Humble Giants

Computational Intelligence for designing Sustainable High-rise Buildings

Delft University of Technology

Faculty of Architecture and the Built Environment

MSc Track Building Technology

Sustainable Design Graduation Studio

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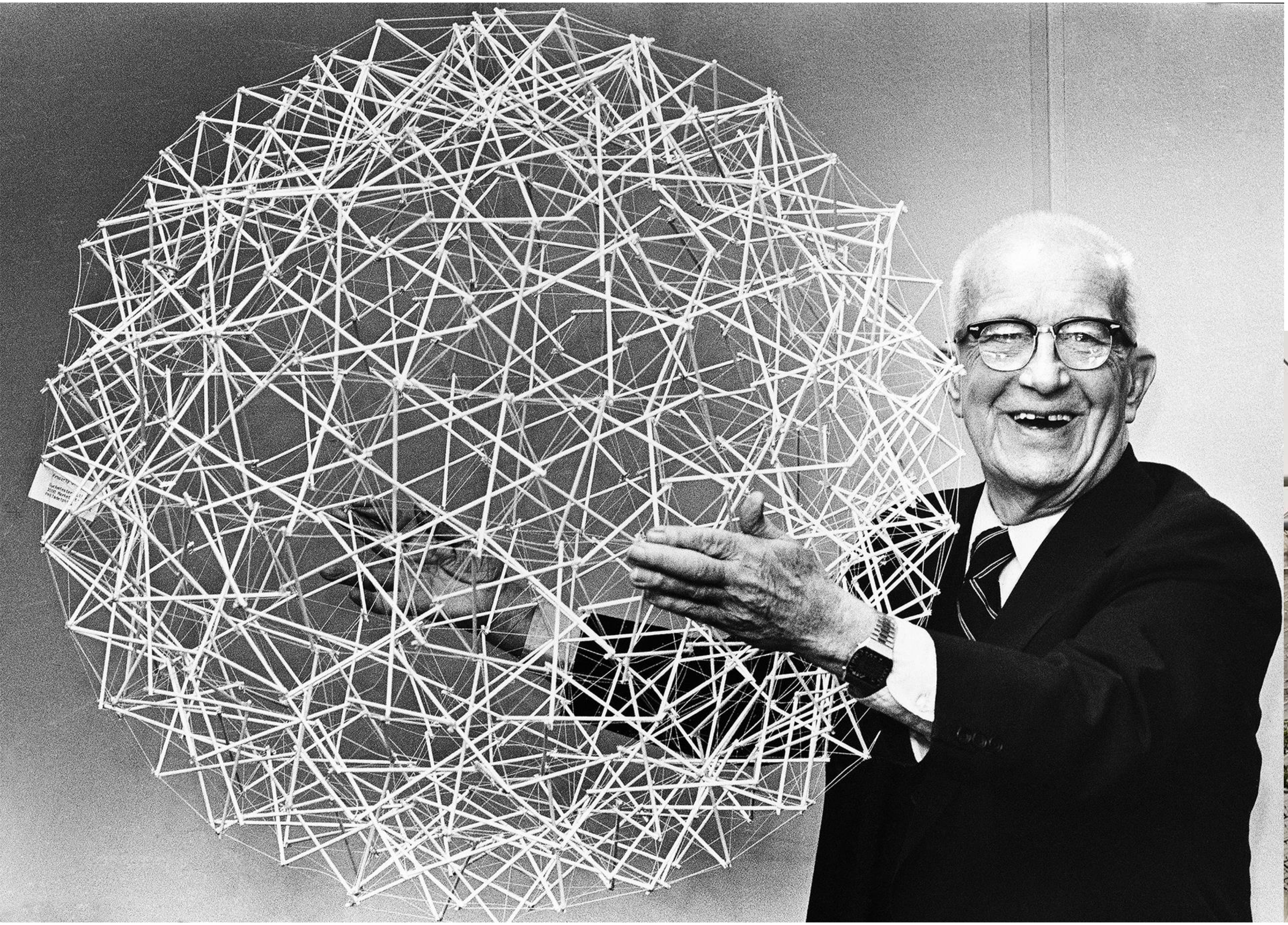
(Daniels, 2019)

High-Tech Origins



Buckminster Fuller – Tensegrity model

"I am a passenger on spaceship earth" – Buckminster Fuller

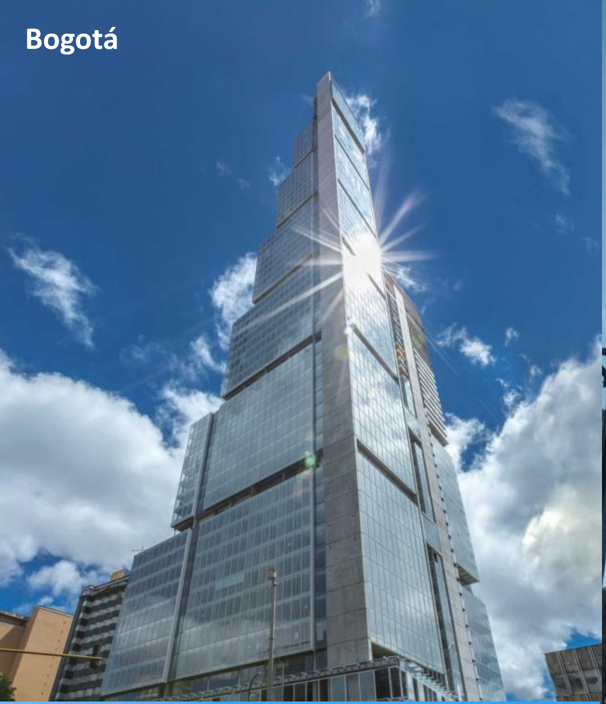
Frei Otto – Munich Olympic Stadium

High-Tech


Norman Foster – HSBC, Honk Kong - 1985


Norman Foster Commerzbank, Frankfurt - 1994


Richard Rogers – Lloyds of London - 1986


Bogotá

New York

Buenos Aires

London

Berlin
DB

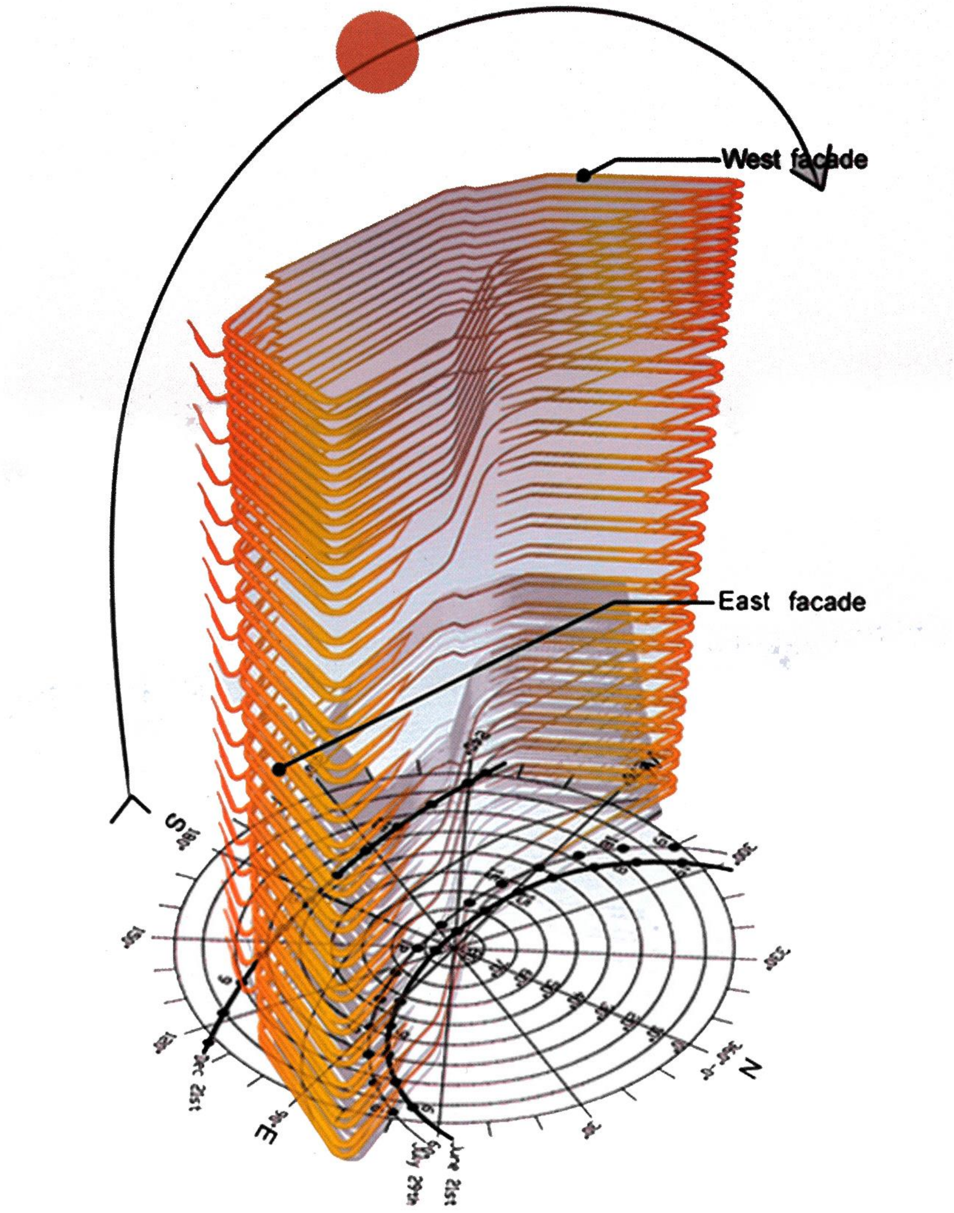
London

Mark Lascelles Thornton, “The Happiness Machine”

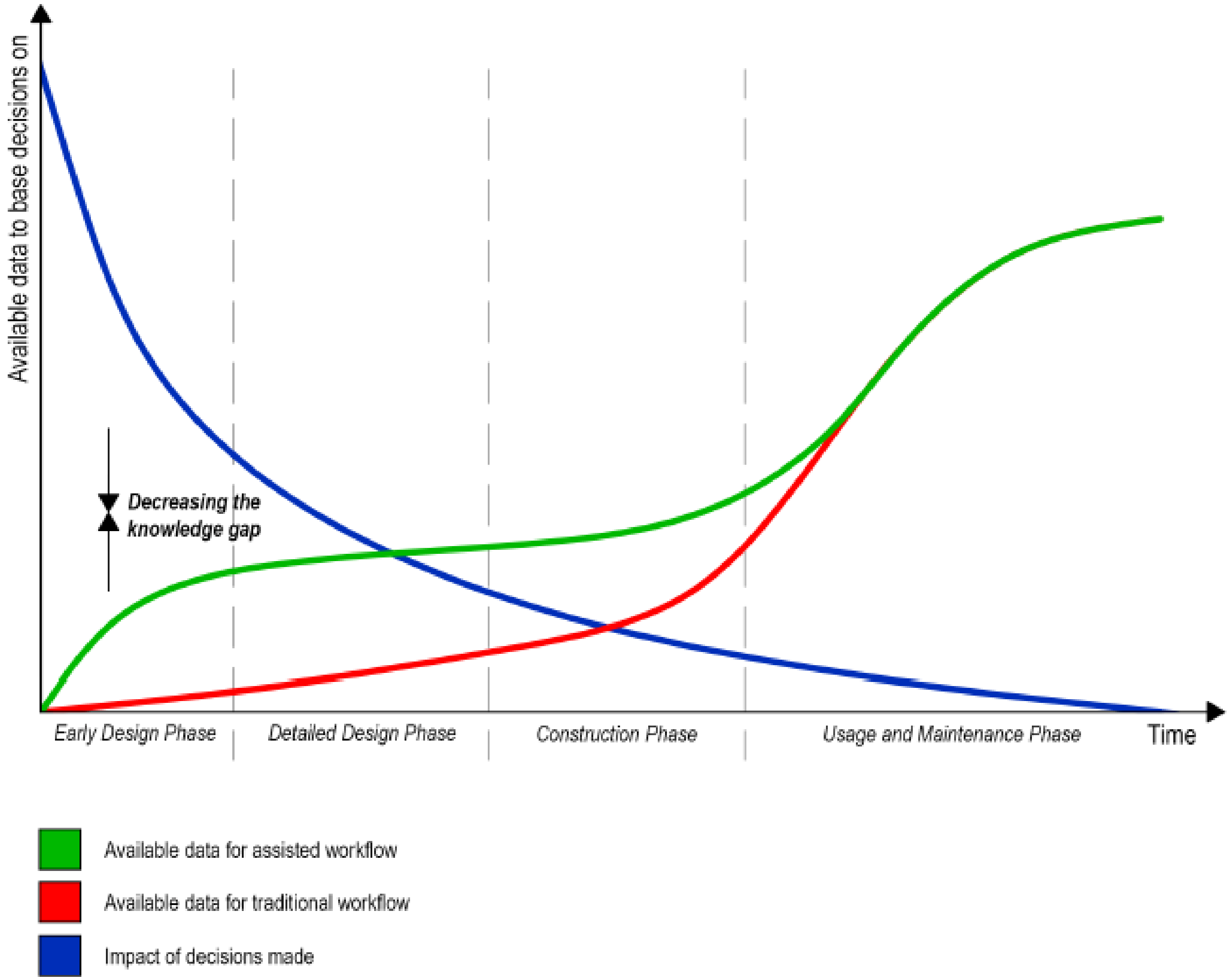
Locality in Design

"Ecological design is not just about low-energy systems; to be fully effective, these technologies need to be thoroughly integrated into the building fabric; they will also be influenced by the physical and climatic conditions of the site. The nature of the problem is, therefore, site-specific…"

- Ken Yeang



Early stage design



Impact of decisions during design process (Hassan A. Sleiman, 2017)

Problem Statement

Sustainable High-Rises *should be designed contemplating locality in design during* ***early concept stage*** *of the design process.* ***Computational simulations*** *and optimization can help the designer to identify promising design solutions,* ***however****, existing simulations are* ***computationally expensive*** *and thus cumbersome during this initial stage, therefore designers rarely design with enough contextual information.*

- High Rises
- Sustainability
- Computational optimization

What is Sustainability?

Themes

- Daylight
- Façade Technologies
- Vitality / Social
- Green / Water
- Wind Shape
- Natural Ventilation

Categories

- Efficient Usage
- Energy Production

Type	1	Daylight	Description	Limitations / Comments	Climate Type	Example	Pg
Use	1.1	Solar Access	Public places designated to have full sunshine "sun Spots" during their most intensive use or high frequency periods	Requires proactive rather than reactive city planning.	Temperate	Rotterdam City Planning	99
Use	1.2a	Solar Orientation	Orientation of the tower specific to the sun path of tropical climate	buiding cores are placed on the hot east and west facades	Tropical	IBM Plaza - Kuala Lumpur	170
Use	1.2b	Solar Orientation	Same principles, temperate climate - Maximize solar gain into interior spaces in winter and maximize solar shading in summer	Peripheral apartments enclose an internal atrium	Temperate	Bishopsgate Tower -London	174
Use	1.3	Diagonal Lighshaft	Atrium and Diagonal lightshaft - diagonal opening through the section of the building	Allows for more natural sunlight to enter deepest sections of the building	Tropical	Solaris Fusionopolis - Singapour	182
Use	1.4	Ecocells	Sun wells that allow daylight to penetrate into the basement levels	Allows for natural sunlight and ventilation	Tropical	Spire Edge - India Manesar	180
Use	1.5	Horizontal Louvers	The size and depth of the louvers was determined by the sunpath	Louvers also serve as light shelves	Tropical	Spire Edge - India Manesar	180

Type	2	Facade Tech	Description	Limitations / Comments	Climate Type	Example	Pg
Prod	2.1	PV Panels on facades	Vertical surface solar energy generation - The farther north / south hemispheres, the more productive the facade can be	Amsterdam: Average maximal Solar angle of 37 (more vertical than horizontal)	Temperate	Amsterdam	
Prod	2.2	Solar Collectors	Use of limited roof space for parabolic solar collectors	Although High-rises do not have extensive roof space	Temperate	Villa Flora	139
Use	2.3	Louvered Facades	Louvered panesl protect the facade from solar gain	Design determined by orientation	Tropical	Menara Mesiniaga	171
Use	2.4	Balconies	Deeply recessed balconies and planter poxes	Provide sunshading	Tropical	Central Plaza Tower	172
Use	2.5	Recessed Windows	Deeply recessed windows	Solar heat gain protection	Tropical	Menara Umno Penang	172
Use	2.6	Buffer Cores	Cores serve as thermal buffers	Located in zones with highest solar heat gain	Tropical	Singapore National Library	176
Use	2.7	Glazing	Low-E	low external thermal transfer value (ETTV) - 39 watts /m2	Tropical	Solaris Fusionopolis - Singapour	184
			Double glazing		Gen	General	
			Double glaziing Argon-filled cavities		Gen	General	
			Triple Glazing		Gen	General	

Type	3	Vitality / Social	Description	Limitations / Comments	Climate Type	Example	Pg
Use	3.1	Ecomimesis	State of stasis, the built environment that imitates an ecosystem that recycles and resuses byproducts to produce zero waste	Is not the result of adding more and more technological gadgetry	Gen	General	168
Use	3.2	Sky Courts / Gardens	Spiraling green garden connected to the surrounding landscape and sky courts and sky gardens	Culminate in rooftop swimming pool	Tropical	Menara Mesiniaga	171
Use	3.3	Vertical spatial continuity	Continuous landscaped ramp through the tower	Spacial continuity between street and the tower	Tropical	EDITT Tower - Singapore	173
Use	3.4	Comunal Skycourt	Sky gardens every 5th level to provide landscaped communal sky courts		Tropical	Bombay Glassworks tower - Mumbai	185

Type	4	Green / Water	Description	Limitations / Comments	Climate Type	Example	Pg
Use	4.1	Vertical Green landscapes	Provides shading, evaporative cooling and micro-climate improvements	High maintenance of Vegetation	Tropical	EDITT Tower - Singapore	173
Prod	4.2	Vertical Greenhouse	Vertical glazed greenhouse could be used for agriculture	Cannot yield as much as commercial farming, but provide locally grown fruit, vegetable, herbs and spice	Temperate	Villa Flora / Harvest Tower	140
Prod	4.3	Rainwater reuse	Rain water catchment, retention, storage and recycling		Tropical	Spire Edge - India Manesar	180
Use	4.4	Efficient Water Fixtures	low-flow rate fixtures and gray water flushing		Temperate	Leza Soho - Hangzhou, China	

Type	5	Wind	Description	Limitations / Comments	Climate Type	Example	Pg
Use	5.1	General Shape & Texture	Iso Standard - wind study to measure effects of building shape, texture and facade during preliminary design stage	Requires existing context, can change with future proposals		Generic	
Use	5.2	Aerodynamic Shape	Structure that promotes air acceleration through building, thus cooling interior by few degrees	Requires computational fluid dynamics (CFD software) or wind tunnel tests	Tropical	Singapore National Library	
Use	5.3	Aerodynamic Shape	Oval Shape	Reduces stress on superstructure generated by wind loads	Tropical	EDITT Tower - Singapore	174
Prod	5.4	Wind Turbines	Turbines in facade on rooftop level		Tropical	Miami COR building	
Use	5.5	Wind wing Wall	A 21 story heigh vertical projecti wall directed towards the prevailing wind	Creates positive and negative pressure zones that are very effective in providing natural ventilation through the common areas	Tropical	Menara Umno Penang	172

Type	6	Natural Ventilation	Description	Limitations / Comments	Climate Type	Example	Pg
Use	6.1	External Atrium	External atrium	Creates a wind shaft to cool the offices facing the atrium	Tropical	Kuala Lumpur Tower -Plaza Atrium	170
Use	6.2	Central Atrium	Central atrium open at the base	Creates a cool microclimate while allowing natural daylight to reach the circulation areas within the building	Tropical	Library of Singapore	176
Use	6.3	Vertical Atria Gardens	Vertical atria gardens / airwells and public spaces	Provide passive cooling	Dry	Ecobay Complex - Abu Dhabi	178
Use	6.4	Service Core Placement	Service core located on the hot side of the building	Naturally ventilated to reduce the air conditioning load on the offices	Tropical	Menara Boustead - Kuala Lumpur	171
Use	6.6	Cooridors	Naturally ventilated single-loaded corriders face the hot wester side of the site	Act as buffer, reducing insolation	Tropical	Casa del Sol - Kuala Lumpur	172

Use Effective Usage
Prod Production

Basic Climate types tropical, dry, temperate, cold and polar

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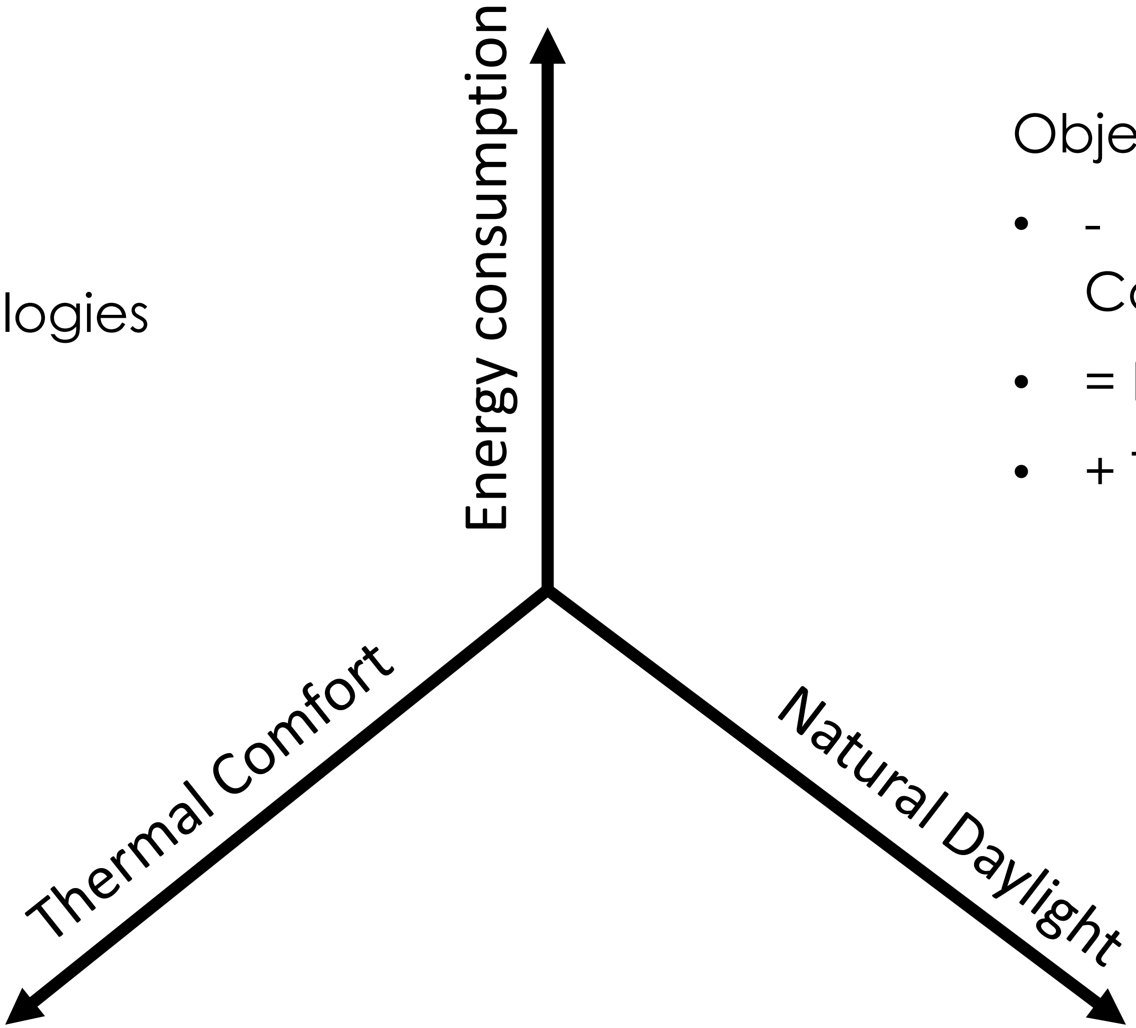


Objectives:

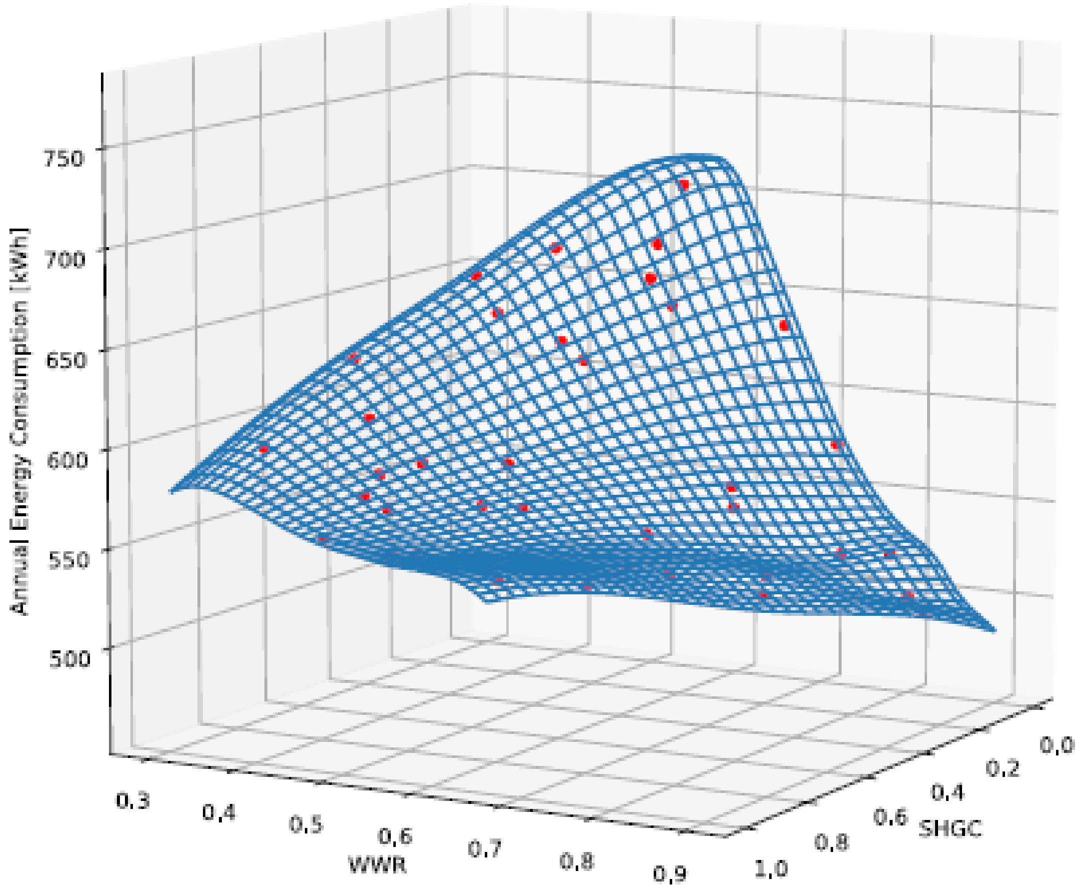
- - Energy Consumption
- = Natural Daylight
- + Thermal Comfort

Surrogate Modeling

Promising Results of up to 80% time reduction

Feed candidates from simulations, the more evaluations the more precise the surrogate will be

Can provide good solutions and contribute the designer for better understanding of the design problems



(Westermann & Evins, 2019)

Research Question

How can a computational method using surrogate modeling be used to quickly identify, and optimize the most influential factors and their combinations for context-based passive solutions of sustainable High-Rise office buildings during their initial design phase?

Sub questions

- How do different location/climates dictate the building's ideal **shape and orientation**?
- How does the general volumetric **context** of surrounding buildings affect its **shape and façade parameters**?
- How does position of its **Core** affect a building´s energy performance in relation to its **location/climate**?
- What is the **pareto-optimality** of these parameters when simultaneously seeking energy consumption, thermal comfort and natural daylight optimums?
- What are the key **validation metrics** and features necessary for obtaining suitable **surrogate models.**

Energy Consumption

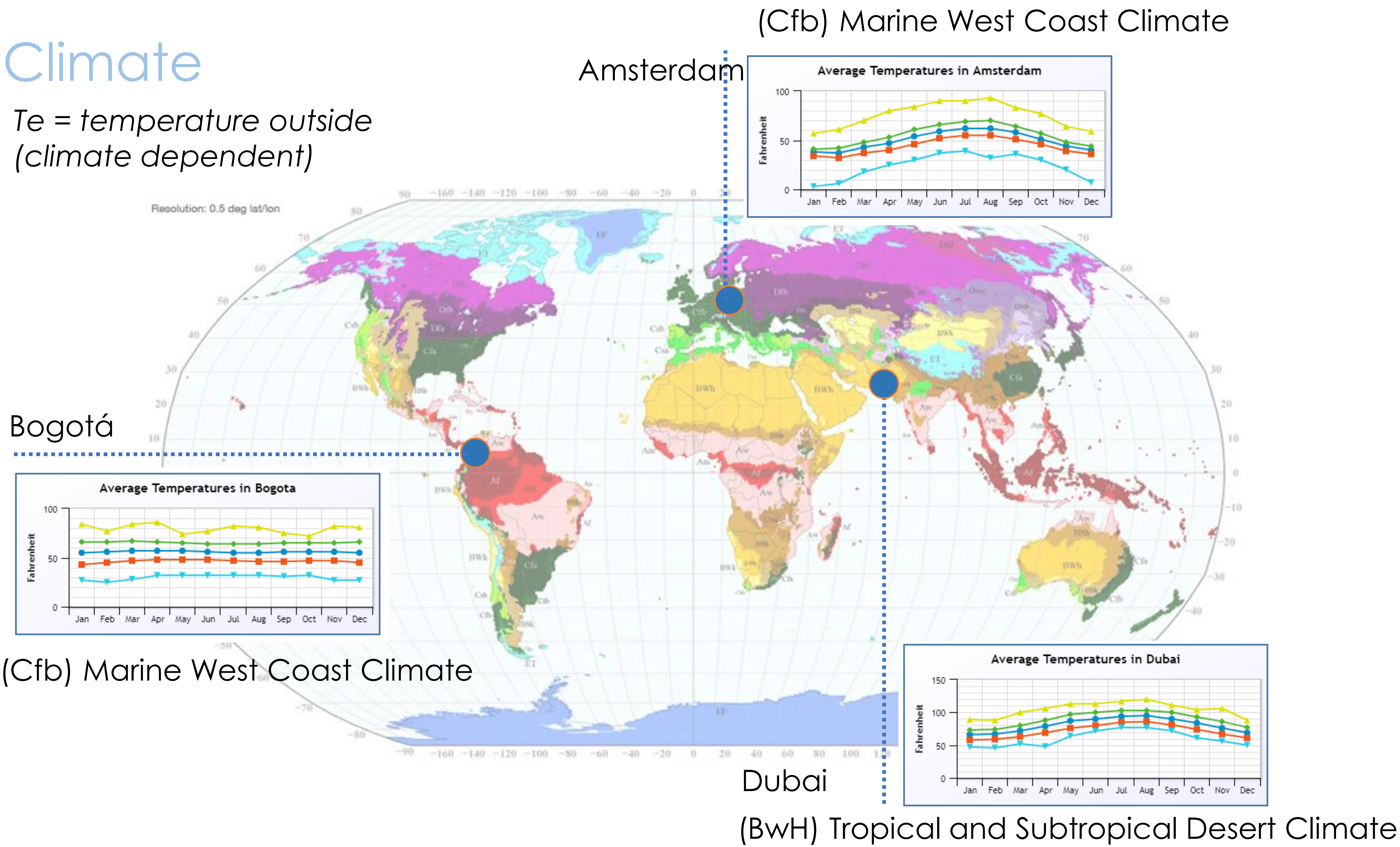
-/+Qtransmission -/+ Qventilation - Qinfiltration + Qsun + Qinternal - Qenergyuse = 0

Qt + Qv + Qi + Qsun + Qint= -Qenergyuse

Qt= Σ U *A*(Te - Ti)	Qv= Vvent*ρ*Cp*(Te – Ti)	Qi= Vi*ρ*Cp*(Te – Ti)	Qsun =Aglass*qsun*g	Qint =
U = U-value *A = area of the façade* *Te = temperature outside (climate dependent)* *Ti = temperature inside (comfort dependent)*	*Vvent = Ventilation flow* *ρ = air density = 1.2* *Cp = air heat capacity* *Te = temperature outside (climate dependent)* *Ti = temperature inside*	*Vi = infiltration flow (0.2)* *ρ = air density = 1.2* *Cp = air heat capacity* *Te = temperature outside (climate dependent)* *Ti = temperature inside (comfort*	*Aglass = glazing area* *g = g-value* *qsun = Radiation on glass (climate dependent)*	Qpeople + *Qlight +* *Qequipment*

Climate

Te = temperature outside
(climate dependent)



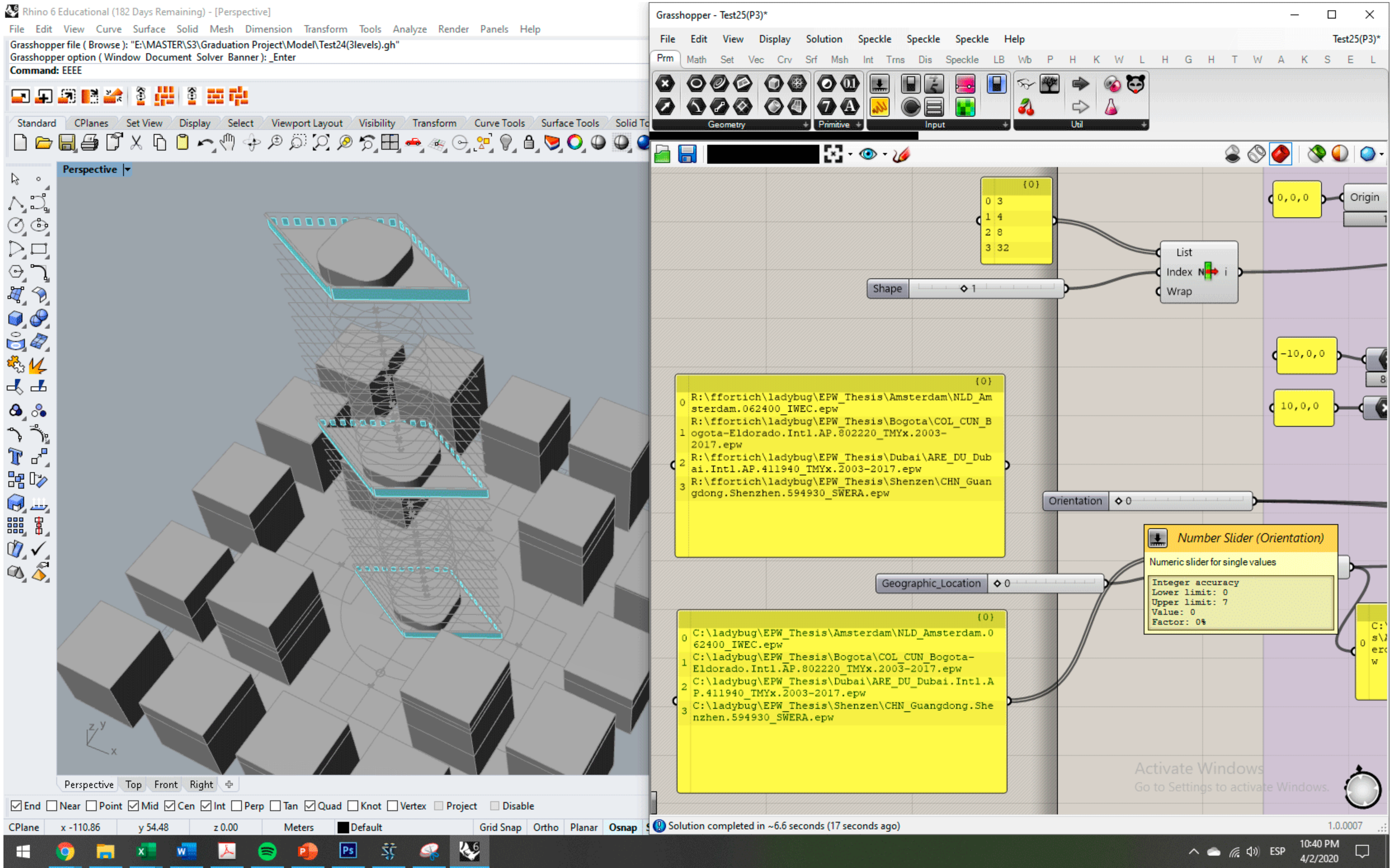
Weather Base, 2020)

Parameters Shape

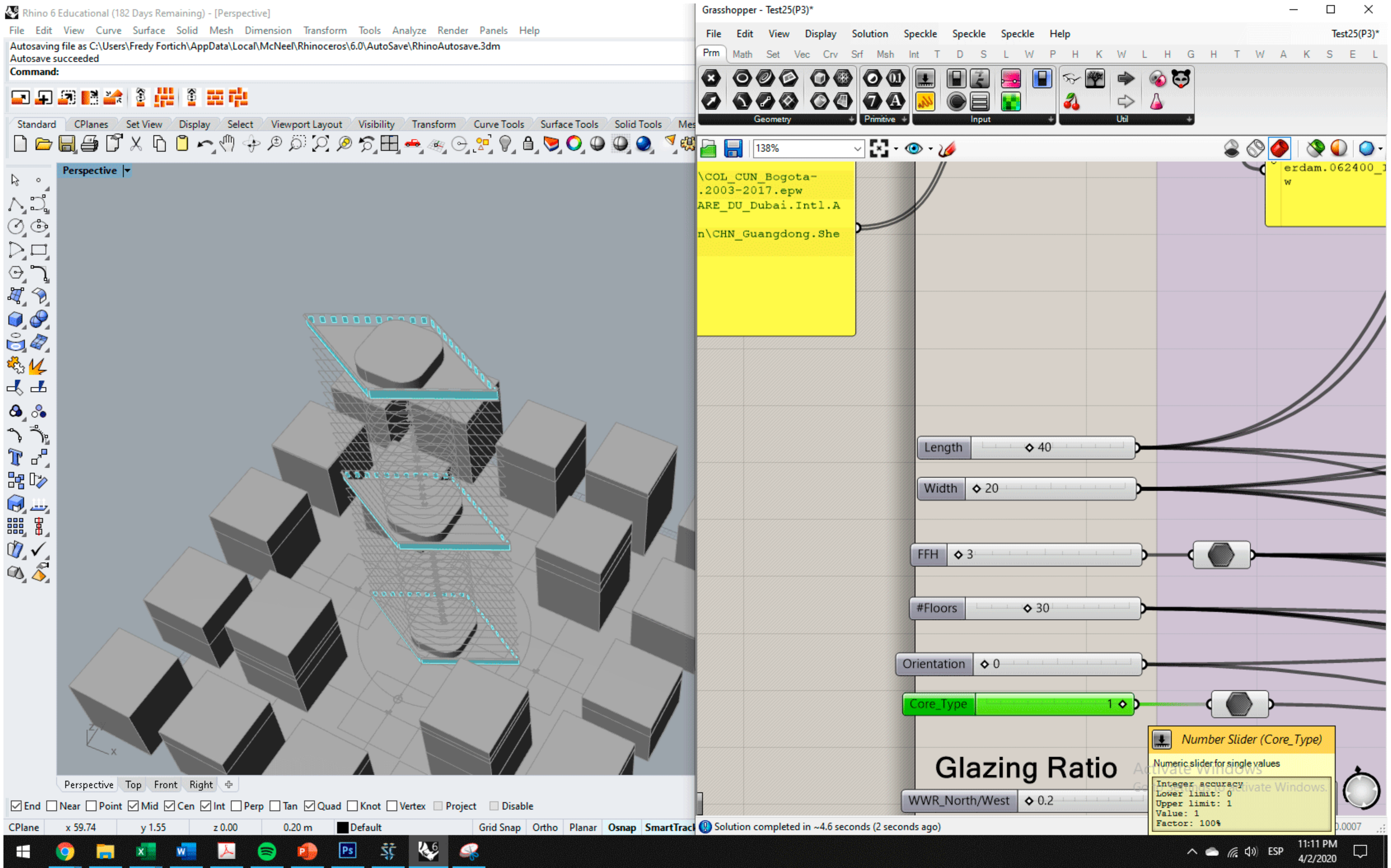
Topic	Parameter type	Building Parameter	ID	Description	Units	Range Min	Range Max	Data Interval	# of Inputs
2a Shape	Dynamic	Building Orientation	BO	Angle in relation to north	°	0	315	45	7
		Shape	BS	General shape: Triangle, Pararellogram, Octagon, Ellipse	# of Segments	3, 4, 8, 32		-	4
		Length	BL	Length of plan	m	20	80	20	4
		Width	BW	Width of plan	m	20	60	20	3
		Analysis Level	AL	Building where building level is performed	floor level	0	30	15	3
		Floor to floor Height	FFH	Distance from floor to next floor	m	3	4.5	0.5	4
		Core_Type	Core	Position of the core in relation to the plan	-	Central Core/ 1 Lateral Core		-	2
		Geographic Location	Loc	Options for 4 different locations and climates	-	Amsterdam / Bogota /Dubai		-	3

- Orientation
- Shape
- Length & Width
- Analysis Level (Context)
- FFH
- Core Type
- Location

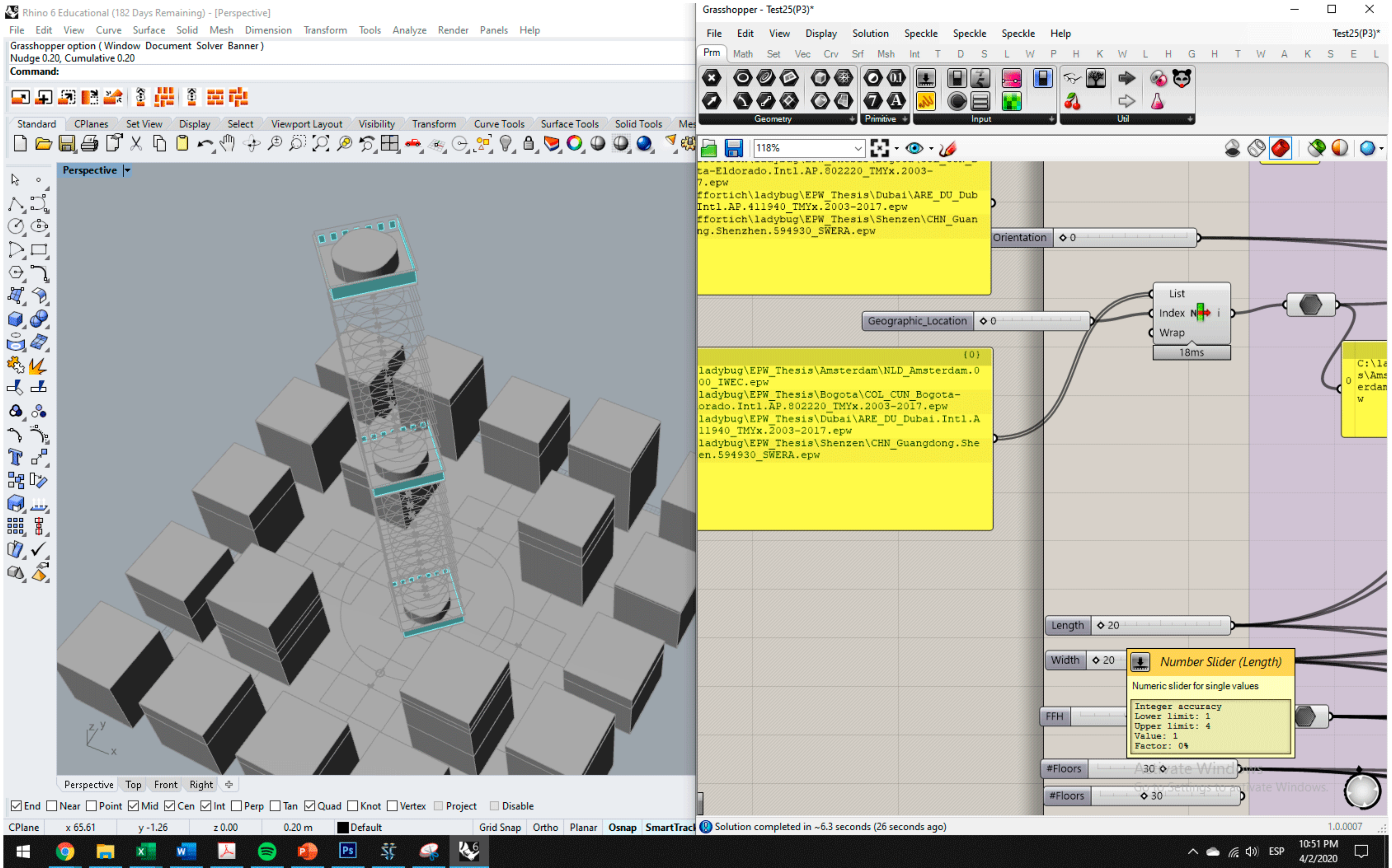
0. Parameters – Orientation



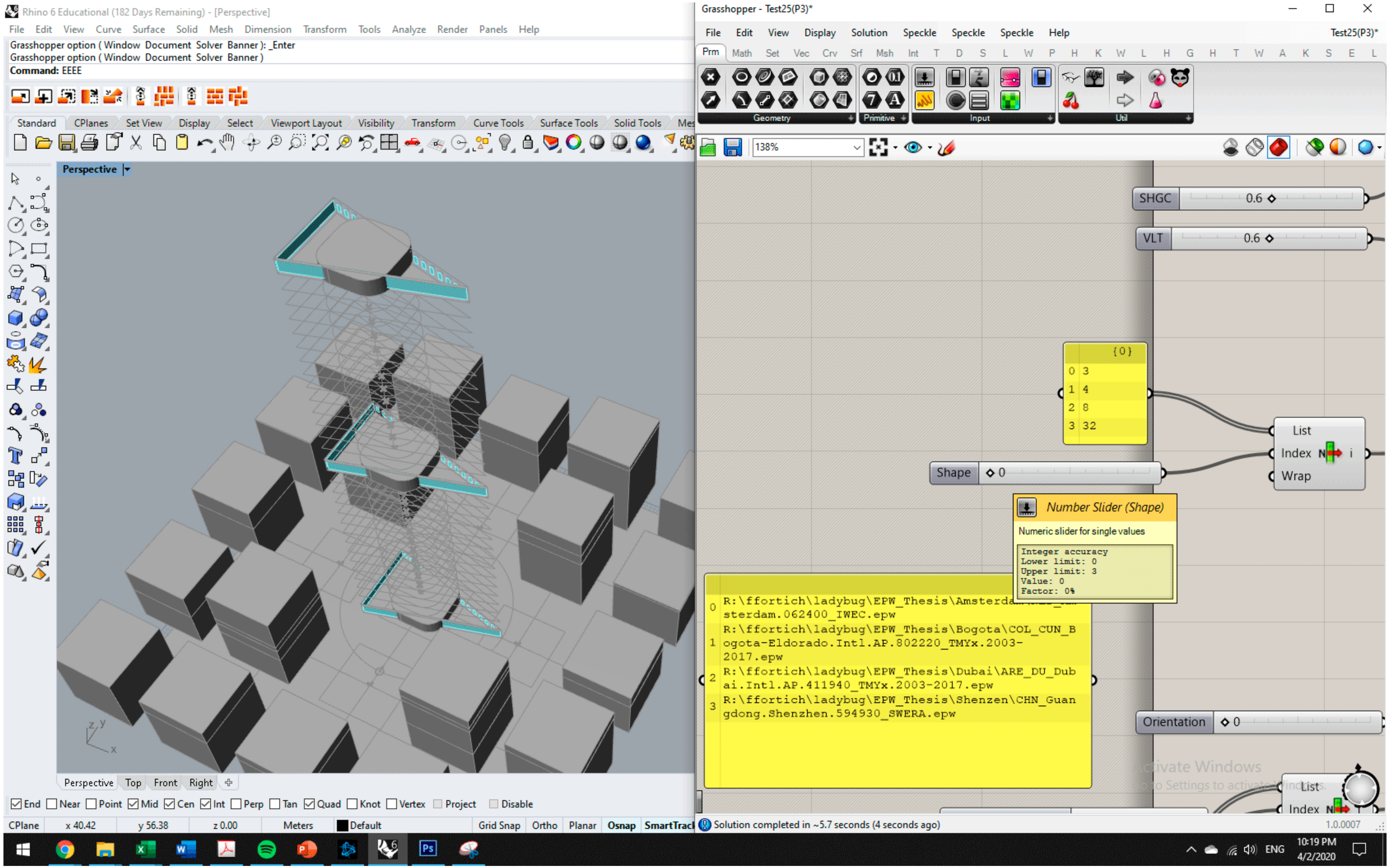
0. Parameters – Core & Orientation



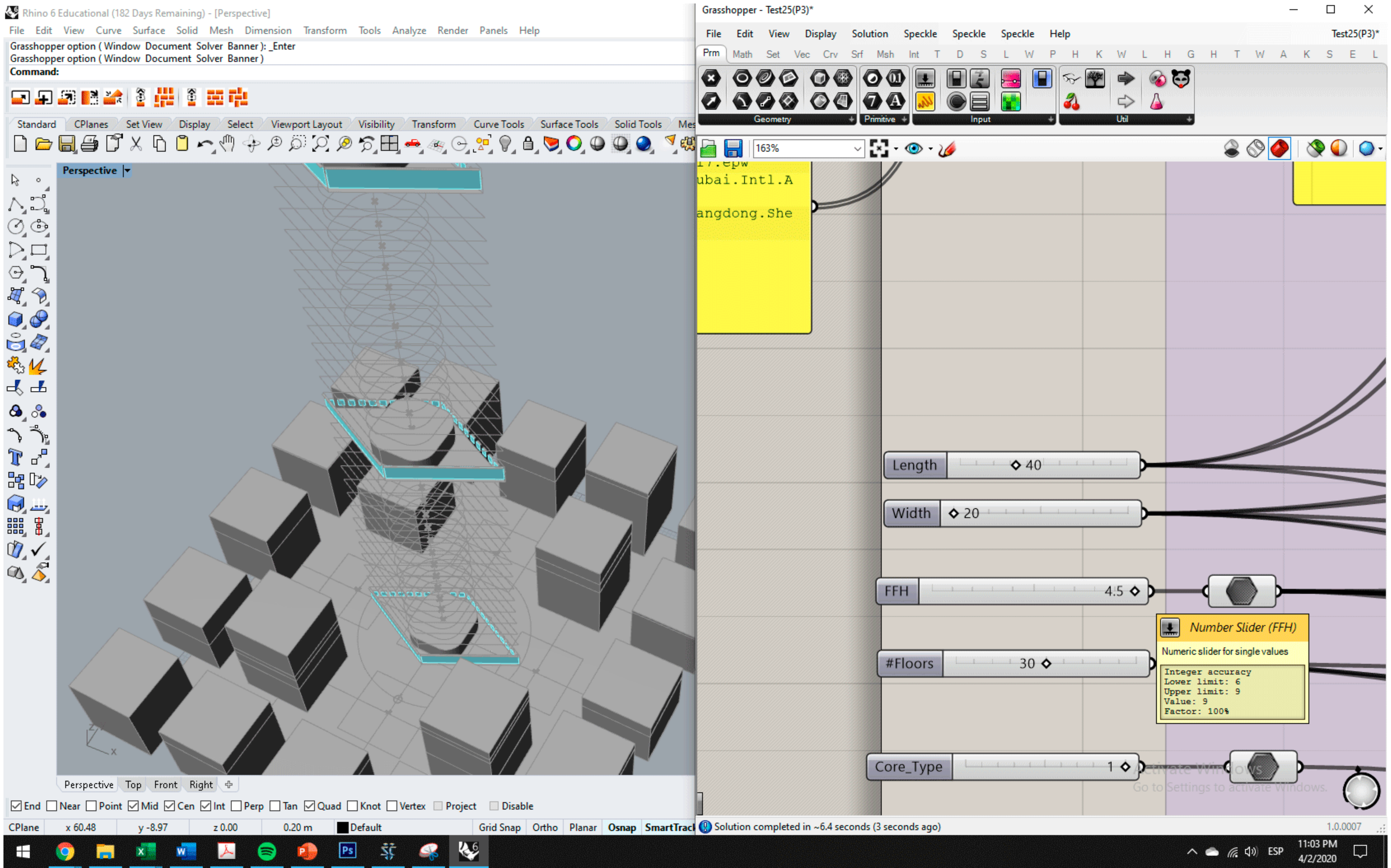
0. Parameters – Length / Width



0. Parameters – Shape



0. Parameters – Floor Heights / Total Height



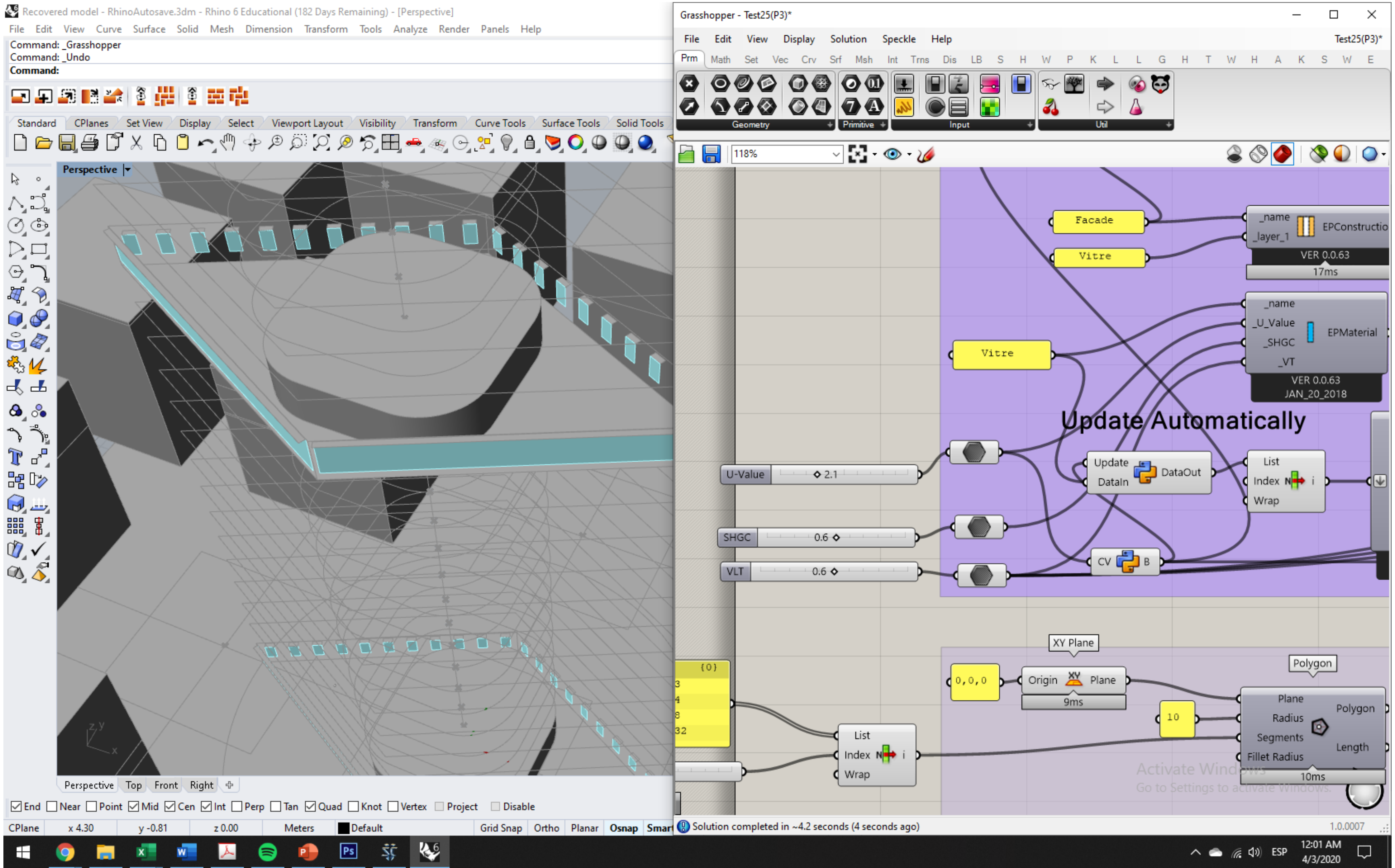
0. Parameters Facade

Topic	Parameter type	Building Parameter	ID	Description	Units	Range Min	Range Max	Data Interval	# of Inputs
2b Facade	Dynamic	Solar Heat Gain Coefficient / g value (0-1)	SHGC	Solar radiation through transparent material such as window glazing	-	0.2	0.8	0.3	3
		WWR_North/West	Nw	Aglass/ Awall	ratio	0.2	0.8	0.2	4
		WWR_West/South	Sw	Aglass/ Awall	ratio	0.2	0.8	0.2	4
		WWR_South/East	Se	Aglass/ Awall	ratio	0.2	0.8	0.2	4
		WWR_East/North	En	Aglass/ Awall	ratio	0.2	0.8	0.2	4
		Visible Light Transmittance	VLT / VT	Glazing	%	30	90	30	3
		Overhang_Size	HS	Overhang length	m	0.4	1.6	0.4	4
		Fin_Size	VS	Vertical Fins, Brise Soleils	m	0.4	1.2	0.4	3
		# of Fins	#Fin	Number of Vertical Fins per window		1	4	1	4
		U value of total window assembly	U Value / α	Rate of heat flow through conduction, convection & radiation	W/m² K	0.7	4.9	0.7	7

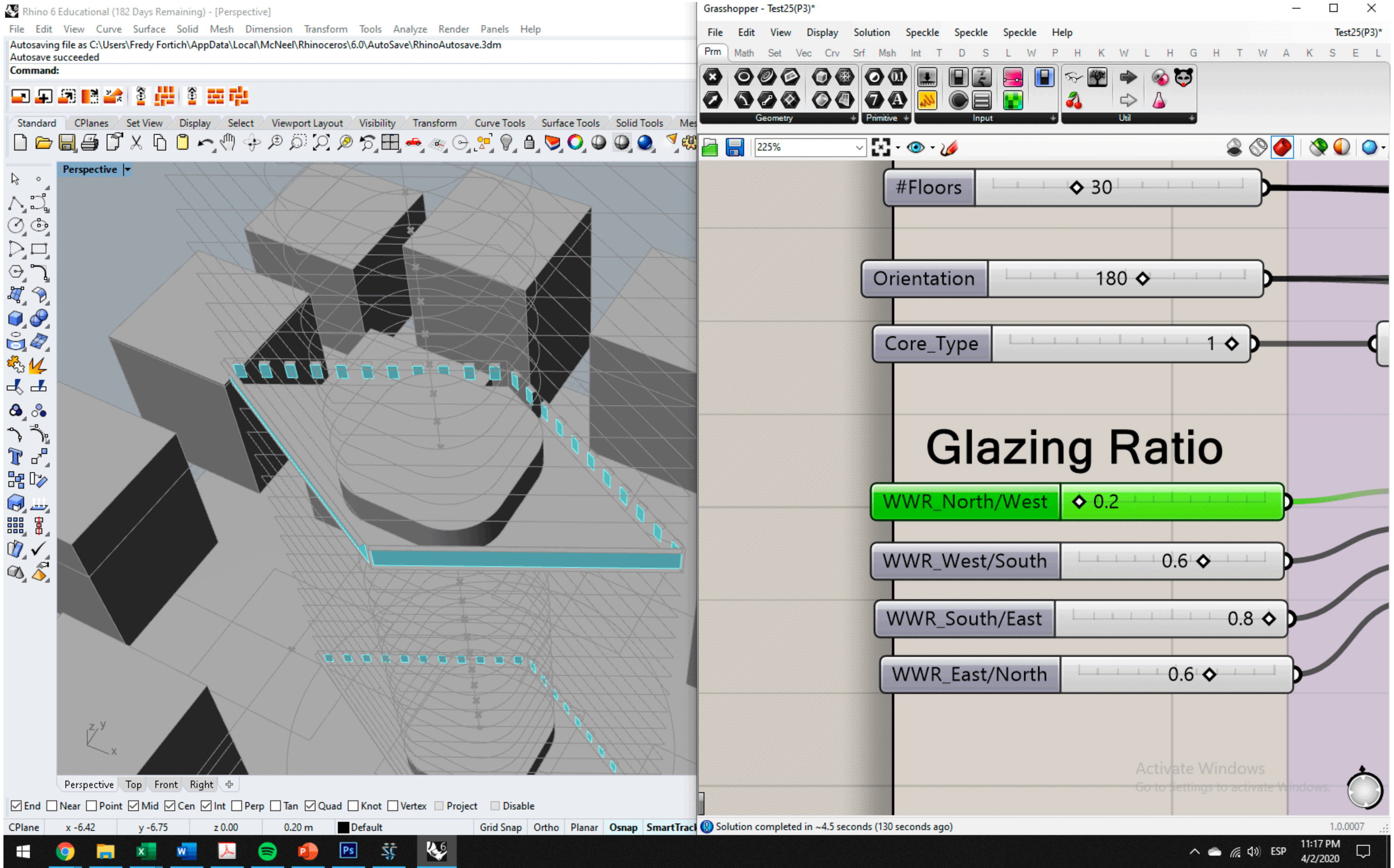
- SHGC
- WWR
- VLT
- Overhangs
- Fins
- U-Value

- 16 inputs

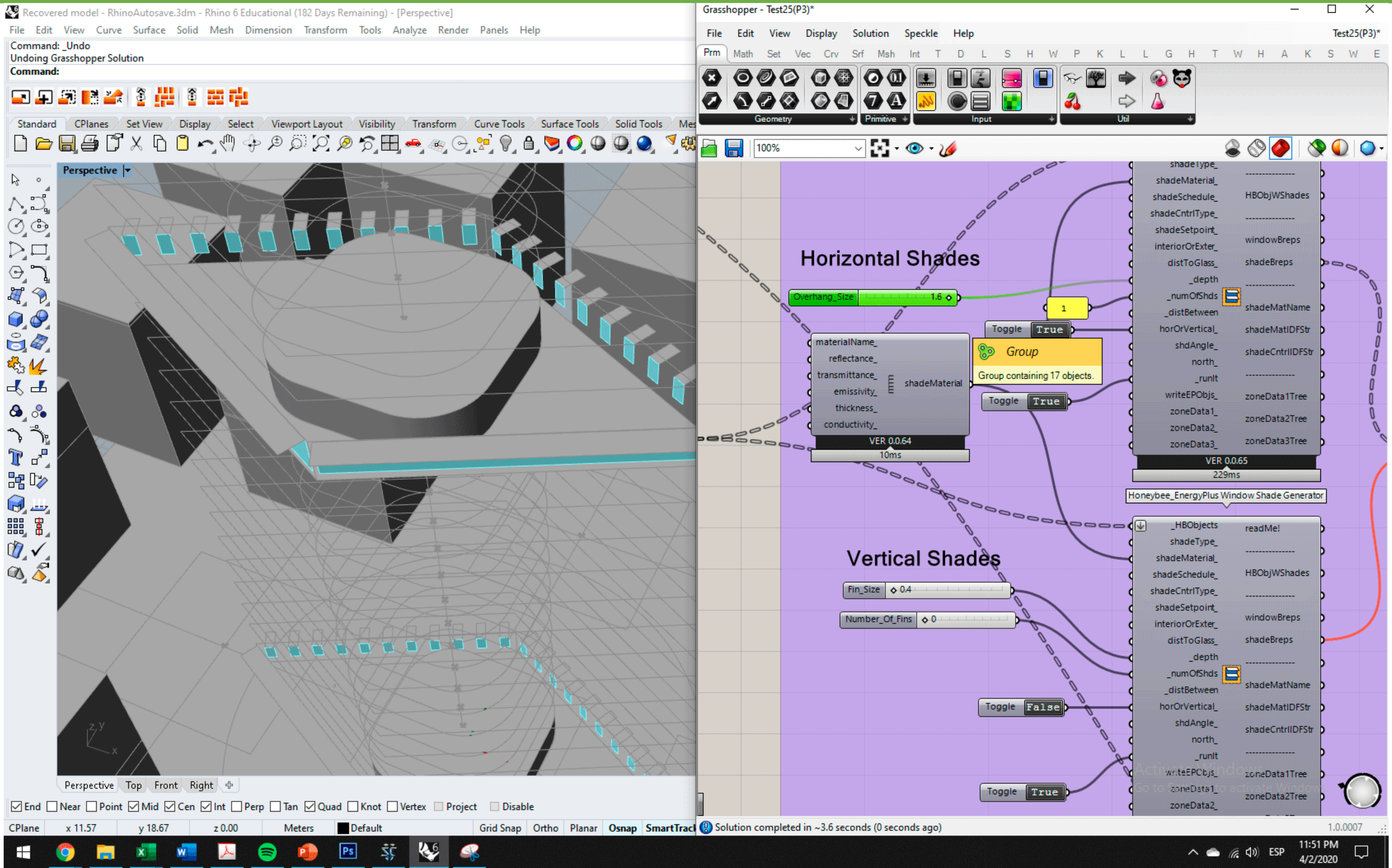
0. Parameters – Glazing Parameters



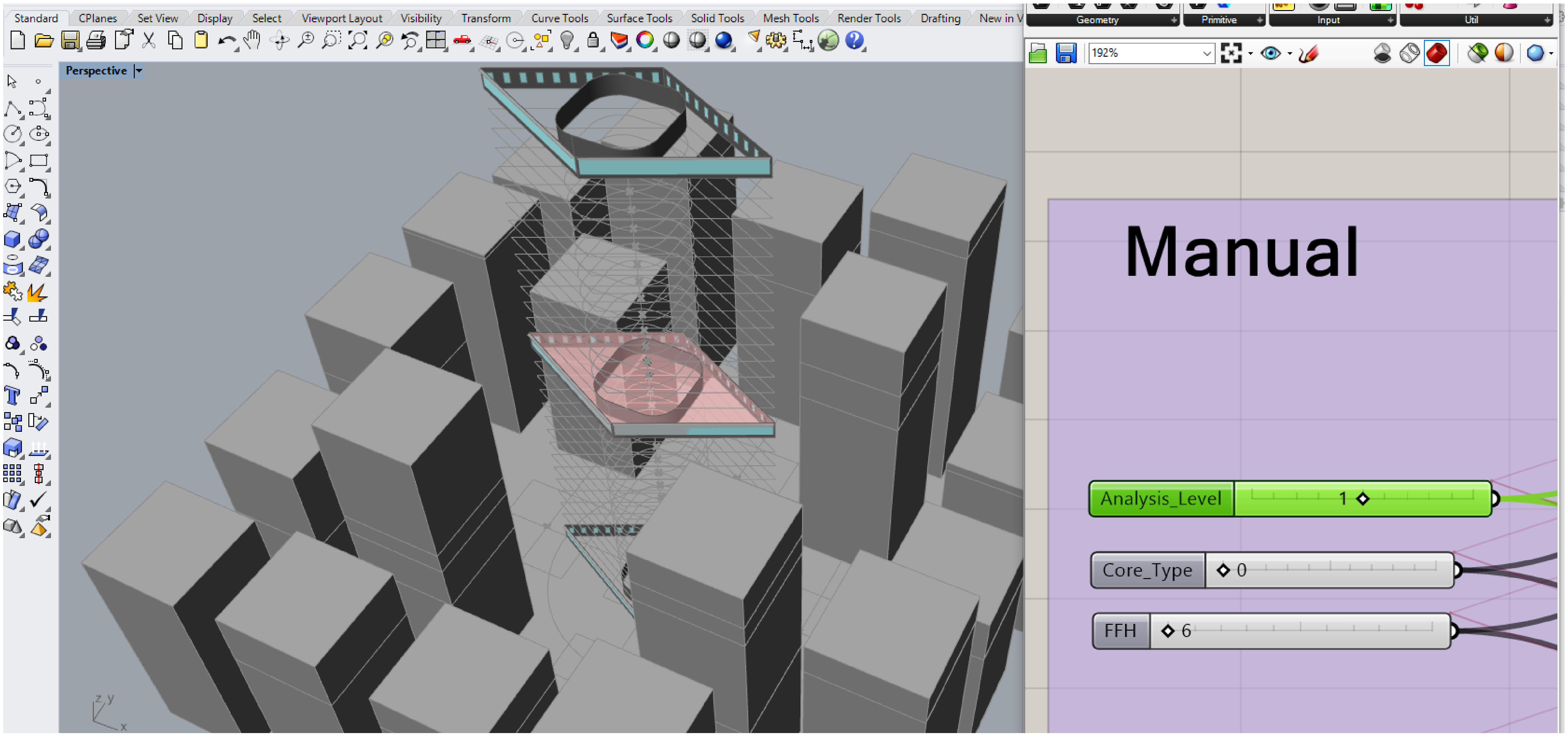
0. Parameters – WWR



0. Parameters – Overhangs & Fins



0. Parameters – Context = Analysis Level



0. Outputs

	Topic	Building Parameter	ID	Description	Units
y1	Energy	Energy Use Intensity (site)	EUI	AED / GBA - Annual total energy consumption related to the area and use	kW h /m2 yr
y2	Daylight	Useful Daylight Illuminance	UDI	Useful daylight illuminance - the annual occurrence of illuminances across the work plane that are within a range considered "useful" by occupants (9).	%
y3	Comfort	% of Time Comfortable	Com	As defined by EN 15251	%
y4	Area	Area of Floorplate	Area	Useful floor area of one floorplate	m^2

Objectives

- Energy Use Intensity (kW h /m2 yr)
- Useful Daylight lluminance (100-2000 luxes)
- % Time Comfortable
- Floorplate Area (m)

Research Findings

General tables for recommended

- Shape
- Orientation
- Aspect Ratio
- Window to wall ratio
- Climate zone

Climate Type/Plan Aspect Ratio		Temperate		Sub-Tropical		Tropical	
		1:1	5:1	1:1	5:1	1:1	5:1
Recommended WWR value (%)	North	10–90	10–70	10–15	15–40	10–50	10–35
	East	35–60	No glazing	10–20	No glazing	10–20	No glazing
	South	65–75	25–35	10–70	10–40	10–80	10–55
	West	10–15	No glazing	10–20	No glazing	10–20	No glazing

Table 5 - Recommended WWR value for different orientations and climates... (Babak Raji, 2017)

	Temperate					Sub-Tropical					Tropical				
Plan shape		A	B	C	D		A	B	C	D		A	B	C	D
<1%	Ellipse		+		+	Ellipse		+		+	Octagon	+			+
	Octagon	+			+						Ellipse		+		+
											Circle		+		+
1–5%	Circle		+		+	Rectangle	+				Square	+			+
	Square	+			+	Octagon	+			+	Rectangle	+			
	Rectangle	+				Circle		+		+	+ shape			+	
5–10%	Triangle					Square	+			+	Triangle				
	Atrium			+		Z shape			+		Courtyard			+	
	U shape			+		Courtyard			+		Z shape			+	
	+ shape			+		H shape			+		H shape			+	
											U shape			+	
>10%	H shape			+		U shape			+		Y shape			+	
	Z shape			+		Triangle									
	Y shape			+		+ shape			+						
						Y shape			+						
MD (%)	12.8					15.7					11.0				

Plan aspect ratio	Temperate	Sub-Tropical	Tropical
<1%	1:1, 2:1, 3:1	3:1, 4:1	1:1, 2:1, 3:1
1–5%	4:1, 5:1	1:1, 2:1, 5:1, 8:1	4:1, 5:1
5–10%	8:1	10:1	8:1, 10:1
>10%	10:1	---	---
MD (%)	12.4	6.0	8.8

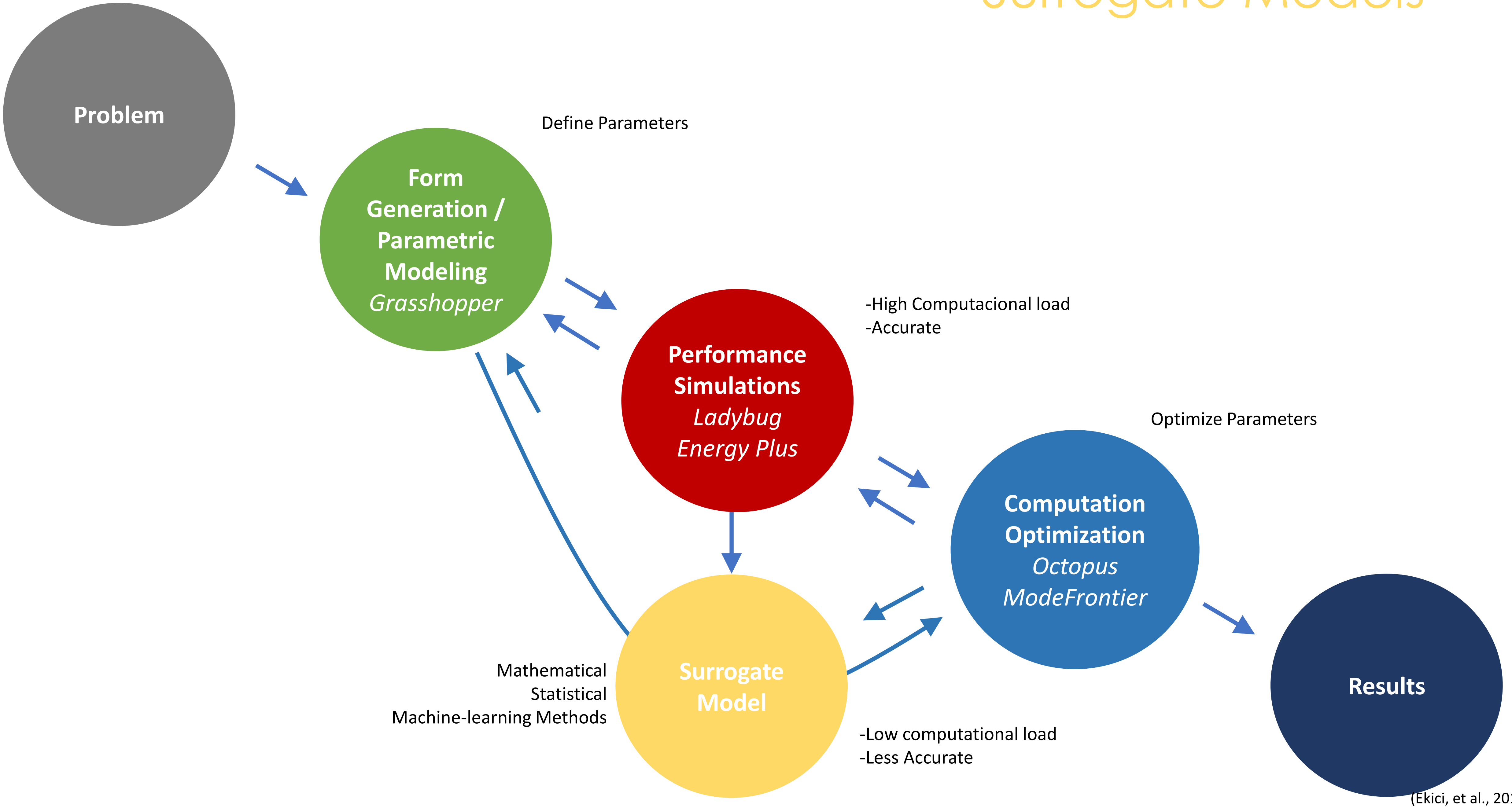
Plan orientation	1:1	3:1	5:1	10:1	1:1	3:1	5:1	10:1	1:1	3:1	5:1	10:1
<1%	0°	0°	0°	0°	0°	0°	0°	0°	0° 45°	0° 45°	0°	0°
1–5%	45°	135° 45°	135°		45°	---	---	---	---	135° 45°	45° 135° 90°	45°
5–10%	---	90°	45° 90°	135°	---	45° 135°	---	---	---	---	---	135° 90°
>10%	---	---	---	45° 90°	---	90°	45° 135° 90°	45° 135° 90°	---	---	---	---
MD (%)	1.2	5.6	8.4	15.1	2.1	12.3	20.4	32.0	0.7	2.8	4.7	7.9

WWR (%): deep plan (1:1)	N	E	S	W	N	E	S	W	N	E	S	W
<1%	10–90	35–60	65–75	10–15	10–15	10–20	10–70	10–20	10–50	10–20	10–80	10–20
1–5%	---	10–35 60–90	10–65 75–90	15–90	15–50	20–90	70–90	20–90	50–90	20–90	80–90	20–90
5–10%	---	---	---	---	50–80	---	---	---	---	---	---	---
>10%	---	---	---	---	80–90	---	---	---	---	---	---	---
MD (%)	0.5	2.8	1.8	4.5	11.3	2.9	1.1	3.1	2.9	3.3	1.1	3.0

WWR (%): narrow plan (5:1)	N	E	S	W	N	E	S	W	N	E	S	W
<1%	10–70	---	25–35	---	15–40	---	10–40	---	10–35	---	10–55	---
1–5%	70–90	---	10–25 35–55	---	10–15 40–75	---	40–90	---	35–70	---	55–90	---
5–10%	---	---	55–85	---	75–90	---	---	---	70–90	---	---	---
>10%	---	---	85–90	---	---	---	---	---	---	---	---	---
MD (%)	3.0	---	10.3	---	6.8	---	5.2	---	8.6	---	3.2	---

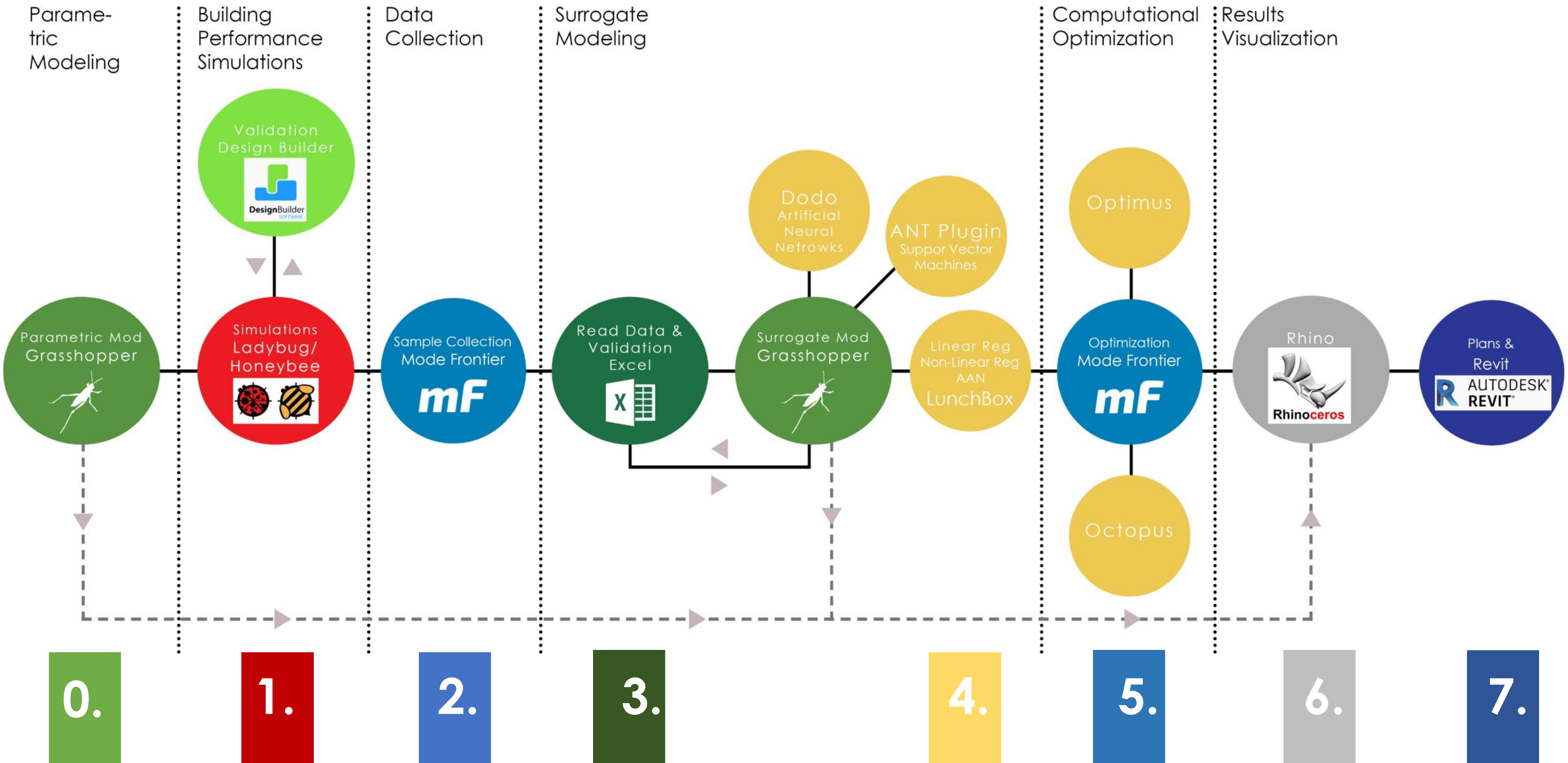
Energy efficiency of design options: <1% (remarkable energy saving); 1–5% (average energy saving); 5–10% (low energy saving); >10% (not recommended). A: High space efficiency; B: Aerodynamic form; C: Narrow plan (NV & daylight access); D: Less material use for external envelope; MD: Maximum deviation; N: North orientation; E: East orientation; S: South orientation; W: West orientation.

Surrogate Models



(Ekici, et al., 2019)

Workflow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Simulations
Ladybug/
Honeybee
Sample Collection
Mode Frontier
mF
Read Data &
Validation
Excel
Dodo
Artificial
Neural
Netrowks
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Suppor Vector
Machines
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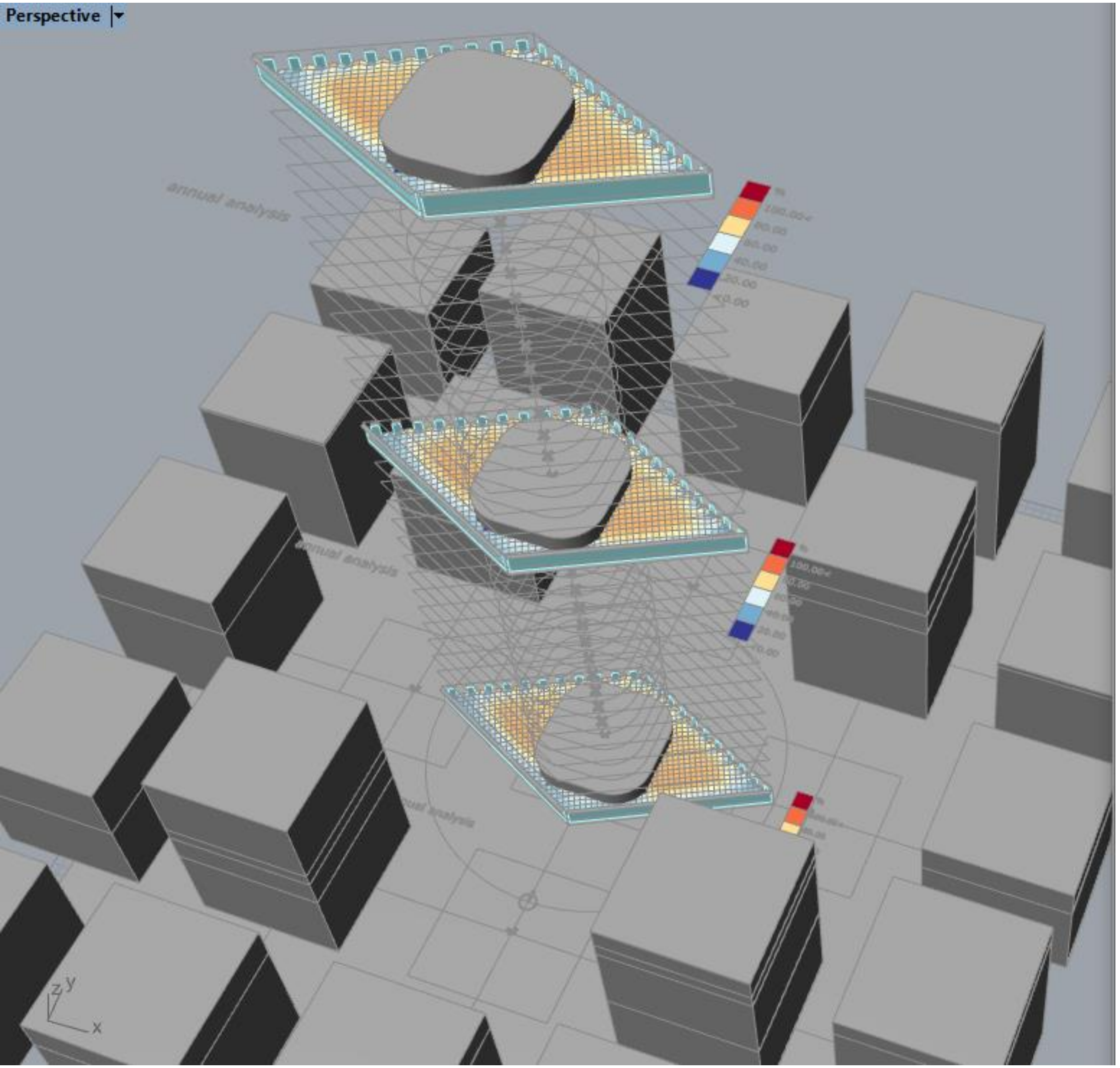
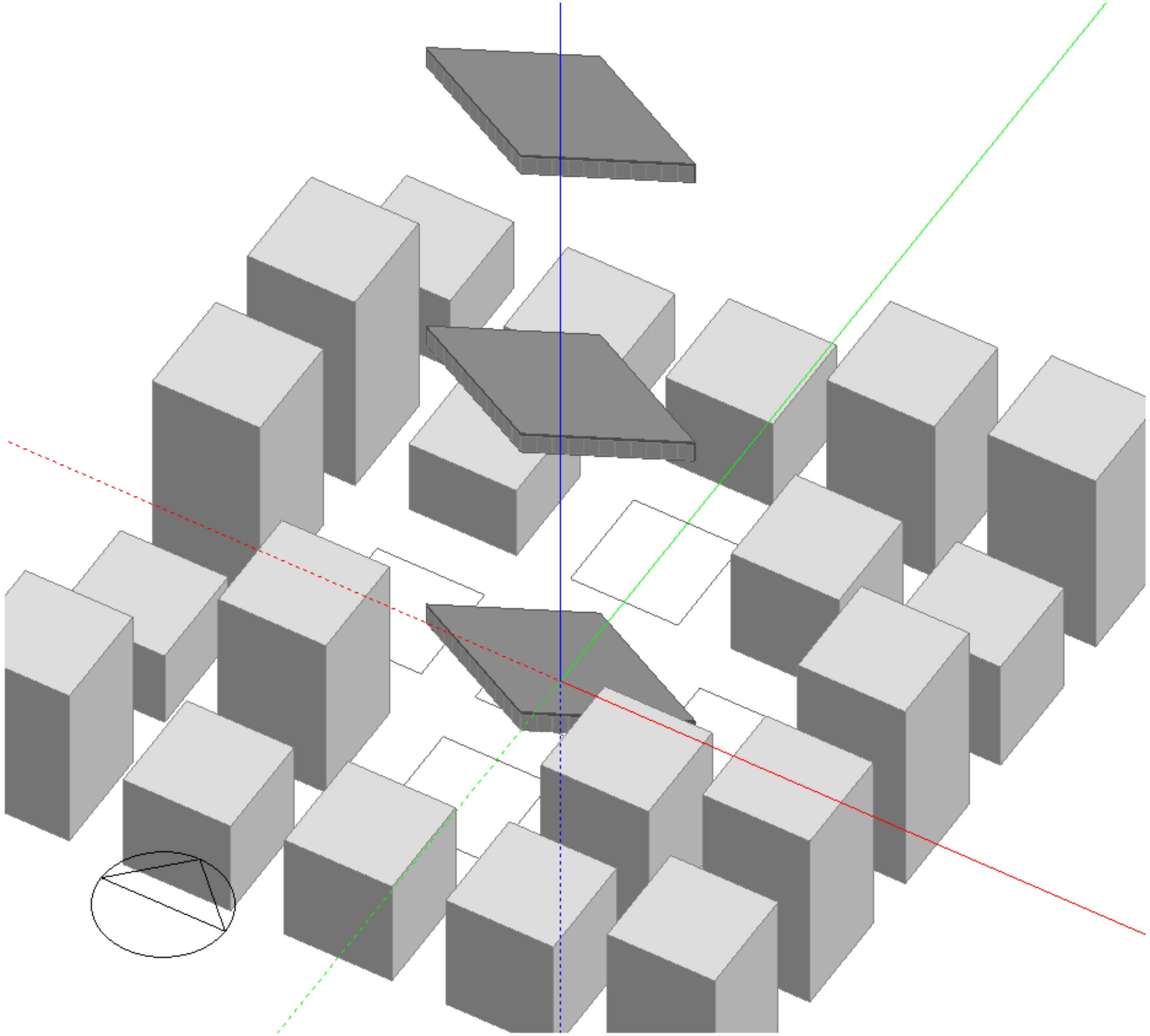
1. Validation in Design Builder



Grasshopper – HoneyBee / LadyBug - EnergyPlus



Design Builder – EnergyPlus

1. Validation in Design Builder

Chosen Parameters for cross model validation

	Grasshopper Model		Design Builder		Units
	Floor 01	**Core 01**	**Floor 01**	**Core 01**	
Shape	Parallelogram	Parallelogram	Parallelogram	Parallelogram	-
Length	40	40	40	40	m
Witdh	20	20	20	20	m
Floor to Floor Height	3.5	3.5	3.5	3.5	m
No. of Floors	30	30	30	30	-
N0 Level	0	0	0	0	m
N Mid Level	52.5	52.5	52.5	52.5	m
N Top Level	105	105	105	105	m
Context Type	Mid rise	Mid rise	Mid rise	Mid rise	-
Exterior Wall	ASHRAE 90.1-2010 Ext Wall Metal ClimateZone 7-8	none	Semi-exposed wall Typical reference - Lightweight	none	-
R-Value	2.939	none	2.881	none	m2-K/w
U-Value	0.34	none	0.347	none	w/m2-K
Internal wall	none	M11 100 mm Lightweight Concrete	none	Project Internal Mass - Concrete -100 mm	-
U-Value	2.6	2.6	2.6	2.6	w/m2-K
Glazing:	Custom		Project external Glazing		-
U-Value	2.08	none	2.08	none	w/m2-K
SHGC	0.691	none	0.691	none	-
VLT	0.74	none	0.744	none	-
Openings					
Window Height	1.5	none	1.5	none	m
Window Spacing	2	none	2	none	m
Sill Height	0.8	none	0.8	none	m
WWR North	20	none	20	none	%
WWR South	80	none	80	none	%
Roof	ASHRAE 90.1-2010 Ext Roof Metal Climate Zone 7-8	ASHRAE 90.1-2010 Ext Roof Metal Climate Zone 7-8	Flat roof - Typical Ref - Lightweight	Flat roof - Typical Ref - Lightweight	-
R-Value	3.45	3.45	3.5	3.5	m2-K/w
U-Value	0.29	0.29	0.286		w/m2-K
HVAC	Ideal Air Loads	Ideal Air Loads	Air to Water Heat Pump (ASHP), Convectors, Nat Vent	Air to Water Heat Pump (ASHP), Convectors, Nat Vent	-
Mechanical Vent					
Heating CoP	Ideal Loads	Ideal Loads	1	1	-
Cooling CoP	Ideal Loads	Ideal Loads	1	1	-

Core Type	Internal	-	Internal	-	-
Activity	Open Office	Office: Corridor	Generic Office Area	Circulation Area	-
Occupancy density	0.0565	0.1173	0.0565	0.1173	pp/m2
Equipement Load	11.77	1.85	11.77	1.85	W/m2
Heating Set Point	21	20	21	20	°C
Heating set Back	12	12	28	12	°C
Cooling Set Point	25	23	25	26	°C
Cooling Set back	28	28	28	28	°C
FractionGlz Operable / Free Aperture	25	-	25	-	%
Min Temp Natural Ventilation Setpoint	24	-	-	-	°C
Min Temp Outside Natural Ventilation	14	-	-	-	°C
Airtightness	0.2	-	0.2	-	ac/h
Heating Sizing Factor	1.25	1.25	1.25	1.25	
Cooling Sizing Factor	1.15	1.15	1.15	1.15	
Timestep per hour	4	4	4	4	
Lighting controls					
Working plane height:	0.75 m	0.75 m	0.75 m	0.75 m	
Normalised power density	5	5	5	5	W/m2-100lux
Control Type	Autodiming with switch off occupancy sensor		3 Stepped		
Lighting Set point	300	300	100	100	

	Grasshopper Model (kWh)		Design Builder (kWh)		Difference %	
Results:	**N00**	**All 3 Levels**	**N00**	**All 3 Levels**	**N00**	**All 3 Levels**
Cooling	7996	24787.6	8364	25696	-4.6	-3.7
Heating	29573	91676.3	27542	96698	6.9	-5.5
Lighting	4591	13773	4708	14357	-2.5	-4.2
Equipment	10924	32772	11494	34482	-5.2	-5.2
Totals	**53084**	**163008.9**	**52108**	**171233**	**1.8**	**-5.0**

1. Validation in Design Builder

	Grasshopper Model (kWh)		Design Builder (kWh)		Difference %	
Results:	N00	All 3 Levels	N00	All 3 Levels	**N00**	**All 3 Levels**
Cooling	7996	24787.6	8364	25696	**-4.6**	**-3.7**
Heating	29573	91676.3	27542	96698	**6.9**	**-5.5**
Lighting	4591	13773	4708	14357	**-2.5**	**-4.2**
Equipment	10924	32772	11494	34482	**-5.2**	**-5.2**
Totals	53084	163008.9	52108	171233	**1.8**	**-5.0**

2. Sampling

Surrogate Model Type													Sampling Methodology				
ANN	RBF	Gaussian Processes	Linear Regression incl. (LASSO, stepwise, nth order terms)	MARS	SVM	Random Forest	Ensembles	Others	Favoured model (only if comparison done	# Inputs	# Outputs	Multiple climate zones?	Sampling Method	Sampling Method adaptive (a) / static (s)	Simulation tool	# Samples (Total)	Checked impact of number of samples?
			x							8	3		Doelhart matrix	s	TRNSYS	1980	
			x						Polynomial	7	5		factorial	s	EnergyPlus	2187	
			x							8	4		factorial	s	EnergyPlus	4096	x
x			x							156	80-90		Markov order	s	EnergyPlus	8*10^-6	
			x							8	2		L18 Taguchi	s	EnergyPlus	18	
			x							15	2		manual	s	Daysim	1900	x
			x					x		2	3		full factorial	s	EnergyPlus	23040	
			x							3	1	x	full factorial	s	TRNSYS	8748	
			x						Stepwise LR	28	3	x	full factorial	s	EnergyPlus	20000	
			x						LR	12	1	x	manual	s	DOE-2.1	1021	
			x							11	1		L12/18 Taguchi, FCC35, BB188, D68, D136, D80, D160		TRNSYS	60-230	x
					x					38	1	x	Sobol	s	EnergyPlus	16k - 50k	
			x						Polynomial	11	2	x	D-optimal	s	TRNSYS	115-210	
x									ANN	29	3	x	LHS	s	EnergyPlus	500	
			x						Polynomial	10	4	x	factorial, Box-Behnken	s	TRNSYS	120	
x									ANN	15	1	x	LHS	s	EnergyPlus	1001	
			x					x	Others	9	3		Sobol	s	Be10	6000	
										27	2		LHS, orthogonal array	s	eQuest	7623	
		x								10	2		optimality criterion	a	VA114	n/a	
		x							GPR	47	1		LHS	s	EnergyPlus	15	x
			x						SRRC	9	3		manual	s	EnergyPlus	2400	
							x		ensemble	9	2	x	LHS	s	CONTAM	500	
		x						x	PCE	24	1		manual	s	TRNSYS	200	
								x		1009	10		pseudo Monte Carlo	s	EneryPlus	5000	
			x			x			RF	8	2		full factorial	s	Ecotect	768	
			x	x					MARS	10	3		LHS	s	EnergyPlus	2000	
		x	x	x	x			x	ensemble	28	2		LHS	s	IDEAS (Modelica)	600	x
			x	x					MARS	10	3		LHS	s	EnergyPlus	5000	x
			x						Stepwise LR	20	1		full factorial	s	EnergyPlus	20000	
			x						MLR	6	1		LHS	s	EnergyPlus	1200	
x									ANN	9	4		manual	s	EnergyPlus	11315	
x										20	5		LHS	s	TRNSYS	450	
x										4	3		LHS	s	TRNSYS	1045	
x									ANN	8	2		manual	s	EnergyPlus	105	
					x					7-1009	2		quasi - Monte Carlo	s	EnergyPlus	5000	
					x				SVM	10	1	x	LHS	s	EnergyPlus	5610	
			x	x	x				SVM	9	3	x	LHS	s	EnergyPlus	5610	
	x									2	1		manual	s	Fluent (CFD)	63	
	x	x	x	x	x				MARS	6	2		pseudo Monte Carlo, Sobol, LHS	a	TRNSYS	50-27k	x
			x							26	6		factorial	s	EnergyPlus	113-193	
			x							5	2		full factorial	s	EnergyPlus	7776	
		x								8	4		expected improvement	a	RSC1	150	x
		x								10	2		optimality criterion	a	EnergyPlus	84-100	x
		x								15	1		expected improvement	a	EnergyPlus	195	
		x								9	2		optimality criterion	a	EnergyPlus	300-1100	x
x										5	5		optimality criterion	a	EnergyPlus	1500	x
			x		x					6	2		optimality criterion	a	EnergyPlus	>90	x
	x									50	3	x	optimality criterion	a	EnergyPlus	5000	
	x									13-40	3		optimality criterion	a	EnergyPlus	500	
			x	x					MARS	14	2		LHS	s	IDEAS (Modelica)	500	
				x						8	2		full factorial	s	Ecotect	768	
x					x	x	x		SVR, ensemble	8	2		full factorial	s	Ecotect	768	
x	x								ANN	9	6		LHS	s	EnergyPlus	1000	
x	x	x		x		x			ANN	14	2		LHS	s	IDEAS (Modelica)	500	x
	x	x	x			x		x	SVM	42	2		initial: LHS, adaptive: space filling	a	EnergyPlus/Daysim	360-430	
x		x	x	x	x	x			GPR	14	4		Sobol	s	BSim	32-8100	x
			x						Polynomial	13	3		factorial	s	SIMBAD	32-470	x

(Paul Westermann, 2019)

Static Vs Adaptive

- 500 Samples
- 3.4 samples per hour
- 147 hours (6 days)
- 1 Desktop Computer

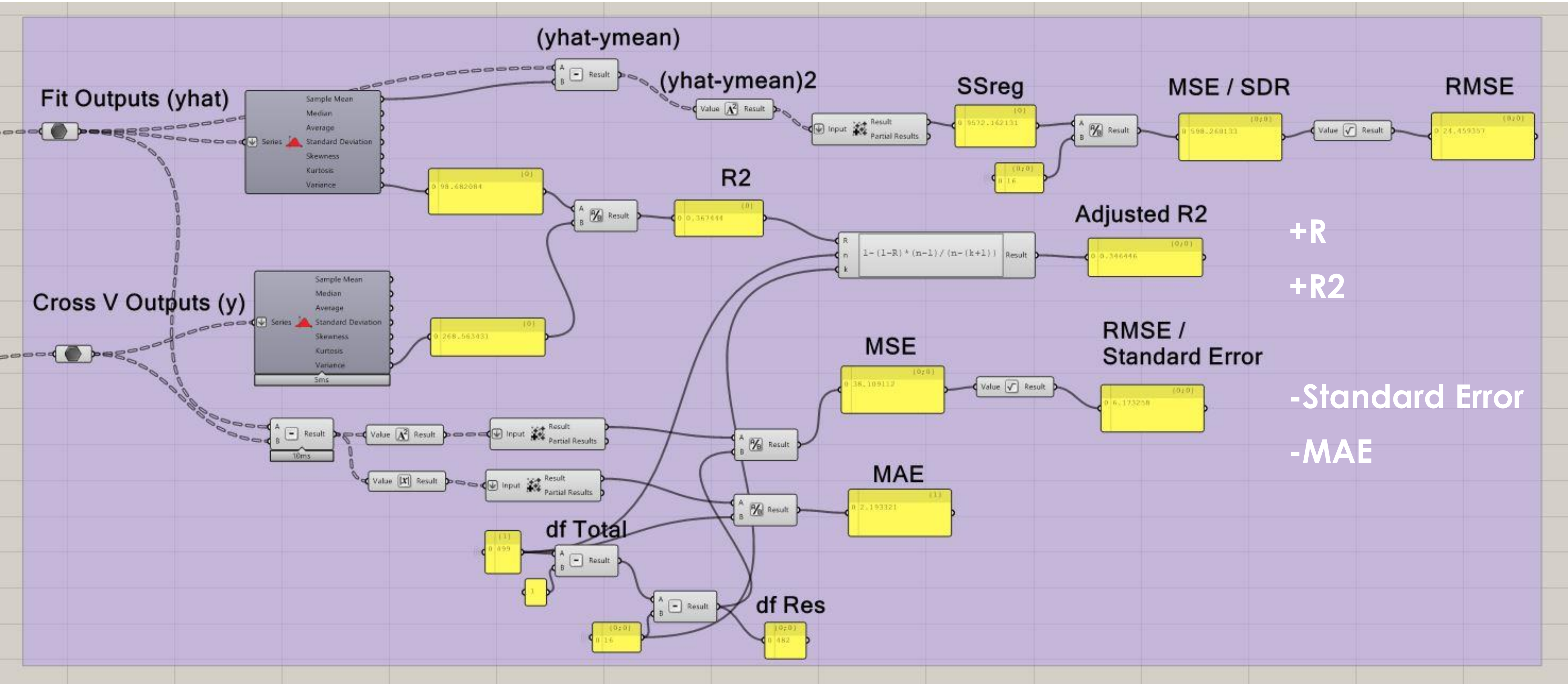
- ULH vs Sobol
- Significant variables : P-Value

	Sobol			ULH		
	EUI	Comfort	UDI	EUI	Comfort	UDI
R^2	0.83434507	0.99935141	0.36186573	0.84796182	0.99945149	0.35780101
Standard Error	11.0616862	1.04635648	11.0250236	9.74086331	0.96024303	10.7197914
P-Value	2.133E-153	0	2.4923E-32	9.339E-186	0	3.0092E-37
Significant Variables	12	3	7	12	6	11

2. P-Values – Linear Regression

	Amsterdam - P-Values				Bogota - P-Values				Dubai P-Values			
	EUI	Area	Comfrt	UDI	*EUI*	Area	Comfrt	UDI	*EUI*	Area	Comfrt	UDI
Analysis Level	2E-13	0.1872	2E-49	0.0736	2E-06	0.1951	2E-89	0.1085	1E-97	0.2017	7E-109	0.1041
Core_Type	5E-57	0.422	0.2164	4E-38	2E-30	0.4055	0.0567	4E-42	0.3377	0.3845	5E-10	7E-42
FFH	2E-43	0.5856	1E-05	0.0109	2E-09	0.5645	0.1502	0.9103	3E-30	0.5888	2E-10	0.9212
Length	8E-76	9E-132	4E-18	2E-08	8E-51	1E-131	0.6818	0.1907	2E-49	2E-131	0.001	0.3912
Number Of_Fins	0.1779	0.905	0.0073	0.3157	0.2657	0.8941	3E-07	0.6192	0.0403	0.9488	2E-05	0.6614
Orientation	0.1596	0.256	0.803	0.3333	0.0503	0.2663	0.6743	0.2783	0.9711	0.3065	0.8088	0.2329
Overhang Size	0.0726	0.6701	9E-06	0.3183	0.0042	0.6896	2E-13	0.0209	0.0082	0.7223	2E-10	0.0127
SHGC	0.0393	0.5282	3E-50	0.9383	2E-10	0.5488	5E-97	0.7809	0.4937	0.5583	1E-73	0.8735
Shape	1E-42	2E-87	0.0014	0.3272	6E-27	4E-87	6E-09	4E-06	3E-38	3E-87	8E-43	4E-06
U_Value	2E-69	0.433	8E-135	0.0851	5E-62	0.4469	2E-97	0.1013	0.0127	0.4687	7E-21	0.1442
VLT	0.0024	0.6506	0.1391	0.0299	0.0137	0.6572	0.0331	4E-10	0.2076	0.6426	0.0384	4E-10
WWR East_North	1E-08	0.9275	0.0455	0.0015	0.0108	0.9608	0.0002	0.1071	1E-12	0.921	1E-06	0.3347
WWR North_West	7E-11	0.8315	3E-07	0.3713	2E-05	0.8223	0.457	0.2038	1E-11	0.7862	0.0145	0.1537
WWR South_East	1E-09	0.0618	9E-06	0.3744	0.0016	0.0583	0.2716	0.0194	8E-15	0.0575	0.0225	0.0101
WWR West_South	8E-13	0.8455	8E-08	0.1799	0.0042	0.8212	0.2138	0.4956	3E-21	0.8491	0.0038	0.3013
Width	2E-60	1E-114	9E-10	8E-05	8E-38	2E-114	0.0185	0.1402	1E-49	6E-114	1E-23	0.463

3. Validation of Surrogate



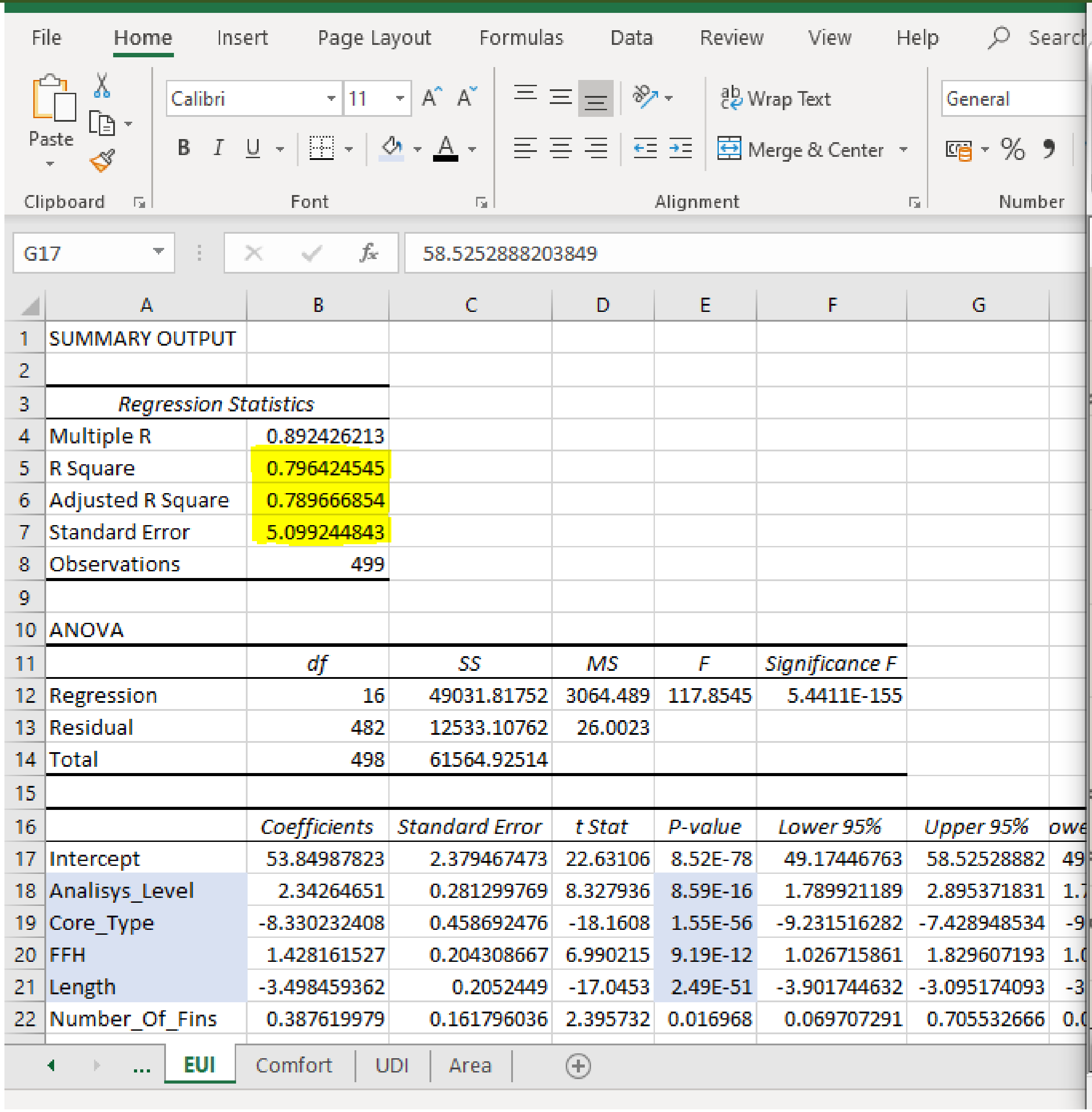
+R

+R2

-Standard Error

-MAE

3. Validation of Surrogate – Linear Regression



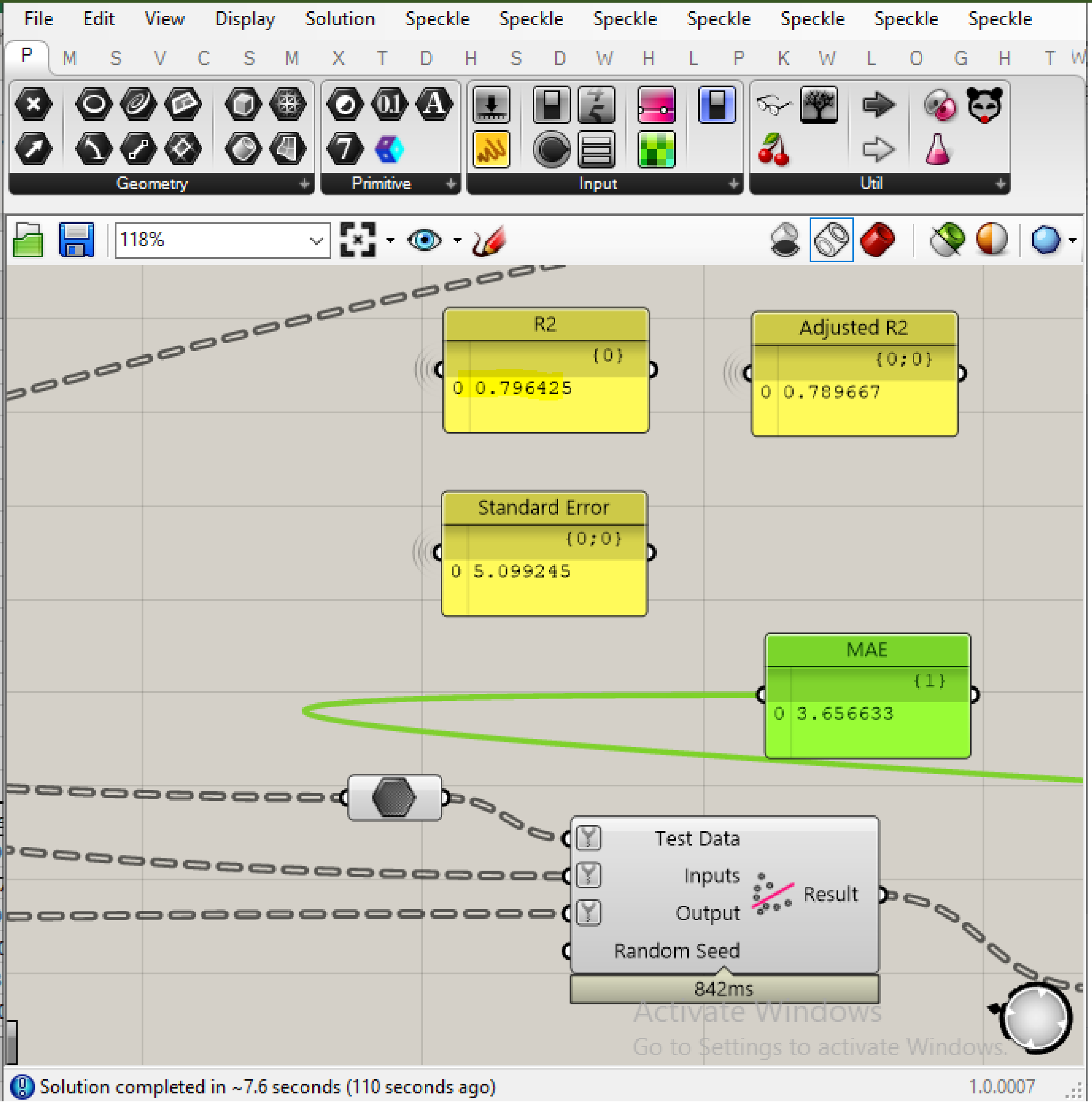
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.892426213
R Square	0.796424545
Adjusted R Square	0.789666854
Standard Error	5.099244843
Observations	499

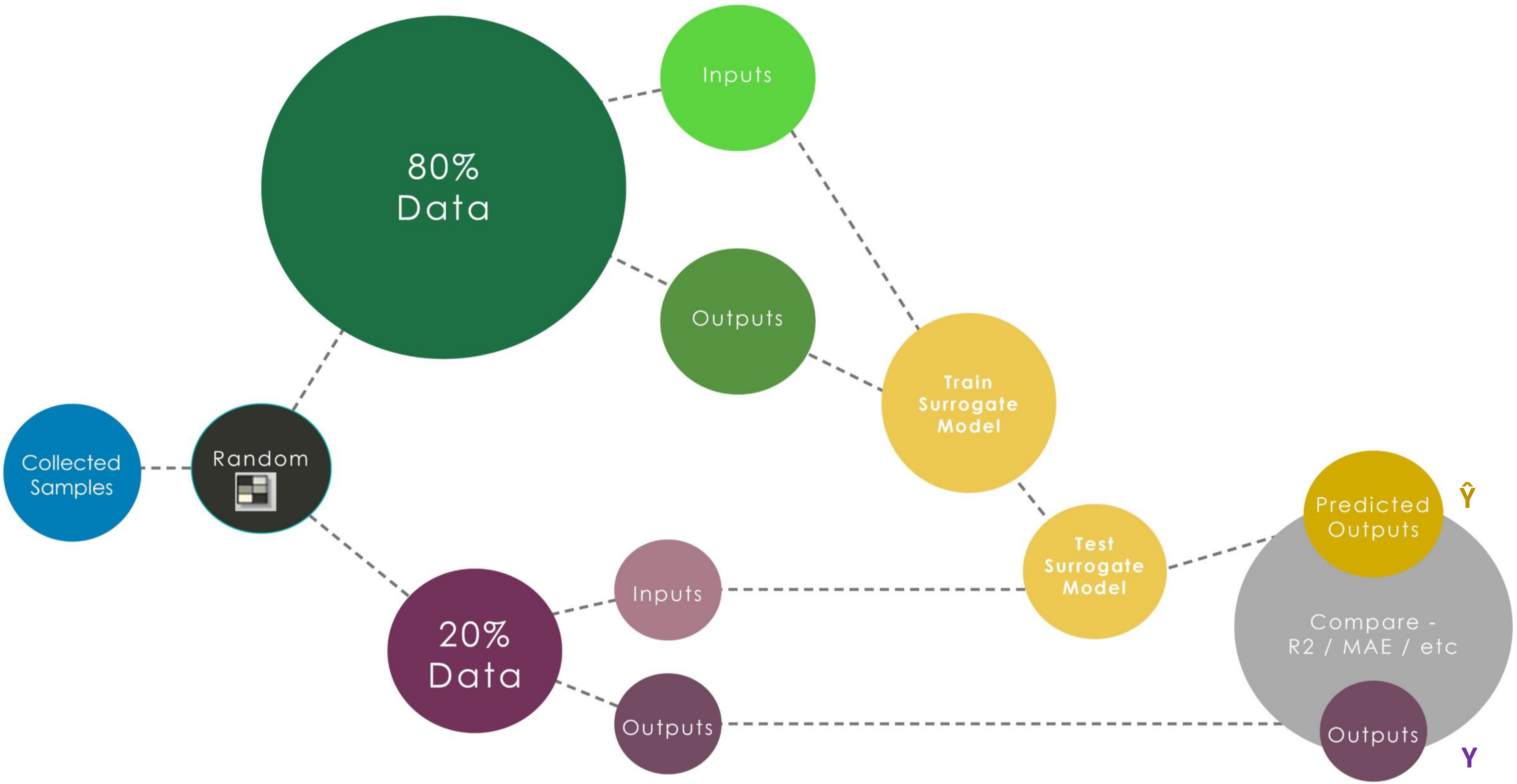
ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	16	49031.81752	3064.489	117.8545	5.4411E-155
Residual	482	12533.10762	26.0023		
Total	498	61564.92514			

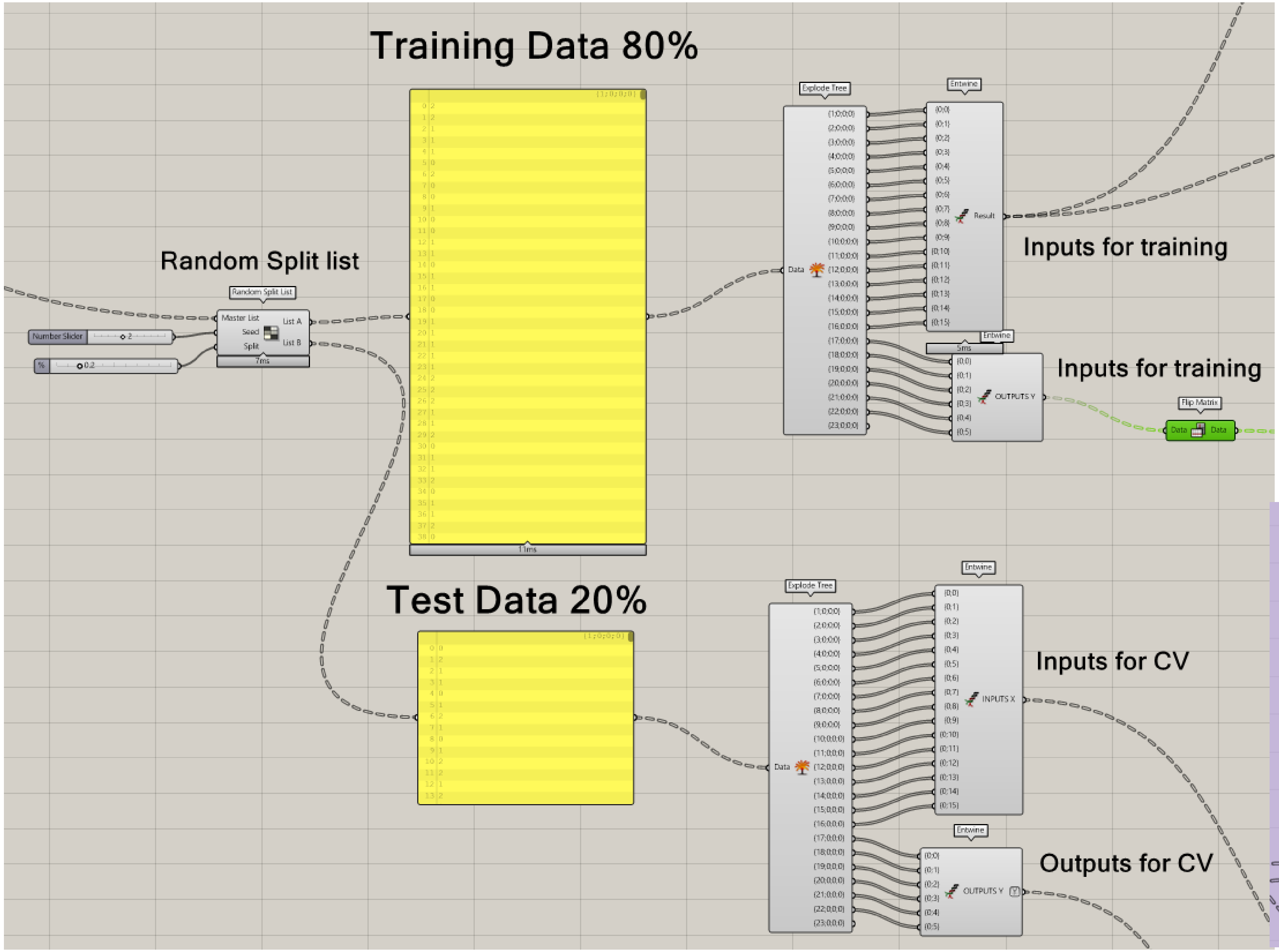
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	53.84987823	2.379467473	22.63106	8.52E-78	49.17446763	58.52528882
Analisys_Level	2.34264651	0.281299769	8.327936	8.59E-16	1.789921189	2.895371831
Core_Type	-8.330232408	0.458692476	-18.1608	1.55E-56	-9.231516282	-7.428948534
FFH	1.428161527	0.204308667	6.990215	9.19E-12	1.026715861	1.829607193
Length	-3.498459362	0.2052449	-17.0453	2.49E-51	-3.901744632	-3.095174093
Number_Of_Fins	0.387619979	0.161796036	2.395732	0.016968	0.069707291	0.705532666



4. Training Surrogate – Cross Validation

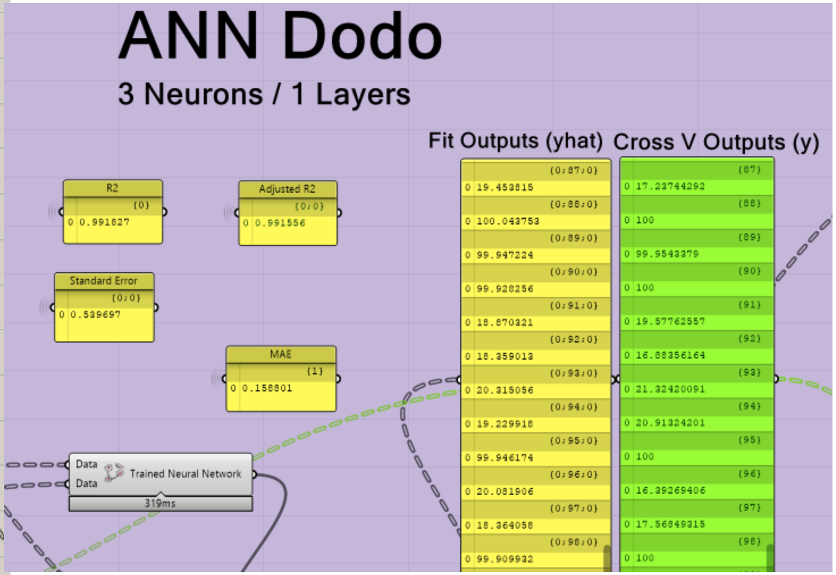


4. Training Surrogate – Cross Validation



Surrogate model types

- Linear Regression
- Non-Linear Regression
- ANN



4. Machine Learning Methods

			R Square	Adjusted R Square	Standard Error	Mean Absolute Error
Multilinear Regression	UDI	Seed 1	0.438801	0.420172	5.044999	1.926218
		Seed 2	0.230504	0.204961	4.951339	1.834723
		Seed 3	0.346347	0.324649	4.78922	1.634628
		Seed 4	0.387203	0.366861	4.680839	1.621017
		Seed 5	0.449362	0.431084	5.576187	1.968647
		Average	0.3704434	0.3495454	5.0085168	1.7970466
Non-Linear Regresssion	UDI	Seed 1	0.49283	0.475994	78.454722	298.25815
		Seed 2	0.251743	0.226905	72.929642	263.21719
		Seed 3	0.355431	0.334035	70.662601	244.83104
		Seed 4	0.38354	0.363077	67.68632	228.81792
		Seed 5	0.429776	0.410847	77.260067	285.12267
		Average	0.382664	0.3621716	73.39867	264.04939
Artificial Neural Network	UDI	Seed 1	0.951914	0.950318	4.104351	1.486348
		Seed 2	0.847411	0.842346	2.072161	0.653077
		Seed 3	0.962942	0.961712	2.037623	0.621746
		Seed 4	0.825666	0.819879	2.190636	0.710077
		Seed 5	0.915687	0.912888	1.899354	0.647612
		Average	0.900724	0.8974286	2.460825	0.823772

Surrogate model types

- Linear Regression
- Non-Linear Regression
- ANN

Conclusion:

- Once trained, Artificial Neural Network works well!

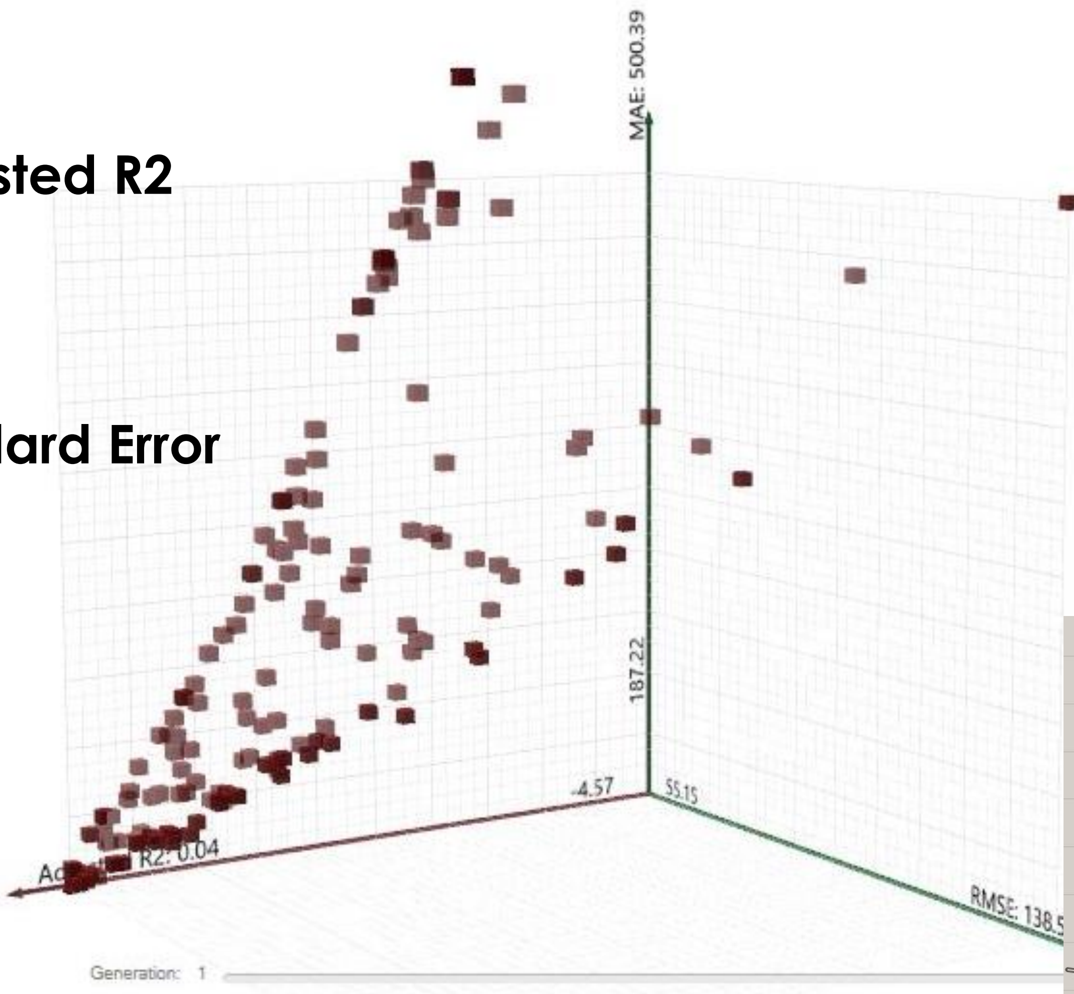
4. Optimization of HyperParameters

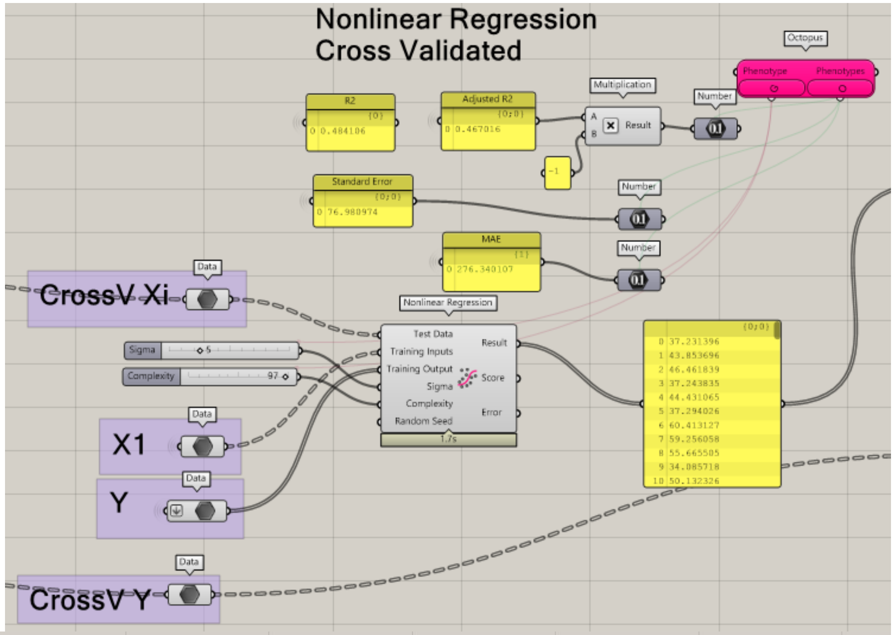
+R2

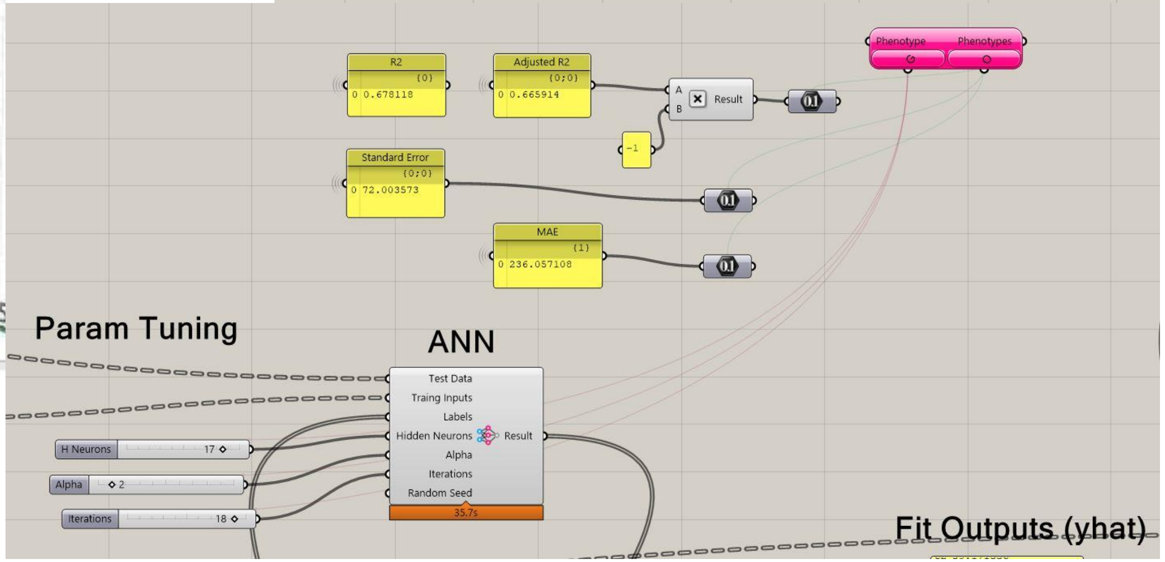
+Adjusted R2

-Standard Error

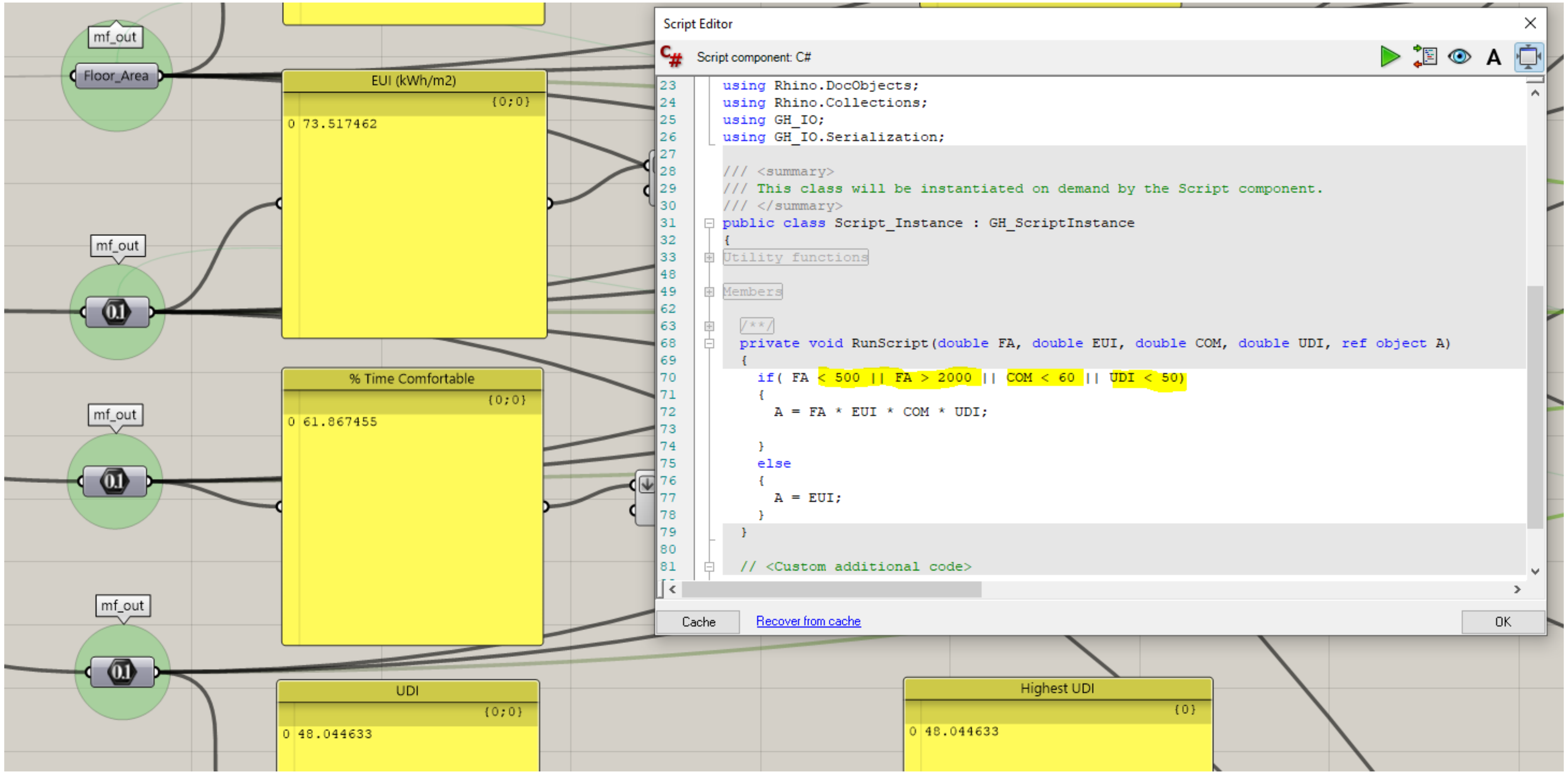
-MAE







5. Optimization – Single Objective Optimization



Energy:
-Lower EUI (kWh / m2 * yr)

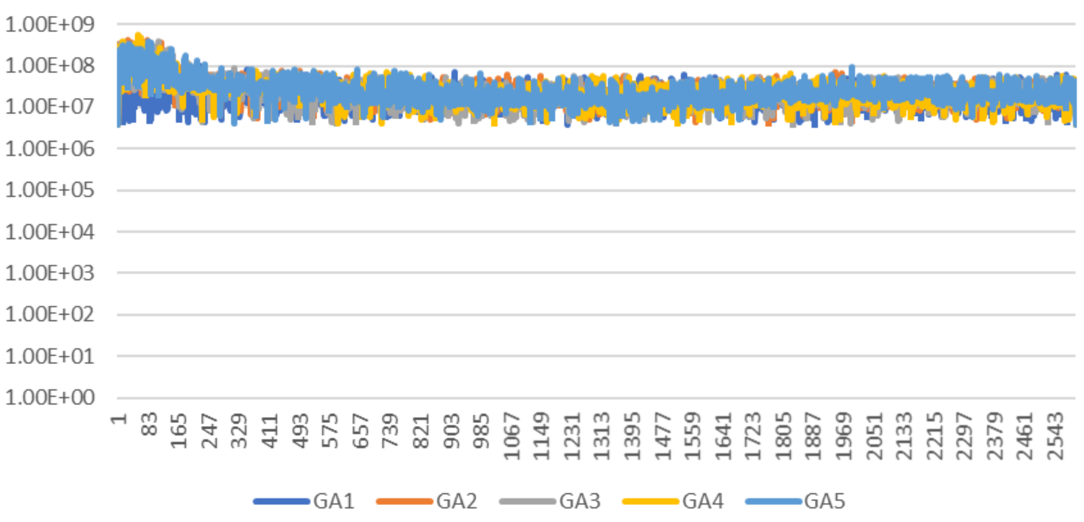
Comfort:
+At least 60% of the time>

Daylight
+Higher UDI (100-2000 lux)
50% of the time

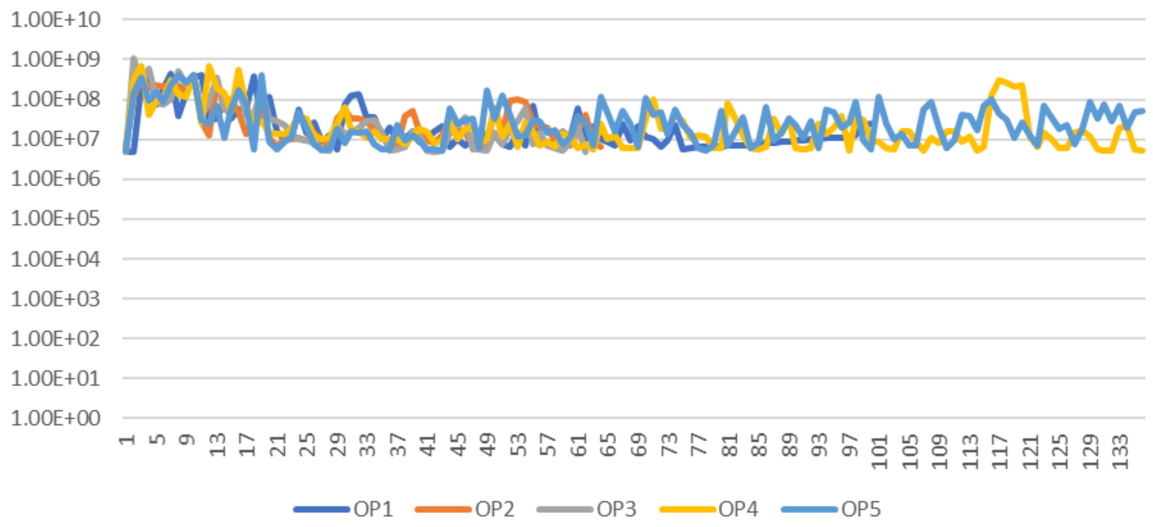
Area
Boundary:
<500 and 2000 m^2>

5. Single-Objective Optimization:

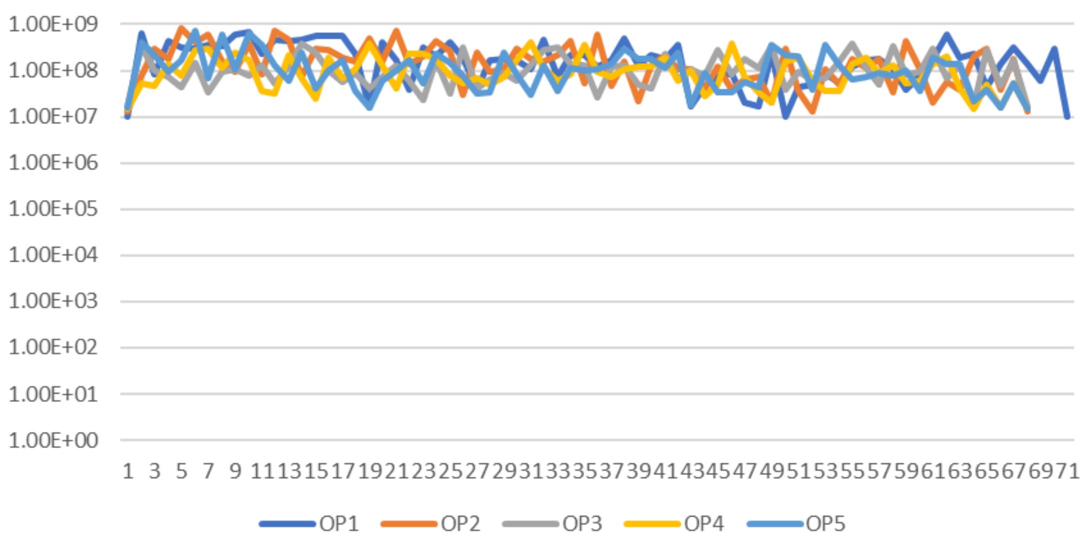
20 minutes



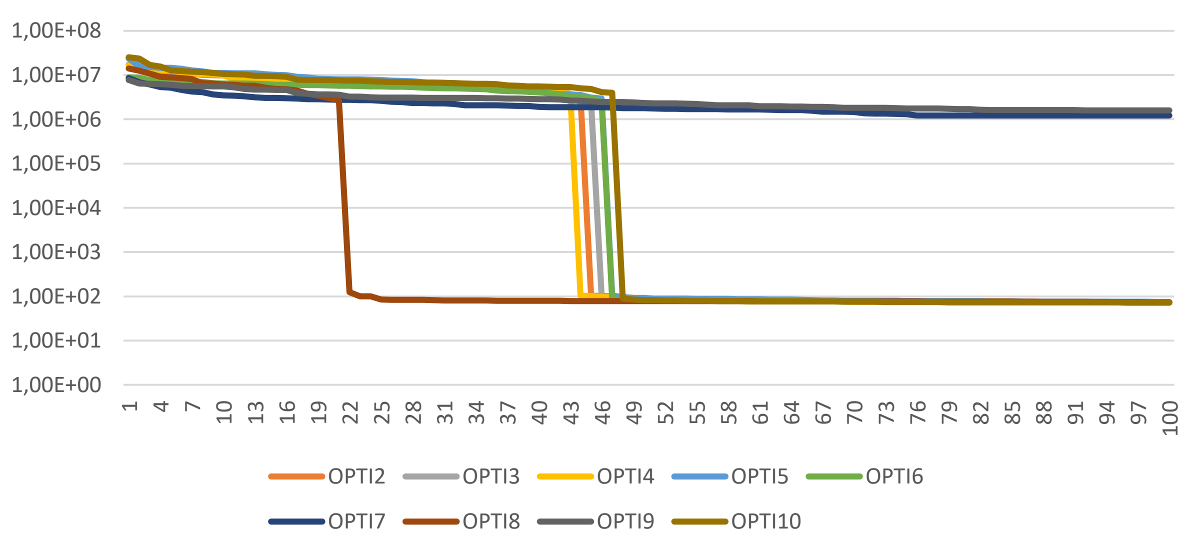
20 minutes



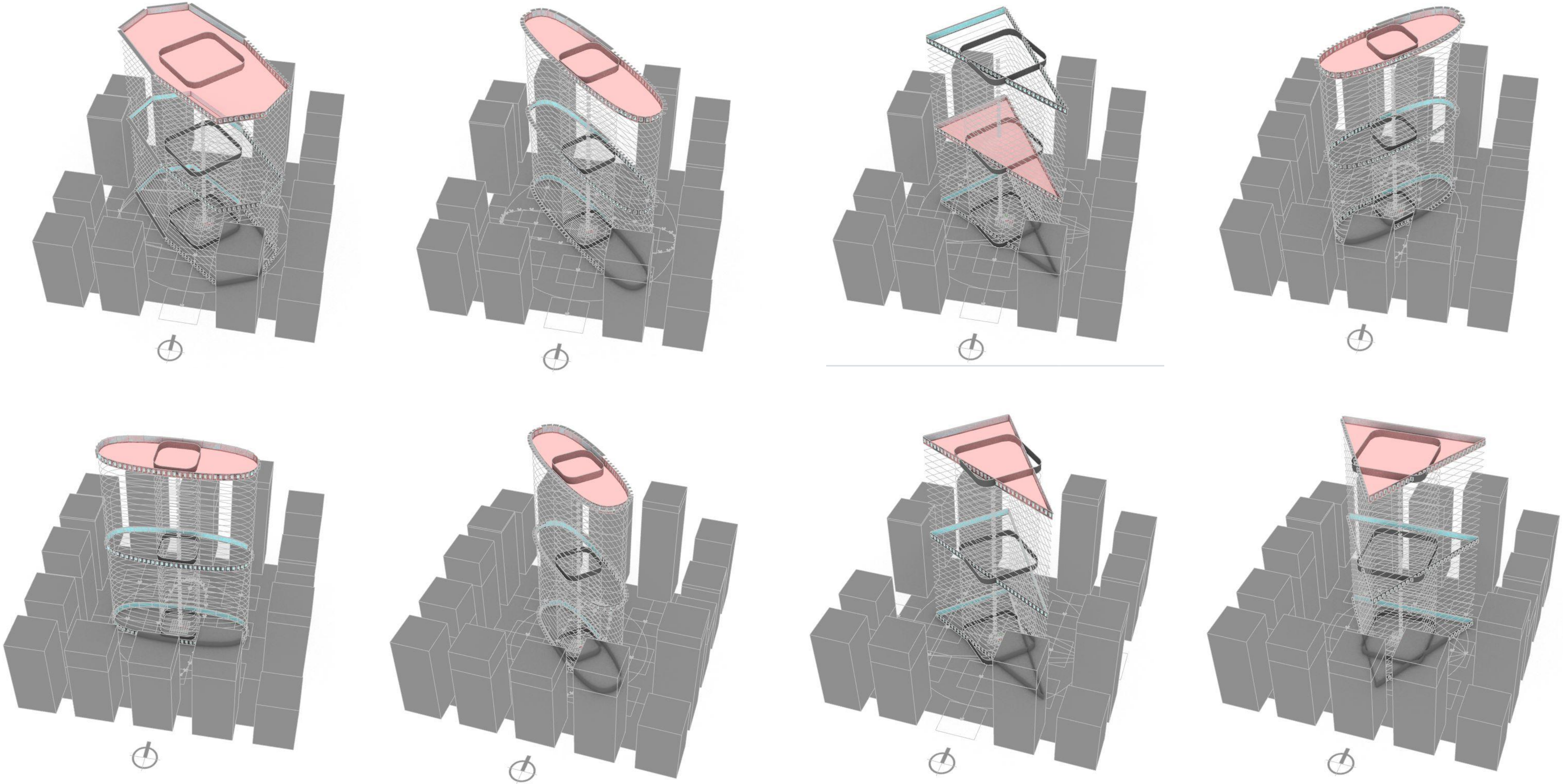
20 minutes



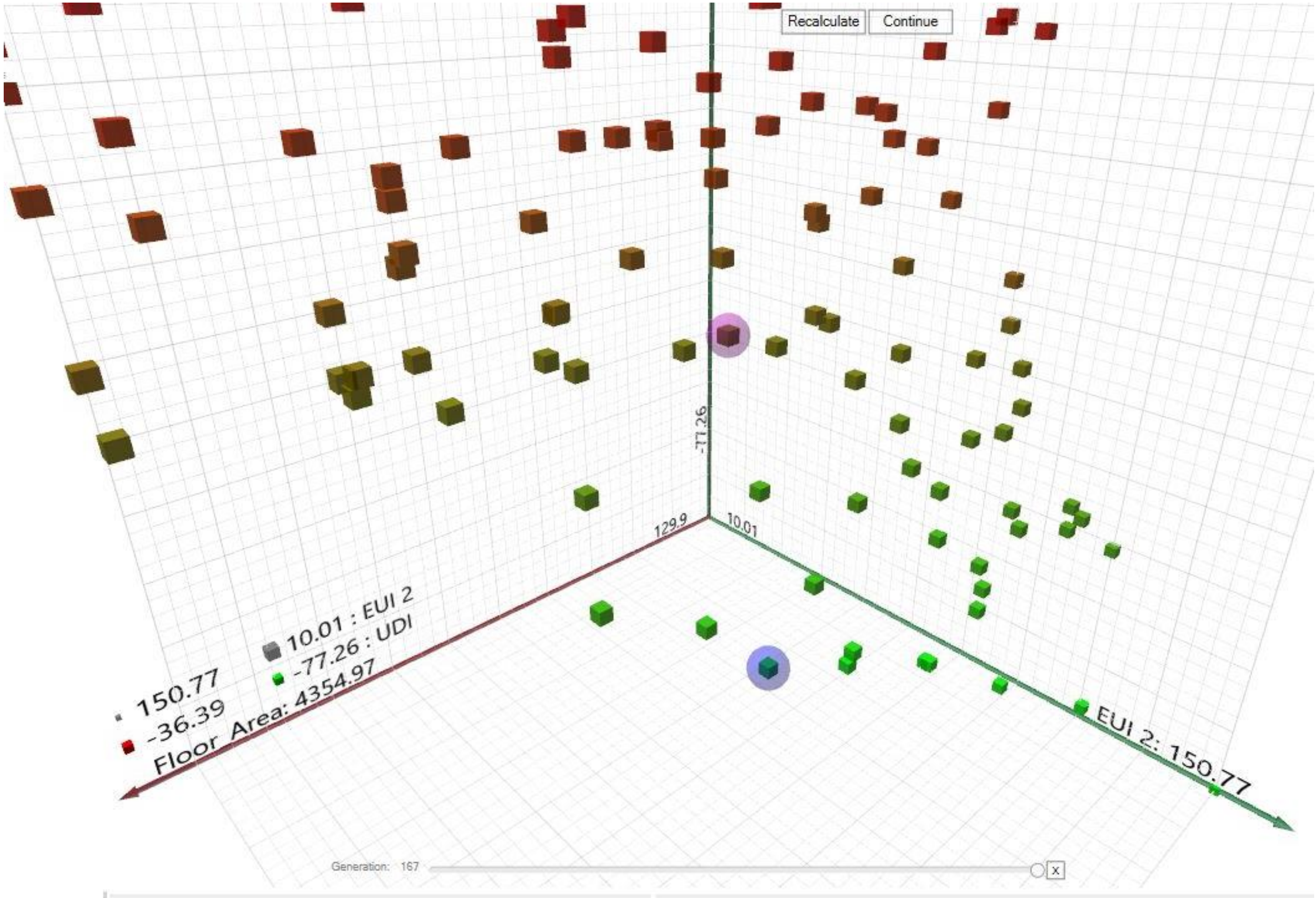
105 seconds



5. Single-Objective Optimization -Optimus jEDE



5. Optimization – Multi-Objective Optimization



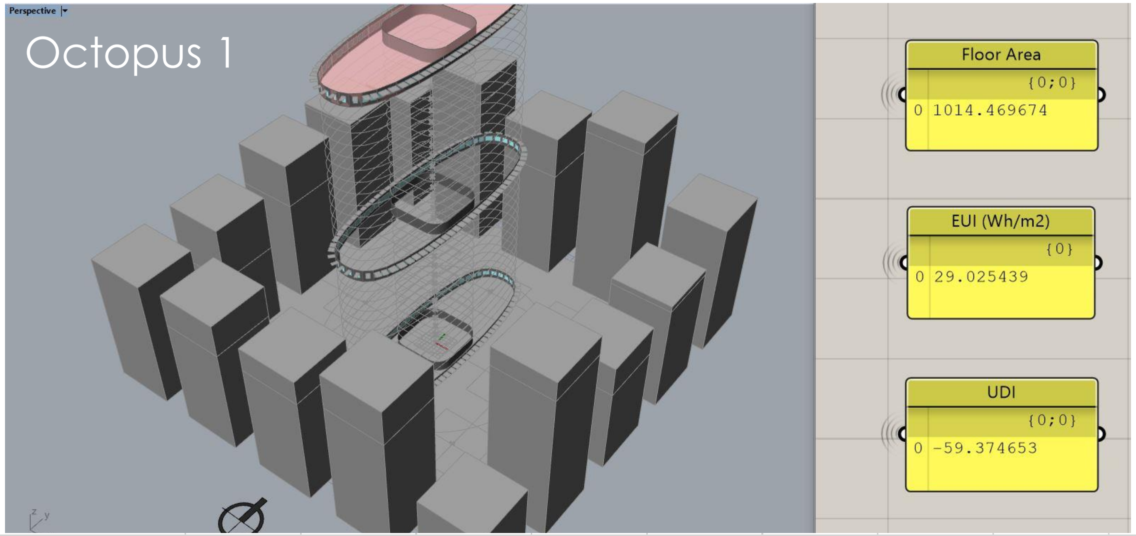
Energy:
-Lower EUI (kWh / m2 * yr)

Comfort:
+At least 60% of the time>

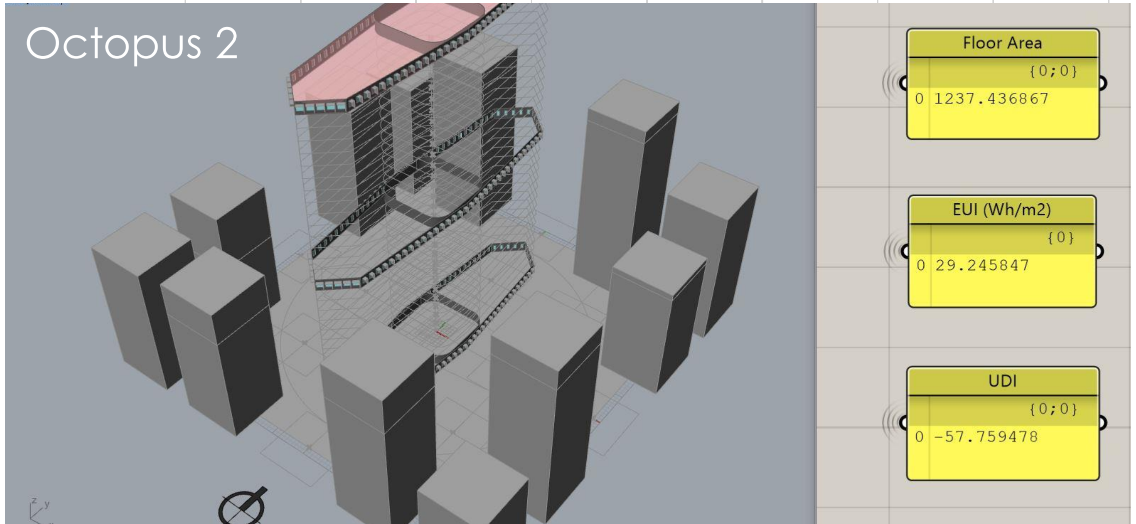
Daylight
+Higher UDI (100-2000 lux)
50% of the time

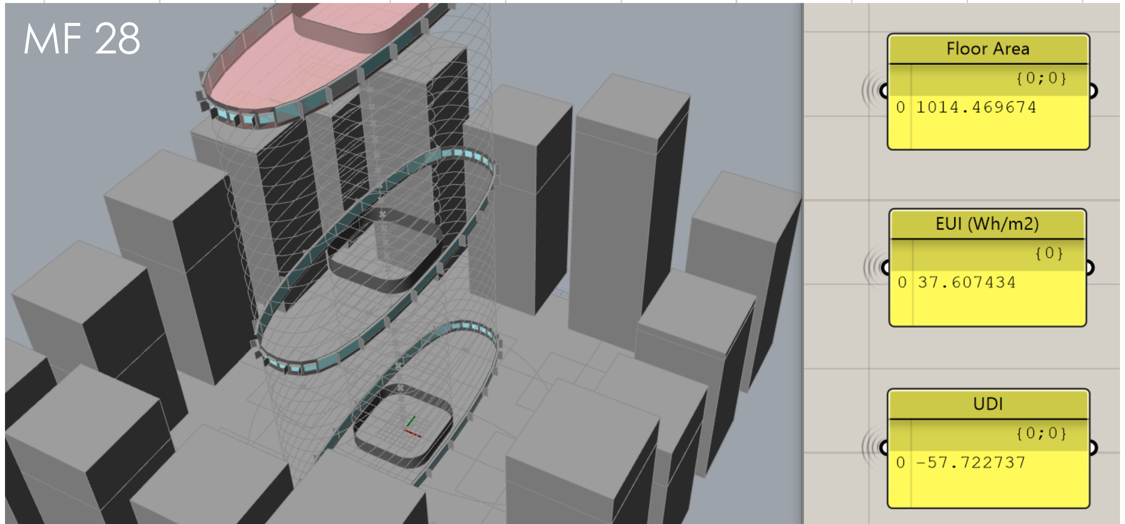
Area
Boundary:
<500 and 2000 m²>

5. Optimization – Bogotá: 1200 m²

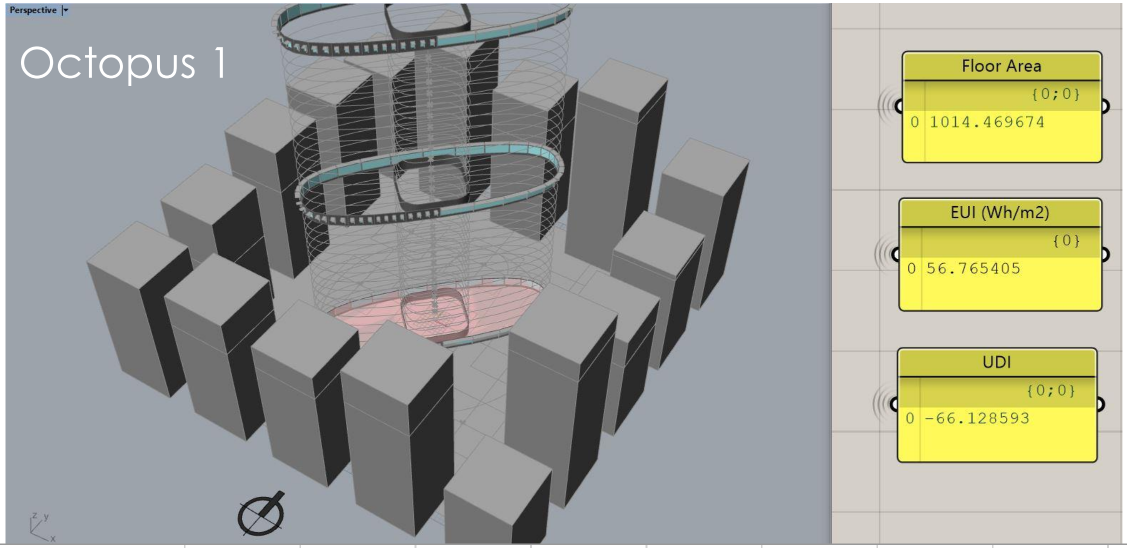


ID	Analysis_	Core_Typ	FFH	Fin_Size	Length	Number_	Orientatic	Overhang	SHGC	Shape	U_Value	VLT	WWR_Ea	WWR_Nc	WWR_So	WWR_W	Width	EUI	UDI	Floor_Area
ModeFrontier 142	0	1	6	1	3	2	0	1	2	1	1	1	4	1	2	2	2	33.352	58.7977	1200
ModeFrontier 480	2	1	8	3	1	4	5	2	3	2	2	2	1	4	4	2	2	48.0427	44.9372	601.041
ModeFrontier 28	0	1	6	3	3	1	6	1	3	3	3	2	4	2	2	4	1	37.6074	57.7227	1014.47
Octopus Solution 1	0	1	6	2	1	0	0	4	3	3	1	1	3	2	1	2	3	29.0254	59.3747	1014.47
Octopus Solution 2	0	1	6	2	4	1	6	2	3	2	1	3	4	1	2	1	1	29.2458	57.7595	1237.44

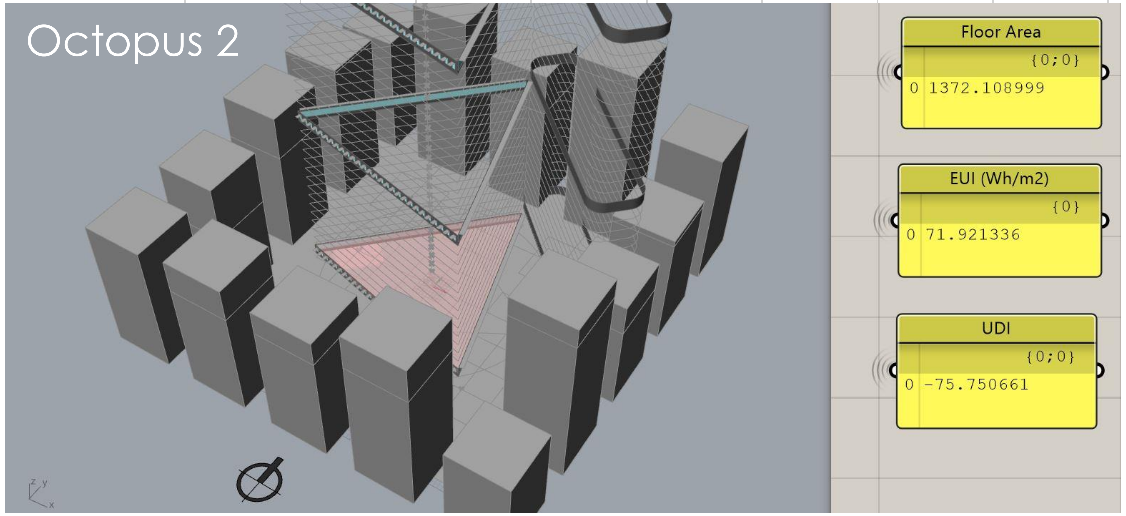


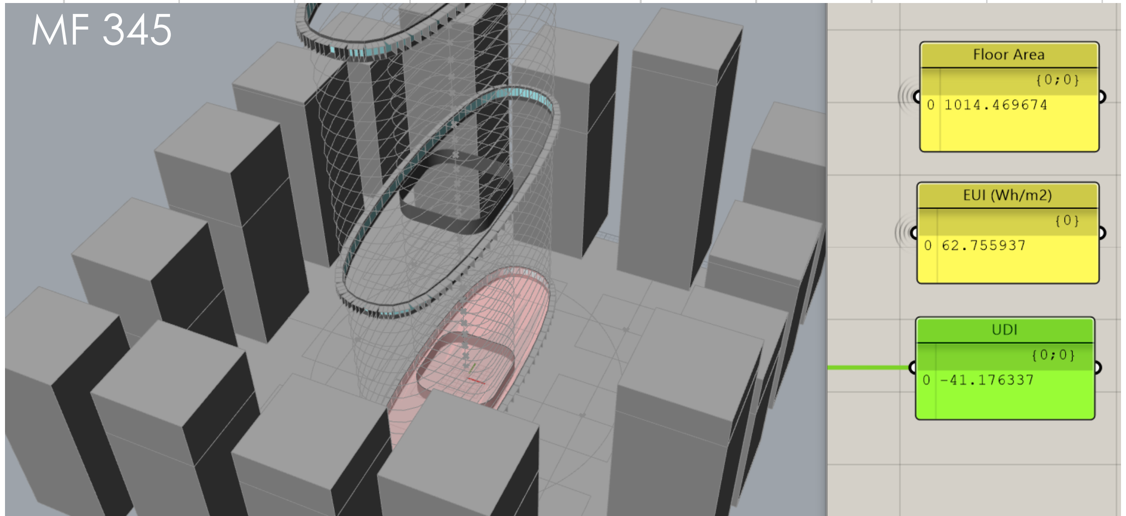


5. Optimization – Amsterdam: 1200 m²

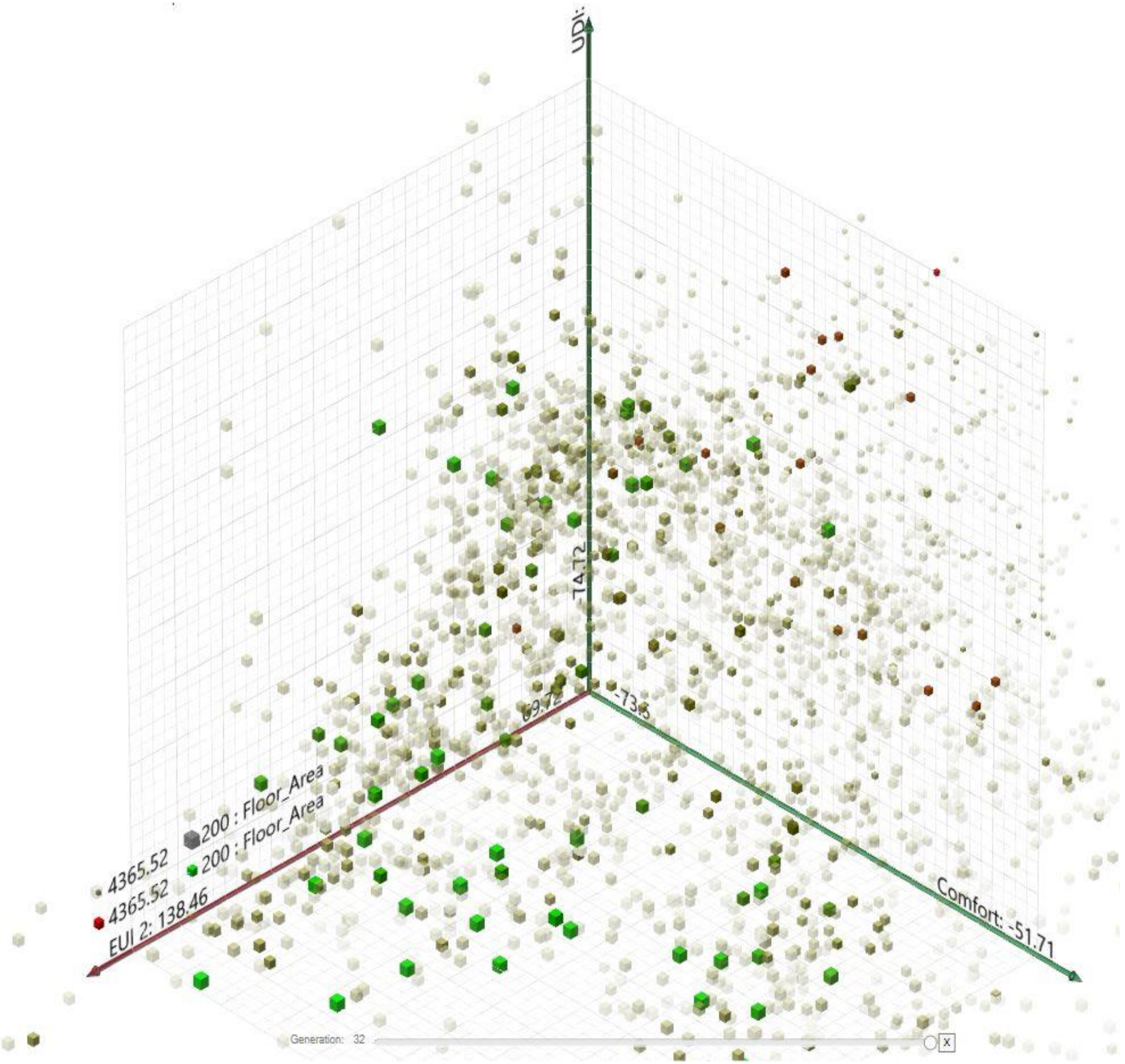


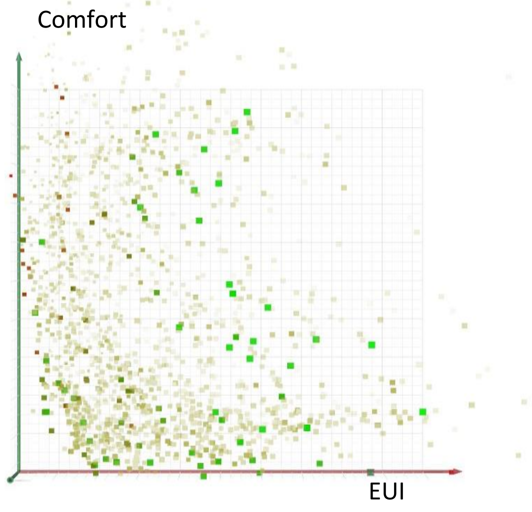
ID	Analysis_	Core_Type	FFH	Fin_Size	Length	Number_(	Orientatic	Overhang	SHGC	Shape	U_Value	VLT	WWR_Eas	WWR_No	WWR_Sou	WWR_We	Width	EUI	UDI	Floor_Area
ModeFrontier 170	2	1	7	1	2	4	5	4	3	3	1	1	3	4	1	2	2	67.7784	41.3556	1395.64
ModeFrontier 383	2	1	6	1	2	2	6	4	2	3	5	3	1	3	3	4	2	88.247	55.9888	1395.64
ModeFrontier345	2	1	6	3	1	3	4	3	3	3	1	2	2	3	2	3	3	62.7559	41.1763	1014.47
Octopus Solution 1	2	1	6	1	1	1	7	3	3	3	1	2	1	4	1	4	3	56.7654	66.1286	1014.46
Octopus Solution 2	2	0	6	3	3	0	7	3	3	0	1	2	1	3	1	4	3	71.9213	75.7507	1372.11

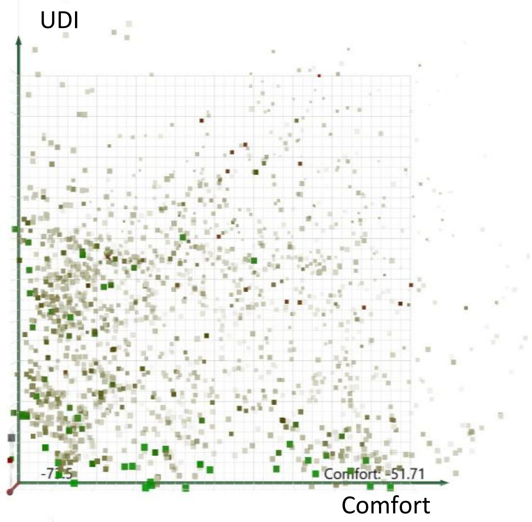




5. Multi-Objective Optimization - Octopus SPEA 2







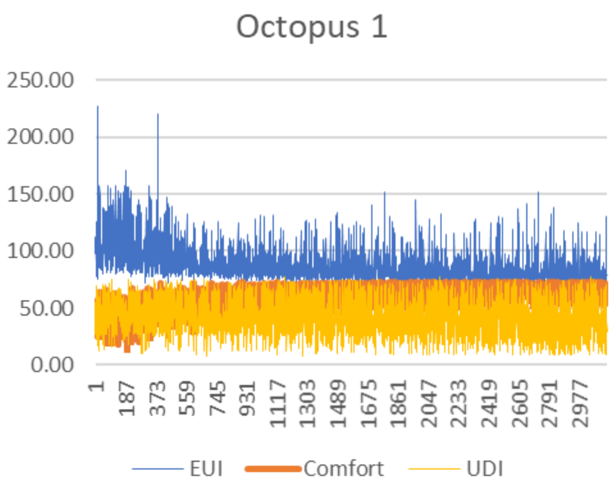
Energy:
-Lower EUI (kWh / m2 * yr)

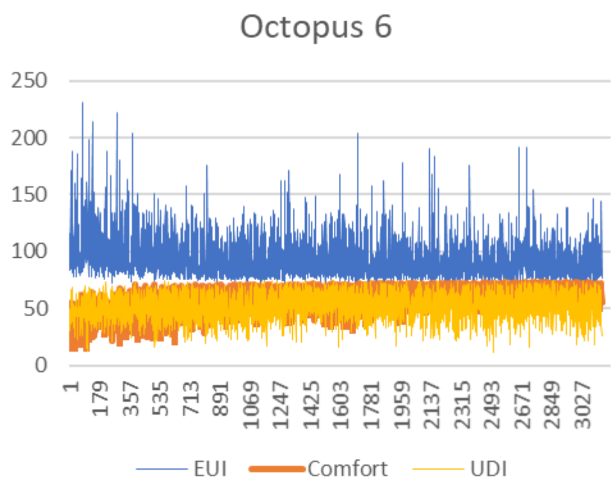
Comfort:
+At least 60% of the time>

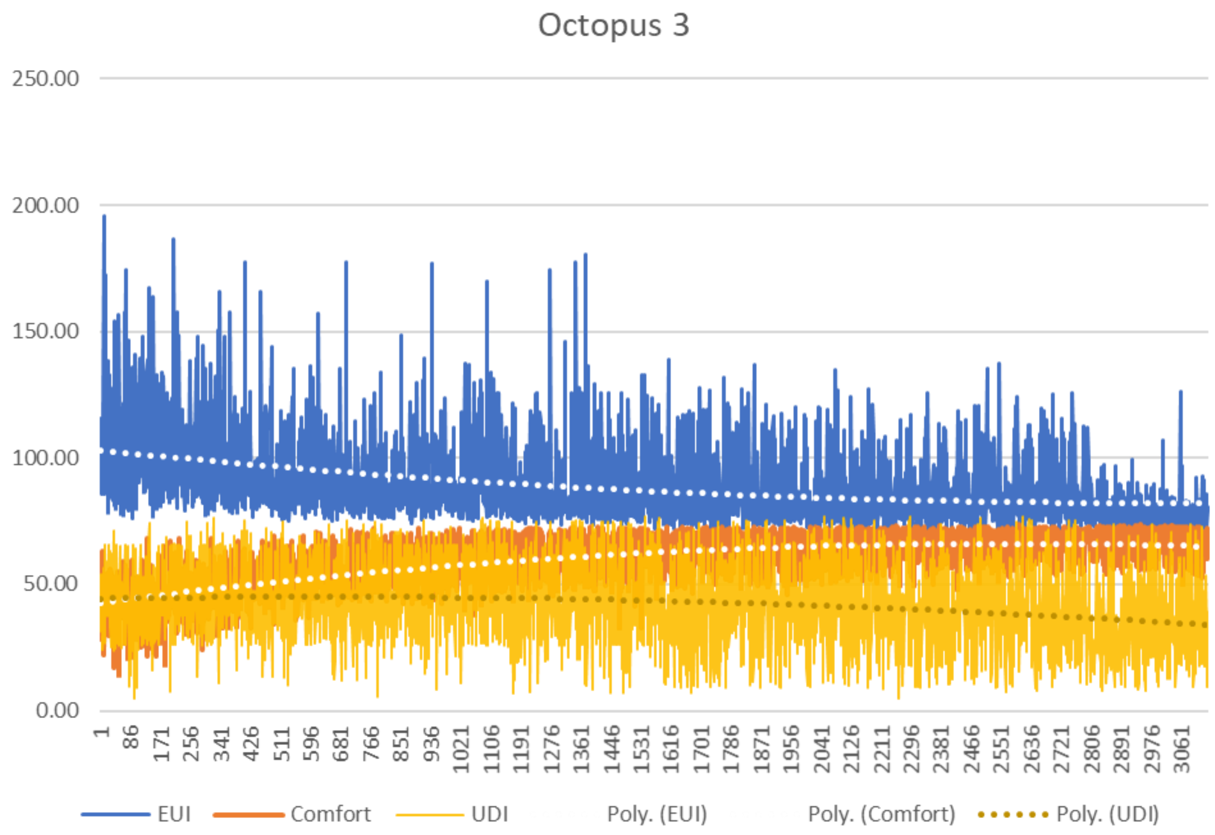
Daylight
+Higher UDI (100-2000 lux)
50% of the time

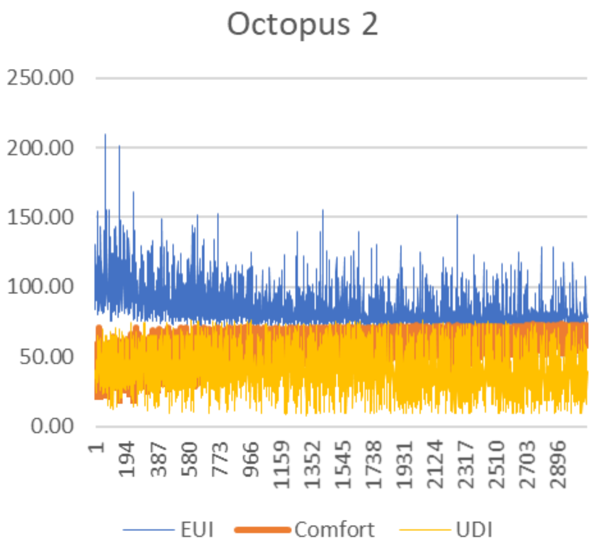
Area
Boundary:
<500 and 2000 m²>

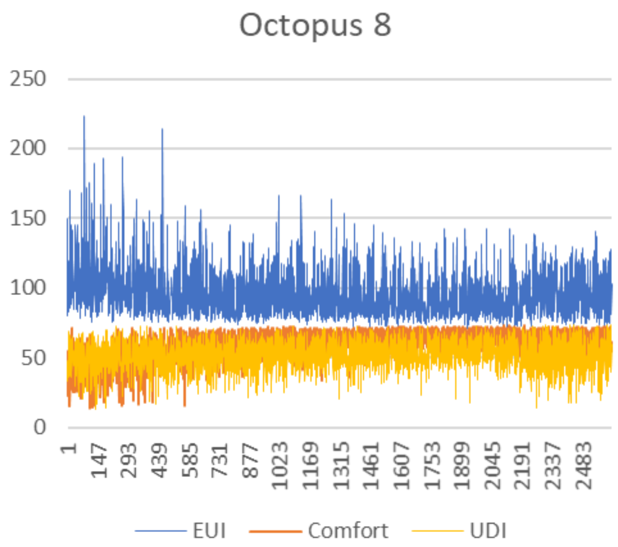
5. Multi-Objective Optimization - Octopus SPEA 2



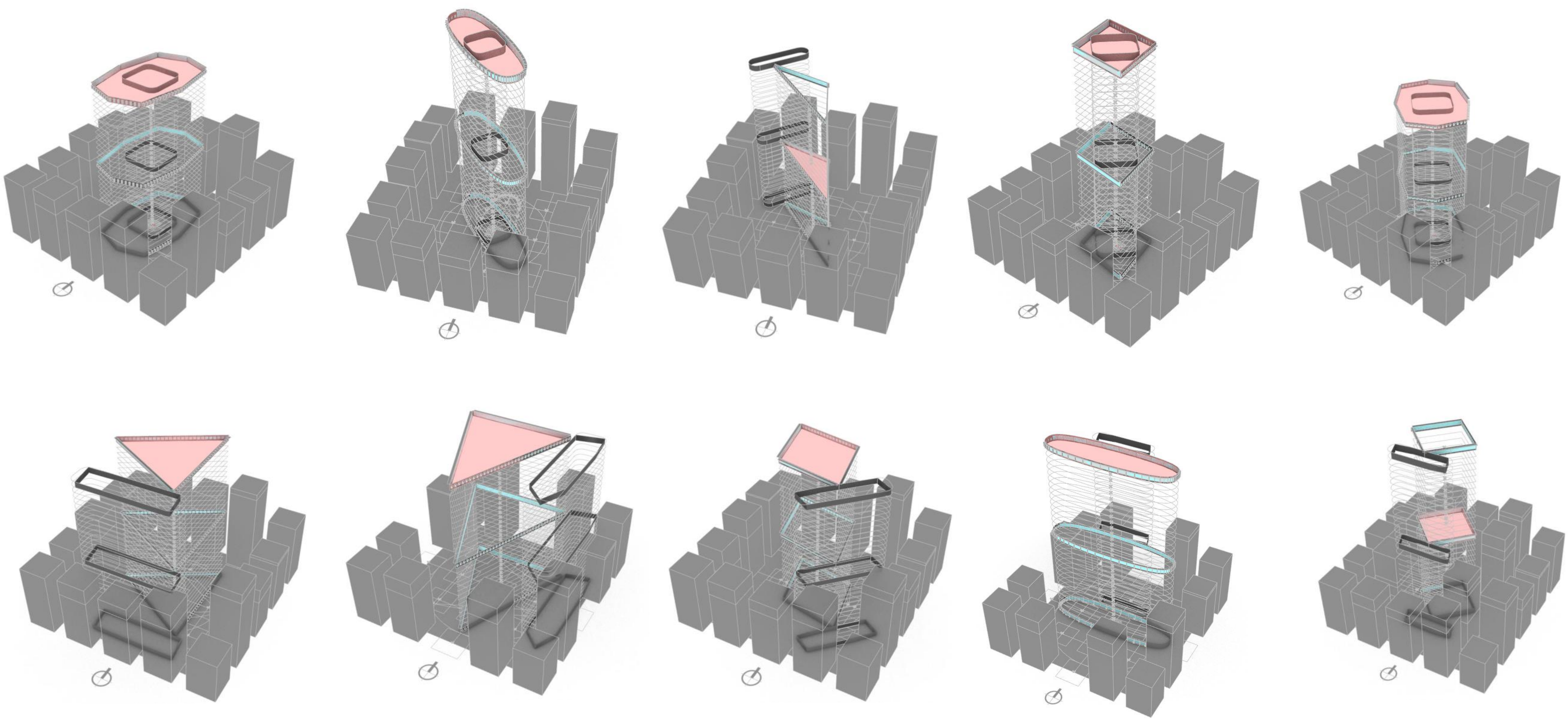








5. Multi-Objective Optimization - Octopus SPEA 2



5. Optimus jEDE / Octopus SPEA 2:

	Opti 1 Input	Opti 2 Input	Opti 3 Input	Opti 4 Input	Opti 5 Input	Opti 6 Input	Opti 7 Input	Opti 8 Input	Opti 9 Input	Opti 10 Input
Analysis_Level	0	0	1	0	0	0	2	0	2	0
Core_Type	1	1	1	1	1	1	1	1	1	1
FFH	6	6	6	6	6	6	6	6	7	6
Length	4	4	4	1	1	1	1	4	1	3
Number_Of_Fins	0	0	0	0	1	3	2	0	0	2
Orientation	0	7	7	7	6	1	7	7	7	6
Overhang_Size	4	4	2	4	1	4	1	1	1	1
SHGC	3	3	3	3	3	3	1	3	2	3
Shape	3	3	0	3	3	3	0	0	0	0
U_Value	1	1	1	1	1	1	7	1	7	1
VLT	3	3	3	3	2	2	3	3	3	3
WWR_East_North	1	1	1	2	1	1	2	2	1	1
WWR_North_West	4	4	4	4	4	4	4	4	2	4
WWR_South_East	1	1	1	1	1	2	1	1	2	1
WWR_West_South	4	2	1	1	4	2	2	1	2	1
Width	2	1	2	3	3	3	1	2	1	3
EUI	72.34	73.23	73.19	73.65	74.80	74.20	1.22E06	73.78	1.60E06	72.57
Comfort	61.68	61.87	61.88	61.45	69.54	59.58		69.54		66.53
UDI	60.37	53.63	62.27	54.77	67.99	61.33		63.41		64.47
Floor Area	2710	1368	1480	1016	1016	1016		1480		1703

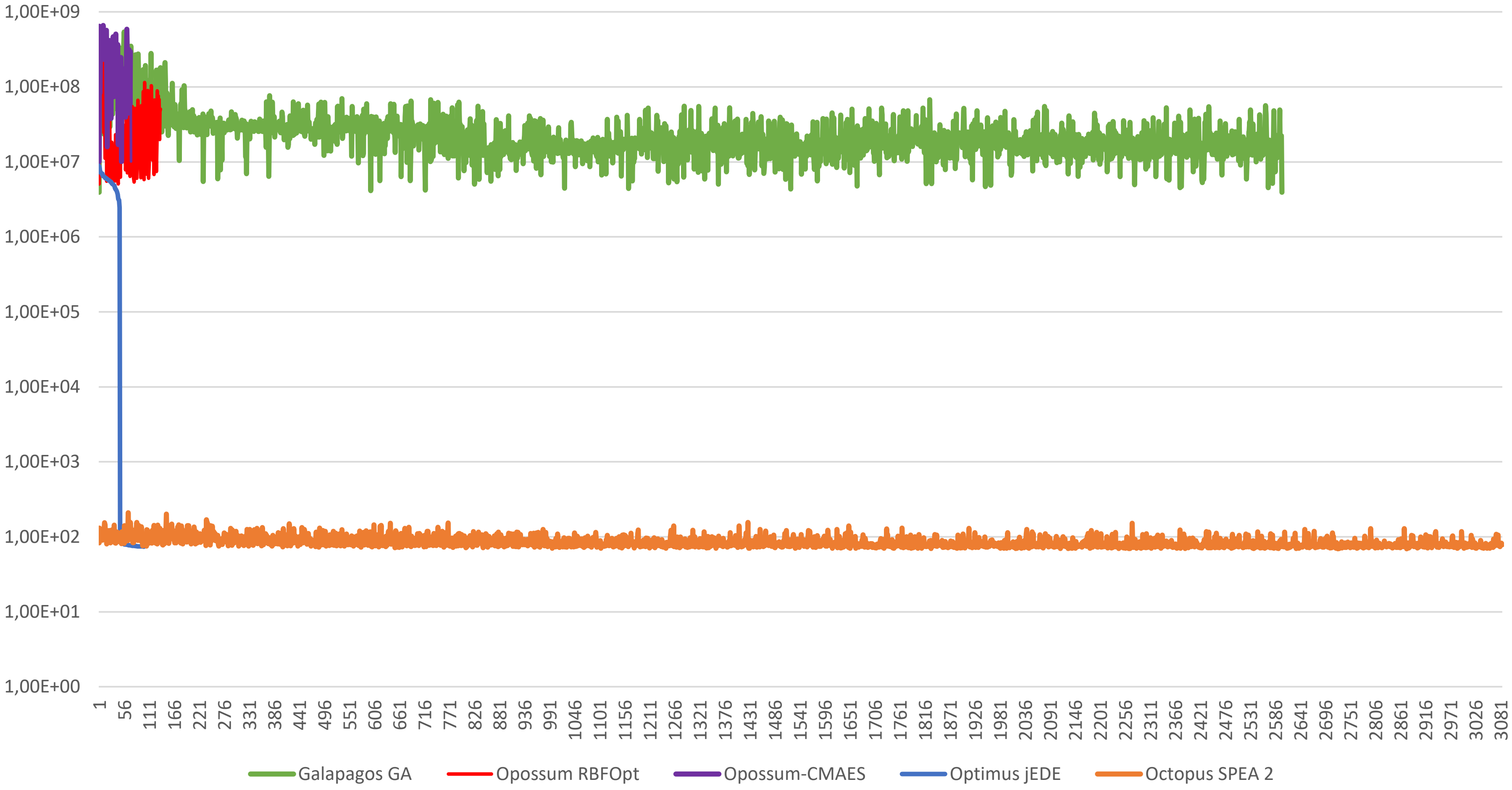
	Oct1 Inputs	Oct2 Inputs	Oct3 Inputs	Oct4 Inputs	Oct5 Inputs	Oct6 Inputs	Oct7 Inputs	Oct8 Inputs	Oct9 Inputs	Oct10 Inputs
Analysis_Level	0	0	1	0	0	0	0	0	0	1
Core_Type	1	1	0	1	1	1	0	0	0	0
FFH	6	8	6	7	6	6	6	6	7	7
Length	3	1	1	3	3	3	4	2	4	2
Number_Of_Fins	4	2	1	0	0	2	0	0	2	2
Orientation	2	5	1	3	7	6	6	5	0	4
Overhang_Size	2	3	1	3	3	1	3	3	1	2
SHGC	3	3	3	3	3	3	3	3	3	3
Shape	2	3	0	1	2	0	0	1	3	1
U_Value	1	1	1	1	1	1	1	1	1	1
VLT	1	2	2	2	2	3	3	2	2	1
WWR_East_North	1	4	4	1	1	1	1	4	3	2
WWR_North_West	4	4	3	1	4	4	4	2	3	3
WWR_South_East	1	4	2	4	2	1	3	3	3	3
WWR_West_South	4	1	1	4	2	1	4	4	1	3
Width	2	3	3	2	2	3	3	3	1	2
EUI	79.23	84.24	99.10	83.91	74.23	87.30	81.31	93.61	86.18	100.48
Comfort	67.60	68.15	64.64	70.18	67.00	68.20	64.84	69.86	66.16	63.72
UDI	69.01	53.46	68.87	70.08	70.84	65.56	59.41	66.03	59.41	70.11
Floor Area	2010.3	1016.0	470.9	1560.0	2010.3	1703.4	2319.6	1560.0	1367.9	1005.0

Optimus jEDE

Single Objective

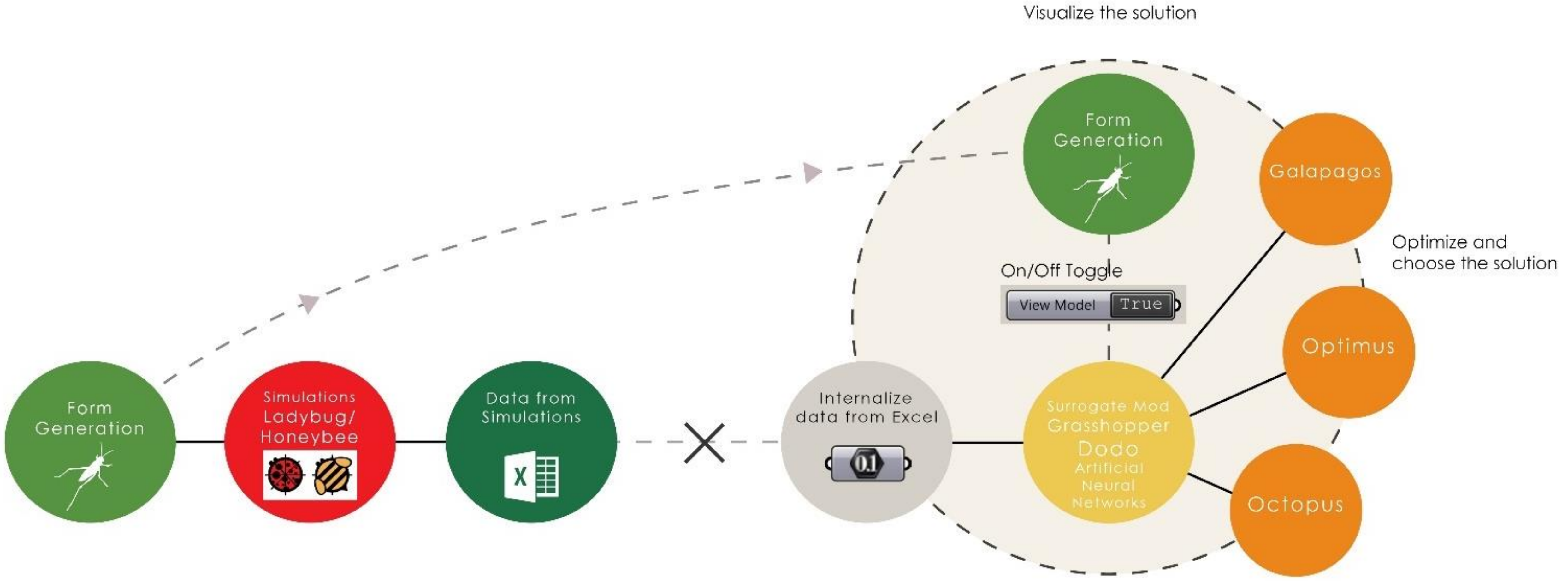
Octopus SPEA 2

5. Optimization Summary

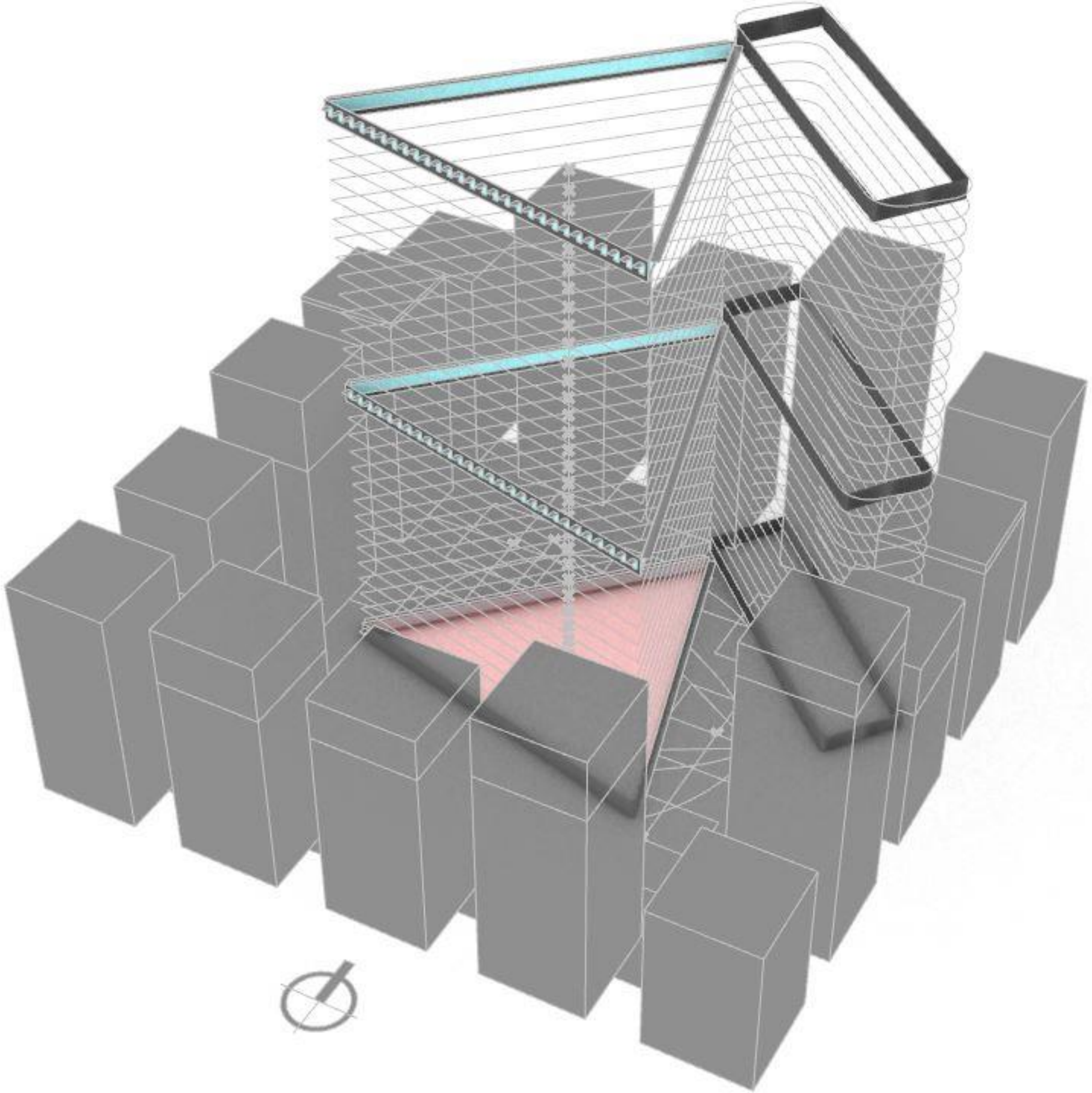


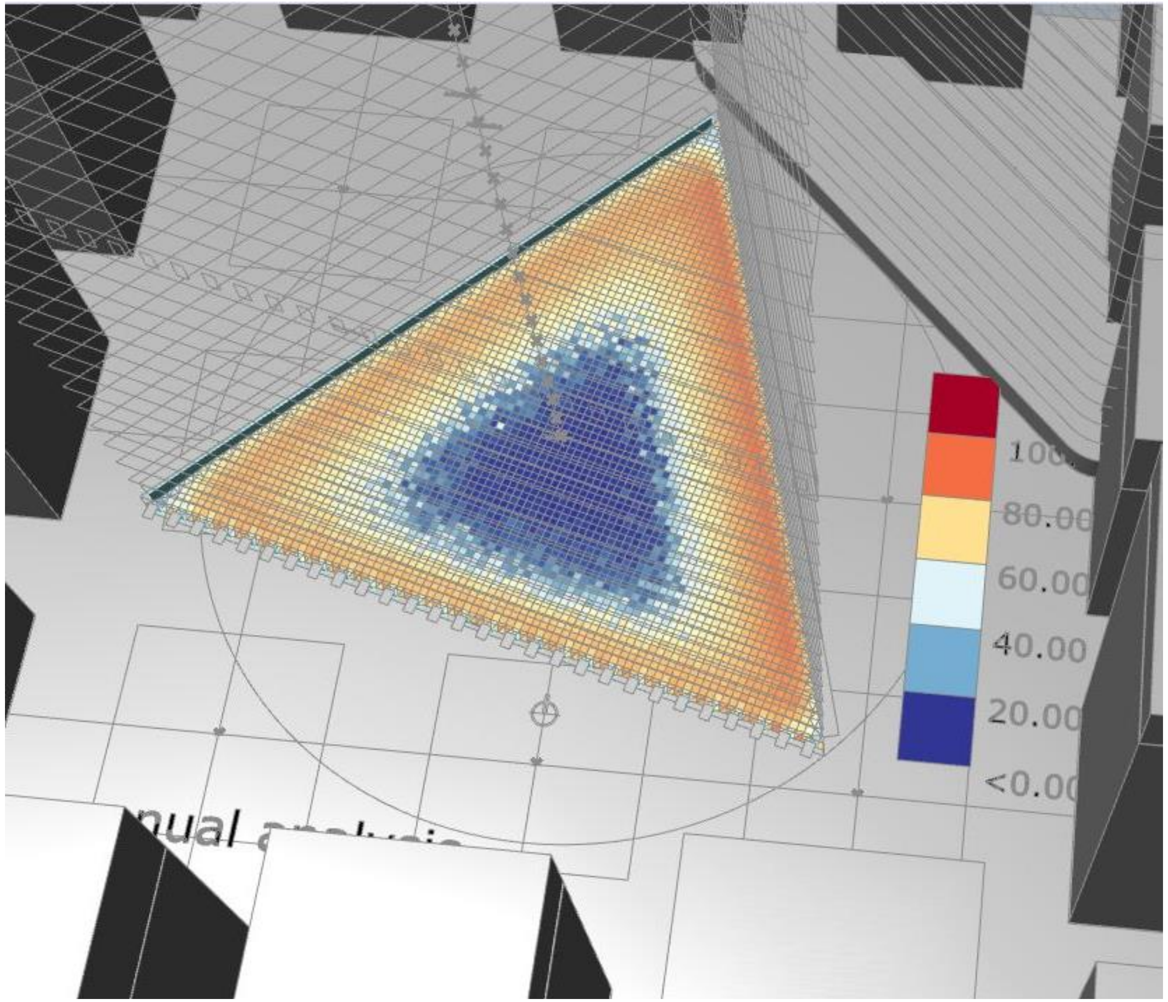
	Galapagos GA	Opossum RBFOpt	Opossum-CMAES	Optimus jEDE	Octopus SPEA 2
F(x)_min_AVG	6.75E+06	5.28E+06	1.41E+07	73.47	82.74
FES	2601	136	76	5000	3186
Time (s)	1200	1200	1200	105	1200

6. Visualizing the results

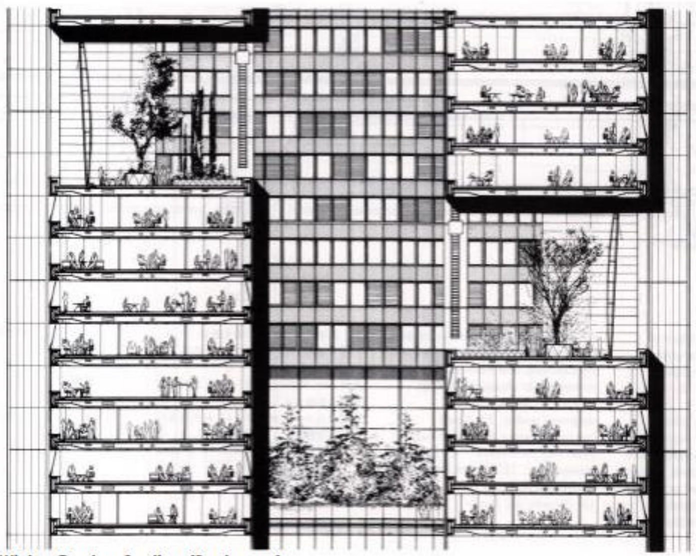


1. Simulation

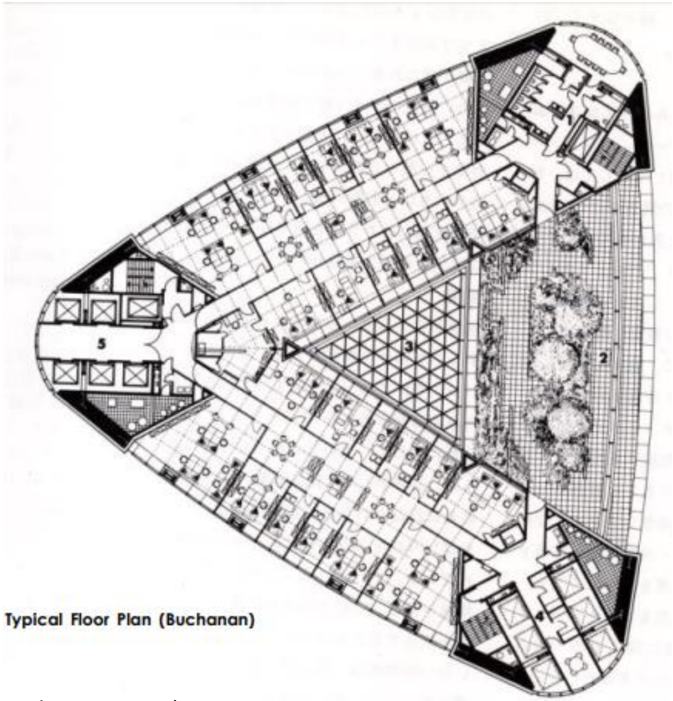




Lina Bo Bardi – Brazilian Modernism

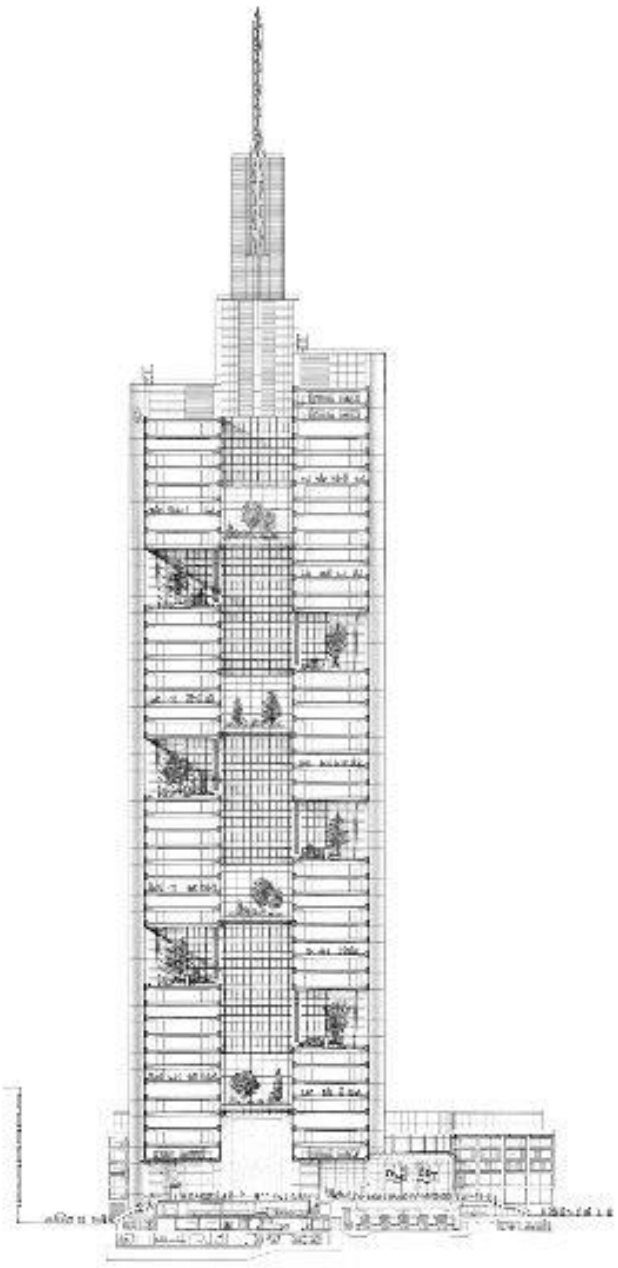


Winter Garden Section (Buchanan)



Typical Floor Plan (Buchanan)

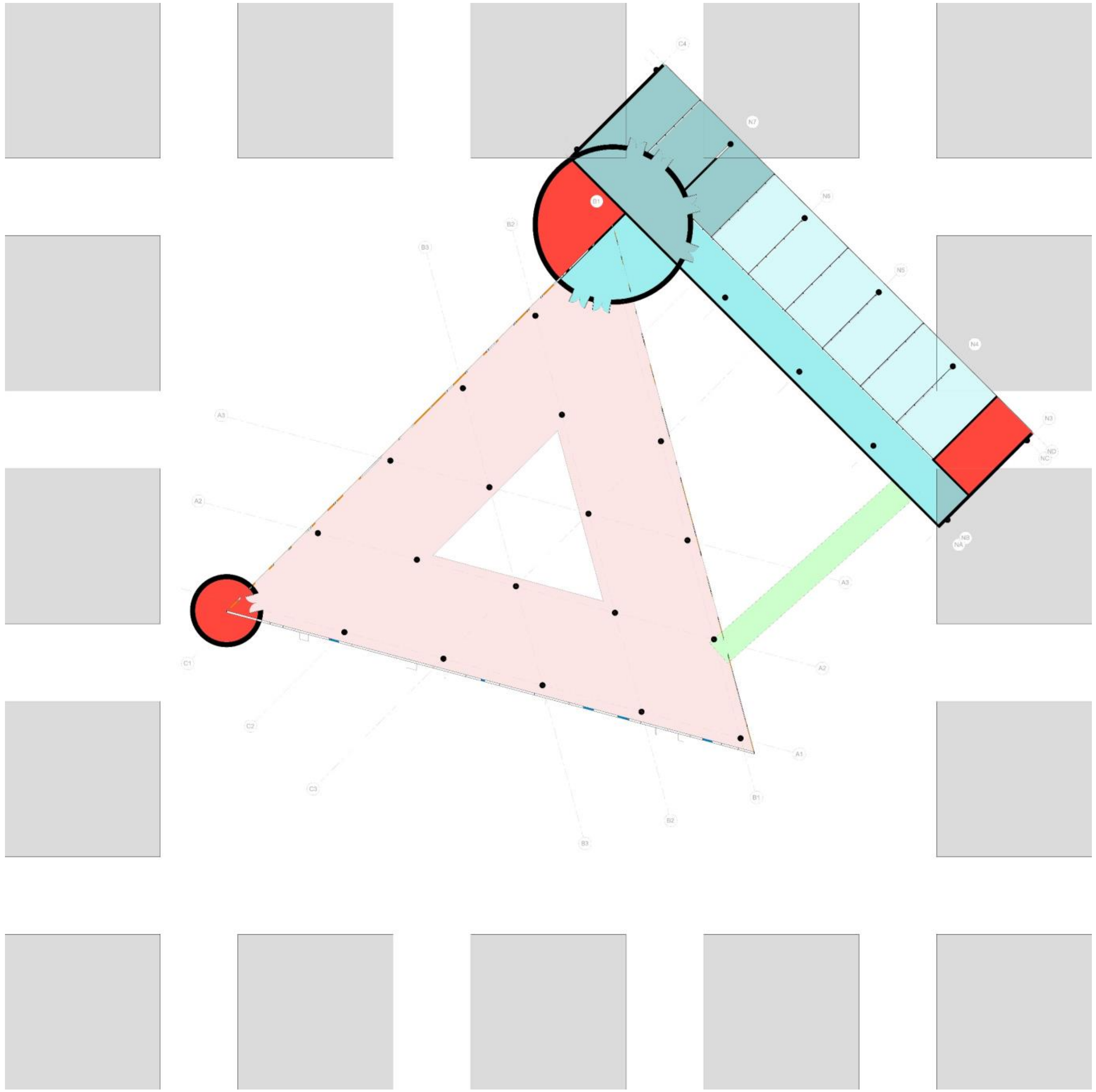
(Buchanan, 1998)



Norman Foster – High Tech

7.

Proposal



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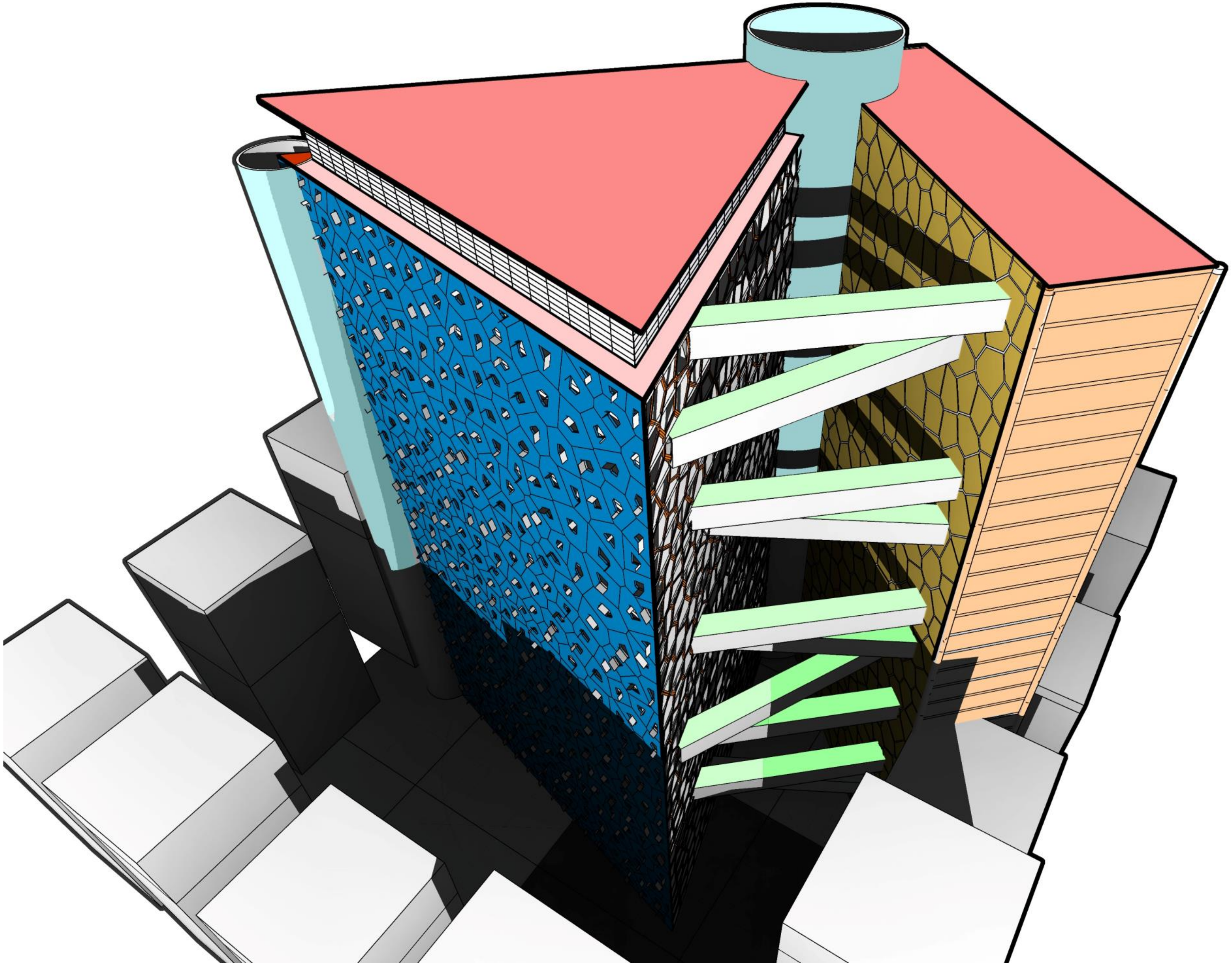

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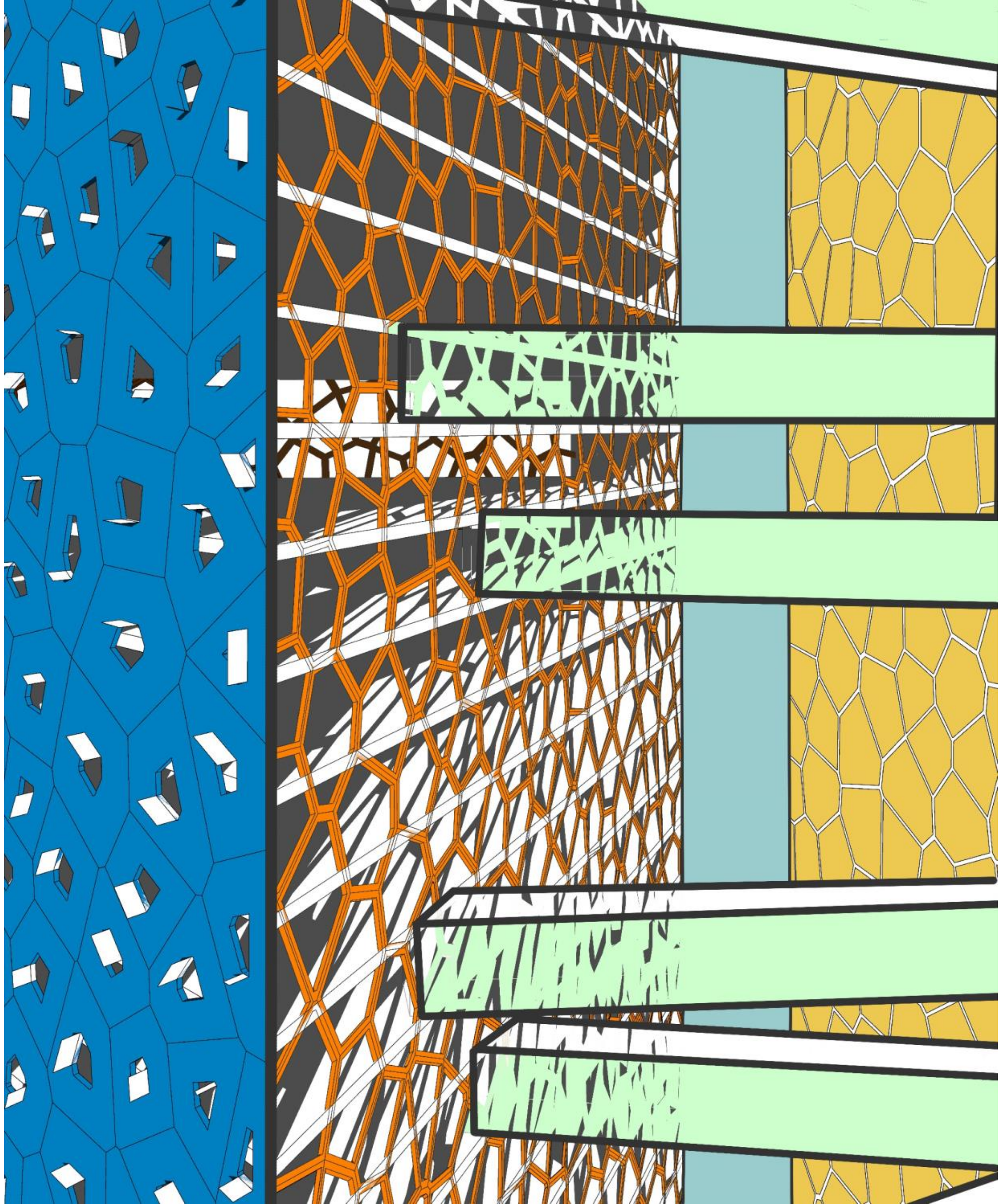
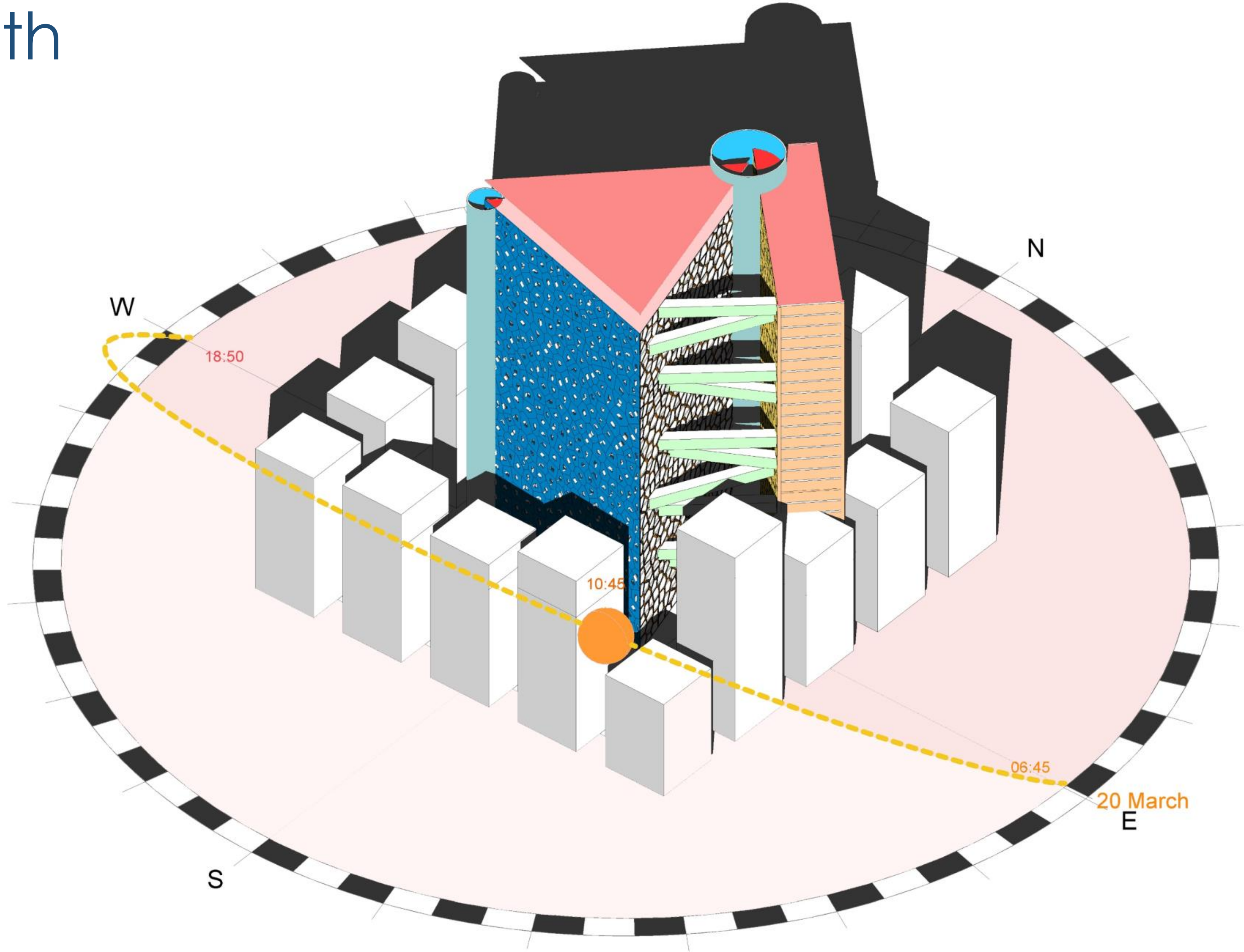
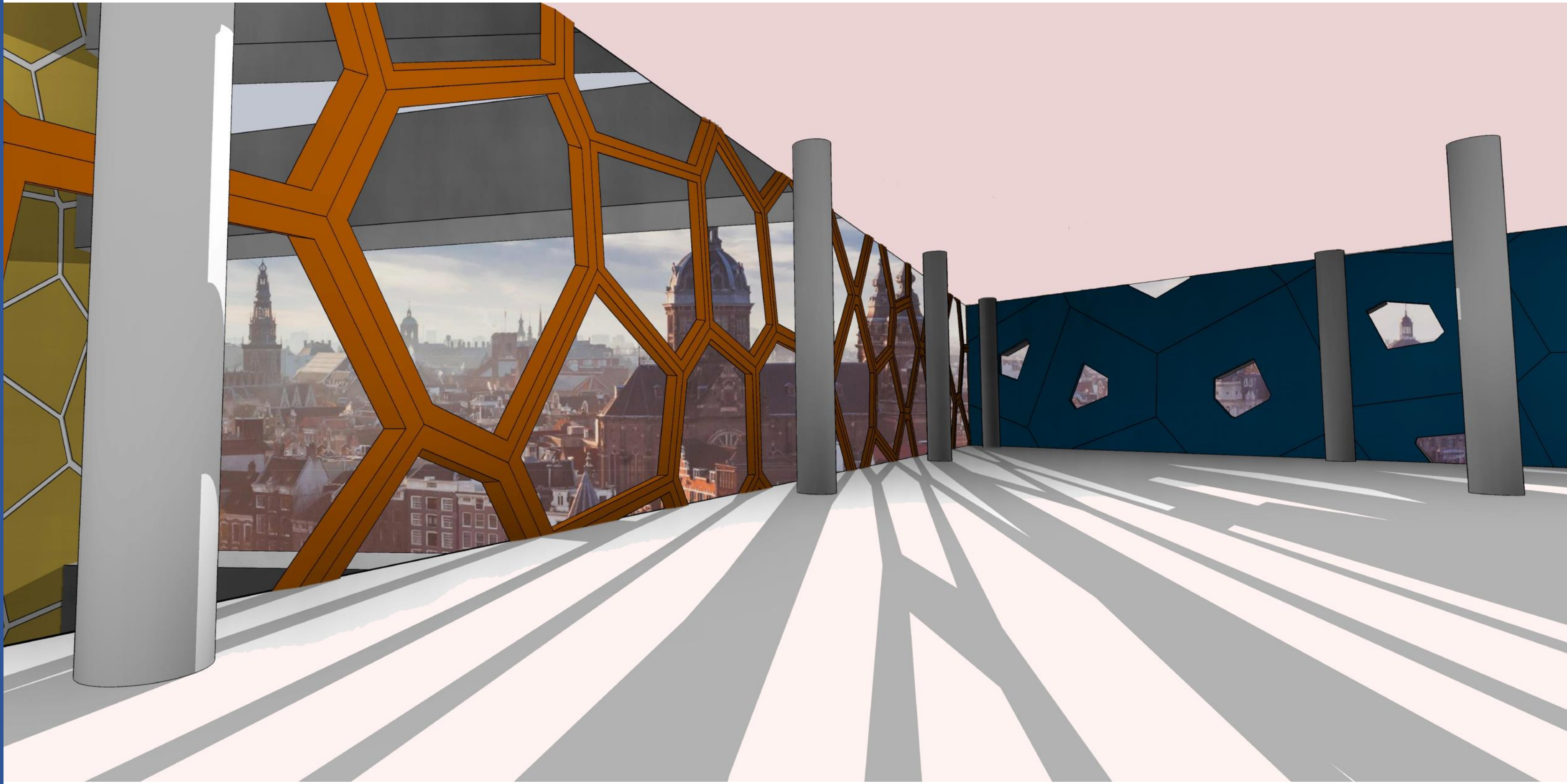
7.



Sunpath



User



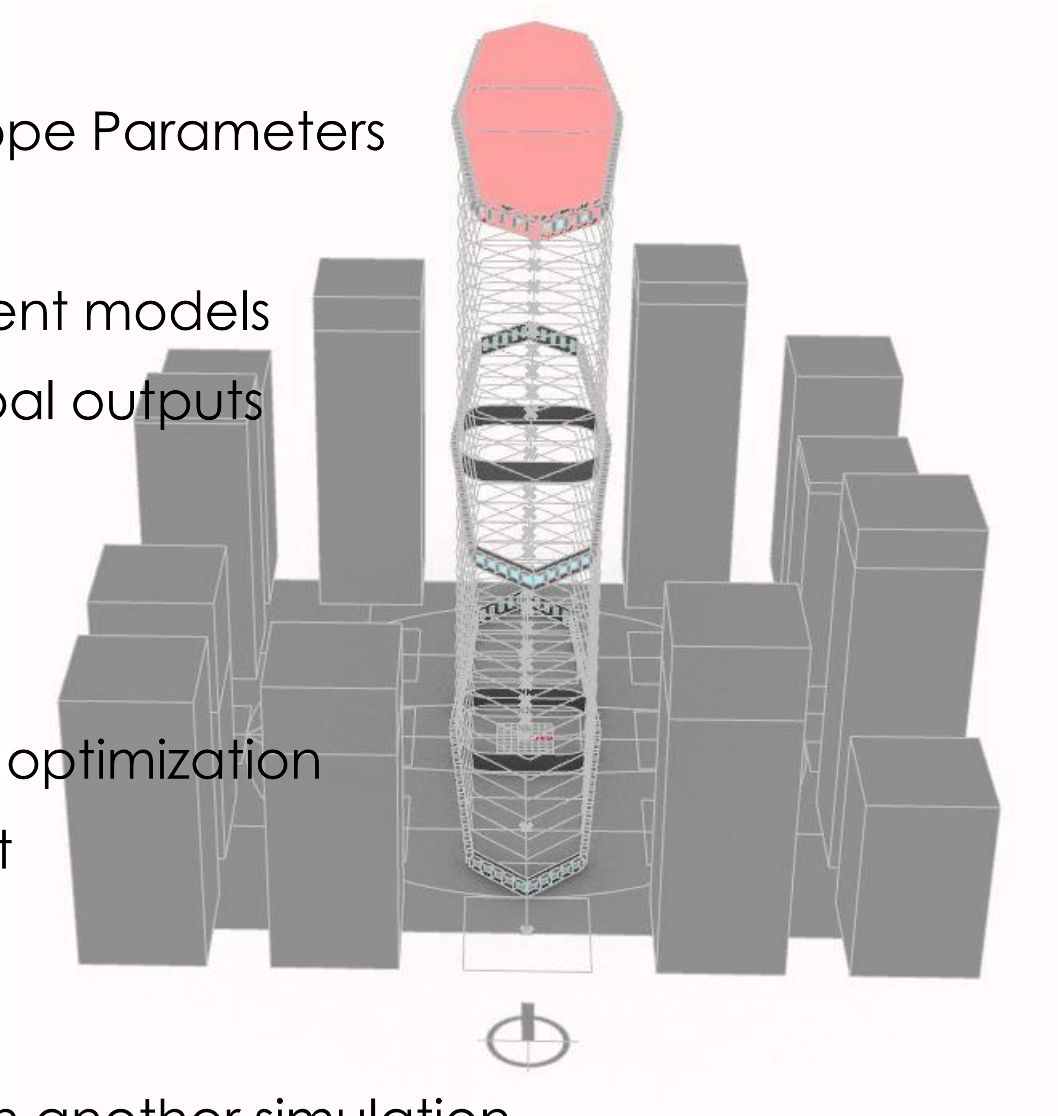
Conclusions

Building Physics:

- Shape Parameters more significant than Envelope Parameters
- Different responses per level and orientation
- Location plays a significant role thus independent models
- Analysis level (context) not as significant in global outputs

Computational:

- High Learning Curve
- Once created, much faster for exploration and optimization
- The more variables & Samples, the more worth it
- A Tool, not a Replacement of human creativity
- Eliminate human bias
- Chosen solution should be double checked with another simulation



Surrogate Model Live

- From 500 simulated samples in 8820 minutes (100%)
- Down to 500 samples in 250 minutes (2.8%)
  (Visualization / Form Generation turned on)
- Down to 500 samples in 189 seconds (0.036%)
  (Visualization / Form Generation turned off)

- 99.96% reduction of the computational load.