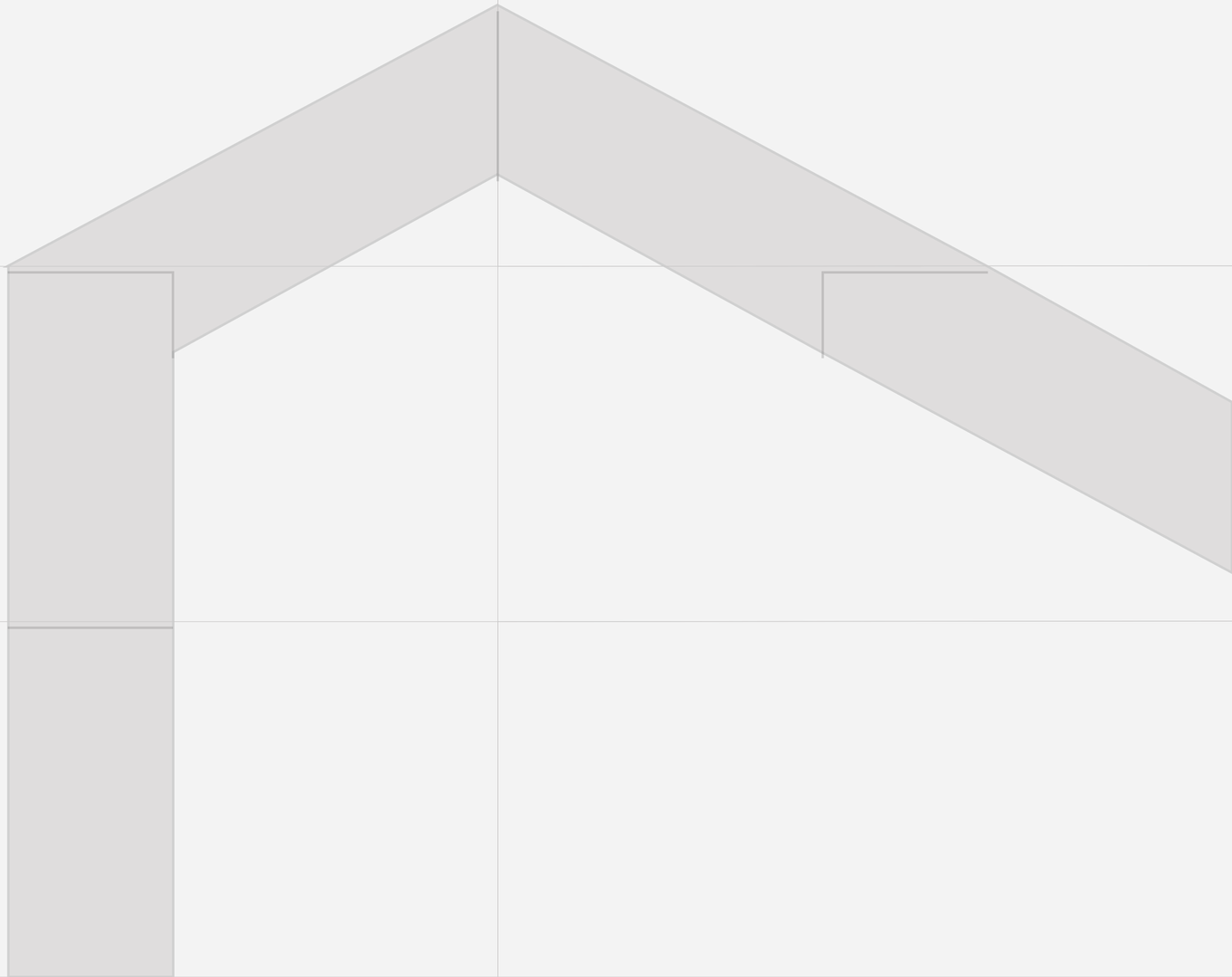
HOUSCAPER

Participatory design tool
for easy access of architectural polygonization
using Boolean Marching Cube Algorithm



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Master track Building Technology

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Board of Examiners
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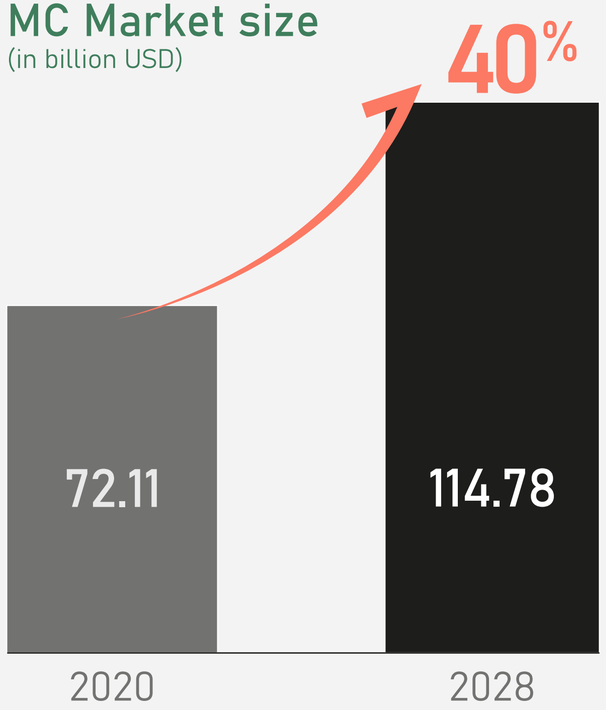
CONTENT

BACKGROUND

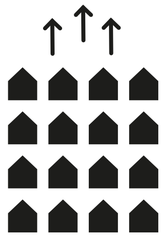
The global market for modular construction is expected to grow rapidly

the growth puts tremendous pressure on the construction industry
to shift into modular construction in a short amount of time.

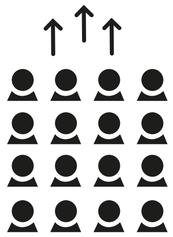
MC Market size
(in billion USD)



Driving factors of increase in MC



Urbanization



Population increase

Aging of workers

Demand for Sustainable constructions

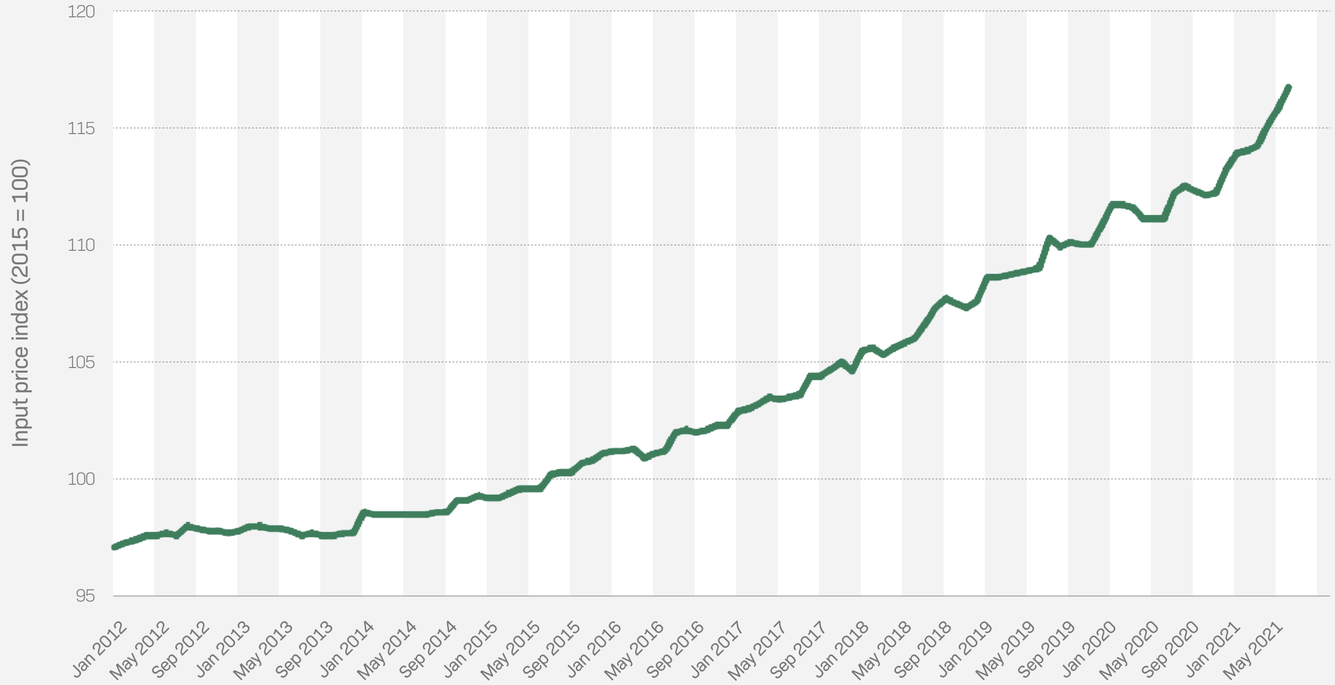
WHY?

Problem statement

Conventional architectural
design and construction **bespoke solution**
from a **bespoke process.**

Making the architecture the most expensive purchase in life.

Input price index of building costs of new dwellings in the Netherlands
(January 2012 - June 2021)



**Source: Monthly price index for new home construction in the Netherlands 2012-2021*
Published by Statista Research Department, Jan 19, 2022

WHY?

Problem statement

Modular construction optimize for
mass production - cost of construction

The demand for lower cost
builds the misperception

Modular construction is repetitive

HOW?

Research question

How to devise a **participatory design tool**
for constructing valid **modular building frames/cladding**
using **computational methods?**

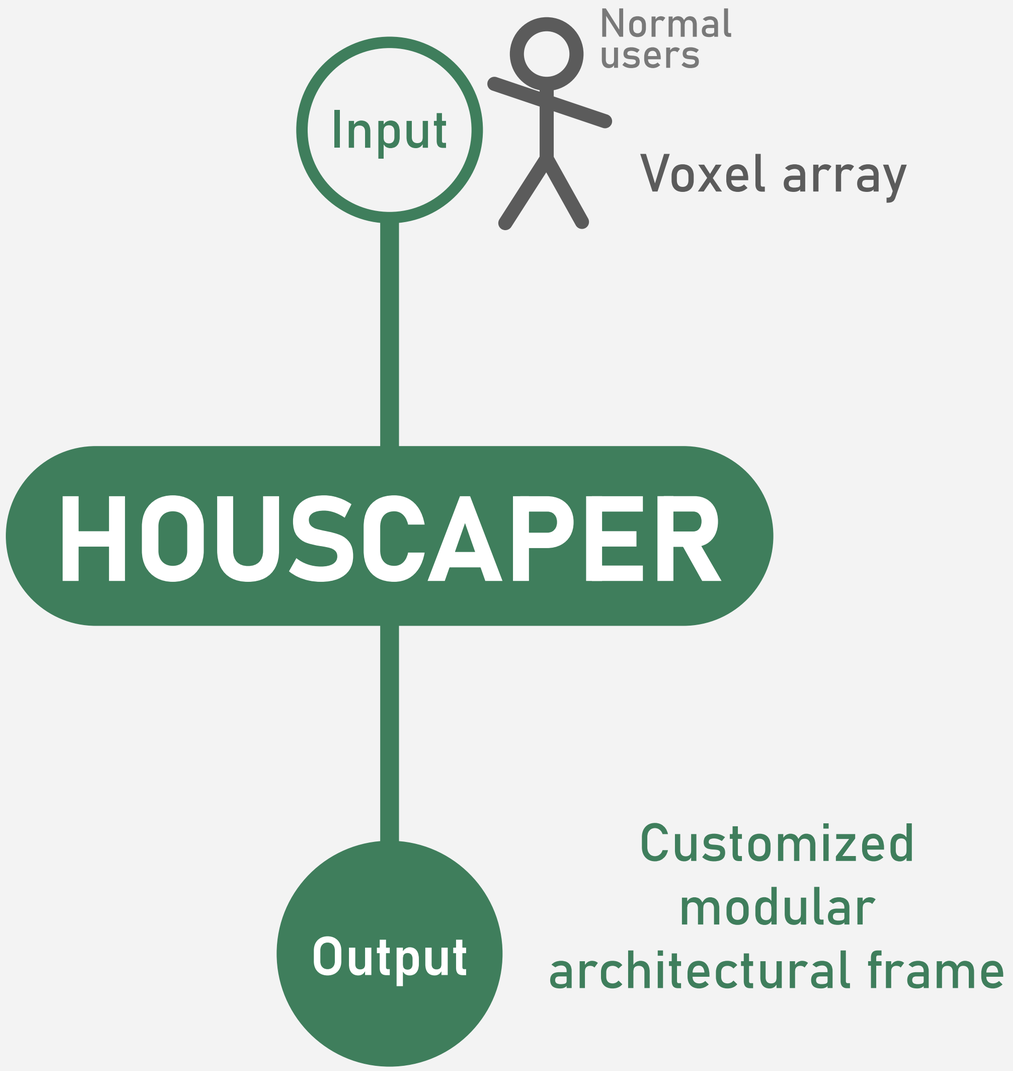
WHAT?

Research objectives

1 Develop an Interactive tool for **normal users** to **customize** their modular architecture from the input voxel array.

Offer a set of architectural tiles that incorporates mass customization and enables **expert users** to develop the tileset.

Offer a **structural validity check** of the frame generated.



WHAT?

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for **normal users** to **customize**
their modular architecture
from the input voxel array.

2 Offer a set of architectural tiles
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Offer a **structural validity check**
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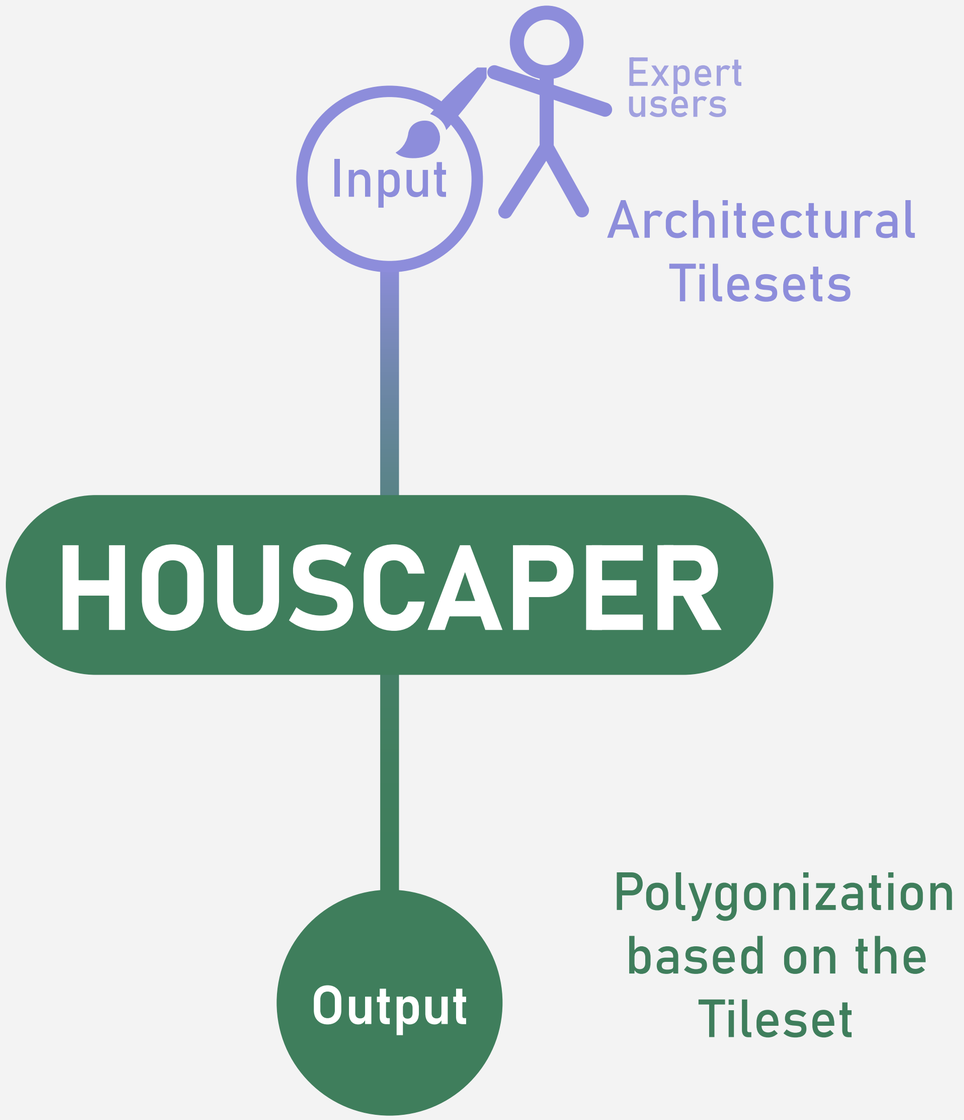

WHAT?

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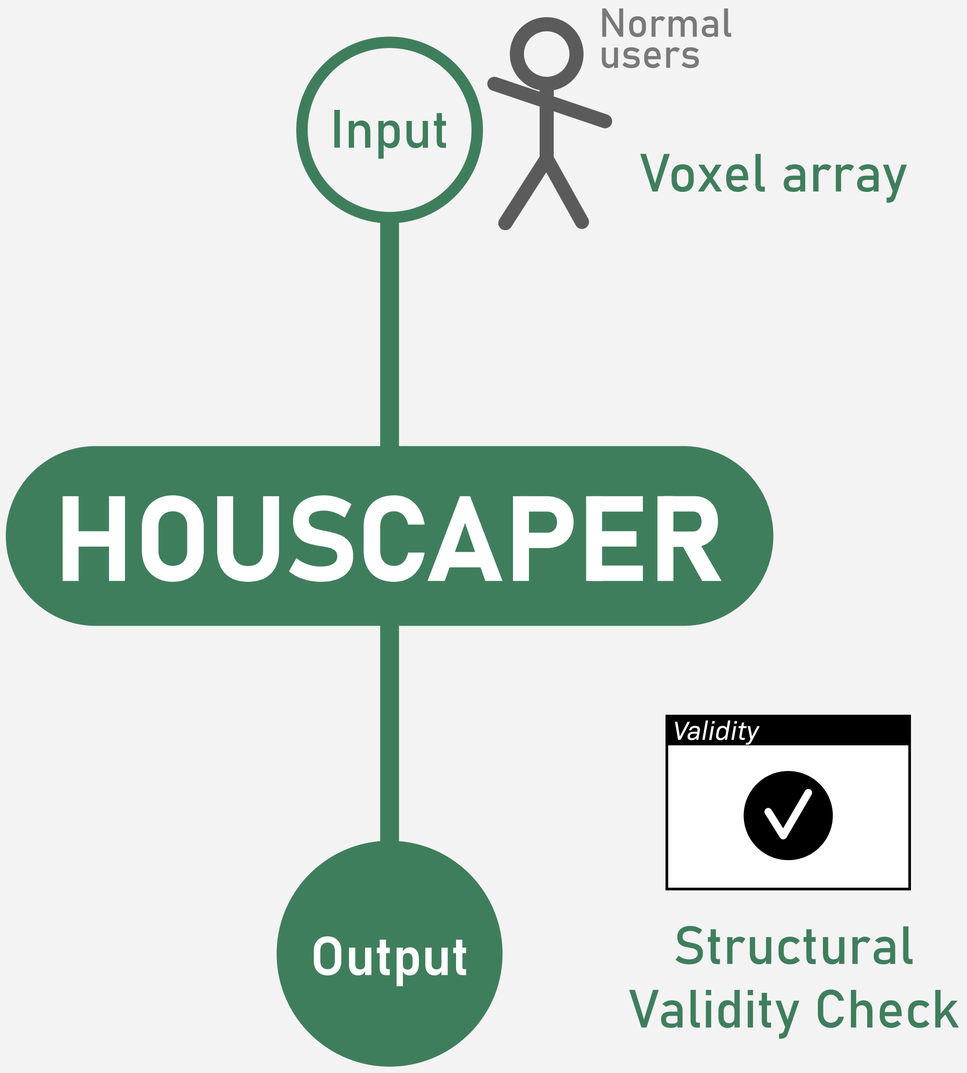
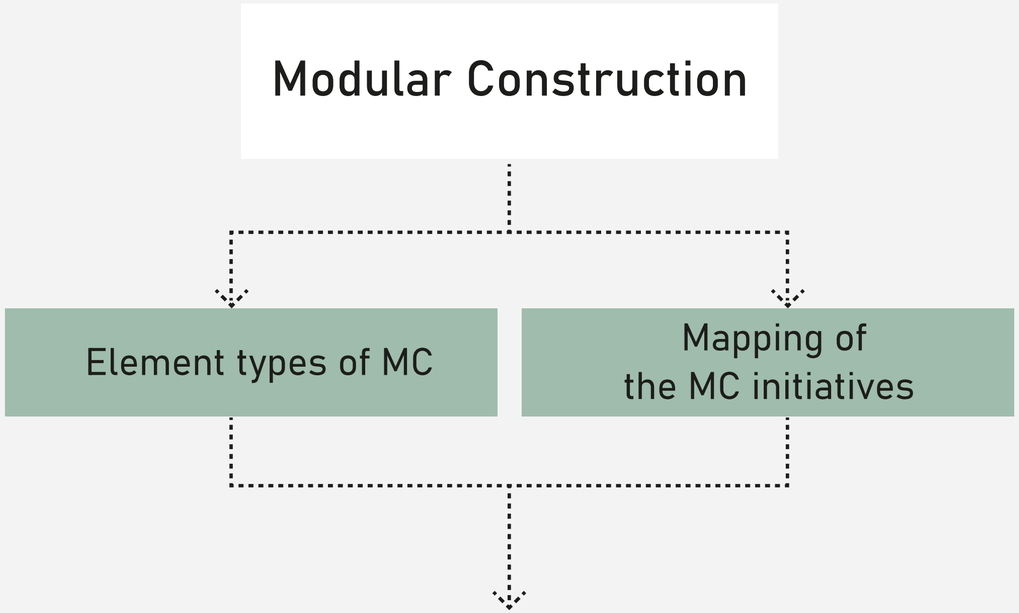
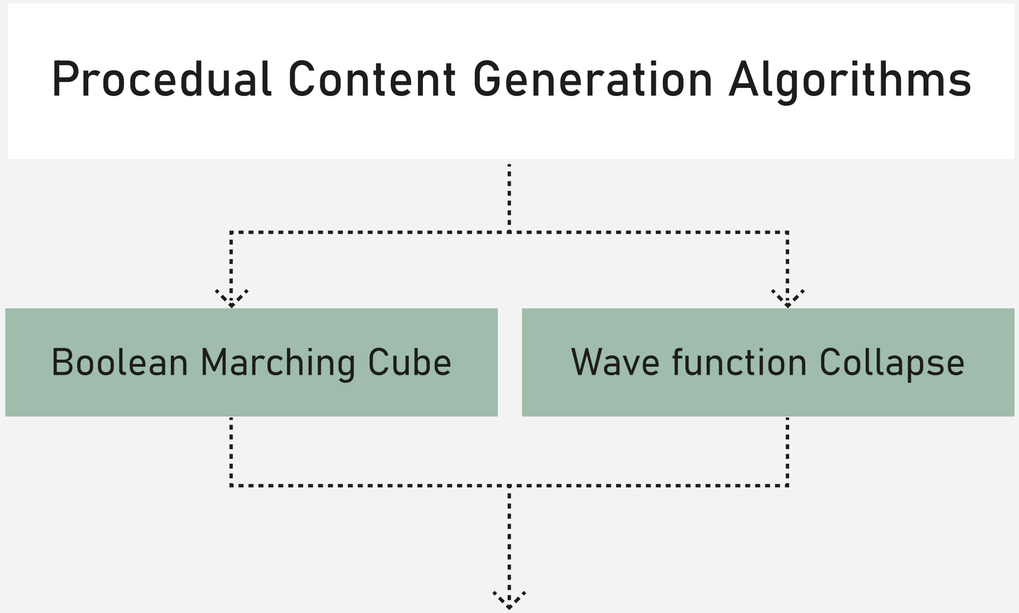


Video

LITERATURE REVIEW



Select the fittest element type

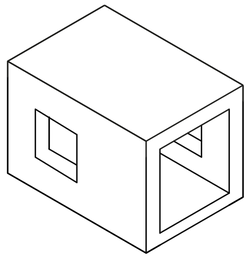


Select the fittest Algorithm

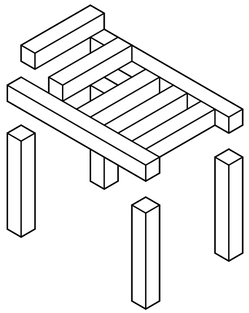
LITERATURE REVIEW

Element Types of Modular construction

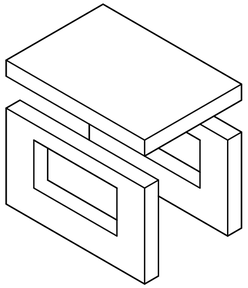
Volumetric



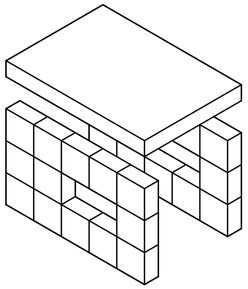
Non- volumetric



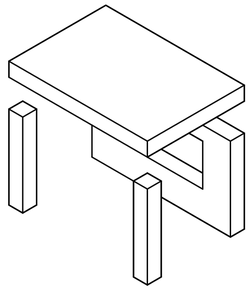
Linear System



Planar System



Block System



Hybrid System

+

- Finished in the factory
- Minimal on-site installation
- No need for scaffolding, and lifts

- Easy to connect
- Widely adapted

- Less space required volumetric system
- Finished in the factory
- Less space required than volumetric

- Prefabricated with insultation
- Liftable by one person

- Mixing of systems can be cheaper to 3%

−

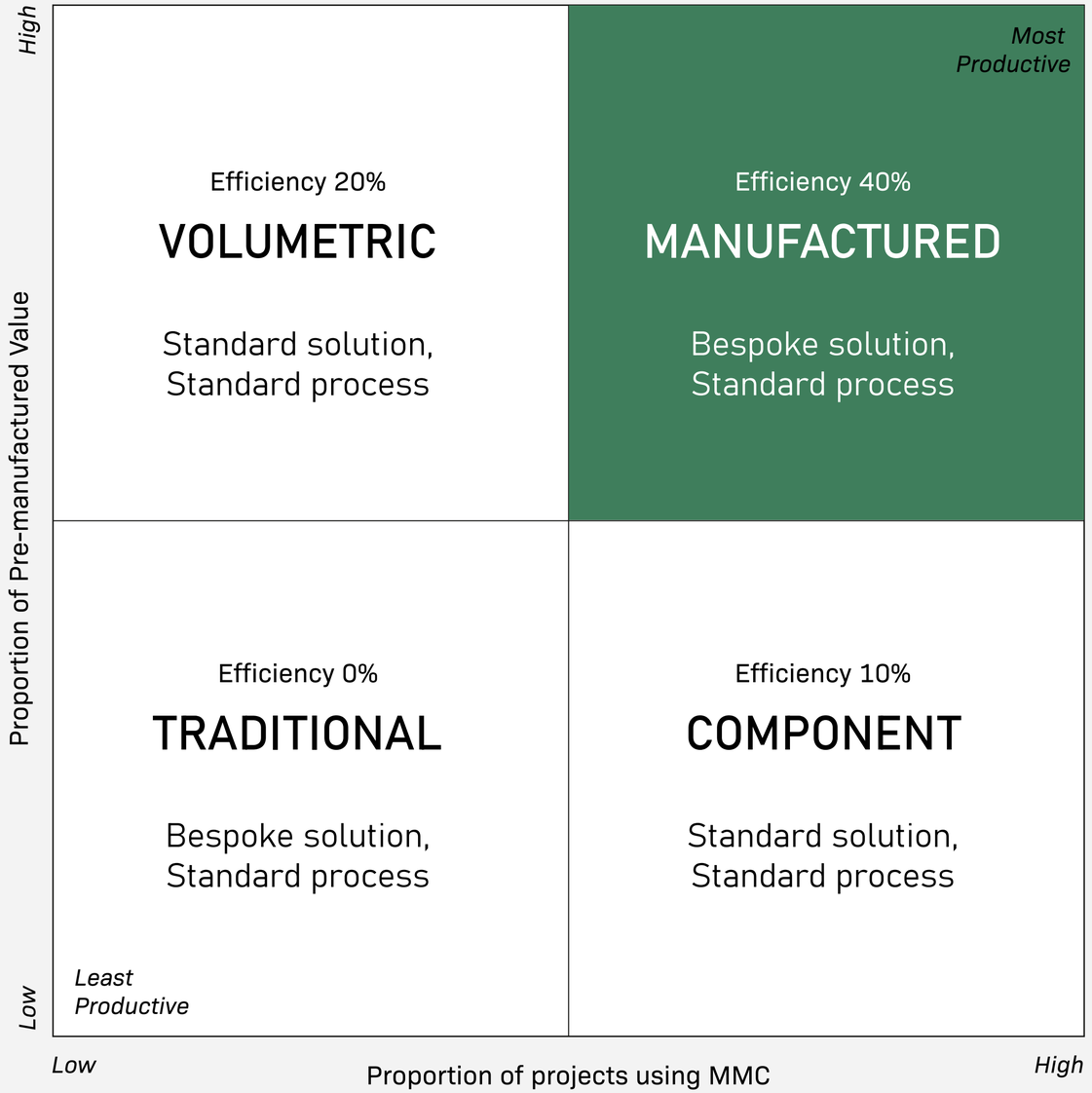
- The size are limited by the load and transportation
- Manufacturing facility significant investment

- Additional parts, process required

- More work on site

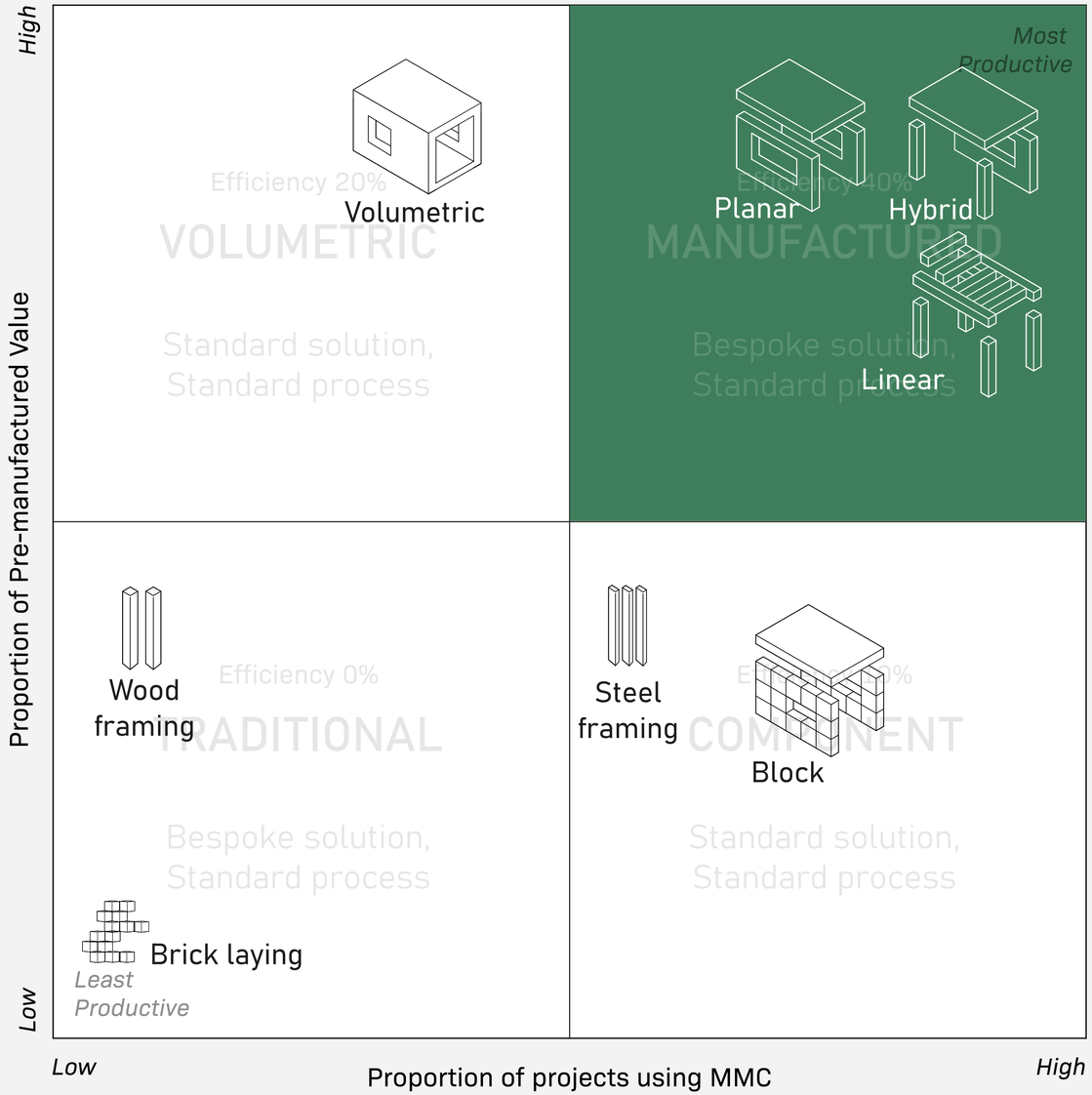
LITERATURE REVIEW

Mapping modern methods of construction (MMC) initiative



LITERATURE REVIEW

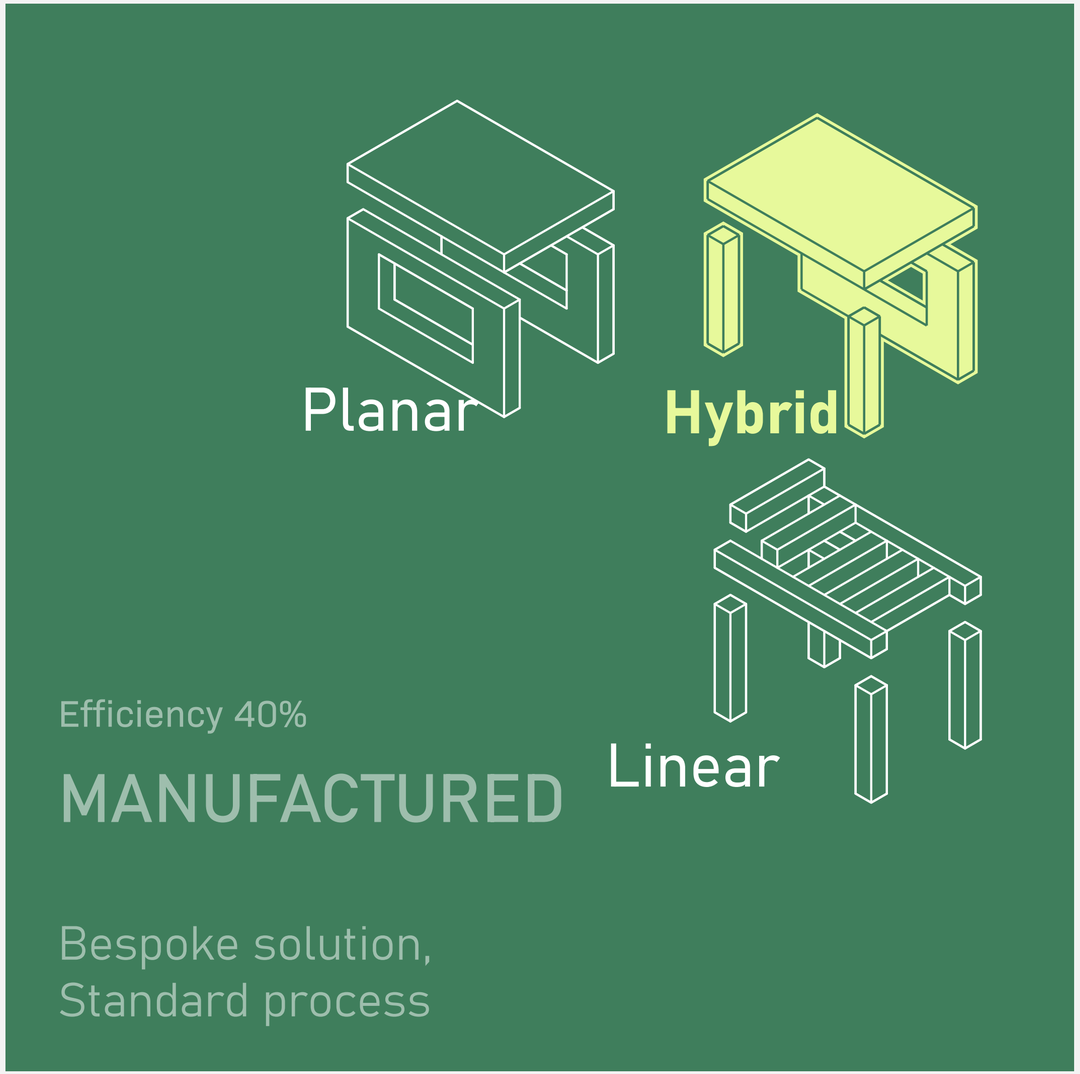
Mapping modern methods of construction (MMC) initiative



LITERATURE REVIEW

CONCLUSION

Mapping modern methods of construction (MMC) initiative



LITERATURE REVIEW

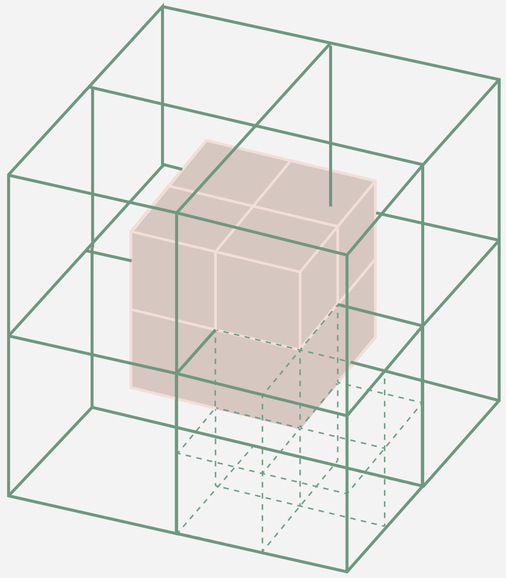
PCG Algorithms

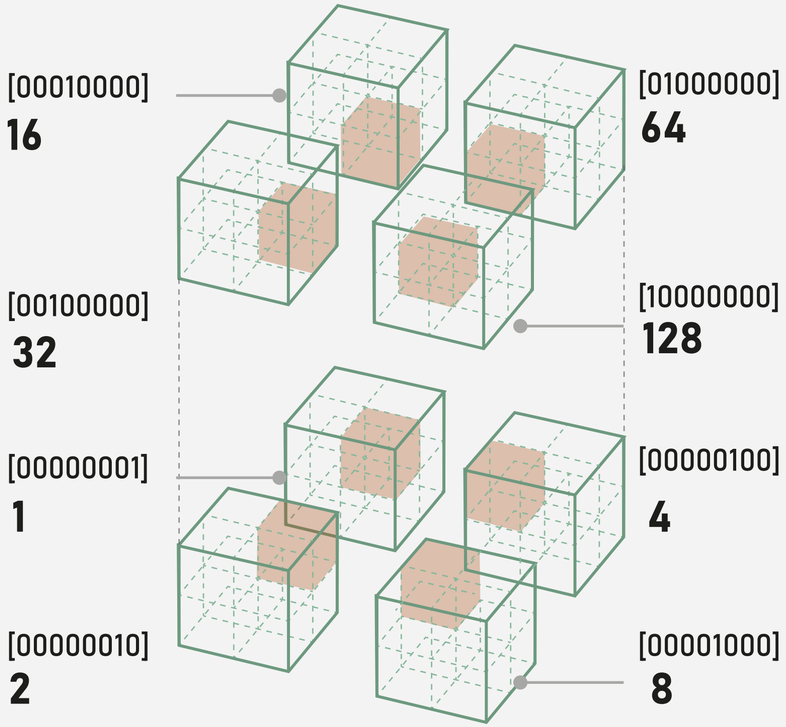
Boolean Marching Cube

The imaginary cubes surrounding the voxel,

A unique ID based on the location of overlapping parts.
When the unique ID is called, the assigned cube tiles are loaded

256 possible configurations (2^8 = 256)





LITERATURE REVIEW

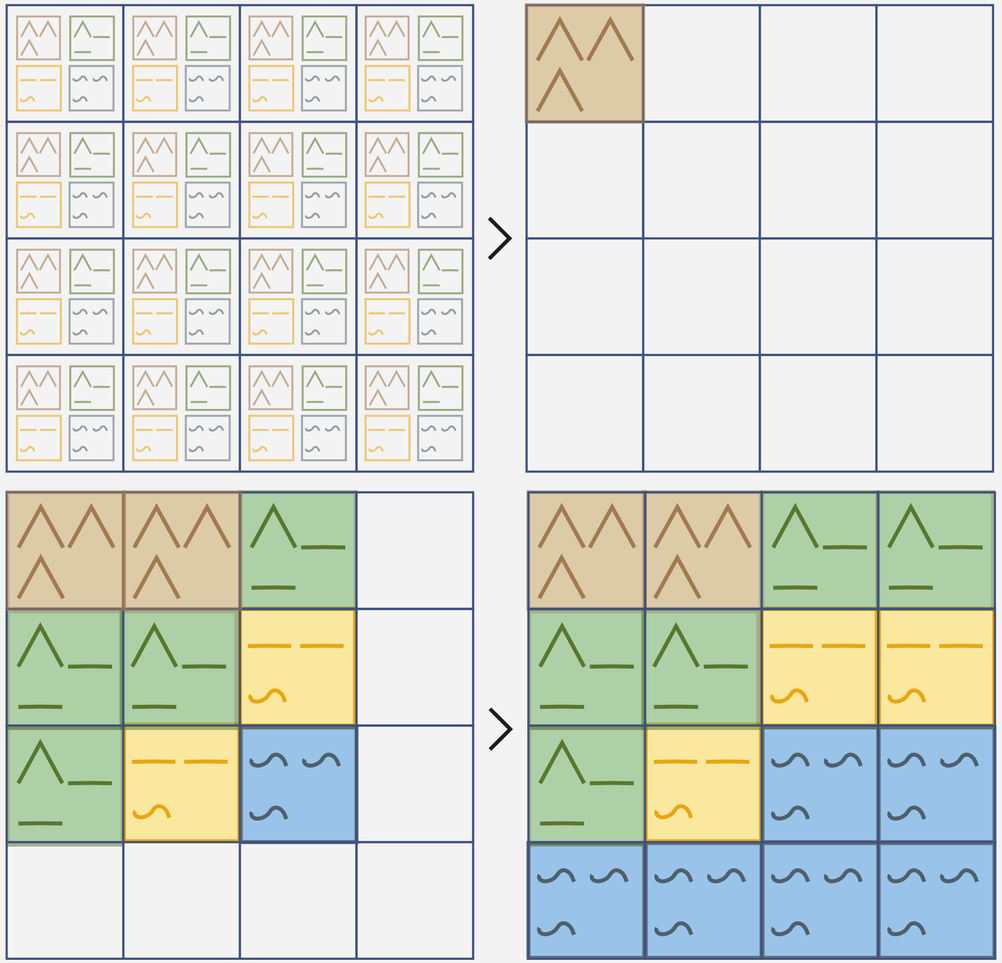
PCG Algorithms

Wave function Collapse

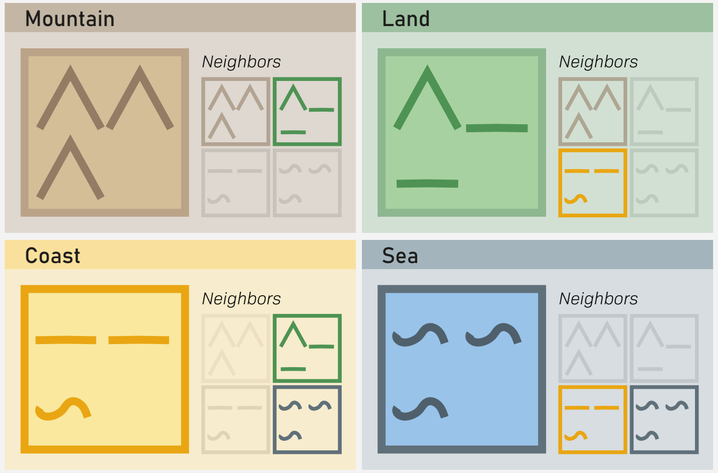
The Wave Function collapse algorithm takes the modules containing information of the neighbor constraints to either allow them to be next to themselves or not.

Uncollapsed grid

Collapsed grid

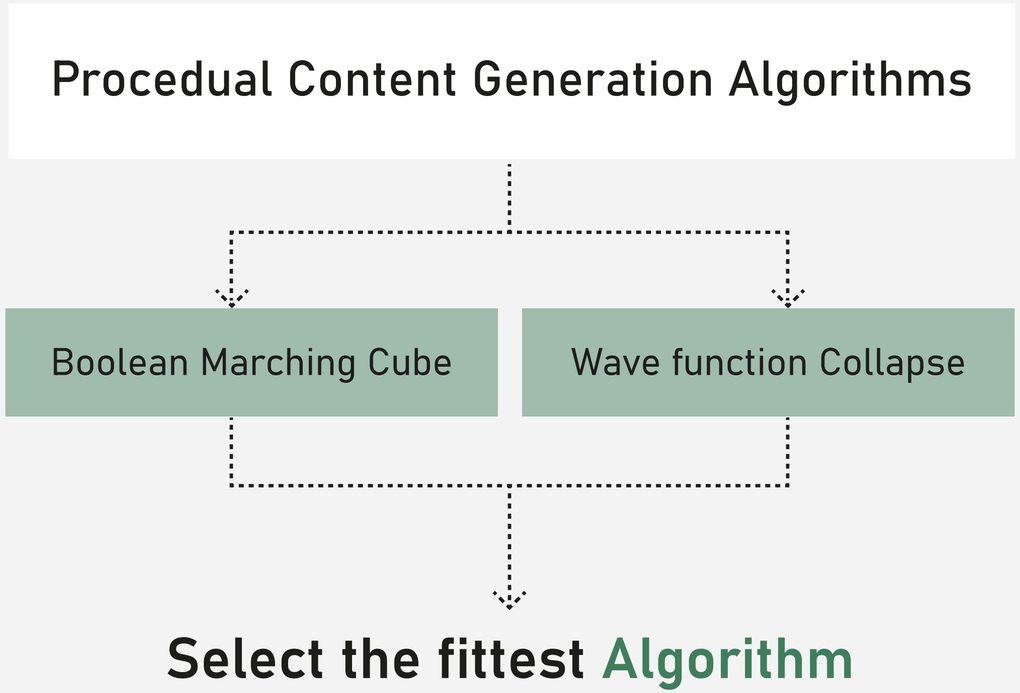


Modules with neighbor contraints



LITERATURE REVIEW

PCG Algorithms



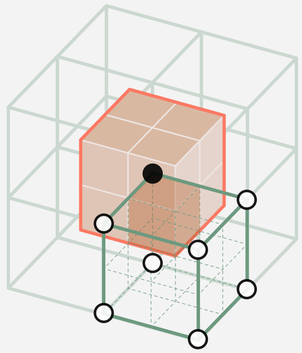
LITERATURE REVIEW

CONCLUSION

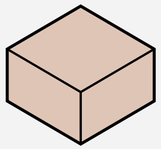
Algorithms

	Wave Function Collapse	Boolean Marching Cube
Degree of which experts can encode design ideas	Medium	High
Challenges experienced by users	High	Low
Do not let the user start from scratch	NO	YES
Actions are traceable and impact on result	NO	YES

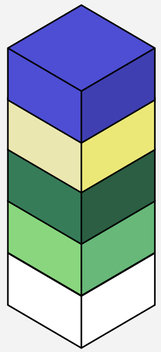
DESIGN DEVELOPMENTS



BMC Terminology



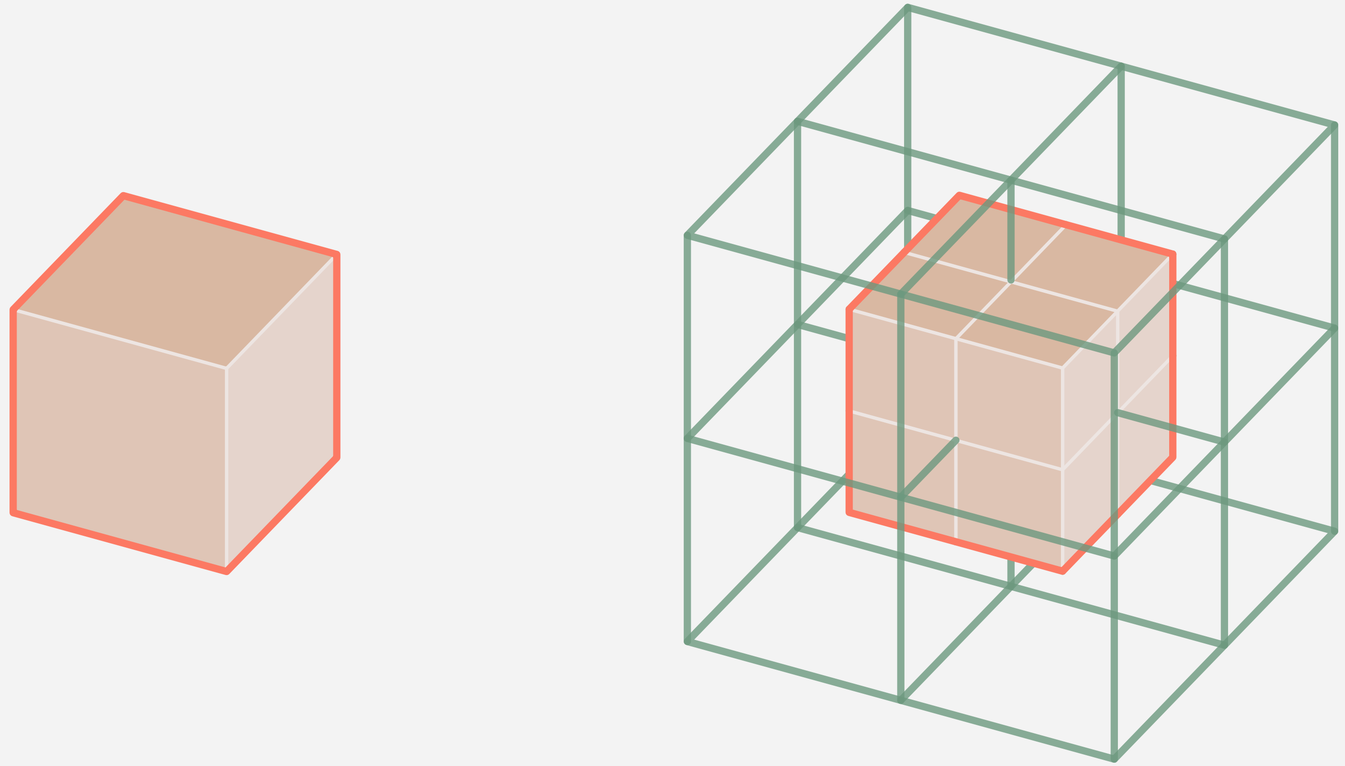
Surface Tilesets



Architectural Tilesets

PRESETTING
_BMC TERMINOLOGY

Voxel

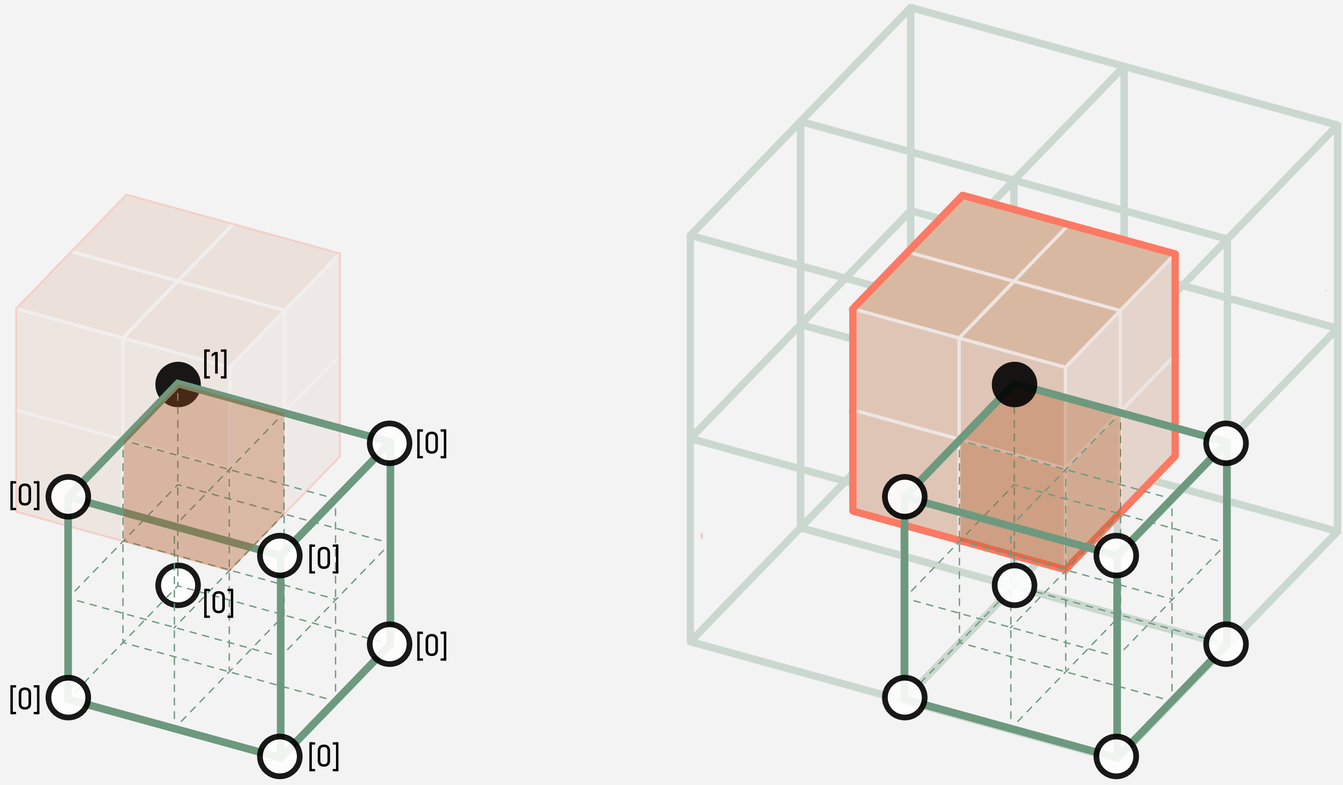


Voxel

A fundamental component in making a modular architecture
and a single unit representation of the initial voxel array from the user input.

PRESETTING
_BMC TERMINOLOGY

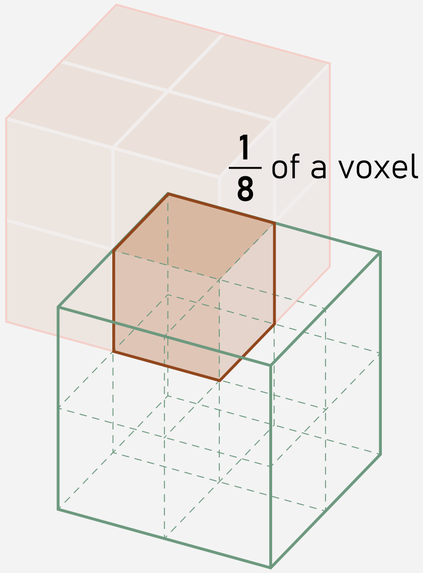
Cube

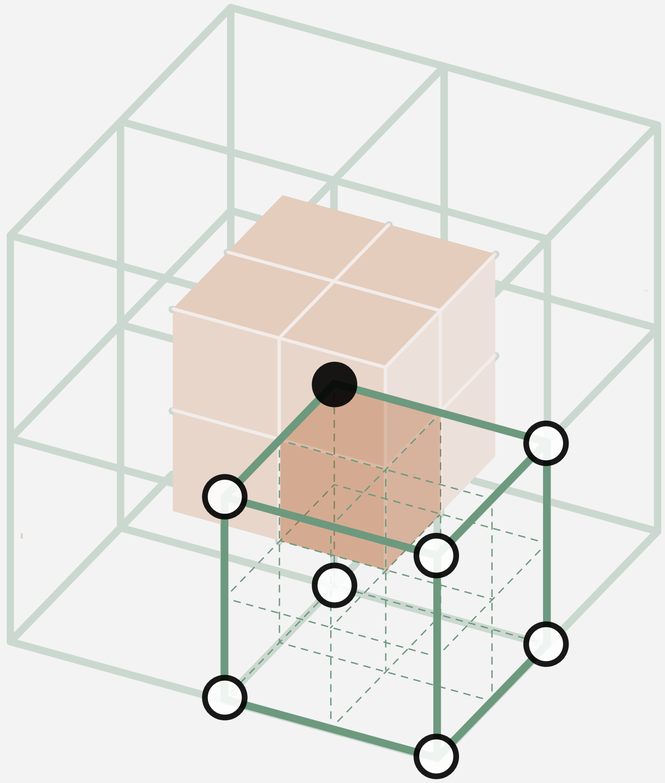


Cube A cube reads the center points of voxels and checks whether the center point is inside the voxel as a boolean value of 0 and 1.

PRESETTING
_BMC TERMINOLOGY

Octant of a voxel



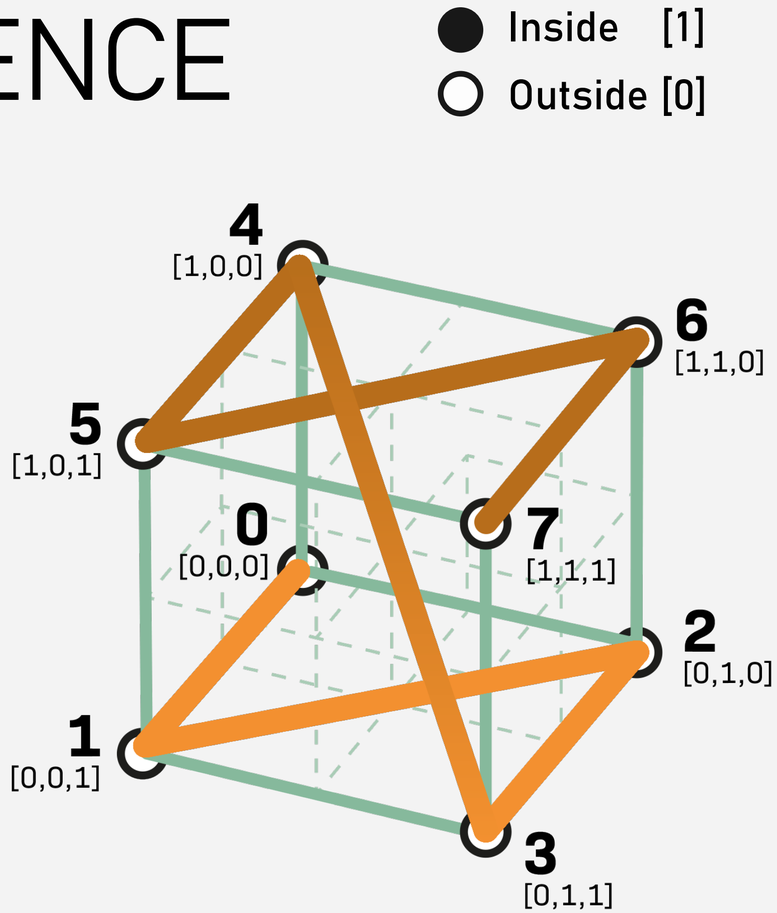


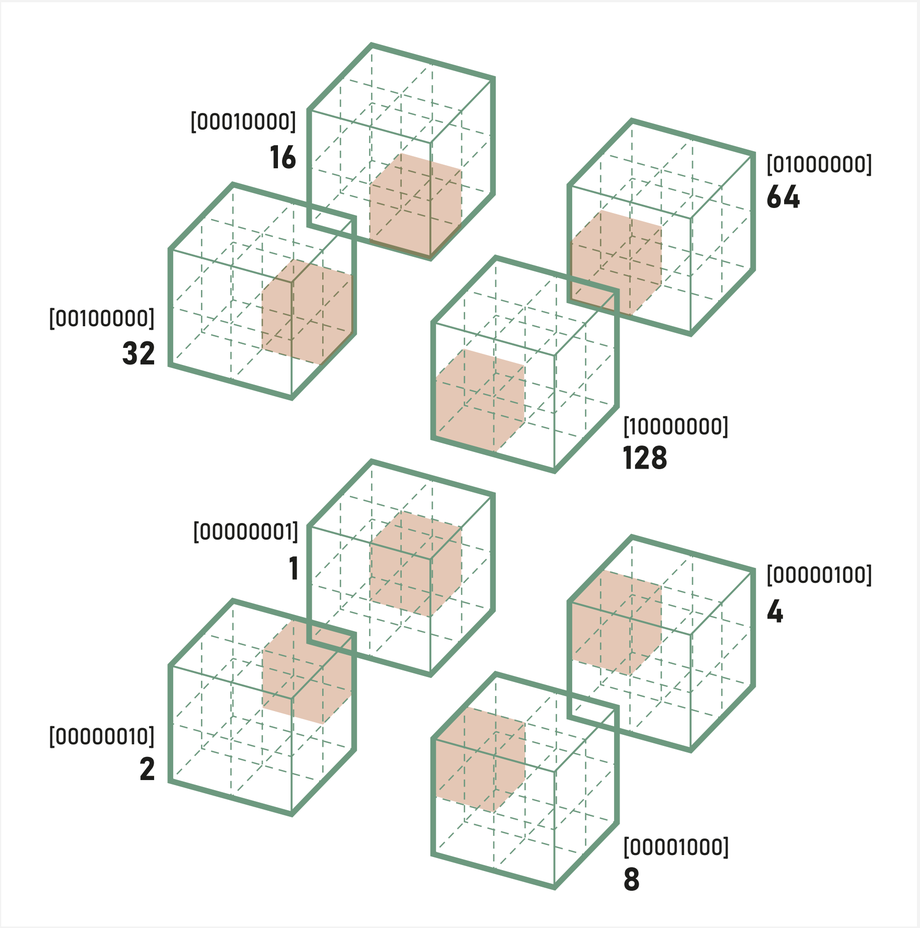
Octant of a voxel (Sub_voxel)

Represents one digit from the cube configuration.
It is the region representing the overlap of a voxel and a cube.

PRESETTING
_BMC SEQUENCE

BMC reading sequence

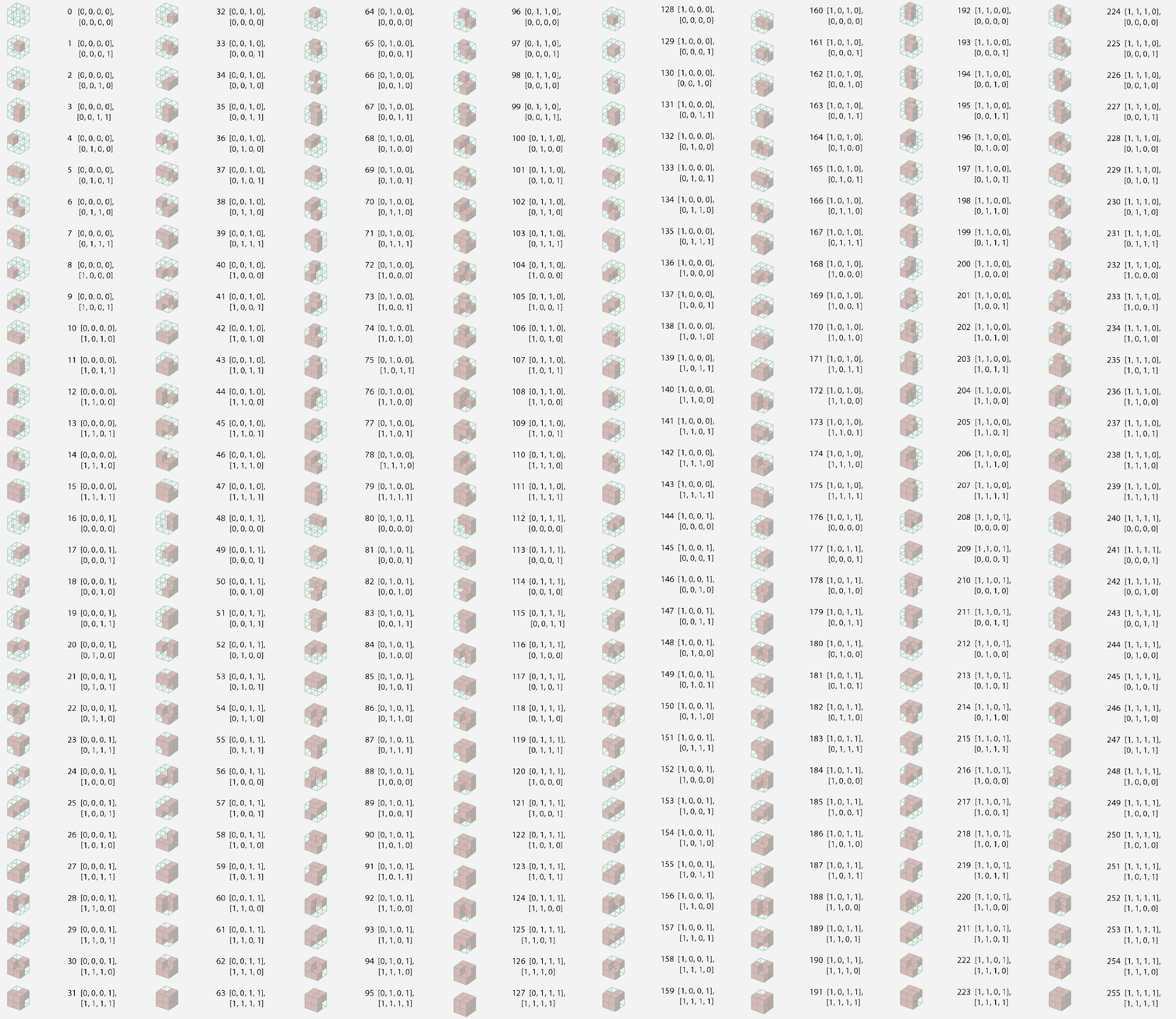




The counting sequence of Sub-voxels is essential in the BMC algorithm
The sequence determines the reading order the unique cube IDs.

PRESETTING
_CUBE OPTIONS

Cutting down tilesets

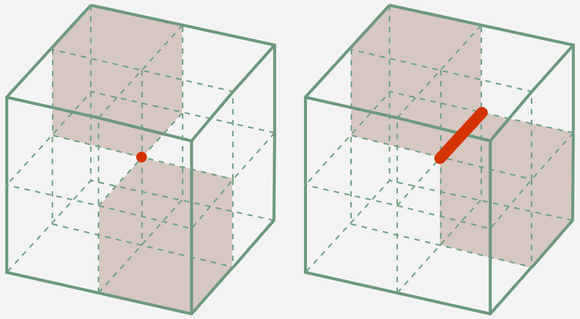


The configuration option of one cube is,

2^8=256 options.

PRESETTING
_CUBE OPTIONS

Cutting down tilesets

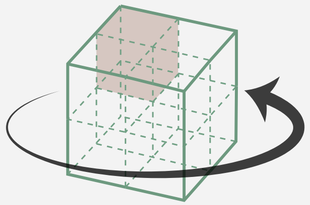


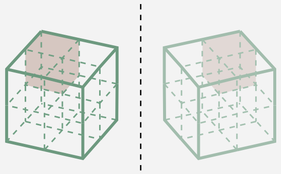
Eliminate
Point-to-point, Edge-to-edge
connections of the modules
do not create
feasible compositions.

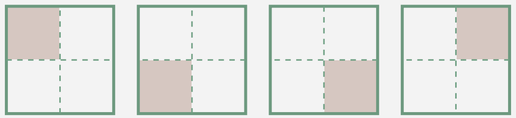
> Cut down to **126 configurations**

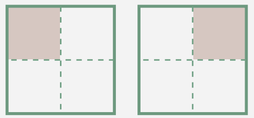
PRESETTING
_GROUPED CUBES

Cutting down tilesets



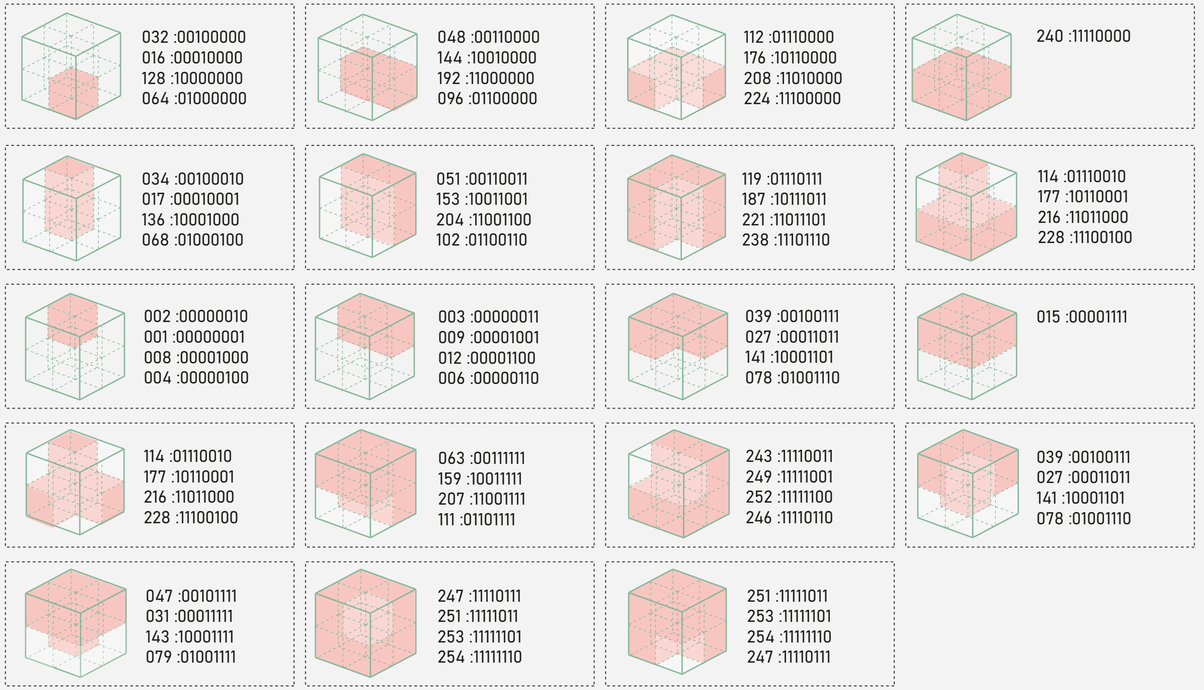


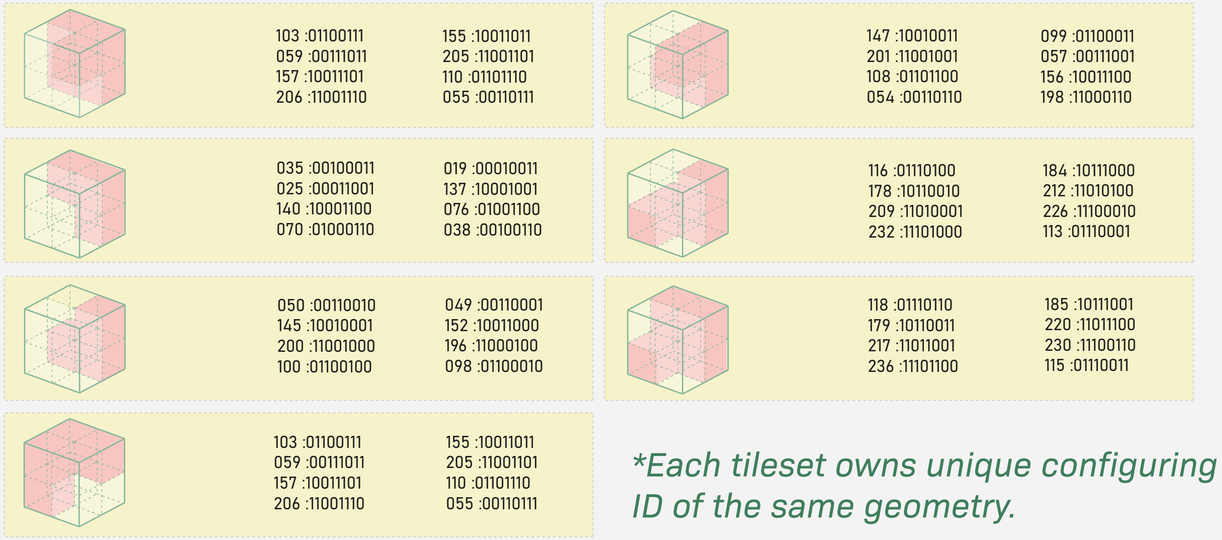




Horizontal symmetry and
orthogonal rotation in four directions
"equivalent upto tiles"

> Leave 26 unique tilesets.





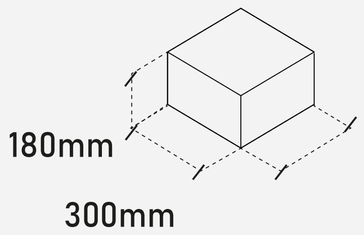
**Each tileset owns unique configuring ID of the same geometry.*

PRESETTING
_DIMENSION

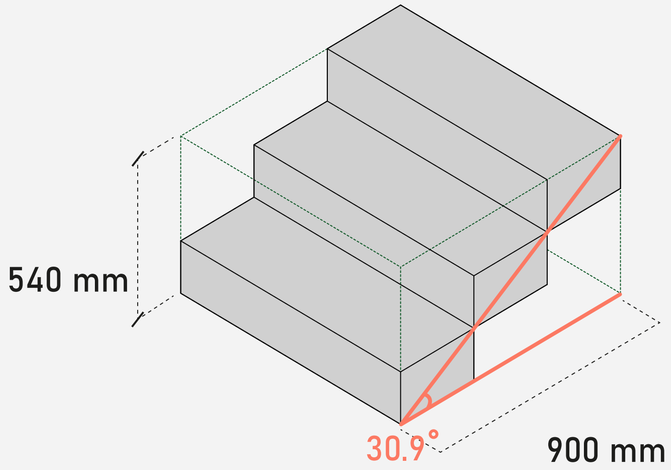
Module dimension defining

General rule for stairs stride

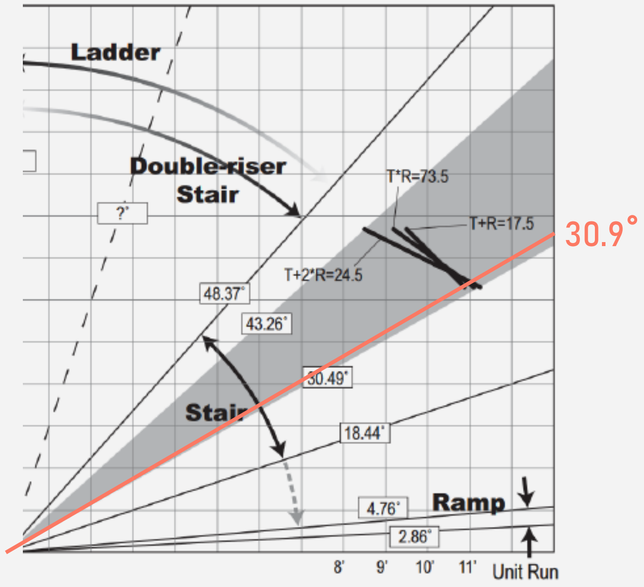
2 Risers + 1 Tread = 660 mm
2 *180 + 300 = 660 mm



The width and height as
multiplication of stair stride
180 * 3 = 540
300 * 3 = 900

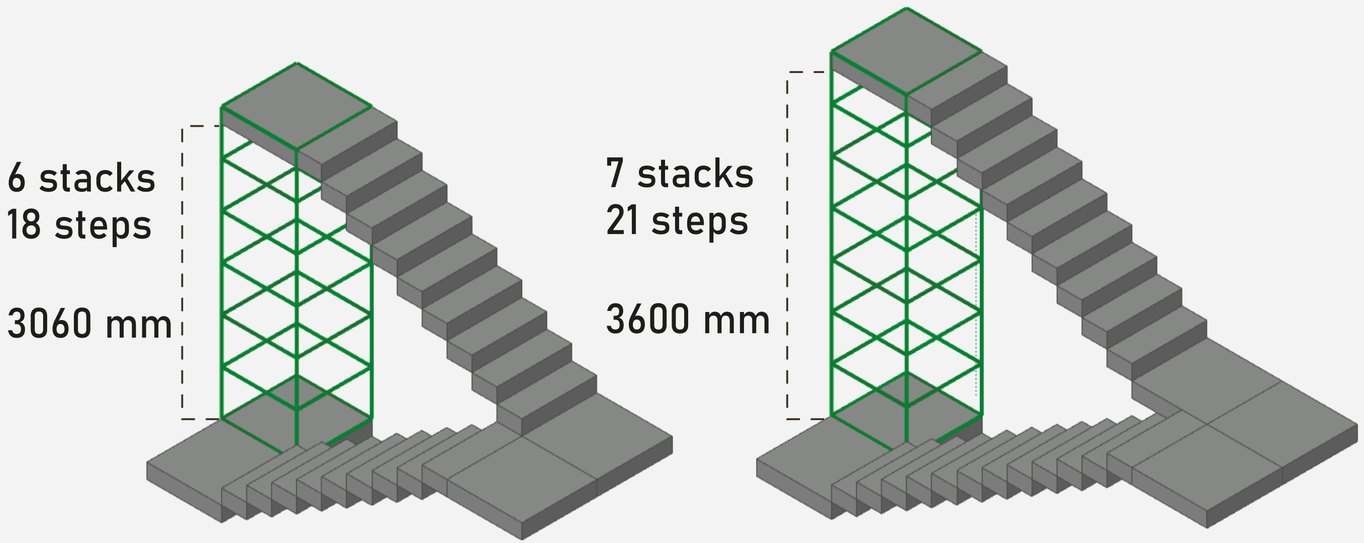


Riser 180/ tread 300 = 0.6
= tan-1(0.6) = 30.9°

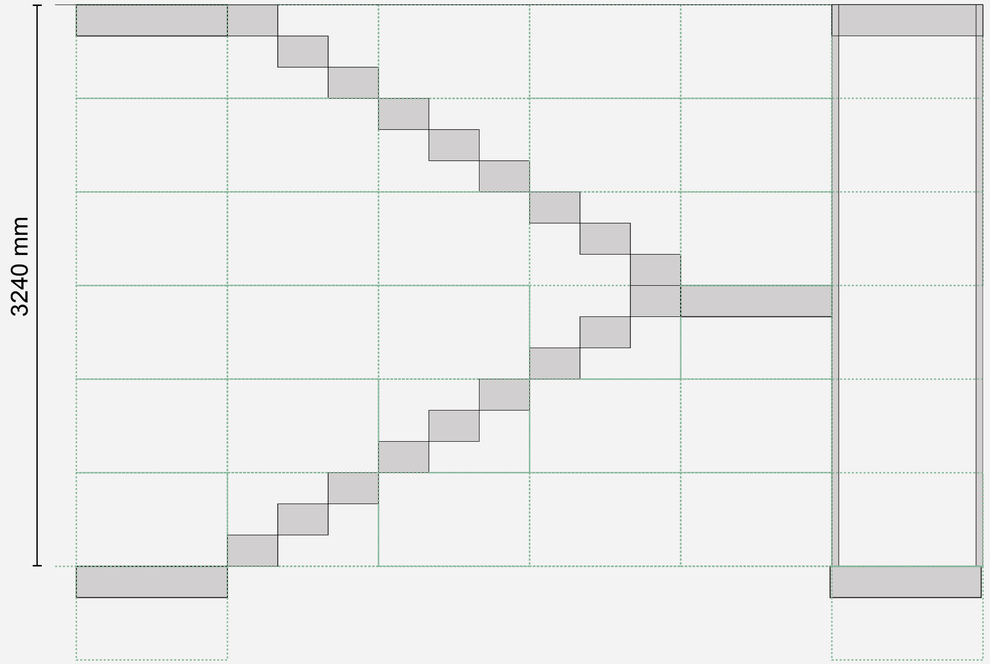


PRESETTING
_DIMENSION

Module dimension defining



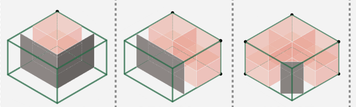
6 of the modules create a
valid floor-to-floor height of 3240 mm
(floor to ceiling height of 3060 mm)



SURFACE TILESETS

Standard
Surface tilesets

Wall tiles

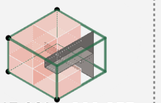


034 017
136 068

051 153
204 102

119 187
221 238

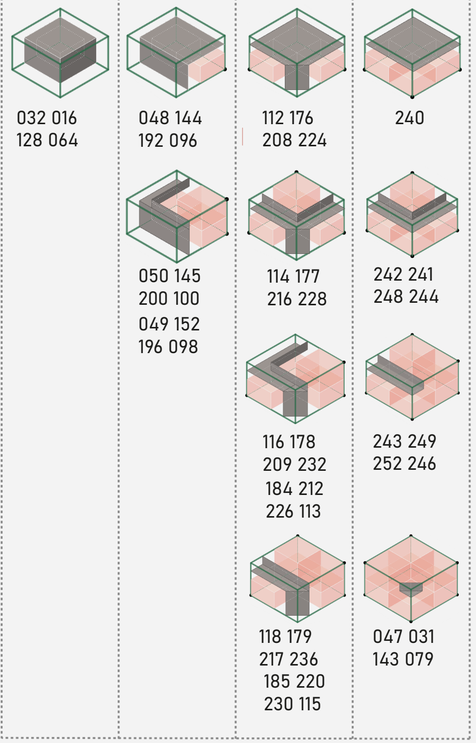
Extra tile



147 201
108 054

099 057
156 198

Roof tiles



032 016
128 064

048 144
192 096

112 176
208 224

240

050 145
200 100
049 152
196 098

114 177
216 228

242 241
248 244

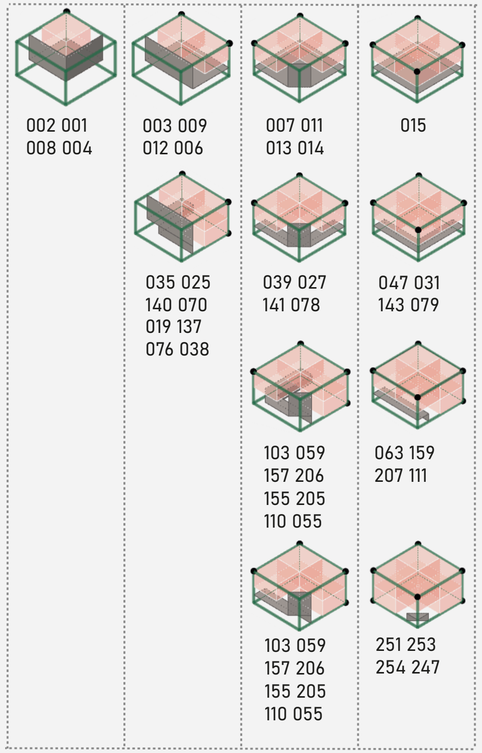
116 178
209 232
184 212
226 113

243 249
252 246

118 179
217 236
185 220
230 115

047 031
143 079

Floor tiles



002 001
008 004

003 009
012 006

007 011
013 014

015

035 025
140 070
019 137
076 038

039 027
141 078

047 031
143 079

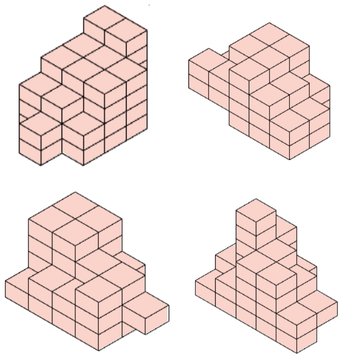
103 059
157 206
155 205
110 055

063 159
207 111

103 059
157 206
155 205
110 055

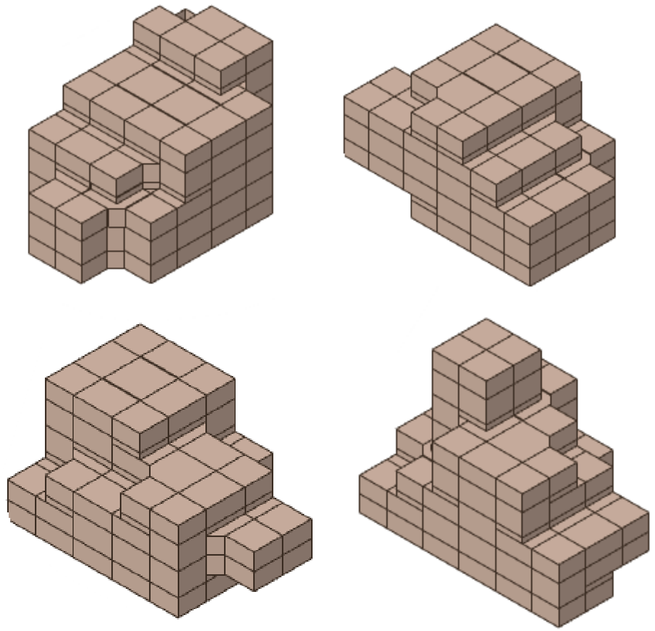
251 253
254 247

Input



BMC

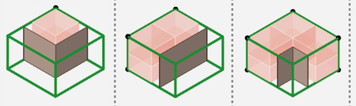
Output



SURFACE TILESETS

Differentiated floor and roof tilesets

Wall tiles

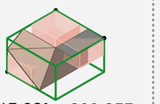


034 017
136 068

051 153
204 102

119 187
221 238

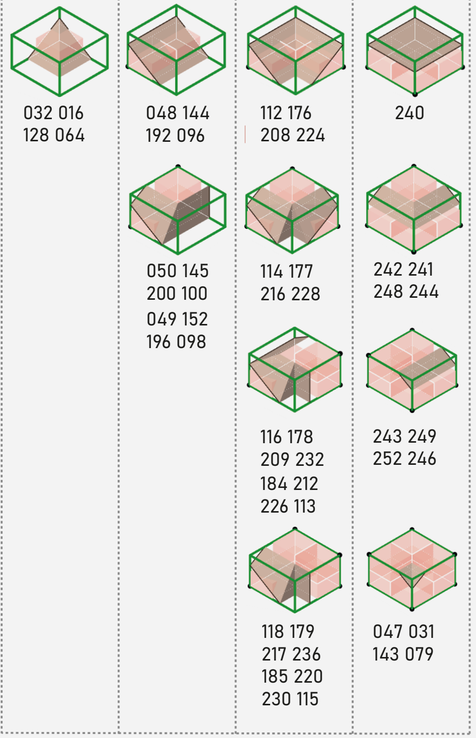
Extra tile



147 201
108 054

099 057
156 198

Roof tiles



032 016
128 064

048 144
192 096

112 176
208 224

240

050 145
200 100

049 152
196 098

114 177
216 228

242 241
248 244

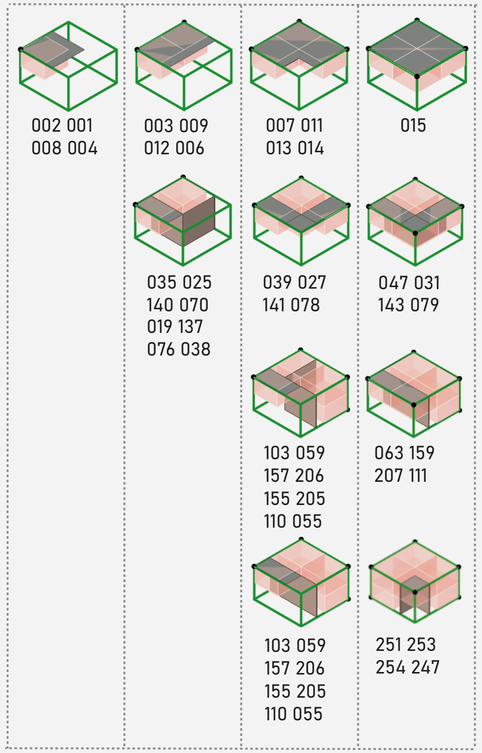
116 178
209 232
184 212
226 113

243 249
252 246

118 179
217 236
185 220
230 115

047 031
143 079

Floor tiles



002 001
008 004

003 009
012 006

007 011
013 014

015

035 025
140 070
019 137
076 038

039 027
141 078

047 031
143 079

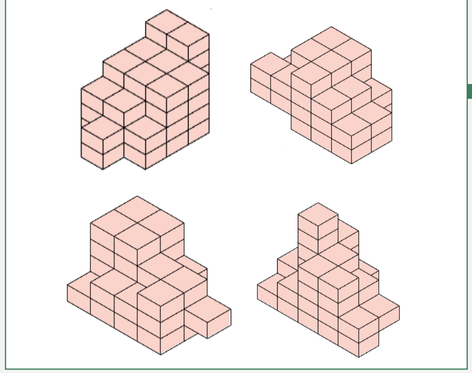
103 059
157 206
155 205
110 055

063 159
207 111

103 059
157 206
155 205
110 055

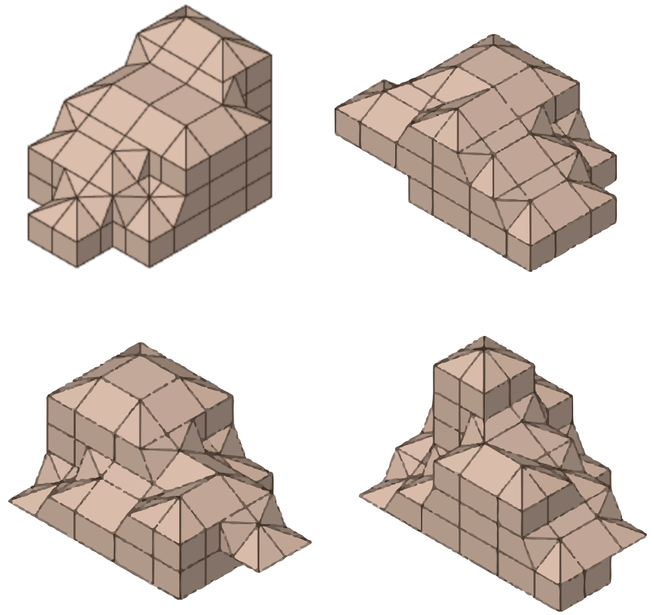
251 253
254 247

Input



BMC

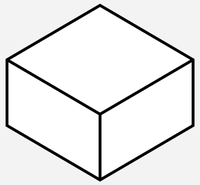
Output



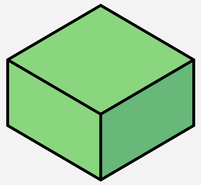
ARCHITECTURAL TILESETS

Voxel function

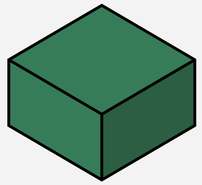
To achieve the architecture variations,
multiple function of voxels need to be placed.



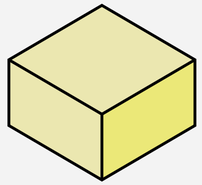
Base Voxel
Octant voxel ID : 1



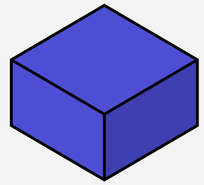
Floor Voxel
Octant voxel ID : 2



Foundation Voxel
Octant voxel ID : 3



Opening Voxel
Octant voxel ID : 4



Window Voxel
Octant voxel ID : 5

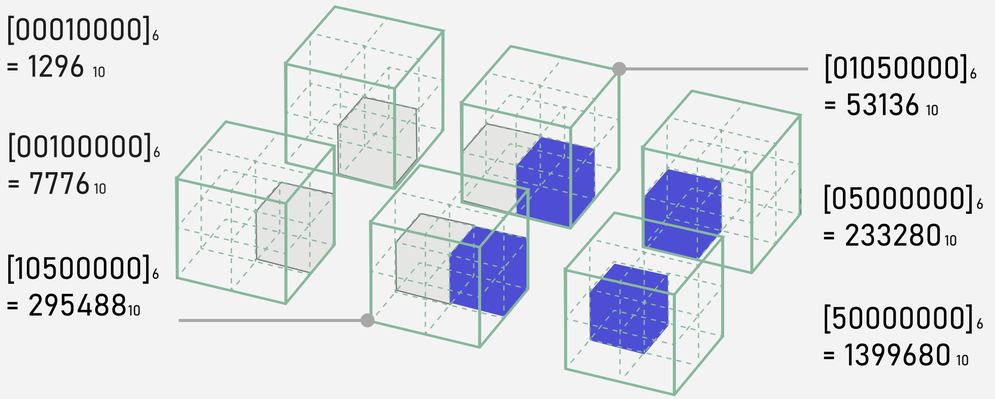
ARCHITECTURAL TILESETS

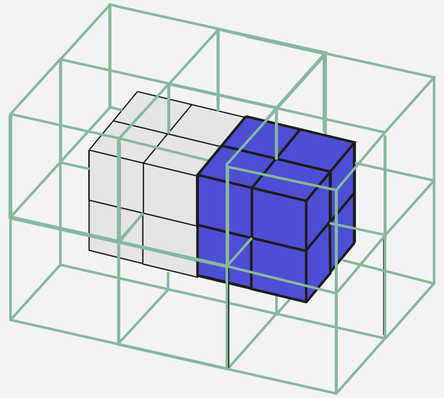
Binary to Heximal

The possible options for sub-voxels are six (0,1,2,3,4 and 5).

Binary to heximal (6 elements)

In 8-digit the possible cube configuration increases 256 to 1679615 (6^8).

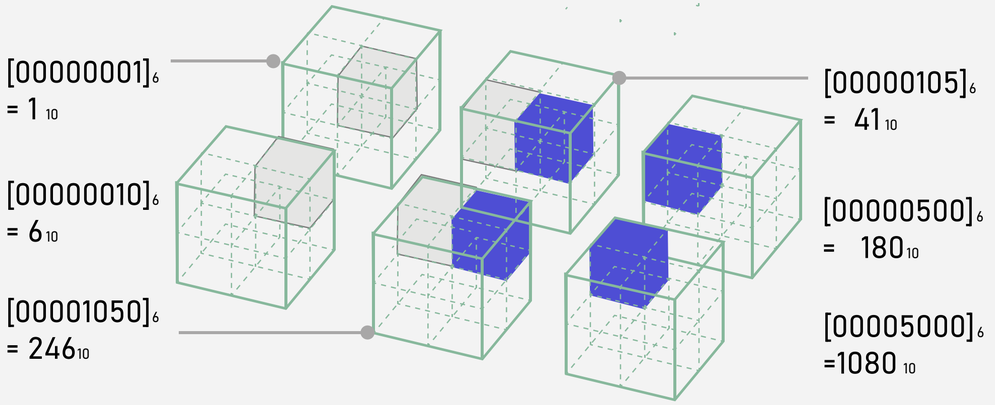




Possible configuration

Binary (256)

Heximal (1679616)



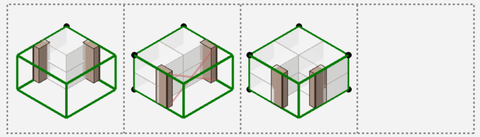
ARCHITECTURAL TILESETS

Architectural tiles (B)

The 26 base tiles classified in different functions

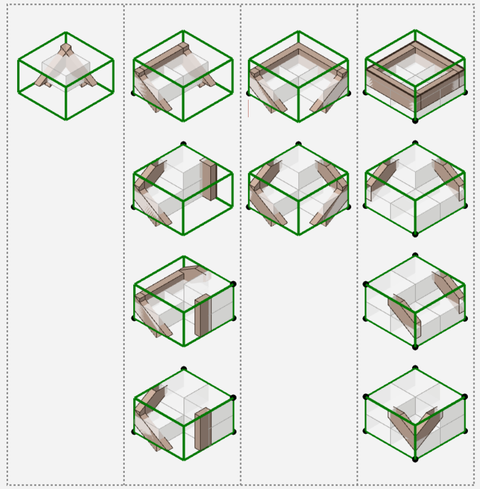
Voxel ID_**1**

Wall frame tiles

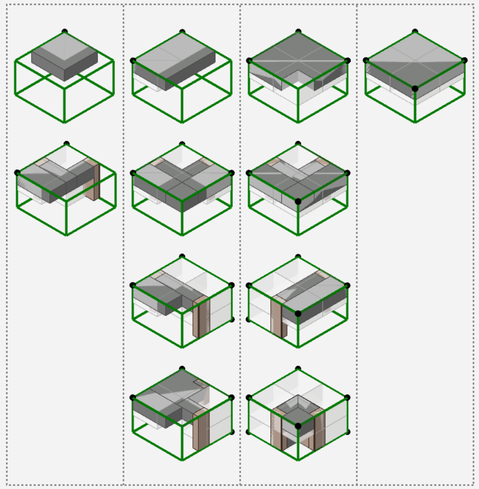


Extra tile

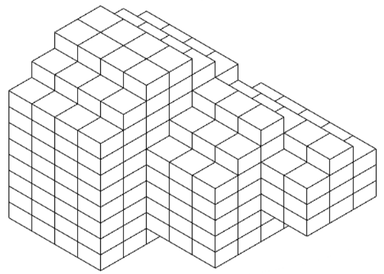
Top frame tiles



Bottom frame tiles

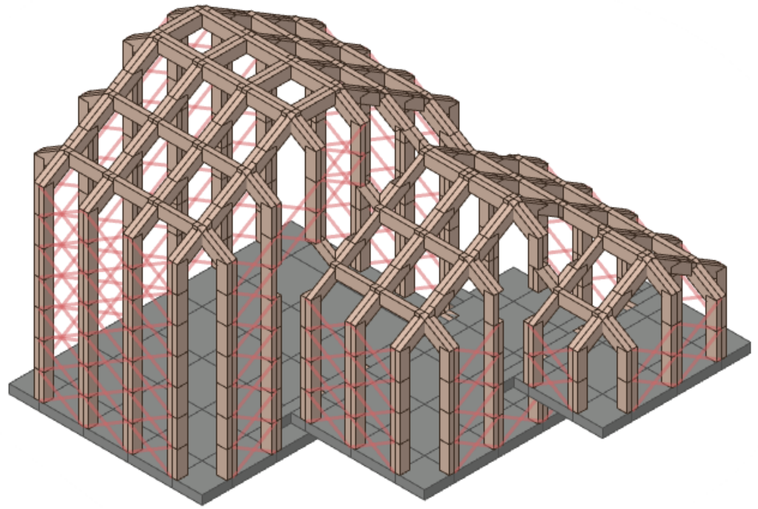


Input



HOUSCAPER

Output



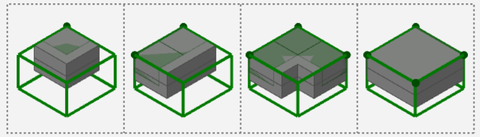
ARCHITECTURAL TILESETS

Foundation tiles
Floor tiles

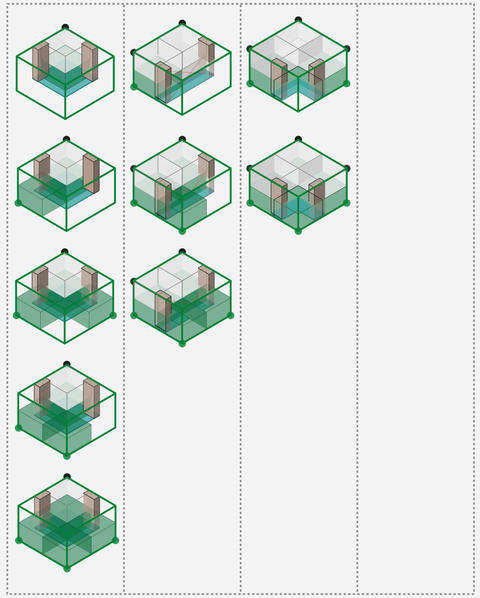
Voxel ID_**3**

Voxel ID_**2**

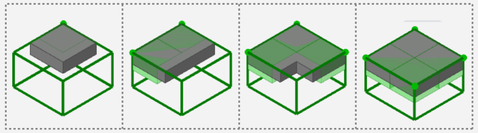
Foundation tiles



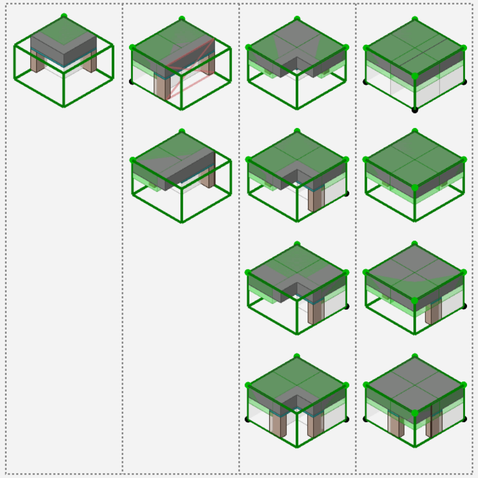
Foundation to frame (Up)



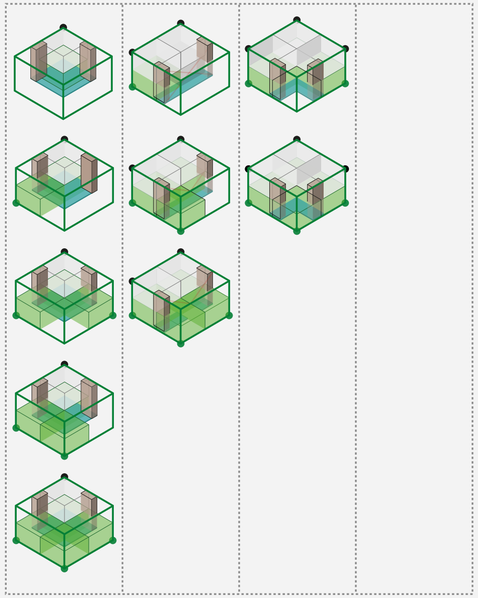
Floor tiles



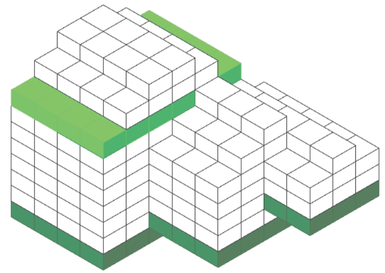
Frame connection (Down)



Floor to frame (Up)



Input



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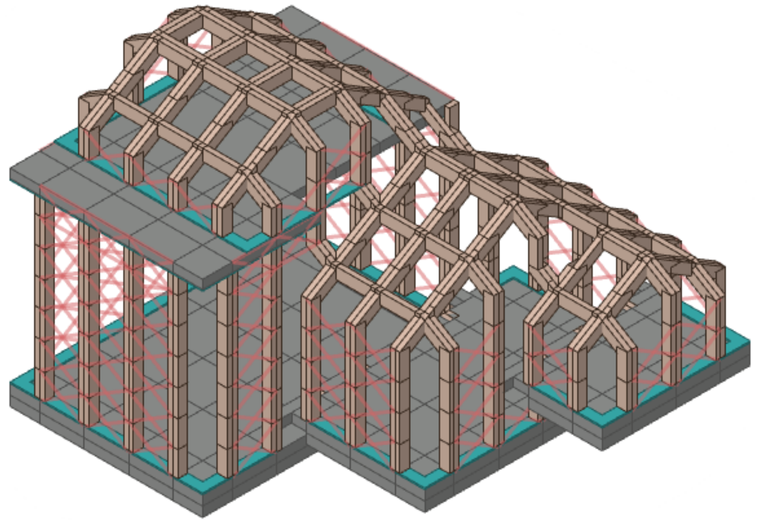
Output



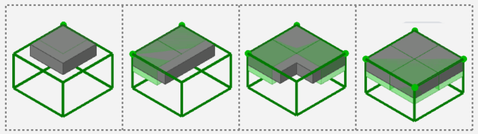
ARCHITECTURAL TILESETS

Foundation tiles
Floor tiles

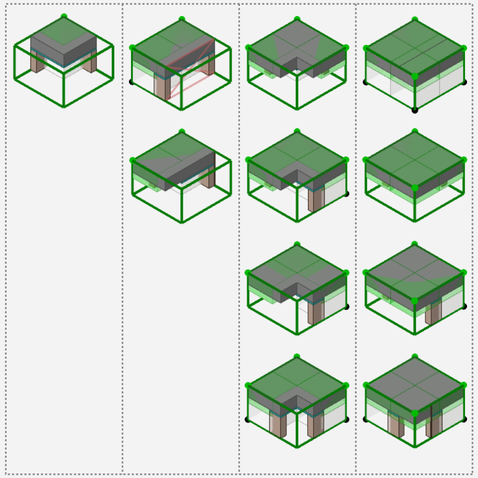
Voxel ID_**3**

Voxel ID_**2**

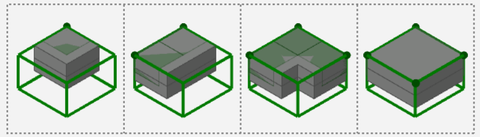
Floor tiles



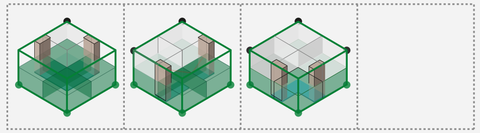
Frame connection (Down)



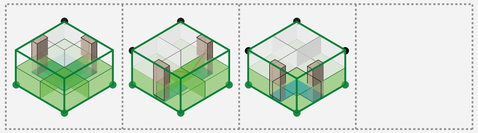
Foundation tiles



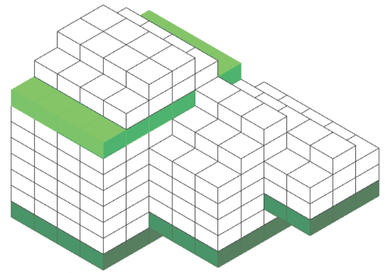
Foundation to frame connection (Up)



Floor to frame connection (Up)

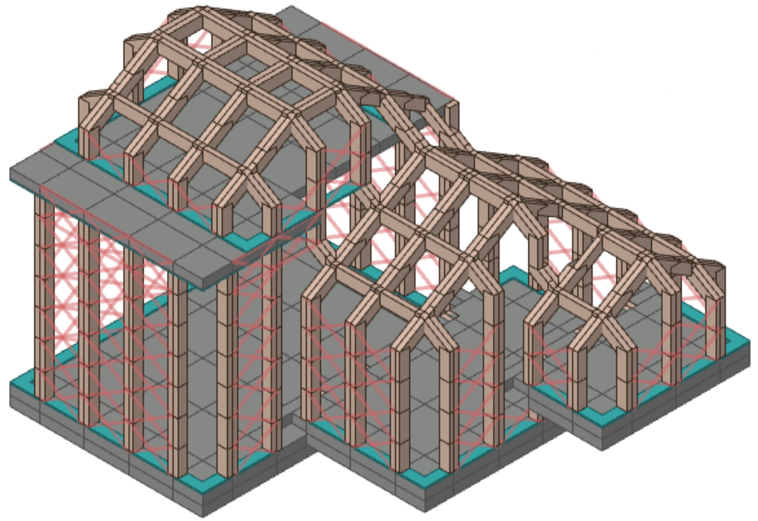


Input



HOUSCAPER

Output



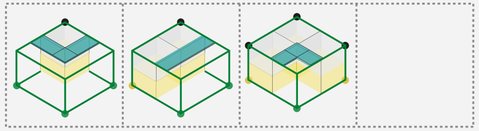
ARCHITECTURAL TILESETS

Opening tiles

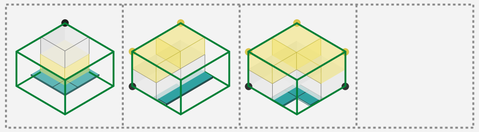
Voxel ID_**4**

Opening tiles

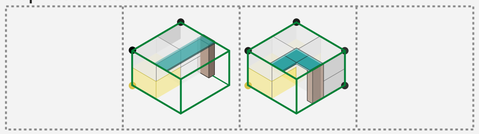
Top-middle tiles



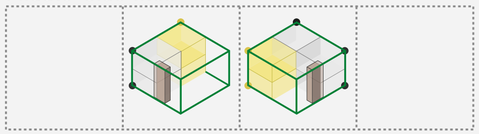
Bottom-middle tiles



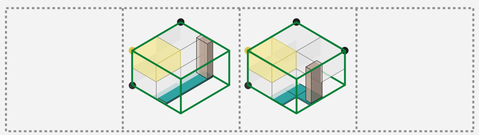
Top-side tiles



Middle-side tiles

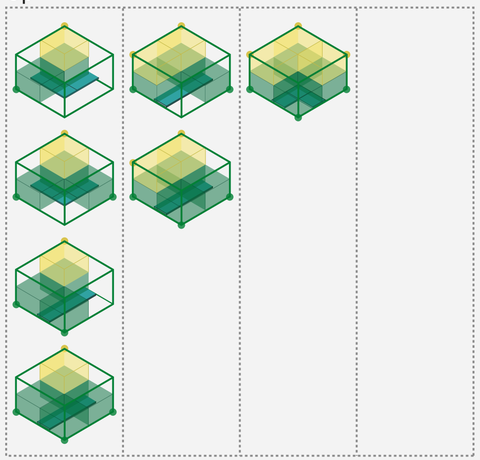


Bottom-side tiles

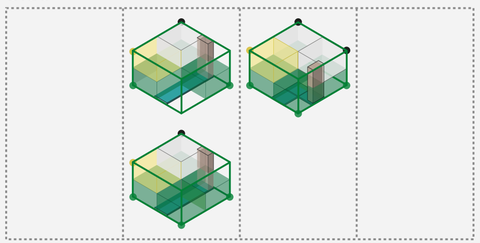


Foundation to opening tiles

Up

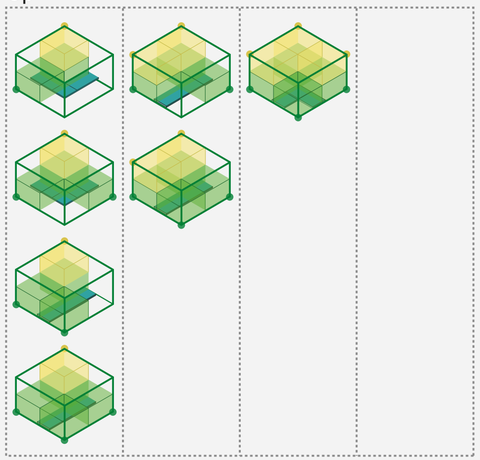


Side

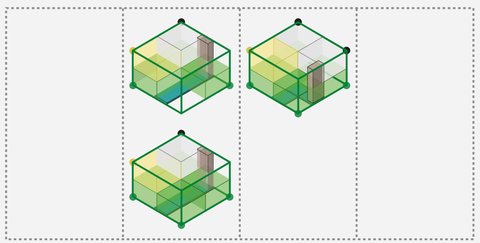


Floor to opening tiles

Up



Side



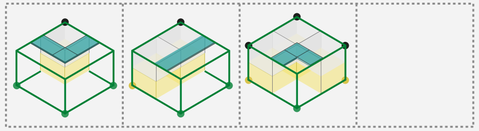
ARCHITECTURAL TILESETS

Opening tiles

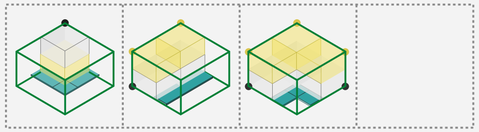
Voxel ID_**4**

Opening tiles

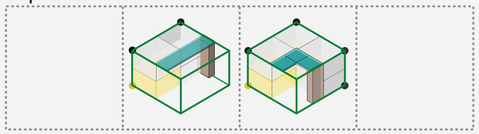
Top-middle tiles



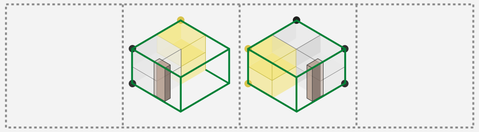
Bottom-middle tiles



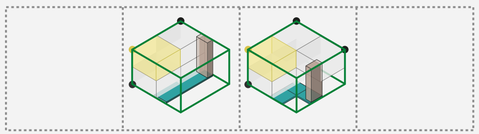
Top-side tiles



Middle-side tiles

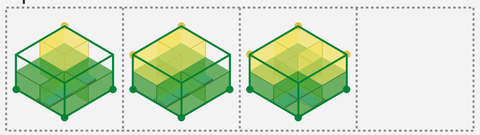


Bottom-side tiles

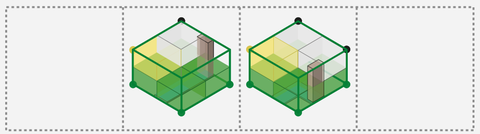


Foundation & Floor to opening tiles

Up



Side



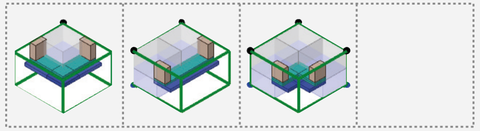
ARCHITECTURAL TILESETS

Window tiles

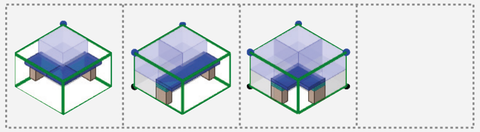
Voxel ID_**5**

Window tiles

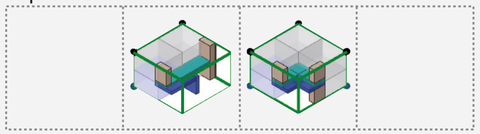
Top-middle tiles



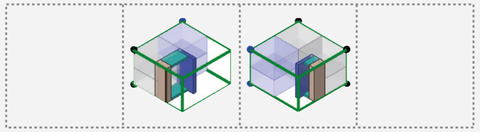
Bottom-middle tiles



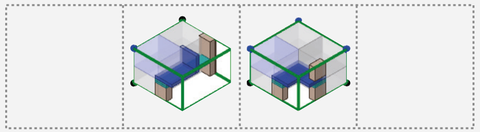
Top-side tiles



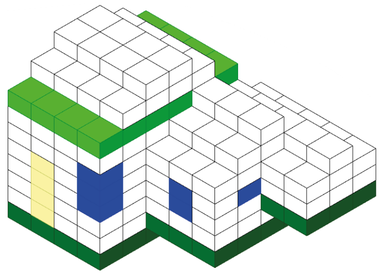
Middle-side tiles



Bottom-side tiles

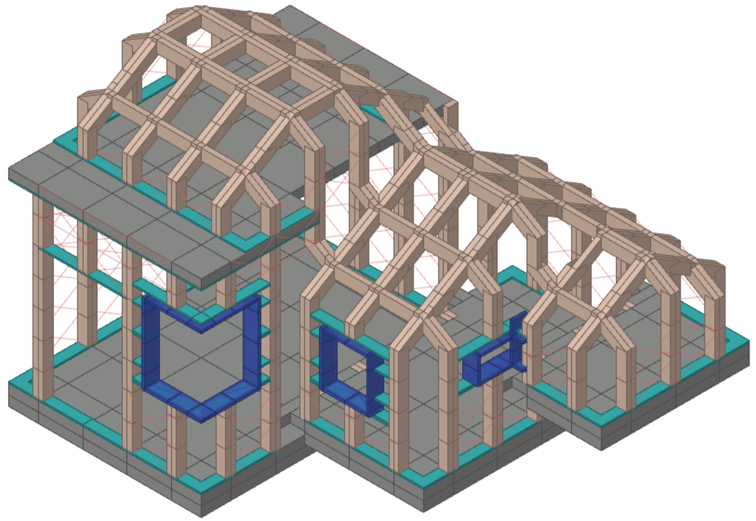


Input



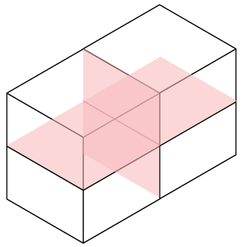
HOUSCAPER

Output

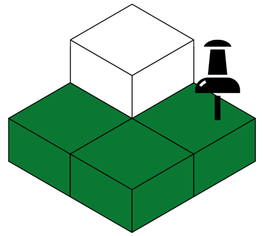


DESIGN RULES

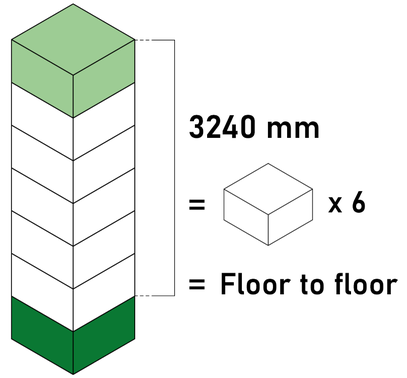
For Normal users



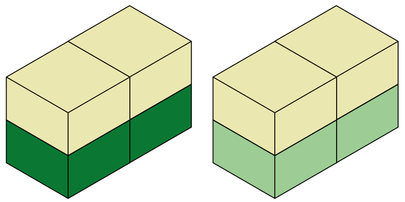
All voxels =
Surface connect



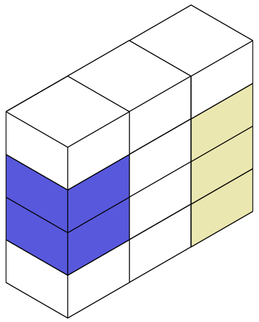
Foundation voxels =
at the bottom



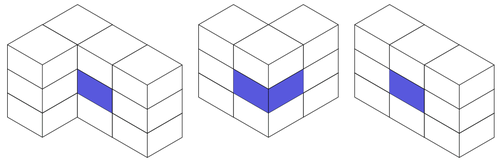
6 stack of tiles
= 3240mm



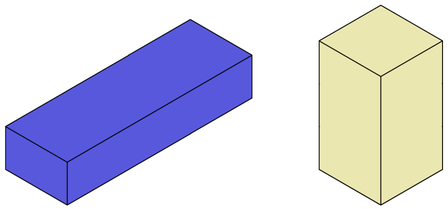
The yellow voxel **starts from green voxels.**



Color voxels
should not be placed next to each other



The minimum units of window tilesets

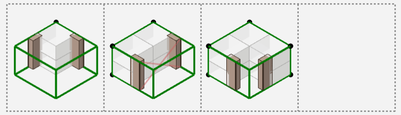


continuous placing in rectangular shape
= bigger openings

ARCHITECTURAL TILESETS OVERVIEW

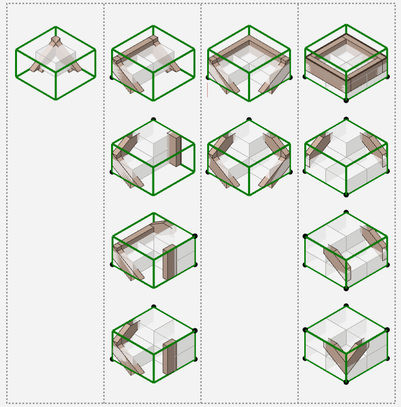
Voxel ID_1

Wall frame tiles

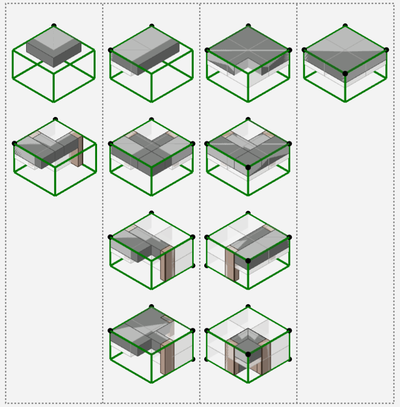


Extra tile

Top frame tiles

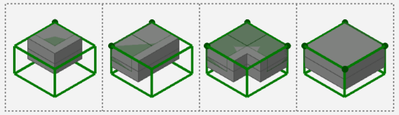


Bottom frame tiles



Voxel ID_3

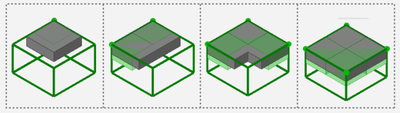
Foundation tiles



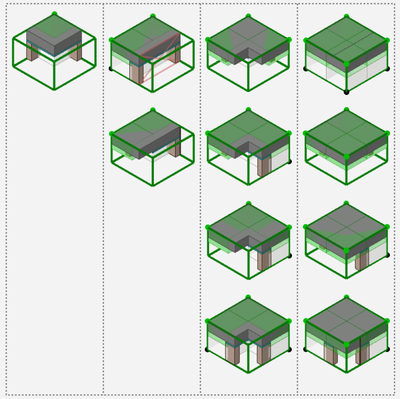
Foundation to frame connection (Up)

Voxel ID_2

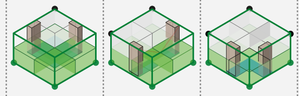
Floor tiles



Frame connection (Down)



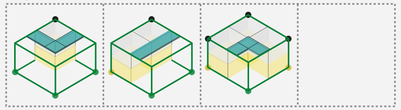
Floor to frame connection (Up)



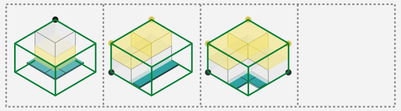
Voxel ID_4

Opening tiles

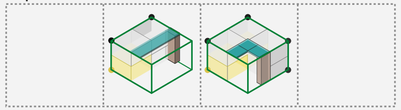
Top-middle tiles



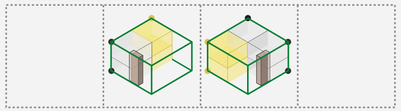
Bottom-middle tiles



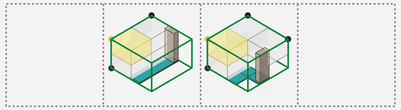
Top-side tiles



Middle-side tiles



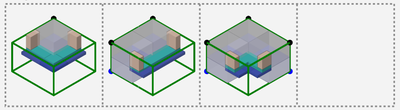
Bottom-side tiles



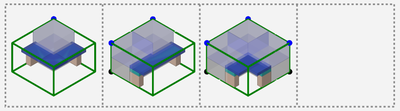
Voxel ID_5

Window tiles

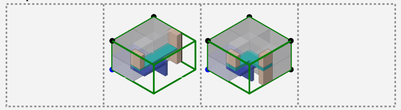
Top-middle tiles



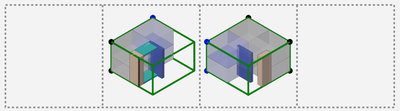
Bottom-middle tiles



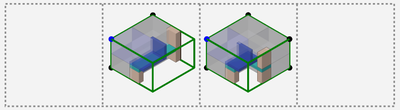
Top-side tiles



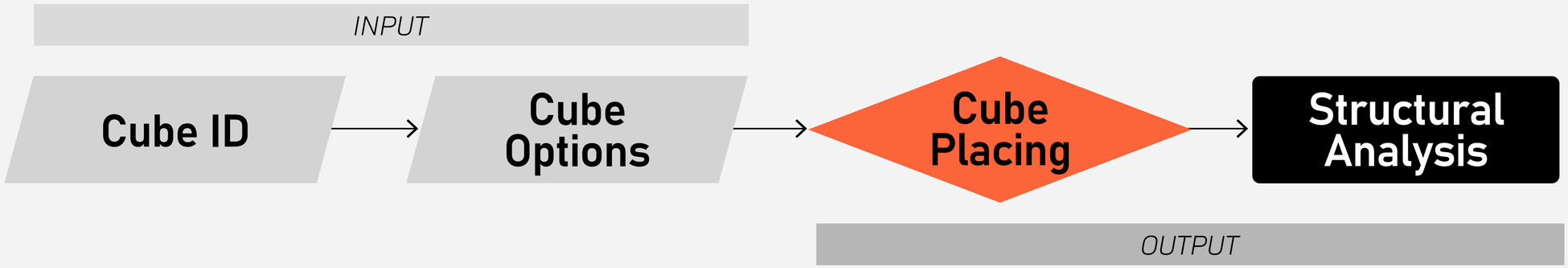
Middle-side tiles

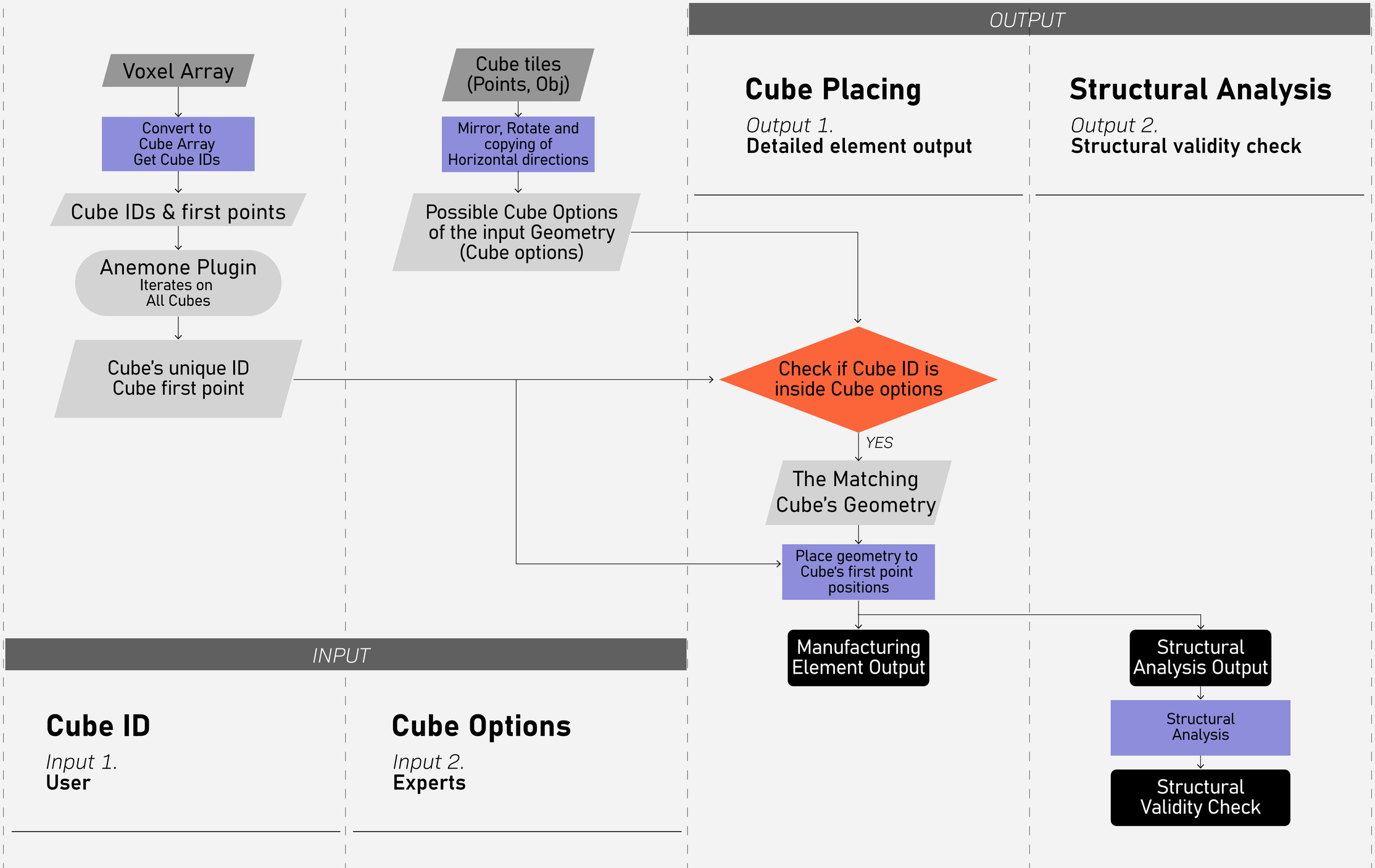


Bottom-side tiles



ALGORITHM DEVELOPMENTS




OUTPUT
Voxel Array
Convert to Cube Array Get Cube IDs
Cube IDs & first points
Anemone Plugin Iterates on All Cubes
Cube's unique ID Cube first point
Cube tiles (Points, Obj)
Mirror, Rotate and copying of Horizontal directions
Possible Cube Options of the input Geometry (Cube options)
Cube Placing
Output 1.
Detailed element output
Structural Analysis
Output 2.
Structural validity check
Check if Cube ID is inside Cube options
YES
The Matching Cube's Geometry
Place geometry to Cube's first point positions
Manufacturing Element Output
Structural Analysis Output
Structural Analysis
Structural Validity Check
INPUT
Cube ID
Input 1.
User
Cube Options
Input 2.
Experts

OUTPUT

Voxel Array

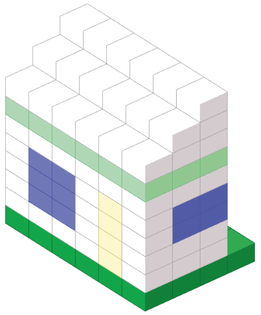
Cube tiles
(Points, Obj)

Cube Placing

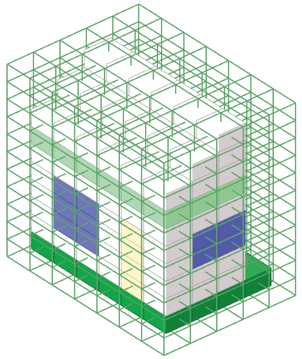
Structural Analysis

Output 2.
Structural validity check

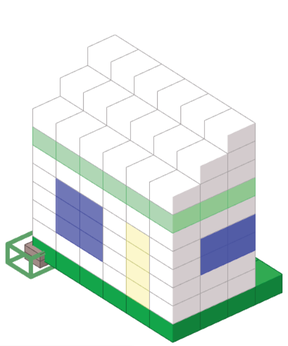
User input voxel array

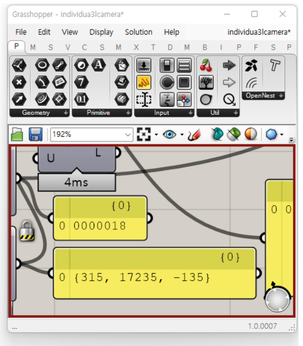


Convert to cube array



Iterate on all cube /
cube id and cube first point





Cube ID

Input 1.
User

Cube Options

Input 2.
Experts

Structural
Analysis Output

Structural
Analysis

Structural
Validity Check

Voxel Array

Convert to
Cube Array
Get Cube IDs

Cube IDs & first points

Anemone Plugin
Iterates on
All Cubes

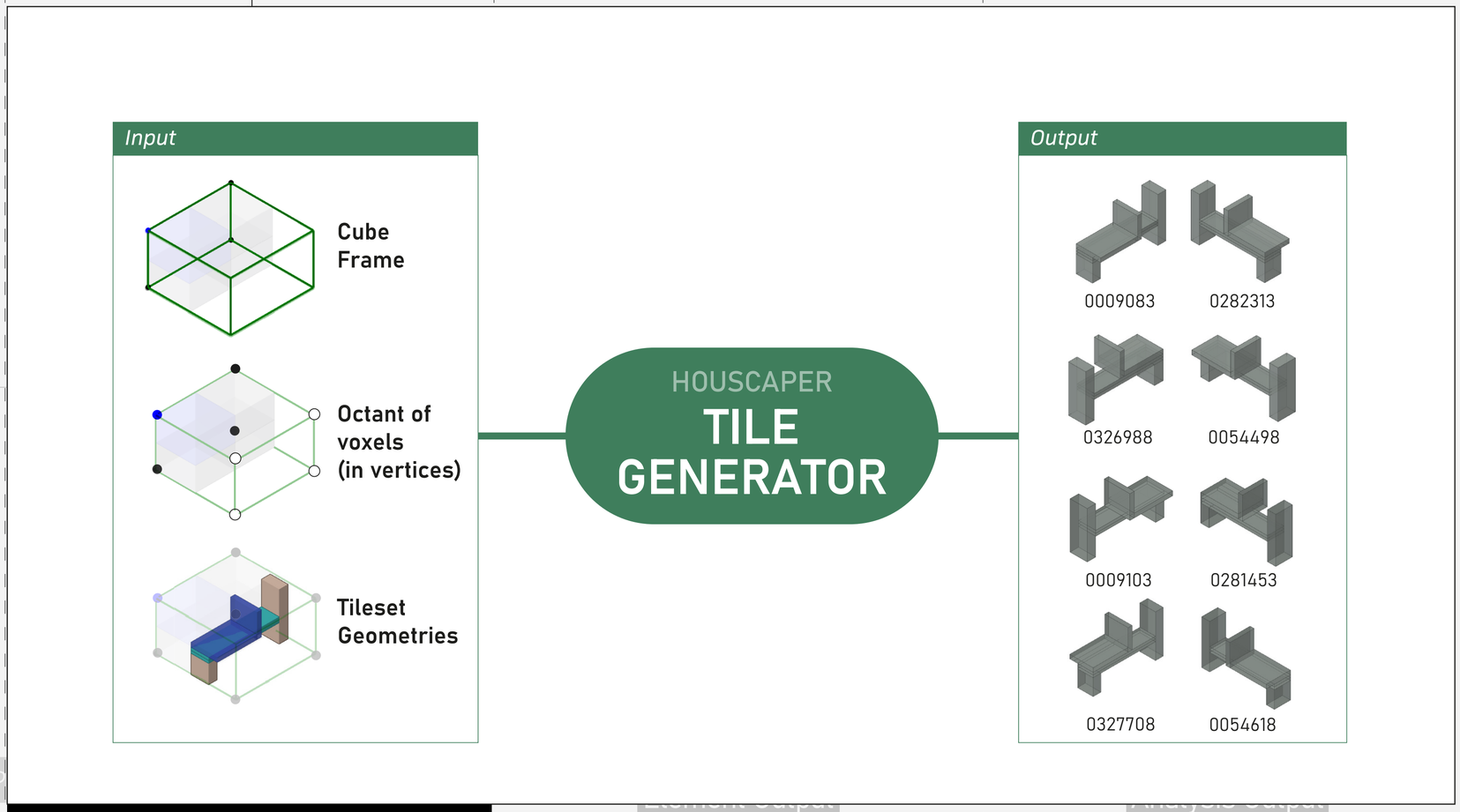
Cube's unique ID
Cube first point

OUTPUT

Cube tiles
(Points, Obj)

Cube Placing

Structural Analysis



INP

Cube ID

Input 1.
User

Cube Options

Input 2.
Experts

Structural
Analysis

Structural
Validity Check

OUTPUT

Voxel Array

Convert to Cube Array Get Cube IDs

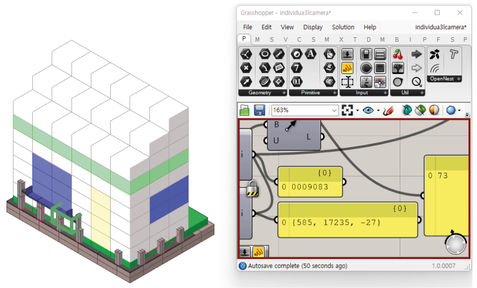
Cube tiles (Points, Obj)

Mirror, Rotate and copying of Horizontal directions

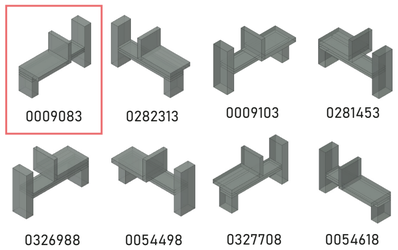
Cube Placing

Output 1.
Detailed element output

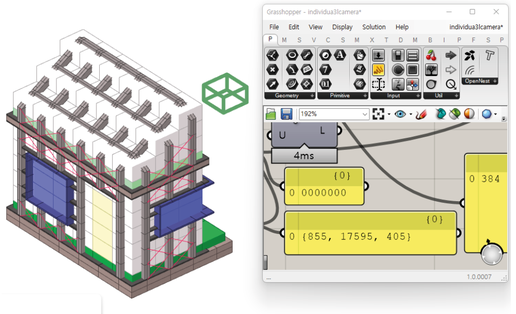
Cube ID



Search for cube id in cube options



Cube placing/ running the algorithm



Input 1.
User

Input 2.
Experts

Structural Analysis

Output 2.
Structural validity check

Structural Analysis Output

Structural Analysis

Structural Validity Check

Voxel Array

Convert to
Cube Array
Get Cube IDs

Cube IDs & first points

Anemone Plugin
Iterates on
All Cubes

Cube's unique ID
Cube first point

Cube tiles
(Points, Obj)

Mirror, Rotate and
copying of
Horizontal directions

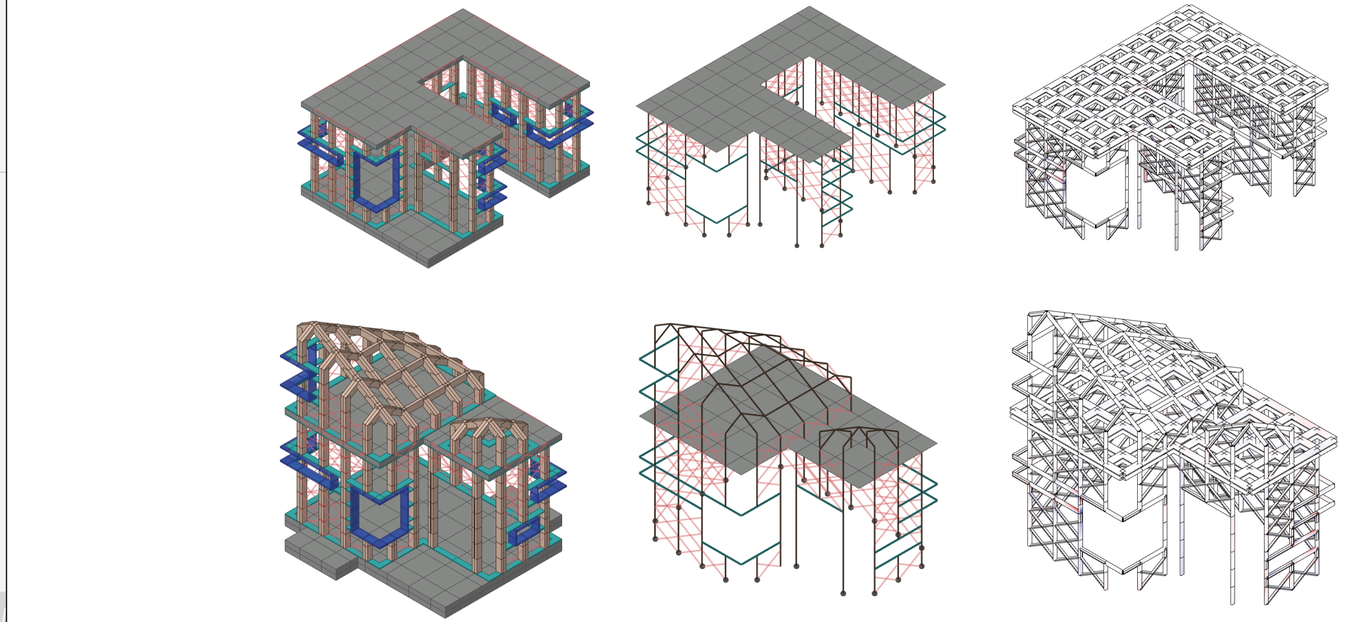
OUTPUT

Cube Placing

Output 1.
Detailed element output

Structural Analysis

Output 2.
Structural validity check



INPU

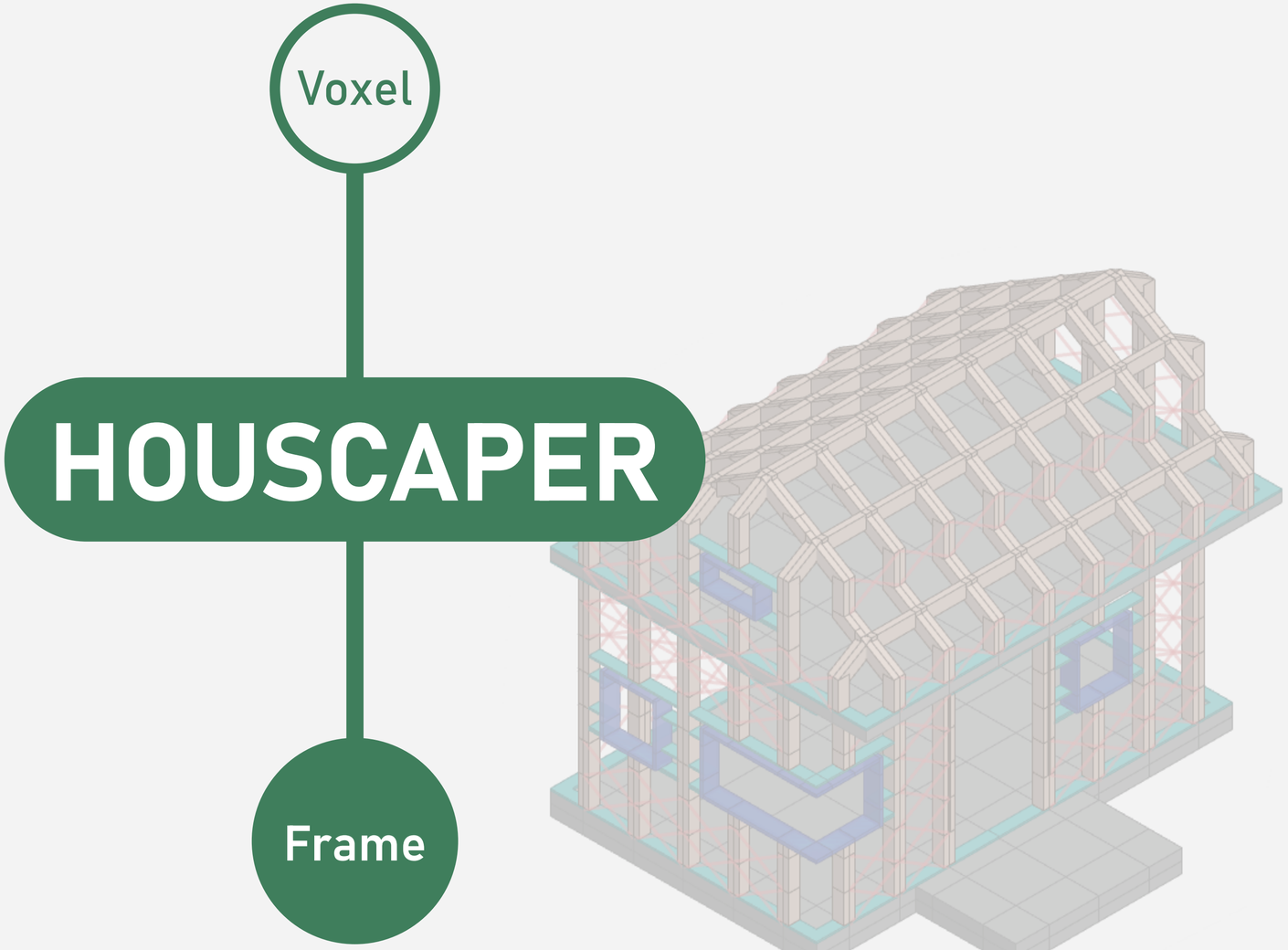
Cube ID

Input 1.
User

Input 2.
Experts

Structural
Validity Check

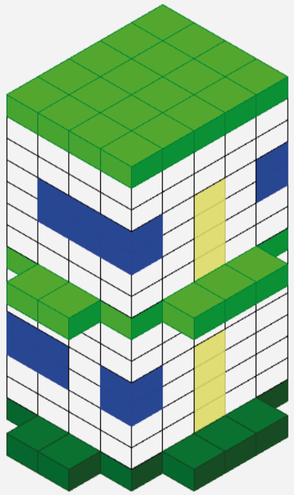
RESULTS

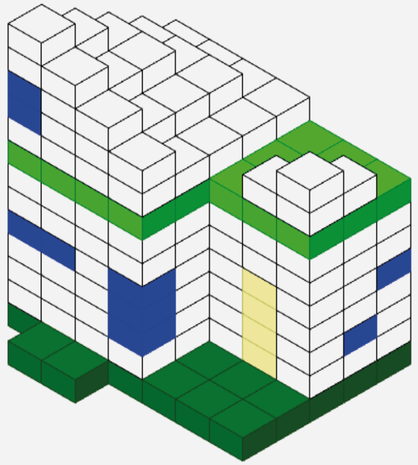


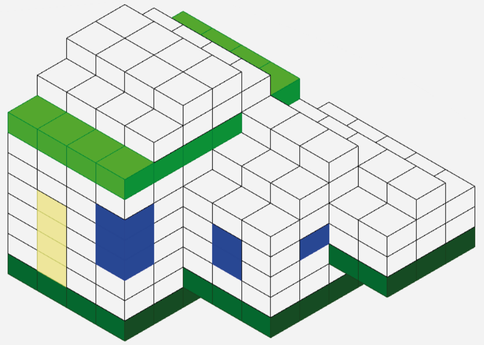
BUILD WITH COLORED VOXELS

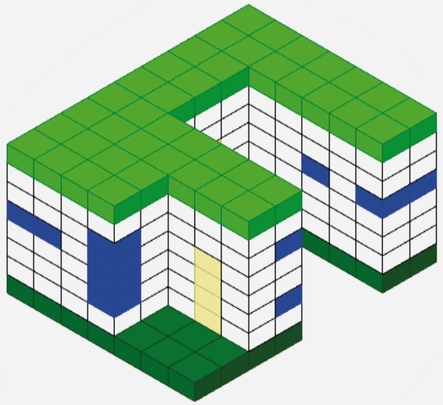
01 Easy stacking of voxels

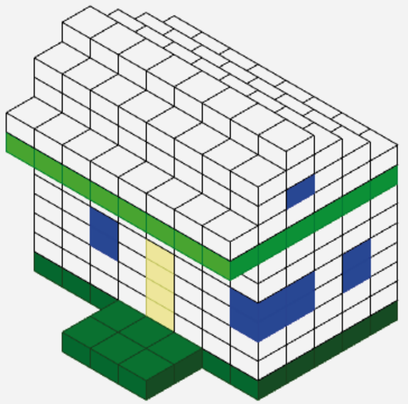
Combinatorial creativeness
in participatorial design.

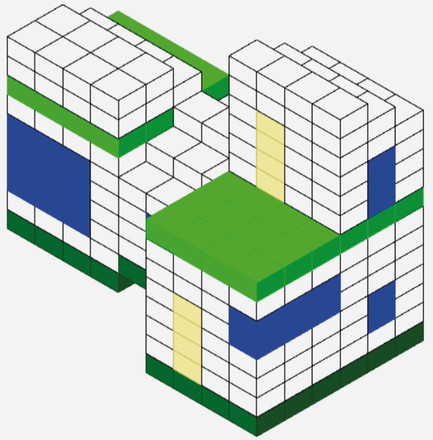








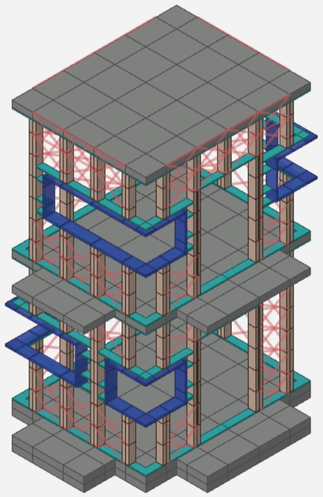


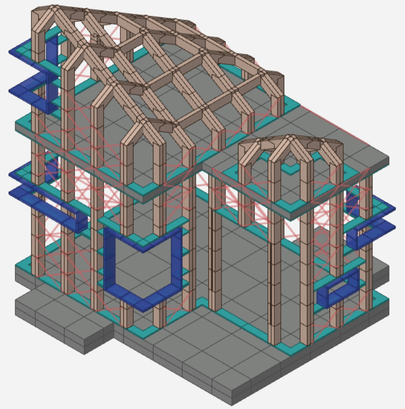


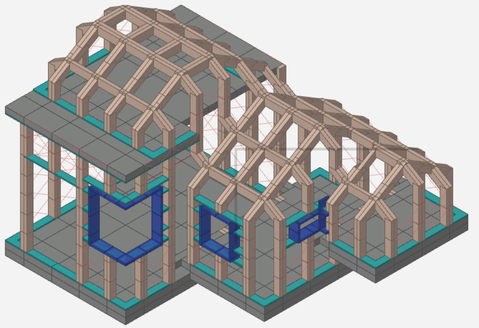
RESULTING ARCHITECTURAL FRAMES

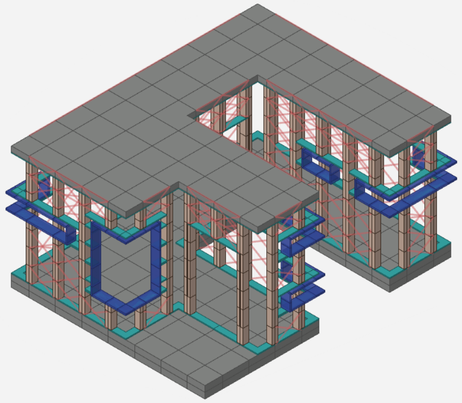
02 Polygonization of modular cube tilesets

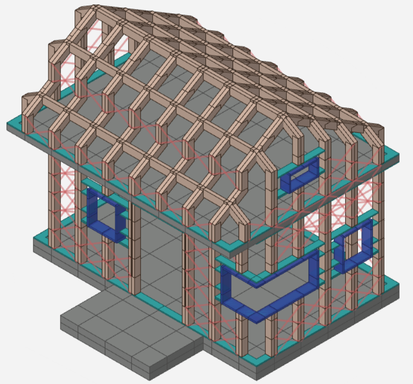
Differenciate materials in different layer savings

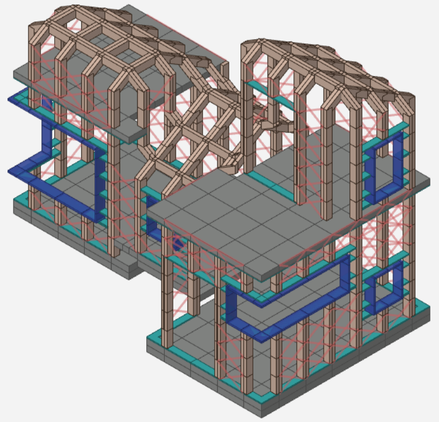










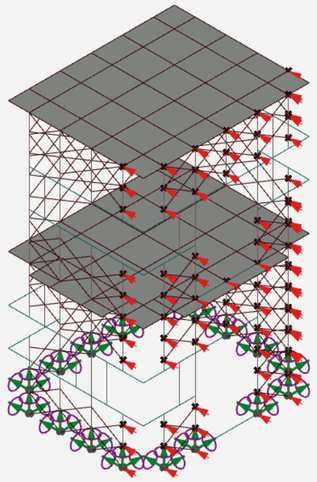


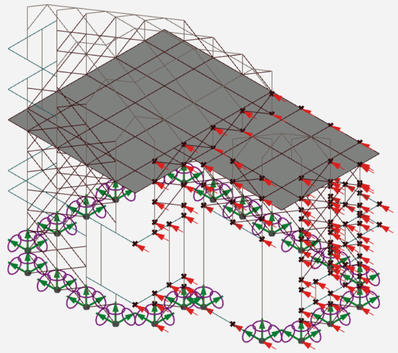
STRUCTURAL VALIDITY CHECK

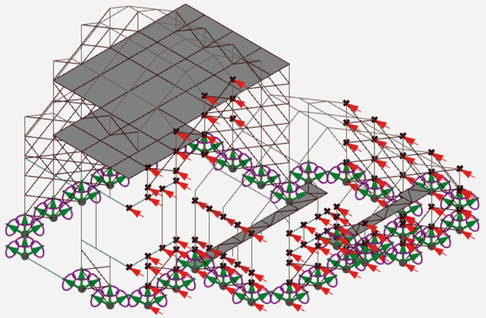
FEM(Karamba)

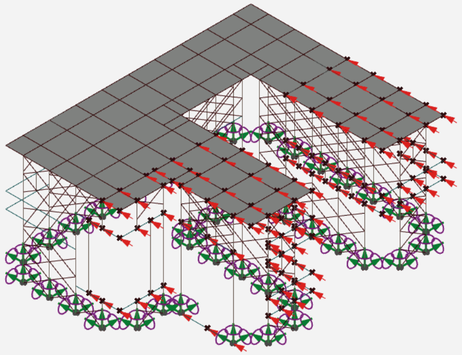
03 Load apply

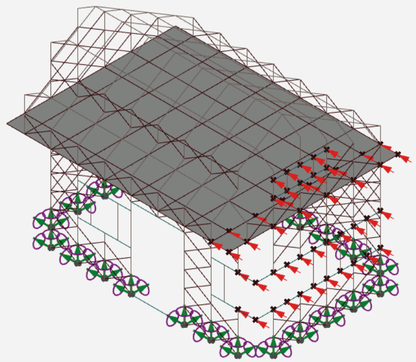
Apply of the structure
load and materiality.

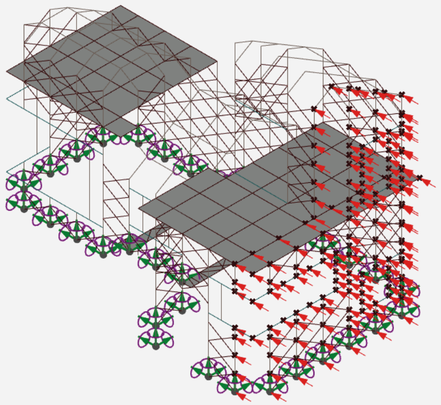












Load Applied

1.5 G	Gravity load
1000N/m	Windload on one side

STRUCTURAL VALIDITY CHECK

FEM(Karamba)

03 Structural envelope

Under assumption of small and medium sized architecture stands with structural envelope

structural analysis can be made

GoDesign Framework

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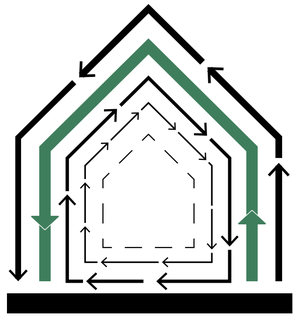
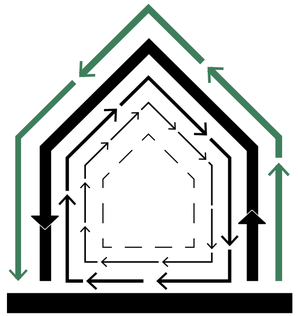
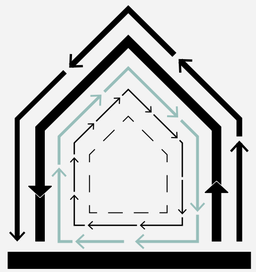


Sturcture > 200 years

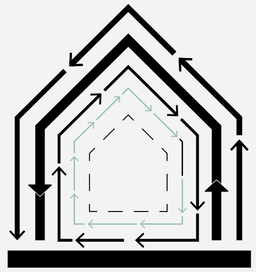


Skin ≈ 50 years

Generative zoning configurations



Systems ≈ 25 years



Space plan ≈ 15 years

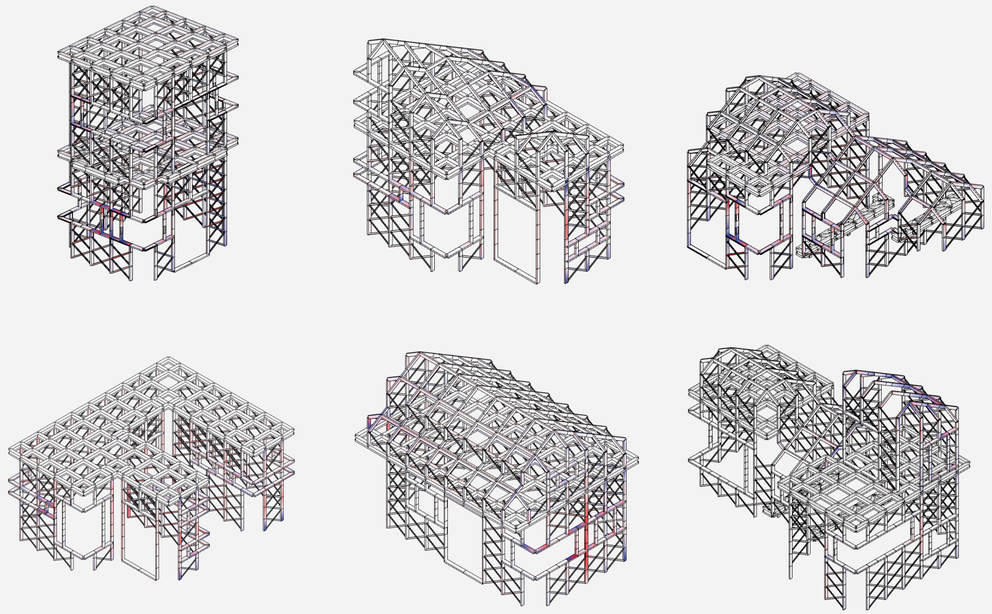
+ Freedom of interior configuration
+ less cost
+ less embodied energy

STRUCTURAL VALIDITY CHECK

FEM(Karamba)

03 material apply

Apply crosssection and materiality.



Materiality

** S355 Steel*

Young's Module	E	205315 MPa
Poisson ratio	ν	0.29
Yield Stress	R_{p02}	425 MPa
Work hardening exponent	n	0.165
Maximum technical stress	$R_{m\ tech}$	557 MPa
Maximum true stress	$R_{m\ true}$	639 MPa
Strain at maximum load	ε_u	14.64%
Stress at rupture	R_f	514 MPa
Strain at rupture	ε_r	15.55%

Cross-section

Vertical Frame	Rectangular section	Height 150 cm Width 50 cm Thickness 1.6 mm
Horizontal Frame	Rectangular section	Height 50mm Width 150 mm Thickness 1.6 mm
Support Frame	Rectangular section	Height 40 mm Width 16 mm Thickness 1.6 mm
Floor Frame	I section	Height 200mm Upper width 100 mm Lower width 100 mm Thickness 1.6 mm

STRUCTURAL VALIDITY CHECK

FEM(Karamba)

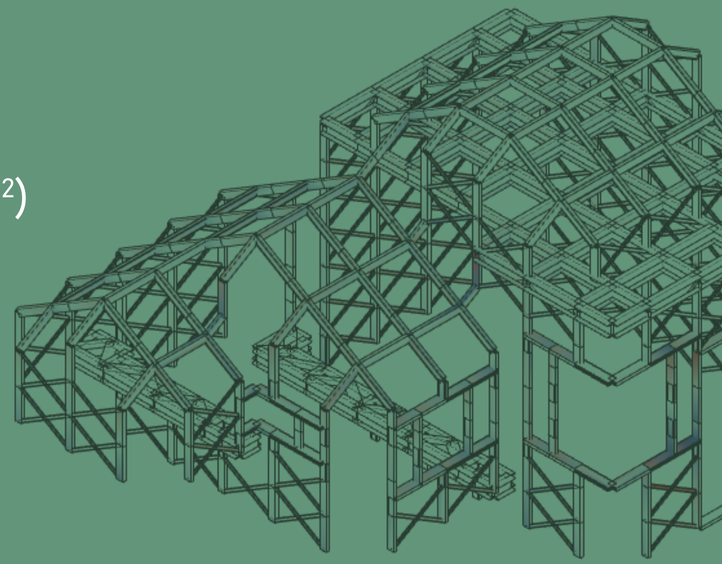
If structure's axial stress is less than

half of the material's technical axial stress (278 n/mm^2)

The structure is valid.

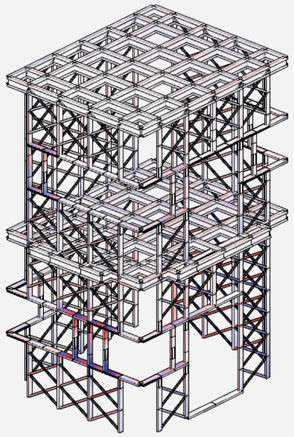
Else,

The structure is not valid.



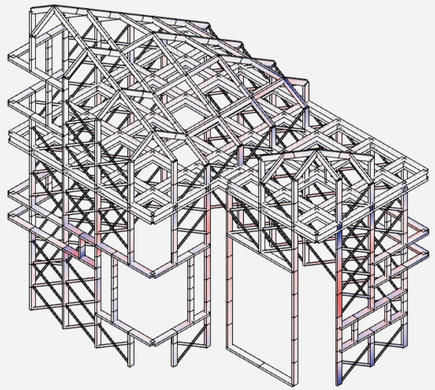
STRUCTURAL VALIDITY CHECK

FEM(Karamba)

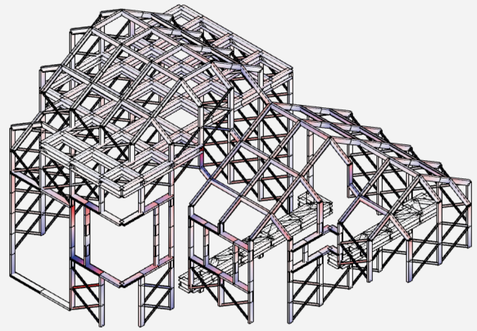


Max compression (n/mm2)	290
Max tension (n/mm2)	286
Max deformation (mm)	20

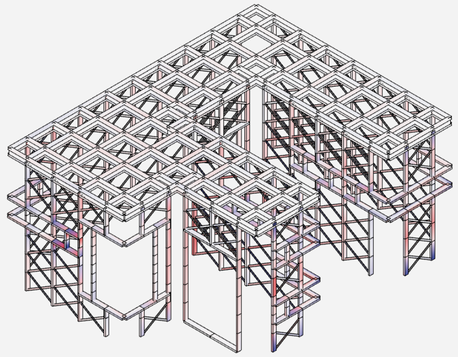
X



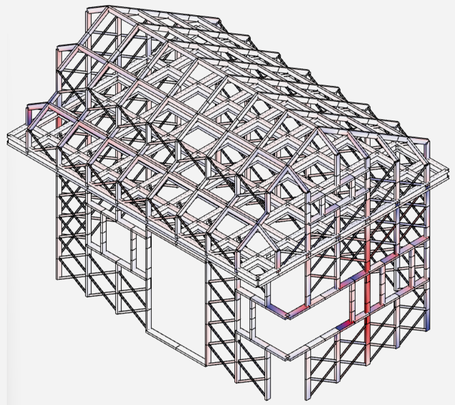
Max compression (n/mm2)	162
Max tension (n/mm2)	145
Max deformation (mm)	12



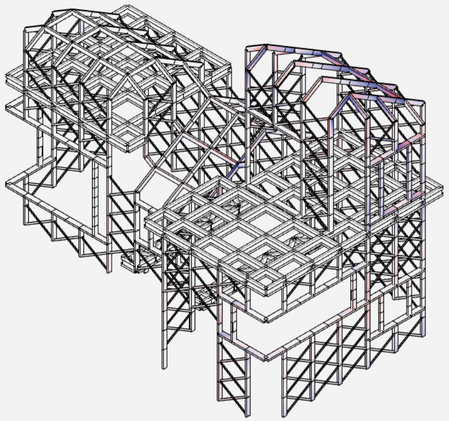
Max compression (n/mm2)	106
Max tension (n/mm2)	68
Max deformation (mm)	6



Max compression (n/mm2)	95.8
Max tension (n/mm2)	95.2
Max deformation (mm)	6.4



Max compression (n/mm2)	247
Max tension (n/mm2)	205
Max deformation (mm)	11



Max compression (n/mm2)	293
Max tension (n/mm2)	291
Max deformation (mm)	110

X

CONCLUSION

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The tool **generates polygonization of the voxel array** using the tileset.
As all parts are completely modular, the finished geometry can be **precisely calculated with the CPQ** (configure, price, quotation) of the material used for the frame generated.

By using a set of design rules and grouping the same geometries, **users can work with a reasonable number of tilesets**. A total of suggested 493 configurations, 109 architectural tilesets are grouped into 72 tilesets. **Expert/designer users can add more designs** by simply assigning a tileset to the system.

The tool can visualize the finished architectural frame and run a structural analysis of the structural envelope, providing an instant validity check of the structural frame. The structural analysis script allows alternation of material and crosssections of linear building elements providing expert users with freedom of choice in materiality.

CONCLUSION

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Limitations

The research has mainly focused on the polygonization aspect of modular housing using a voxel array. The modeling of the parts remains basic to give users a simple visual impression of the tool.

The structural analysis also works with linear modular components by assigning crosssections and material properties in FEM analysis.

However, site property variations and specifications are ignored to bring more generality to the project.

CONCLUSION

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Futrure works

1. A web version, a lighter version of the tool designed for the mass as a publishable SaaS (software as a Service), enables public access to the device for both the mass and the experts.

2. Development of a generative design method for the voxel array design. Already optimization methods introduced in GoDesign show possibilities to generative design the zone configuration.

3. Develop a script enabling the parts outside of Module sizes, such as the truss inside th wall and roof. The trusses connecting edge-to-edge point of frame sizes often exceed the modules' size.

THANK YOU.