P5

GENERATIVE SOLAR CLIMATIC CONFIGURATION

a model for feed-forward optimization
of building envelopes
as to solar energy potential

Student
Anastasia Florou

Supervisors
Dr.ir. Pirouz Nourian
Dr.ir. Eleonora Brembilla
Ir. Shervin Azadi

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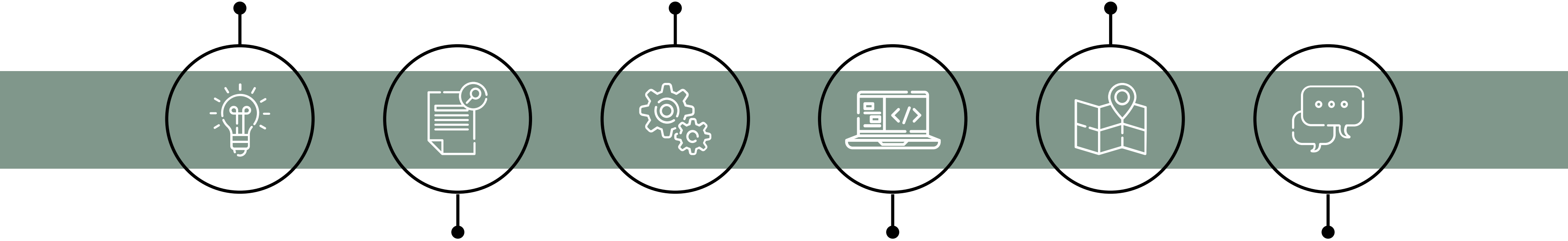


RESEARCH FRAMEWORK

LITERATURE REVIEW

PROPOSED METHODOLOGY

VERIFICATION & BENCHMARKING

CASE STUDY

CONCLUSIONS

01

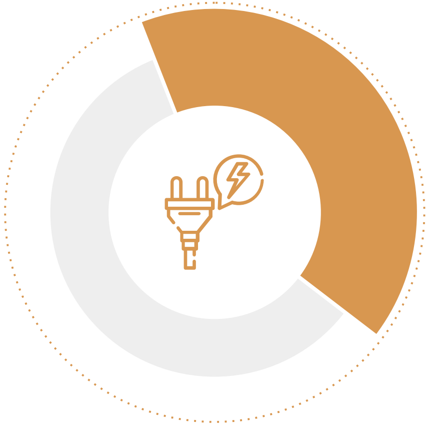
RESEARCH FRAMEWORK

Context / Motivation
Research Objective
Research Question
Problem Scope
Research Methodology

CONTEXT / MOTIVATION

30%

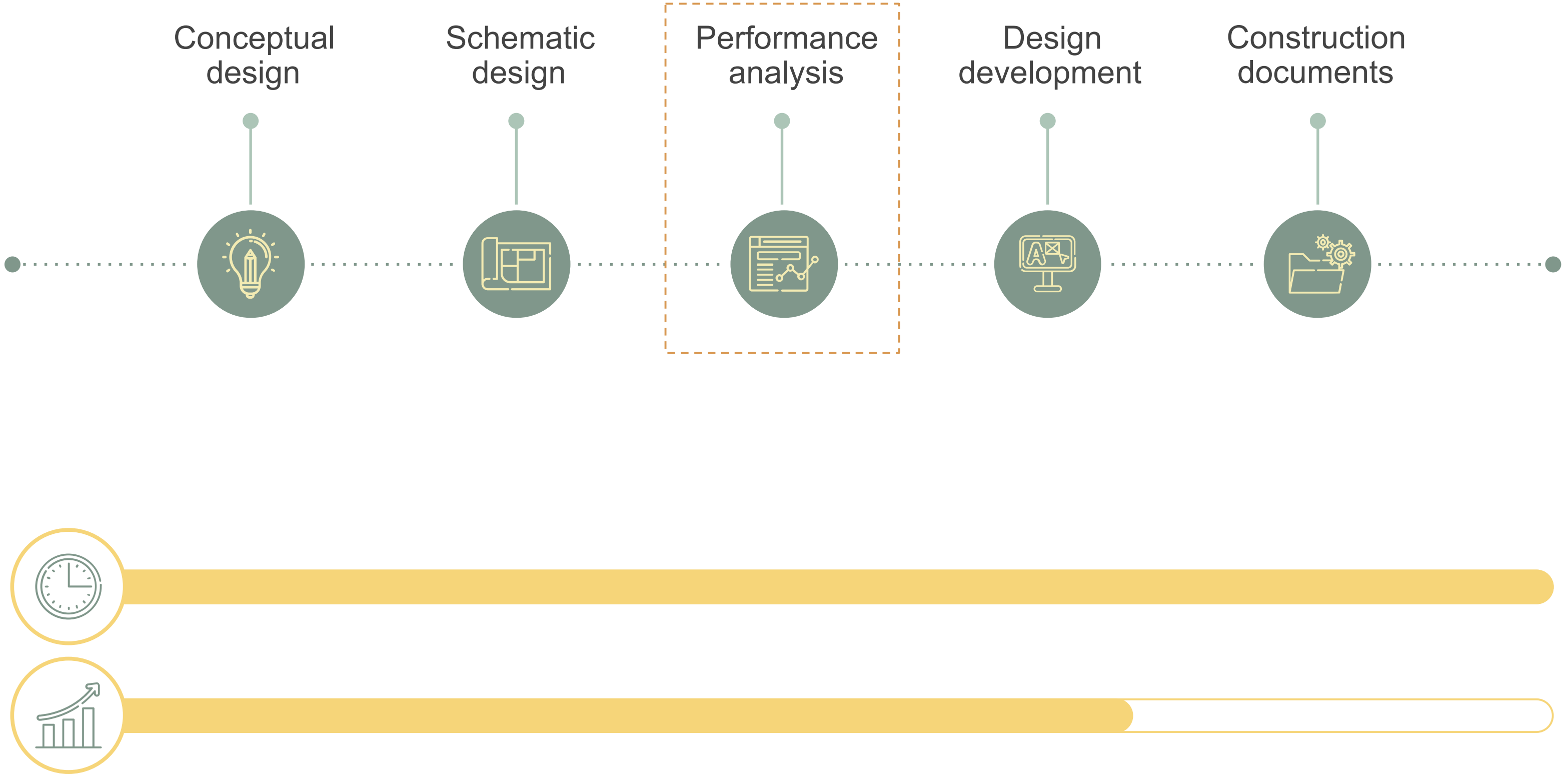
of global
CO2 emissions



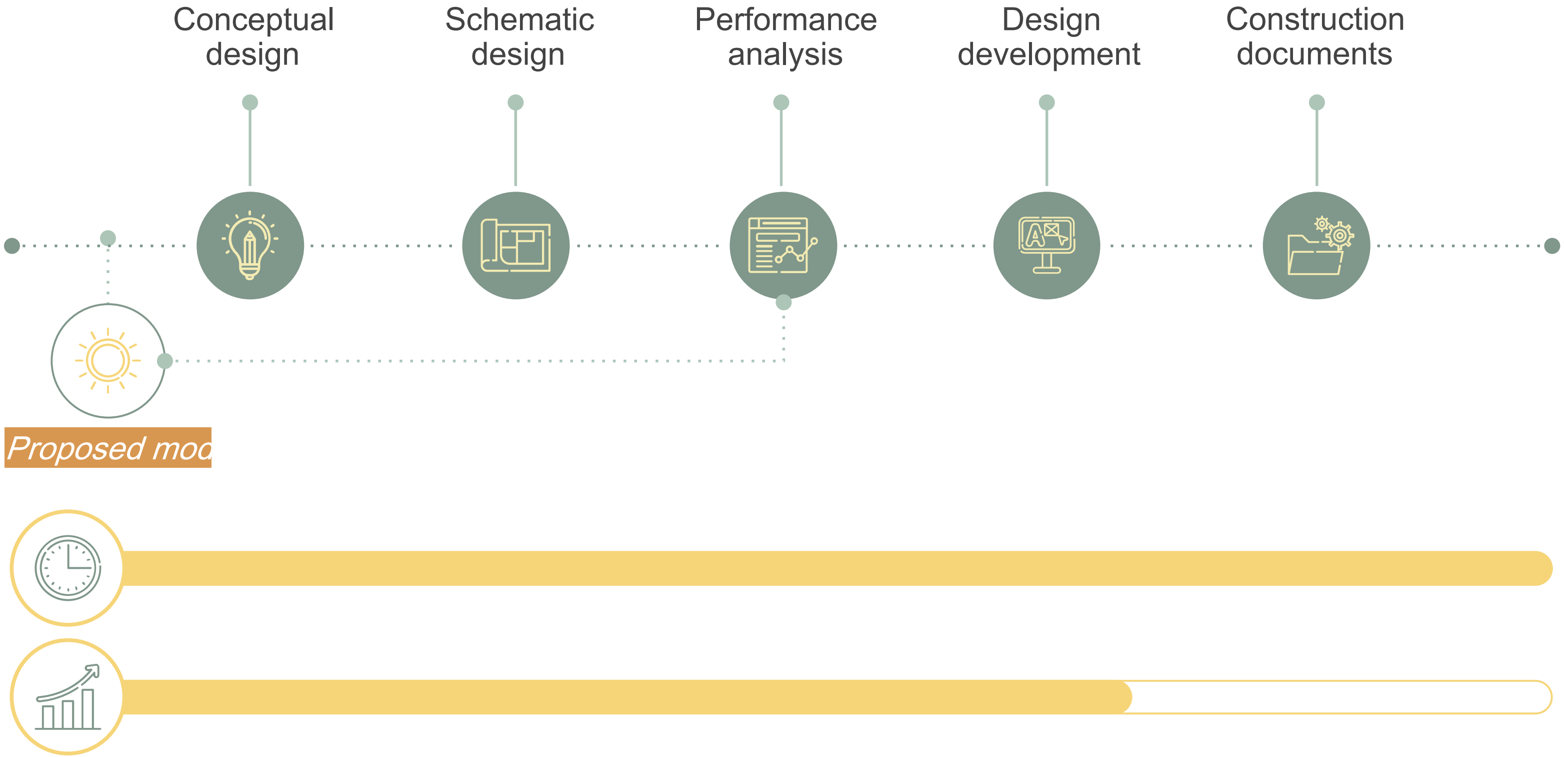
40%

of global final
energy consumption

CONTEXT / MOTIVATION



RESEARCH OBJECTIVE



Conceptual design

Schematic design

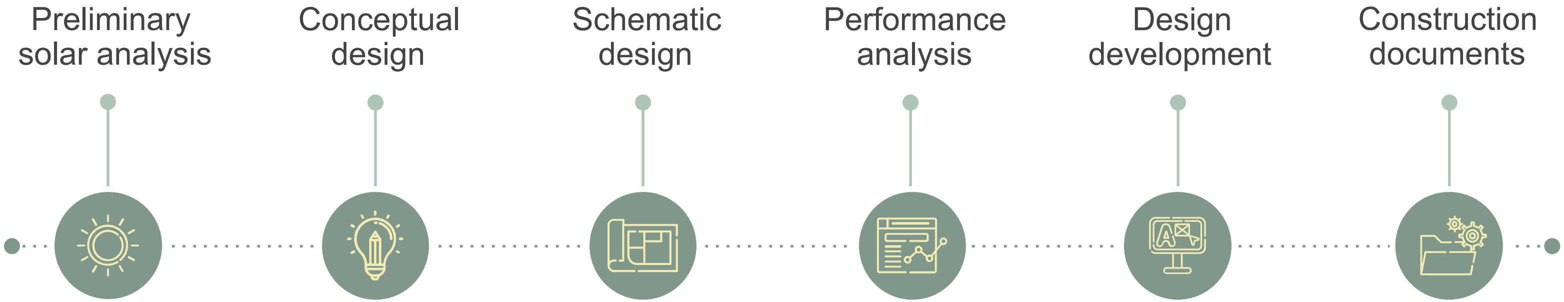
Performance analysis

Design development

Construction documents

Proposed mod

RESEARCH OBJECTIVE



Preliminary solar analysis

Conceptual design

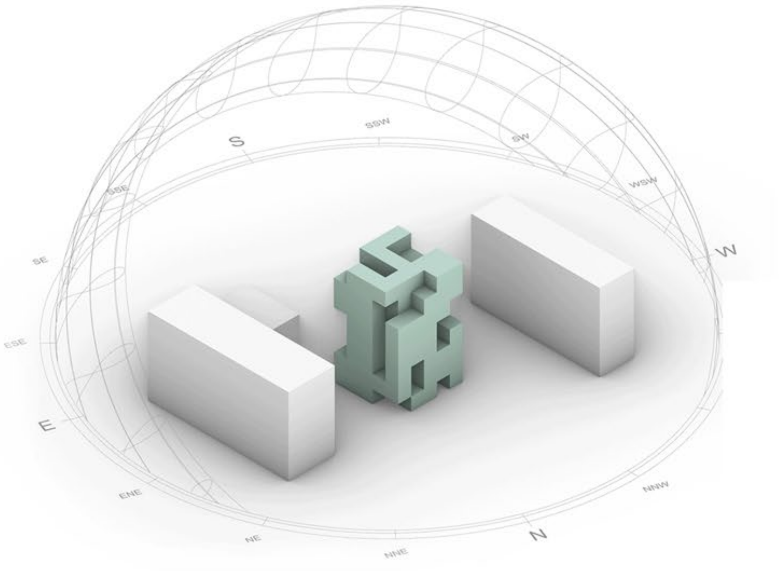
Schematic design

Performance analysis

Design development

Construction documents

RESEARCH OBJECTIVE



solar potential

RESEARCH QUESTION

“How to develop a computational framework,
for early-stage design approximation
of a building’s envelope shape (massing),
in order to maximize its solar energy potential?”

RESEARCH SUB-QUESTION

“How to develop a computational framework, for early-stage design approximation of a building’s envelope shape, in order to maximize its solar energy potent?”

- How to translate the solar potential of a building to performance criteria?

RESEARCH SUB-QUESTION

*“How to develop a computational framework, for early-stage desig
approximation of a building’s envelope shape,
in order to maximize its solar energy potential?”*

- How to translate the solar potential of a building to performance criteria?
- How to define the most important criteria for the early stage design?

RESEARCH SUB-QUESTION

“How to develop a computational framework, for early-stage design approximation of a building’s envelope shape, in order to maximize its solar energy potential?”

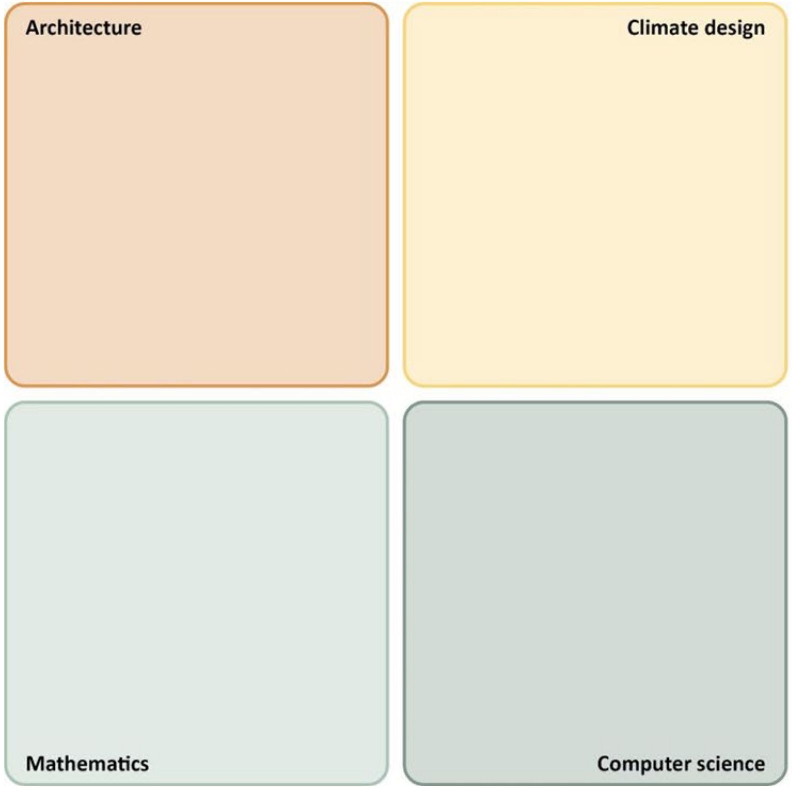
- How to translate the solar potential of a building to performance criteria?
- How to define the most important criteria for the early stage design?
- How to turn the performance criteria into performance indicators in order to evaluate them?

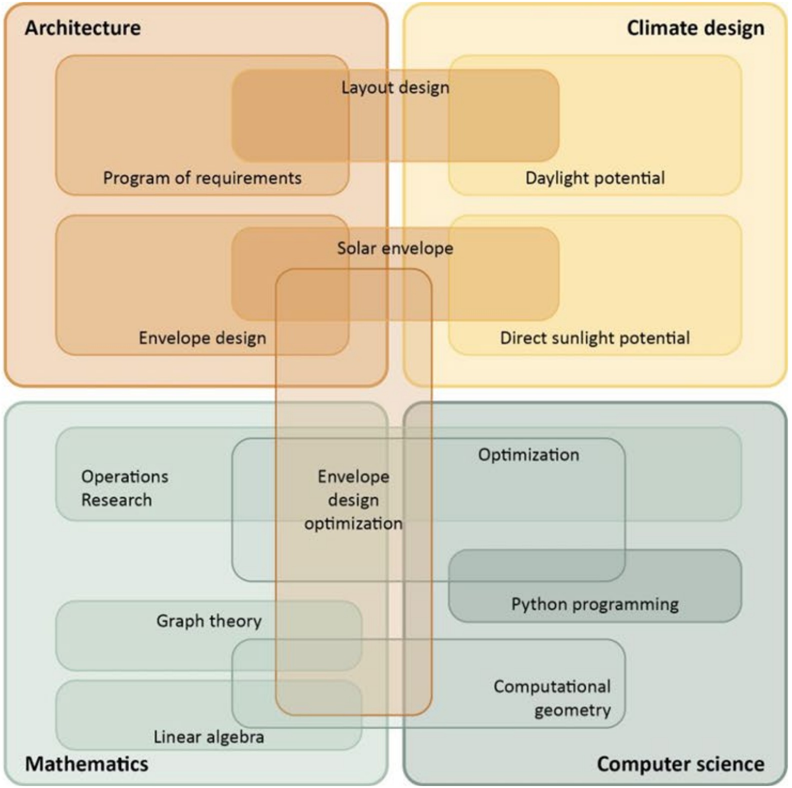
RESEARCH SUB-QUESTION

“How to develop a computational framework, for early-stage design approximation of a building’s envelope shape, in order to maximize its solar energy potential?”

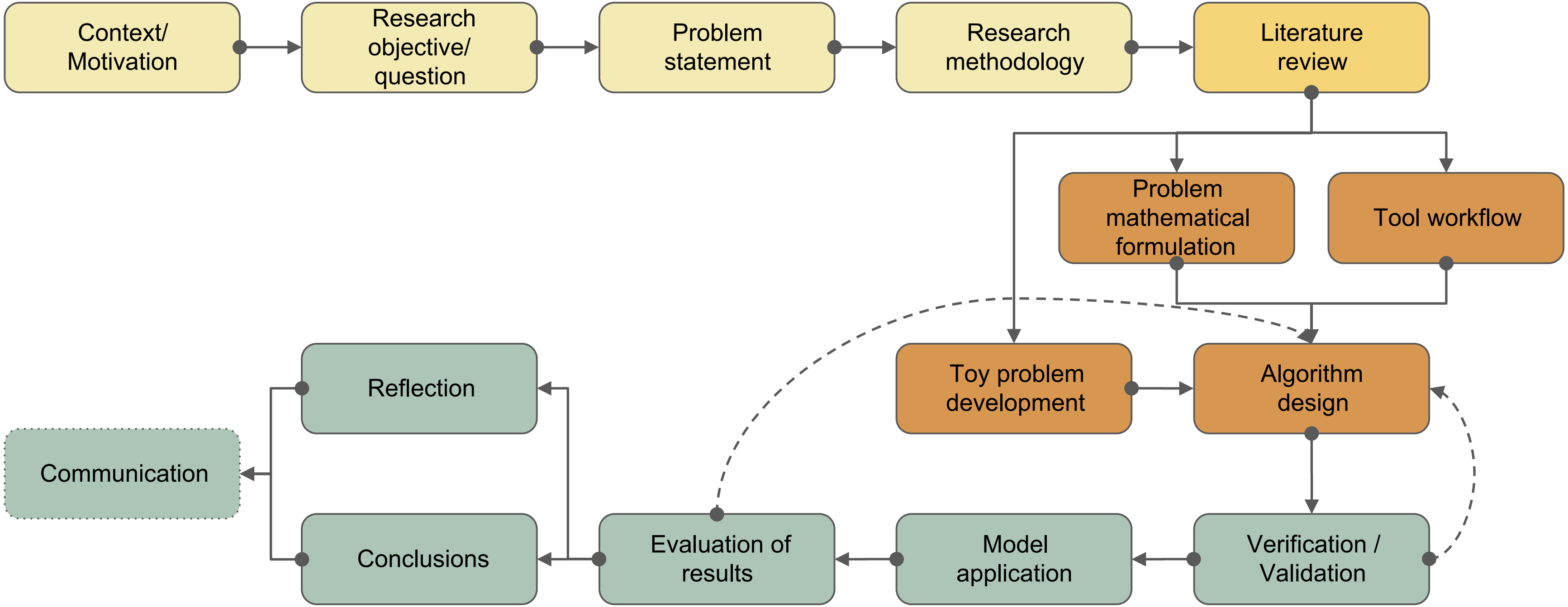
- How to translate the solar potential of a building to performance criteria?
- How to define the most important criteria for the early stage design?
- How to turn the performance criteria into performance indicators in order to evaluate them?
- How to validate such a computational framework / model?

RESEARCH SCOPE





RESEARCH METHODOLOGY

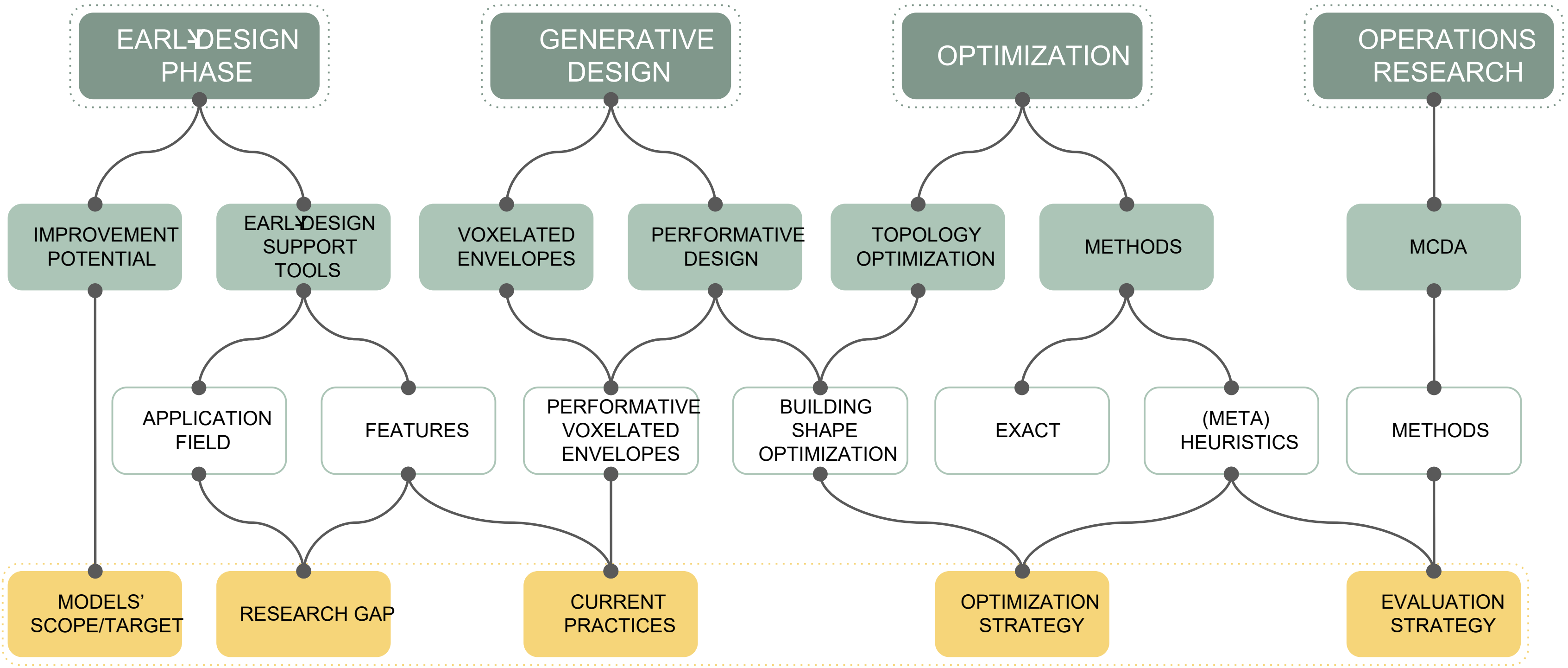


02

LITERATURE REVIEW

Early-design phase
Design support tools
Building shape
Multi-criteria decision analysis
Voxel-based envelopes

TAXONOMY



EARLY-DESIGN PHASE

GENERATIVE DESIGN

OPTIMIZATION

OPERATIONS RESEARCH

IMPROVEMENT POTENTIAL

EARLY-DESIGN SUPPORT TOOLS

VOXELATED ENVELOPES

PERFORMATIVE DESIGN

TOPOLOGY OPTIMIZATION

METHODS

MCDA

APPLICATION FIELD

FEATURES

PERFORMATIVE VOXELATED ENVELOPES

BUILDING SHAPE OPTIMIZATION

EXACT

(META) HEURISTICS

METHODS

MODELS' SCOPE/TARGET

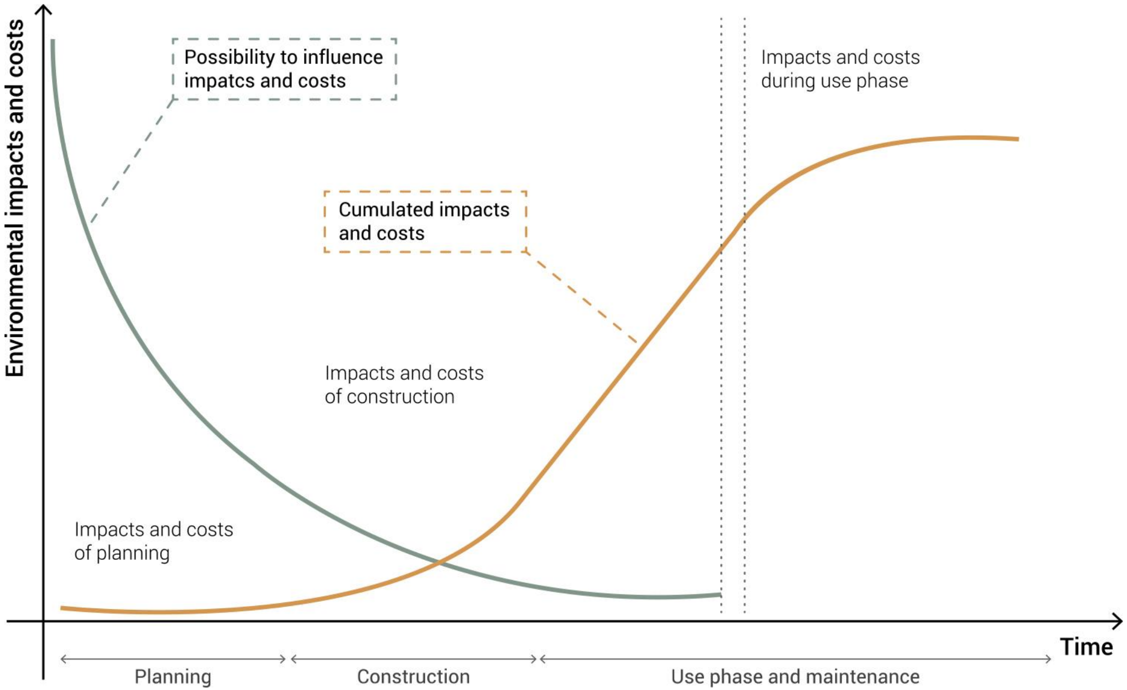
RESEARCH GAP

CURRENT PRACTICES

OPTIMIZATION STRATEGY

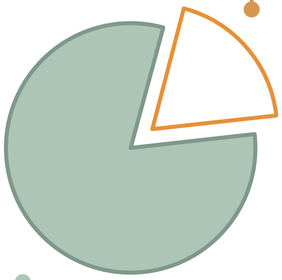
EVALUATION STRATEGY

EARLY DESIGN DECISIONS



Influence of design decisions on life cycle impacts and costs (according to N. Kohler and S. Moffatt)[2]

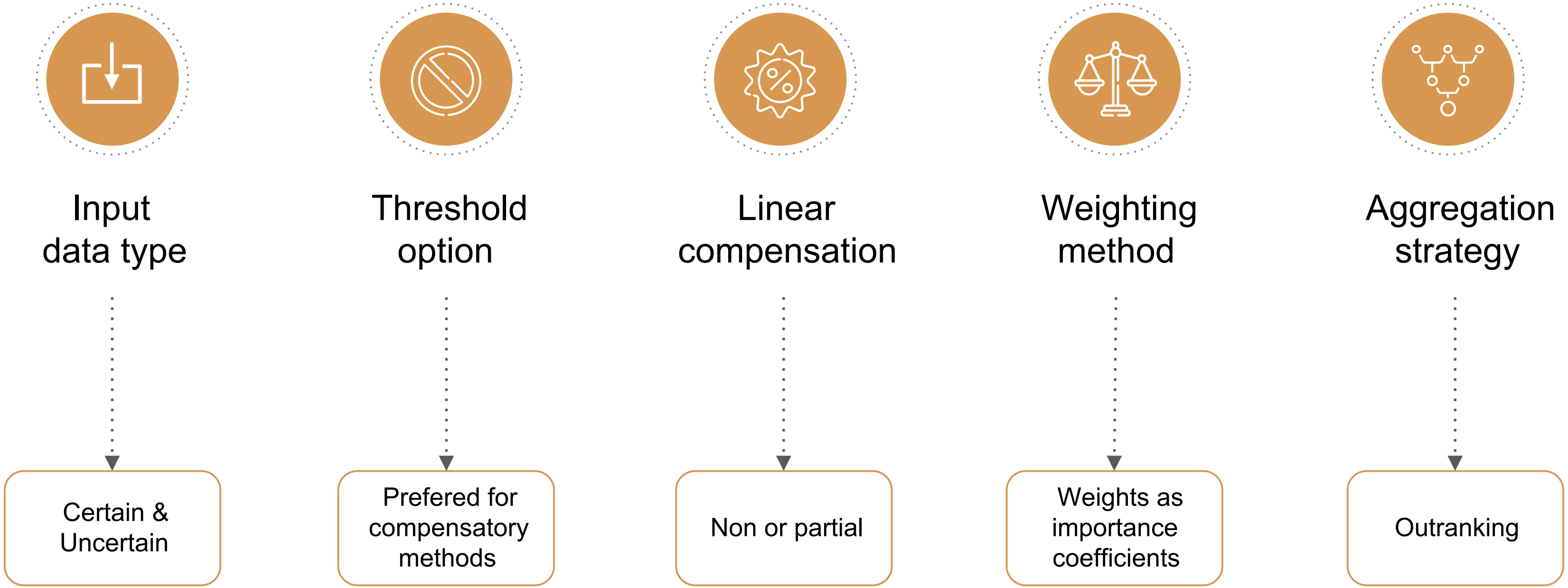
20%
Early-design decisions



80%
Final design decisions[1]

MULTI-CRITERIA DECISION ANALYSIS

Important features



Input data type → Certain & Uncertain

Threshold option → Prefered for compensatory methods

Linear compensation → Non or partial

Weighting method → Weights as importance coefficients

Aggregation strategy → Outranking

VOXEL-GENERATED ENVELOPE MODELS

✓

- analysis of the unoccupied space
- visualization of directionality of physical properties
- possibility to explore the design space interactively
- framework as a suggestive mechanism for form generation

✗

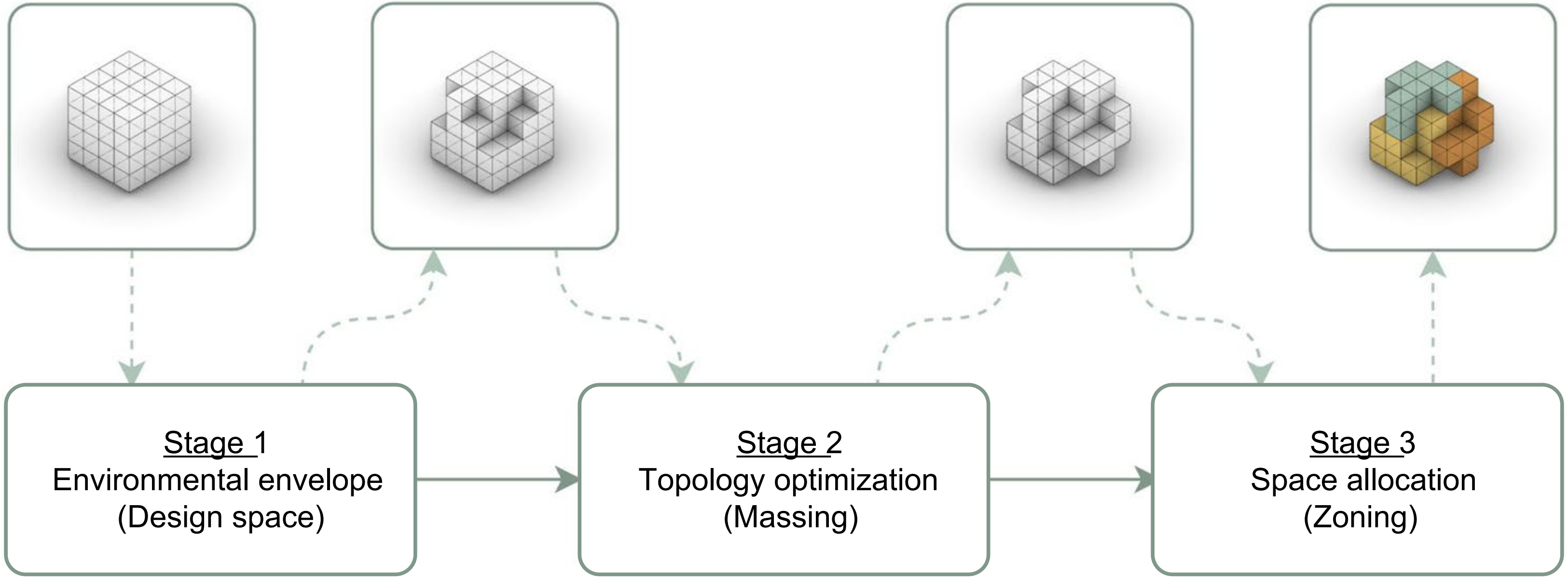
- high computation power and time demand
- lack of clear problem formulation
- interdependencies of elements not taken into account
- mostly dependent on existing simulation software

03

PROPOSED METHODOLOGY

General Framework
Problem formulation
Mathematical representation
Methodology
Algorithm design

GENERAL FRAMEWORK

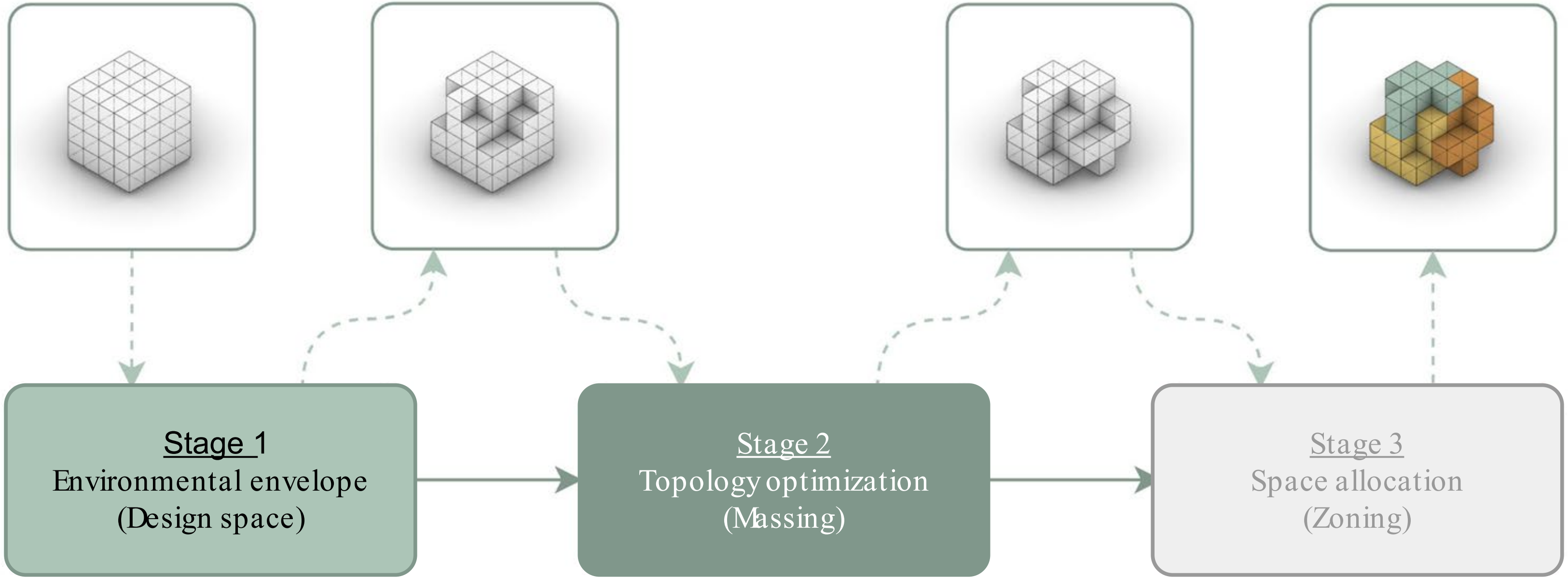


Stage 1
Environmental envelope
(Design space)

Stage 2
Topology optimization
(Massing)

Stage 3
Space allocation
(Zoning)

GENERAL FRAMEWORK



STAGE 1

SOLAR ENVELOPE

PROBLEM FORMULATION

> *"Given a specific location (plot and context) and a building code,
> it is sought to define the minimum voxels that need to be removed,
> in order for the surrounding facades to receive at least
> the minimum permitted direct sunlight hours."*

STAGE 1

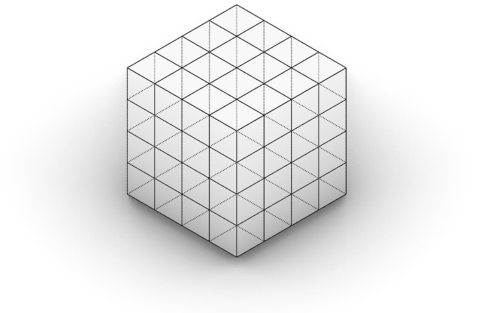
PROBLEM FORMULATION

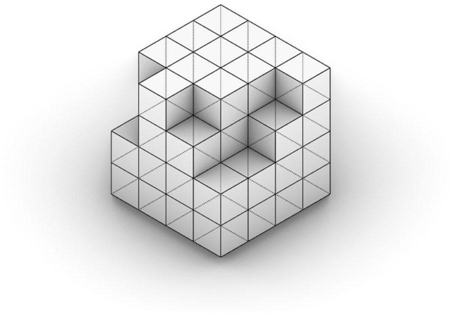
Input

- location data (plot & context)
- time frame
- building regulations

Output

- set of voxels allowing the surrounding facades to receive the minimum sunlight hours



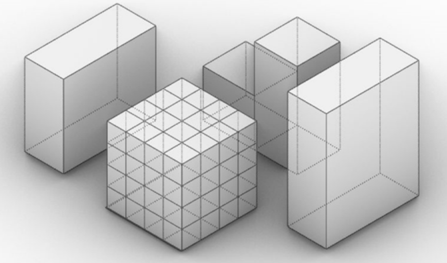


STAGE 1

METHODOLOGY

Step 1

Voxelate maximum buildable volume



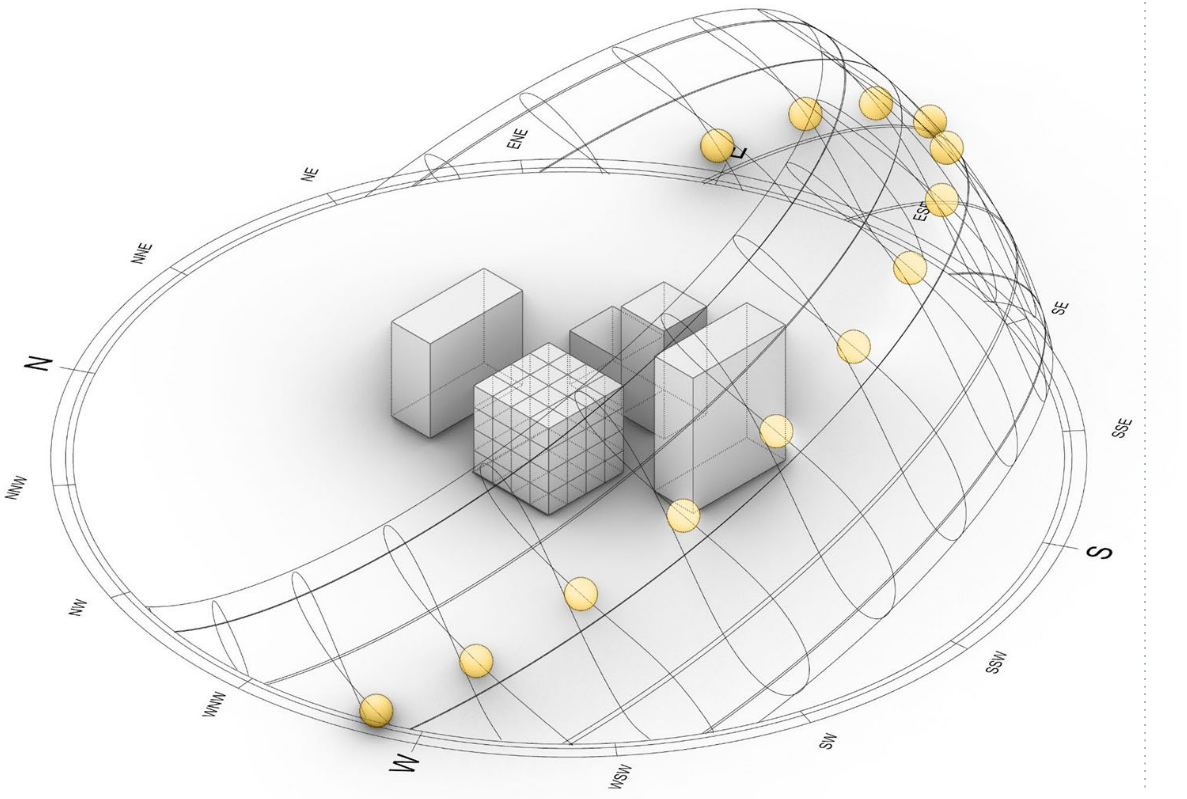
STAGE 1

METHODOLOGY

Step 2

insert regulations’ time-frame

create sunpath according to time-frame and time step



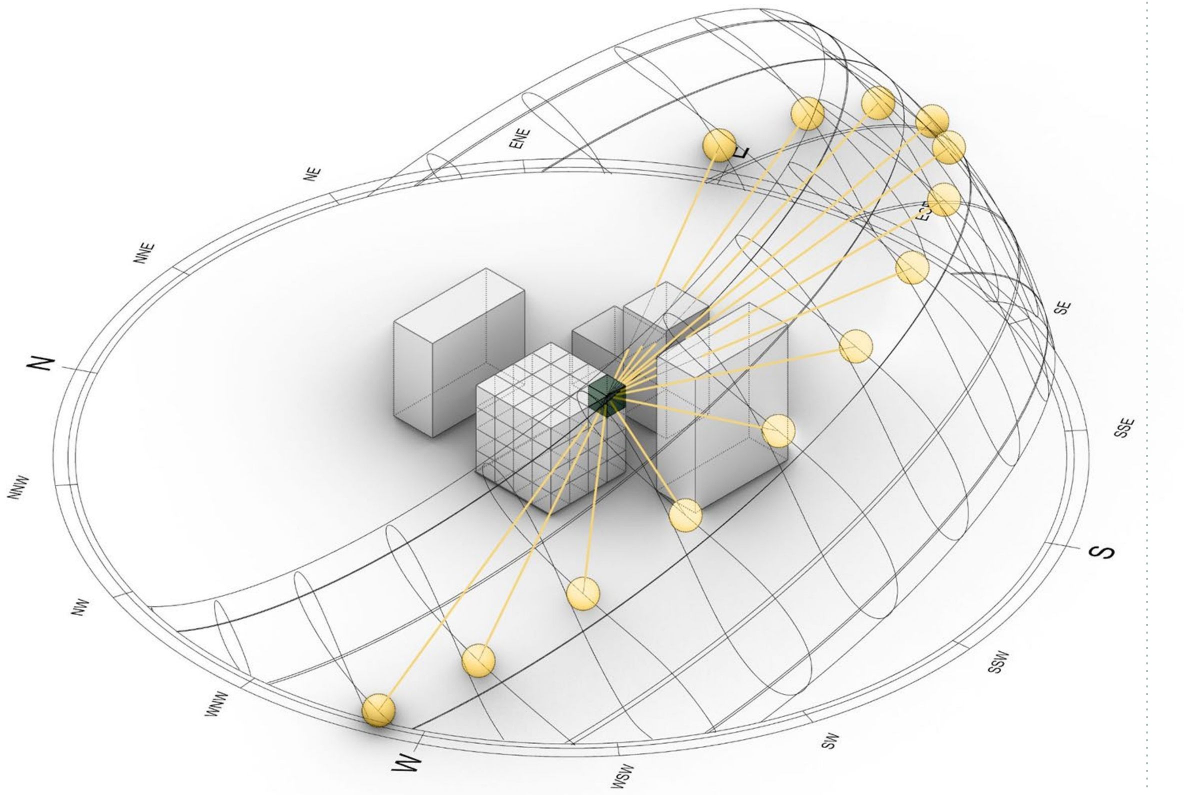
STAGE 1

METHODOLOGY

Step 3

for each voxel:

shoot rays from centroid towards the sun objects

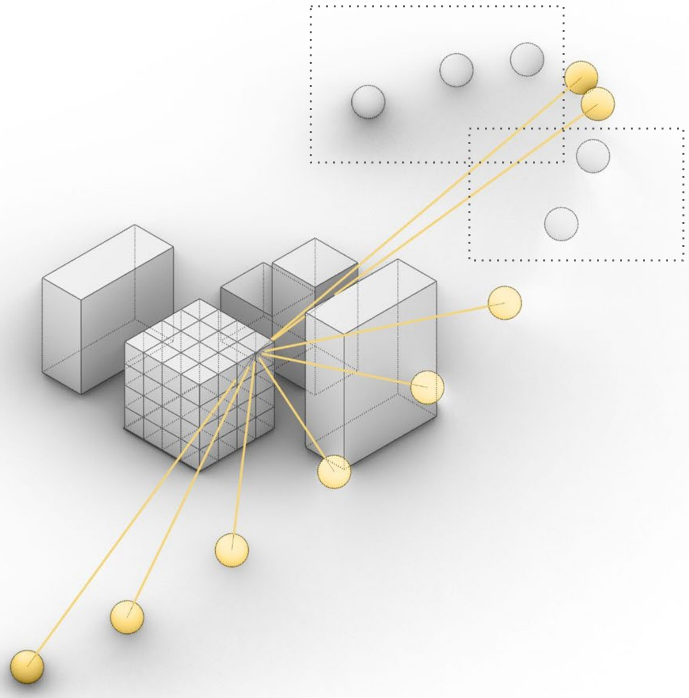


STAGE 1

METHODOLOGY

Step 4

discard the rays which are obstructed by the context



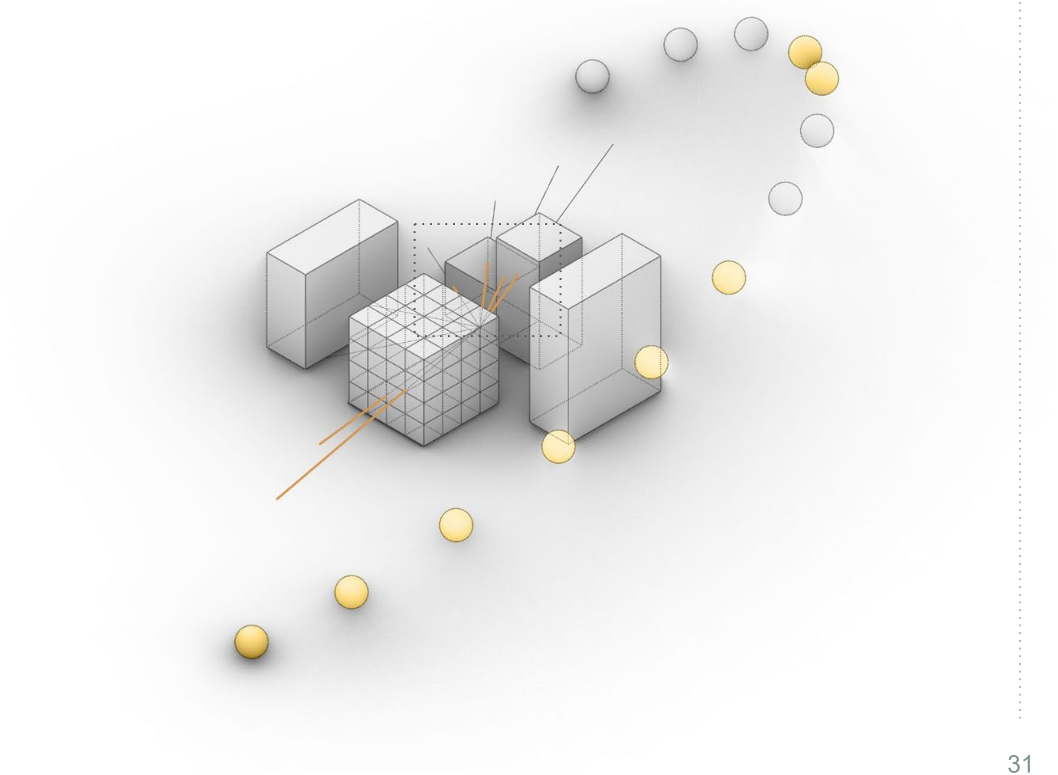
STAGE 1

METHODOLOGY

Step 5

for the remaining rays:

shoot backwards and check the intersection with the context

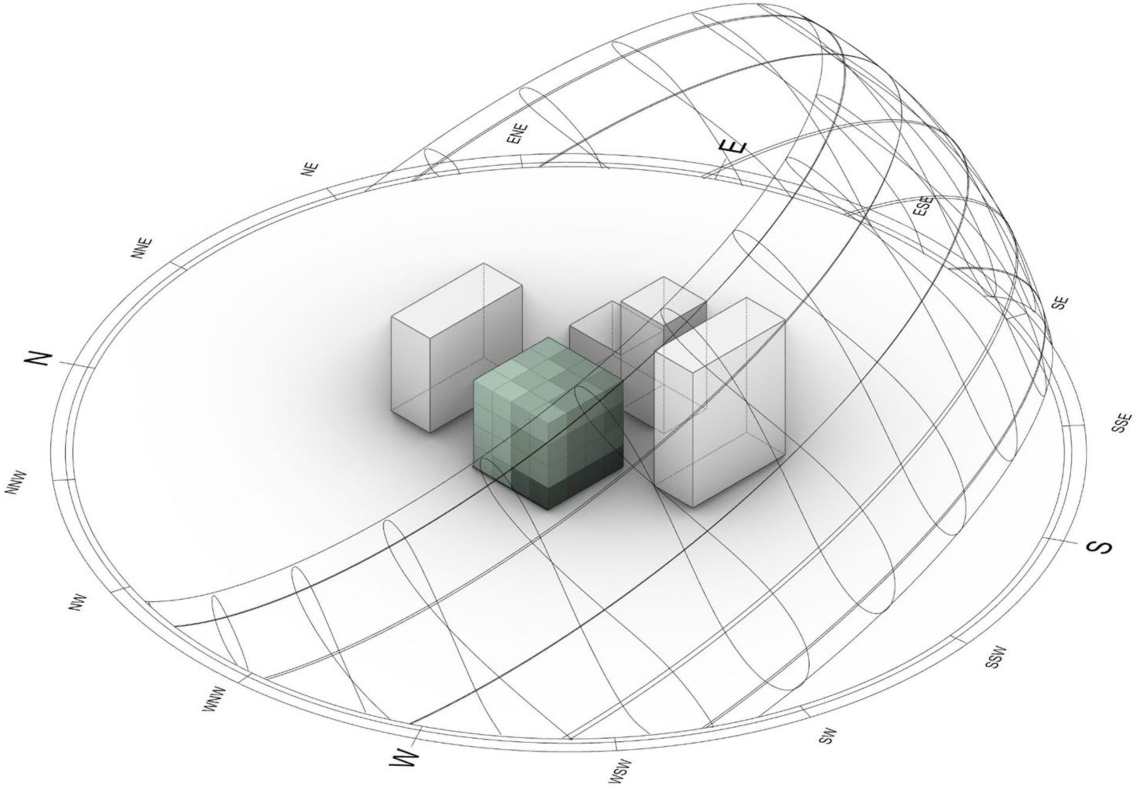


STAGE 1

METHODOLOGY

Step 6

aggregate sun obstruction
hours per voxel per day

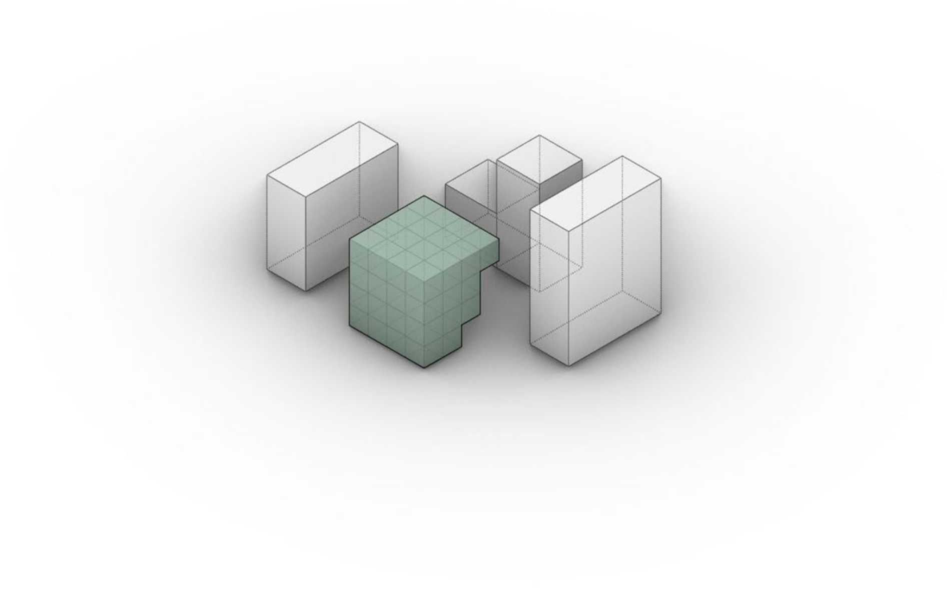


STAGE 1

METHODOLOGY

Step 7

remove the voxels that do not comply with building regulations



STAGE 1

STAGE 2

MASSING

PROBLEM FORMULATION

> *"Given a specific location and a building's programme of requirements,*
> *indicating the minimum area needed, it is sought to find*
> *an envelope topology (and thus shape) of a nearly optimal solar potential,*
> *according to the following objectives and constraints:"*

STAGE 2

PROBLEM FORMULATION

Objectives

- maximize the aggregated Direct Normal Solar Irradiation
- maximize the aggregated Direct Normal Solar Illumination
- maximize the Direct Skylight factor
- maximize compactness

Constraints

- the total remaining area must be at least equal to the minimum needed area (PoR)
- the total remaining area must not exceed the maximum allowed floor space

PROBLEM FORMULATION

Objectives

Solar Potential

- maximize the aggregated *Direct Normal Solar Irradiat*
- maximize the aggregated *Direct Normal Solar Illuminat*
- maximize the *Direct Skylight Ho*
- maximize compactness

Constraints

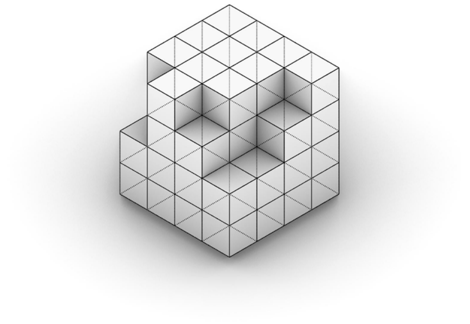
- the total remaining area must be at least equal to the minimum needed area (PoR)
- the total remaining area must not exceed the maximum allowed floor space

STAGE 2

PROBLEM FORMULATION

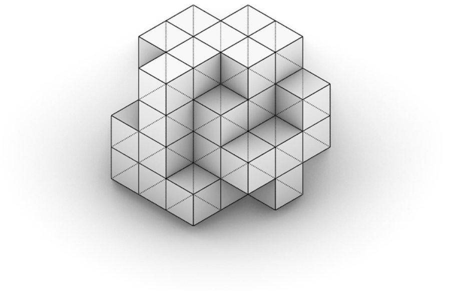
Input

- location data
- minimum area needed (PoR)
- design bounds (solar envelope)
- optimization target



Output

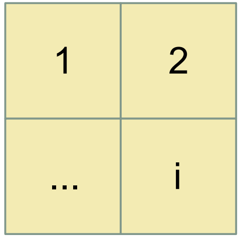
- set of voxels approximating the envelope shape of nearly-optimal solar potential



STAGE 2

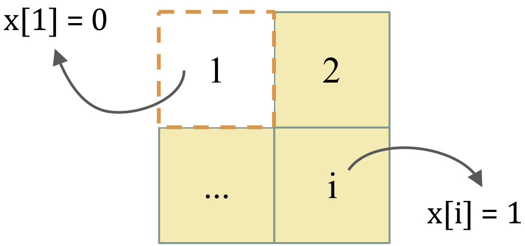
MATHEMATICAL REPRESENTATION

Design Spac



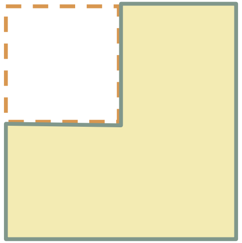
all the discrete elements*i*,
$i \in [0,n)$

Element Opacity



i can take 2 values
0: unoccupied
1: occupied

Transparency Vecto

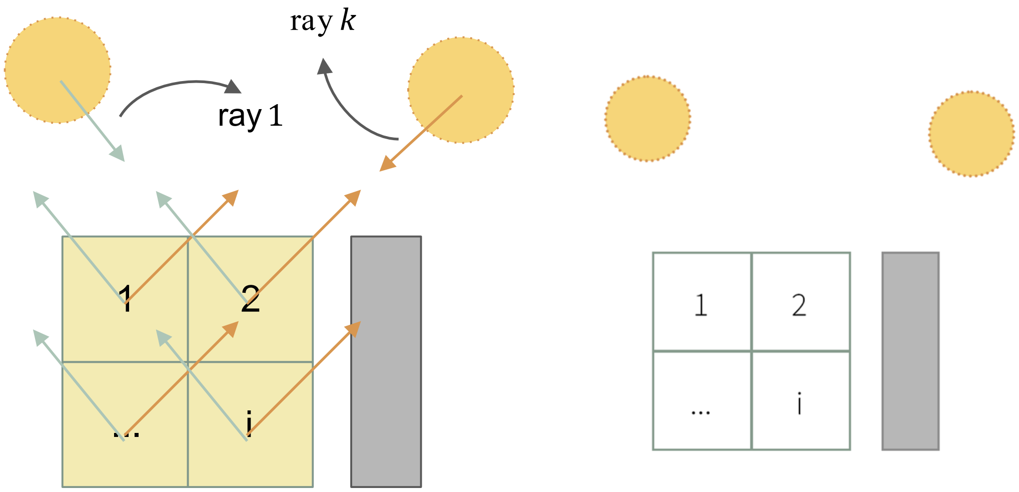


x_j represents one possible envelope shape
$x_j = [0\ 1\ 1\ 1]$

STAGE 2

MATHEMATICAL REPRESENTATION

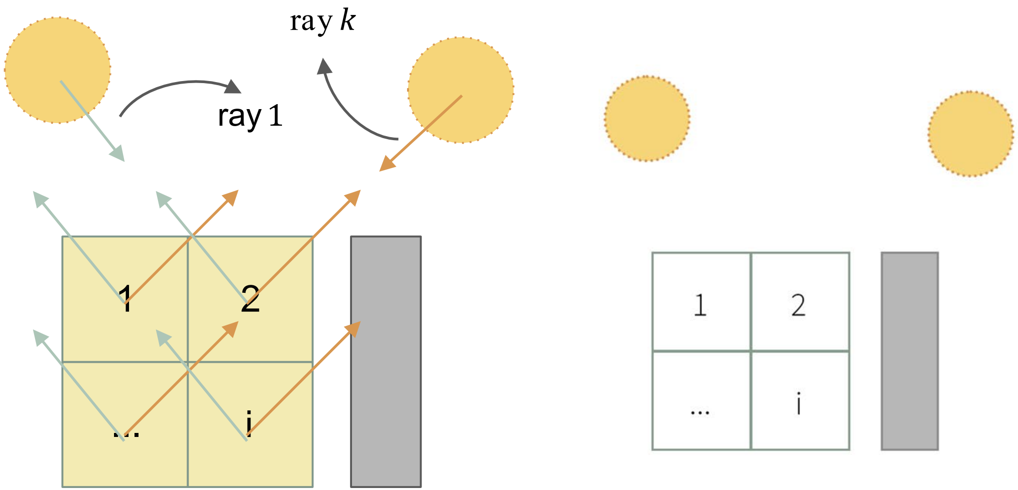
Intervisibilities Graph



$$\Omega = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 & 0 \\ 3 & 0 & 0 & 0 & 0 \\ n & 0 & 0 & 0 & 0 \end{array} \quad \begin{array}{cccc} 1 & 2 & 3 & n \\ \hline 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{array}$$

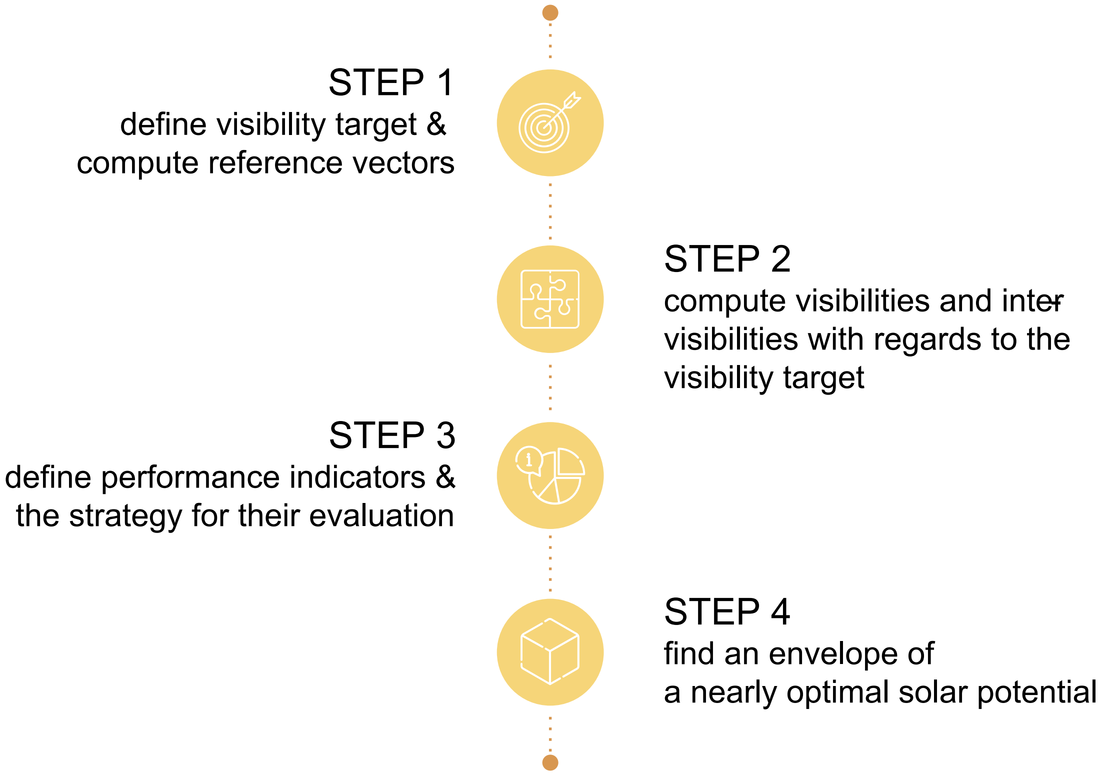
MATHEMATICAL REPRESENTATION

Unobstructed Rays Matr



$$U = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 0 & 0 & 0 & 0 \\ m & 0 & 0 & 0 & 0 \end{array}$$

METHODOLOGY



STEP 1
define visibility target &
compute reference vectors

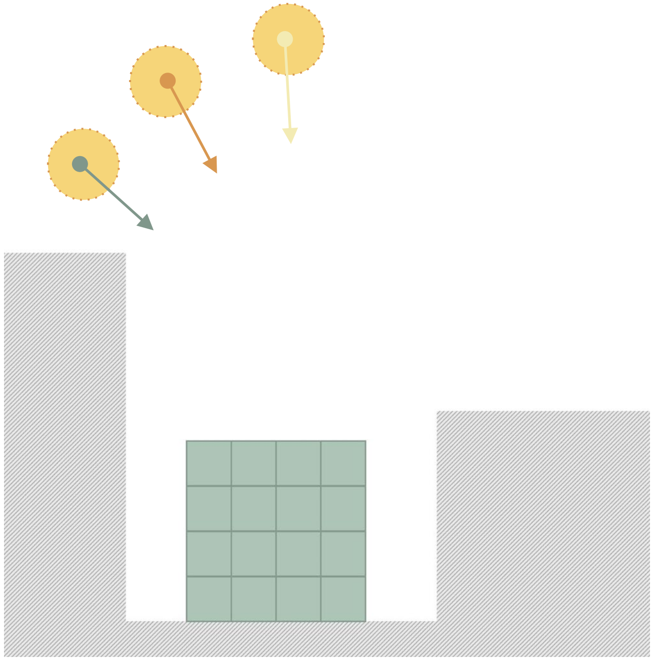
STEP 2
compute visibilities and inter-visibilities with regards to the
visibility target

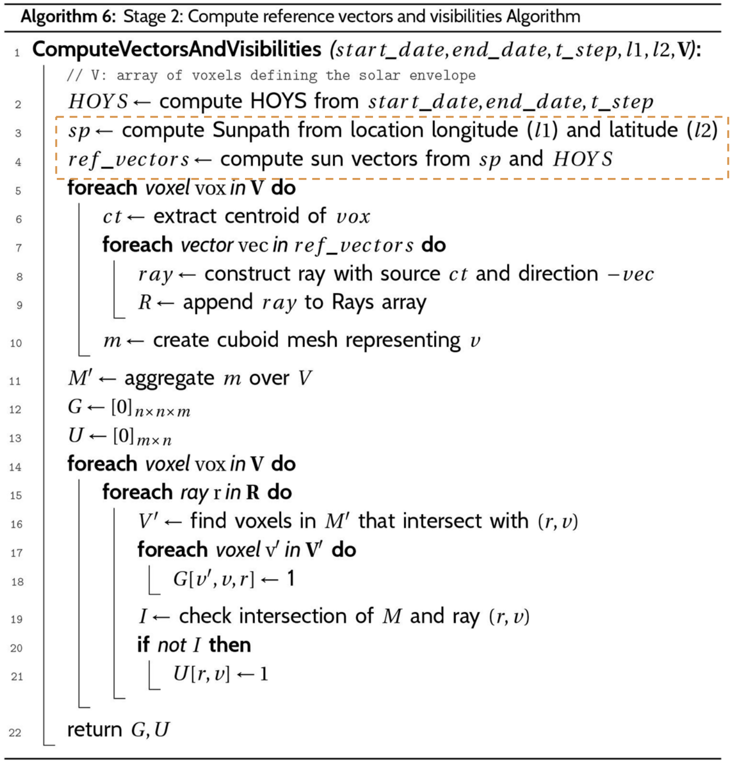
STEP 3
define performance indicators &
the strategy for their evaluation

STEP 4
find an envelope of
a nearly optimal solar potential

STAGE 2

METHODOLOGY_Step1



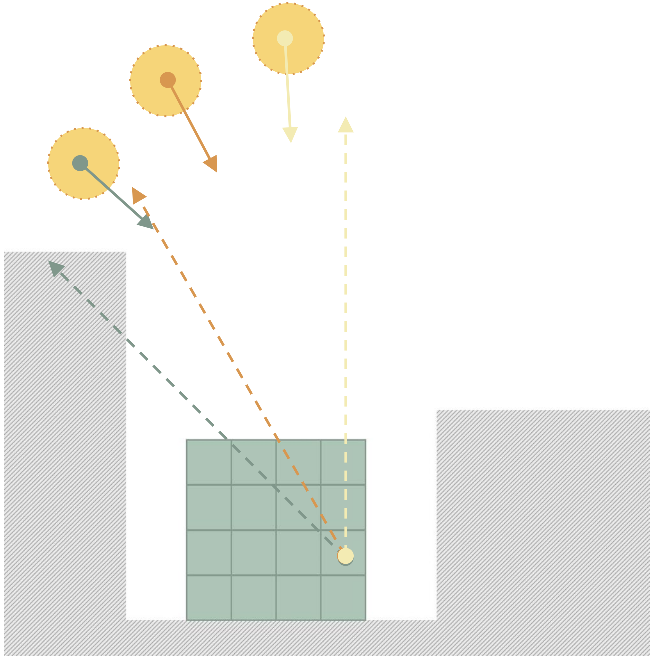


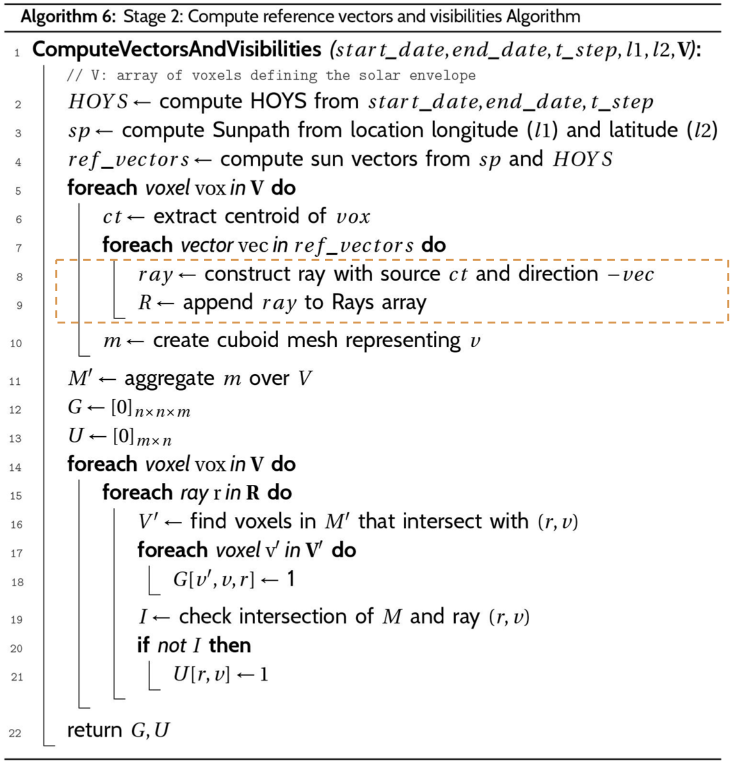
Algorithm 6: Stage 2: Compute reference vectors and visibilities Algorithm

```
ComputeVectorsAndVisibilities ($start\_date, end\_date, t\_step, l1, l2, \mathbf{V}$):
    // V: array of voxels defining the solar envelope
    $HOYS \leftarrow$ compute HOYS from $start\_date, end\_date, t\_step$
    $sp \leftarrow$ compute Sunpath from location longitude ($l1$) and latitude ($l2$)
    $ref\_vectors \leftarrow$ compute sun vectors from $sp$ and $HOYS$
    foreach voxel vox in V do
        $ct \leftarrow$ extract centroid of $vox$
        foreach vector vec in $ref\_vectors$ do
            $ray \leftarrow$ construct ray with source $ct$ and direction $-vec$
            $R \leftarrow$ append $ray$ to Rays array
        $m \leftarrow$ create cuboid mesh representing $v$
    $M' \leftarrow$ aggregate $m$ over $V$
    $G \leftarrow [0]_{n \times n \times m}$
    $U \leftarrow [0]_{m \times n}$
    foreach voxel vox in V do
        foreach ray r in R do
            $V' \leftarrow$ find voxels in $M'$ that intersect with $(r, v)$
            foreach voxel v' in V' do
                $G[v', v, r] \leftarrow 1$
            $I \leftarrow$ check intersection of $M$ and ray $(r, v)$
            if not $I$ then
                $U[r, v] \leftarrow 1$
    return $G, U$
```

STAGE 2

METHODOLOGY_Step2





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    foreach voxel vox in $\mathbf{V}$ do
        foreach ray r in $\mathbf{R}$ do
            $V' \leftarrow$ find voxels in $M'$ that intersect with $(r, v)$
            foreach voxel v' in $\mathbf{V}'$ do
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            $I \leftarrow$ check intersection of $M$ and ray $(r, v)$
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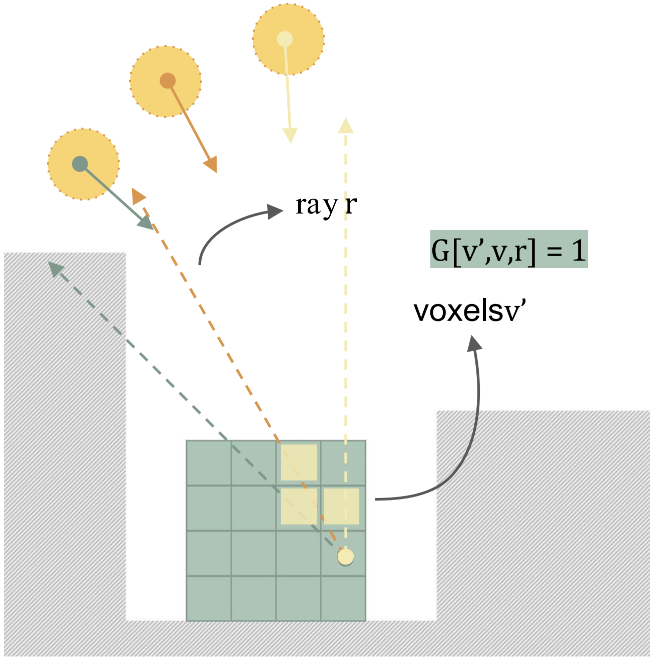
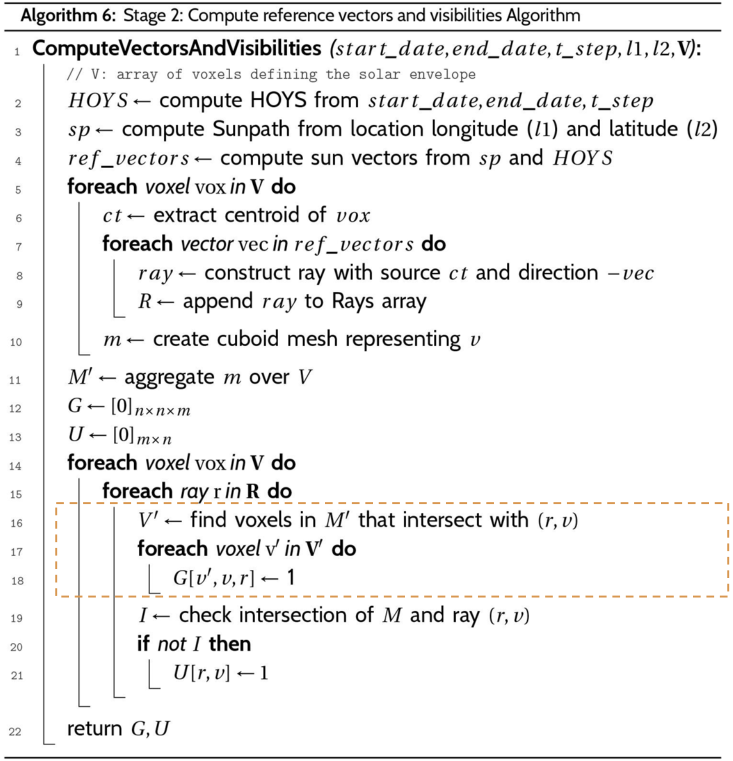
```

STAGE 2

METHODOLOGY_Step2





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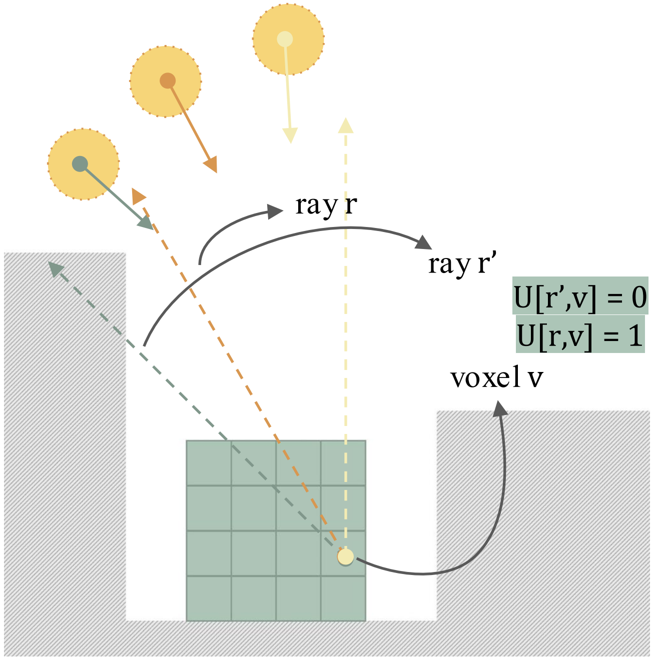
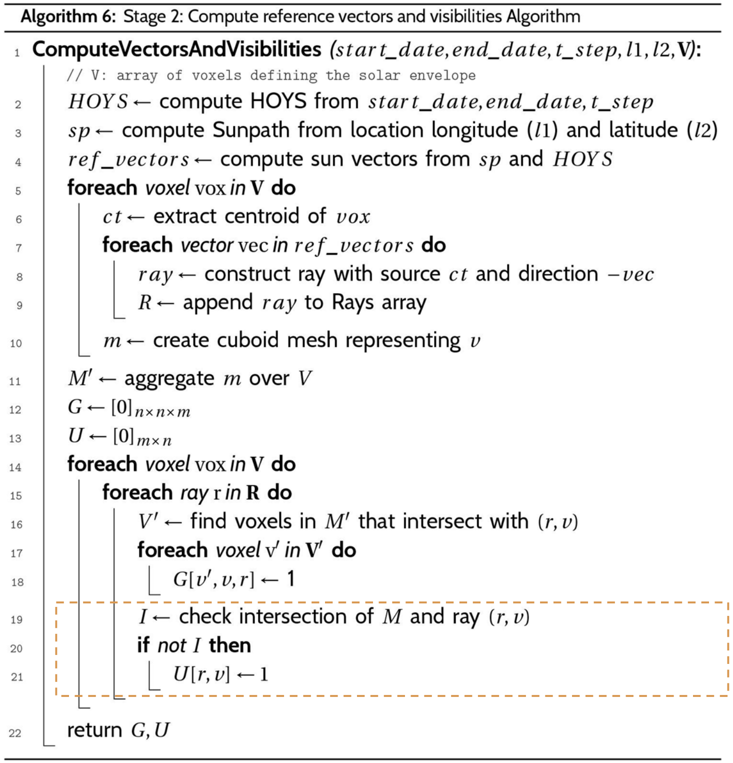
STAGE 2

METHODOLOGY_Step2



STAGE 2



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            if not $I$ then
                $U[r, v] \leftarrow 1$
    return $G, U$
```

METHODOLOGY_Step3

Ray-defined factors

(e.g. Direct Normal Irradiation)

$$f(\mathbf{x}) = (\mathbf{G},\mathbf{U},\mathbf{x},\mathbf{w})$$

U: rays visibility matrix
G: intervisibilities graph
x: transparency vector
w: ray weights

Shape-related factors

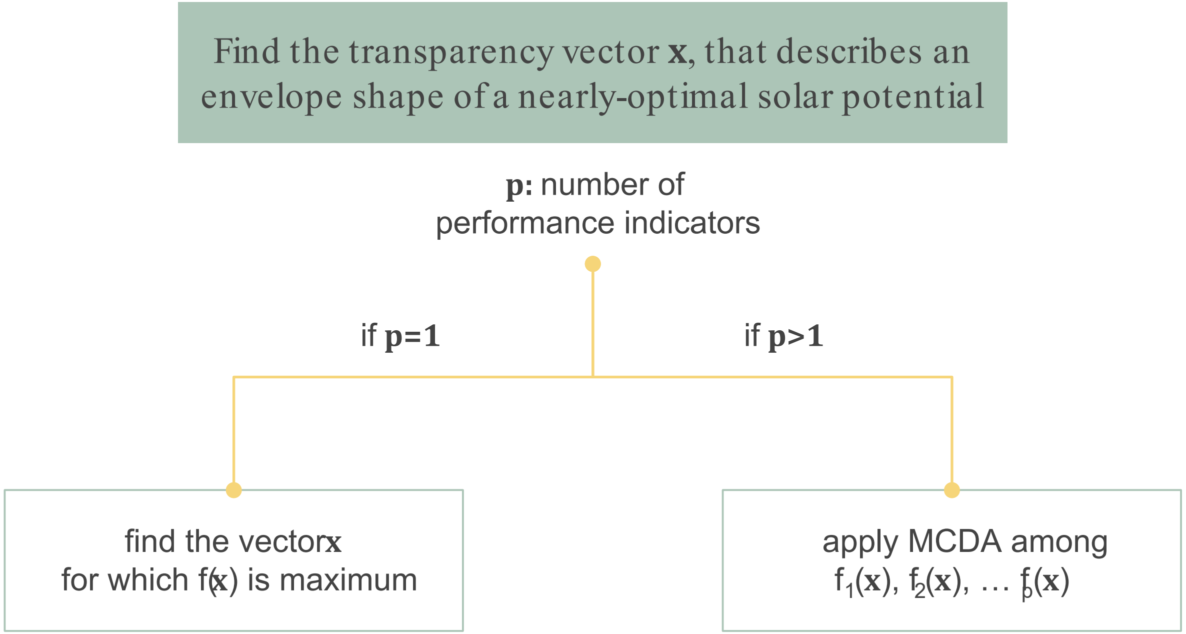
(e.g. Relative Compactness)

$$f_{rc}(\mathbf{x}) = 6*(V(\mathbf{x}))^{2/3}/A(\mathbf{x})$$

A(x): total surface of exterior faces
V(x): volume inclosed in these faces

STAGE 2

METHODOLOGY_Step4



Find the transparency vector **x**, that describes an envelope shape of a nearly-optimal solar potential

p: number of performance indicators

if **p=1**

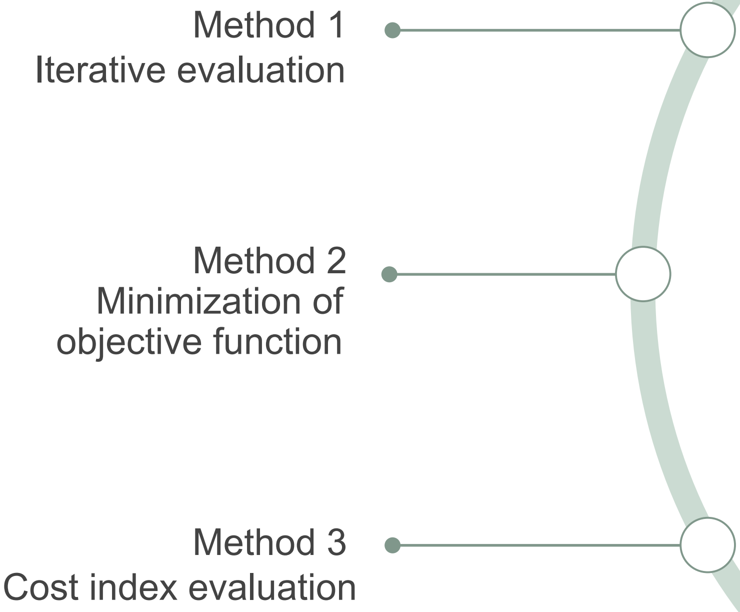
if **p>1**

find the vector**x** for which f(**x**) is maximum

apply MCDA among $f_1(\mathbf{x})$, $f_2(\mathbf{x})$, … $f_p(\mathbf{x})$

STAGE 2

METHODOLOGY_Step4



Method 1
Iterative evaluation

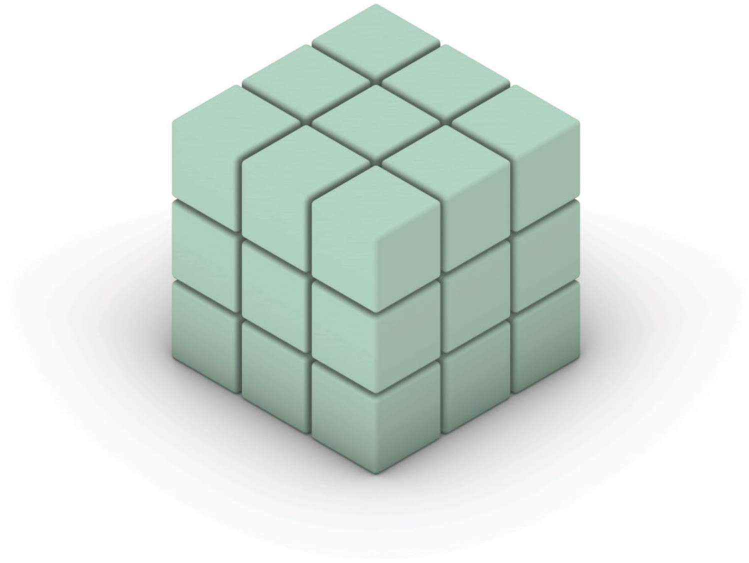
Method 2
Minimization of
objective function

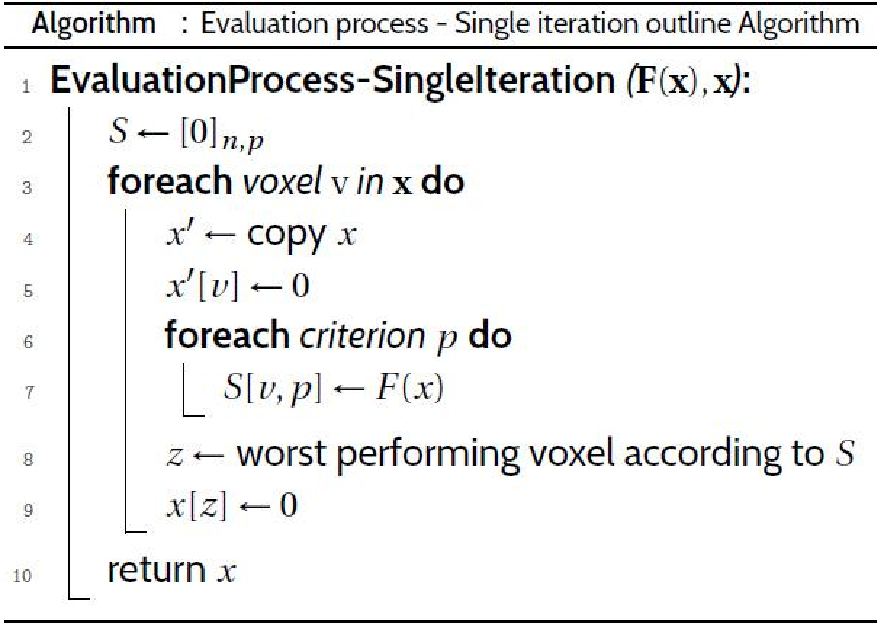
Method 3
Cost index evaluation

STAGE 2

METHODOLOGY_Step4

Method 1: Iterative evaluatio





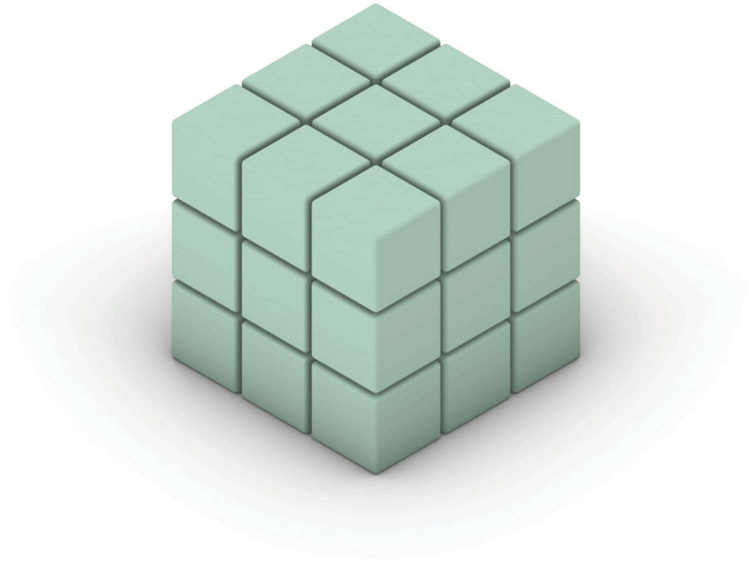
Algorithm : Evaluation process - Single iteration outline Algorithm

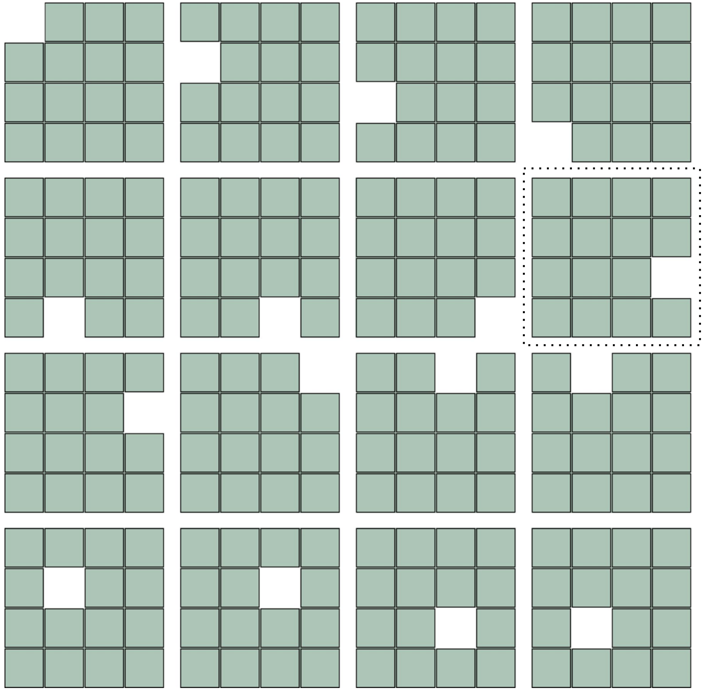
```
EvaluationProcess-SingleIteration ($\mathbf{F}(\mathbf{x}), \mathbf{x}$):
    $S \leftarrow [0]_{n,p}$
    foreach voxel v in x do
        $x' \leftarrow$ copy $x$
        $x'[v] \leftarrow 0$
        foreach criterion $p$ do
            $S[v,p] \leftarrow F(x)$
        $z \leftarrow$ worst performing voxel according to $S$
        $x[z] \leftarrow 0$
    return $x$
```

STAGE 2

METHODOLOGY_Step4

Method 1: Iterative evaluatio

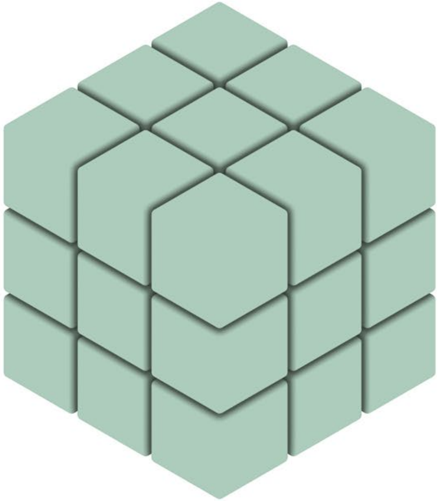


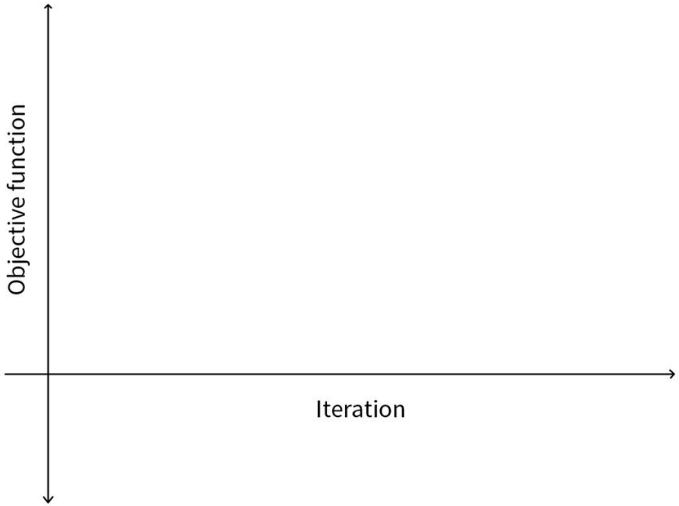


STAGE 2

METHODOLOGY_Step4

Method 2: Minimization of scalar objective functi





<u>Objective function</u>
f($\mathbf{x}$)

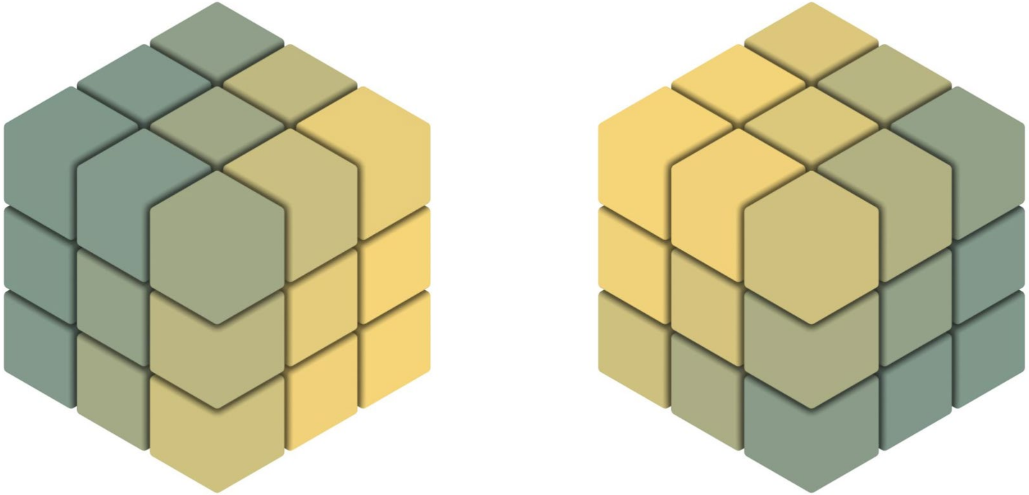
<u>Constraints</u>
sum($\mathbf{x}$) > min needed voxels

<u>Bounds</u>
x ∈ $[\mathbf{0},\mathbf{1}]$

STAGE 2

METHODOLOGY_Step4

Method 3: Cost index evaluatic



Obscuring index

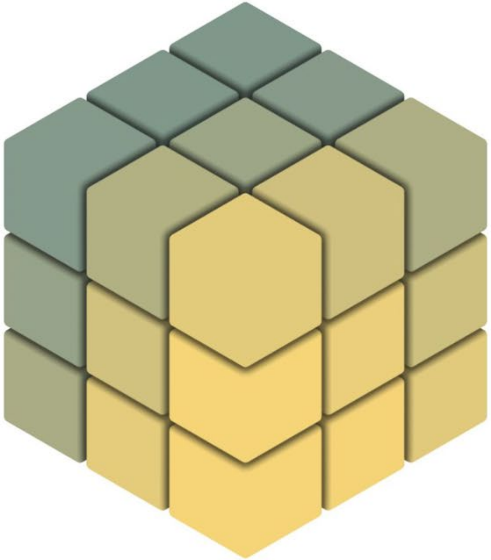
$$O_1 = [\mathbf{G}_{k,i,j}{}^{T}]_{mxnxn} \bullet [\mathbf{x}_i]_{nx1}$$

Obscured index

$$O_2 = [\mathbf{G}_{k,j,i}{}^{T}]_{mxnxn} \bullet [\mathbf{x}_i]_{nx1}$$

METHODOLOGY_Step4

Method 3: Cost index evaluatic



Obscuring index

$O_1 = [\mathbf{G}_{k,i,j}{}^{T}]_{mxnxn} \bullet [\mathbf{x}_i]_{nx1}$

Obscured index

$O_2 = [\mathbf{G}_{k,j,i}{}^{T}]_{mxnxn} \bullet [\mathbf{x}_i]_{nx1}$

Unobstructed rays

$(O_1 - O_2) \odot \mathbf{U}$

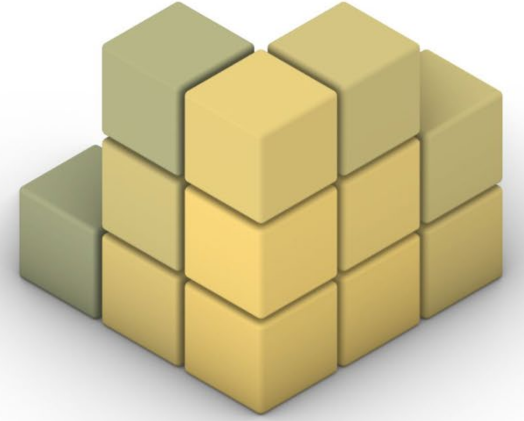
Cost index

$C(\mathbf{x}) = \mathbf{w}^{T}((O_1 - O_2) \odot \mathbf{U})$

STAGE 2

METHODOLOGY_Step4

Method 3: Cost index evaluatic



Obscuring index

$O_1 = [\mathbf{G}_{k,i,j}{}^{T}]_{mxnxn} \bullet [\mathbf{x}_i]_{nx1}$

Obscured index

$O_2 = [\mathbf{G}_{k,j,i}{}^{T}]_{mxnxn} \bullet [\mathbf{x}_i]_{nx1}$

Unobstructed rays

$(O_1 - O_2) \odot \mathbf{U}$

Cost index

$C(\mathbf{x}) = \mathbf{w}^{T}((O_1 - O_2) \odot \mathbf{U})$

STAGE 2

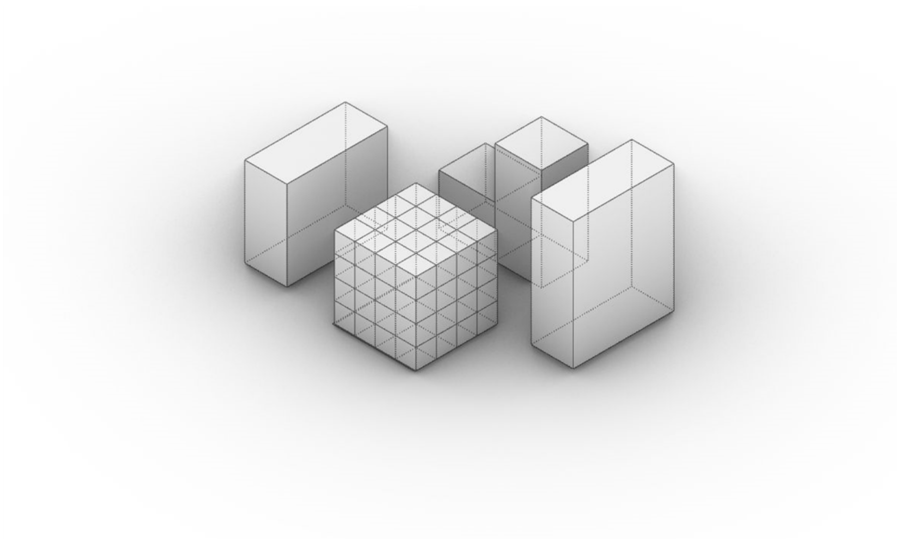
04

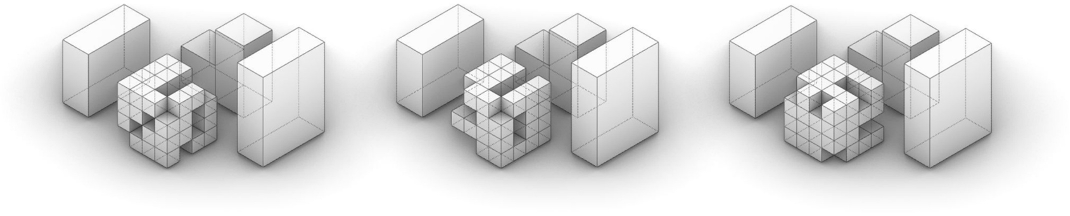
VERIFICATION & BENCHMARKING

Visibility Evaluation function
Combining Performance indicators
Diversity of results
Methods Comparison

VISIBILITY EVALUATION FUNCTION

Set-Up





VISIBILITY EVALUATION FUNCTION

Verification proces

PROCESS 1
(ray-mesh intersections)

- compute ray-mesh intersections
- assign weights (w) to rays
- aggregate scores in time and in space to reach a final score (s1a, s1b, s1c)

PROCESS 2
(vectorized computations)

- apply the visibility evaluation function to compute the final score (s2a, s2b, s2c)
- $f(x) = w^T(U \odot (J - \min(J, G^T x)))x$

s1 = s2

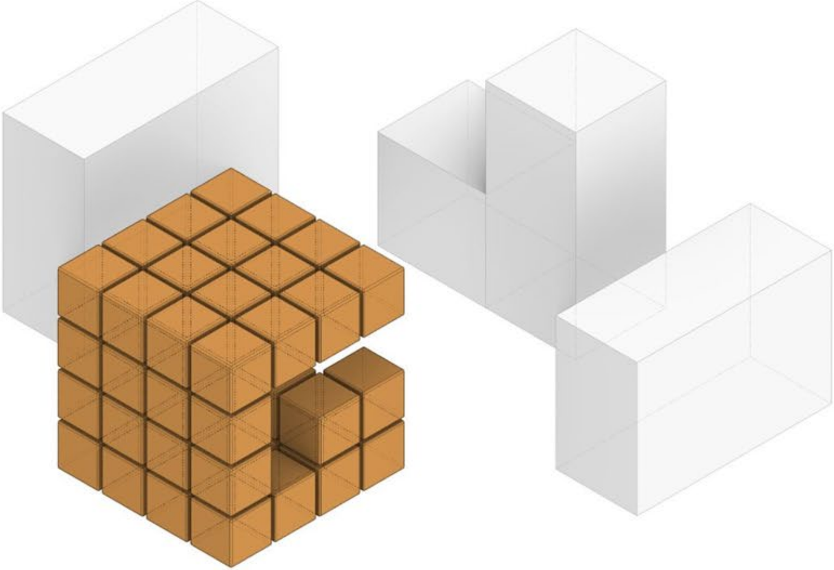
VISIBILITY EVALUATION FUNCTION

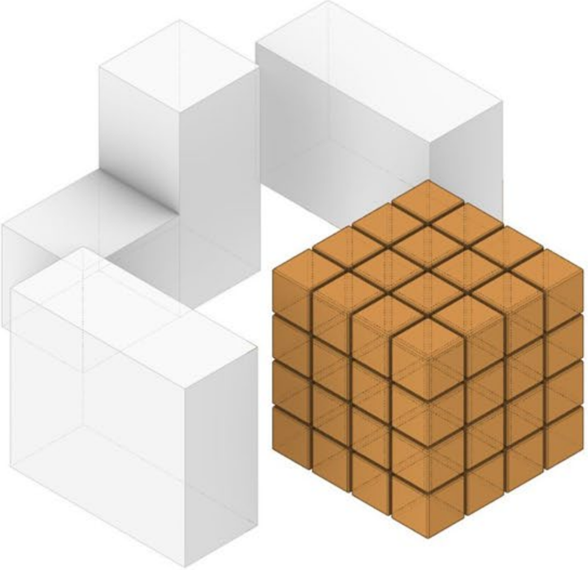
Time comparisor

Number of voxels	t1 - Process 1 [ms]	t2- Process 2 [ms]
64	1320	20
150	8240	125
340	404000	200

ITERATIVE EVALUATION_Combining Indicators

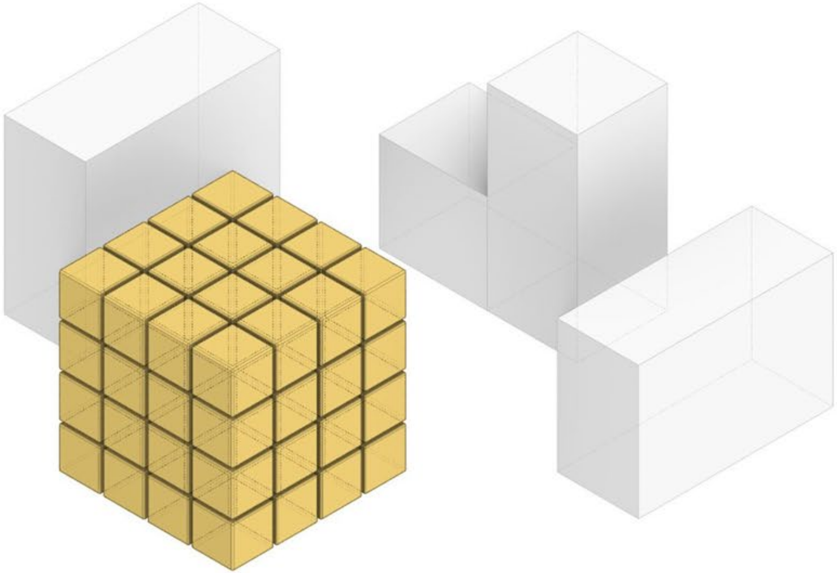
Performance Indicator 1: Direct Normal Irradiati

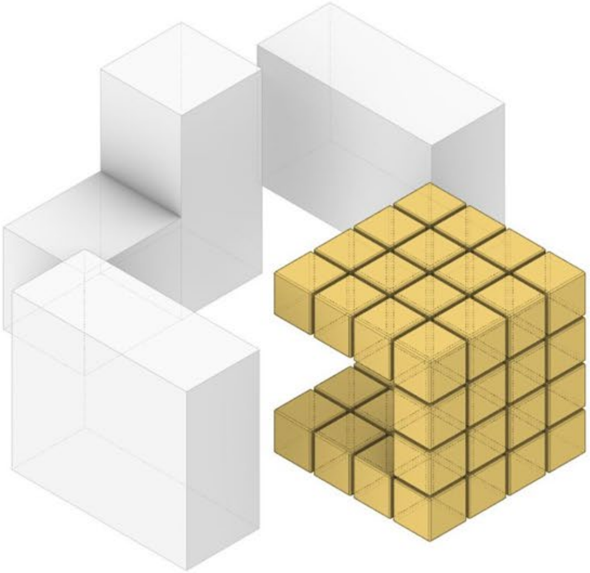




ITERATIVE EVALUATION_Combining Indicators

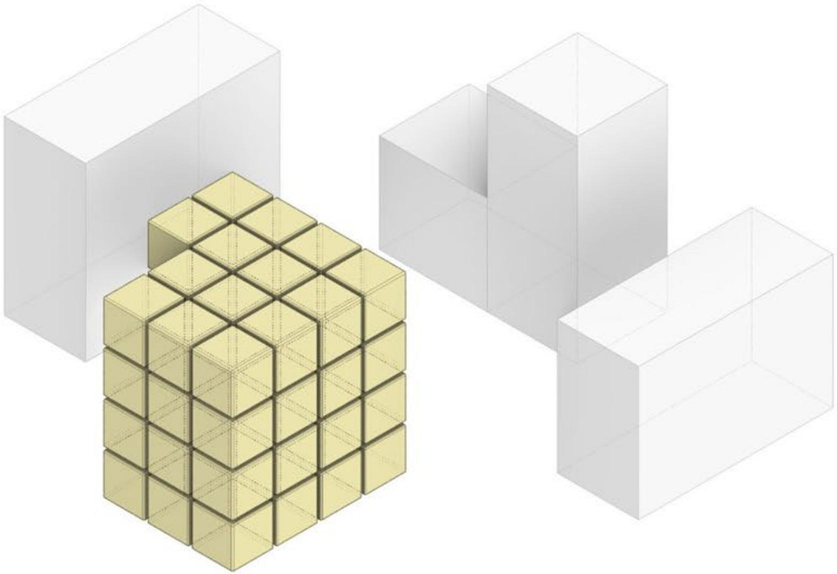
Performance Indicator 2: Direct Skylight fact

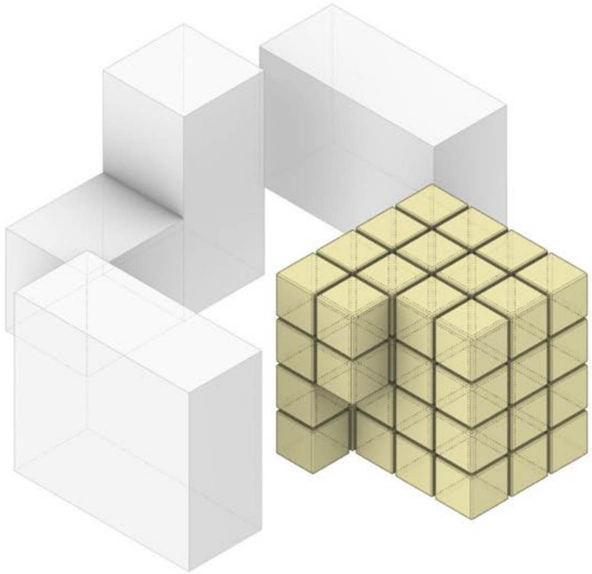




ITERATIVE EVALUATION_Combining Indicators

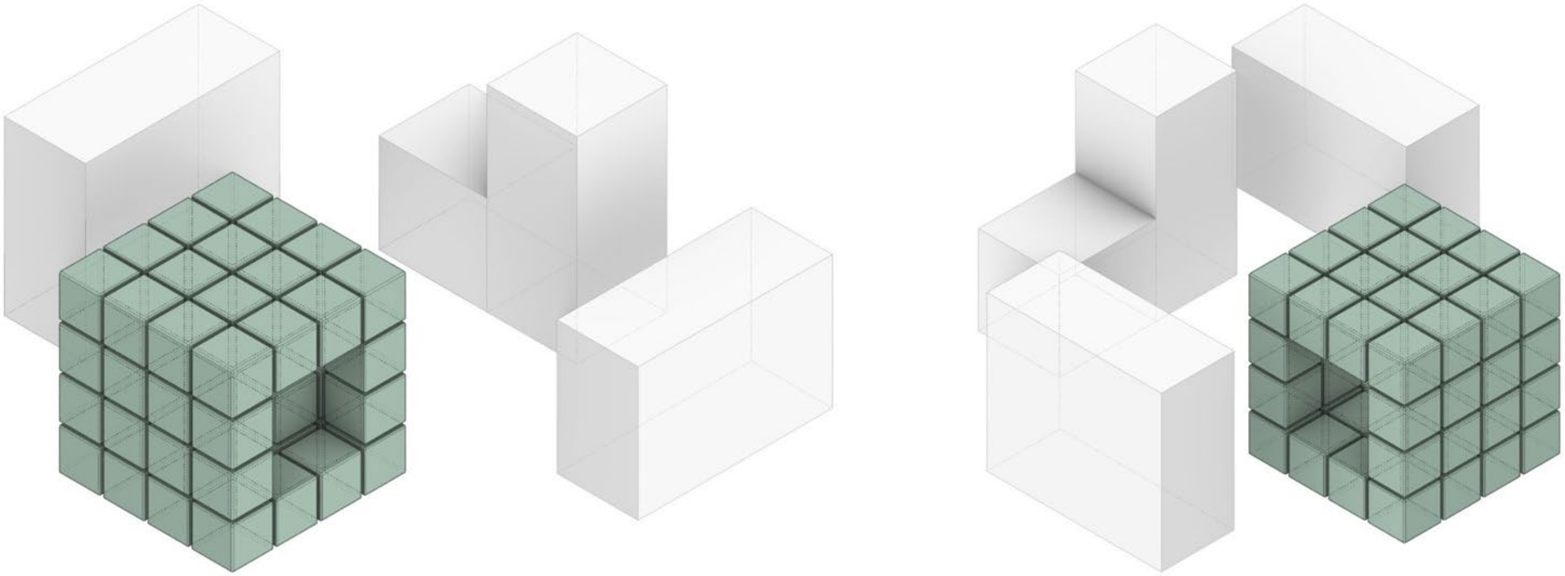
Performance Indicator 3: Relative Compactne





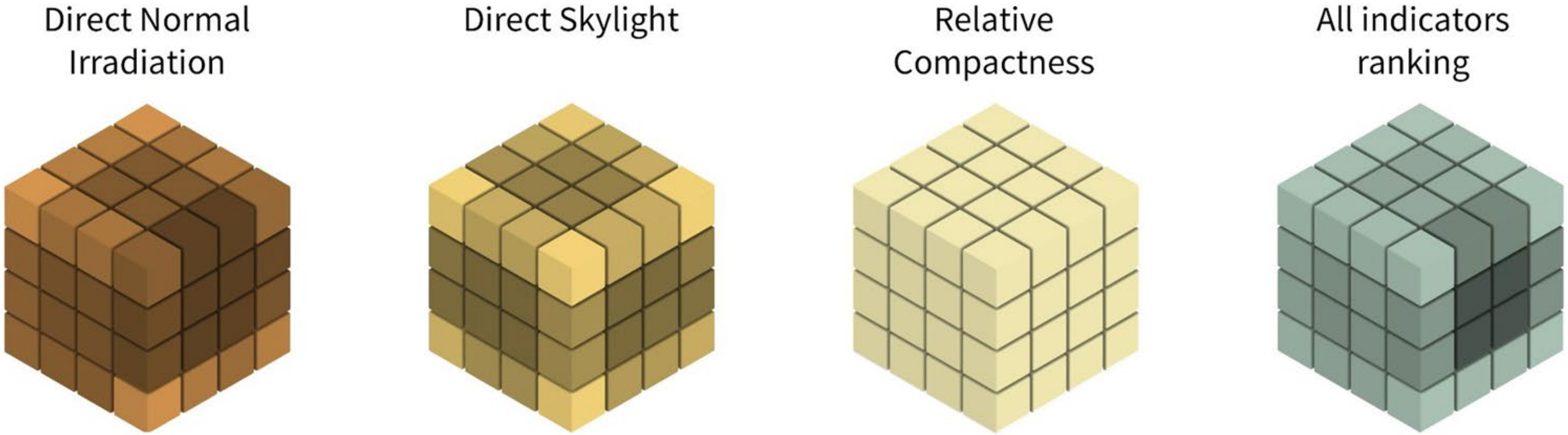
ITERATIVE EVALUATION_Combining Indicators

Combining indicators- MCDA



ITERATIVE EVALUATION_Combining Indicators

Ranking per indicato



Direct Normal Irradiation

Direct Skylight

Relative Compactness

All indicators ranking

DIVERSITY OF RESULTS

Variables

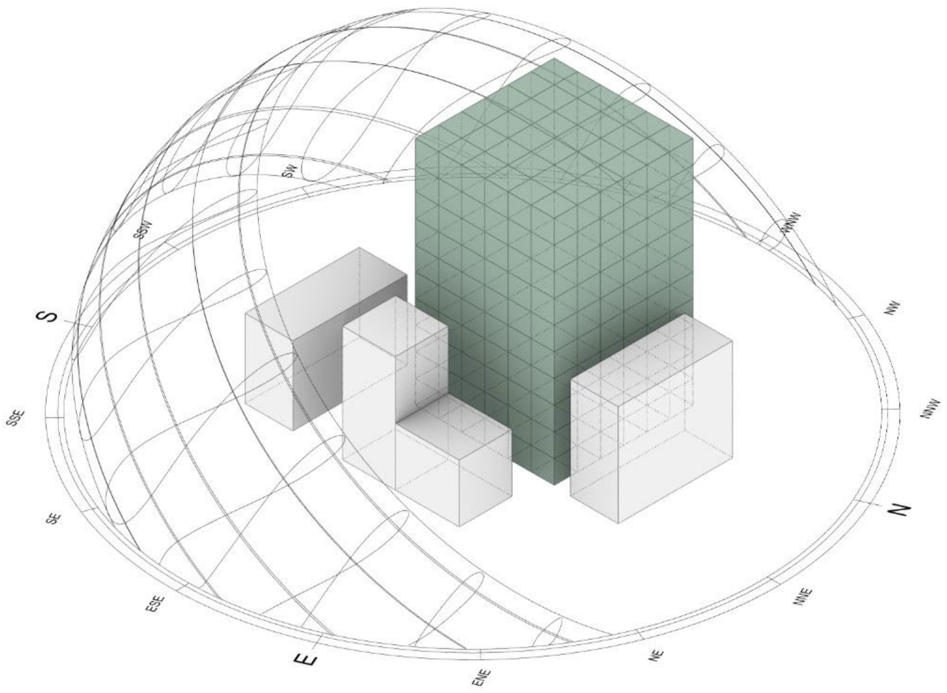
Envelope resolution
voxel size

Context
urban environment

Location
longitude & latitude

Optimization target
period to maximize solar potential

DIVERSITY OF RESULTS_Resolution



Envelope resolution

○ L ○ M ○ H

Context

● 1 ○ 2 ○ 3

Performance indicators

● DNI ○ DS ● RC

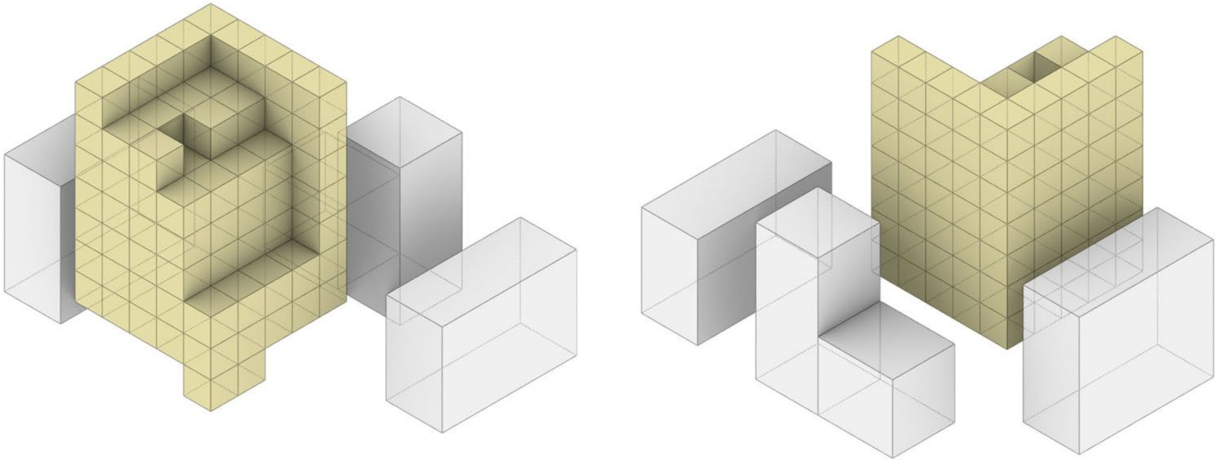
Optimization target

● A ● W ● Sp ● Su

Location

DIVERSITY OF RESULTS_Resolution

Method 1



Envelope resolution

● L ○ M ○ H

Context

● 1 ○ 2 ○ 3

Performance indicators

● DNI ○ DS ● RC

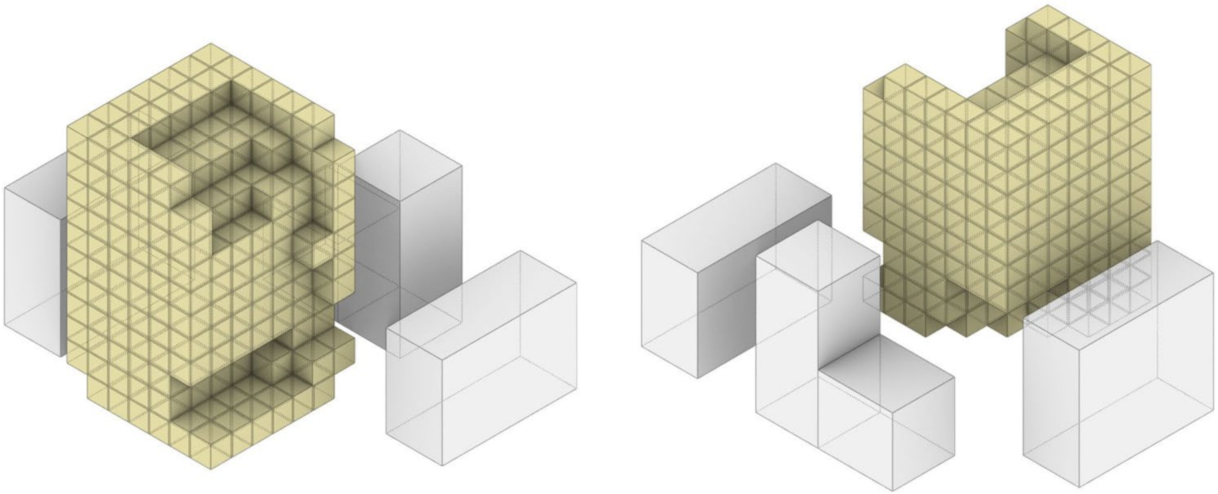
Optimization target

● A ● W ● Sp ● Su

Location

DIVERSITY OF RESULTS_Resolution

Method 1



Envelope resolution

○ L ○ M ● H

Context

● 1 ○ 2 ○ 3

Performance indicators

● DNI ○ DS ● RC

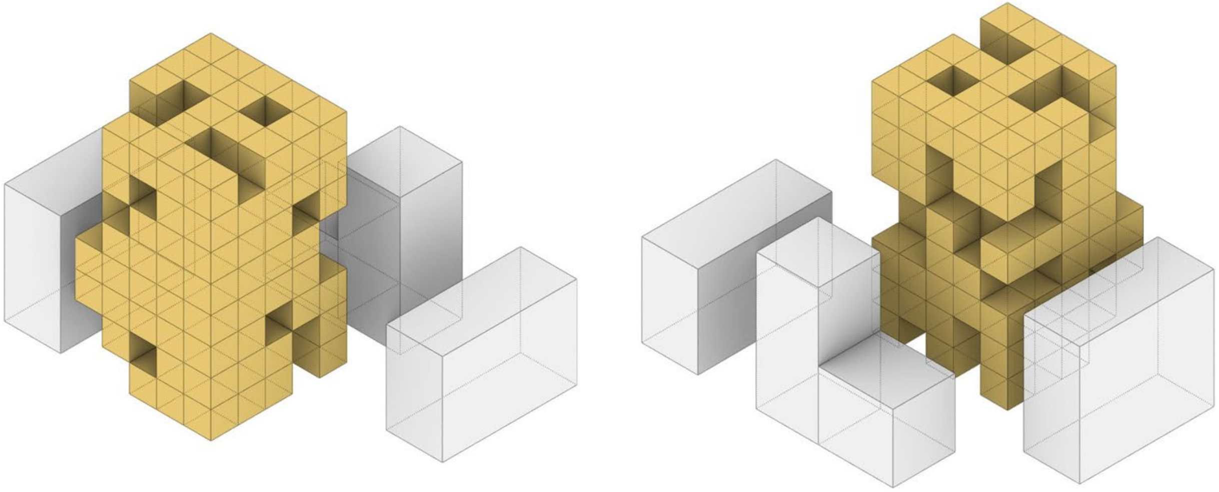
Optimization target

● A ● W ● Sp ● Su

Location

DIVERSITY OF RESULTS_Resolution

Method 2



Envelope resolution

● L ○ M ○ H

Context

● 1 ○ 2 ○ 3

Performance indicators

● DNI ○ DS ● RC

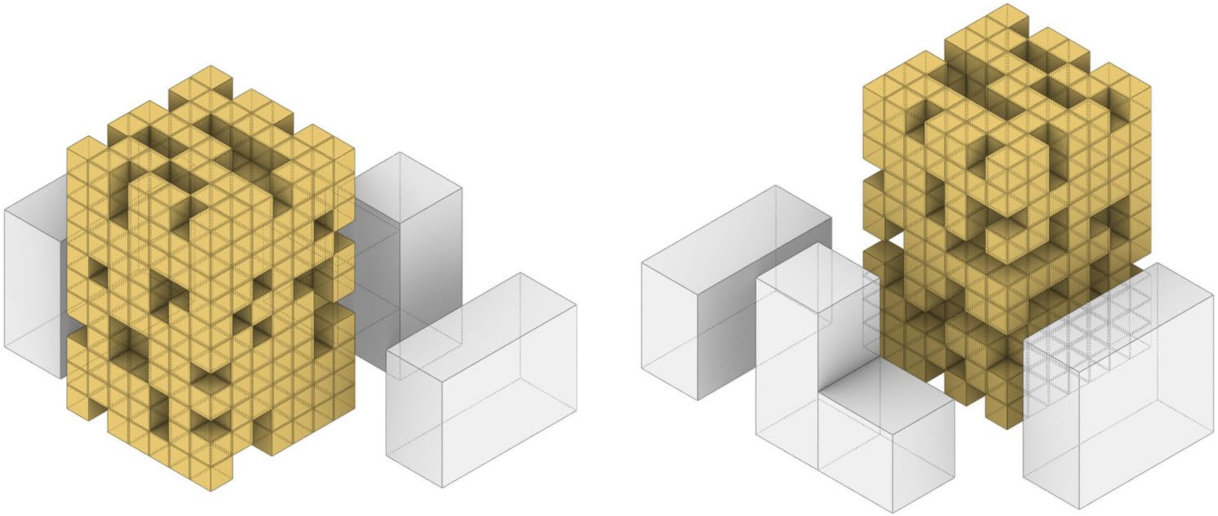
Optimization target

● A ● W ● Sp ● Su

Location

DIVERSITY OF RESULTS_Resolution

Method 2



Envelope resolution

○ L ○ M ● H

Context

● 1 ○ 2 ○ 3

Performance indicators

● DNI ○ DS ● RC

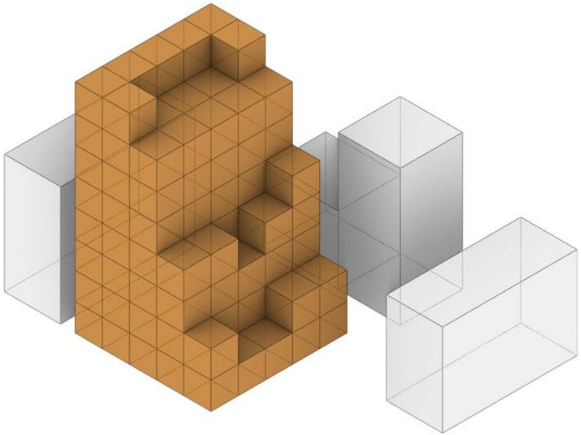
Optimization target

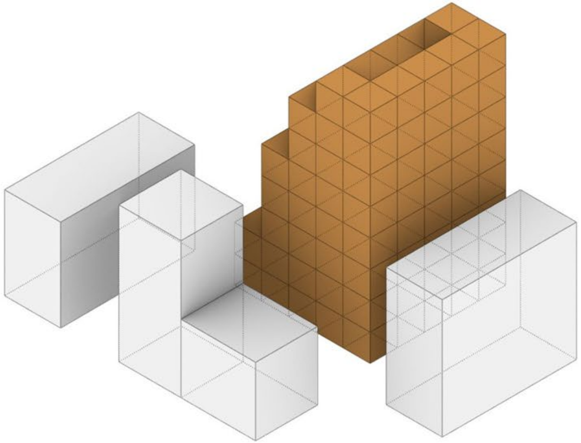
● A ● W ● Sp ● Su

Location

DIVERSITY OF RESULTS_Resolution

Method 3





Envelope resolution

● L ○ M ○ H

Context

● 1 ○ 2 ○ 3

Performance indicators

● DNI ○ DS ● RC

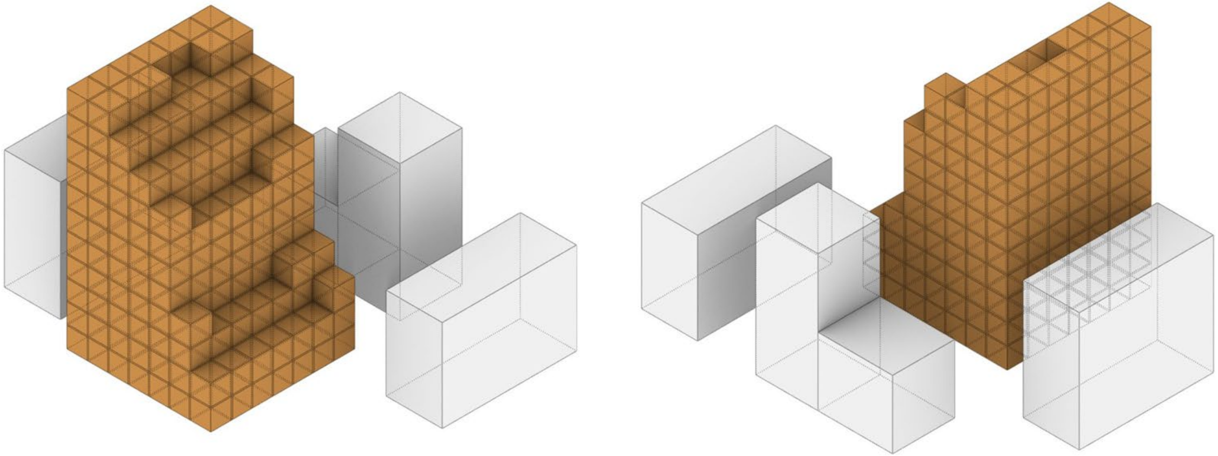
Optimization target

● A ● W ● Sp ● Su

Location

DIVERSITY OF RESULTS_Resolution

Method 3



Envelope resolution

○ L ○ M ● H

Context

● 1 ○ 2 ○ 3

Performance indicators

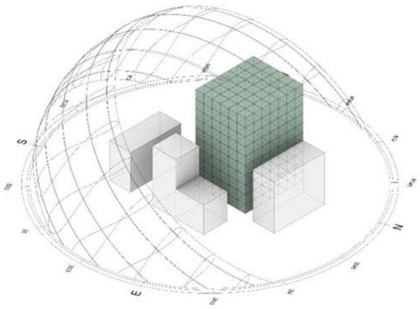
● DNI ○ DS ● RC

Optimization target

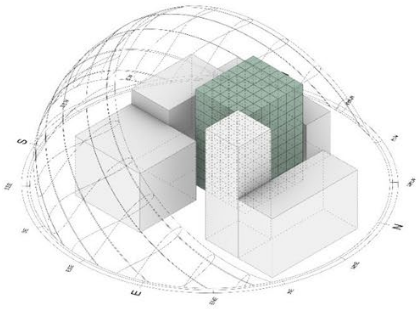
● A ● W ● Sp ● Su

Location

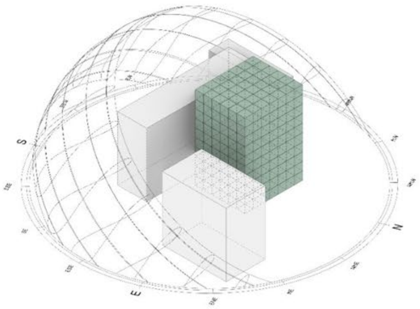
DIVERSITY OF RESULTS_Context



Option1
Low sparse context



Option2
Mix-height dense context



Option3
High mid-sparse context

Envelope resolution

○ ● ○
L M H

Context

○ ○ ○
1 2 3

Performance indicators

● ○ ●
DNI DS RC

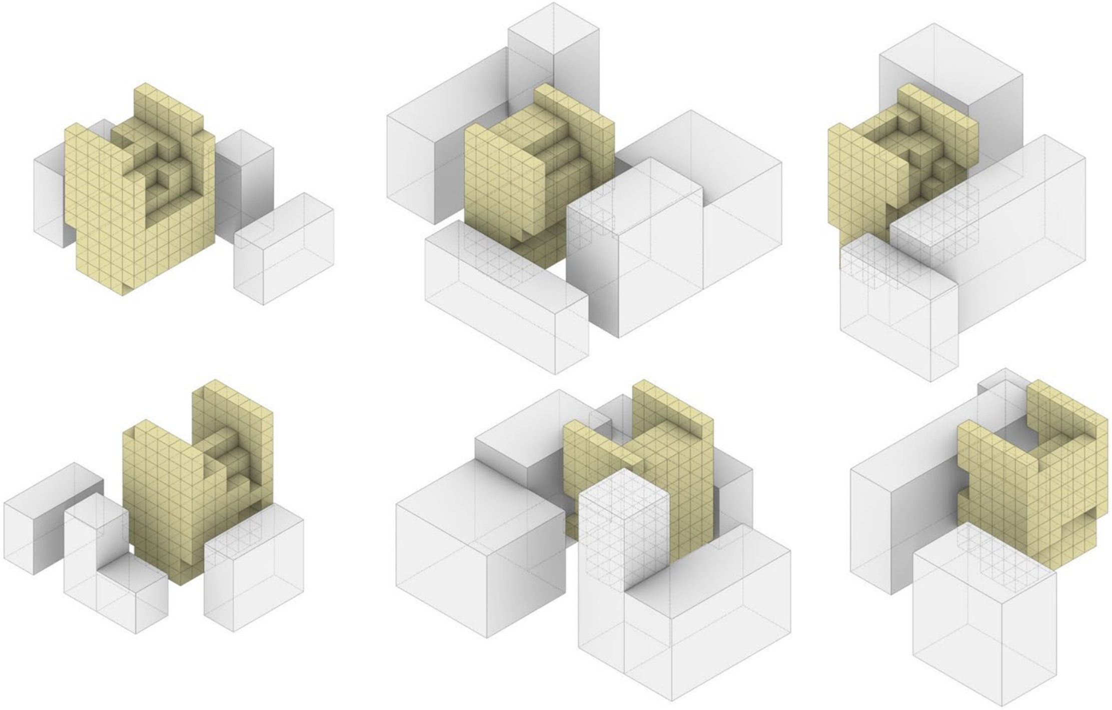
Optimization target

● ● ● ●
A W Sp Su

Location

DIVERSITY OF RESULTS_Context

Method 1



Envelope resolution

○ L ● M ○ H

Context

● 1 ● 2 ● 3

Performance indicators

● DNI ○ DS ● RC

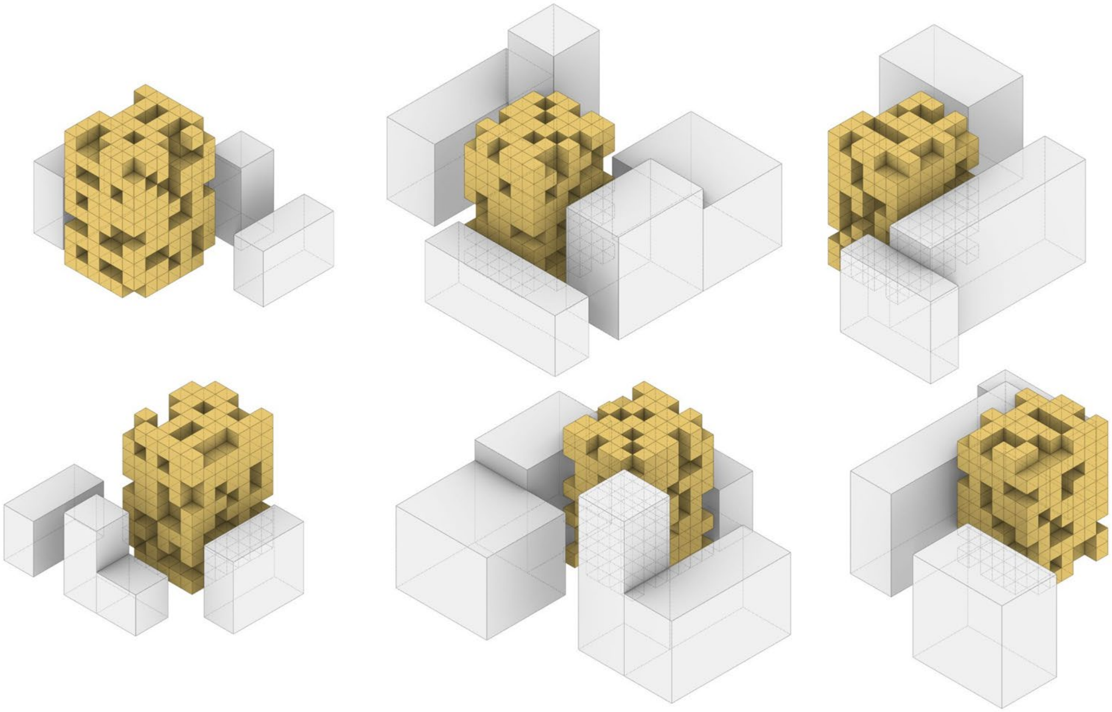
Optimization target

● A ● W ● Sp ● Su

Location

DIVERSITY OF RESULTS_Context

Method 2



Envelope resolution

○ L ● M ○ H

Context

● 1 ● 2 ● 3

Performance indicators

● DNI ○ DS ● RC

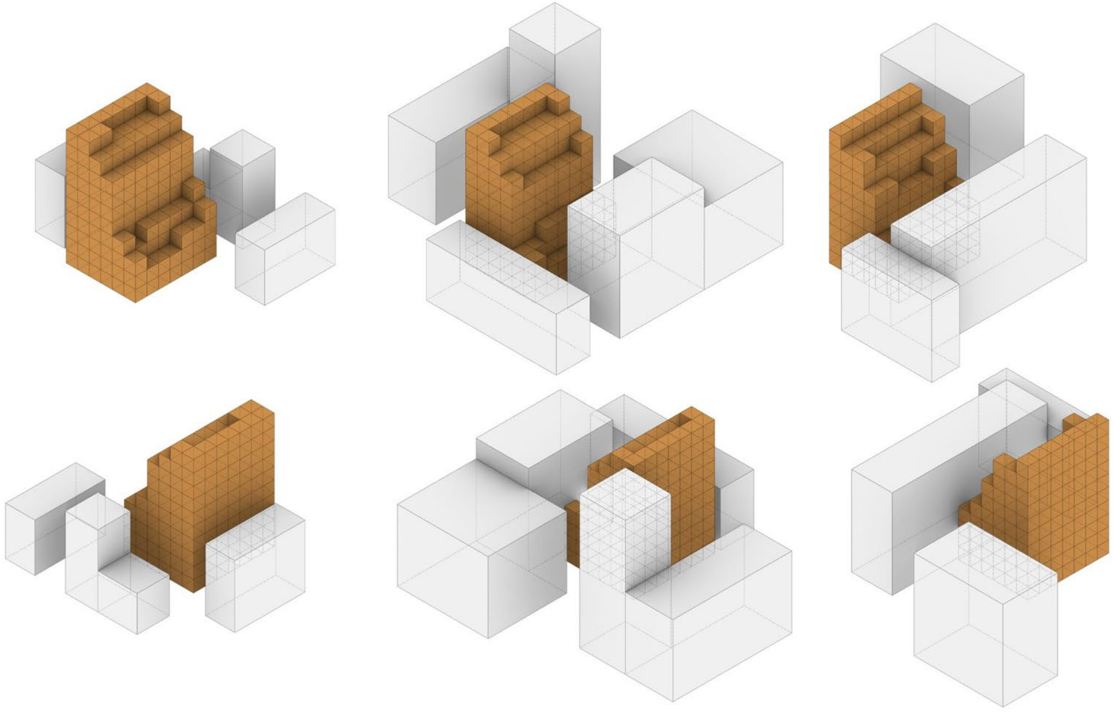
Optimization target

● A ● W ● Sp ● Su

Location

DIVERSITY OF RESULTS_Context

Method 3



Envelope resolution

○ L ● M ○ H

Context

● 1 ● 2 ● 3

Performance indicators

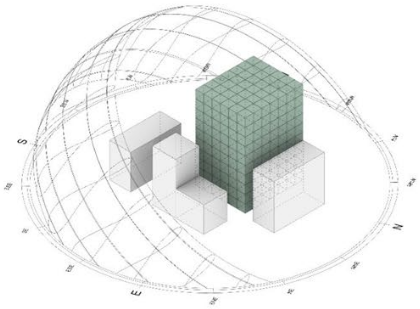
● DNI ○ DS ● RC

Optimization target

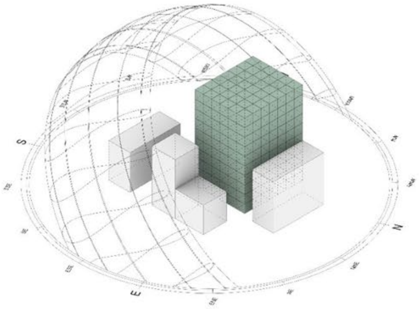
● A ● W ● Sp ● Su

Location

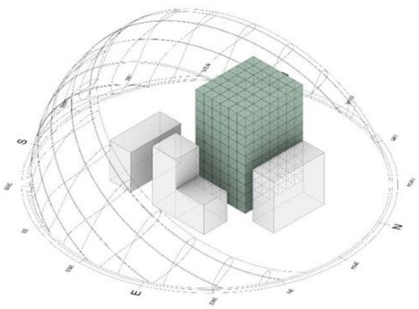
DIVERSITY OF RESULTS_Location



Netherlands
Amsterdam



Greece
Athens



Norway
Oslo

Envelope resolution

○ ● ○
L M H

Context

● ○ ○
1 2 3

Performance indicators

● ○ ●
DNI DS RC

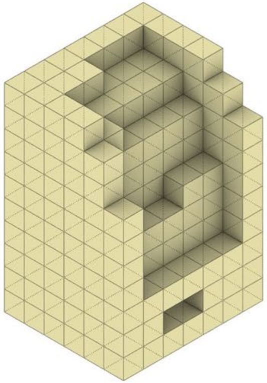
Optimization target

● ● ● ●
A W Sp Su

Location

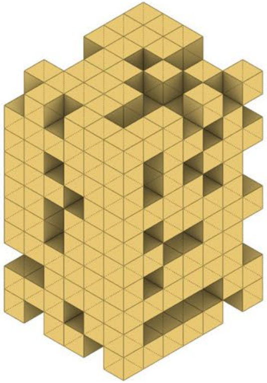
DIVERSITY OF RESULTS_Location

Method 1



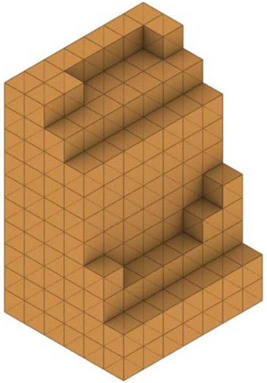
RC = 64%

Method 2

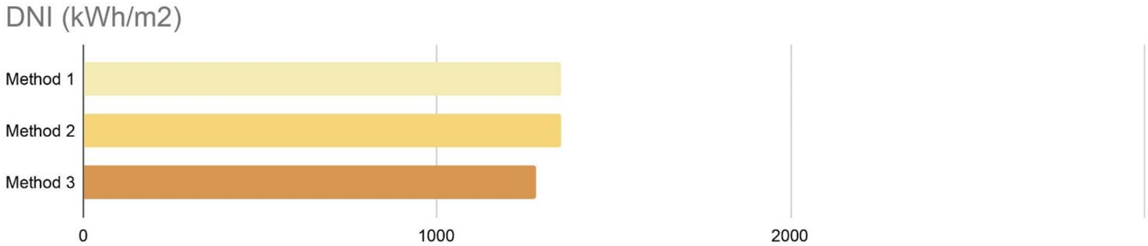


RC = 45%

Method 3



RC = 74%



Envelope resolution

○ L ● M ○ H

Context

● 1 ○ 2 ○ 3

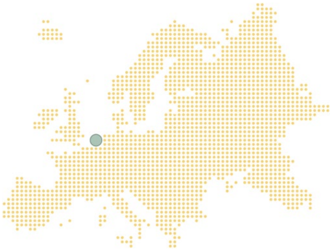
Performance indicators

● DNI ○ DS ● RC

Optimization target

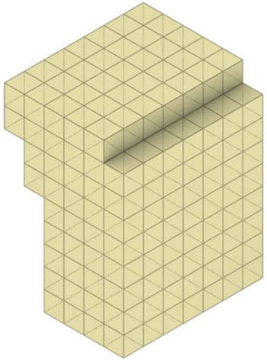
● A ● W ● Sp ● Su

Location



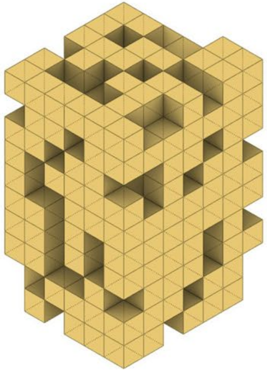
DIVERSITY OF RESULTS_Location

Method 1



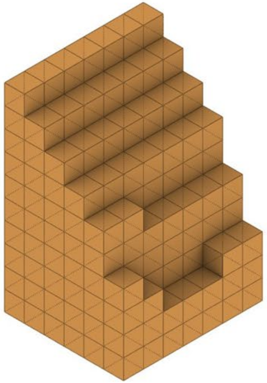
RC = 73%

Method 2

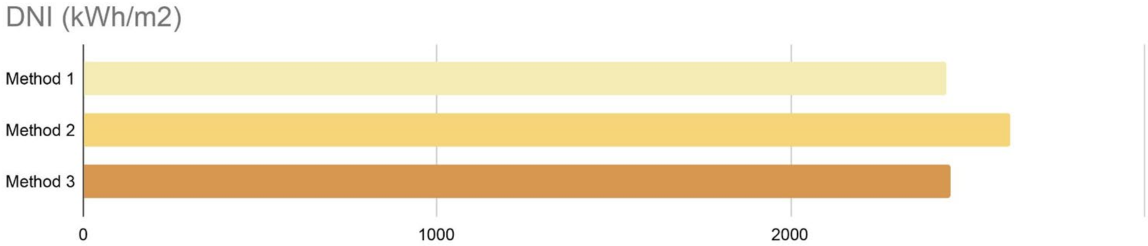


RC = 40%

Method 3



RC = 72%



Envelope resolution

○ L ● M ○ H

Context

● 1 ○ 2 ○ 3

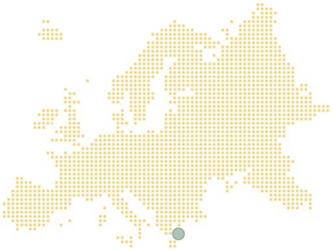
Performance indicators

● DNI ○ DS ● RC

Optimization target

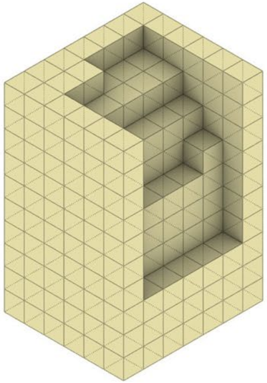
● A ● W ● Sp ● Su

Location



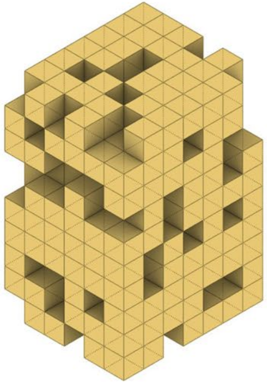
DIVERSITY OF RESULTS_Location

Method 1



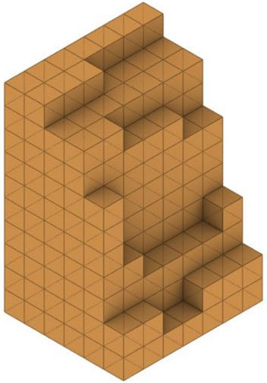
RC = 69%

Method 2



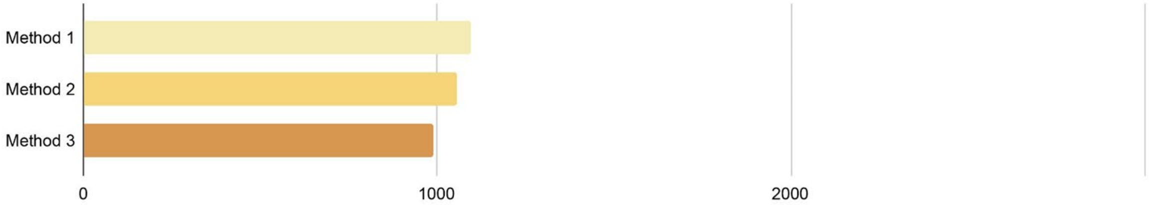
RC = 40%

Method 3



RC = 71%

DNI (kWh/m2)



Envelope resolution

○ ● ○

L M H

Context

● ○ ○

1 2 3

Performance indicators

● ○ ●

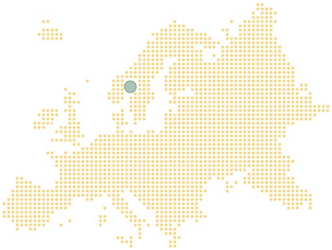
DNI DS RC

Optimization target

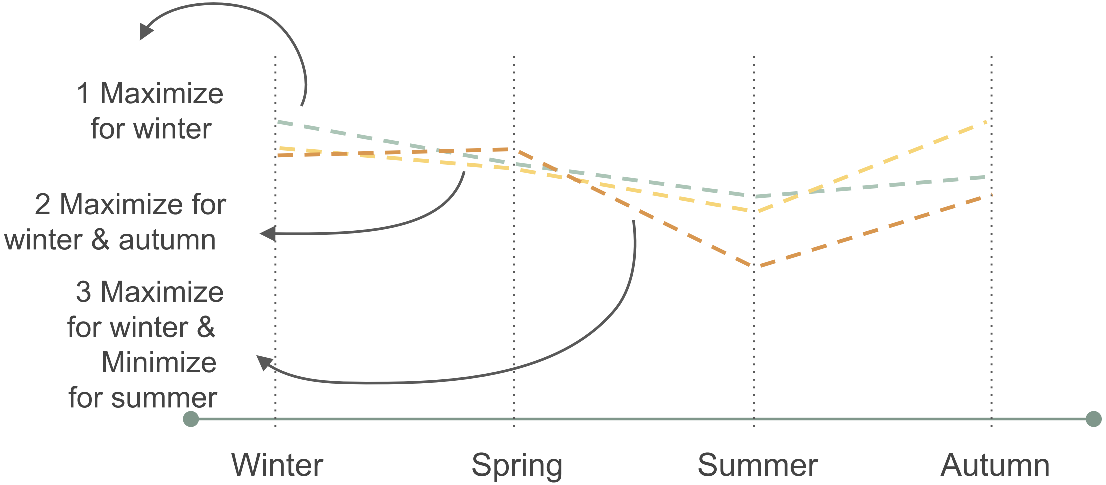
● ● ● ●

A W Sp Su

Location



DIVERSITY OF RESULTS_Optimization target



1 Maximize for winter

2 Maximize for winter & autumn

3 Maximize for winter & Minimize for summer

Envelope resolution

○ L ● M ○ H

Context

● 1 ○ 2 ○ 3

Performance indicators

● DNI ○ DS ● RC

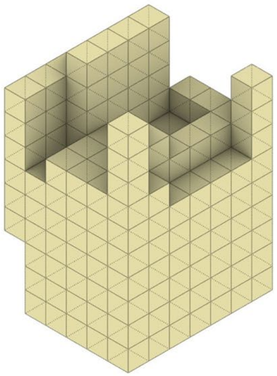
Optimization target

○ A ○ W ○ Sp ○ Su

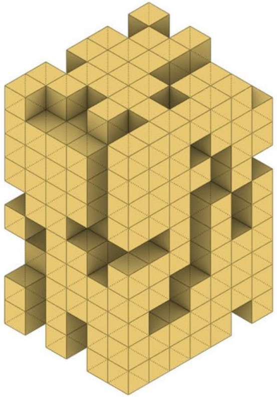
Location

DIVERSITY OF RESULTS_Optimization target

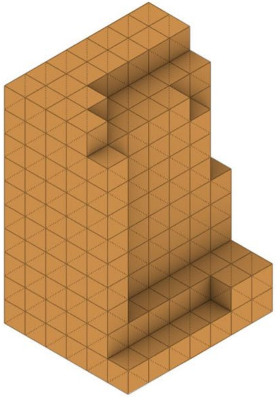
Method 1

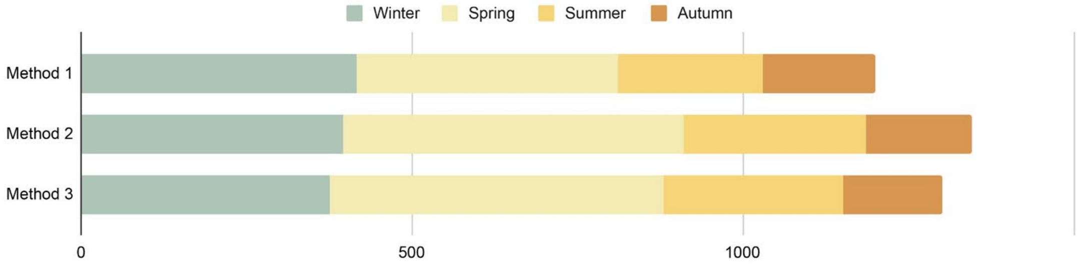


Method 2



Method 3





Envelope resolution

○ L ● M ○ H

Context

● 1 ○ 2 ○ 3

Performance indicators

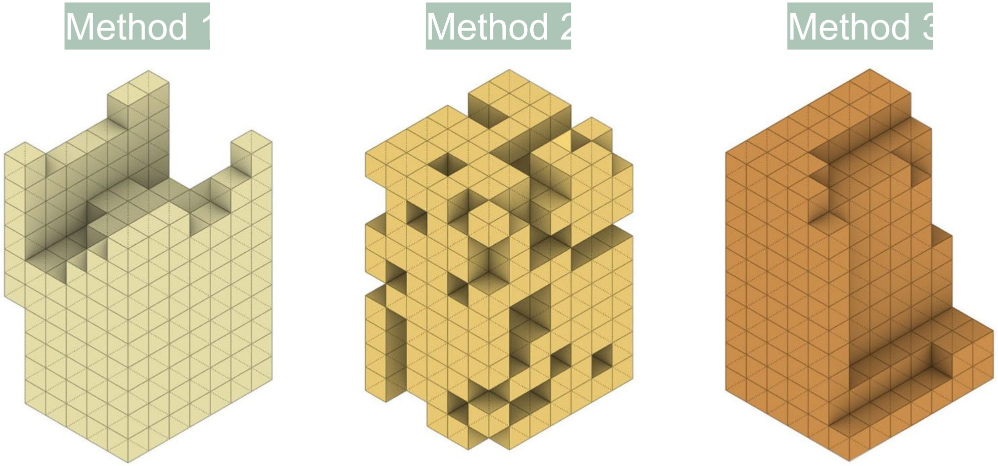
● DNI ○ DS ● RC

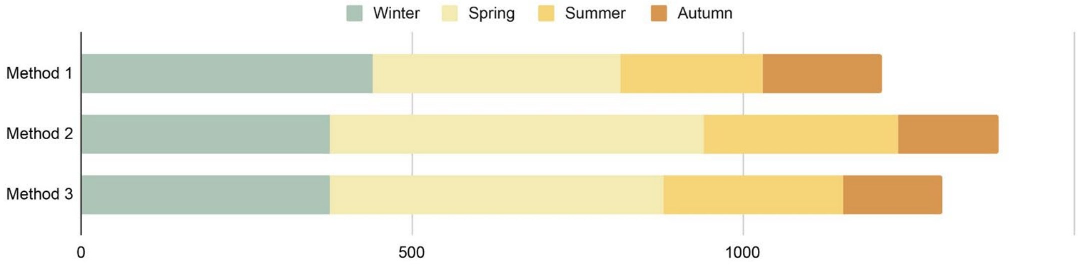
Optimization target

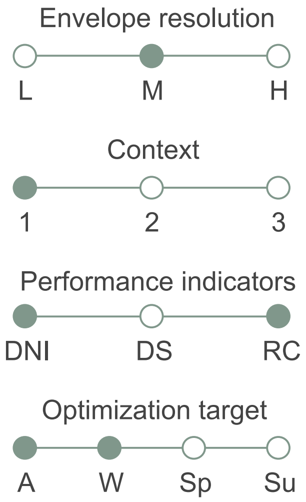
○ A ● W ○ Sp ○ Su

Location

DIVERSITY OF RESULTS_Optimization target







Envelope resolution

○ L ● M ○ H

Context

● 1 ○ 2 ○ 3

Performance indicators

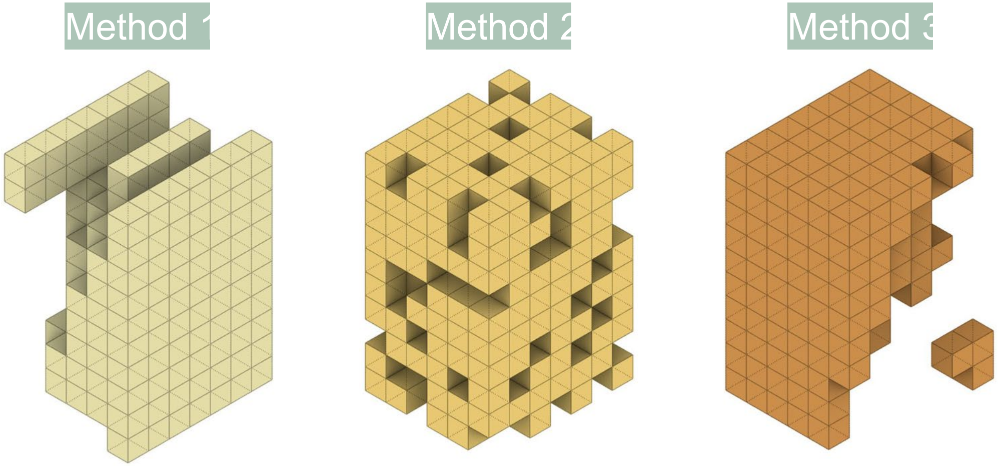
● DNI ○ DS ● RC

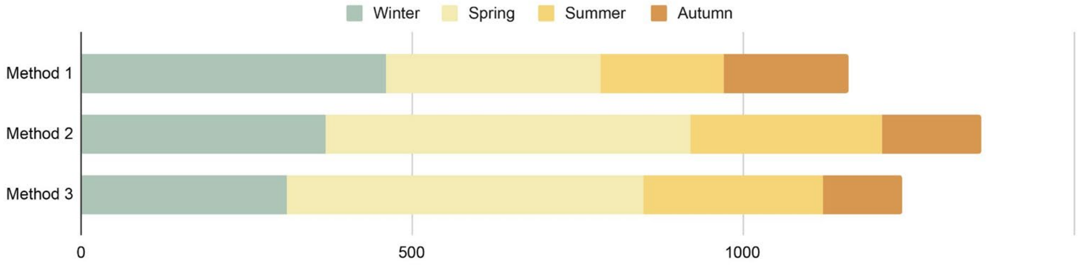
Optimization target

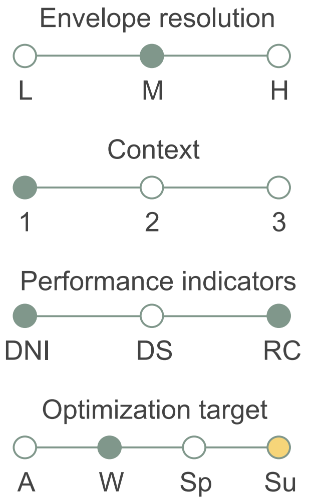
● A ● W ○ Sp ○ Su

Location

DIVERSITY OF RESULTS_Optimization target

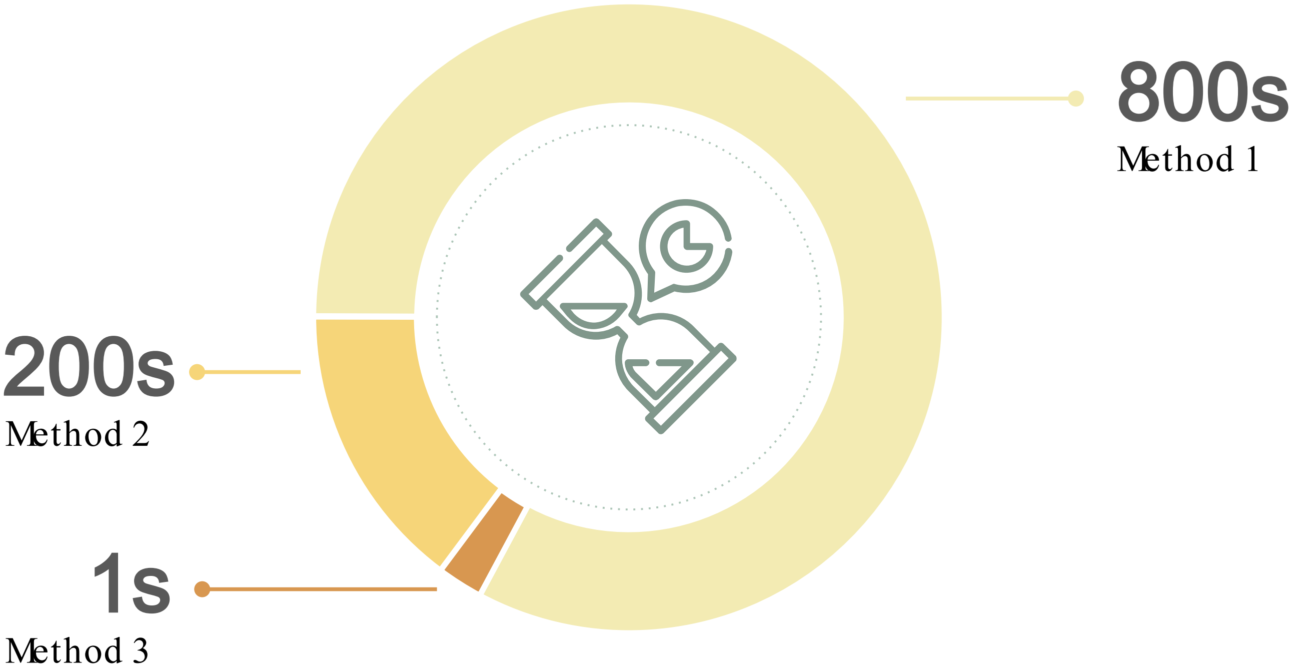






Location

DIVERSITY OF RESULTS_Average time



METHODS COMPARISON

	Computational power demand	Diversity of results	Solar potential	Relative compactness	Ease of interpretation	Control over the process
Method 1	+	+++	+++	++	++	+++
Method 2	++	+	++	+	+	+
Method 3	+++	++	+	+++	+++	++

METHODS COMPARISON

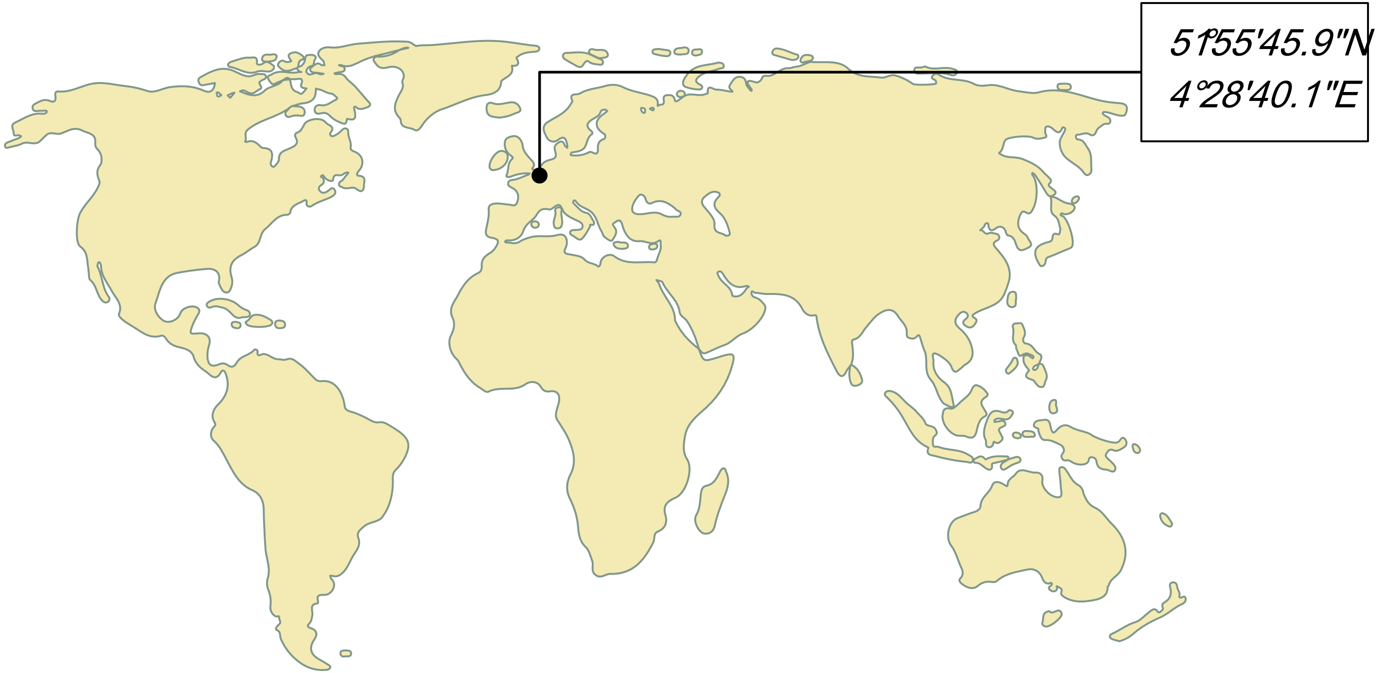
	Computational power demand	Diversity of results	Solar potential	Relative compactness	Ease of interpretation	Control over the process
Method 1	+	+++	+++	++	++	+++
Method 2	++	+	++	+	+	+
Method 3	+++	++	+	+++	+++	++

05

CASE STUDY

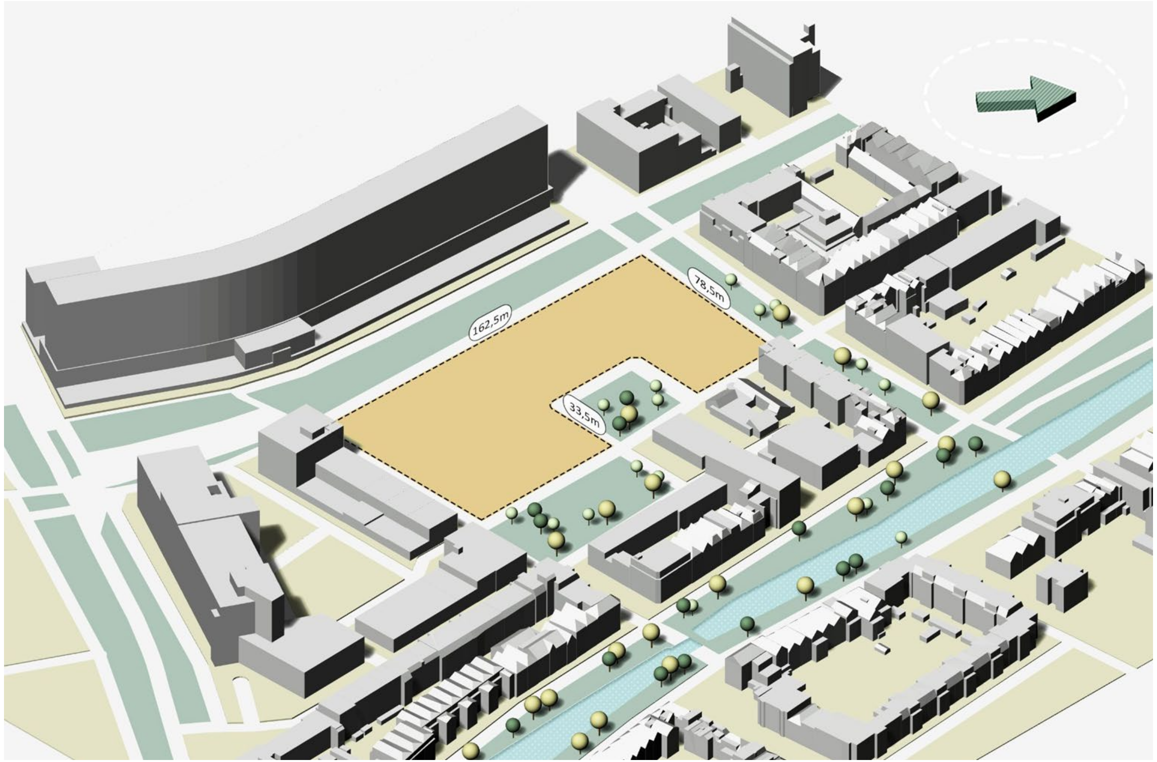
Selected site
Intervisibilities calculation
Cost index calculation
Removal process
Massing result

LOCATION

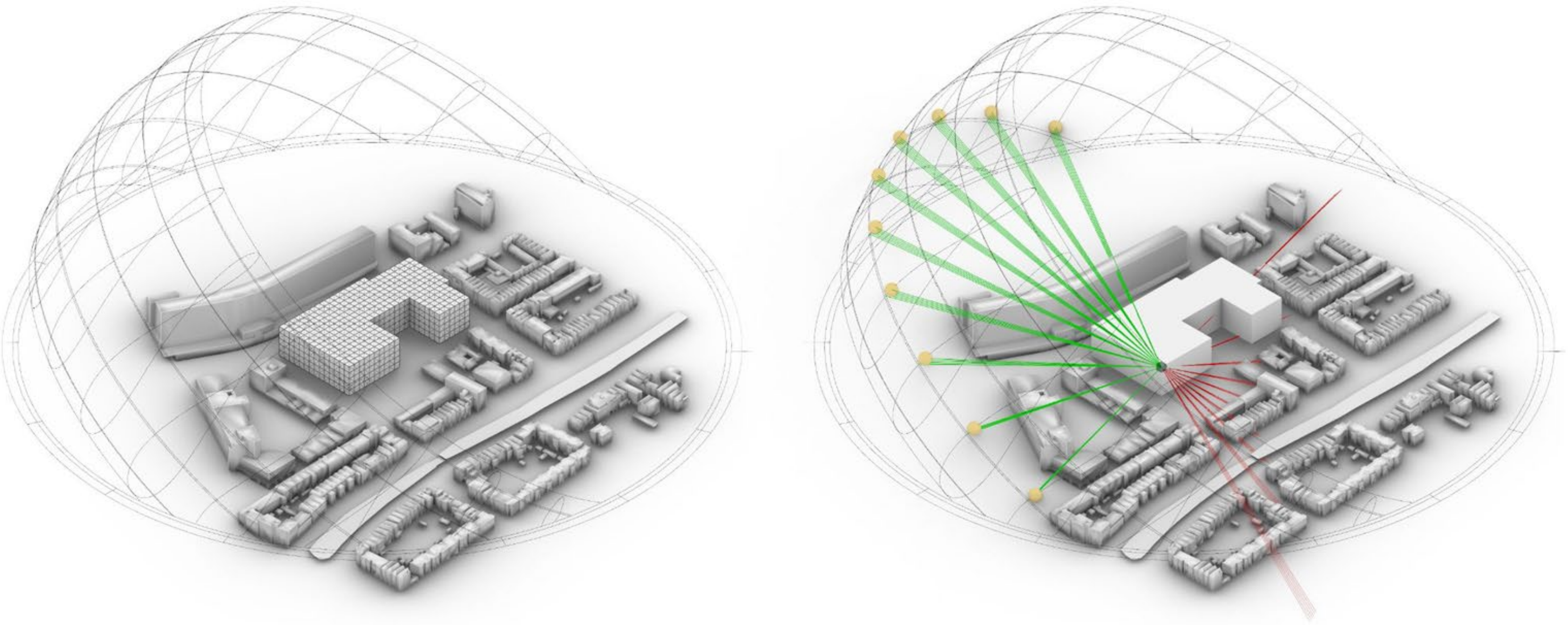


51°55'45.9"N
4°28'40.1"E

ROTTERDAM-SITE

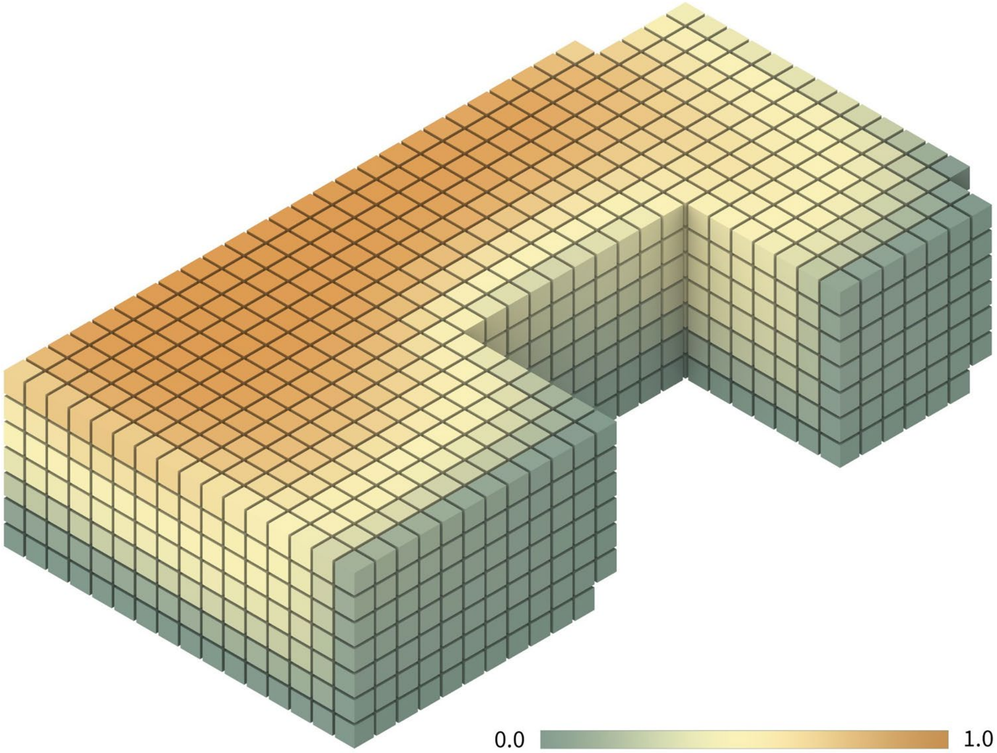


COMPUTE INTERVISIBILITIES



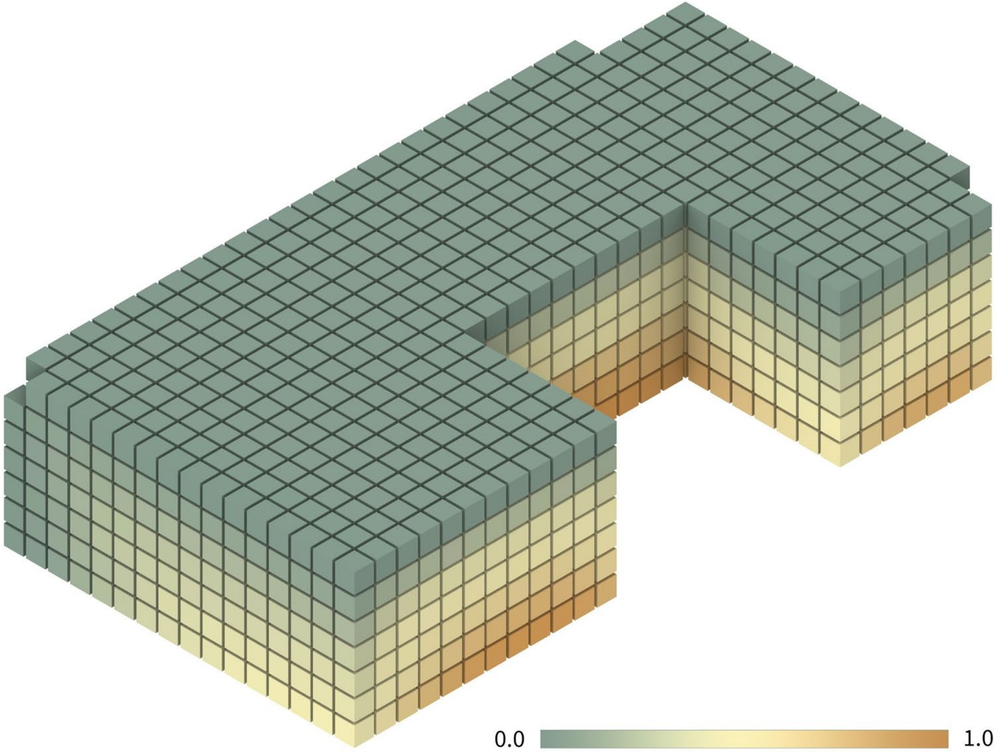
COST INDEX CALCULATION

Obscuring inde



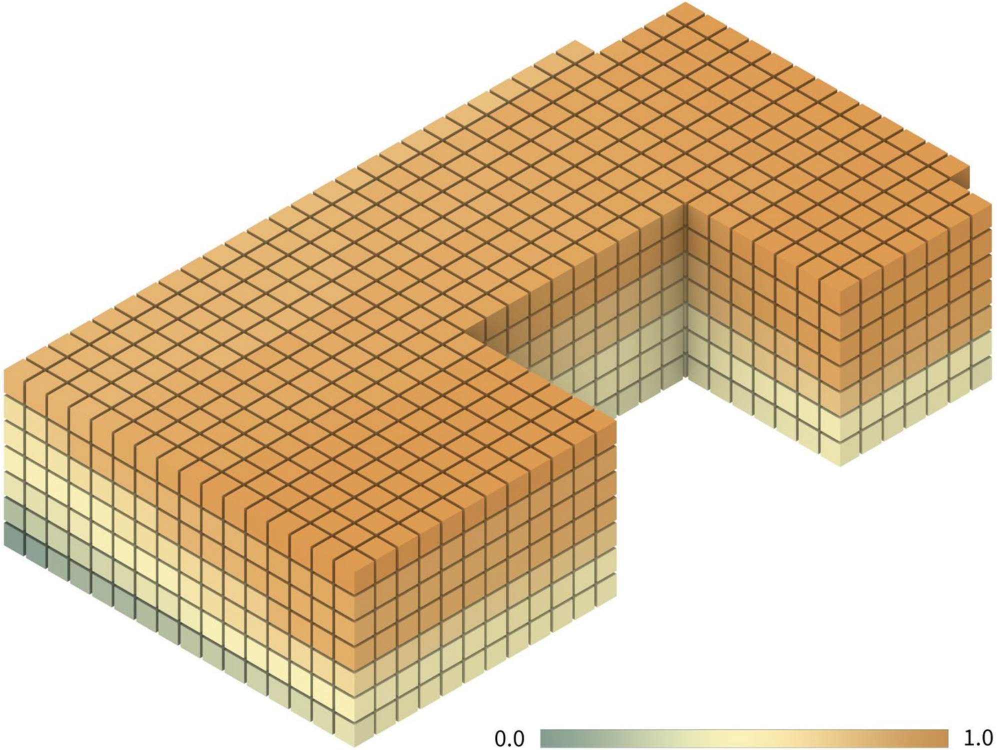
COST INDEX CALCULATION

Obscured inde



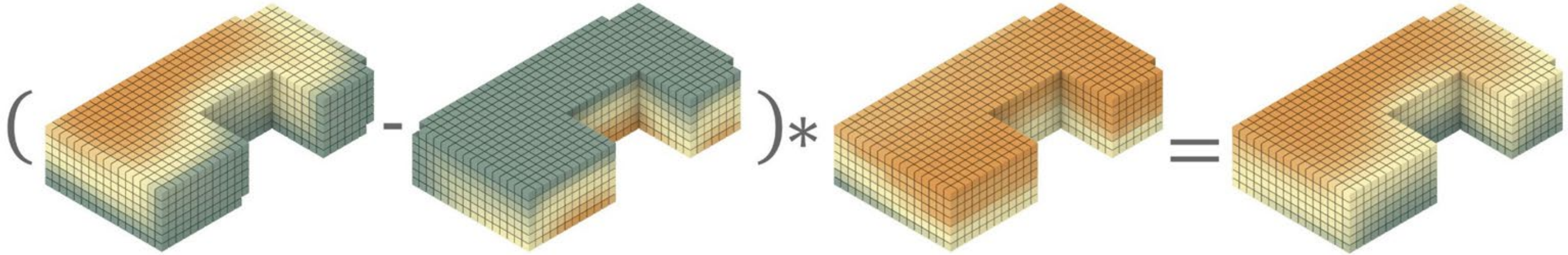
COST INDEX CALCULATION

Solar potentia



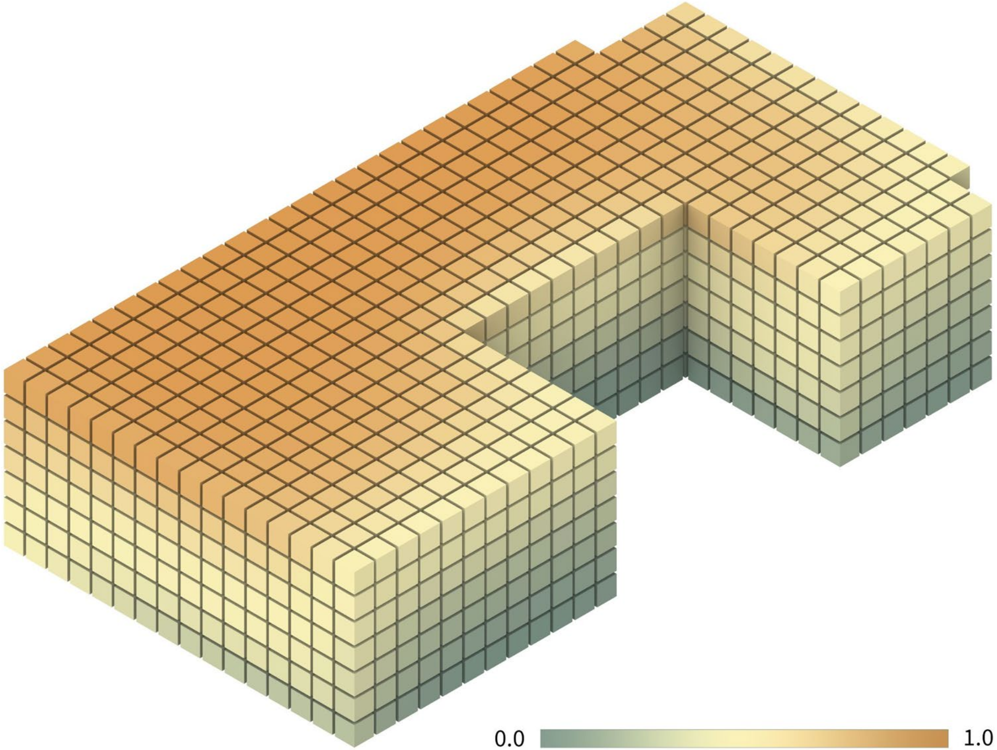
COST INDEX CALCULATION

Combining factors

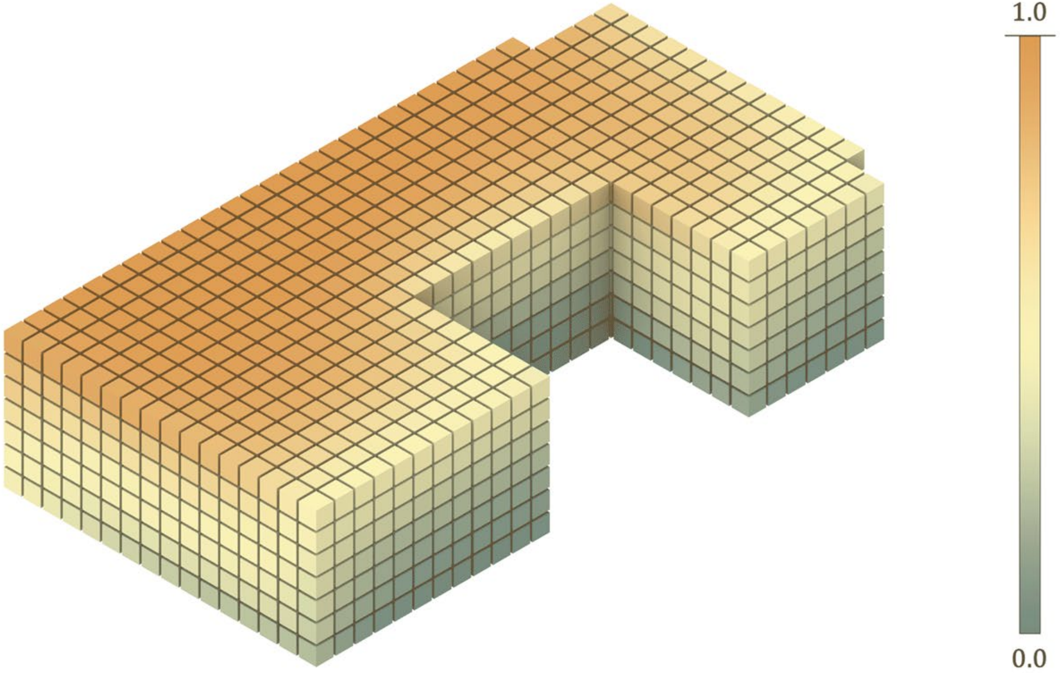


COST INDEX CALCULATION

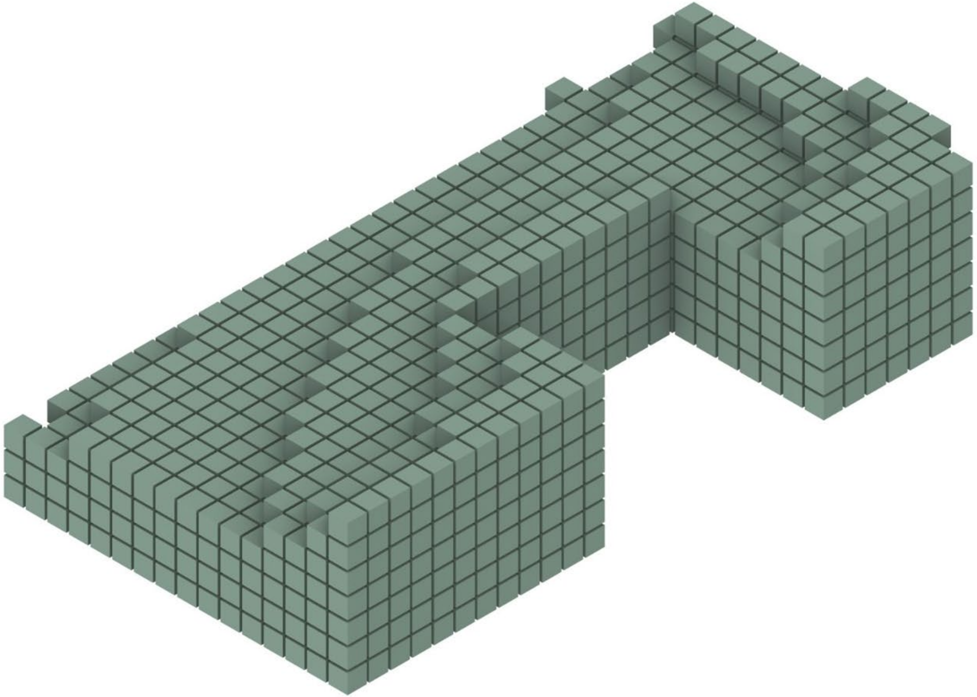
Cost index



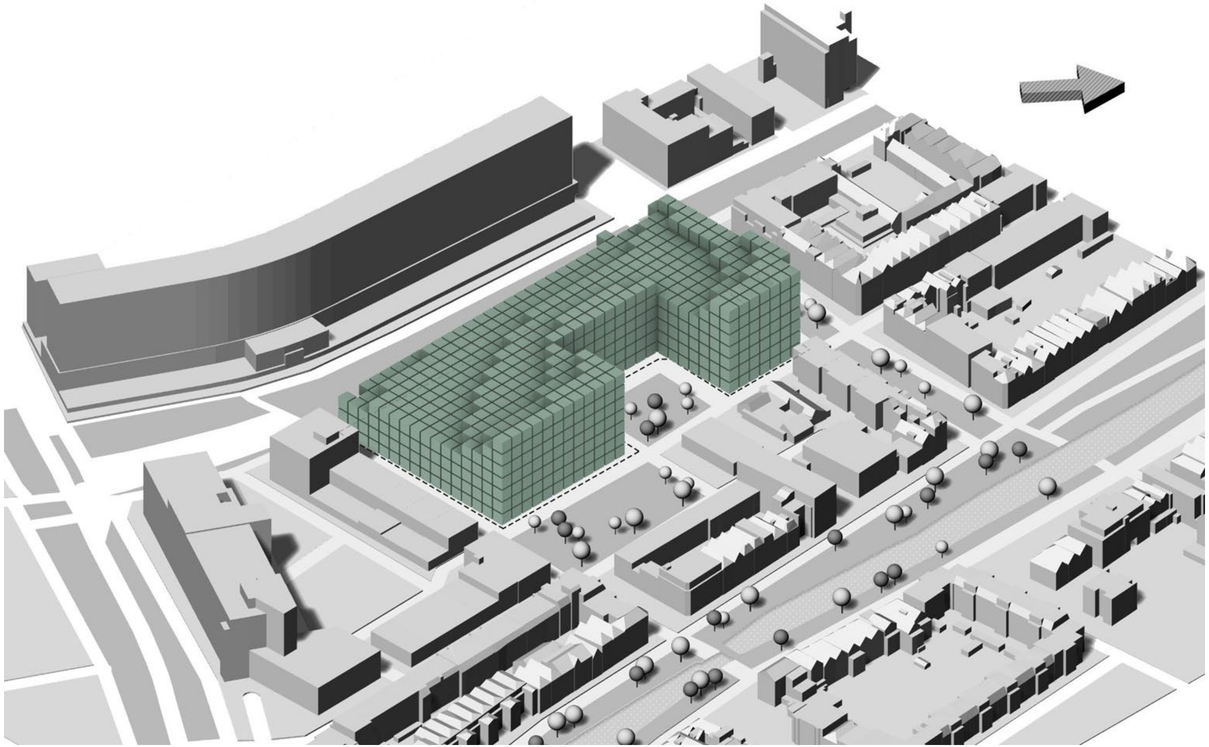
REMOVAL PROCESS



MASSING RESULT



MASSING RESULT



06

CONCLUSION & REFLECTION

Interpretation of results
Limitations
Reflection
Relevance
Future development

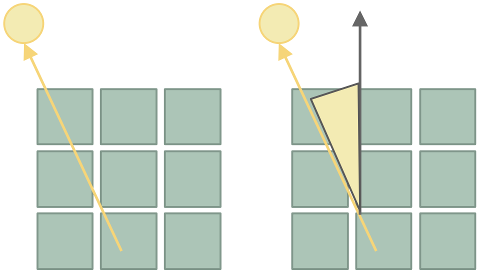
ACHIEVEMENTS

+ Computationally heavy ray-mesh intersection computed only once
+ Evaluation process through simple vectorized calculations
+ Adjustable to different situations
+ Can be applied for different optimization targets
+ Able to give a variety of results (explore big part of the design space)

LIMITATIONS

DIRECTIONALITY NOT TAKEN INTO ACCOUNT

angle of incidence neglected, comparable but not numerically accurate results



COMPUTATIONALLY HEAVY

Method 1&2
time & power

FUTURE DEVELOPMENTS

+ Develop stage 3 - Zoning

+ Possibility of include more spatial-related indicators

+ Add sophistication:
  - Compute intervisibilities per face (take angle of incidence into account)
  - Include a diffused sunlight part indicator

+ Algorithm improvements

RELEVANCE

SOCIAL

- improvement of the comfort and livability of spaces
- high energy efficient buildings
- CO2 emissions reduction

SCIENTIFIC

- facilitation and acceleration of the design process
- adaptability to future requirements due to the computational nature
- open source nature: reproducibility and constant improvement

THANK YOU

REFERENCES

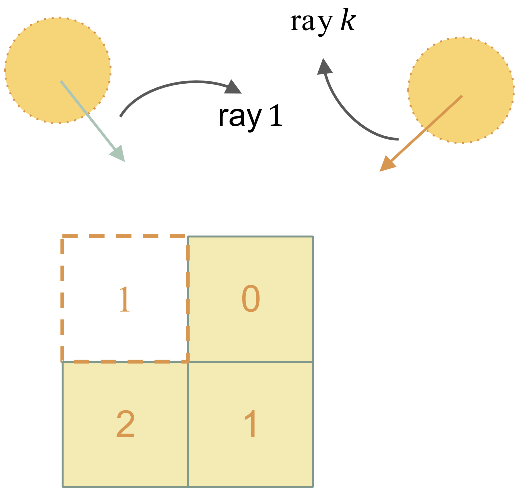
[1] N. Kohler and S. Moffatt, Life-Cycle Analysis of the Built Environment, United Nations Environment Programme Division of Technology, Industry and Economic Publication, UNEP Industry and Environment, 2003.

[2] U. Bogenstätter, “Prediction and optimization of life-cycle costs in early design,” Building Research &amp; Information, vol. 28, no. 5-6, pp. 376–386, 2000.

DISCUSSION SLIDES

MATHEMATICAL REPRESENTATION

Visibility Evaluation function



$$[\Omega_{i,j,k}]_{n\times n\times m} = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 0 & 0 & 1 & 1 \\ 2 & 0 & 0 & 0 & 1 \\ 3 & 0 & 0 & 0 & 0 \\ n & 0 & 0 & 0 & 0 \end{array} \quad \begin{array}{cccc} 1 & 2 & 3 & n \\ \hline 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{array}$$

$$[X_i]_{n\times 1} = \begin{array}{c|c} 1 & 0 \\ 2 & 1 \\ 3 & 1 \\ n & 1 \end{array}$$

$$[U_{k,i}]_{m\times n} = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 1 & 1 & 1 & 1 \\ m & 1 & 1 & 1 & 0 \end{array}$$

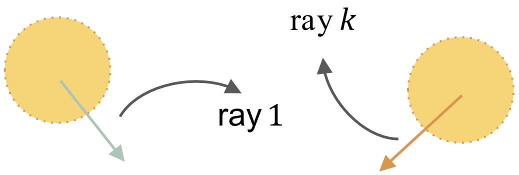
Total obstruction of each voxel per ray

$$[\Omega^T{}_{k,j,i}]_{m\times n\times n}\,[X_i]_{n\times 1} = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 0 & 0 & 0 & 1 \\ m & 1 & 0 & 2 & 0 \end{array}$$

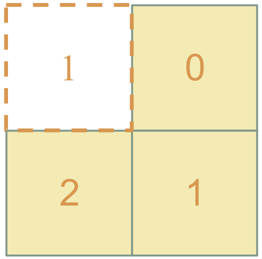
$$[J_{k,i}]_{m\times n} = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 1 & 1 & 1 & 1 \\ m & 1 & 1 & 1 & 1 \end{array}$$

MATHEMATICAL REPRESENTATION

Visibility Evaluation function



$$[\Omega_{i,j,k}]_{n\times n\times m} = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 0 & 0 & 1 & 1 \\ 2 & 0 & 0 & 0 & 1 \\ 3 & 0 & 0 & 0 & 0 \\ n & 0 & 0 & 0 & 0 \end{array} \quad \begin{array}{cccc} 1 & 2 & 3 & n \\ \hline 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{array} \qquad [x_i]_{n\times 1} = \begin{array}{c|c} 1 & 0 \\ 2 & 1 \\ 3 & 1 \\ n & 1 \end{array} \qquad [U_{k,i}]_{m\times n} = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 1 & 1 & 1 & 1 \\ m & 1 & 1 & 1 & 0 \end{array}$$



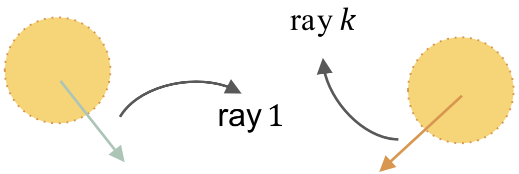
1	0
2	1

Simple obstruction of each voxel per ray

$$\min(J,\Omega^T x) = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 0 & 0 & 0 & 1 \\ m & 1 & 0 & 1 & 0 \end{array} \qquad [J_{k,i}]_{m\times n} = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 1 & 1 & 1 & 1 \\ m & 1 & 1 & 1 & 1 \end{array}$$

MATHEMATICAL REPRESENTATION

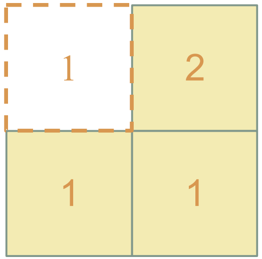
Visibility Evaluation functior



$$[\Omega_{i,j,k}]_{n \times n \times m} = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 0 & 0 & 1 & 1 \\ 2 & 0 & 0 & 0 & 1 \\ 3 & 0 & 0 & 0 & 0 \\ n & 0 & 0 & 0 & 0 \end{array} \quad \begin{array}{cccc} 1 & 2 & 3 & n \\ \hline 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{array}$$

$$[x_i]_{n \times 1} = \begin{array}{c|c} 1 & 0 \\ 2 & 1 \\ 3 & 1 \\ n & 1 \end{array}$$

$$[U_{k,i}]_{m \times n} = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 1 & 1 & 1 & 1 \\ m & 1 & 1 & 1 & 0 \end{array}$$



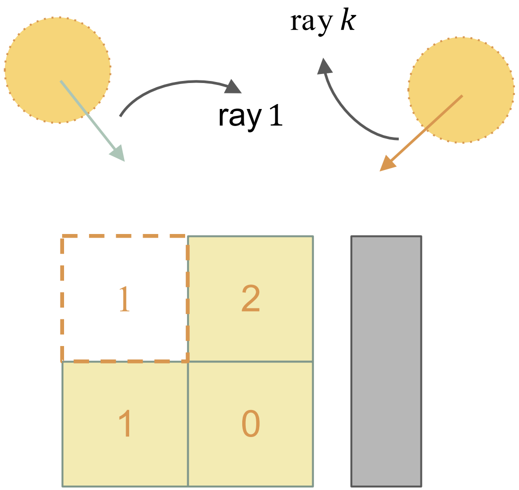
Visibility of each voxel per ray

$$J - \min(J, \Omega^T x) = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 1 & 1 & 1 & 0 \\ m & 0 & 1 & 0 & 1 \end{array}$$

$$[J_{k,i}]_{m \times n} = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 1 & 1 & 1 & 1 \\ m & 1 & 1 & 1 & 1 \end{array}$$

MATHEMATICAL REPRESENTATION

Visibility Evaluation functior



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$$[x_i]_{n\times 1} = \begin{array}{c|c} 1 & 0 \\ 2 & 1 \\ 3 & 1 \\ n & 1 \end{array}$$

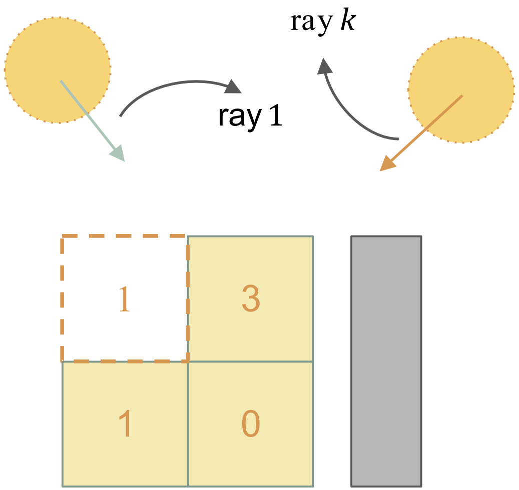
$$[U_{k,i}]_{m\times n} = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 1 & 1 & 1 & 1 \\ m & 1 & 1 & 1 & 0 \end{array}$$

Discard obstructed rays (contextual shading)

$$U\odot(J - \min(J,\Omega^T x)) = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 1 & 1 & 1 & 0 \\ m & 0 & 1 & 0 & 0 \end{array}$$

MATHEMATICAL REPRESENTATION

Visibility Evaluation functior



$$[\Omega_{i,j,k}]_{n\,x\,n\,x\,m} = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 0 & 0 & 1 & 1 \\ 2 & 0 & 0 & 0 & 1 \\ 3 & 0 & 0 & 0 & 0 \\ n & 0 & 0 & 0 & 0 \end{array} \quad \begin{array}{cccc} 1 & 2 & 3 & n \\ \hline 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{array}$$

$$[x_i]_{n\,x\,1} = \begin{array}{c|c} 1 & 0 \\ 2 & 1 \\ 3 & 1 \\ n & 1 \end{array}$$

$$[U_{k,i}]_{m\,x\,n} = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 1 & 1 & 1 & 1 \\ m & 1 & 1 & 1 & 0 \end{array}$$

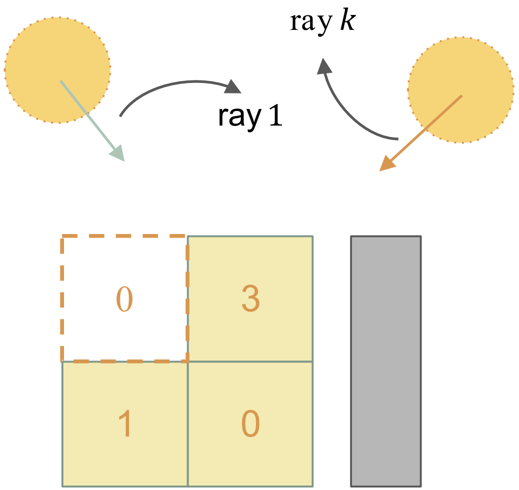
Apply weights to rays

$$w^T(U \odot (J - \min(J, \Omega^T x))) = \begin{array}{cccc} 1 & 2 & 3 & n \\ \hline 1 & 3 & 1 & 0 \end{array}$$

$$[w_k]_{m\,x\,1} = \begin{array}{cc} 1 & m \\ \hline 1 & 2 \end{array}$$

MATHEMATICAL REPRESENTATION

Visibility Evaluation function



$$[\Omega_{i,j,k}]_{n\times n\times m} = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 0 & 0 & 1 & 1 \\ 2 & 0 & 0 & 0 & 1 \\ 3 & 0 & 0 & 0 & 0 \\ n & 0 & 0 & 0 & 0 \end{array} \quad \begin{array}{cccc} 1 & 2 & 3 & n \\ \hline 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{array}$$

$$[x_i]_{n\times 1} = \begin{array}{c|c} 1 & 0 \\ 2 & 1 \\ 3 & 1 \\ n & 1 \end{array}$$

$$[U_{k,i}]_{m\times n} = \begin{array}{c|cccc} & 1 & 2 & 3 & n \\ \hline 1 & 1 & 1 & 1 & 1 \\ m & 1 & 1 & 1 & 0 \end{array}$$

<u>Discard visibility of unoccupied voxels</u>

$$w^T(U\odot(J - \min(J,\Omega^T x)))x = 4$$

METHODOLOGY_Step3

Ray-defined factors
(e.g. Direct Normal Irradiation)

$$f_1(\mathbf{x}) = \mathbf{w}^{T}(\mathbf{U}\odot(\mathbf{J} - \min(\mathbf{J},\mathbf{G}^{T}\mathbf{x})))\mathbf{x}$$

U: rays visibility matrix
G: intervisibilities graph
x: transparency vector
w: ray weights

Shape-related factors
(e.g. Relative Compactness)

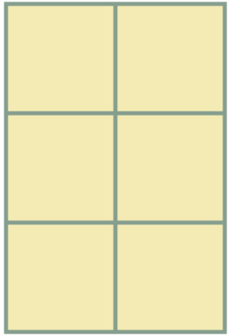
$$f_{rc}(\mathbf{x}) = 6*(V(\mathbf{x}))^{2/3}/A(\mathbf{x})$$

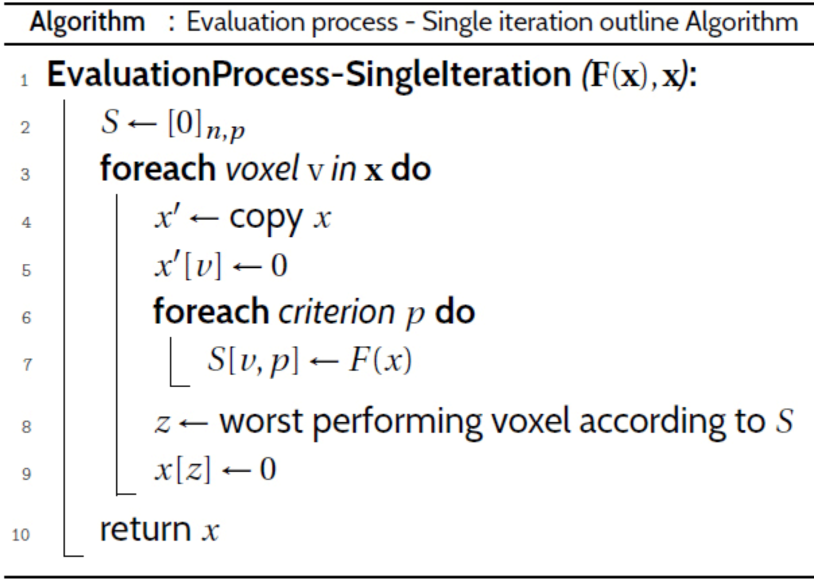
A(x): total surface of exterior faces
V(x): volume inclosed in these faces

STAGE 2

METHODOLOGY_Step4

Method 1: Iterative evaluatio





Algorithm : Evaluation process - Single iteration outline Algorithm

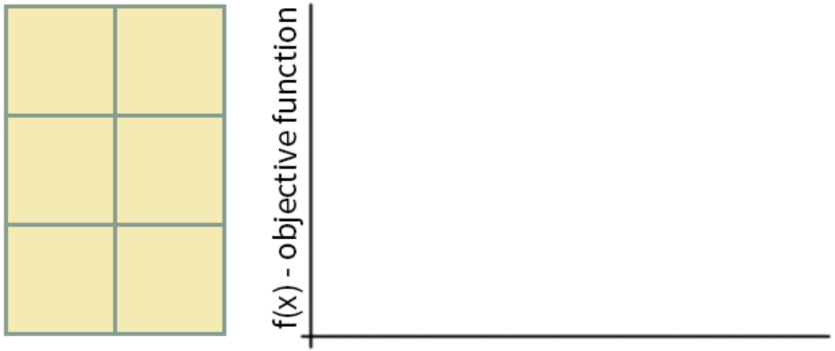
```
EvaluationProcess-SingleIteration ($\mathbf{F}(\mathbf{x}), \mathbf{x}$):
    $S \leftarrow [0]_{n,p}$
    foreach voxel $\mathrm{v}$ in $\mathbf{x}$ do
        $x' \leftarrow$ copy $x$
        $x'[v] \leftarrow 0$
        foreach criterion $p$ do
            $S[v,p] \leftarrow F(x)$
        $z \leftarrow$ worst performing voxel according to $S$
        $x[z] \leftarrow 0$
    return $x$
```

STAGE 2

METHODOLOGY_Step4

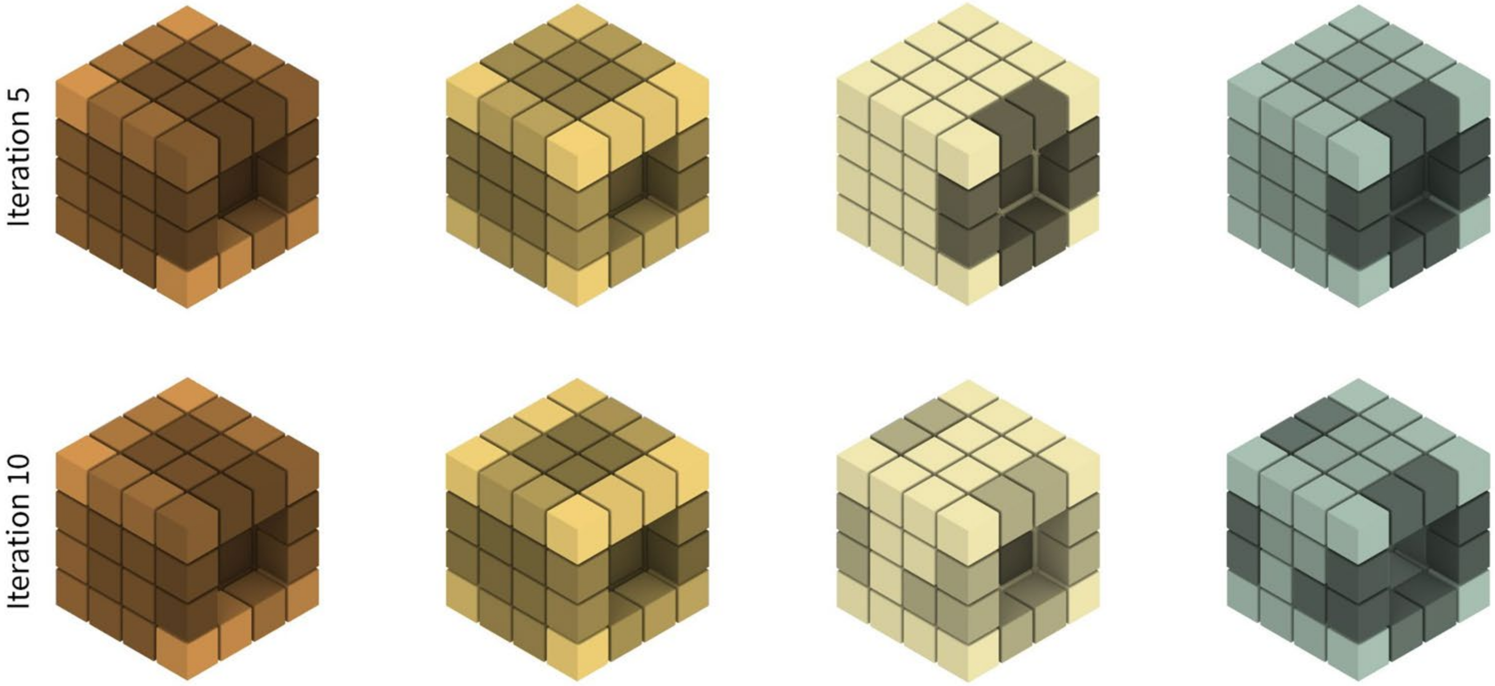
Method 2: Minimize Objective functio

Design Space

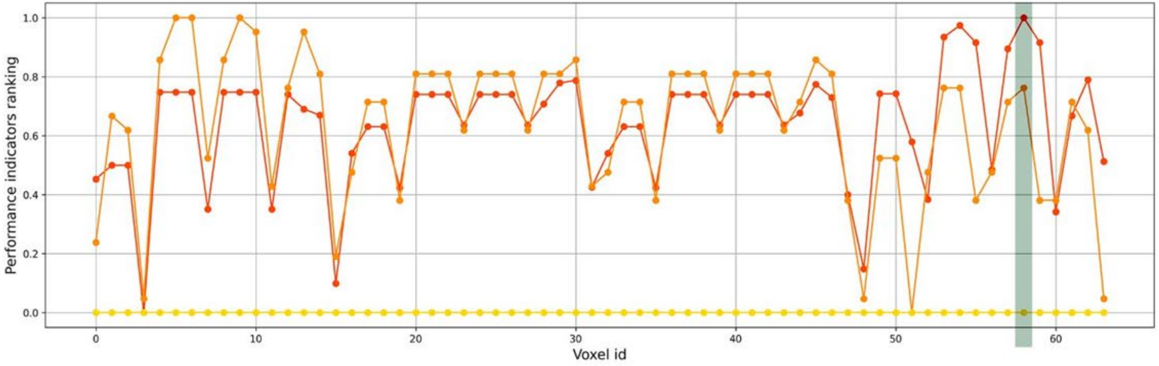


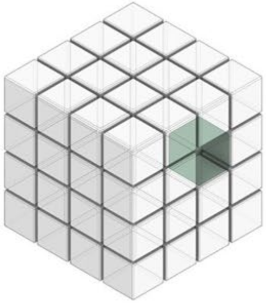
$x = [1\ 1\ 1\ 1\ 1\ 1]$

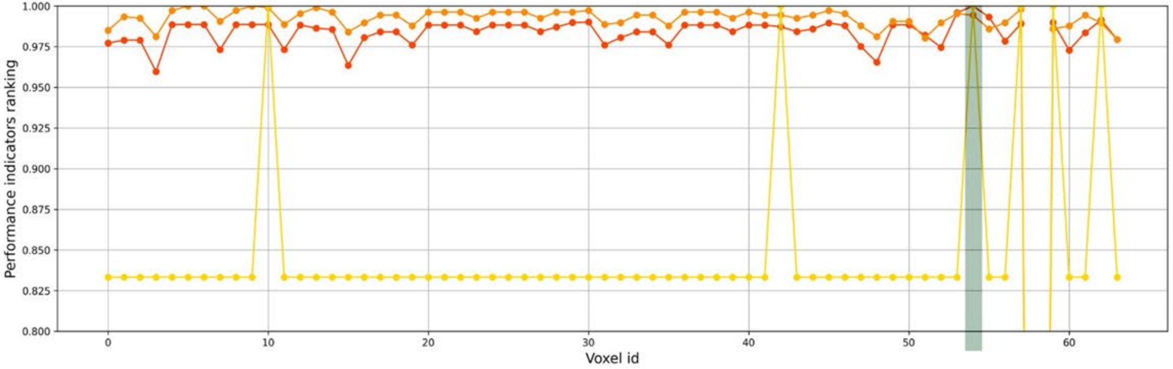
ITERATIVE EVALUATION STAGES

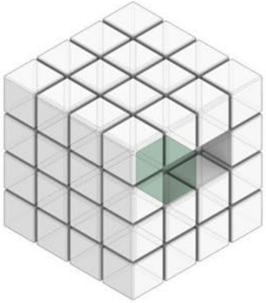


ITERATIVE EVALUATION STAGES

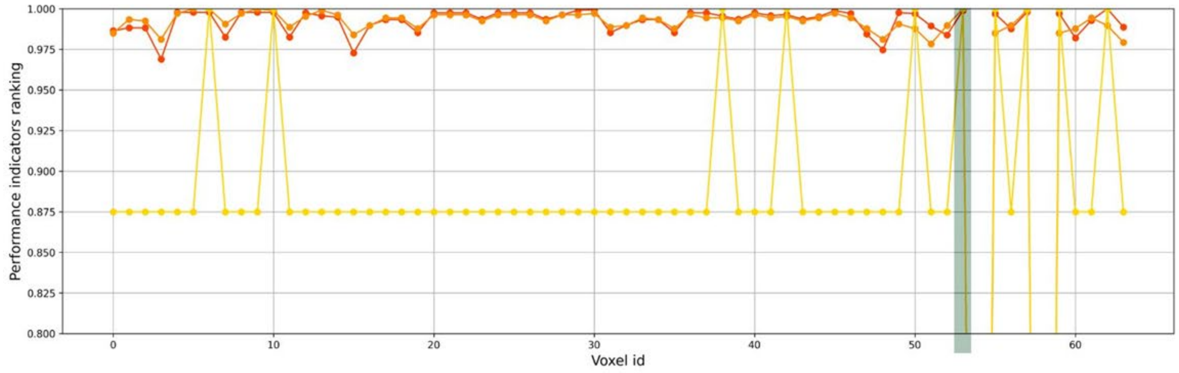


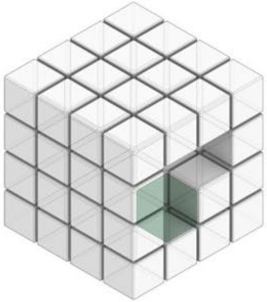


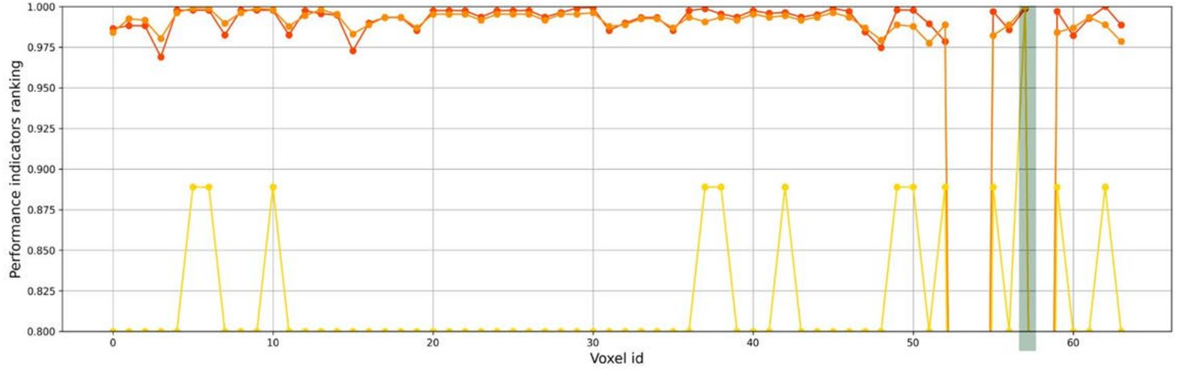


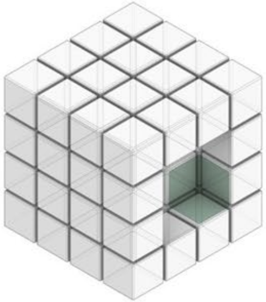


ITERATIVE EVALUATION STAGES



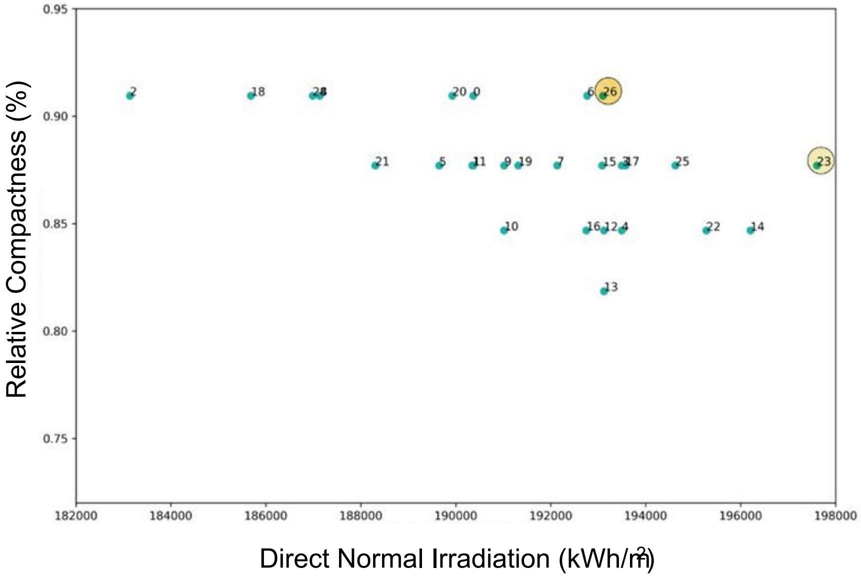


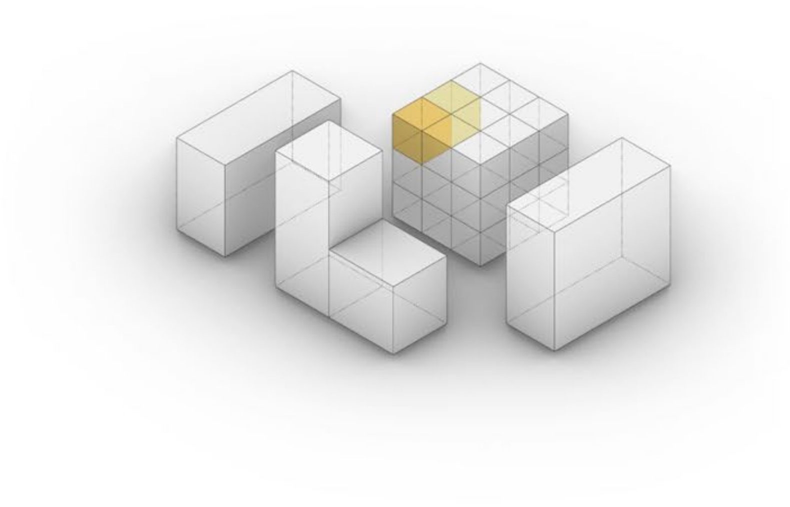




ITERATIVE EVALUATION STAGES

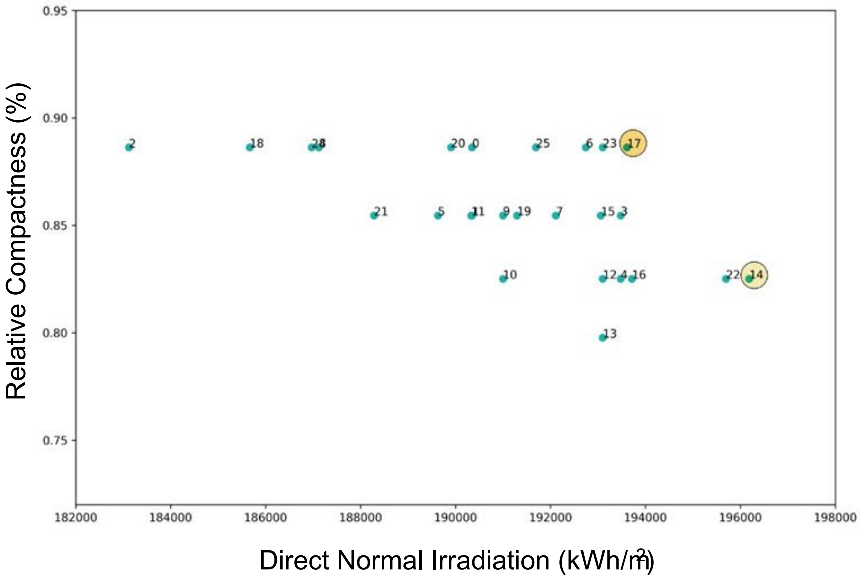
Iteration 1

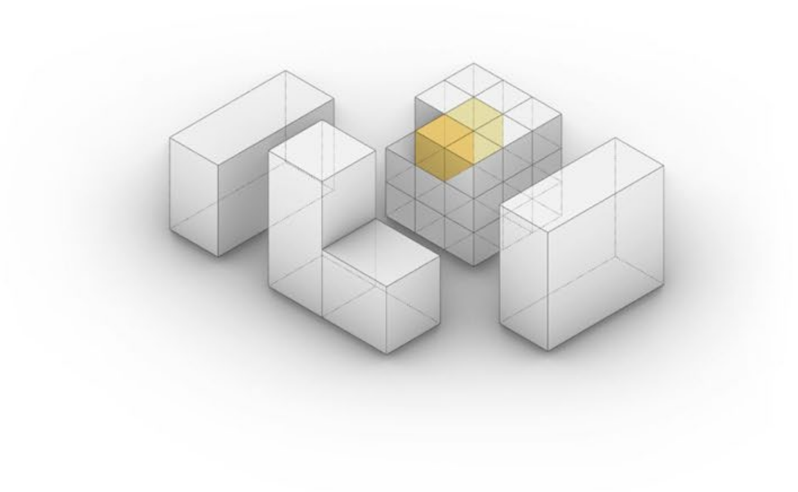




ITERATIVE EVALUATION STAGES

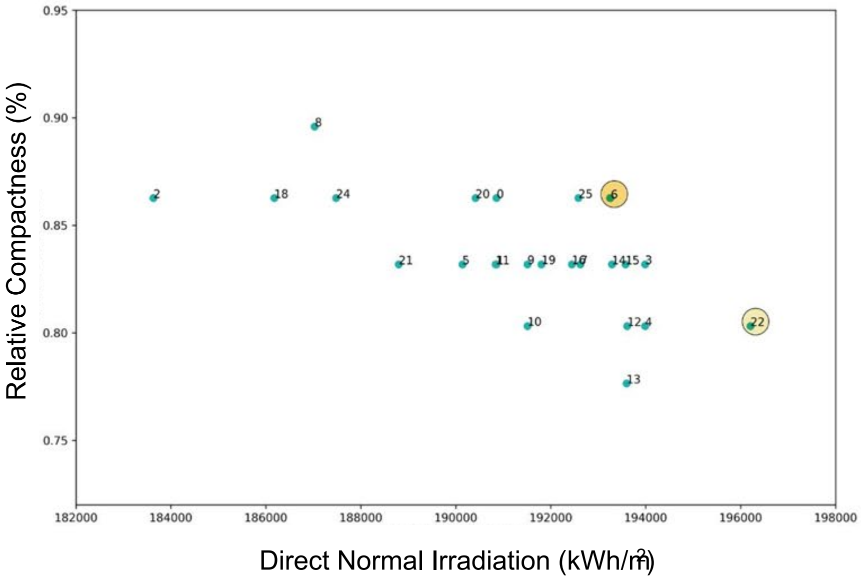
Iteration 2

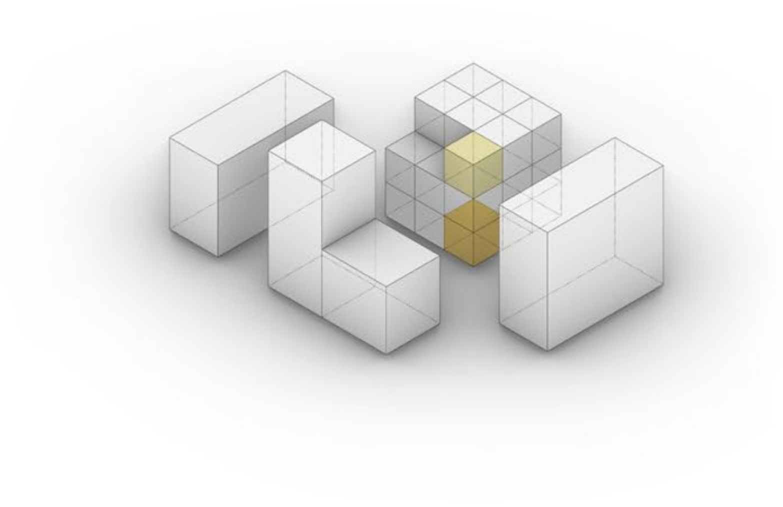




ITERATIVE EVALUATION STAGES

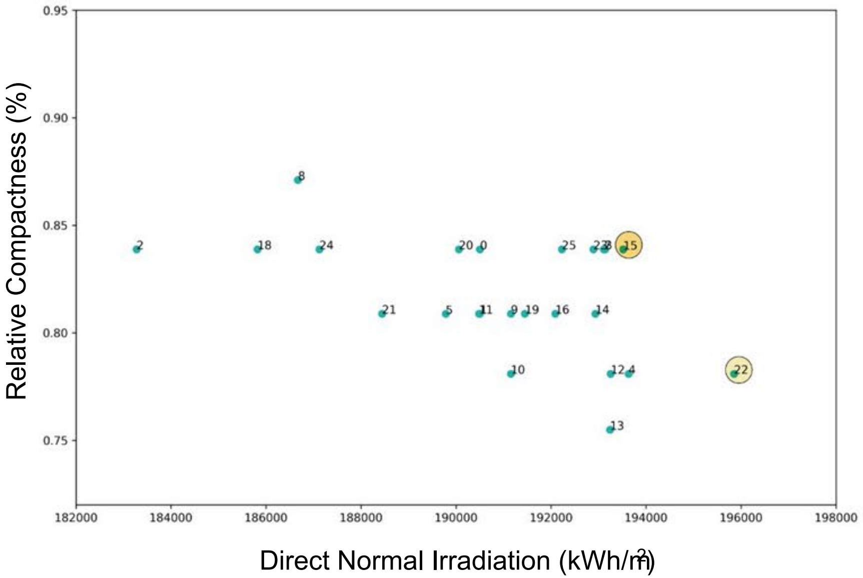
Iteration 3

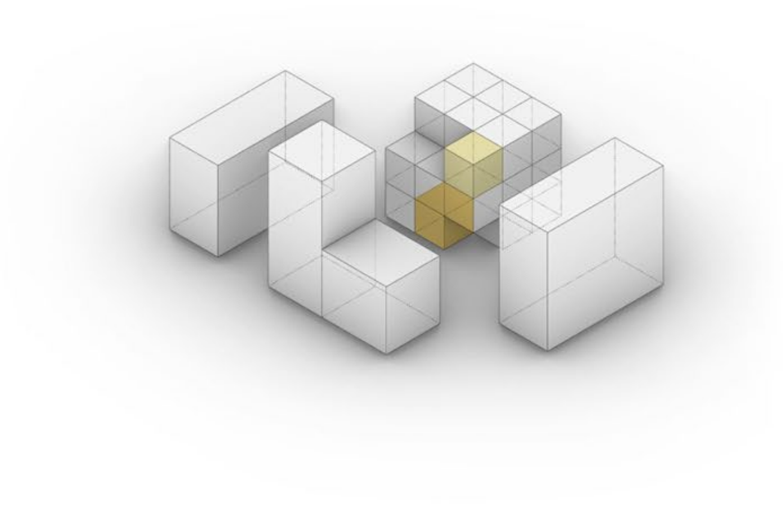




ITERATIVE EVALUATION STAGES

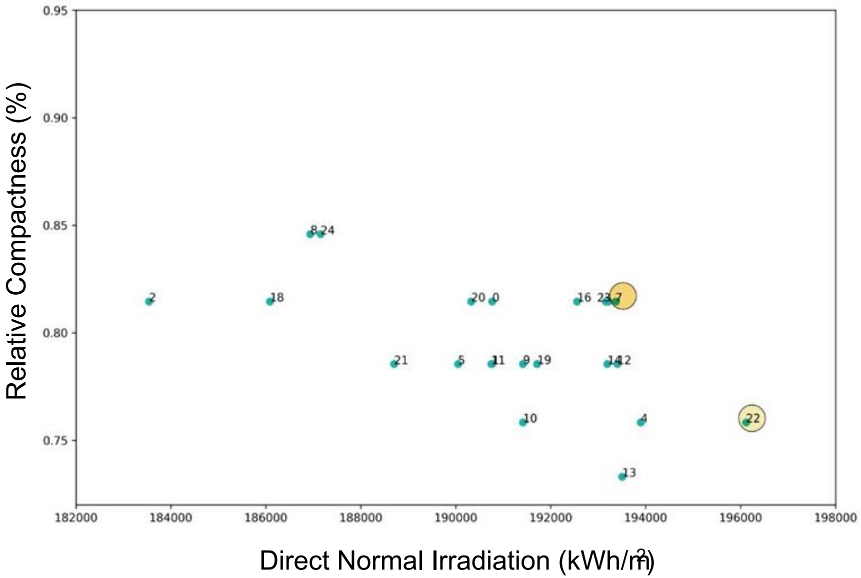
Iteration 4

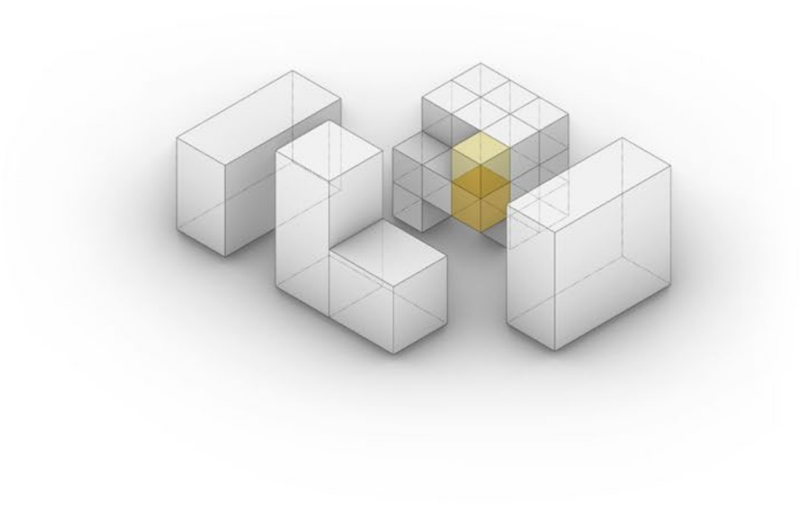




ITERATIVE EVALUATION STAGES

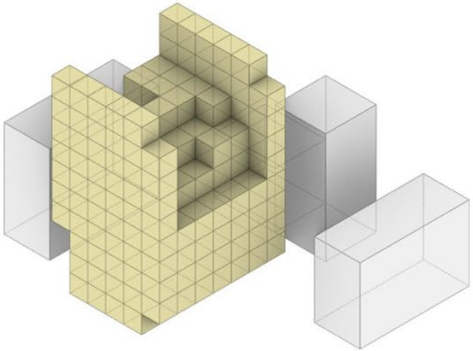
Iteration 5

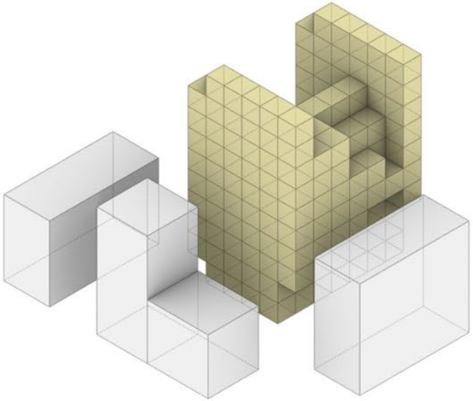




DIVERSITY OF RESULTS_Context

Method 1





Envelope resolution

○ L ● M ○ H

Context

● 1 ○ 2 ○ 3

Performance indicators

● DNI ○ DS ● RC

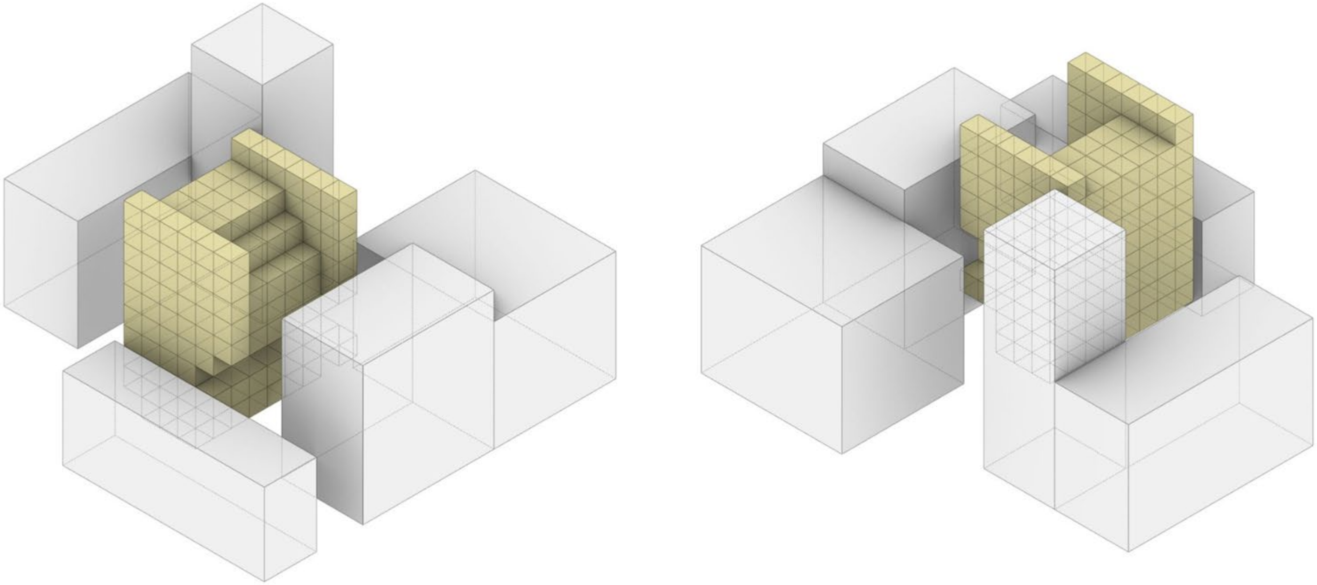
Optimization target

● A ● W ● Sp ● Su

Location

DIVERSITY OF RESULTS_Context

Method 1



Envelope resolution

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Context

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Performance indicators

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Optimization target

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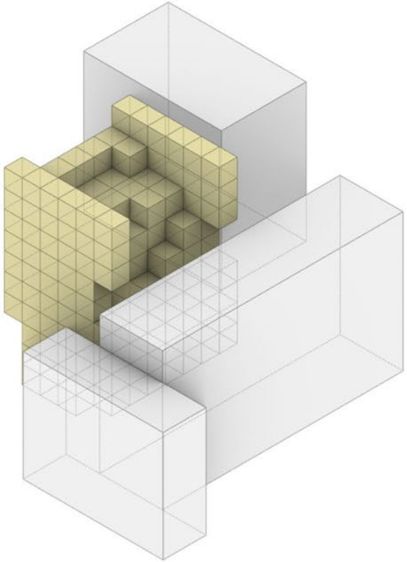
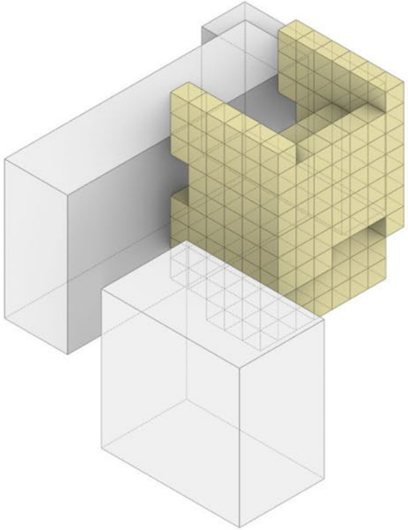
Location

DIVERSITY OF RESULTS_Context

Method 1





Envelope resolution

○ L ● M ○ H

Context

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Performance indicators

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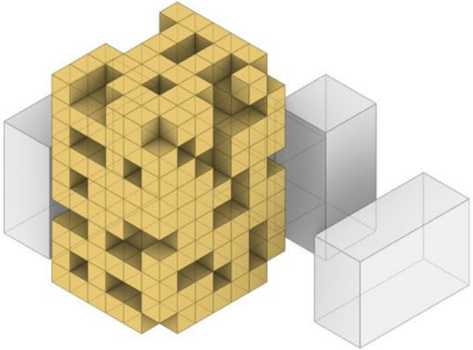
Optimization target

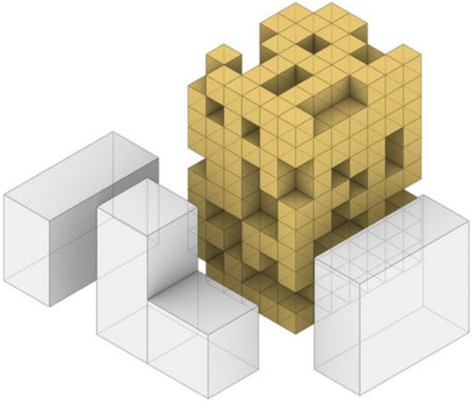
● A ● W ● Sp ● Su

Location

DIVERSITY OF RESULTS_Context

Method 2





Envelope resolution

○ L ● M ○ H

Context

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Performance indicators

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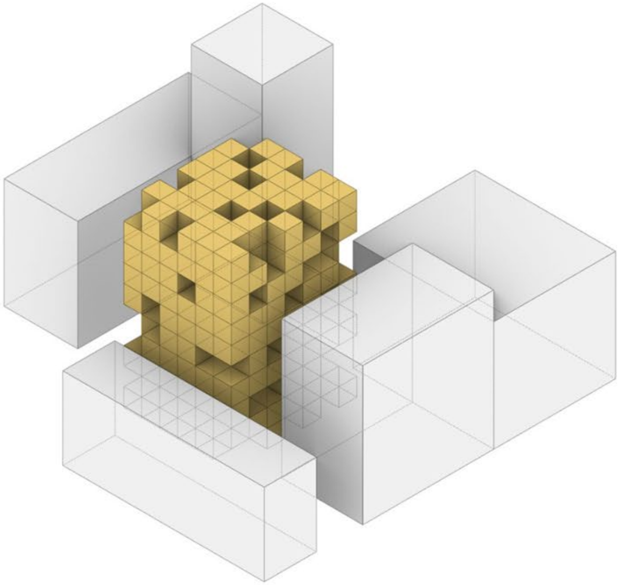
Optimization target

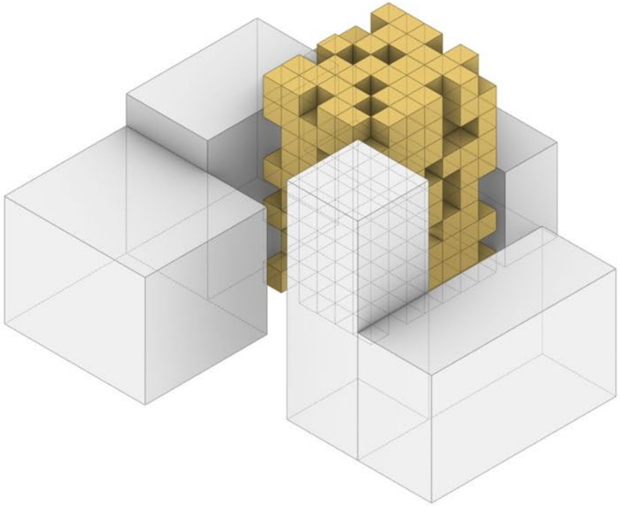
● A ● W ● Sp ● Su

Location

DIVERSITY OF RESULTS_Context

Method 2





Envelope resolution

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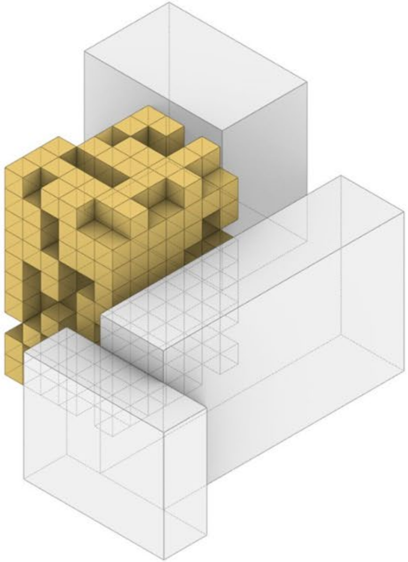
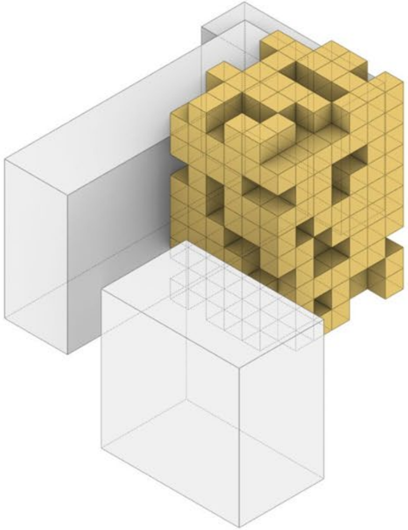
DIVERSITY OF RESULTS_Context

Method 2





Envelope resolution

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○ 1 ○ 2 ● 3

Performance indicators

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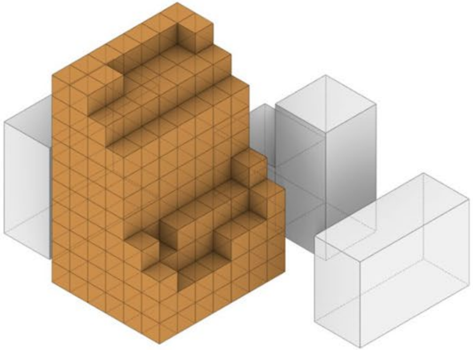
Optimization target

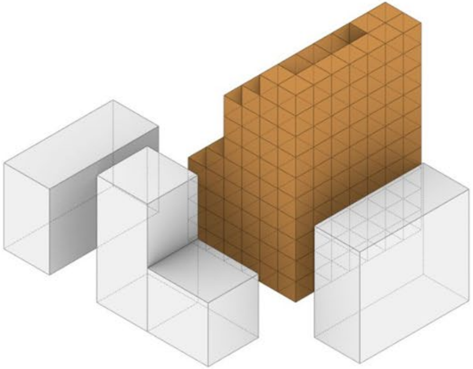
● A ● W ● Sp ● Su

Location

DIVERSITY OF RESULTS_Context

Method 3





Envelope resolution

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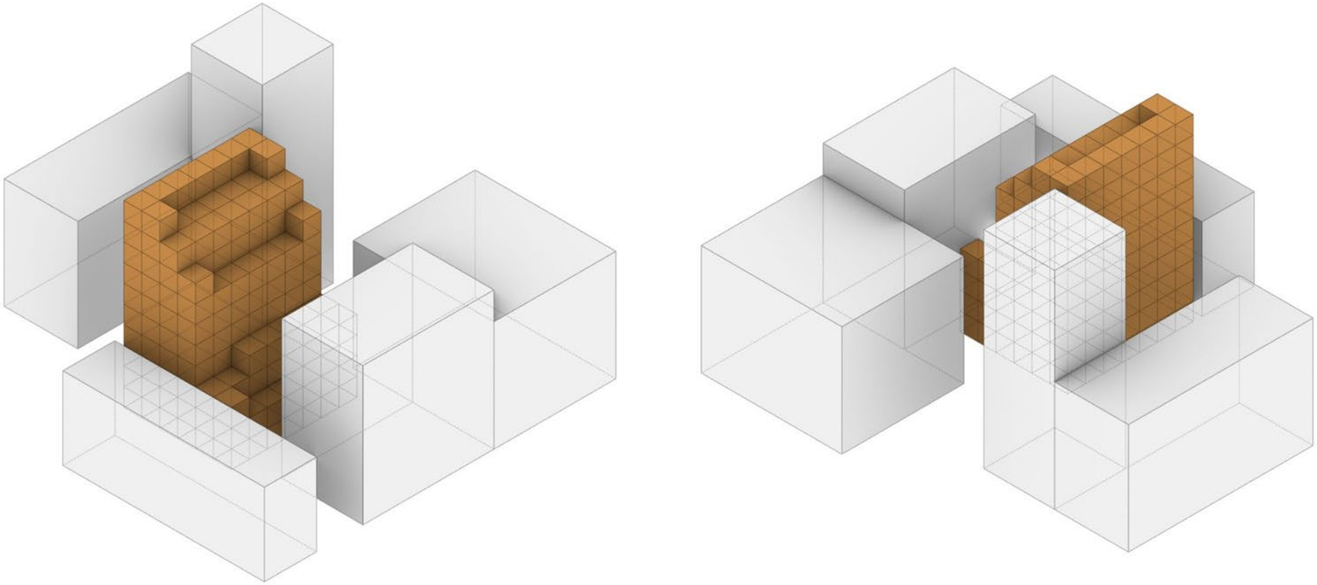
DIVERSITY OF RESULTS_Context

Method 3



Envelope resolution

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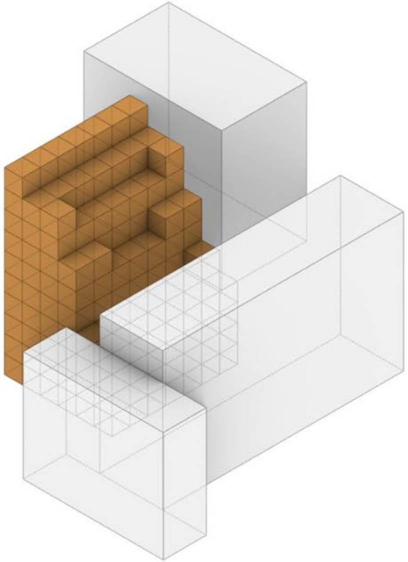
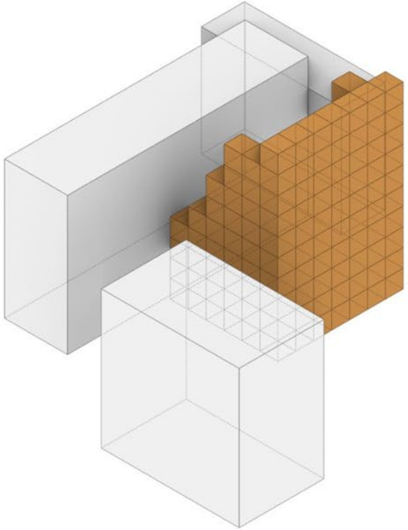
DIVERSITY OF RESULTS_Context

Method 3





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