Building Technology Graduation Project

MSc Architecture, Urbanism & Building Sciences
Academic year 2021-2022

WOOD-BASED 3D PRINTING

POTENTIAL & LIMITATION TO 3D PRINT A WINDOW FRAME WITH PURE LIGNIN & CELLULOSE

STUDENT: CHRISTOPHER BIERACH

MENTORS: SERDAR ASUT, ULRICH KNAACK

CONSULTANT: MICHELA TURRIN

EXTERNAL SUPERVISOR: RICHARD GOSSELINK

EXTERNAL HELP: PAUL DE RUITER & CHRISTIAN

LOUTER COLLEAGUE: ALEXSANDER ALBERTS

COELHO

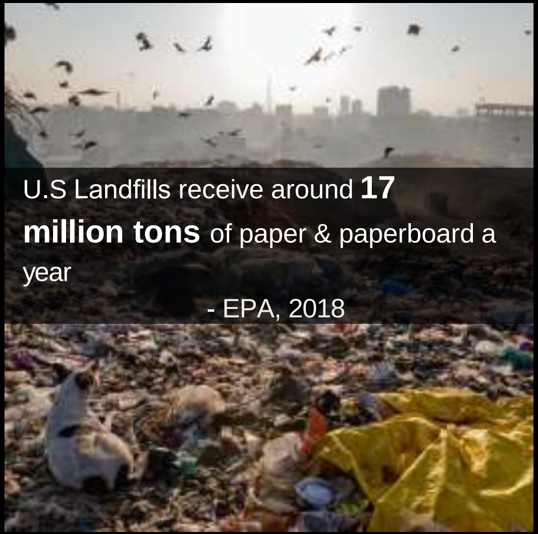
OVERALL PROBLEM STATEMENT

GLOBAL

In Europe buildings are responsible for **36%** of CO2 emissions.

- EU commission, 2020

1.



U.S Landfills receive around **17 million tons** of paper & paperboard a year

- EPA, 2018

2.

Almost **50 million tons** of Lignin is burnt every year

- C&EN, 2016

3.

POLLUTION VS SUSTAINABILITY

LINEAR VS CIRCULAR

DESTRUCTION VS REGENERATION

LITERATURE REVIEW

STATE OF THE ART: CELLULOSE & OR LIGNIN

4. 

COMESTIBLE CELLULOSE

6. 

3D PRINTING WITH WOOD WASTE

5. 

3D PRINTING WITH LIGNIN

MAIN PROBLEM STATEMENT

LOCAL

13
.

5.

5.

NOT FULLY BIO-BASED

NOT PRINTABLE

NOT PART OF BUILDING INDUSTRY

RESEARCH QUESTION

What are the potential and limitations of 3D printing a window frame with pure cellulose and lignin ?

SUB-QUESTIONS

Contextual Framework (Exploratory phase)

Why are we looking into AM and wood-based material?

How can it be used sustainably & circularly?

What is the state-of-the-art technology with wood waste or by-products?

Design Evaluation (Experimental phase)

What are the constraints that need to be considered? (extruder, scale of print, access to the laboratory, final recipe) ?

Which printing process is better for 3D printing with cellulose and lignin as feedstocks?

Which tests are necessary to evaluate a window frame?

How can we improve the material recipe made by Thomas Liebrand?

Design Integration (Prototyping phase)

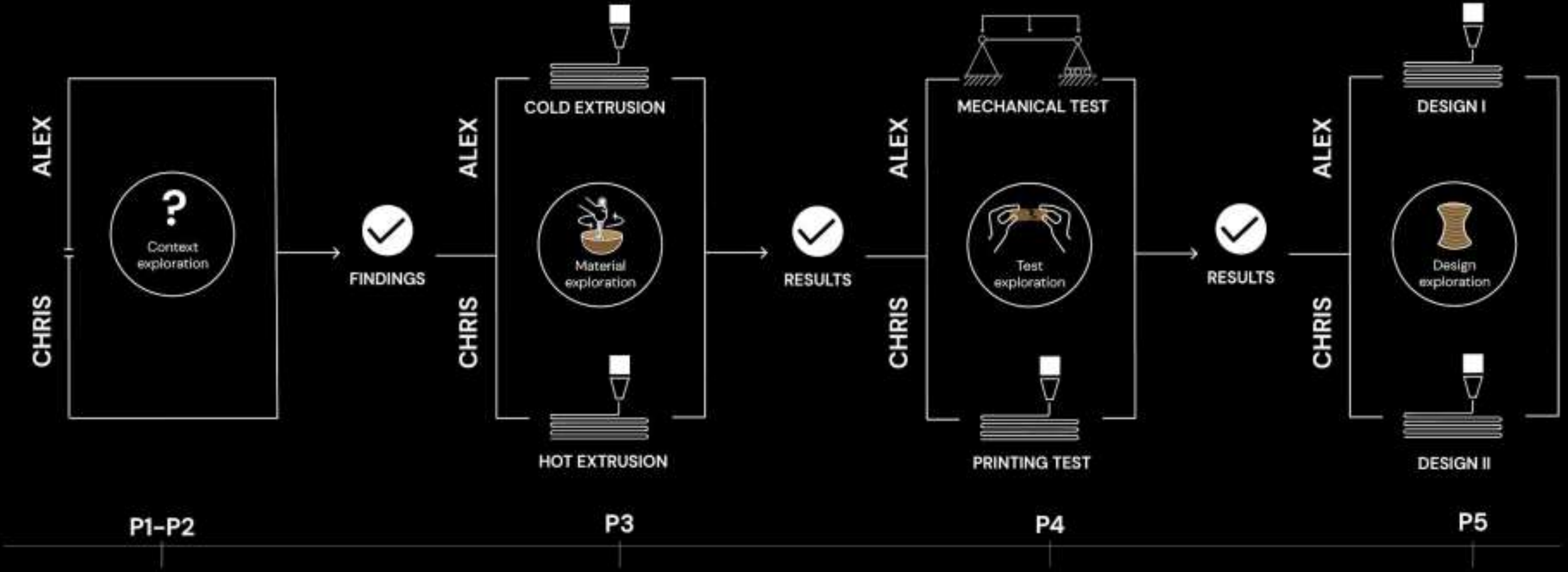
Can we 3D print a window frame?

Which limitations and advantages will influence the shape of the window frame?

Can we replace and/or enhance the performance of a window frame with additive manufacturing?

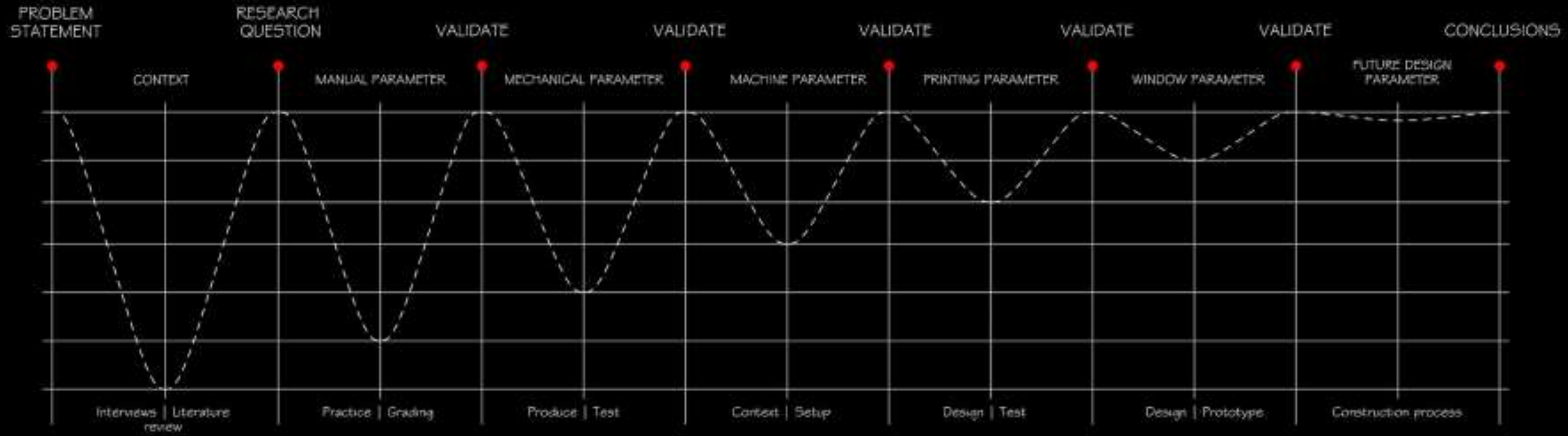
WORKFLOW OVERVIEW

PROCESS



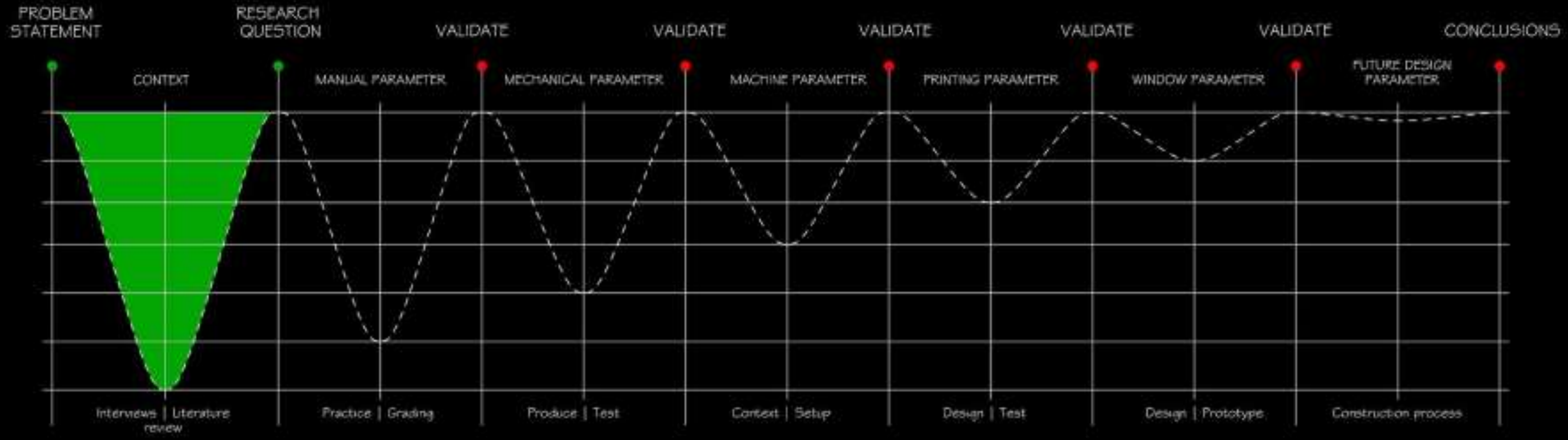
WORKFLOW OVERVIEW

TIMELINE



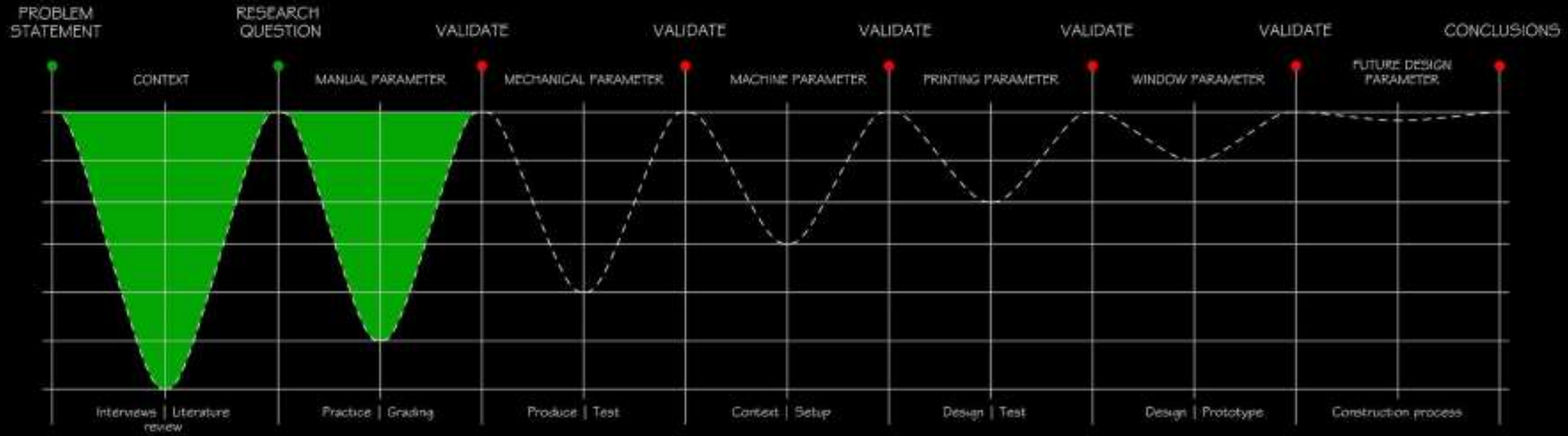
MANUAL PARAMETER

PRACTICE | GRADING



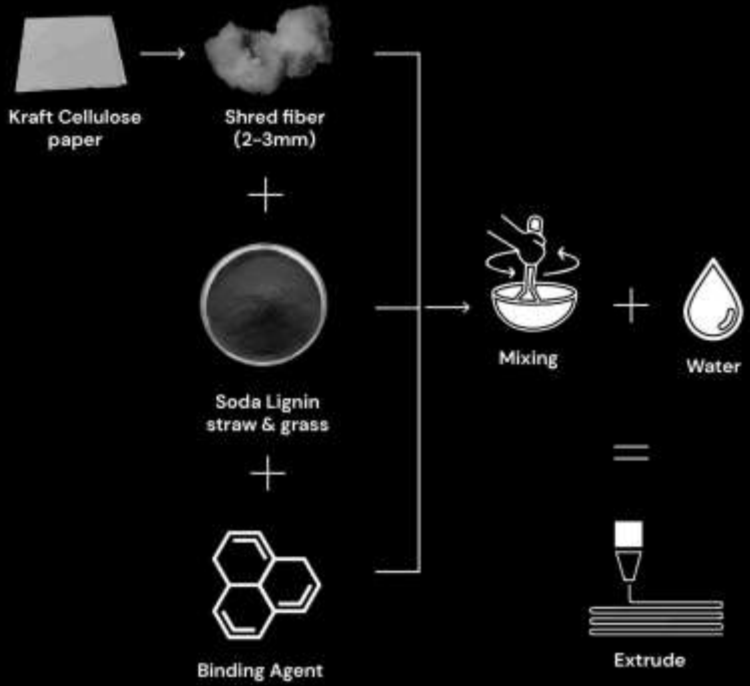
MANUAL PARAMETER

PRACTICE | GRADING

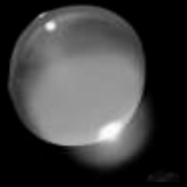


MATERIAL PROCESS

OVERVIEW



BINDING AGENTS OVERVIEW



MIX 1
**ACETON
E**

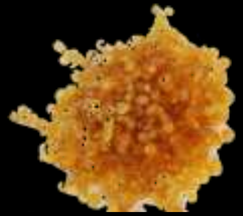
MIX 2
DMSO

MIX 3
**XANTHAN
GUM**

MIX 4
**CORN
STARCH**

MIX 5
**GLYCERIN
E**

MIX 6
**ALGINAT
E**



MIX 7
**BONE
GLUE**

MIX 8
**WOOD
GLUE**

MIX 9
**METHYLCELLULOS
E**

MIX 10
**BEESWA
X**

MATERIAL EXPERIMENTATION - HOT & COLD

OVERVIE
W

MIX 1
ACETONE

MIX 2
DMSO

MIX 3
XANTHAN GUM

MIX 4
CORN
STARCH

MIX 5
GLYCERIN
E

MIX 6
ALGINATE

MIX 7
BONE
GLUE

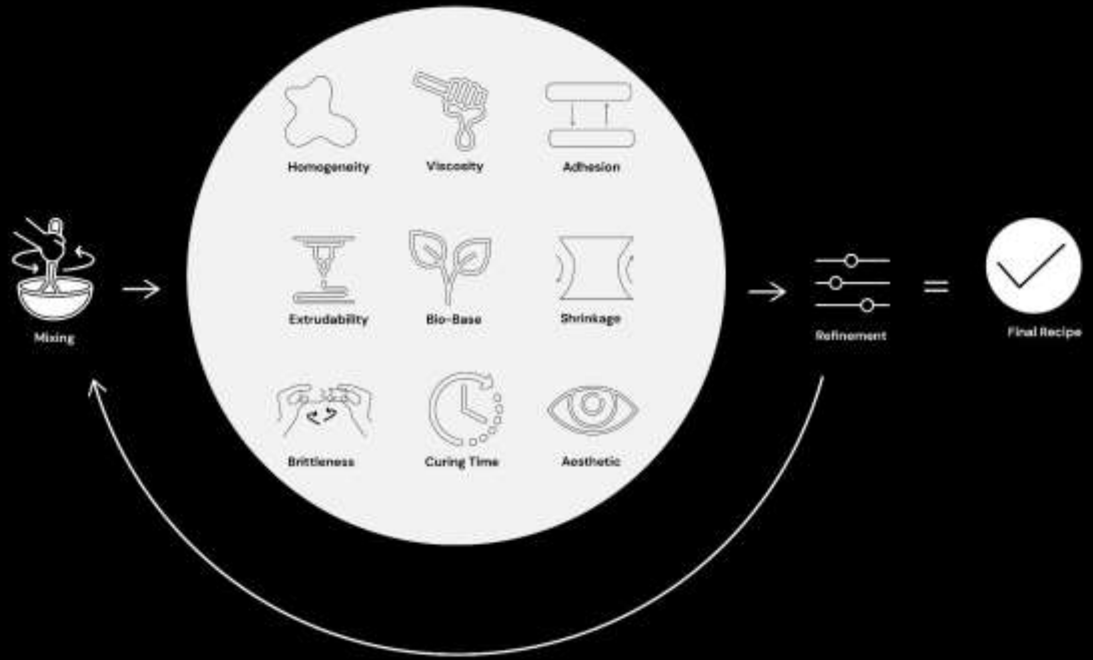
MIX 8
WOOD GLUE

MIX 9
METHYLCELLULOS
E

MIX 10
BEESWA
X

MATERIAL GRADING

PRINCIPLES



PROMISING MIXES - HOT & COLD

GRADING SYSTEM

MIX 1
ACETON
E

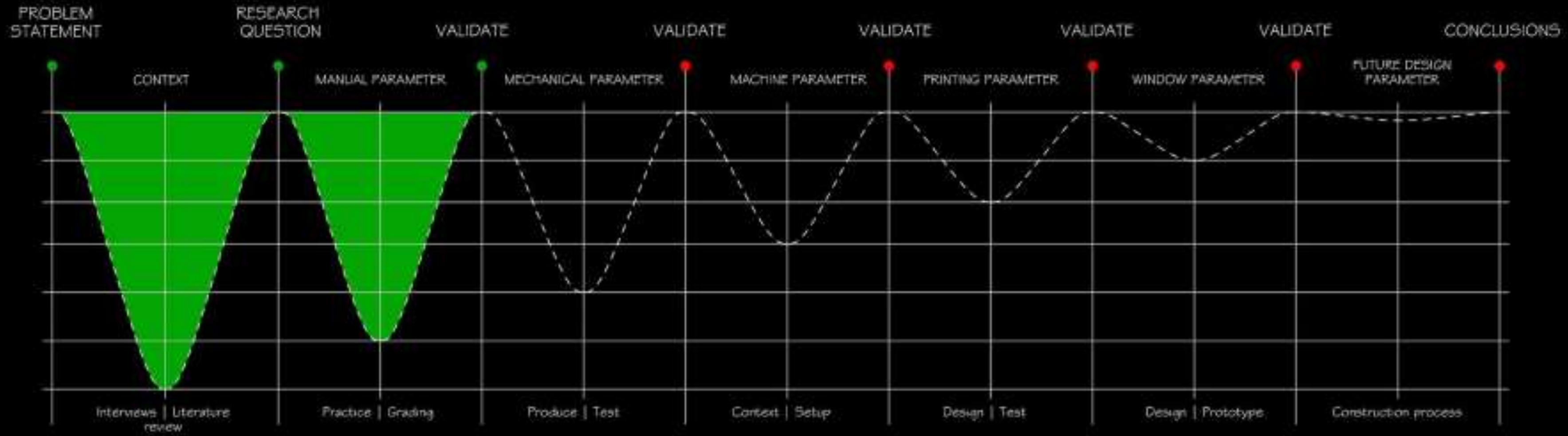
MIX 2
DMSO

MIX 8
WOOD
GLUE

MIX 9
METHYLCELLULOS
E

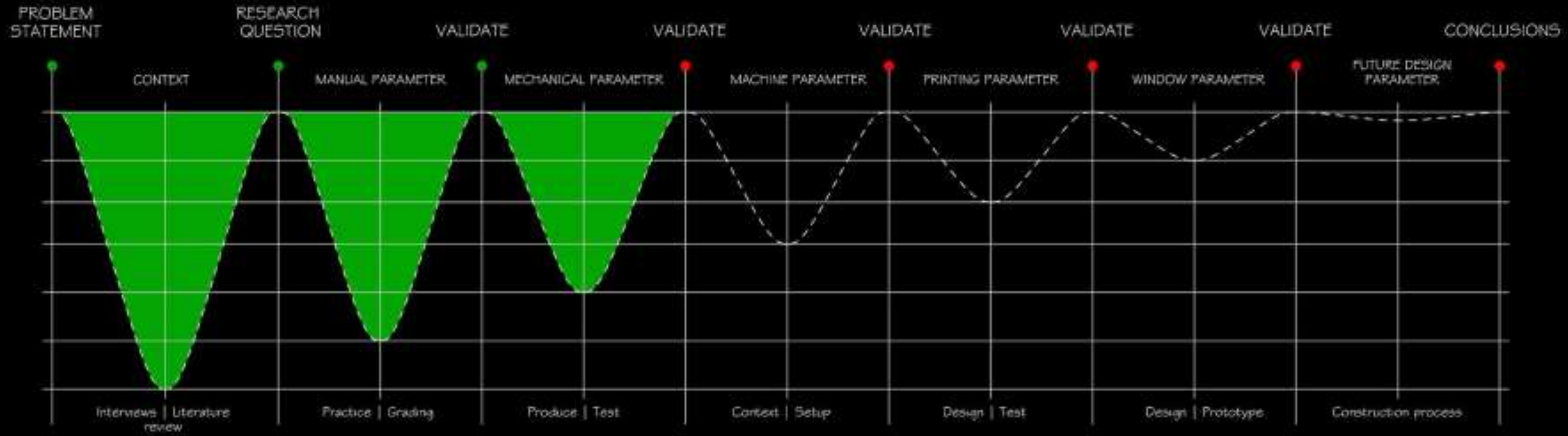
MECHANICAL PARAMETER

PRODUCE | TEST



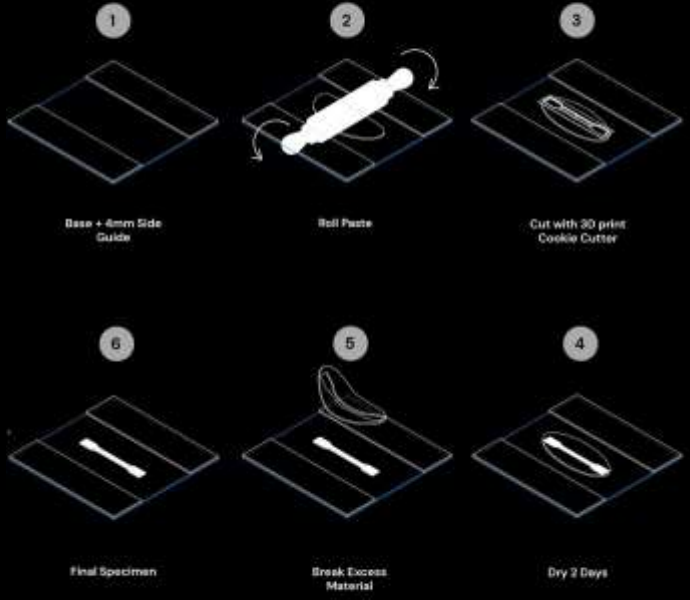
MECHANICAL PARAMETER

PRODUCE | TEST

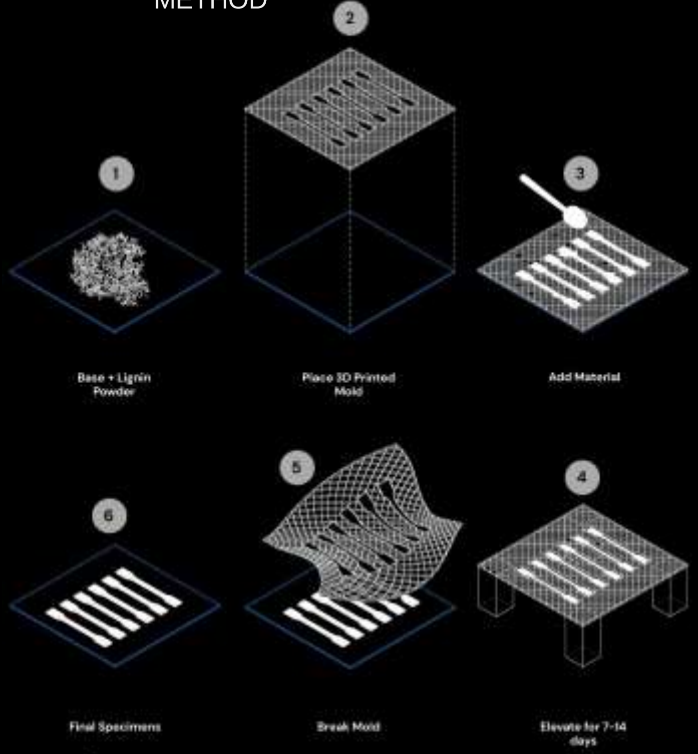


SPECIMEN PRODUCTION

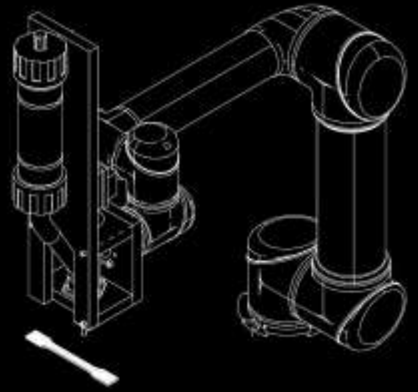
METHOD



MC & WG



A + DMSO

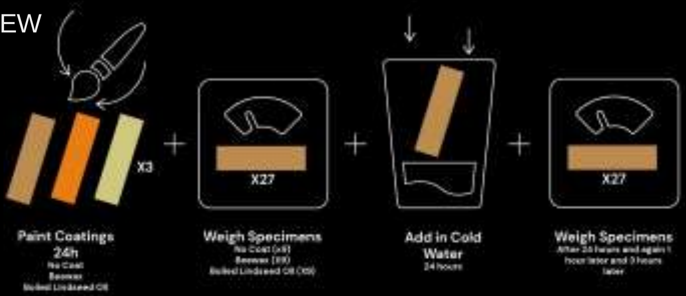


MC

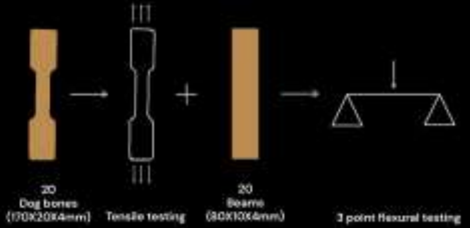
MECHANICAL TESTS

OVERVIEW

WATER RESISTANCE TEST



STRUCTURAL TEST

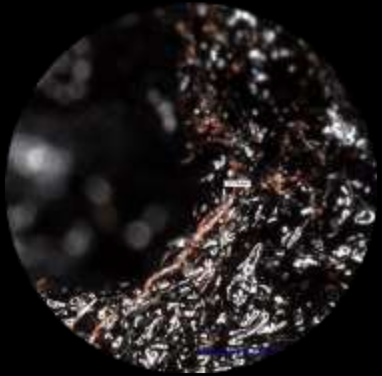


MICROSCOPE TEST

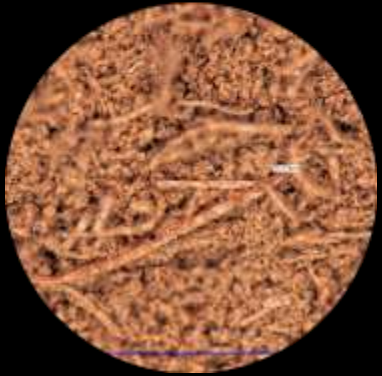
POROSITY, HOMOGENEITY, FIBER ORIENTATION

MICROSCOPE COMPARISON

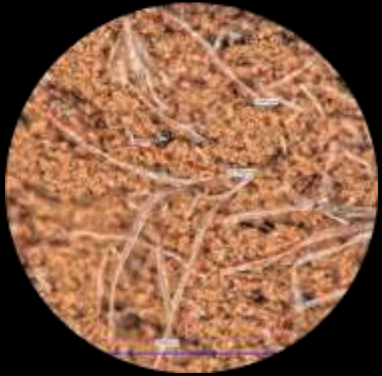
MIX 1
ACETON
E



MIX 2
DMSO



MIX 9
METHYLCELLULOS
E



MIX 8
WOOD
GLUE

5.

THOMAS
LIEBRAND
ACETONE

WATER ABSORPTION - NO COAT

WATER PROPERTIES COMPARISON

1
1.

MIX 8
WOOD
GLUE

MIX 1
ACETON
E

MIX 2
DMSO

Pine heartwood

MIX 9
METHYLCELLULOS
E

WATER ABSORPTION - LINSEED OIL

WATER PROPERTIES COMPARISON

1

1.

MIX 8
WOOD
GLUE

MIX 1
ACETON
E

MIX 2
DMSO

MIX 9
METHYLCELLULOS
E

Pine heartwood

YIELD STRENGTH (TENSILE TEST)

MECHANICAL PROPERTIES COMPARISON

8.

PINE
WOOD

9.

ARBOBLEN
D

10
.

FUNGAL LIKE
ADHESIVE
MATERIAL (FLAM)

MIX 9 (MC)

FLEXURAL MODULUS (3 POINT BENDING TEST)

MECHANICAL PROPERTIES COMPARISON

8.

9.

10.

PINE WOOD

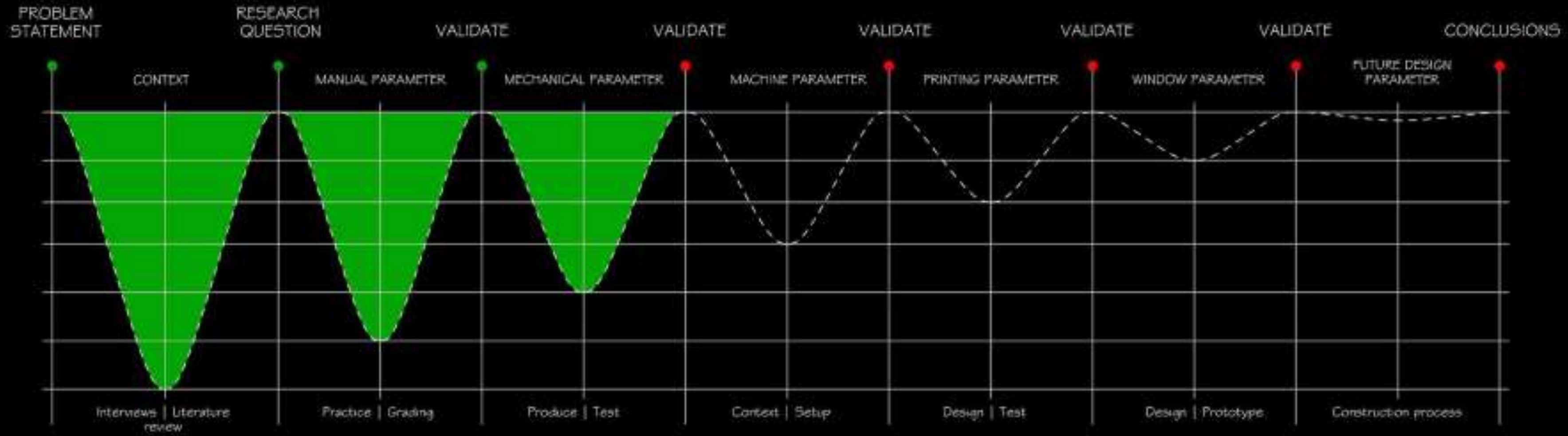
ARBOBLEND

MIX 9 (MC)

FLAM

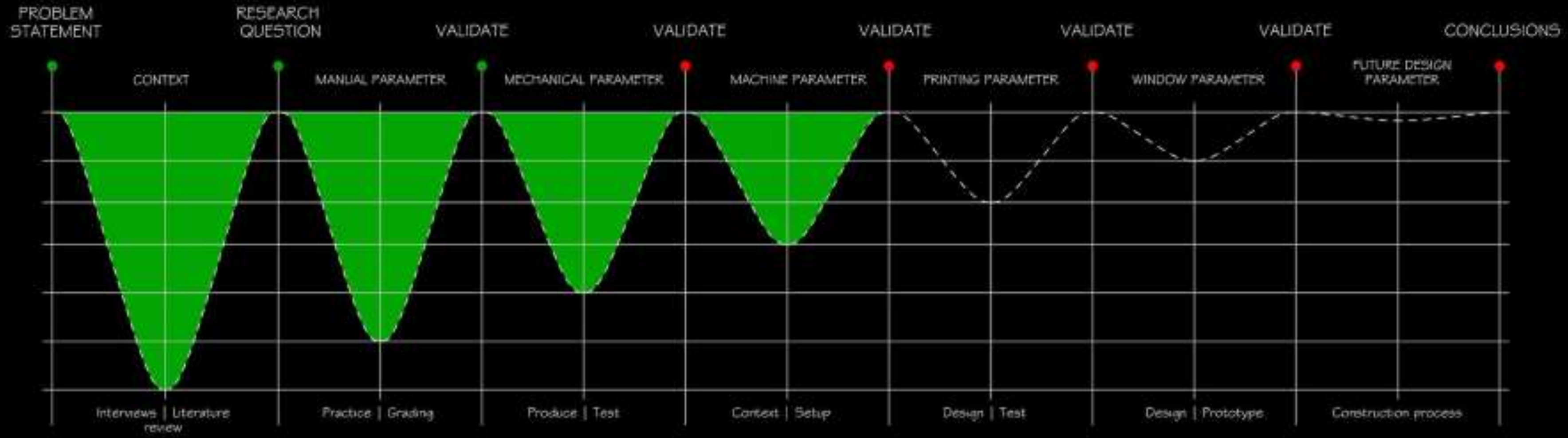
MACHINE PARAMETER

CONTEXT | SETUP

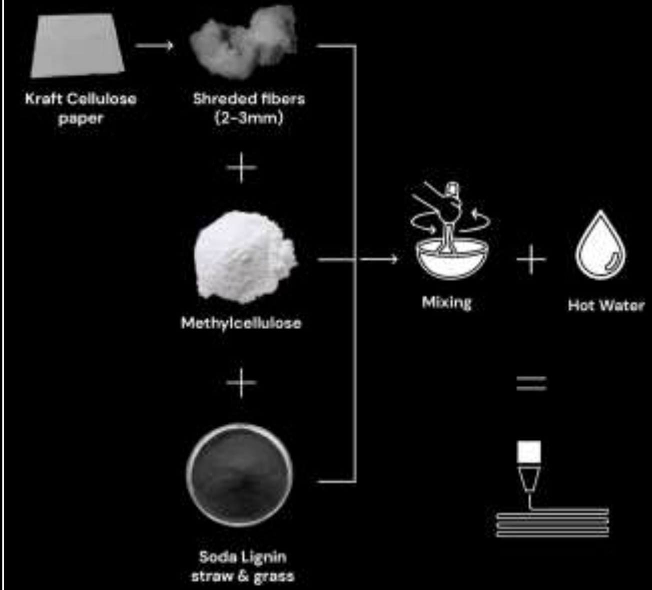


MACHINE PARAMETER

CONTEXT | SETUP

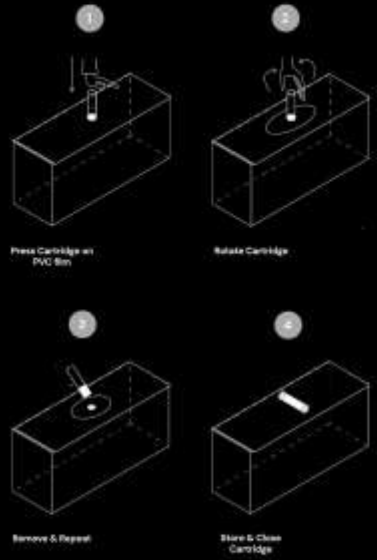


MATERIAL SETUP

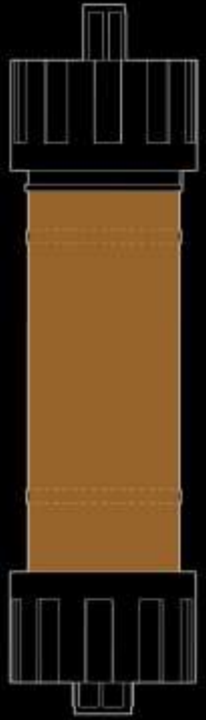


BEST MIX = 11.7 L + 1.2 C + 9.8 MC + 25.4 W

MIXING PROCESS



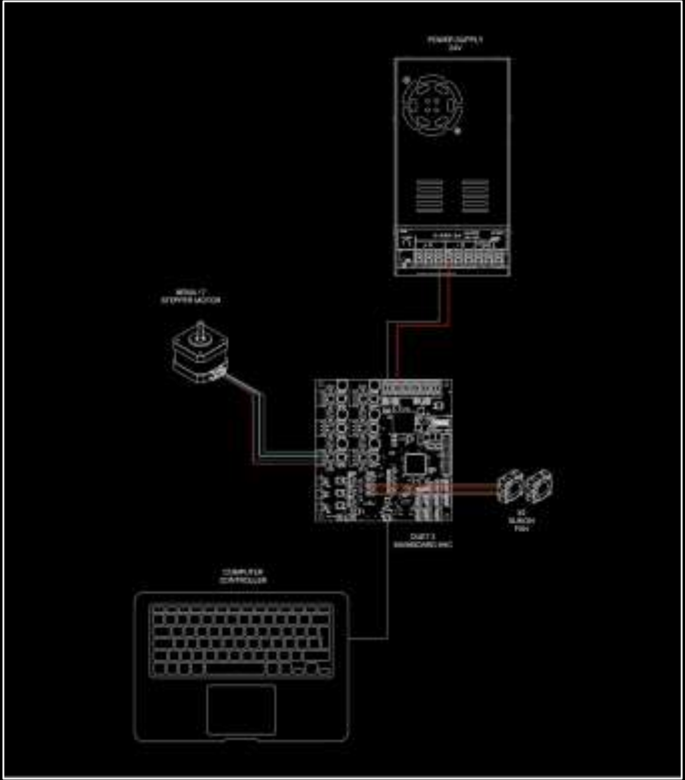
CARTIDGE MIX = 164 L + 16 C + 27.5 MC + 356 W



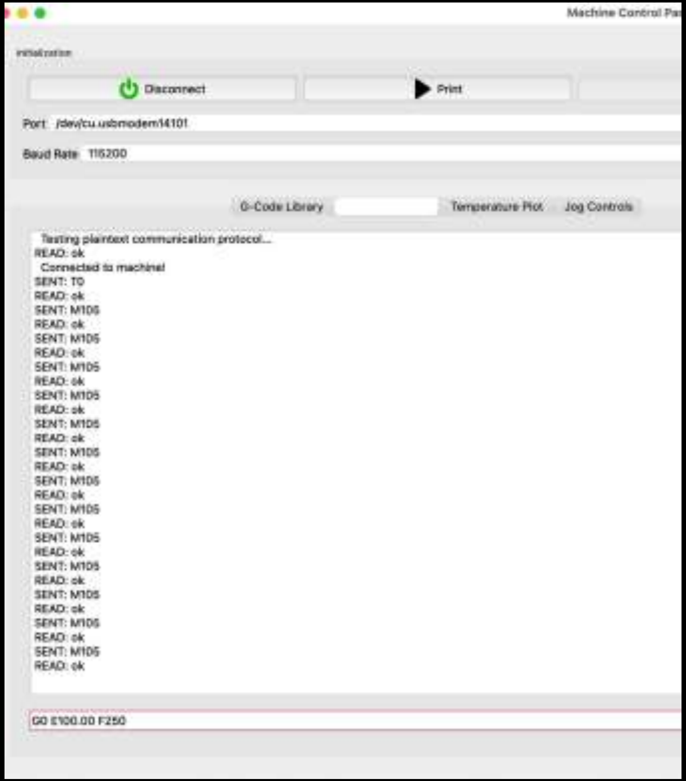
FULL CARTRIDGE

FIRMWARE | HARDWARE | SOFTWARE SETUP

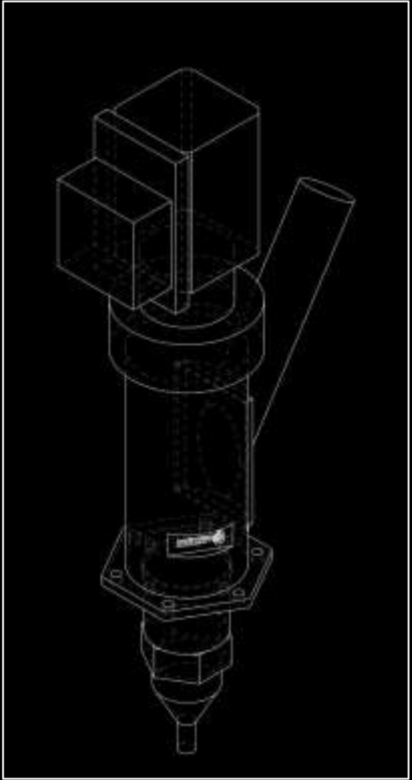
LOCAL



WIRING SETUP (DUET 3, NEMA17)



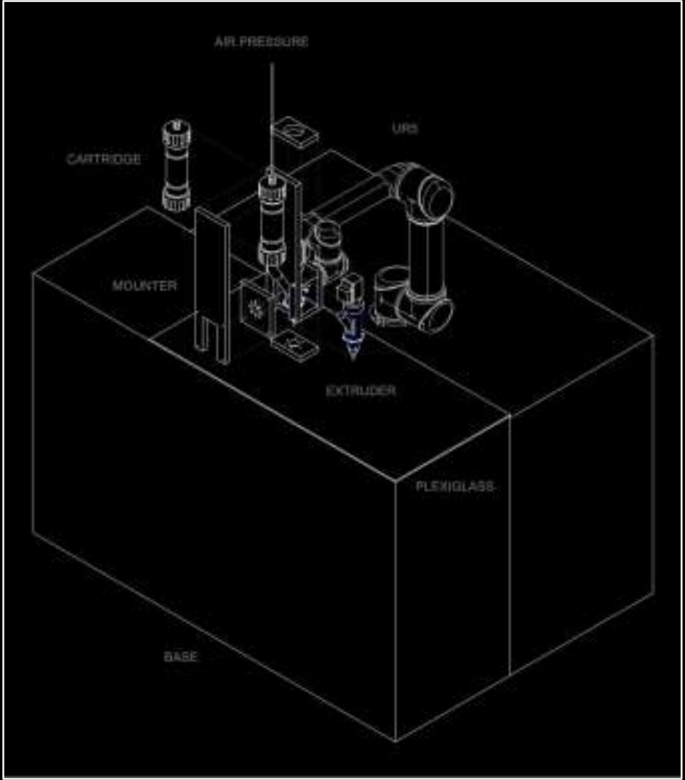
SLICING SOFTWARE (SIMPLIFY3D)



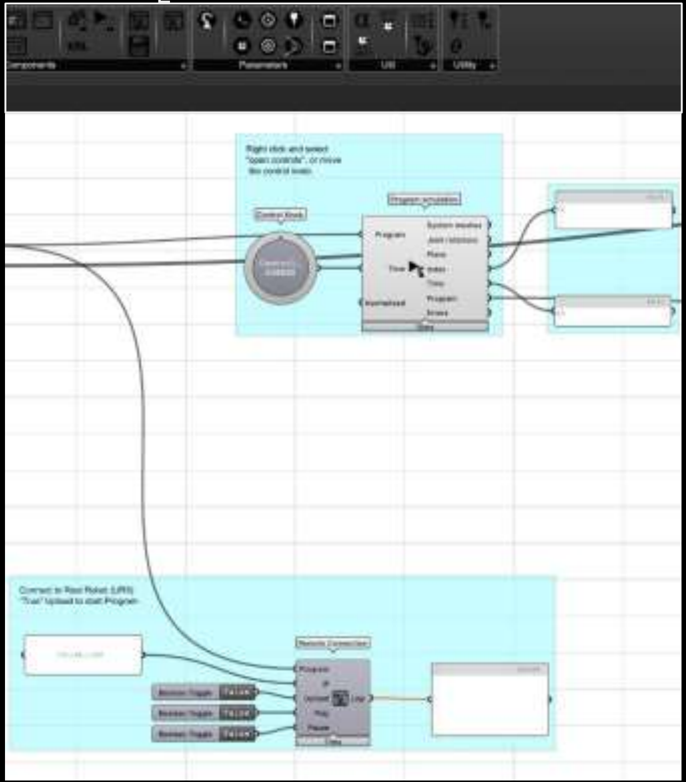
LDM WASP EXTRUDER XL 3.0

FIRMWARE | HARDWARE | SOFTWARE SETUP

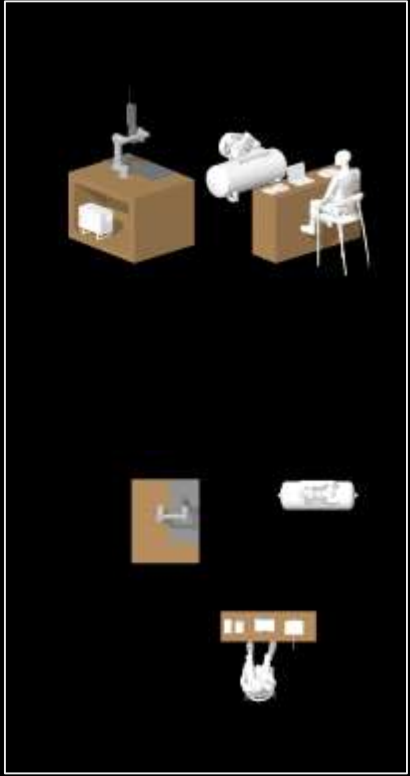
GLOBA
L



3D PRINTING SETUP (CUSTOM TOOL)



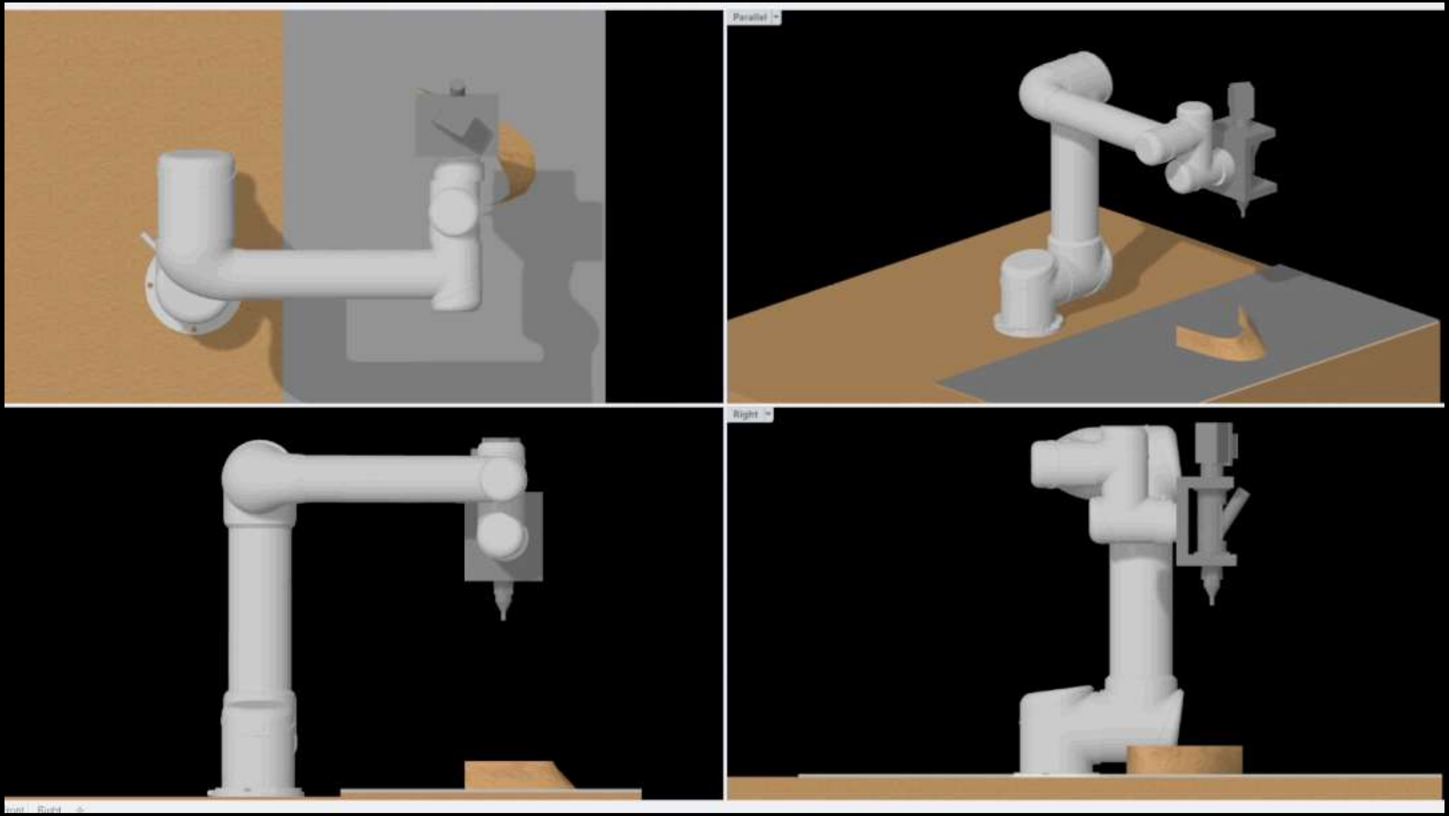
ROBOTS PLUG-IN CONTROLLER

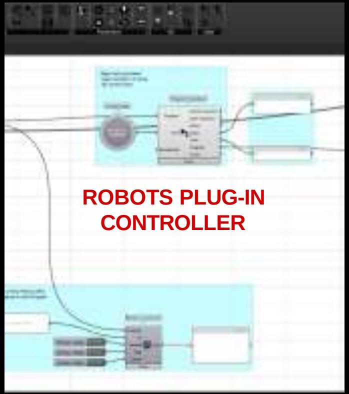


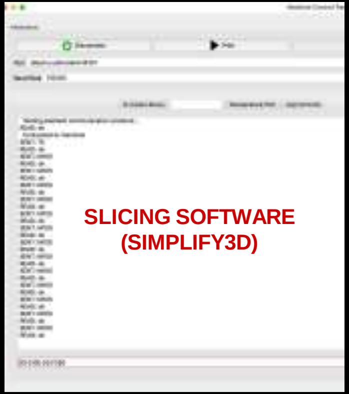
SIMULATED WORKSPACE

SIMULATED OVERVIEW

MATERIAL, FIRMWARE, HARDWARE, SOFTWARE SETUP

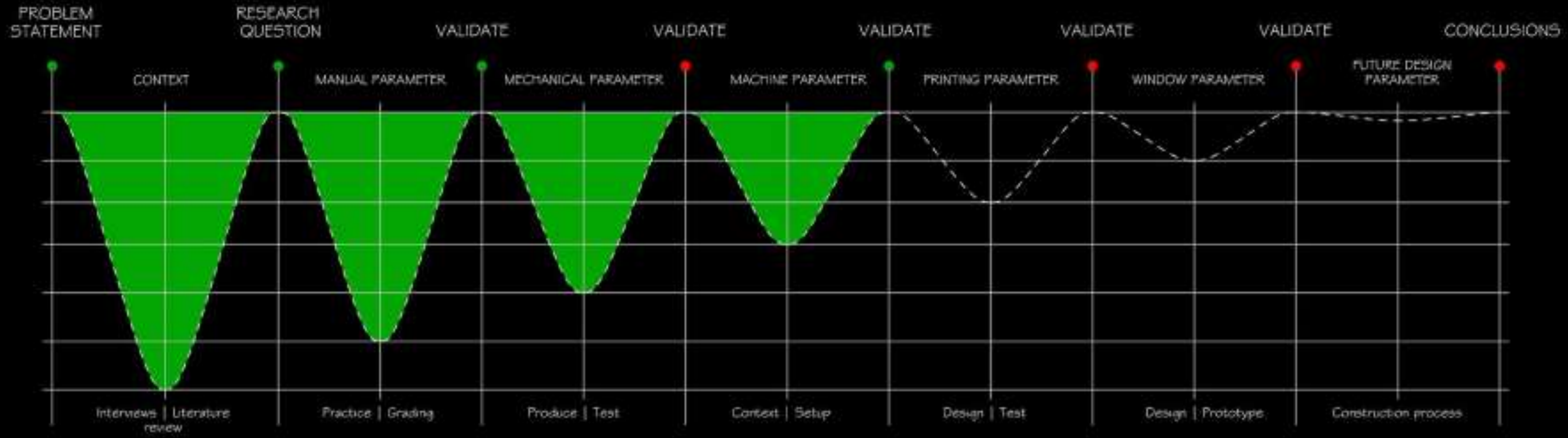






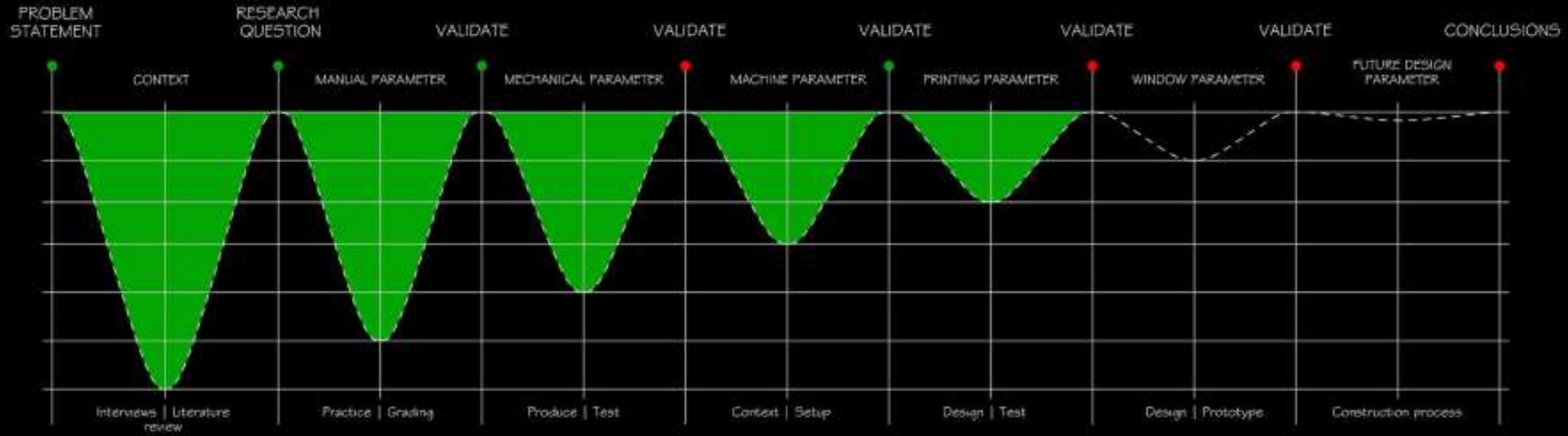
PRINTING PARAMETER

DESIGN | TEST



PRINTING PARAMETER

DESIGN | TEST

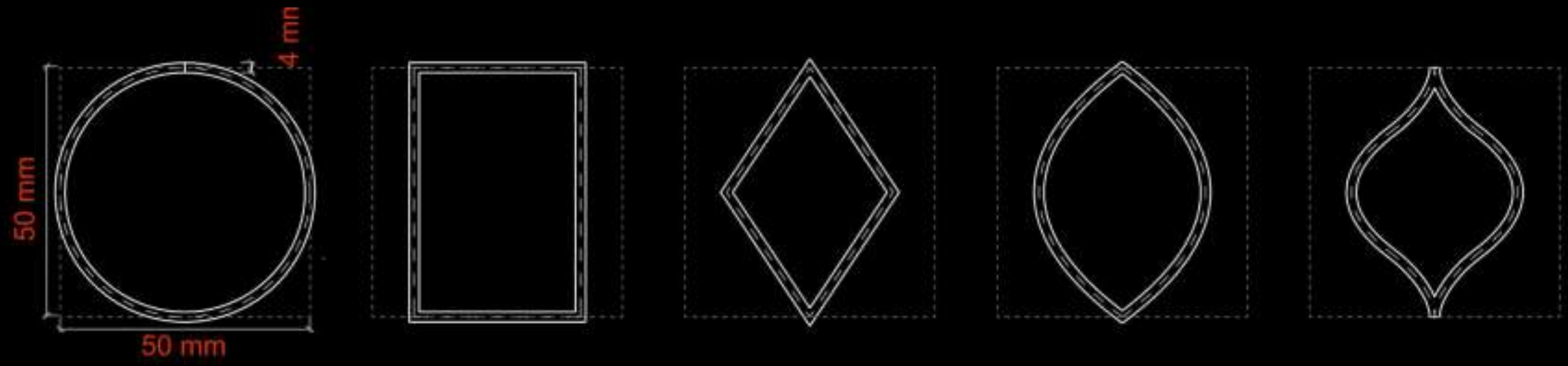


PRINCIPAL GEOMETRY TESTING

LIMITATION & POTENTIAL







CIRCL
E

RECTANGLE &
SQUARE

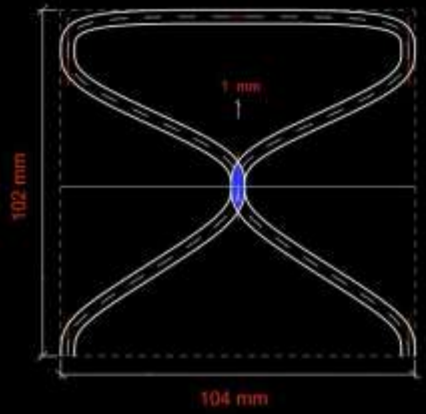
DIAMOND

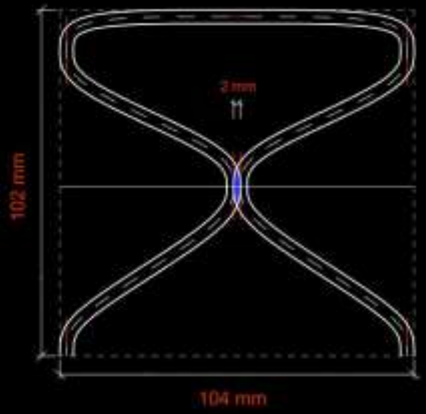
EY
E

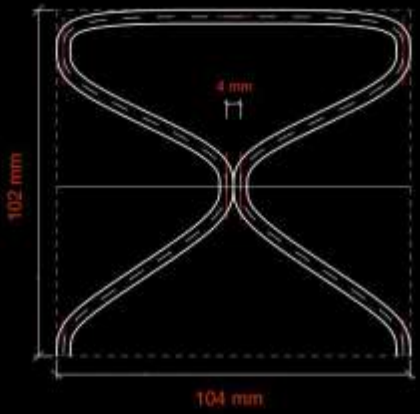
OLIVE

OVERLAP TESTING

LIMITATION & POTENTIAL

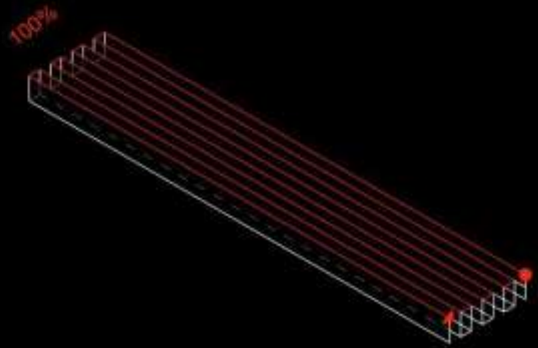


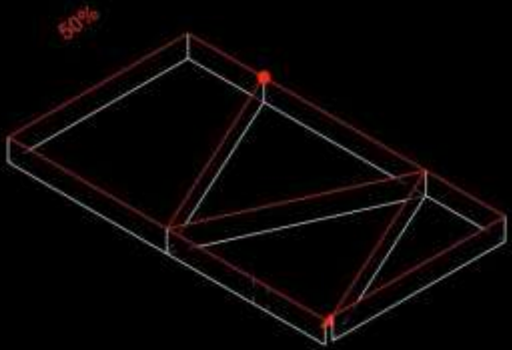


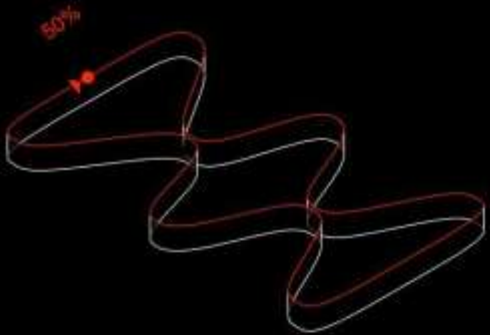


INFILL & TOOLPATH TESTING

LIMITATION & POTENTIAL

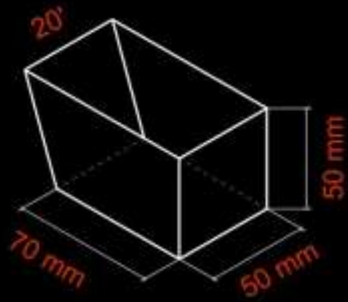






OVERHANG TESTING

LIMITATION & POTENTIAL



STRAIGH
T

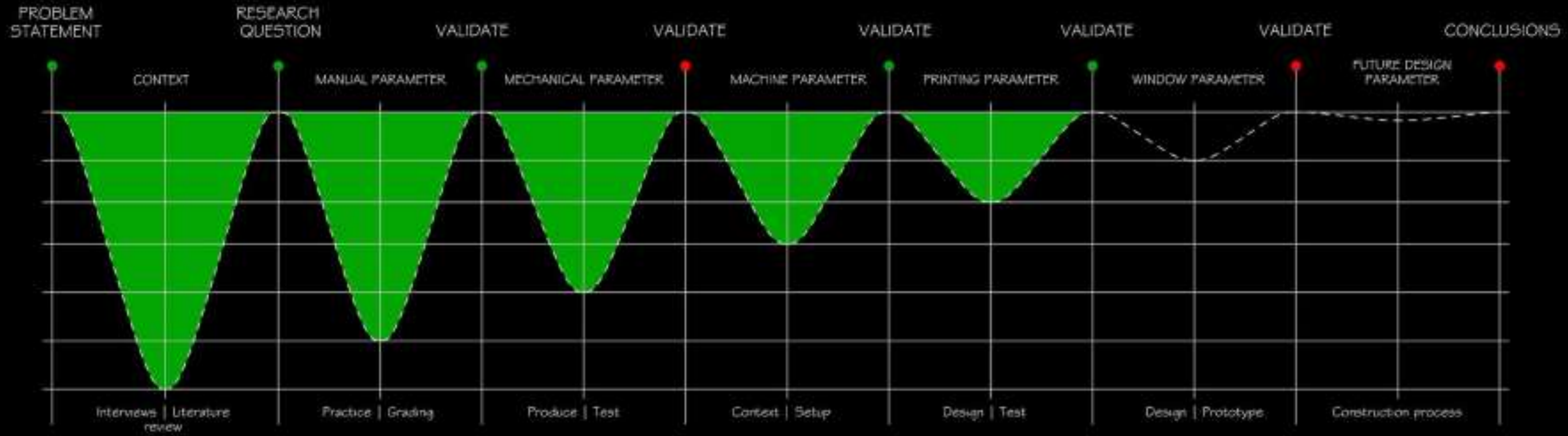
CURVE
D

STRAIGHT
INFILL

CURVED
INFILL

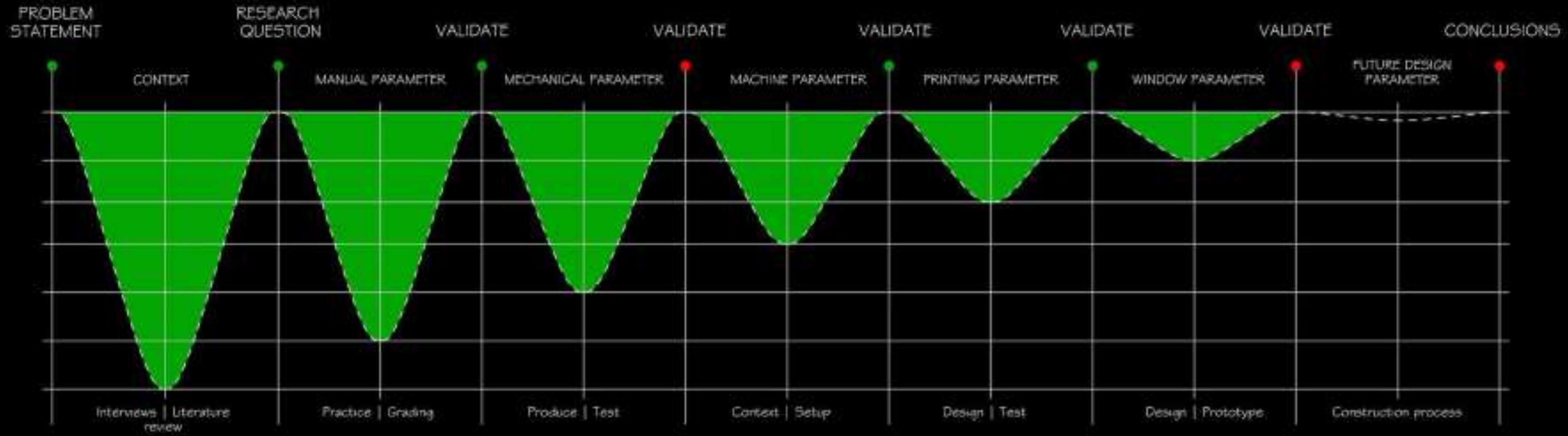
WINDOW PARAMETER

DESIGN | PROTOTYPE



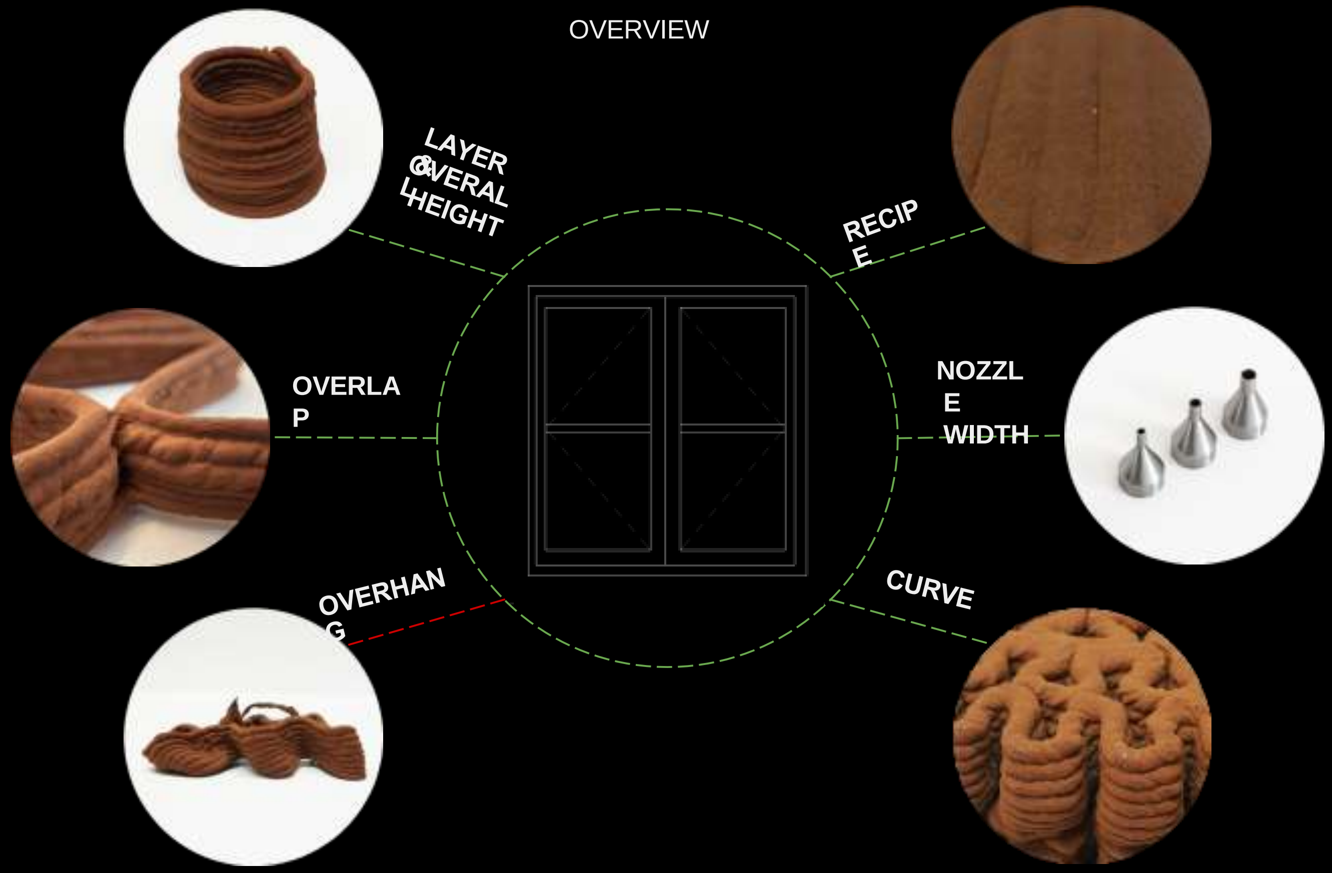
WINDOW PARAMETER

DESIGN | PROTOTYPE



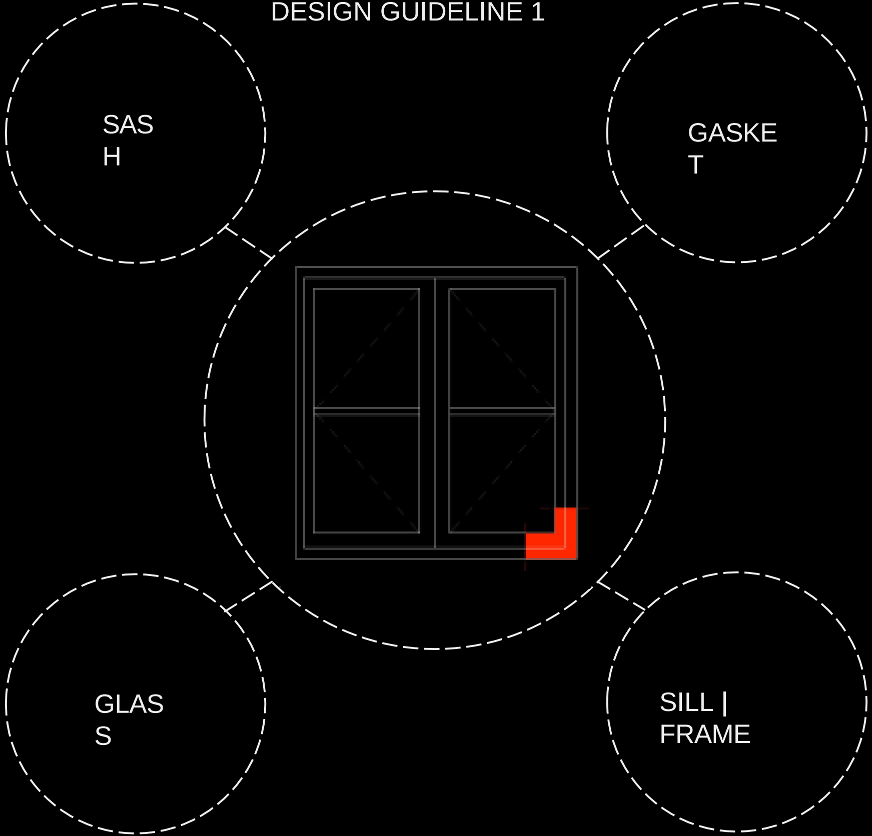
DESIGN CONSIDERATIONS

OVERVIEW



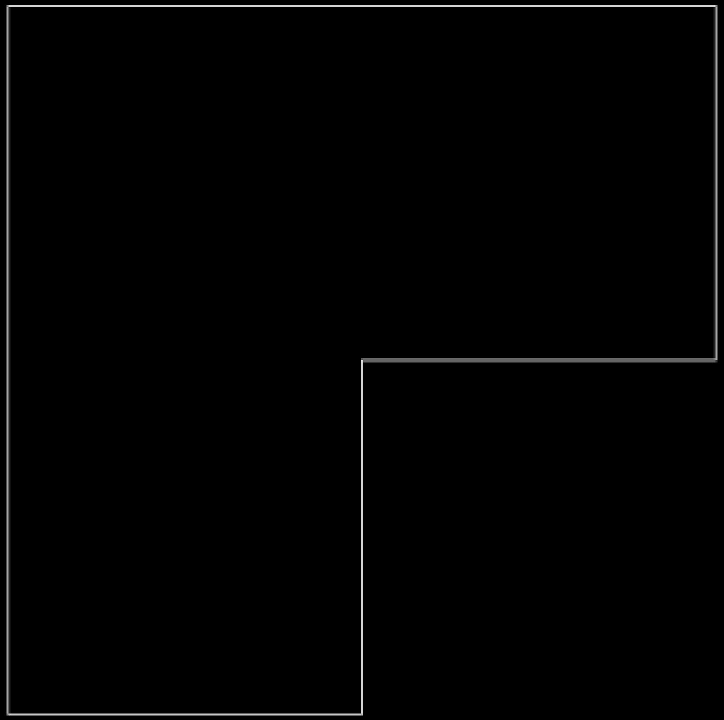
CORNER OF WINDOW FRAME TYPOLOGY

DESIGN GUIDELINE 1



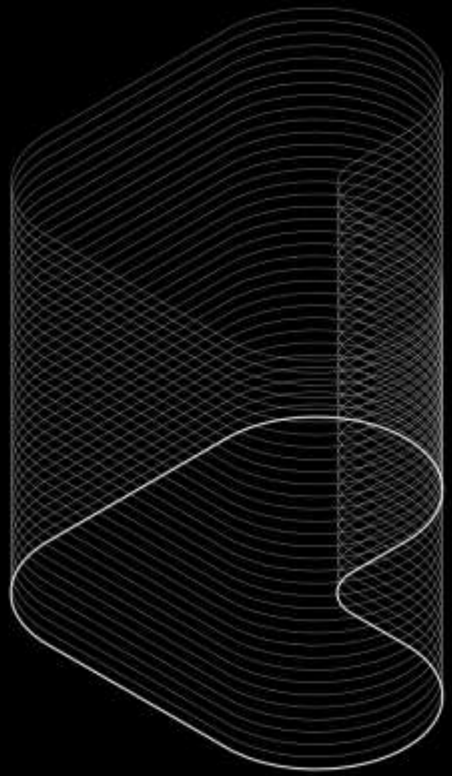
STRAIGHT TO CURVE BORDER

DESIGN GUIDELINE 2



HEIGHT & OVERHANG

DESIGN GUIDELINE 3



TOOLPATH RESTRICTION

DESIGN GUIDELINE 4

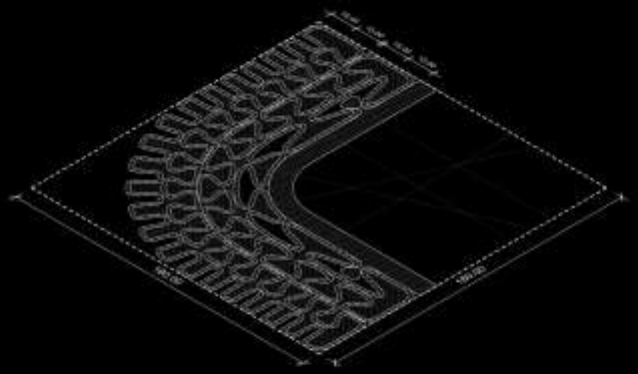
LINEA
R

CURVE
D

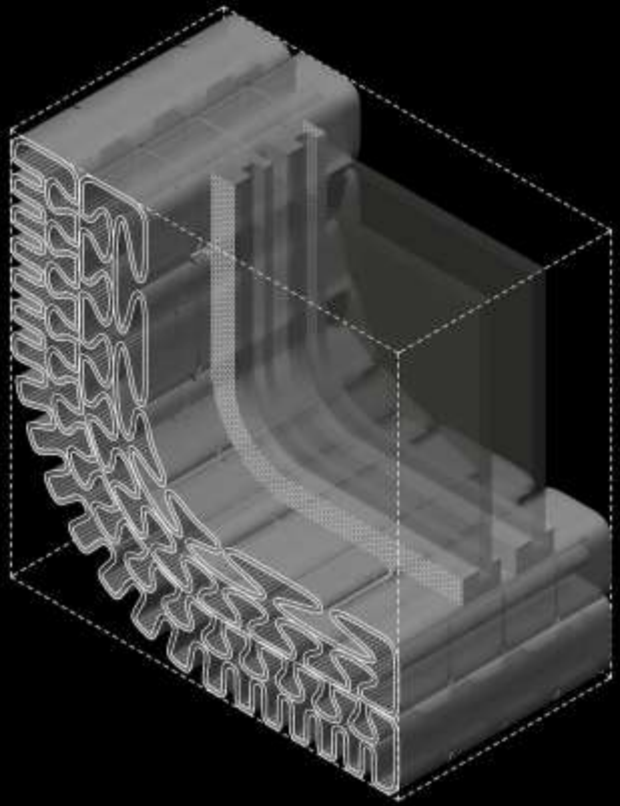
VORONO
I

FINAL MODEL

CONSTRUCTION



FINAL DIGITAL PROTOTYPE



CONSIDERATIONS

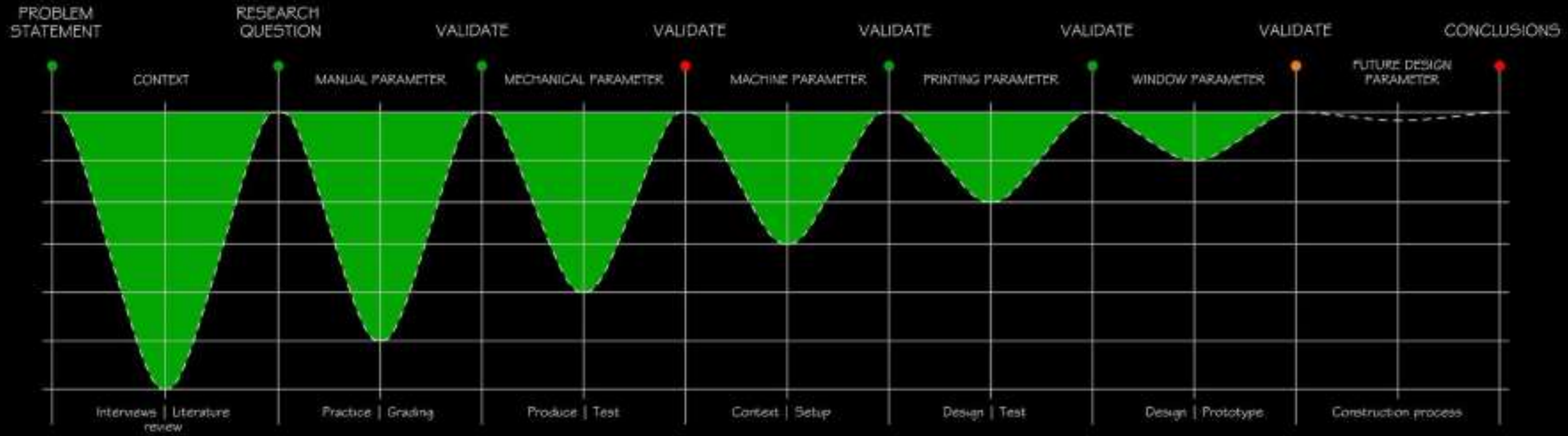
LIMITATION & POTENTIAL

CONNECTION TO GASKET

CONNECTION TO FRAME

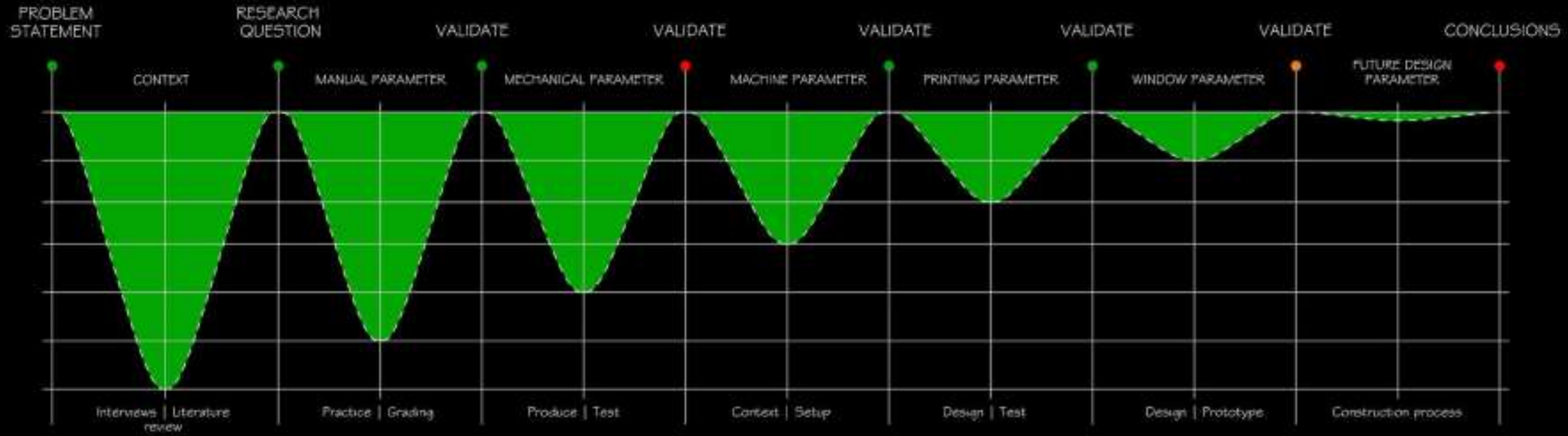
FUTURE VISION

CONSTRUCTION PROCESS



FUTURE VISION

CONSTRUCTION PROCESS



CASE
STUDY

WINDOW FRAME

14
.

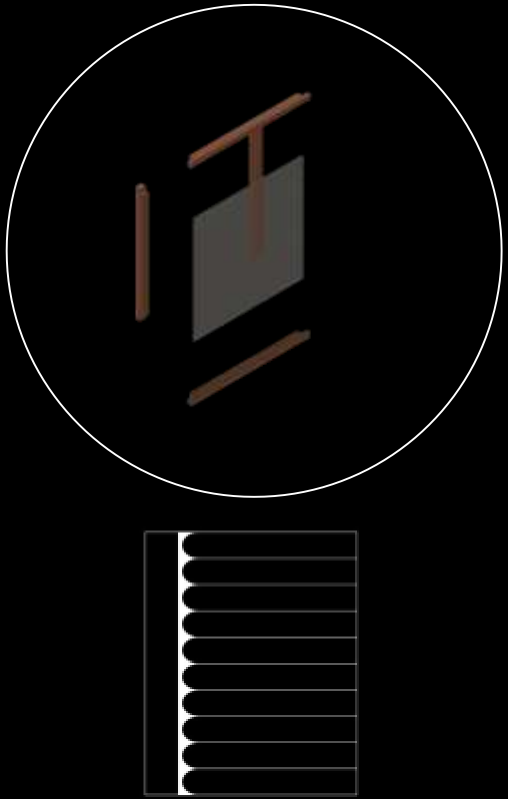
DECA
Y

CONNECTIO
N

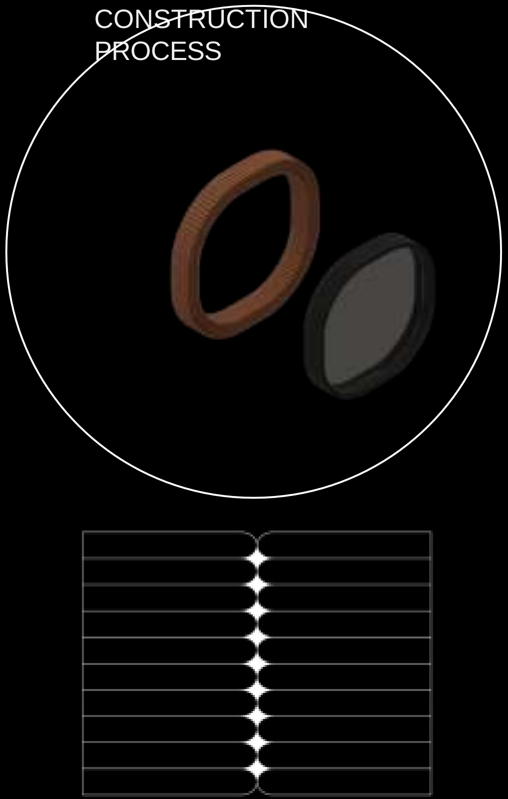
LINEA
R

APPLICATIONS

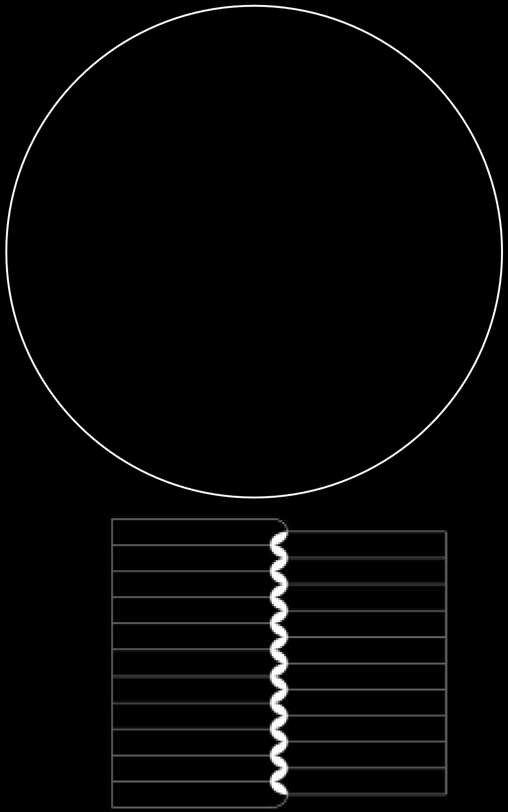
CONSTRUCTION PROCESS



PAST



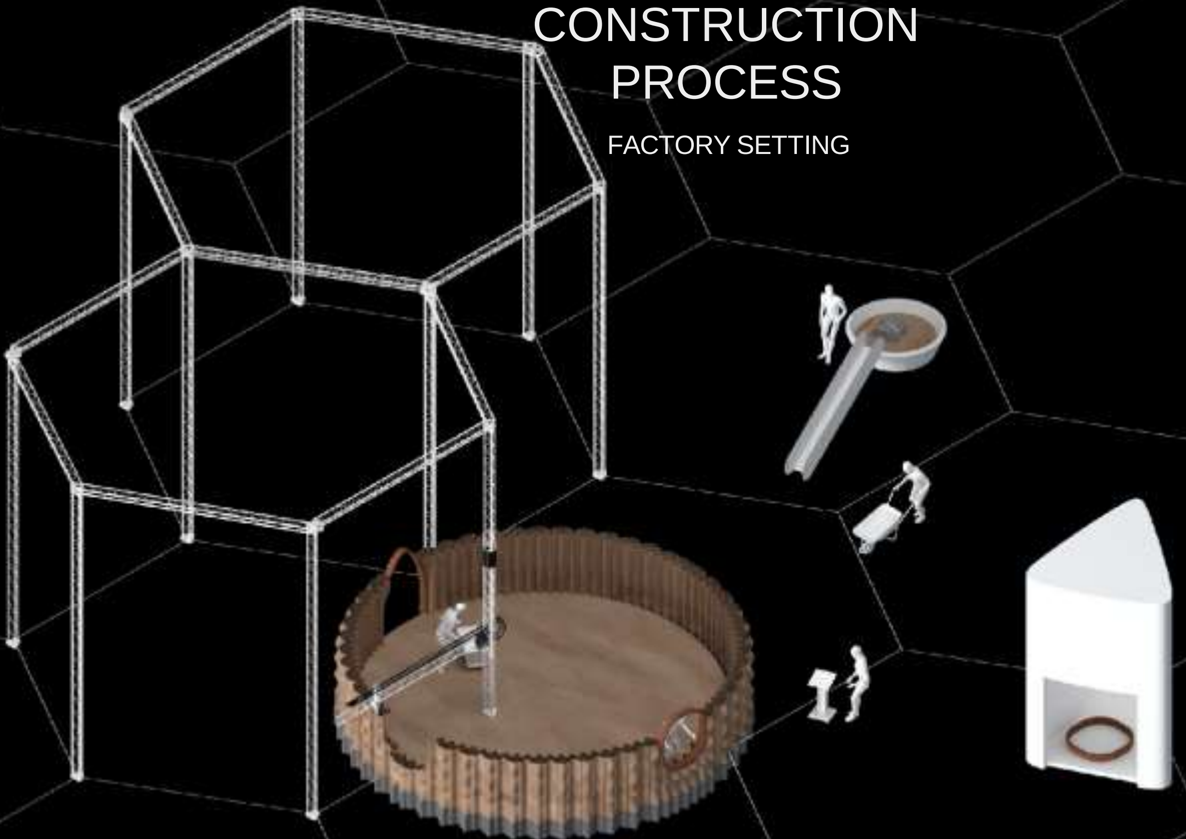
PRESENT



FUTURE

CONSTRUCTION PROCESS

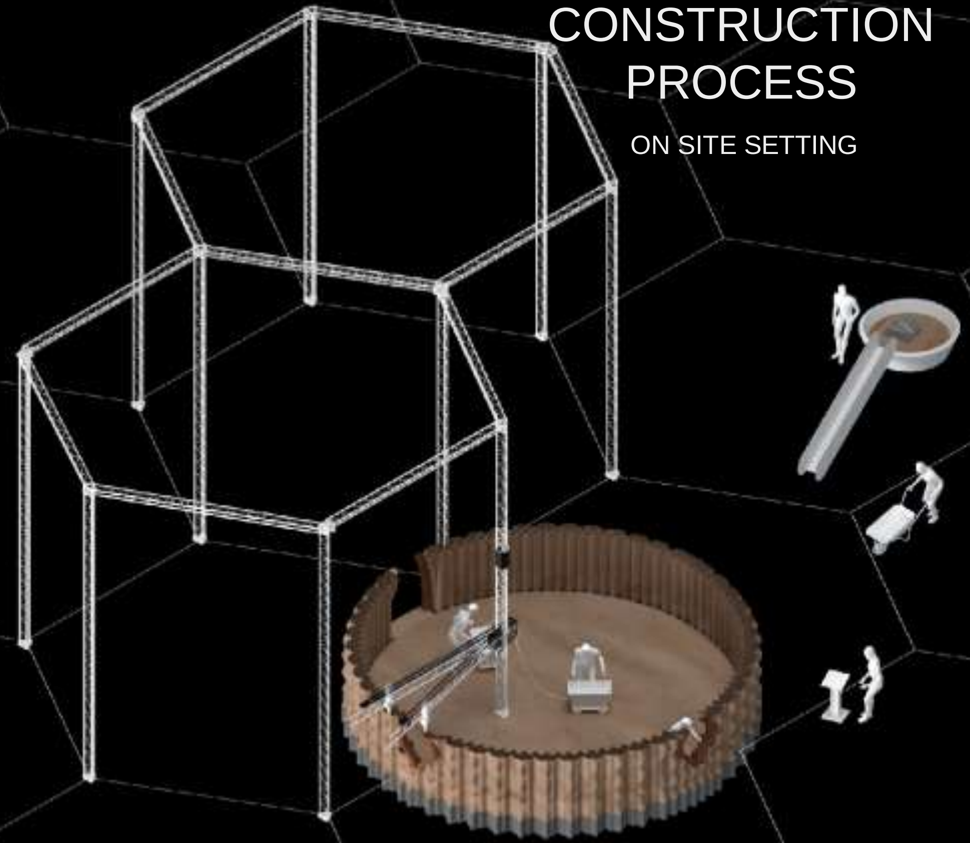
FACTORY SETTING



HEIGHT & OVERHANG

CONSTRUCTION PROCESS

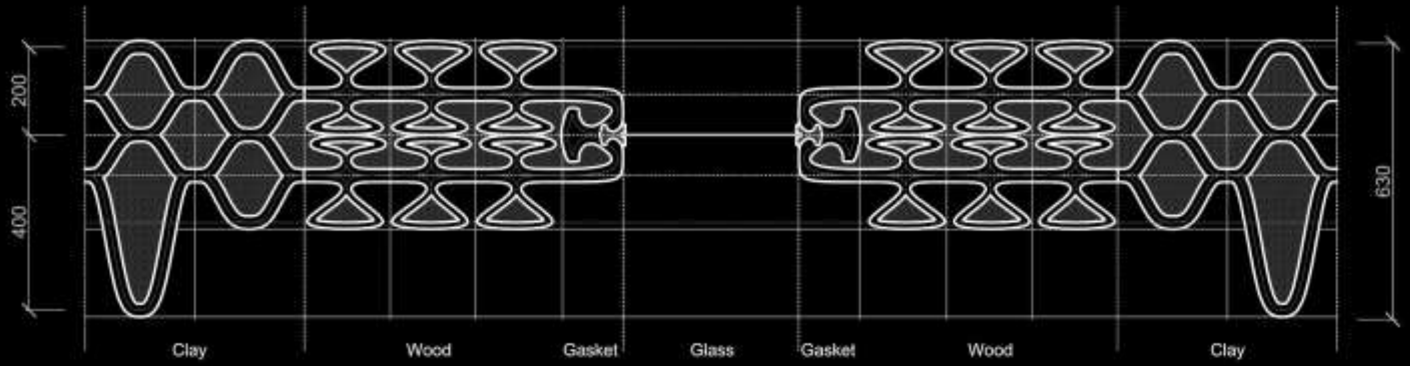
ON SITE SETTING



HEIGHT & OVERHANG

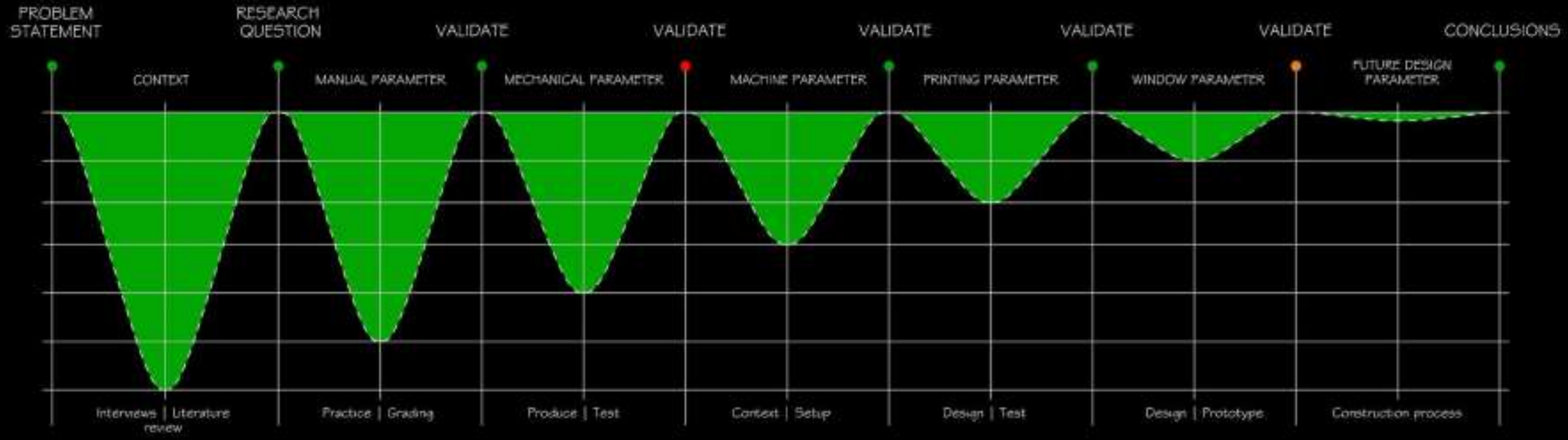
FUTURE
CONNECTION

CONNECTION FROM WALL TO FRAME



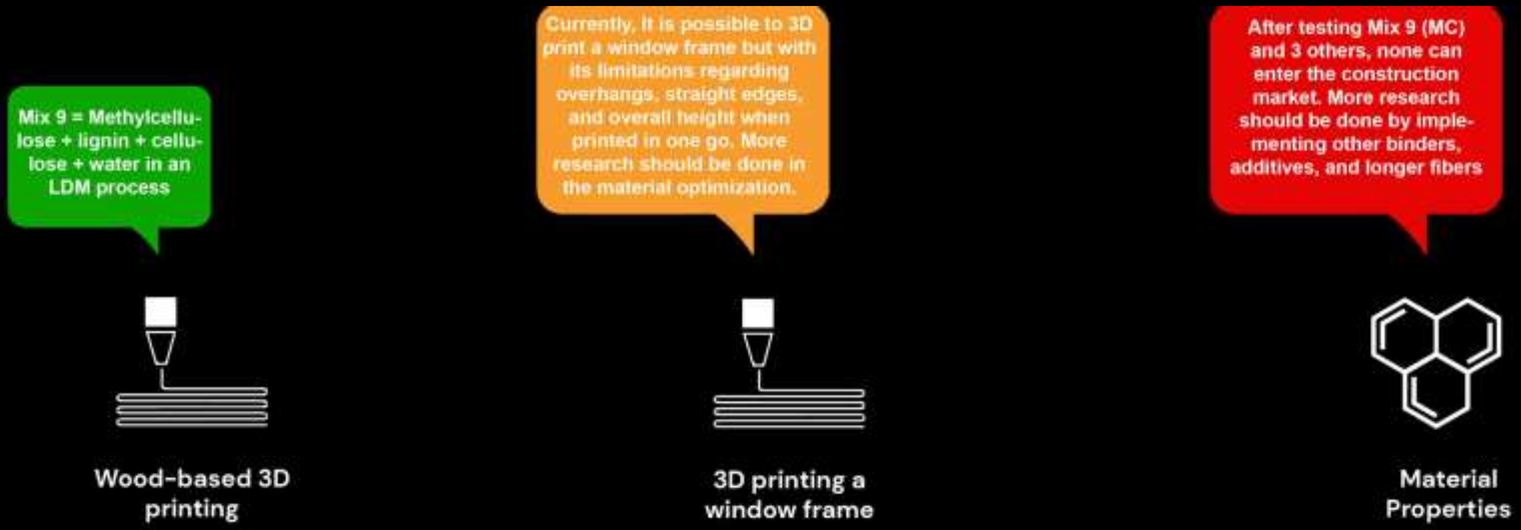
CONCLUSION
S

WHAT'S NEXT



CONCLUSIONS

REFLECTION



THANK YOU

QUESTIONS?

APPENDI
X

REFERENCES

MATERIAL MIXTURE

REFERENCES	THOMAS LIEBRAND	GABRIELLA ROSSI	MARTINA BAMBI & RONALD HELGERS	MAX LATOUR	MAX LATOUR
BASE MATERIALS	CELLULOSE, LIGNIN, ACETONE, WATER	CELLULOSE, WOODFLOUR, XANTHAN GUM, GLYCEROL, CALCIUM	wood flour, water, methylcellulose (also tried wool paper glue, bentonite, alcohol, agar agar, potato starch)	PAPER PULP, COFFEE BEANS AND CLAY	White turning clay 1000-1300c, wit-witbaak, filter coffee, mycelium
RECIPE	10g WATER + 26g ACETONE + 40g LIGNIN + 5g CELLULOSE	cellulose floc 10%, woodflour 7% (sawdust), xanthan gum 2% (sugar) , glycerol 8% (sugar alcohol) , calcium 1%)	wood flour 600g, water 2070g, methylcellulose 135 g, color additive	7 liters of White turning clay 1000-1300c, 25% chamotte, 2% dry paper pulp	N.I.
PROS	- Homogenous - High viscosity - High adhesion	Good elastic performances	- Bentonite helps to harden the material	N.I.	Successful material experiments to grow mycelium through a clay based material
LIMITATIONS	- Not a natural solvent - No mechanical tests made - Does not look like wood - Take time to dry	low strength properties (depend on fiber length)	- melts when wet - not biobased glue	The estimated proportions are not very accurate (clay is lost during the process)	N.I.

REFERENCES

MATERIAL MIXTURE

REFERENCES	THOMAS LIEBRAND	GABRIELLA ROSSI	MARTINA BAMBI & RONALD HELGERS	MAX LATOUR	MAX LATOUR
BASE MATERIALS	CELLULOSE, LIGNIN, ACETONE, WATER	CELLULOSE, WOODFLOUR, XANTHAN GUM, GLYCEROL, CALCIUM	wood flour, water, methylcellulose (also tried wool paper glue, bentonite, alcohol, agar agar, potato starch)	PAPER PULP, COFFEE BEANS AND CLAY	White turning clay 1000-1300c, wit-witbaak, filter coffee, mycelium
RECIPE	10g WATER + 26g ACETONE + 40g LIGNIN + 5g CELLULOSE	cellulose floc 10%, woodflour 7% (sawdust), xanthan gum 2% (sugar) , glycerol 8% (sugar alcohol) , calcium 1%)	wood flour 600g, water 2070g, methylcellulose 135 g, color additive	7 liters of White turning clay 1000-1300c, 25% chamotte, 2% dry paper pulp	N.I.
PROS	- Homogenous - High viscosity - High adhesion	Good elastic performances	- Bentonite helps to harden the material	N.I.	Successful material experiments to grow mycelium through a clay based material
LIMITATIONS	- Not a natural solvent - No mechanical tests made - Does not look like wood - Take time to dry	low strength properties (depend on fiber length)	- melts when wet - not biobased glue	The estimated proportions are not very accurate (clay is lost during the process)	N.I.

REFERENCES

3D PRINTING

RESEARCH & REFERENCE	THOMAS LIEBRAND	GABRIELLA ROSSI	MARTINA BAMBI & RONALD HELGERS	MAX LATOUR	MAX LATOUR
AM TYPE	LDM	LDM	LDM	LDM	LDM
TEMPERATURE	COLD PROCESS	COLD PROCESS (hot process in the future)	COLD PROCESS	COLD PROCESS	COLD PROCESS
NOZZLE SETTINGS	1.6 mm	N.I.	2-8mm	4 mm	3 mm
LAYER HEIGHT	2mm, 5mm	0.5MM?	0.2mm-0.4mm	4 mm	2.3 mm
LAYER WIDTH	29mm	2-4MM?	30MM	5 mm	4.5 mm
FLOW	200%, 600%, 800%	2 BAR PRESSURE	6 BAR PRESSURE	start:30-40 main:28	start:65 main:55-60
SPEED	5 mm/s	35 mm/s	NOT INDICATED	start:60 main:100	start:80 main:95-100
PROS	N.I	- Printable at a large scale - Geometrical freedom to design complex joints	- Large fibers = Increase strength connects material better, small fibers = get a smoother, nicer finish	N.I.	- Coffee grain enhances the structural capacities of the wet clay
LIMITATIONS	- Only printed with a syringe - Requires metal installation	- Evaporative surface - Dries unequally	- low drying process: Added 3 hair dries on the printer while printing the artifact - No scientifc tests	- Difficult to extrude because it contracted in the tank - When exits nozzle, material expands causes issues which increase the amount of layers printed.	N.I.

REFERENCES

FINAL PROTOTYPE

RESEARCH & REFERENCE	THOMAS LIEBRAND	GABRIELLA ROSSI	MARTINA BAMBI & RONALD HELGERS	MAX LATOUR	MAX LATOUR
SIZE	circle 38mm and triangle 40mm, height 150mm	80 X 50 X 25 cm	80 cm heigh	186 X 171 X 286 mm	186 X 171 X 286mm
SHRINKAGE	Medium	25 %	N.I.	N.I	N.I.
WATER ABSORPTION	Low	High	N.I.	High	High
CONCLUSIONS	N.I.	- Geometrical based influence: Cylindar loose 70% of its weight after 7 days - High evaporative rate: shrinks 25% in height (check infill structure of the cavities and amount of air)	Print 80 cm high continuous feeding vase with different colors in 1.5 days with 6 batches of 10-15L. Very strong when not in contact with water.	The speed and flow are percentages of the feedrate and extrusion value respectively, they depend on the code and pressure as well.	successful material experiments to grow mycelium through a clay based material with both coffee and paper pulp and those individually.

GRADING ANALYSIS
MIX1

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 1	24g Lignin, 2g Cellulose, 8g Water, 11.2g Acetone	Homogenous, easy to mix when using a mixer in a closed beaker, easy to extrude, viscous & black color	COLD MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 1	1	1	1	1	-1	0	0	0	-1	2

GRADING ANALYSIS
MIX2

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 2	25g lignin, 2g cellulose, 20g dmso, 10g water	Homogenous, hard to mix, viscous, easy to extrude & black color	COLD MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 2	1	1	1	1	1	0	0	-1	0	4

GRADING ANALYSIS
MIX3

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 3	Lignin, Cellulose, Water, Xanthan Gum	Non-homogeneous covered in residual lignin powder, which retained the gel-like consistency and did not solidify	COLD MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 3	-1	-1	-1	-1	1	0	0	-1	-1	-5

GRADING ANALYSIS
MIX4

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 4	Lignin, Cellulose, Water, Corn Starch	Extrudable material. However, the homogeneity, viscosity, and adhesion characteristics are not as promising as previous mixes	HOT MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 4	0	-1	-1	-1	1	0	-1	0	1	-2

GRADING ANALYSIS
MIX5

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 5	Lignin, Cellulose, Water, Glycerine	non homogeneous with low viscosity and adhesion, not extrudable by hand. dry material with a crumbly aspect & gel-like consistency	COLD OR HOT MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 5	-1	-1	-1	-1	1	0	0	-1	0	-4

GRADING ANALYSIS
MIX6

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 6	Lignin, Cellulose, Water, ALGINATE	similar behavior to xanthan gum	COLD OR HOT MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 6	-1	-1	-1	-1	1	0	0	0	0	-3

GRADING ANALYSIS
MIX7

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 7	Lignin, Cellulose, Water, Bone glue	Homogeneous paste, with high viscosity and adhesion, but still not easy to extrude by hand.	HOT MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 7	1	1	1	0	1	-1	0	0	-1	2

GRADING ANALYSIS
MIX8

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 8	10g Lignin, 1g Cellulose, 30g Wood Glue	Use water bath method, mix is homogenous, easy to mix, medium hard to extrude by hand, & viscous	COLD OR HOT MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 8	1	1	1	1	-1	0	1	0	1	5

GRADING ANALYSIS
MIX9

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 9	25g Lignin, 3g Cellulose, 5g Methylcellulose, 60g Hot Water,	Homogenous, easy to mix when the water is warm (80C) otherwise hardens, brown color, the more viscous the worse the printability	HOT MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 9	1	1	1	1	1	-1	0	1	1	6

GRADING ANALYSIS
MIX10

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 10	Lignin, Cellulose, Water, Beewax	non-homogeneous paste with moderated viscosity and low adhesion. Dried quickly, compromising the material's extrudability.	HOT MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 10	-1	-1	-1	-1	0	0	-1	1	-1	-5

REFERENCES

MECHANICAL PROPERTIES COMPARISON

	FLEXURAL STRENGHT	MODULUS ELASTICITY (BENDING)	YIELD STRENGHT	MODULUS ELASTICITY (TENSION)	REFERENCE
BEECH, AMERICAN	-	9.5 GPa	86.2 MPa	-	(USDA Forest Service, 2010)
OAK, OVERCUP	-	9.8 GPa	77.9 MPa	-	(USDA Forest Service, 2010)
PINE, EASTERN WHITE	-	8.5 GPa	73.1 MPa	-	(USDA Forest Service, 2010)
SPRUCE, ENGELMANN	-	8.9 GPa	84.8 MPa	-	(USDA Forest Service, 2010)
PARTICLEBOARD	-	2.8 - 4.1 GPa	15 - 24 MPa	-	(USDA Forest Service, 2010)
MDF	-	3.6 GPa	36 MPa	-	(USDA Forest Service, 2010)
OSB	-	4.4 - 6.3 GPa	22 - 35MPa	-	(USDA Forest Service, 2010)
PLYWOOD	-	7 - 8.6 GPa	34 - 43 MPa	-	(USDA Forest Service, 2010)
GLULAM	-	9 - 14.5 GPa	29 - 63 MPa	-	(USDA Forest Service, 2010)
PLA + WOOD POWDER	-	3 GPa	30 MPa	-	(Gardner et al., 2019)
PLA + LIGNIN (40WT%)	-	1.93 GPa	29.25 MPa	-	(Tanase-Opedal et al., 2019)
WOOD POWDER + GLUE	-	3 - 3.94 GPa	30 - 57 MPa	-	(Das et al., 2021a)
TECNARO ARBOBLEND	-	4.3 GPa	58 MPa	-	(www.albis.com)
FLAM!	-	0.26 GPa	6.12 MPa	-	(Sanandiya et al., 2018)
METHYLCELLULOSE MIX	8.59 - 10.60 MPa	0.67 - 1.05 GPa	3.21 - 4.06 MPa	0.33 - 0.56 GPa	-

REFERENCES

WATER PROPERTIES COMPARISON					
	WATER ABSORPTION LINDSEED COATING	WATER RETENTION LINDSEED COATING	WATER ABSORPTION NO COATING	WATER RETENTION NO COATING	REFERENCE
MIX 1: ACETONE	20.74%	3.48%	24.62%	2.16%	-
MIX 2: DMSO	30,80%	14.85%	28.23%	7.12%	-
MIX 8: WOOD GLUE	8.27%	3.91%	10.35%	4,82%	-
MIX 9: METHYLCELLULOSE	70.89%	30.52%	134.91%	58.79%	-
PINE HEARTWOOD	84%	-	100%	-	(Lejavs et al. , 2021)
PINE SAPWOOD	21%	-	100%	-	(Lejavs et al. , 2021)
SPRUCE WOOD	39%	-	100%	-	(Lejavs et al. , 2021)

TENSILE ANALYSIS

Methylcellulose Mix								
	Specimens							
	A1.1	A1.2	A1.3	A1.4	A1.5	A1.6	MC.01	MC.02
σ_{uts} Ultimate Tensile Strength [Mpa]	3,60	2,94	4,29	4,07	0,00	0,00	3,37	3,74
σ_{ys} Yield Strength [Mpa]	3,51	2,89	3,79	4,06	0,00	0,00	3,21	3,63
E Modulus of Elasticity [Gpa]	0,37	0,25	0,56	0,45	0,00	0,00	0,33	0,52

FLEXURAL ANALYSIS

Methylcellulose Mix

	Specimens				
	B1.1	B1.2	B1.3	B1.4	B1.5
F Failure Load [N]	30,37	27,99	22,91	28,26	28,57
σ_{FS} Flexural Strength [Mpa]	9,41	10,00	8,59	10,60	10,85
E Flexural Modulus [Gpa]	0,90	0,67	0,82	1,02	1,05

TENSILE ANALYSIS

Methylcellulose Mix - EXTRUDED SPECIMENS					
	Specimens				
	A5.1	A5.2	A5.3	A5.4	A5.5
σ_{UTS} Ultimate Tensile Strength [Mpa]	3,14	3,45	3,23	2,43	2,64
σ_{YS} Yield Strength [Mpa]	2,58	3,10	2,98	2,38	2,51
E Modulus of Elasticity [Gpa]	0,42	0,46	0,52	0,44	0,40

TENSILE ANALYSIS

Methylcellulose Mix - EXTRUDED SPECIMENS			
	Specimens		
	B5.1	B5.2	B5.3
F Failure Load [N]	68,77	62,35	68,51
σ_{FS} Flexural Strength [Mpa]	9,55	8,48	9,52
E Flexural Modulus [Gpa]	0,60	0,64	0,61

TENSILE ANALYSIS

Acetone Mix					
	Specimens				
	B2.1	B2.2	B2.3	B2.4	B2.5
F Failure Load [N]	61,87	37,16	61,37	38,48	30,04
σ_{FS} Flexural Strength [Mpa]	9,37	6,86	9,74	5,70	4,77
E Flexural Modulus [Gpa]	0,15	0,22	0,20	0,37	0,33

TENSILE ANALYSIS

Acetone Mix					
	Specimens				
	A2.1	A2.2	A2.3	A2.4	A2.5
σ_{UTS} Ultimate Tensile Strength [Mpa]	1,76	1,26	1,70	1,09	0,98
σ_{YS} Yield Strength [Mpa]	1,09	1,25	1,51	0,81	0,97
E Modulus of Elasticity [Gpa]	0,28	0,11	0,20	0,13	0,13

TENSILE ANALYSIS

Wood Glue Mix					
	Specimens				
	A3.1	A3.2	A3.3	A3.4	A3.5
σ_{UTS} Ultimate Tensile Strength [Mpa]	6,99	6,69	7,66	7,04	6,66
σ_{YS} Yield Strength [Mpa]	4,81	3,58	4,26	3,58	3,74
E Modulus of Elasticity [Gpa]	0,30	0,58	0,41	0,64	0,77

TENSILE ANALYSIS

Wood Glue Mix					
	Specimens				
	B3.1	B3.2	B3.3	B3.4	B3.5
F Failure Load [N]	122,78	143,36	173,33	166,05	158,29
σ_{FS} Flexural Strength [Mpa]	20,67	23,89	28,89	27,28	27,06
E Flexural Modulus [Gpa]	0,67	0,64	0,79	0,90	0,79

NO COATING ANALYSIS

No Coating - Pure Material

		Weight (g)				Water Absorption			Water Retention (after 1h)			Water Retention (after 3h)		
		Initial	After 24h	After 1h	After 3h	Quantity (g)	Weight Ratio	Average	Quantity (g)	Weight Ratio	Average	Quantity (g)	Weight Ratio	Average
Methylcellulose	C1.1	2,00	4,90	4,40	3,22	2,90	145,00%	134,91%	2,40	120,00%	114,22%	1,22	61,00%	58,79%
	C1.2	2,41	5,45	4,99	3,87	3,04	126,14%		2,58	107,05%		1,46	60,58%	
	C1.3	2,50	5,84	5,39	3,87	3,34	133,60%		2,89	115,60%		1,37	54,80%	
Wood Glue	C2.1	6,50	7,15	6,96	6,81	0,65	10,00%	10,35%	0,46	7,08%	7,33%	0,31	4,77%	4,82%
	C2.2	5,78	6,37	6,21	6,06	0,59	10,21%		0,43	7,44%		0,28	4,84%	
	C2.3	5,35	5,93	5,75	5,61	0,58	10,84%		0,40	7,48%		0,26	4,86%	
Acetone	C3.1	3,46	4,34	4,13	3,48	0,88	25,43%	24,62%	0,67	19,36%	19,31%	0,02	0,58%	2,16%
	C3.2	5,38	6,66	6,39	5,55	1,28	23,79%		1,01	18,77%		0,17	3,16%	
	C3.3	6,21	7,74	7,44	6,38	1,53	24,64%		1,23	19,81%		0,17	2,74%	
DMSO	C4.1	4,37	5,54	5,34	4,43	1,17	26,77%	28,23%	0,97	22,20%	23,82%	0,06	1,37%	7,12%
	C4.2	6,58	8,55	8,26	7,36	1,97	29,94%		1,68	25,53%		0,78	11,85%	
	C4.3	5,90	7,55	7,30	6,38	1,65	27,97%		1,40	23,73%		0,48	8,14%	

LINSEED OIL ANALYSIS

Linseed Oil Coating

		Weight (g)				Water Absorption			Water Retention (after 1h)			Water Retention (after 3h)		
		Initial	After 24h	After 1h	After 3h	Quantity (g)	Weight Ratio	Average	Quantity (g)	Weight Ratio	Average	Quantity (g)	Weight Ratio	Average
Methylcellulose	C1.7	2,43	4,42	4,05	3,24	1,99	81,89%	70,89%	1,62	66,67%	58,64%	0,81	33,33%	30,52%
	C1.8	3,14	5,20	4,86	4,07	2,06	65,61%		1,72	54,78%		0,93	29,62%	
	C1.9	2,90	4,79	4,48	3,73	1,89	65,17%		1,58	54,48%		0,83	28,62%	
Wood Glue	C2.7	5,39	5,81	5,69	5,60	0,42	7,79%	8,27%	0,30	5,57%	5,73%	0,21	3,90%	3,91%
	C2.8	5,69	6,21	6,05	5,94	0,52	9,14%		0,36	6,33%		0,25	4,39%	
	C2.9	6,97	7,52	7,34	7,21	0,55	7,89%		0,37	5,31%		0,24	3,44%	
Acetone	C3.7	3,40	4,19	3,92	3,53	0,79	23,24%	20,74%	0,52	15,29%	14,57%	0,13	3,82%	3,48%
	C3.8	4,60	5,69	5,40	4,81	1,09	23,70%		0,80	17,39%		0,21	4,57%	
	C3.9	5,89	6,79	6,54	6,01	0,90	15,28%		0,65	11,04%		0,12	2,04%	
DMSO	C4.7	5,12	6,63	6,38	5,79	1,51	29,49%	30,80%	1,26	24,61%	26,06%	0,67	13,09%	14,85%
	C4.8	5,21	6,90	6,67	6,20	1,69	32,44%		1,46	28,02%		0,99	19,00%	
	C4.9	4,89	6,38	6,14	5,50	1,49	30,47%		1,25	25,56%		0,61	12,47%	

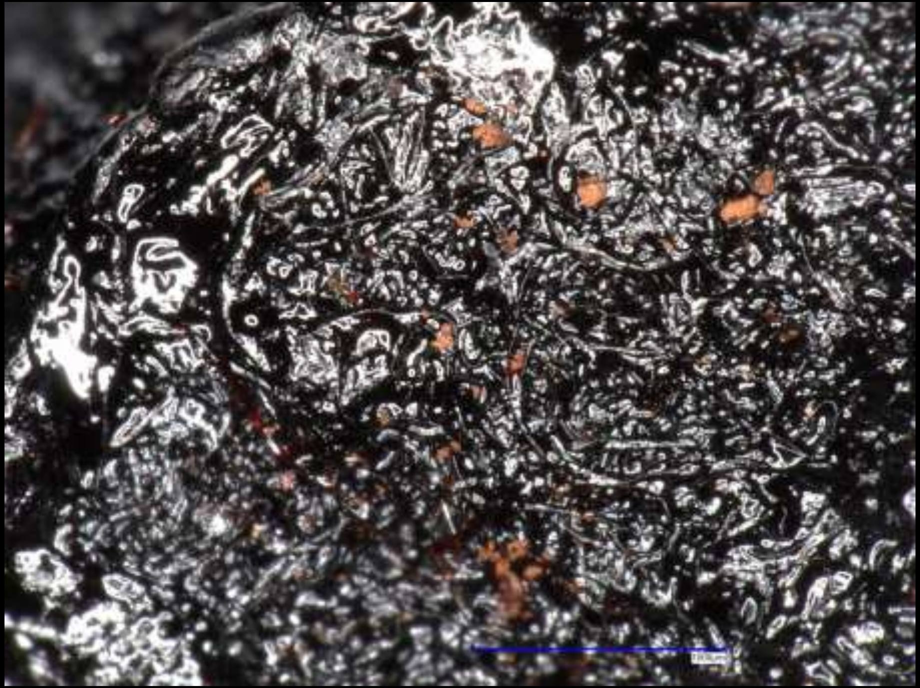
BEESWAX ANALYSIS

Bee Wax Coating

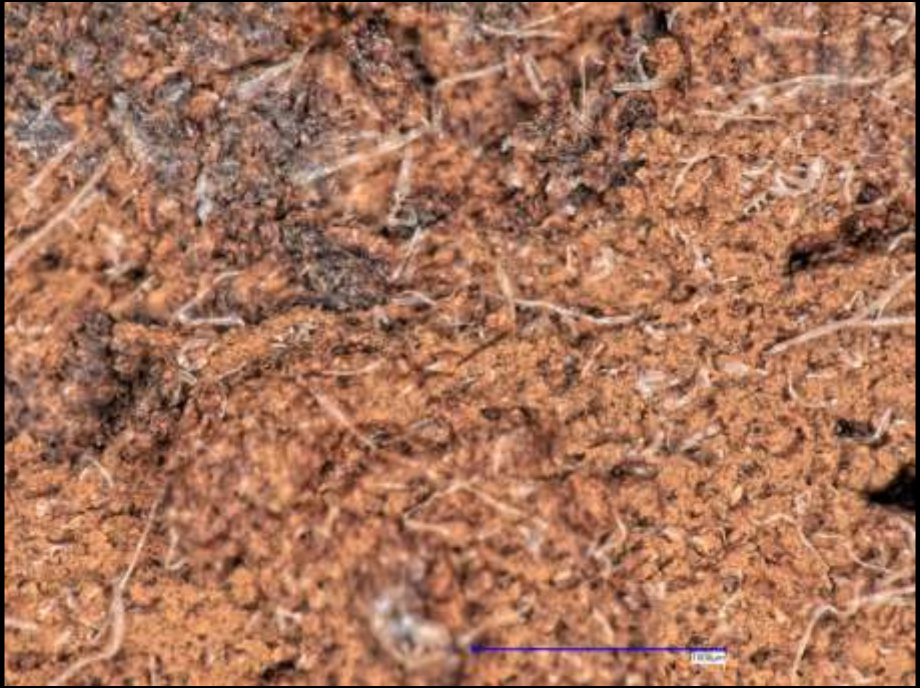
		Weight (g)				Water Absorption			Water Retention (after 1h)			Water Retention (after 3h)		
		Initial	After 24h	After 1h	After 3h	Quantity (g)	Weight Ratio	Average	Quantity (g)	Weight Ratio	Average	Quantity (g)	Weight Ratio	Average
Methylcellulose	C1.4	4,69	7,89	7,68	7,01	3,20	68,23%	69,61%	2,99	63,75%	64,40%	2,32	49,47%	46,75%
	C1.5	3,00	5,05	4,89	4,34	2,05	68,33%		1,89	63,00%		1,34	44,67%	
	C1.6	3,10	5,34	5,16	4,53	2,24	72,26%		2,06	66,45%		1,43	46,13%	
Wood Glue	C2.4	7,14	7,47	7,31	7,25	0,33	4,62%	3,60%	0,17	2,38%	1,41%	0,11	1,54%	0,98%
	C2.5	6,53	6,71	6,59	6,57	0,18	2,76%		0,06	0,92%		0,04	0,61%	
	C2.6	7,59	7,85	7,66	7,65	0,26	3,43%		0,07	0,92%		0,06	0,79%	
Acetone	C3.4	6,28	7,61	7,38	6,68	1,33	21,18%	20,35%	1,10	17,52%	17,52%	0,40	6,37%	7,13%
	C3.5	5,55	6,66	6,55	6,02	1,11	20,00%		1,00	18,02%		0,47	8,47%	
	C3.6	5,64	6,76	6,60	6,01	1,12	19,86%		0,96	17,02%		0,37	6,56%	
DMSO	C4.4	6,99	7,82	7,60	7,47	0,83	11,87%	10,44%	0,61	8,73%	7,83%	0,48	6,87%	6,15%
	C4.5	7,34	8,22	8,01	7,86	0,88	11,99%		0,67	9,13%		0,52	7,08%	
	C4.6	7,10	7,63	7,50	7,42	0,53	7,46%		0,40	5,63%		0,32	4,51%	

ACETONE CROSS SECTION

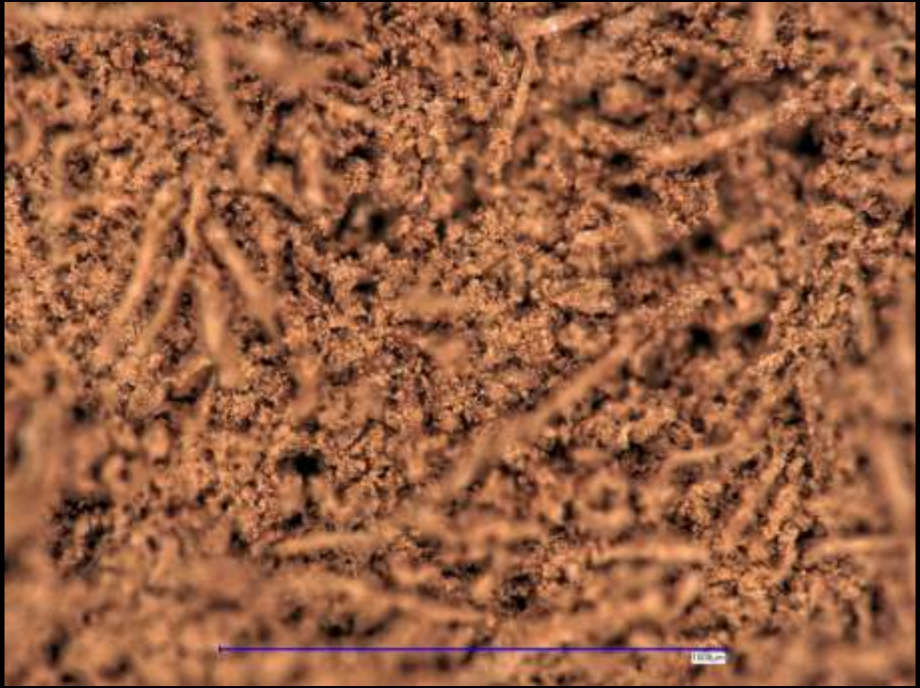
DMSO CROSS SECTION

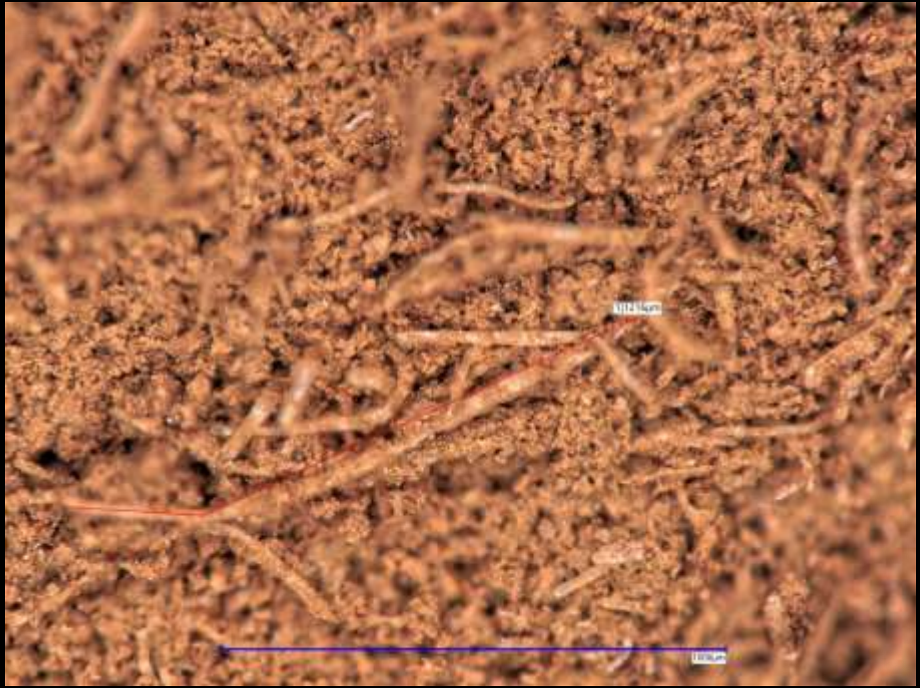


WOOD GLUE CROSS SECTION



METHYLCELLULOSE CROSS SECTION





REFERENCES

1. https://www.scmp.com/comment/insight-opinion/article/1695119/hong-kong-needs-more-flats-we-must-be-sensible-about-how
2. https://www.nationalgeographic.org/encyclopedia/mining/
3. https://www.nationalheraldindia.com/science-and-tech/europe-to-launch-satellite-to-tackle-greenhouse-gas-emissions
4. https://www.naibooksellers.nl/materials-in-progress-innovations-for-designers-and-architects.html
5. https://repository.tudelft.nl/islandora/search/author%3A%22Liebrand%2C%20Thomas%22
6. https://www.ronaldhelgers.com/
7. https://www.azuremagazine.com/article/forust-3d-printed-wood/
8. https://en.sg-veneers.com/veneer-world/veneer-gallery/detail/carolina-pine-1.html
9. https://www.tecnaro.de/en/arboblend-arbofill-arboform/
10. https://3dprintingindustry.com/news/singaporean-research-details-the-3d-printing-of-chitinous-bio-composites-170484/
11. https://sciendo.com/pdf/10.2478/plua-2021-0005
12. https://repository.tudelft.nl/islandora/object/uuid%3Aa8abc460-155c-4584-9952-dca7e439844b
13. https://www.storaenso.com/en/newsroom/news/2019/8/bio-based-carbon-materials-for-batteries
14. https://www.dezeen.com/2018/06/04/eindhoven-university-technology-project-milestone-3d-printed-concrete-houses/