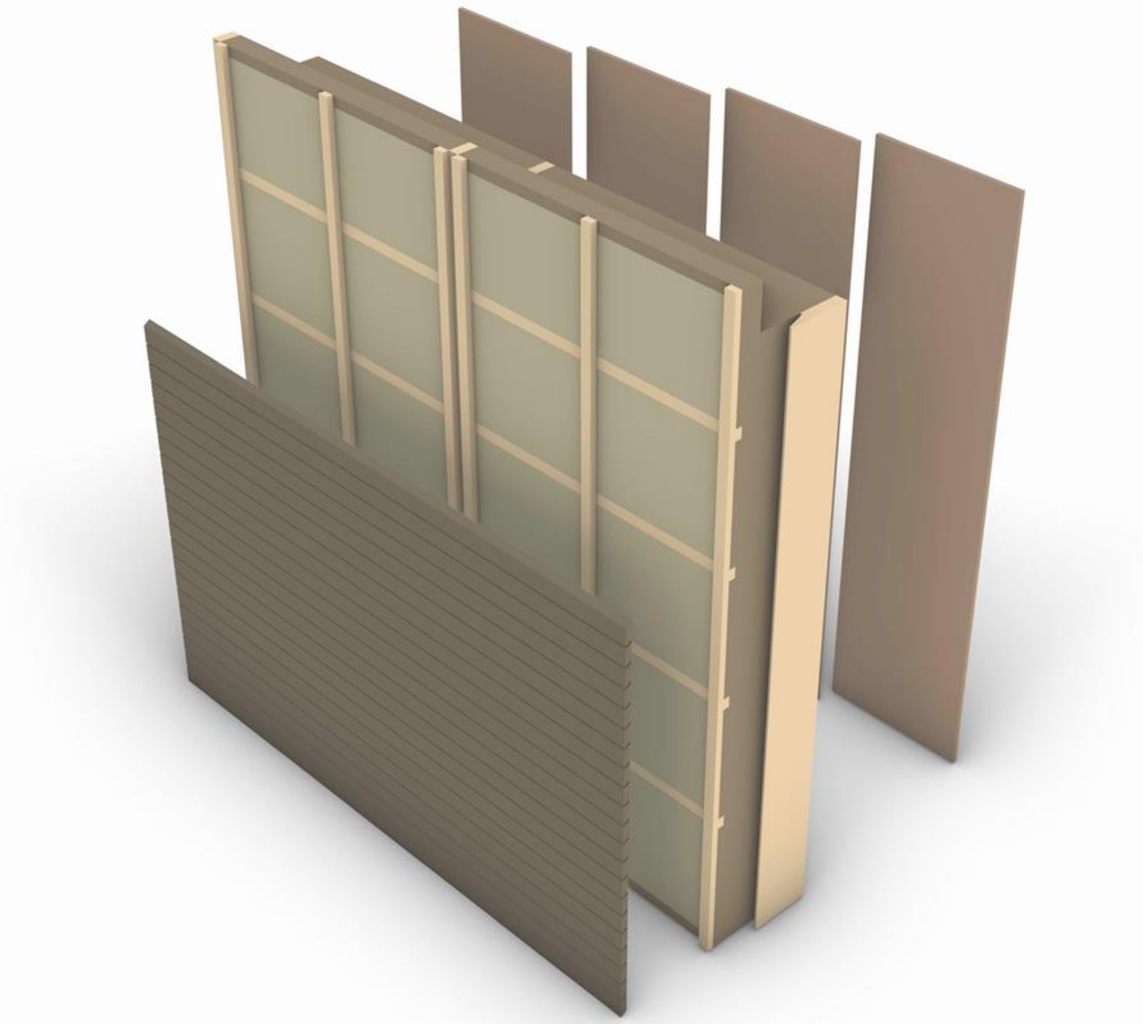
Design- Prefab Wall Component. Production – Connectors for assembly on site



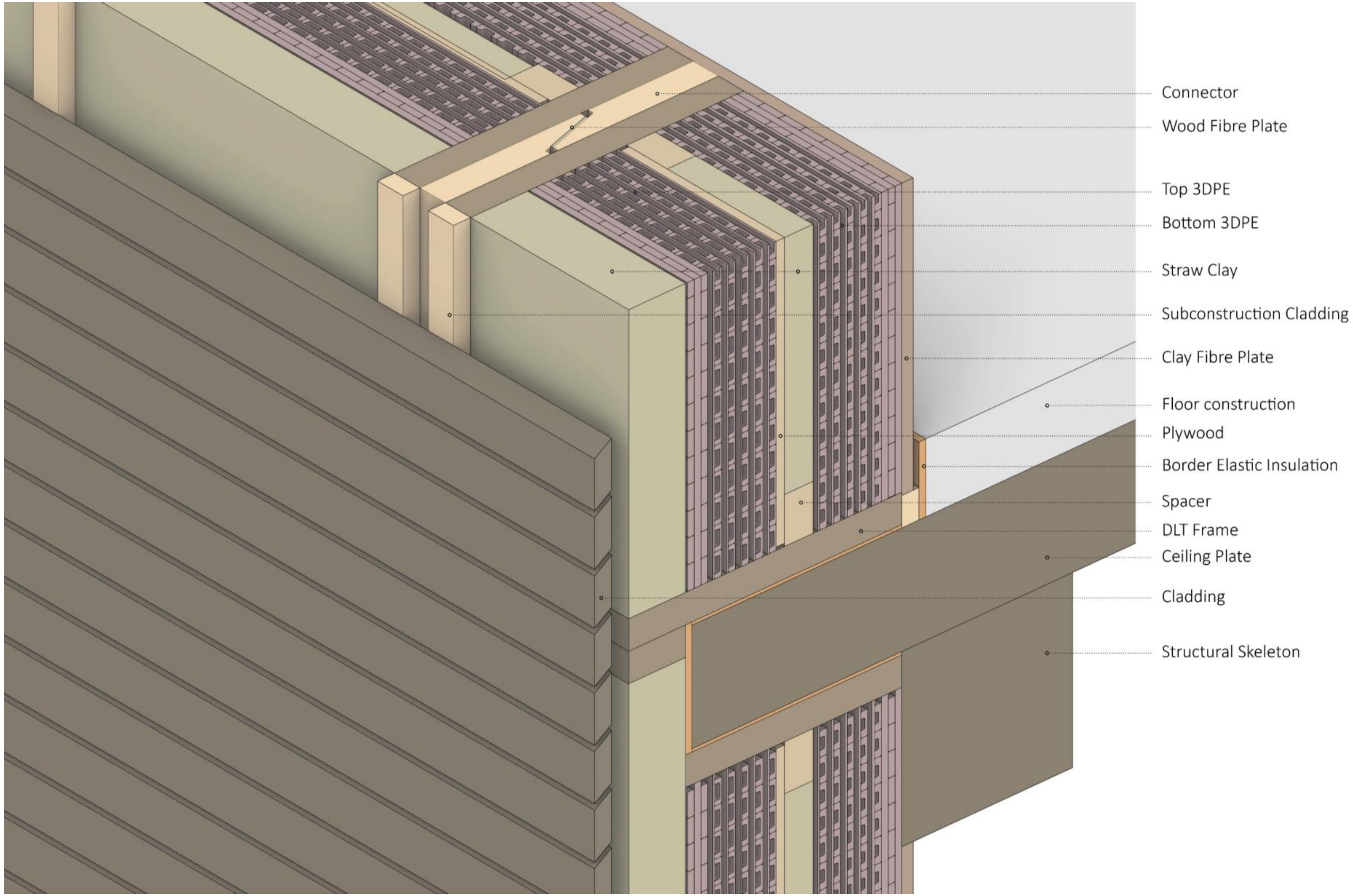
Design- Prefab Wall Component. Production – Cladding inside (Clay Fibre Plate), outside (Charred Wood)



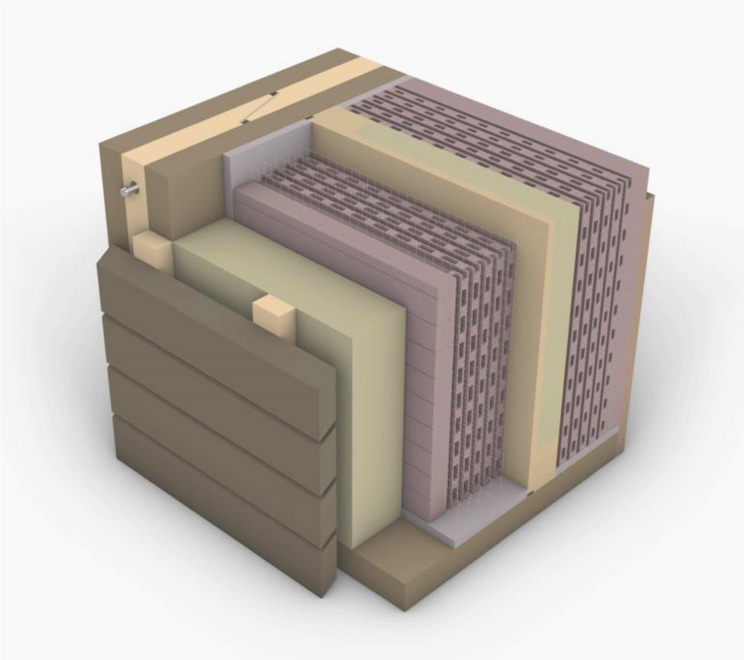
Design- Prefab Wall Component. Production – Cladding get mounted after the assembly on site



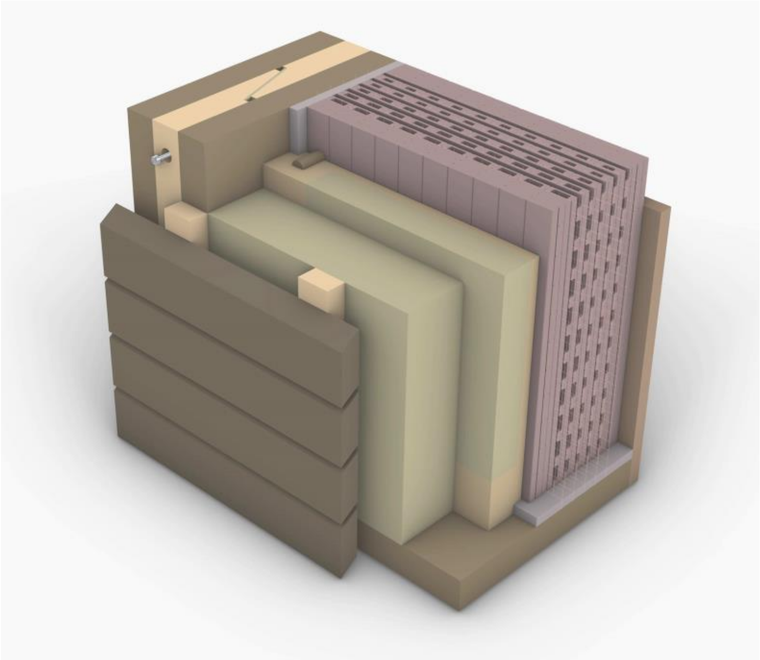
 Prefab Wall Component. Production – Horizontal and vertical section axonometry



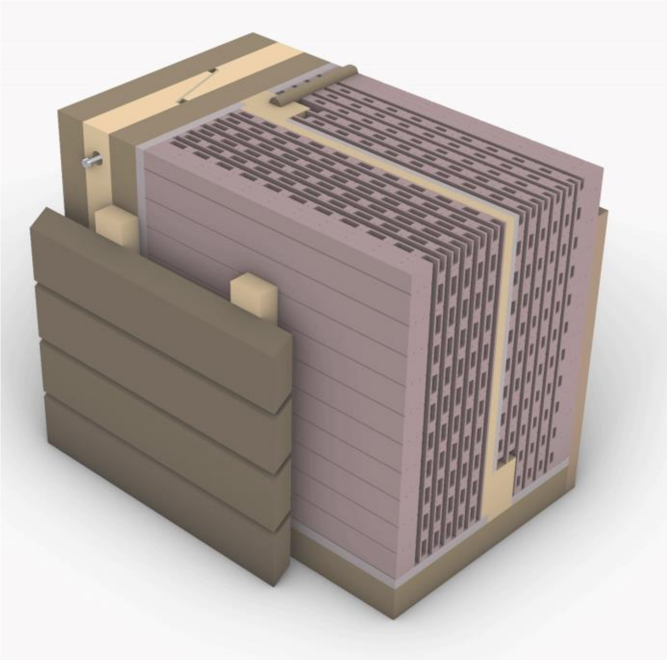
Design- Possible cross section design – various options



Thermal split version for cavity windows

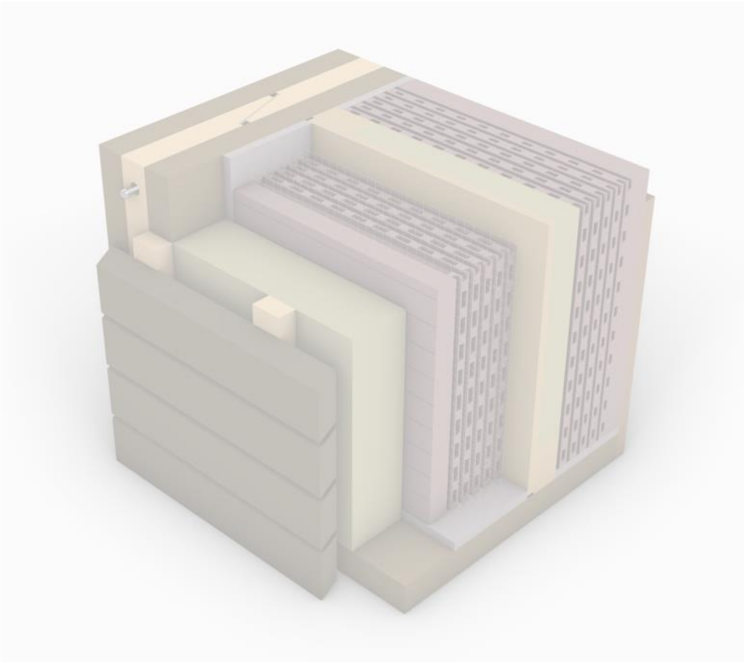


Outside insulation for standard windows

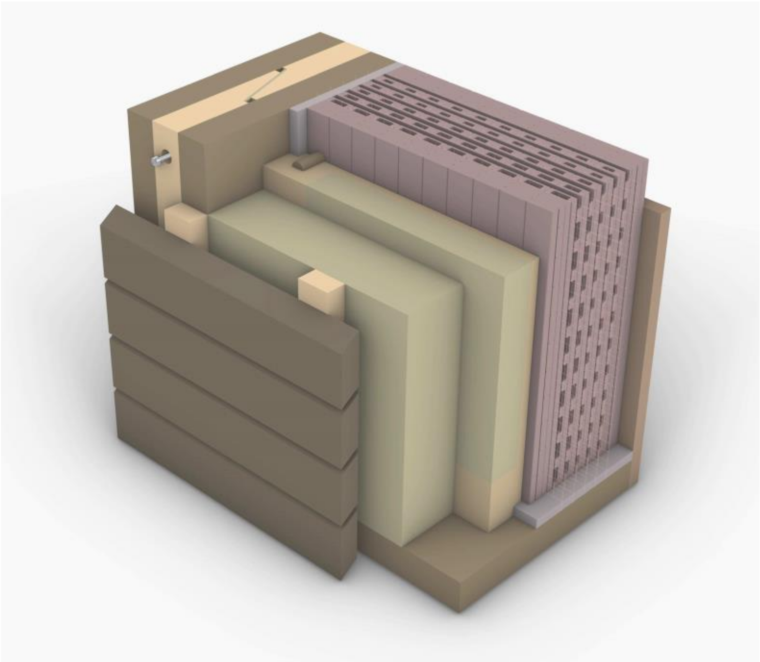


Outside insulation for standard windows

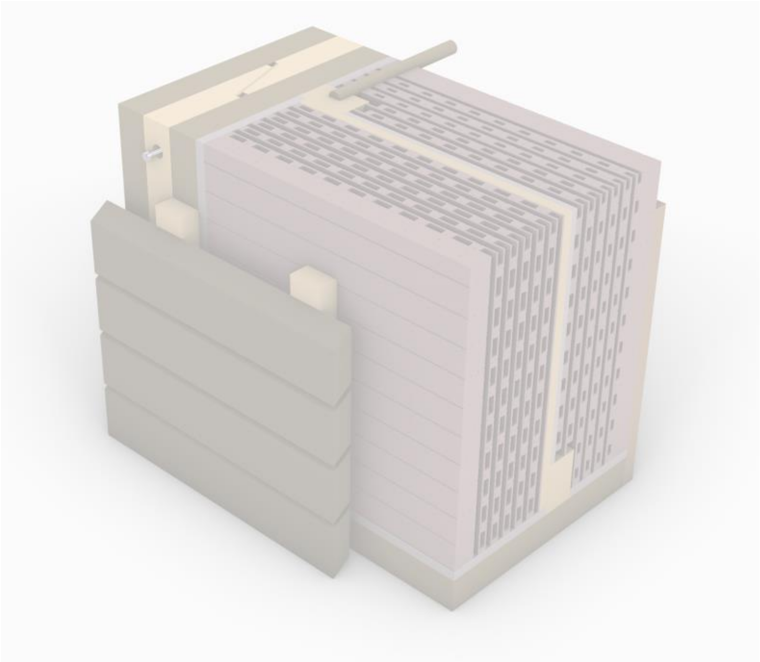
Design- Possible cross section design – chosen design



Thermal split version for cavity windows



Outside insulation for standard windows



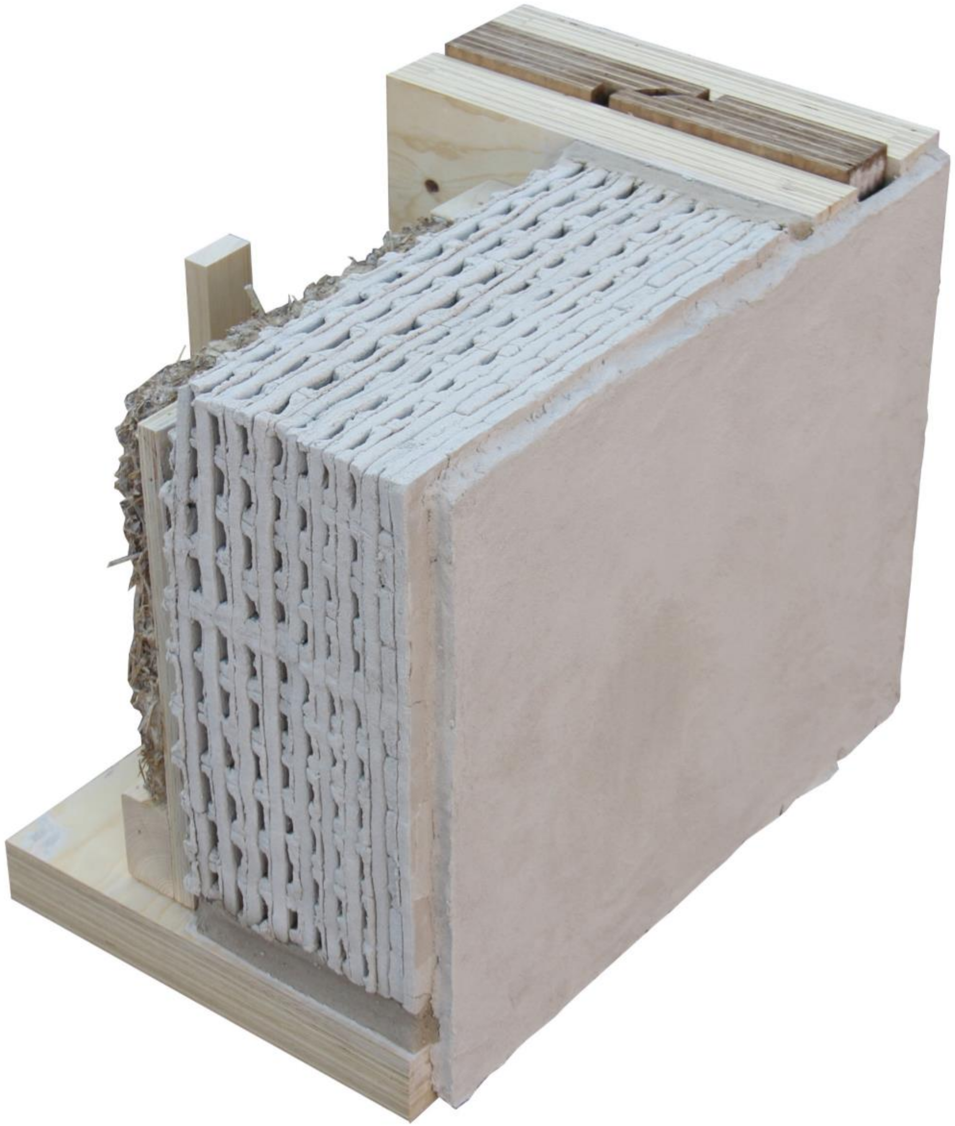
Outside insulation for standard windows

Design- Prototype

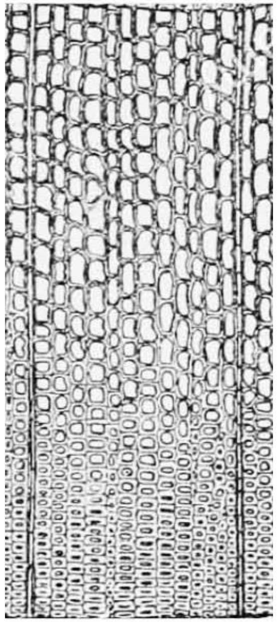
Design- Prototype

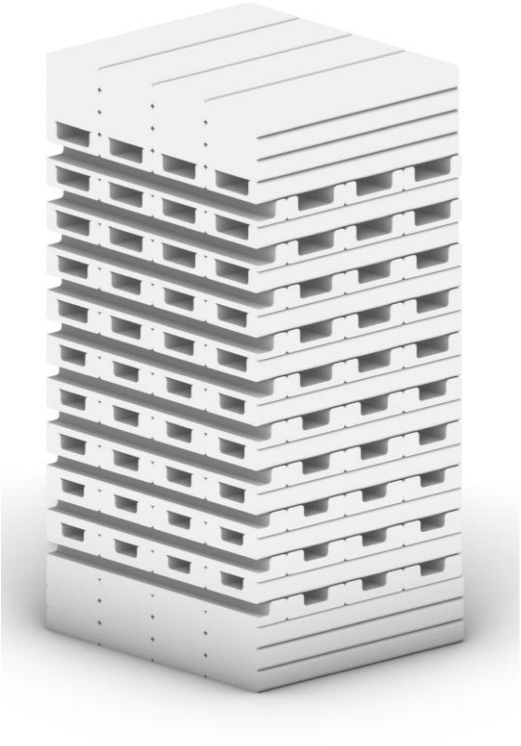
Design- Prototype, Top view and elevations

Design- Prototype



Design- Proof of concept





Conclusion -

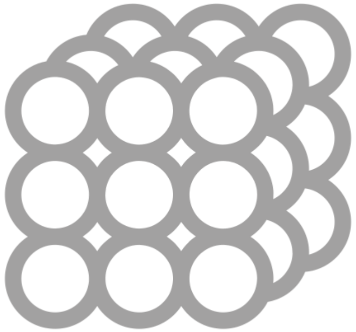
- Method of fabrication: 3d printing could increase the efficiency of clay bodies by decreasing the density and increasing the insulation properties.
- Gradient cross section pattern because of customized nozzles, not because of complex toolpaths.
- Informative workflow between Nozzle, Toolpath and Component design, based on limitations due to experiments results in a feasible design.
- All tested nozzles are suitable for a density decrease when laid down.
- Combining multiple nozzle types could further decrease the density.
- The dryer the mixture the better : high pressure extruder necessary

Conclusion

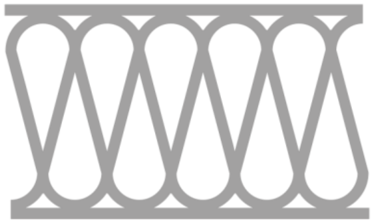
The efficiency was evaluated according to:

Reduced Printing Time

+



Density per Volume Shift



Added Function

Increased Efficiency

Outlook - Impact, Future Development, Discussion

- Developing a building component is possible, but requires further intensive research in various fields.

- Panelising the component further results in smaller 3DPE infills and eases printing and post production.

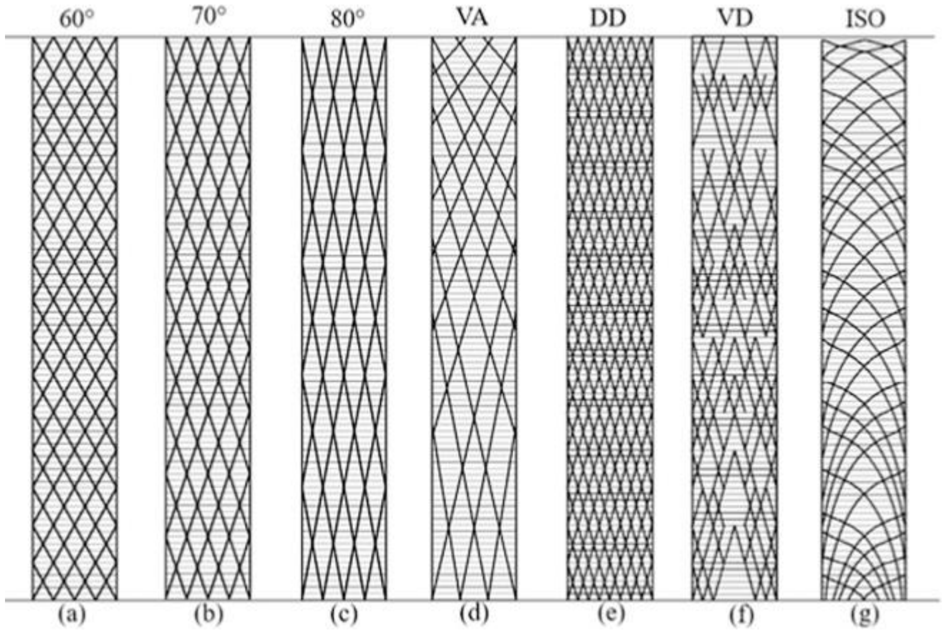
- Exploring the possibilities of contour crafting: Cutting off the extrusion, integrating fibres and granules in the printing process

- 3DPE is hard to scale, speeding up the production is crucial.

Outlook - Impact, Future Development, Discussion

Framework Houses

1959-73. © 2018 Hilla Becher. Credit: MoMA

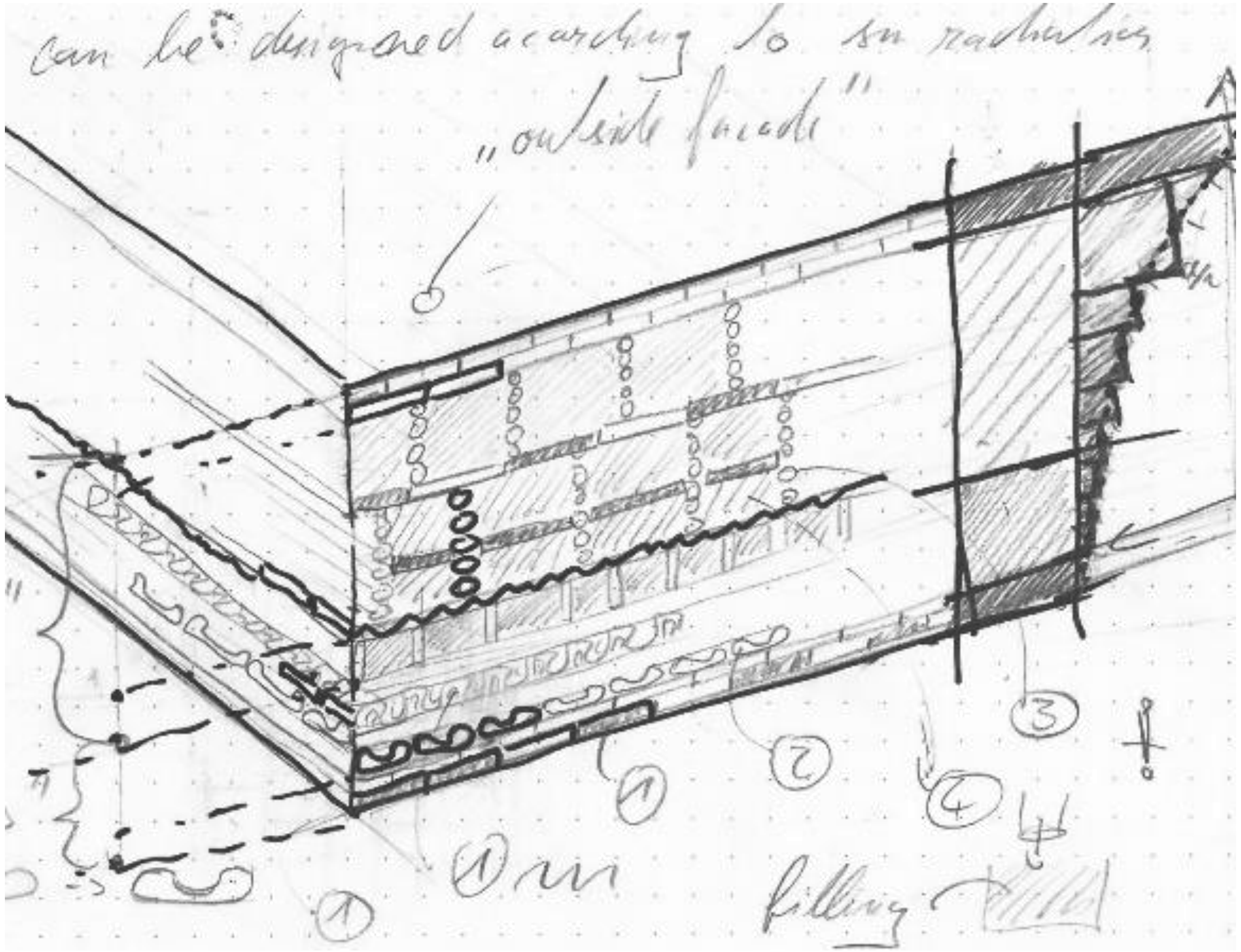


Optimization of structural patterns

Tomei, V., Imbimbo, M., & Mele, E. (2018)

Future Developments

Multiple nozzle concepts



Closing statement

3DP with customized nozzles enables a gradient density decrease of an earthen material mixture.

Applying this material within a clay-timber hybrid construction allows the use of clay in multi-storey buildings.

The combination of digital fabrication, clay and timber allows a regional and circular built environment.

Thank you for your attention!

Questions are welcome from the audience as well!

References

- Dethier J. (2019). Lehmbaukultur - von den Anfängen bis heute, Detail Edition Plädoyer für den Lehmbau, 8-19
- ERDEN, production Hall http://www.lehmtonerde.at/de/aktuell/#news226
- Andy Goldsworthy, Dethier J. (2019). Lehmbaukultur
- alamy.com https://www.alamy.com/fig-94-querschnittsansicht-des-holzes-der-weitanne-abtes-pectinata
- Can Stock Photo, https://www.canstockphoto.com/construction-and-demolition-debris-19040132.html
- Wasp, GAIA , https://www.3dwasp.com/en/3d-printed-house-gaia/
- Volkswagen AG, https://www.volkswagenag.com/de/news/stories/2018/05/shared-intelligence-a-choreography-with-2000-robots.html
- VPB: https://de.wikipedia.org/wiki/Lochziegel
- Riccabona C. (2004) Baukonstruktionslehre 1, Manz Verlag
- https://www.3dwasp.com/en/concrete-3d-printer-delta-wasp-3mt-concrete/
- Framework house: Bernd Becher, Hilla Becher. Framework Houses, 1959-73. © 2018 Hilla Becher. Credit: MoMA; gift from Hilla Becher. Under terms of "Fair Use“
- Tomei, V., Imbimbo, M., & Mele, E. (2018). Optimization of structural patterns for tall buildings: The case of diagrid. Engineering Structures, 171, 280-297.