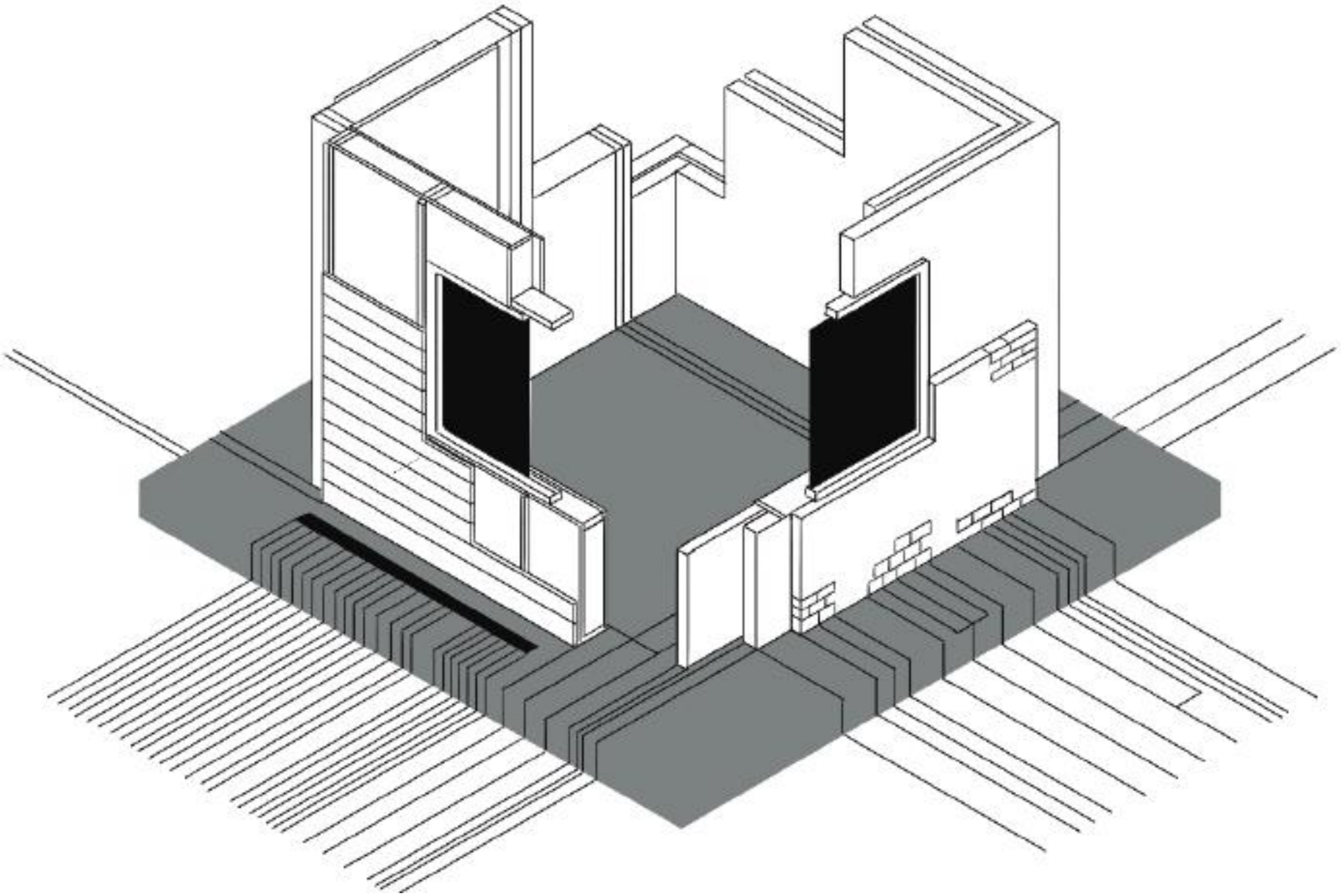
Dynamic Façade Design for Sustainability: A Computational Approach to Reducing Embodied and Operational Carbon in Façade Elements



Lars Vedder

[redacted]

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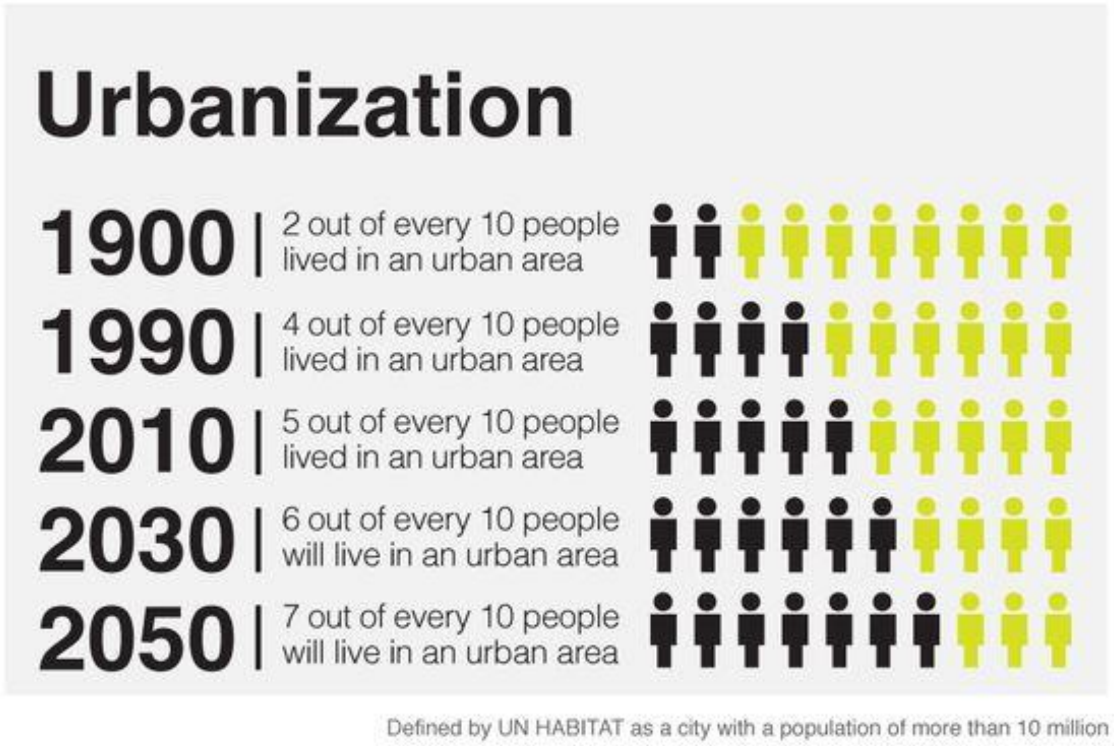
Urbanization

URBANISATION AND
POPULATION PREDECTIONS

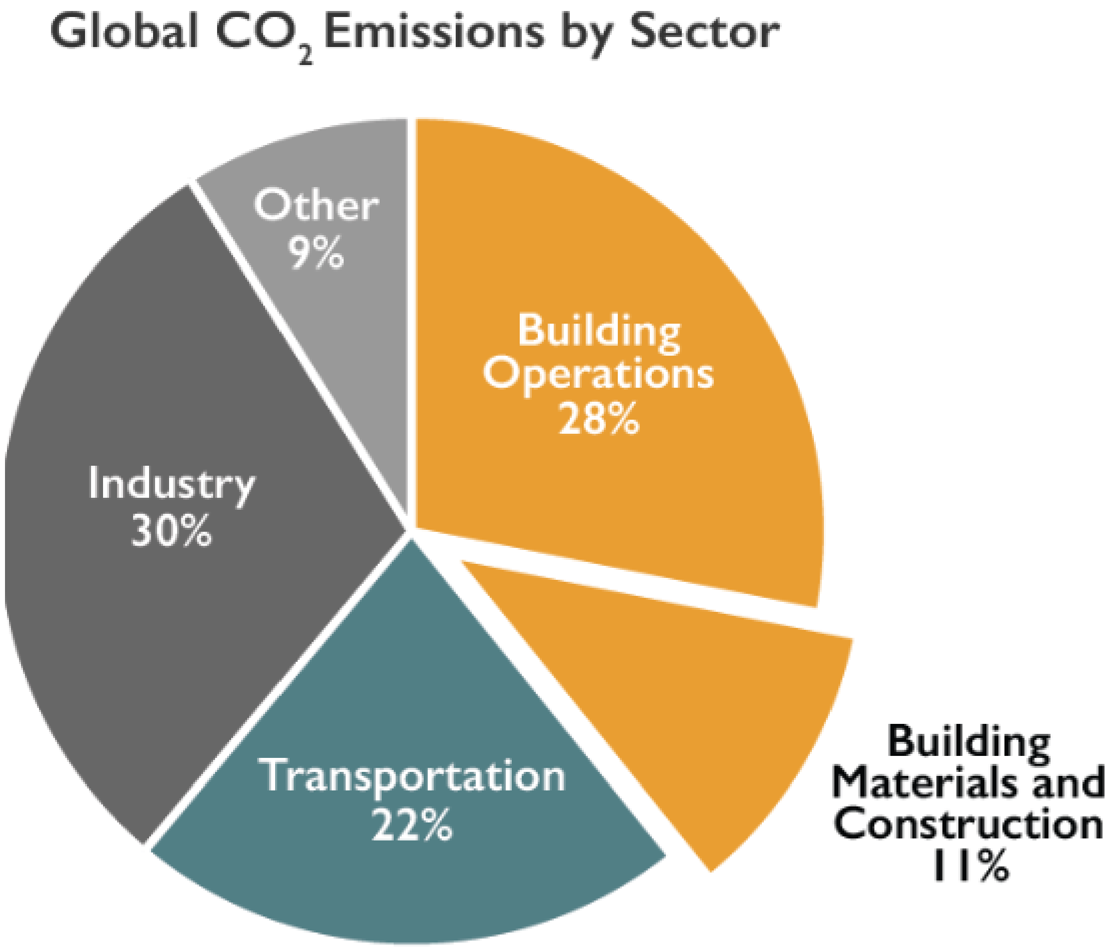
- Currently, 55% of the global population lives in cities, with that percentage expected to rise to 68% by 2050 (United Nations, May 16, 2018)
- Population prediction: 9.7 billion by 2050 (UN, 2017)



Carbon emissions

Energy demand and carbon emissions of the built environment

the building sector consumes 35% of global resources, 40% of total energy, 12% of the world's drinkable water, and nearly 40% of global carbon emissions (Saint-Gobain, 22 August 2017).



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Climate Mitigation Measures

The main objective of the regulation is to cut greenhouse gas emissions by 85-90% by 2050, thereby keeping the temperature rise below 2 degrees Celsius (European Parliament and Council of the European Union, 2010).

- Beng
- MPG

Compared to operational emissions, and despite their growing importance, legislation tackling embodied GHG emissions is uncommon (J. Steinmann et al. 2022). It is now anticipated that embodied GHG emissions in construction around the world must be cut back by at least 40% by 2030 to reach a net-zero carbon emission balance by 2050, as required by the Paris Agreement on Climate Change (UNEP, 2021).

Problem statement

- Urban densification is leading to more mid to high-rise buildings, increasing the demand for sustainable design practices.
- Current legislation primarily targets the reduction of operational carbon (energy use during a building's life).
- **Embodied carbon** is becoming a more significant concern.

Understanding these trade-offs in façade design, especially in the early phase of a design, has a lot of potential for sustainable mid to high-rise architecture.

Aim of the study

- **Investigate the impact of different façade typologies** on the embodied and operational carbon of mid to high-rise buildings.
- **Focus on the early design phase** to integrate sustainability considerations from the outset.
- **Develop a computational workflow** to simulate and optimize façade designs for embodied energy and carbon performance.
- **Identify optimal façade combinations** that minimize environmental impact while meeting regulatory standards.
- **Provide actionable insights and data** for architects, designers, and stakeholders to make informed decisions.

Research question

"How do different dynamic façade variables influence the embodied and operational carbon of mid to high-rise residences during the early design phase, and what optimal combinations can be identified to minimize environmental impact while meeting regulatory standards?"

Sub questions

What is the definition of mid to high-rise, and what are the most prevalent facade typologies that apply to mid to high-rise buildings?

How do different façade materials affect the embodied energy and carbon footprint of mid- to high-rise buildings?

What are the regulatory standards for façade design in terms of embodied energy and embodied carbon?

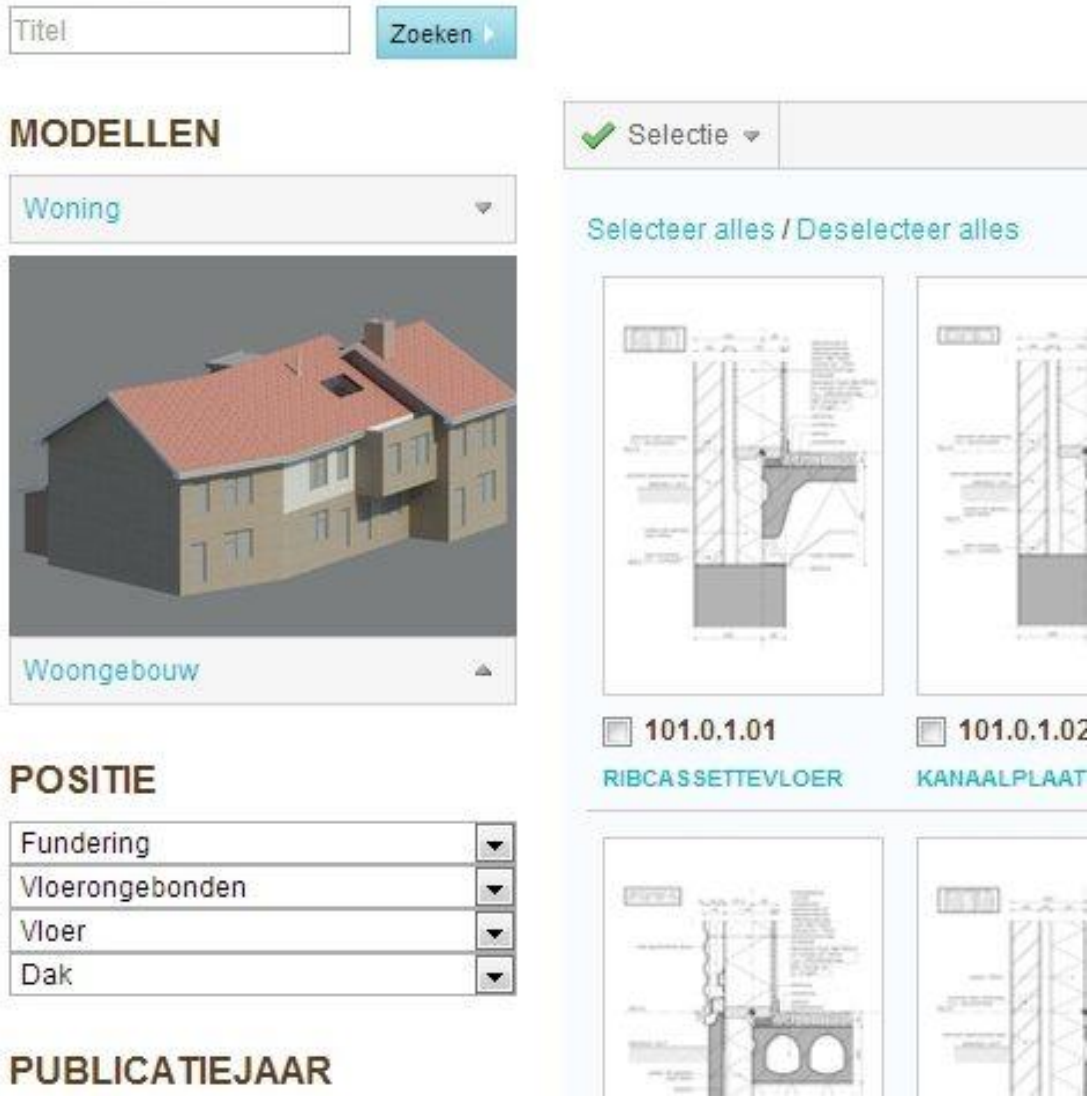
How is the integrated dynamic model established, and how does it perform compared to traditional software?

How do dynamic variables influence the embodied and operational carbon of mid- to high-rise buildings?”

Methodology

Literature Review

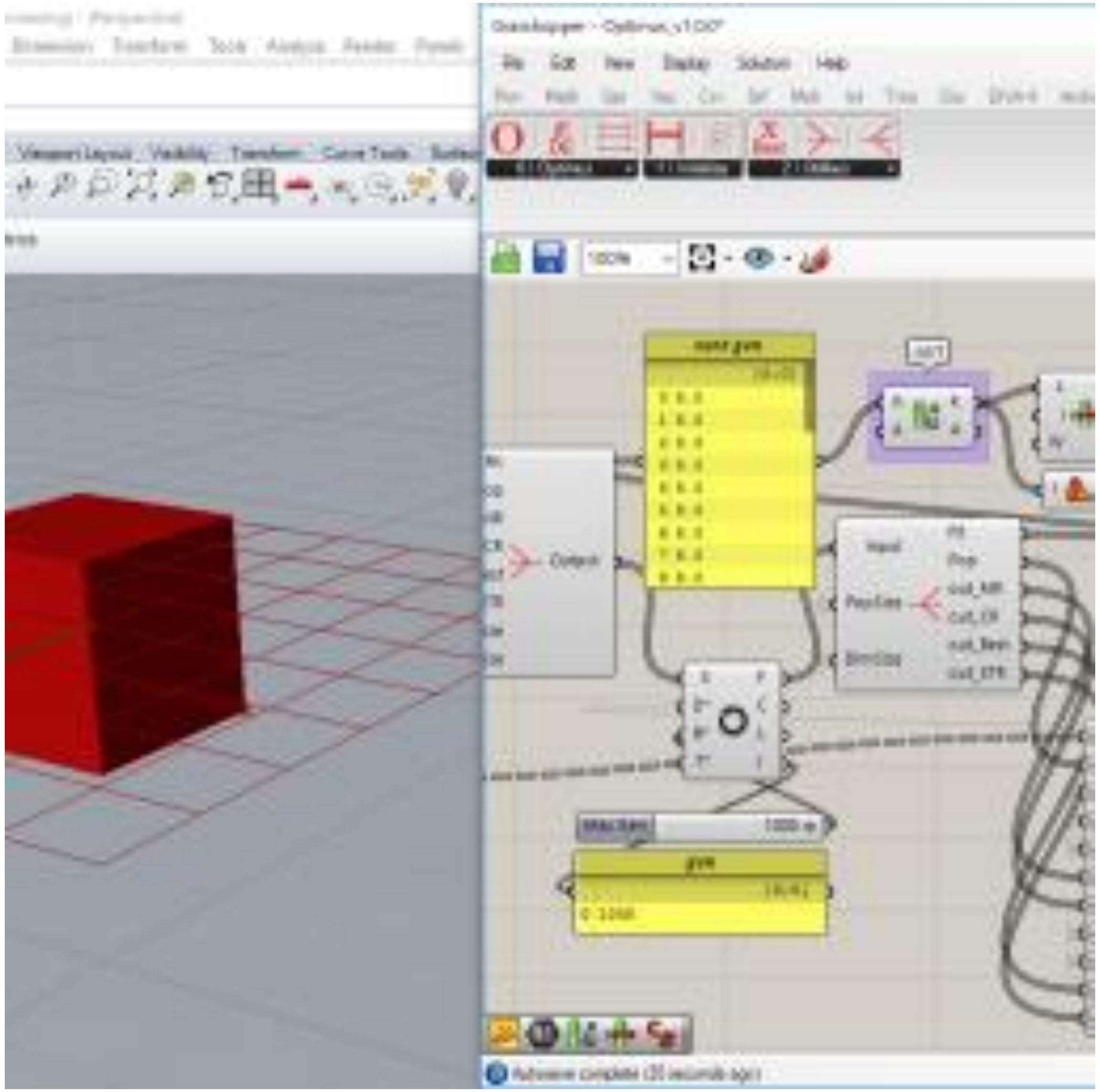
- Define mid to high-rise buildings
- Analyze existing literature and regulatory documents
- Identify common façade typologies for mid to high-rise
- Research computational models



Methodology

Make a parametric model

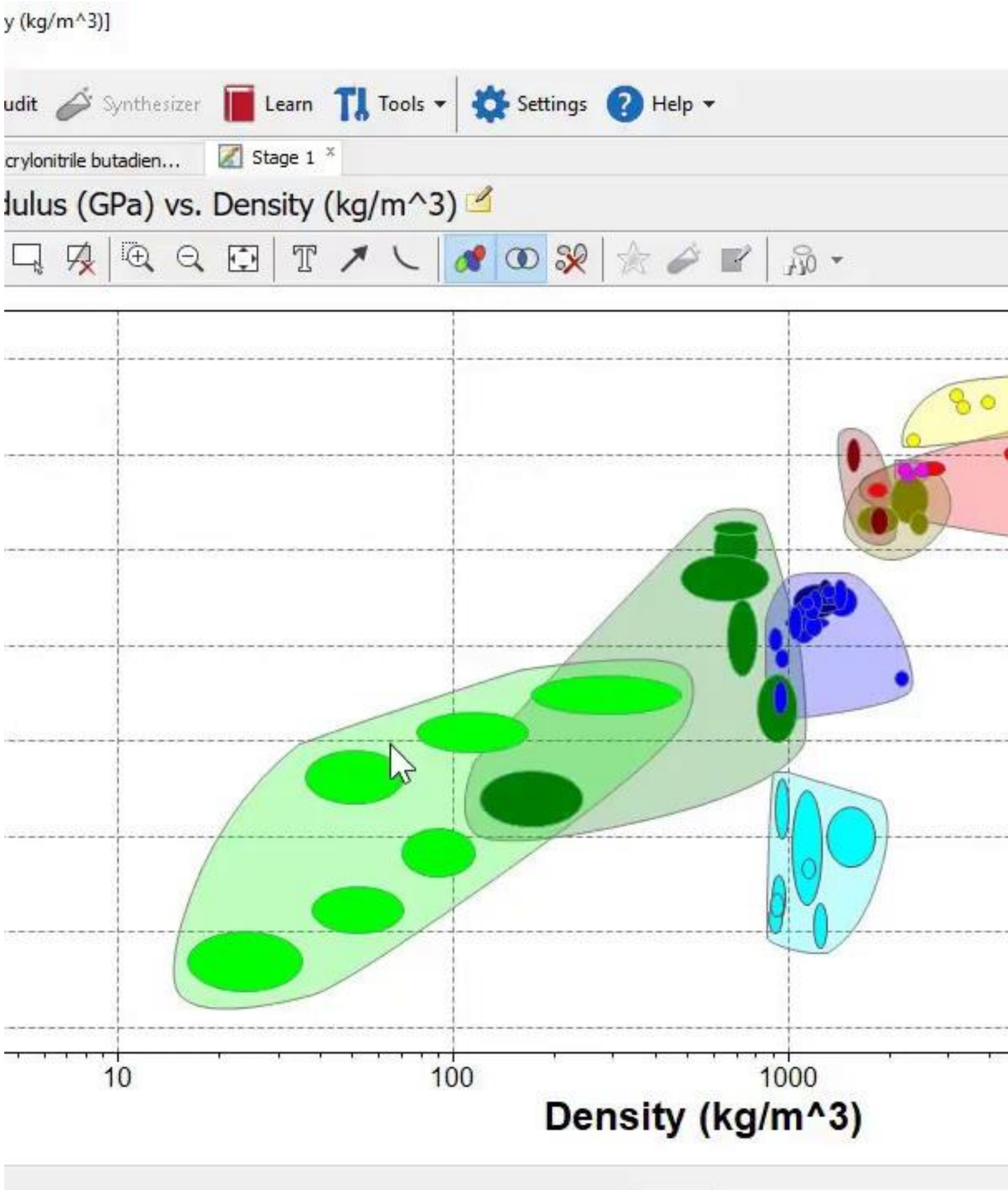
- Develop computational workflow to model façade typologies
- Use Grasshopper and plugins for simulation of energy and carbon performance



Methodology

Material Analysis

- Get the materials volumes used in the façade typologies
- Find material properties
- Analyze materials' embodied carbon footprint



Relevance

What we know

- Urbanization and High-Rise Construction: Increased urban densification drives the growth of mid to high-rise buildings.
- Environmental Impact: High-rise buildings consume more energy and resources than low-rise structures.
- Legislation Focus: Most regulations focus on reducing operational carbon (energy usage during a building's life).
- Façade Design Importance: Building orientation, shape, and envelope significantly impact energy performance and occupant comfort.

What we don’t know

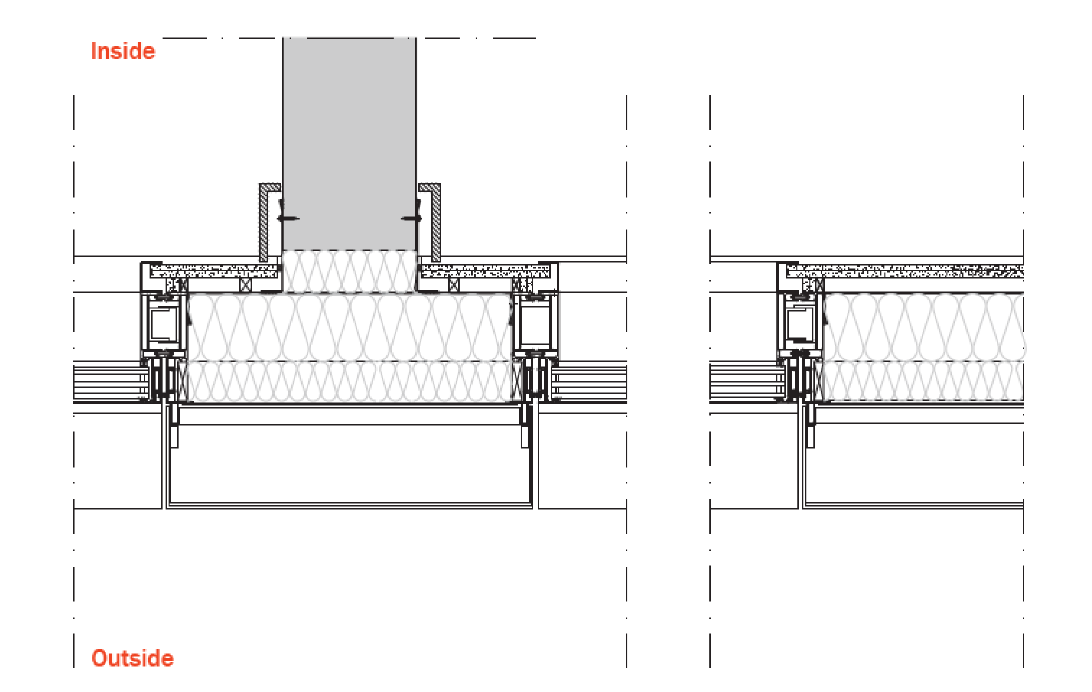
- Focus on Embodied Carbon: Address the underexplored impact of embodied carbon in façade typologies.
- Early Design Integration: Provide tools to evaluate embodied carbon impacts early in the design process.
- Optimization of Façades: Identify optimal façade combinations to balance embodied and operational carbon.
- Sustainable Design Support: Offer actionable data for architects and stakeholders to make informed, environmentally responsible design decisions.

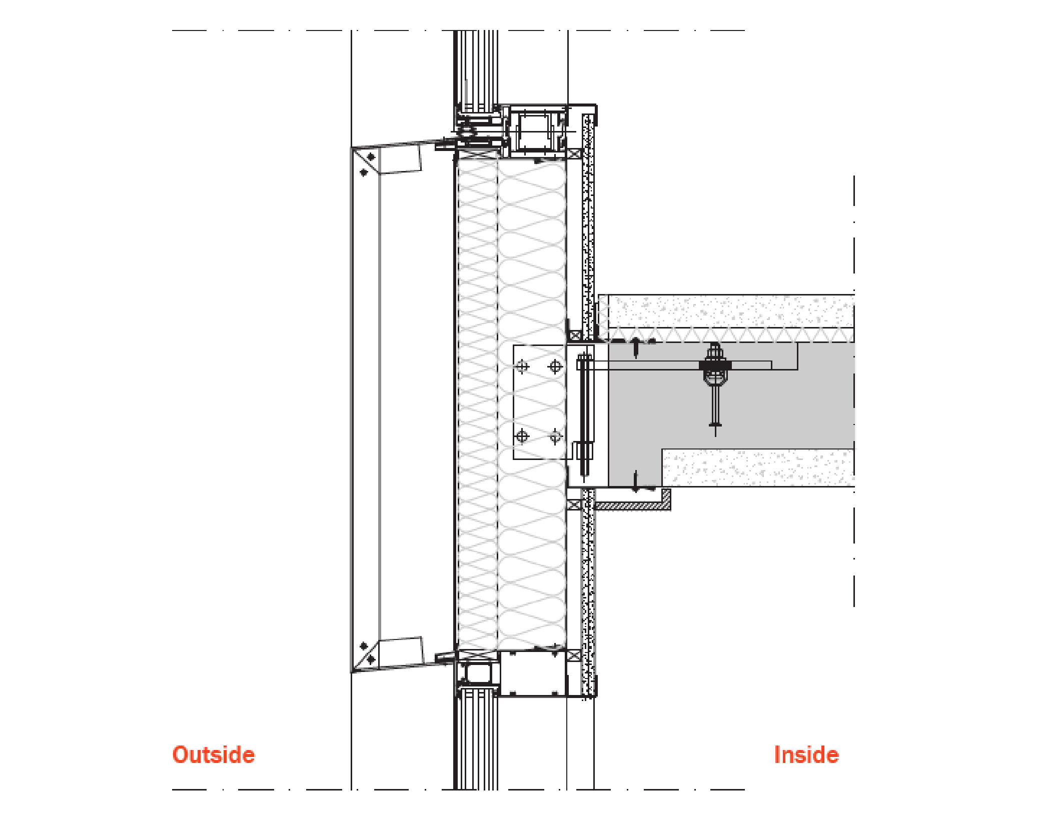
Defining Facades for Mid to High-Rise Buildings

- Wide range of options for aesthetic and performance goals.

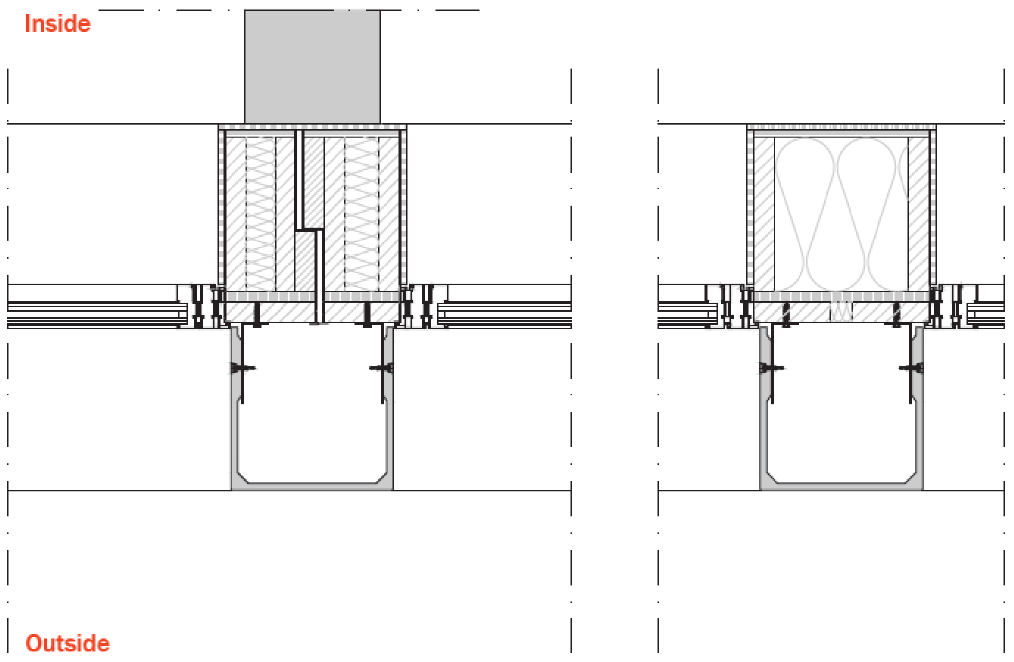
- Non load bearing
- Prefabricated
- Scalable

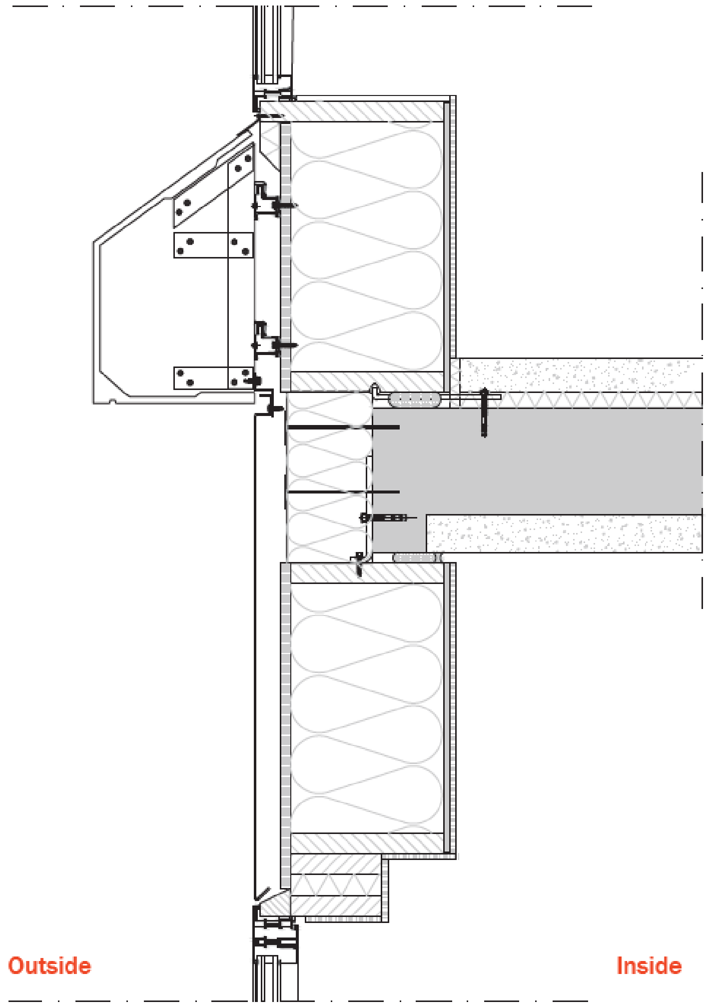
Aluminum Element Facade



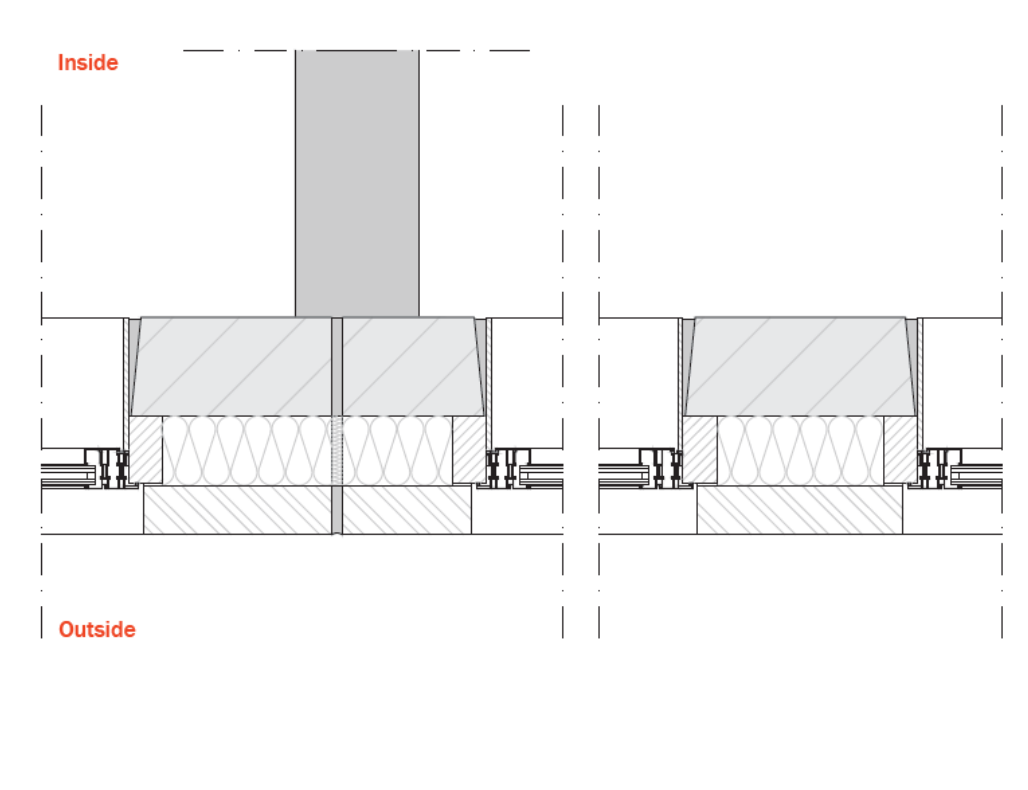


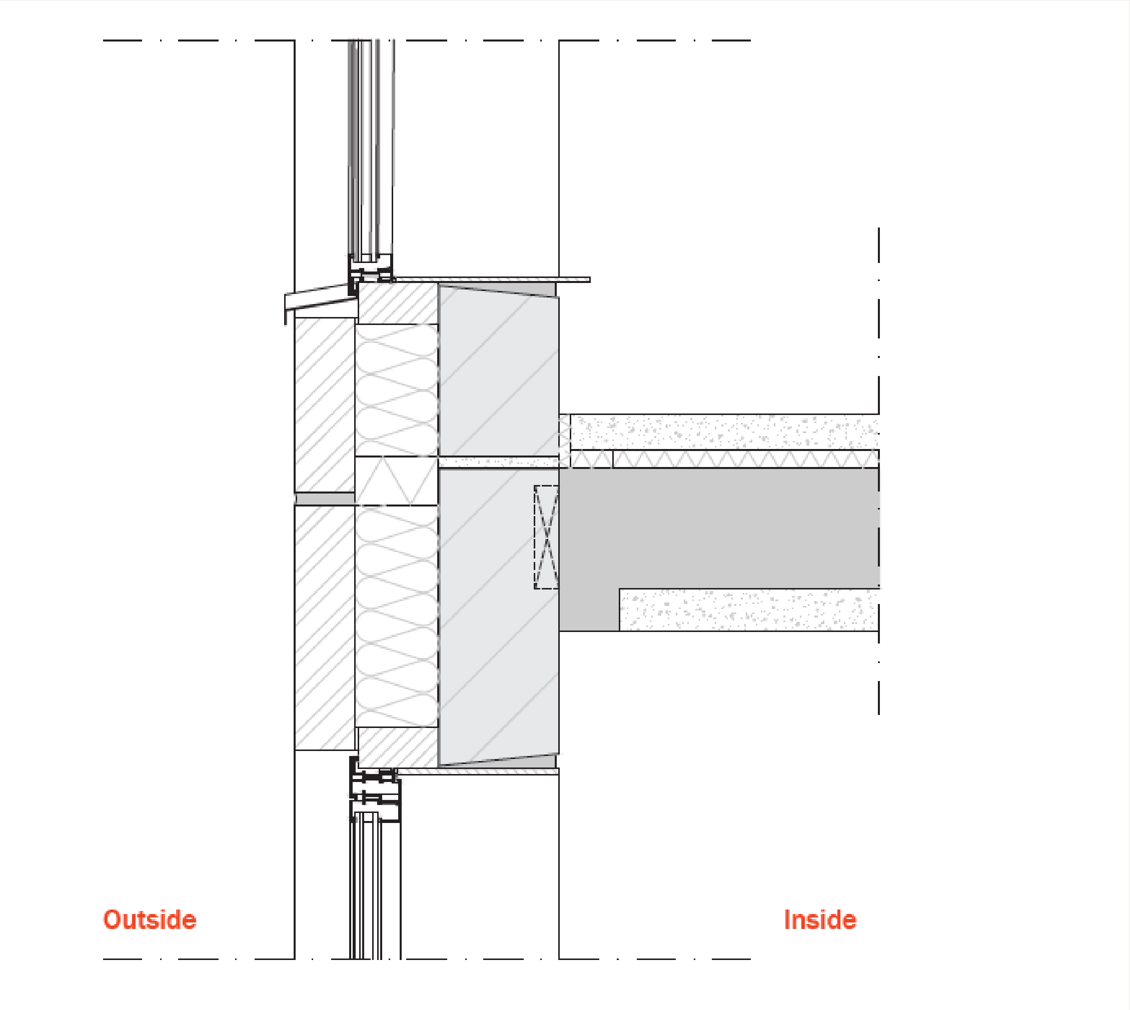
Timber Element Facade

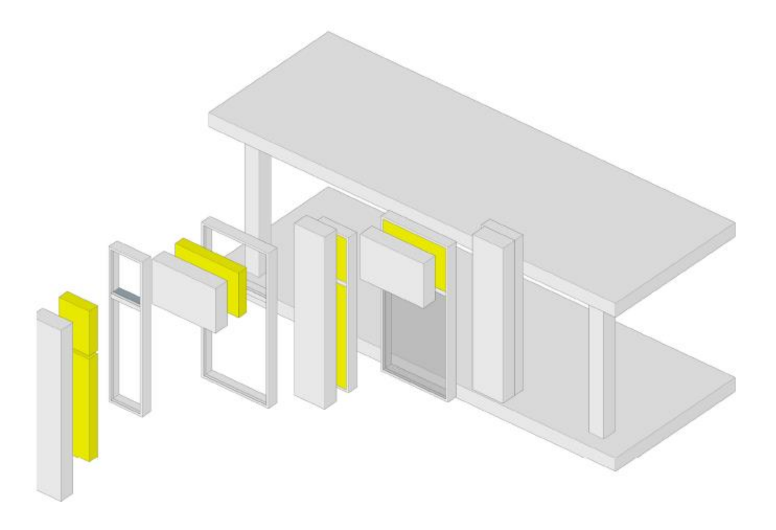


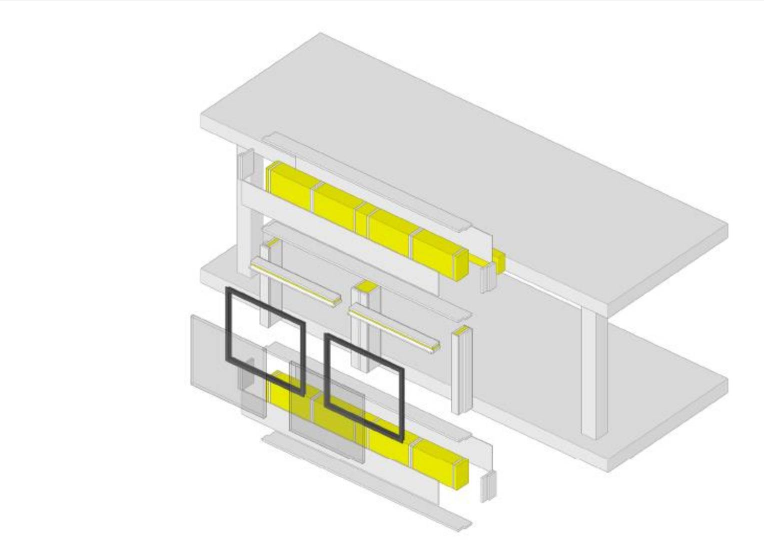


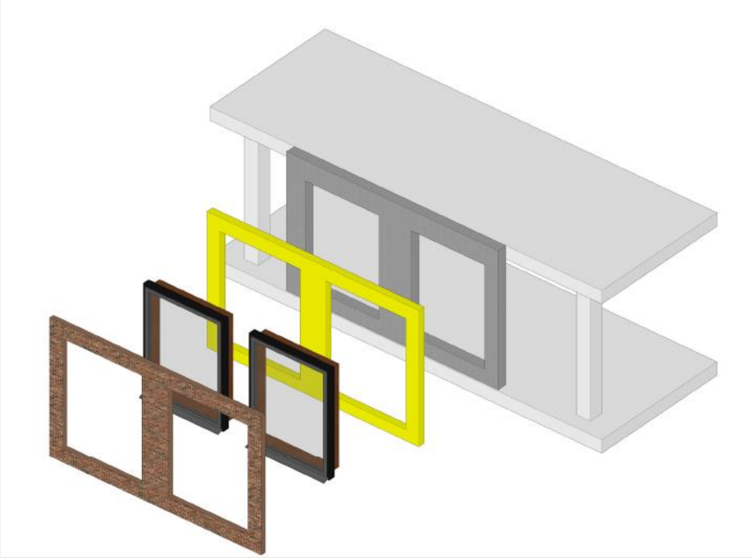
Prefab Concrete Facade









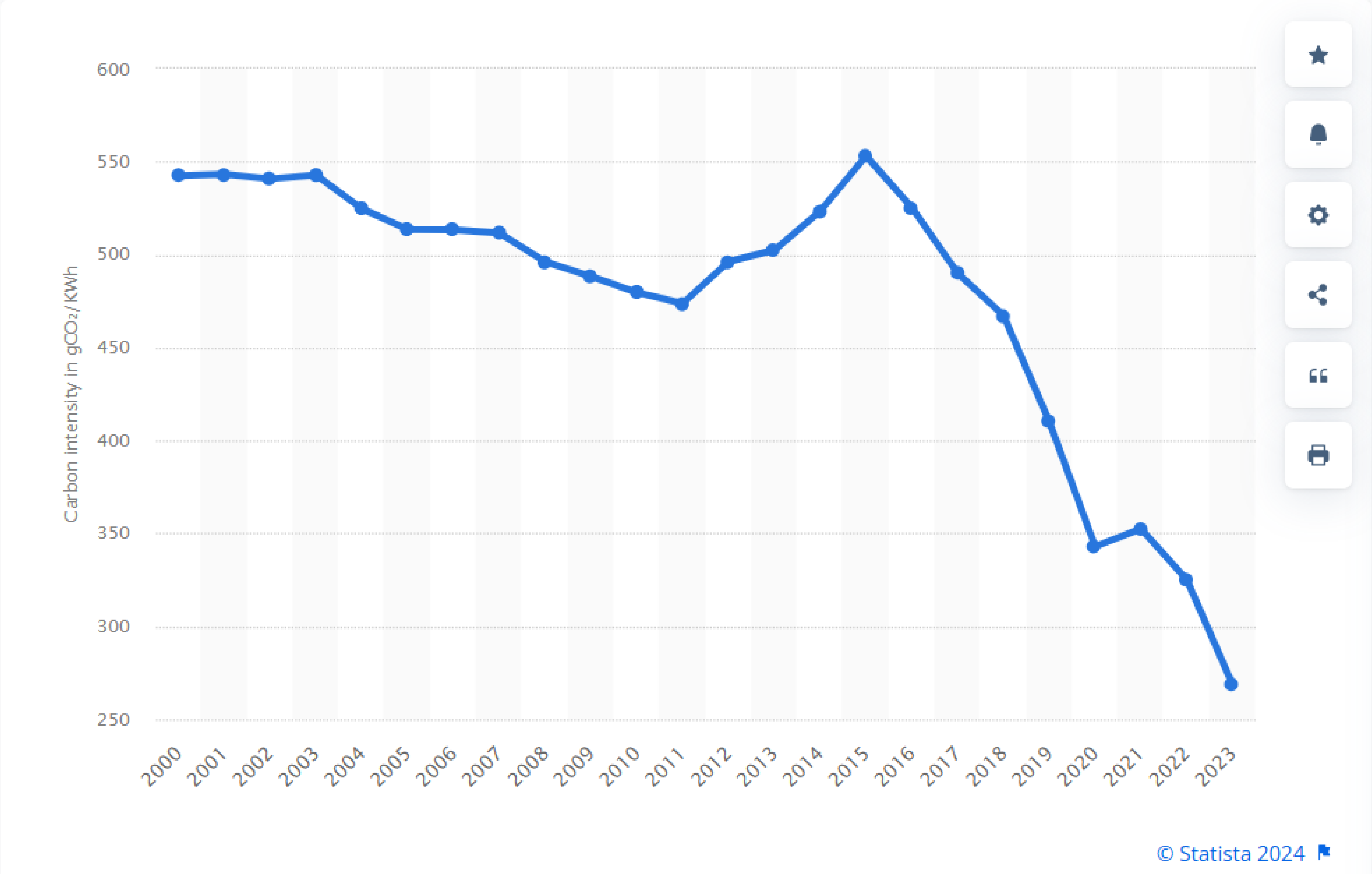


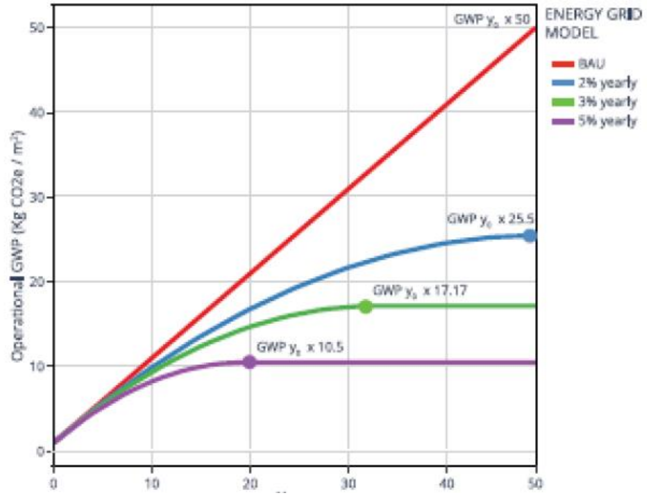
Embodied & Operational carbon

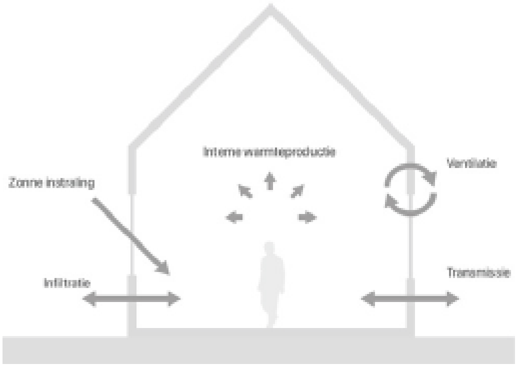
Energy & Environment › Emissions

Carbon intensity of the power sector in the Netherlands from 2000 to 2023

(in grams of CO_2 per kilowatt-hour)







Brick							
Properties					Avarage		
Density	1980	-	2070	kg/m^3	2025	kg/m^3	Edupack
Conductivity	0.8	-	0.4	W/m*C	0.6	W/m*C	Edupack
Spec heat	750	-	850	J/kg*C	800	J/kg*C	Edupack
Embodied carbon	0.239	-	0.264	Kg/kg	0.2515	Kg/kg	Edupack
Recycle				✗			Edupack
biodegrade				✗			Edupack
Renewable resource				✗			Edupack
Carbon storage				✗			

Aluminium, wrought (6061, T4)							
Properties					Avarage		Source
Density	2690	-	2730	kg/m^3	2710	kg/m^3	Edupack
Conductivity	221.2	-	229.9	W/m*C	225.55	W/m*C	Edupack
Spec heat	934	-	972	J/kg*C	953	J/kg*C	Edupack
Embodied carbon	7.47	-	8.6	Kg/kg	8.035	Kg/kg	Edupack
Recycle				✓			Edupack
biodegrade				✗			Edupack
Renewable resource				✗			
Carbon storage				✗			

Zink							
Properties					Avarage		Source
Density	5710	-	7160	kg/m^3	6435	kg/m^3	Edupack
Conductivity	100	-	134	W/m*C	117	W/m*C	Edupack
Spec heat	394	-	480	J/kg*C	437	J/kg*C	Edupack
Embodied carbon	327	-	367	Kg/kg	347	Kg/kg	Edupack
Recycle				✓			Edupack
biodegrade				✗			Edupack
Renewable resource				✗			Edupack
Carbon storage				✗			

Regulatory Frameworks:

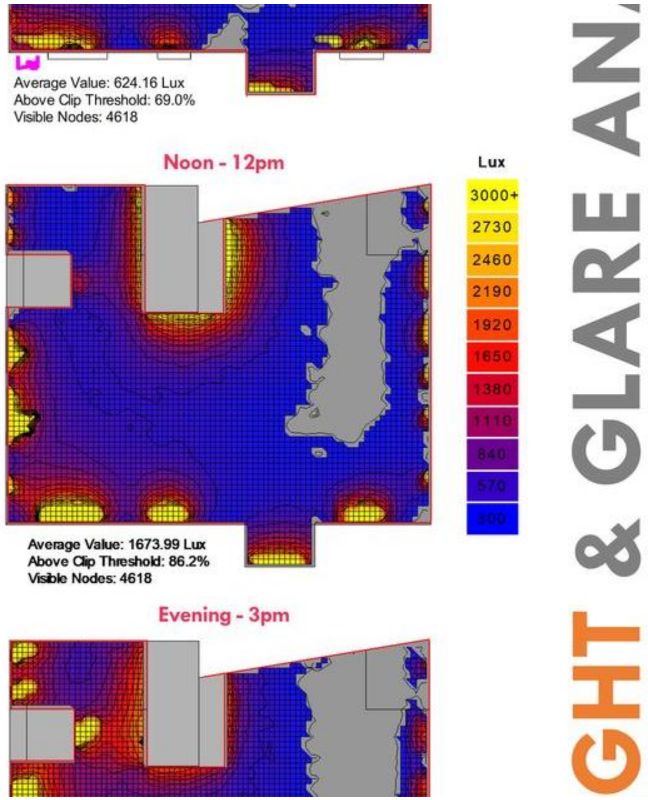
- **Bouwbesluit 2012**: Dutch regulations ensuring safety, energy efficiency, and usability.
- **EPC (Energy Performance Certificate)** & **BENG (Nearly Zero Energy)**: Frameworks assessing energy demand, fossil fuel use, and renewable energy generation.
- **MPG (Environmental Performance Calculation)**: Assesses material usage and environmental impact via life cycle assessments (LCA).

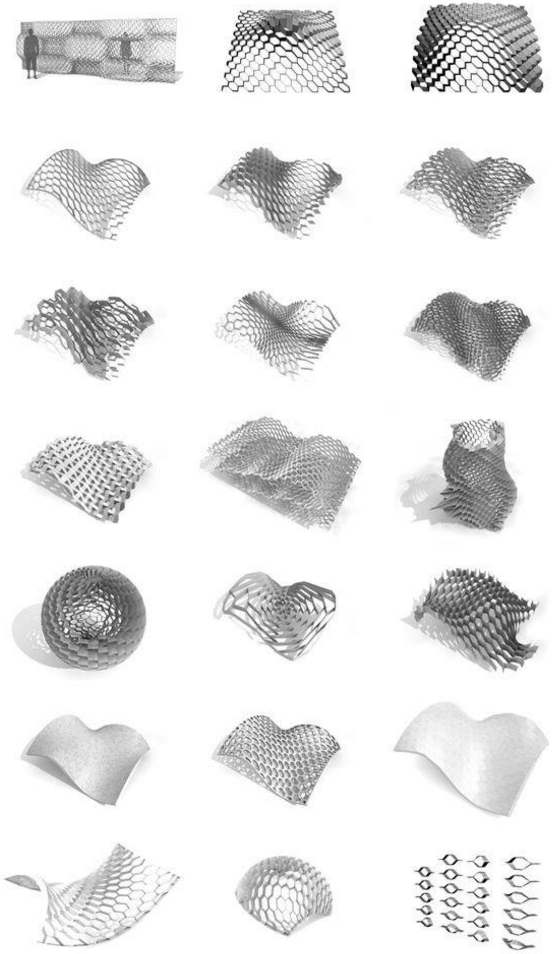
Important Regulatory Considerations:

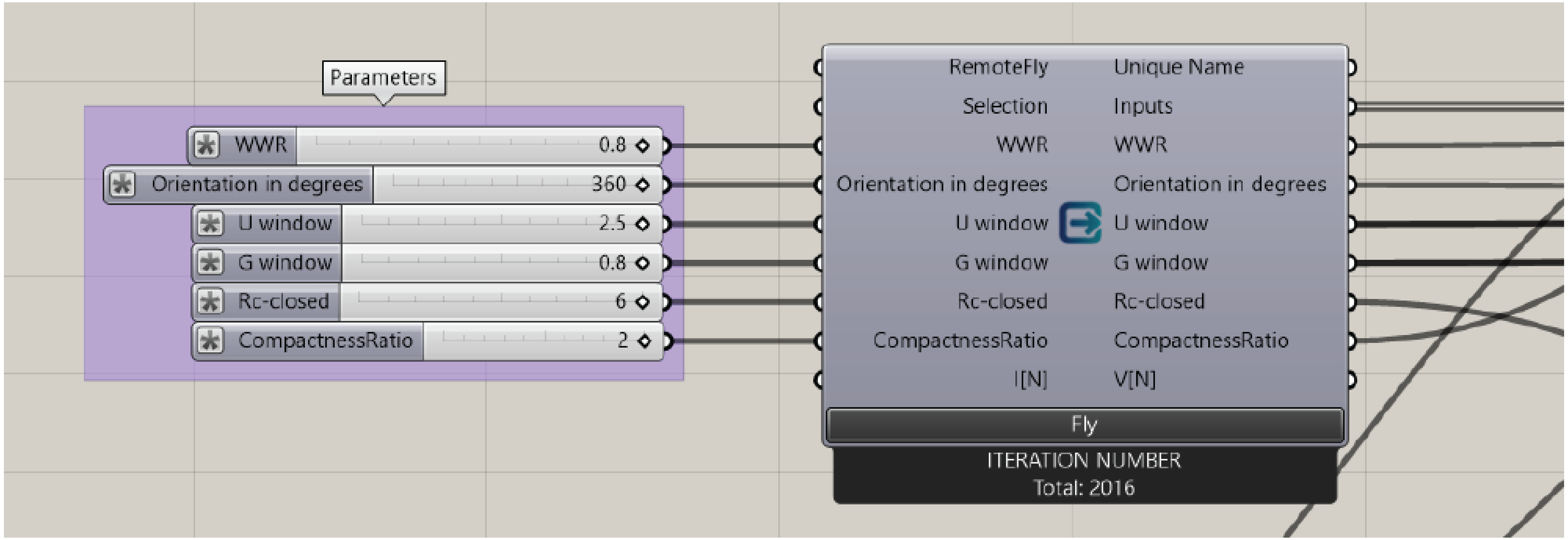
- **Safety**: Façades must adhere to **fall and fall-through protection** (critical for high-rise buildings, affecting glass specifications).
- **Energy Efficiency**: Minimum **thermal insulation** required (Rc-value ≥ 4.7 m^2K/W) to reduce energy loss.
- **Daylight Access**: Adequate daylight must be provided, with glazing area ≥ 10% of room’s usable floor area.
- **Energy Demand (BENG):** Measures energy demand in $kWh/m^2/yr$ to ensure buildings are energy-efficient.
- **Sustainability (MPG):** Focuses on material impact and sustainability, using LCA costs per m^2 for a 75-year lifespan.

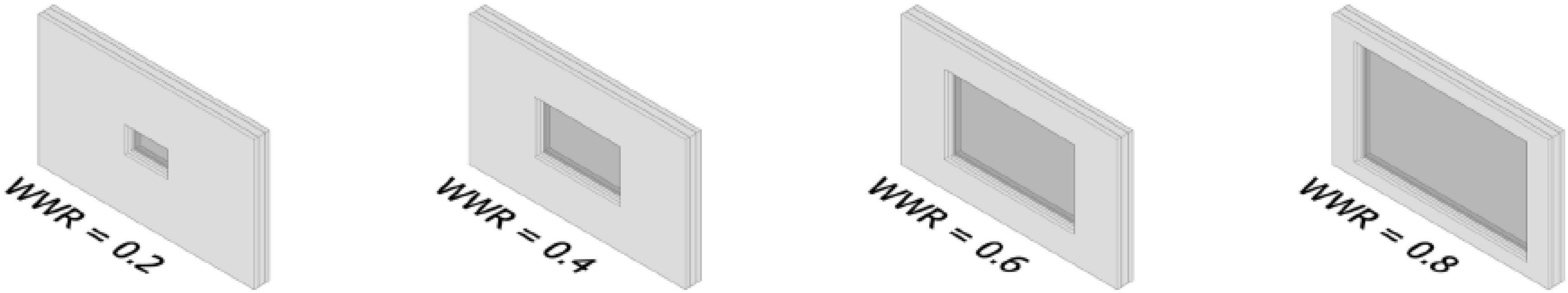
Evolution of software

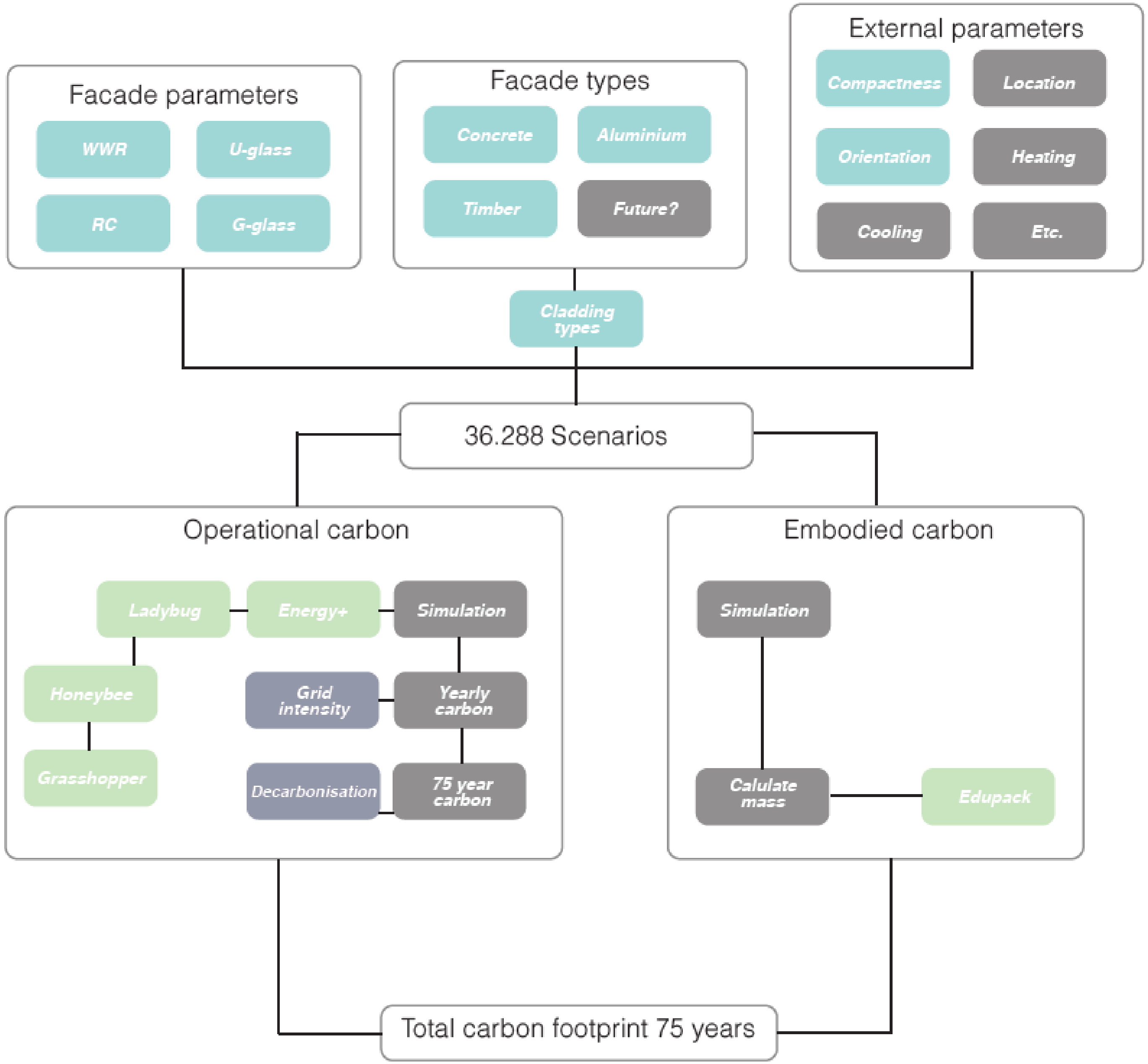
- Traditional Software (CAD)
- Building Information Modeling (BIM)
- Building Performance Simulation (BPS)
- Computational and Parametric Design






Parameters
WWR
0.8
Orientation in degrees
360
U window
2.5
G window
0.8
Rc-closed
6
CompactnessRatio
2
RemoteFly
Selection
WWR
Orientation in degrees
U window
G window
Rc-closed
CompactnessRatio
I[N]
Unique Name
Inputs
WWR
Orientation in degrees
U window
G window
Rc-closed
CompactnessRatio
V[N]
Fly
ITERATION NUMBER
Total: 2016


WWR = 0.2
WWR = 0.4
WWR = 0.6
WWR = 0.8



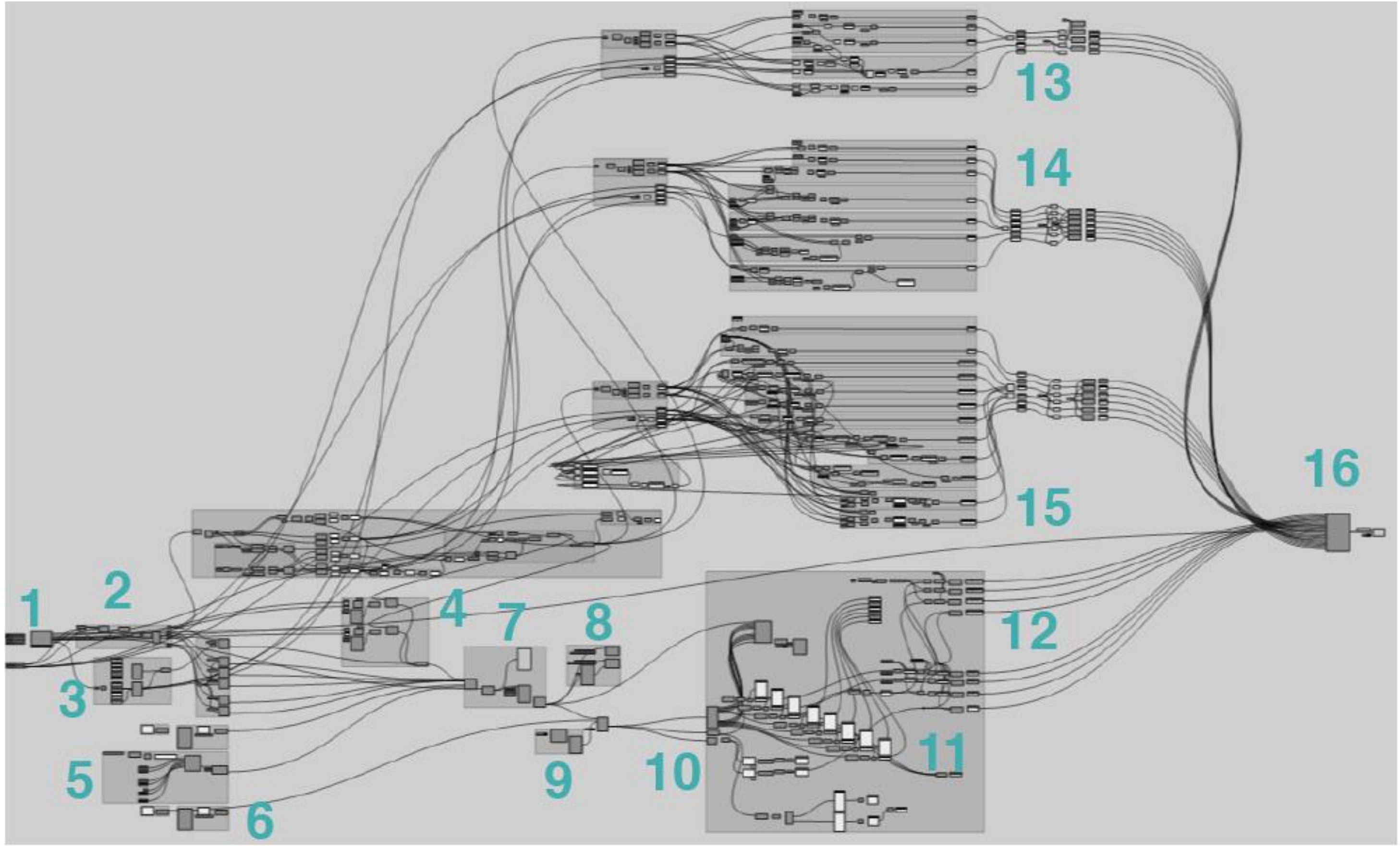
Facade parameters
WWR
U-glass
RC
G-glass
Facade types
Concrete
Aluminium
Timber
Future?
External parameters
Compactness
Location
Orientation
Heating
Cooling
Etc.
Cladding types
36.288 Scenarios
Operational carbon
Ladybug
Energy+
Simulation
Honeybee
Grid intensity
Yearly carbon
Grasshopper
Decarbonisation
75 year carbon
Embodied carbon
Simulation
Calulate mass
Edupack
Total carbon footprint 75 years

Parameters

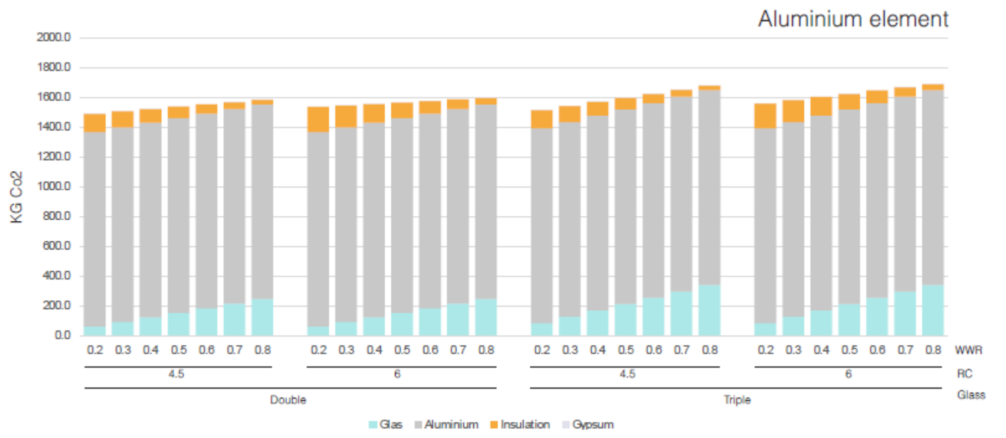
Fixed variables			
Weatherfile	Amsterdam	Amsterdam	
Program			
	Elecric load	2	W/m2
	Lighting load	3	W/m2
	People load	0.02	People/m2
	Infiltration	0.000241	m3/s/m2
HVAC inputs			
	Heating setpoint	21	C
	Heating suply temp	35	C
	Heating limit	75	W/m2
	Cooling setpoint	25	C
	Cooling suply temp	15	C
	Cooling Limit	60	W/m2
	Heat recovery	0.5	
	Cooling COP	3	
	Heating COP	4	
	Economizer	DifferentialDryBulb	
	Carbon intensity	268.5	g/kWh

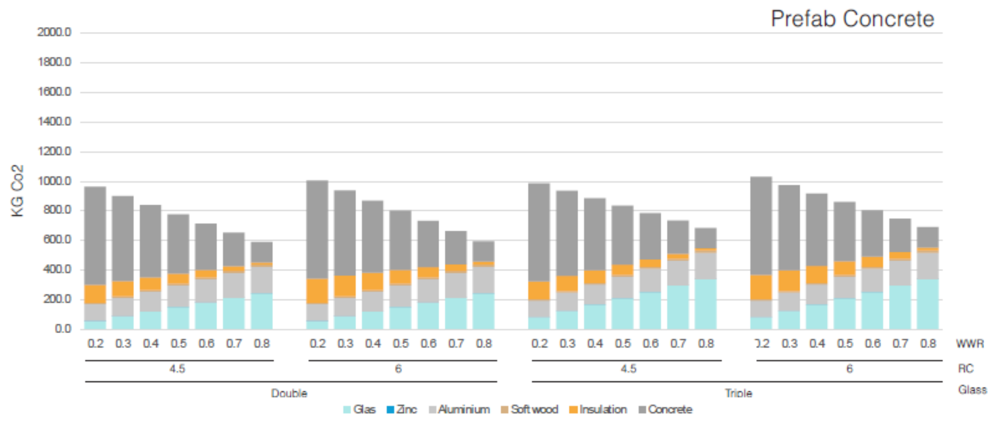
Dynamic variables		
Window wall ratio	0.2 0.3 0.4 0.5 0.6 0.7 0.8	
		7
Facade orientation	North South West East	
		4
Wall assembly	Concrete HSB ALU	
		3
U-glas	1 1.5 2 2.5	
		4
G-value	0.8 0.65 0.5	
		3
Rc-closed	4.5 6	
		2
Compactness	1 1.5 2	
		3
Facade claddings	Concrete 100 Brick 100 wood 40 Aluminium 7 Keramiek 40 brick strips 30	
		6
Total variations		36288

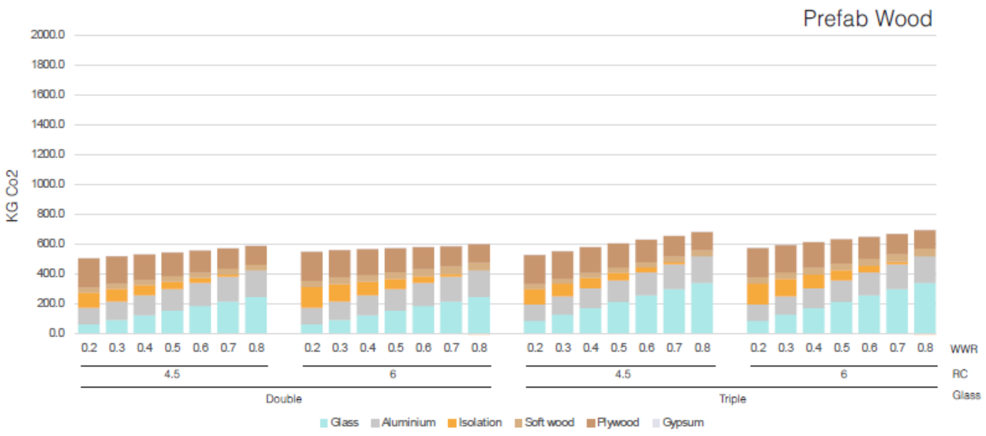
Grasshopper script

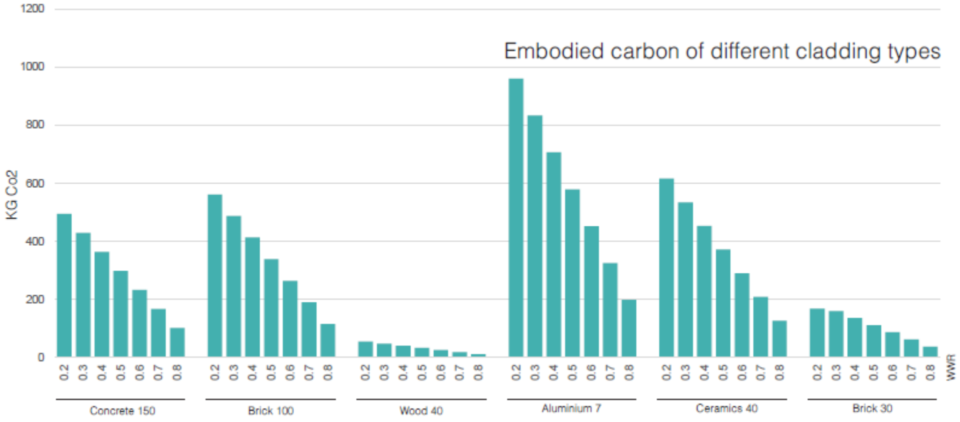


Simulation Results

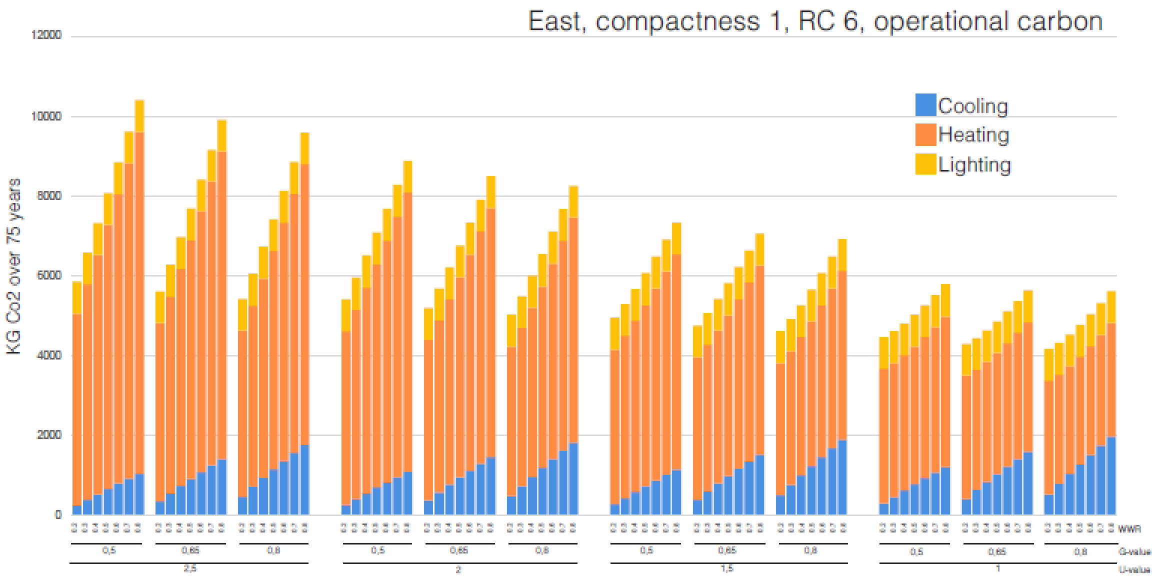


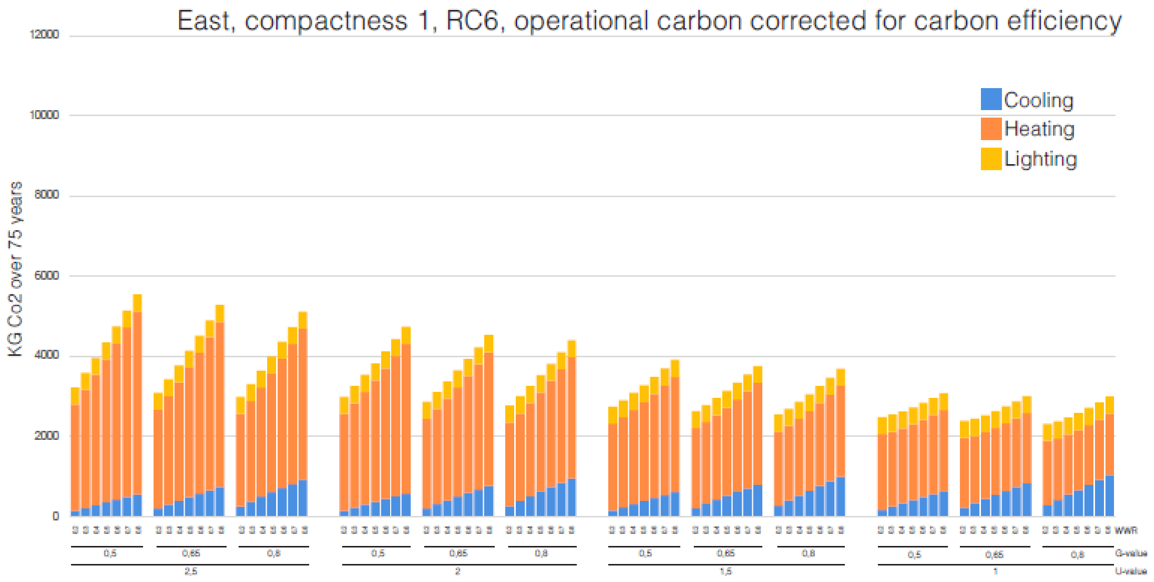




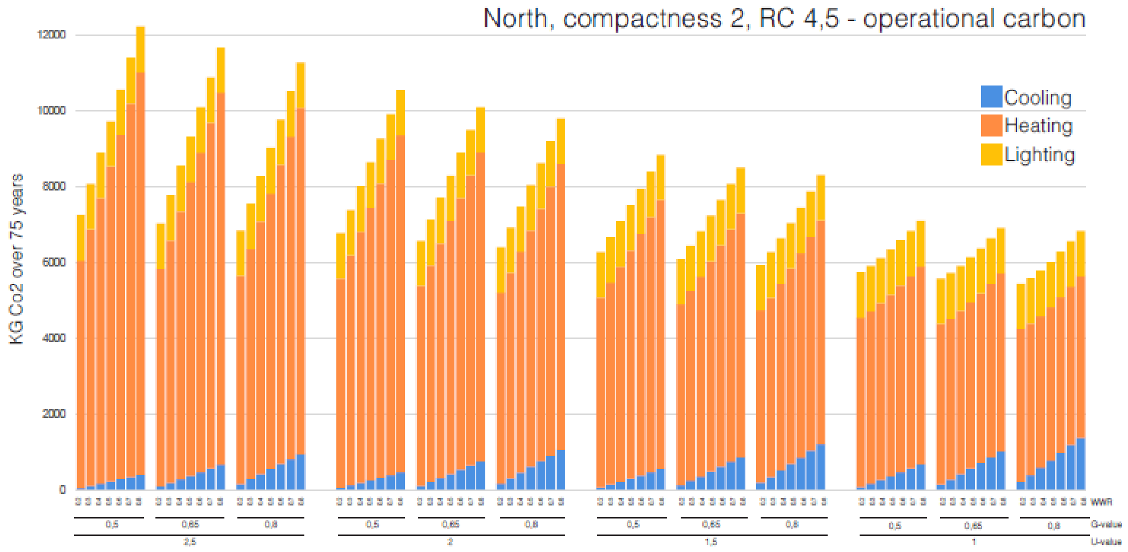


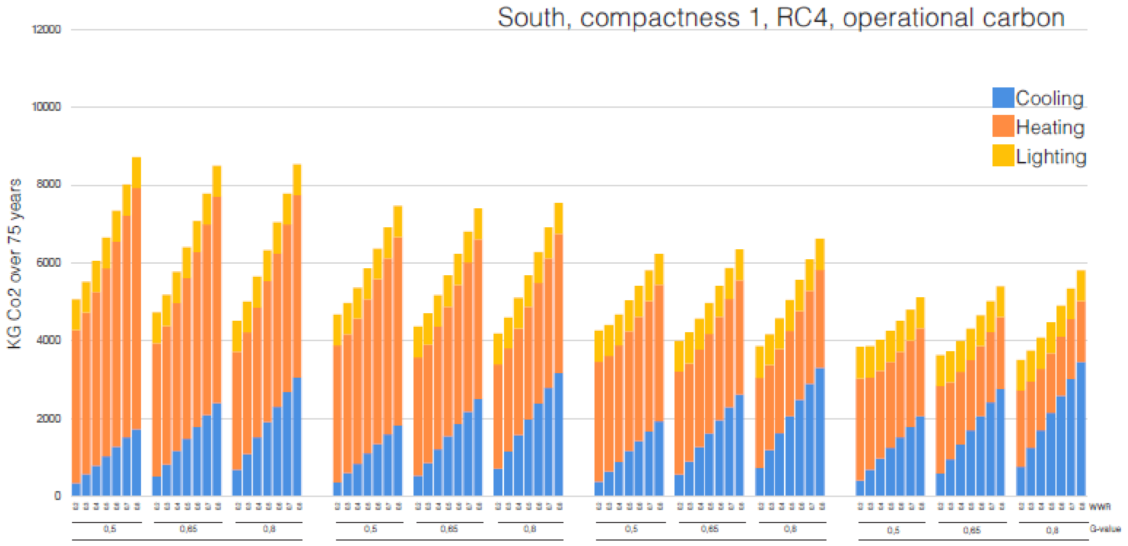
Simulation Results

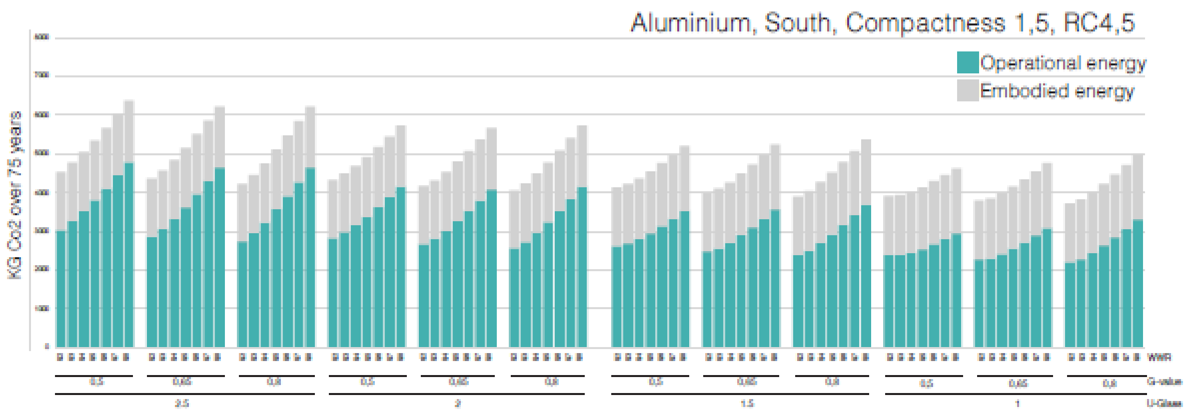


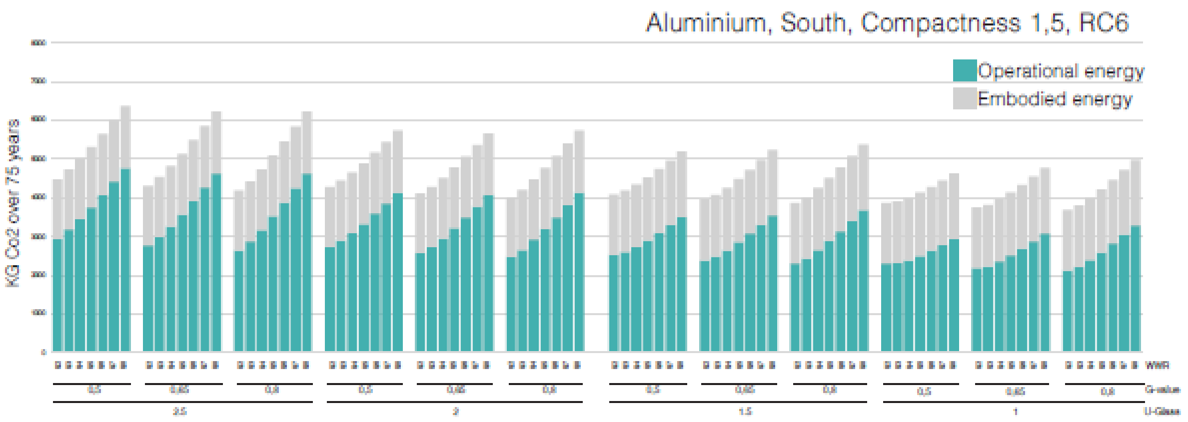


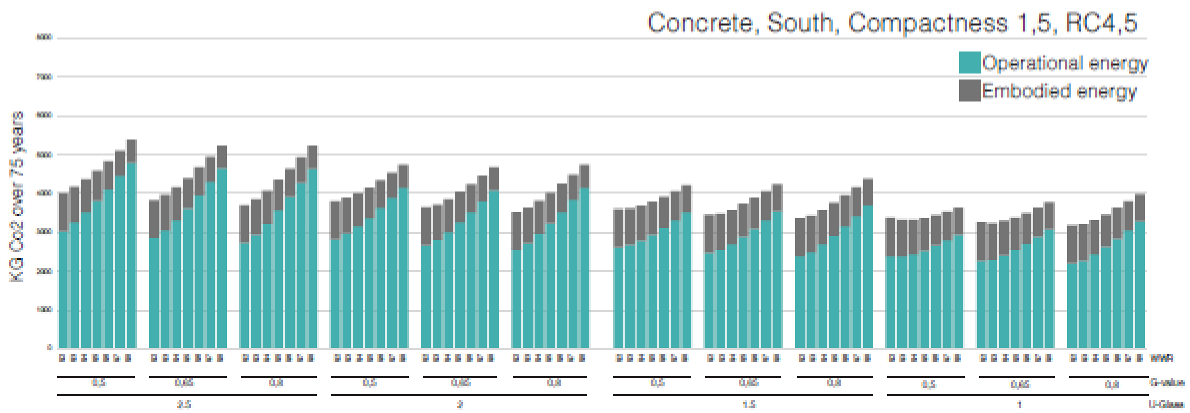
Simulation Results

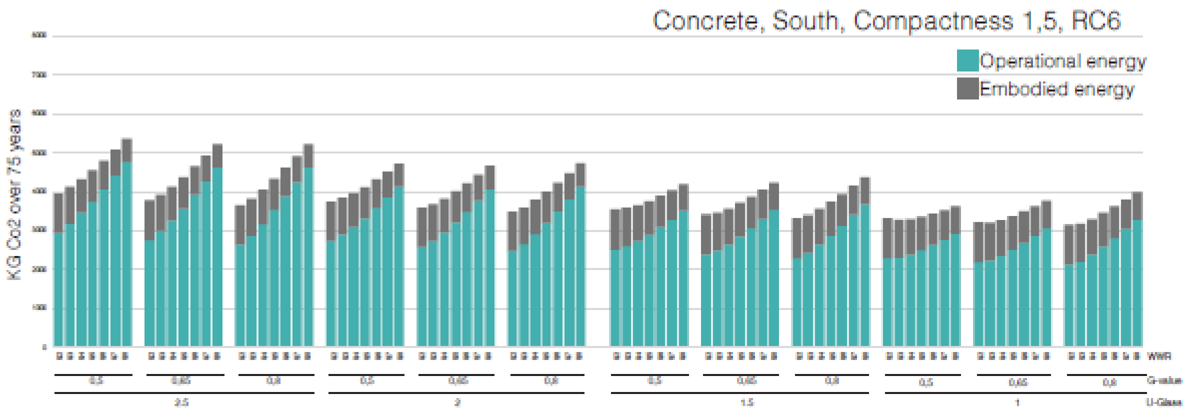


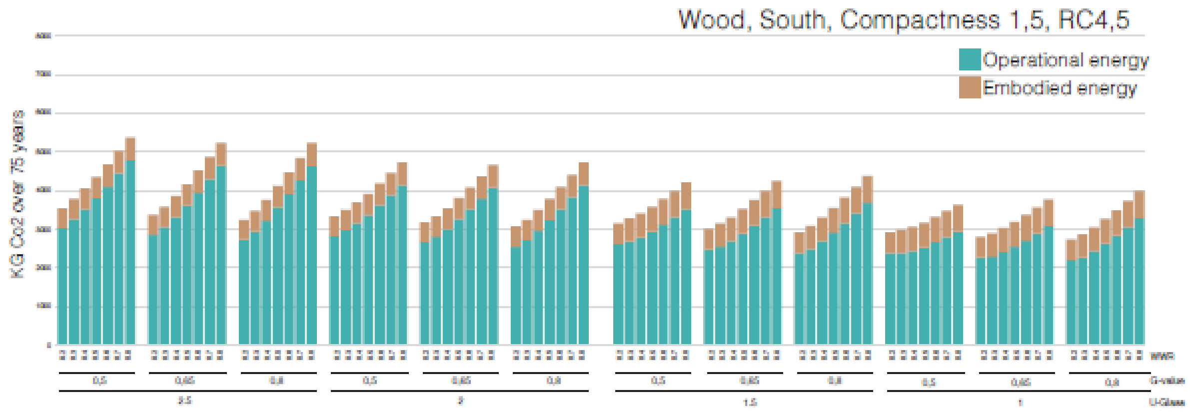


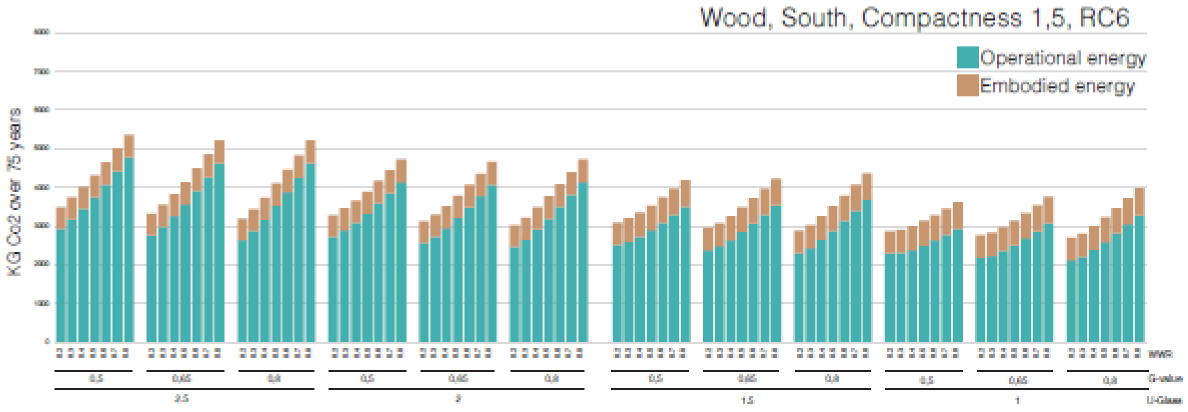

Aluminium, South, Compactness 1,5, RC4,5
Operational energy
Embodied energy
KG Co2 over 75 years

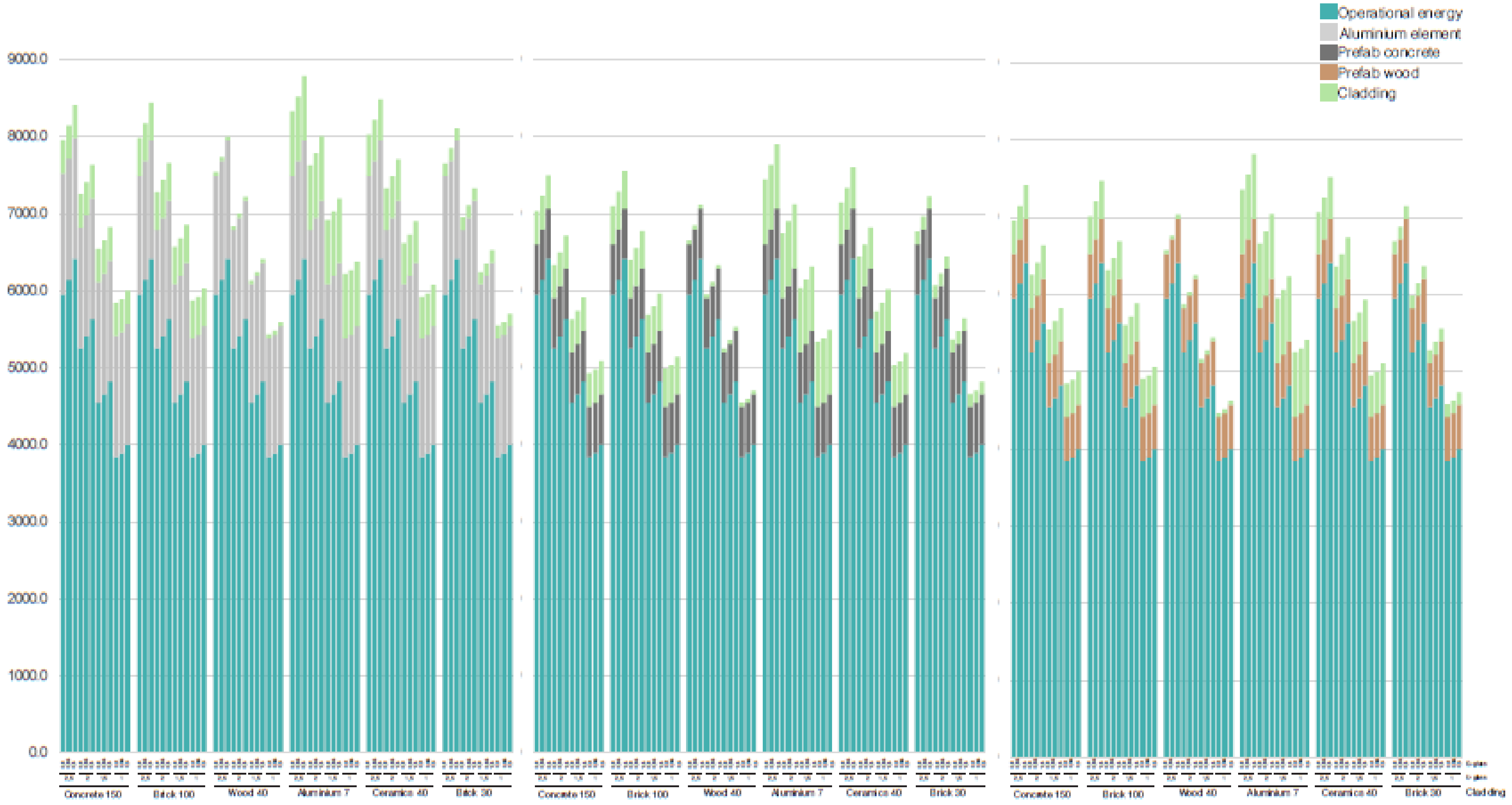

Aluminium, South, Compactness 1,5, RC6
Operational energy
Embodied energy
KG Co2 over 75 years


Concrete, South, Compactness 1,5, RC4,5
Operational energy
Embodied energy
KG Co2 over 75 years


Concrete, South, Compactness 1,5, RC6
Operational energy
Embodied energy
KG Co2 over 75 years


Wood, South, Compactness 1,5, RC4,5
Operational energy
Embodied energy
KG Co2 over 75 years


Wood, South, Compactness 1,5, RC6
Operational energy
Embodied energy
KG Co2 over 75 years



Operational energy
Aluminium element
Prefab concrete
Prefab wood
Cladding
9000.0
8000.0
7000.0
6000.0
5000.0
4000.0
3000.0
2000.0
1000.0
0.0
Concrete 150
Brick 100
Wood 40
Aluminium 7
Ceramics 40
Brick 30
Cladding

Scenario’s

Situation

The case concerns an apartment located on the south façade with a compactness ratio of 1.5. In the preliminary design (VO), the architect designed a window-to-wall ratio (WWR) of 50%, using glazing with a g-value of 0.65 and a U-value of 1.5. The façade is designed as an aluminium unitized system with aluminium cladding.

The architect wishes to reduce carbon emissions without changing the aesthetic aspects of the design.

As an advising party, my first step is to reduce the embodied carbon by changing the construction method to a timber frame element (HSB) with aluminium cladding. Since the timber structure is not visible, and the aluminium appearance remains unchanged, the visual design is preserved.

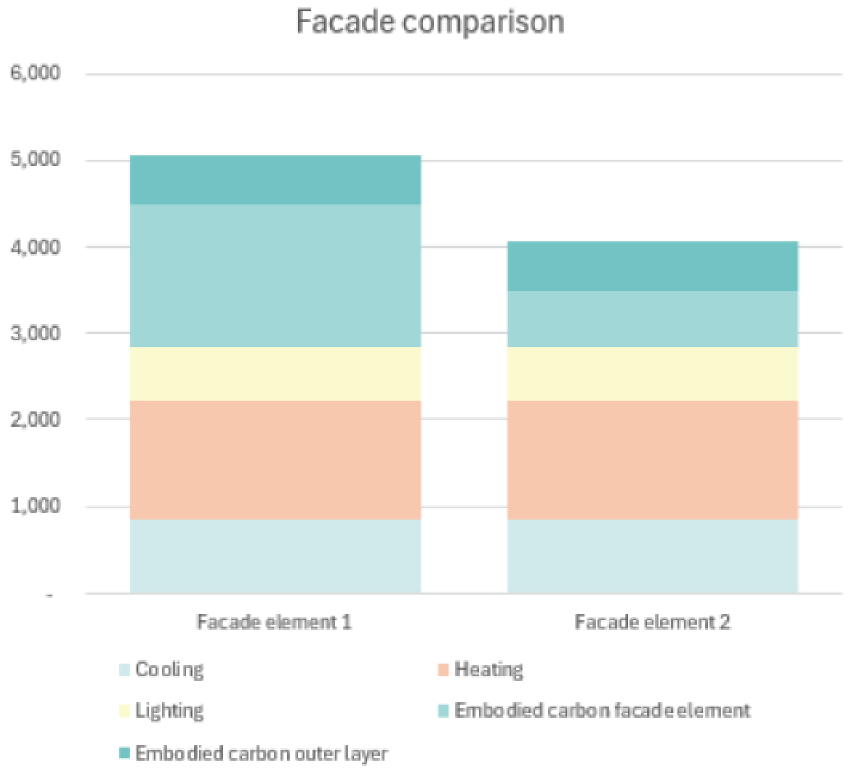
In the graph is a reduction found of 1000kg embodied carbon

Inputs facade element 1		
Building parameters	Orientation	360
	Compactness	1.5
Facade parameters	WWR	0.5
	G-value window	0.65
	U-value window	1.5
	RC-value closed	6
Building technique	Facade element	Aluminium Element
	Outer layer	Aluminium 7

Outputs facade element 1		
Total Operational carbon	2,854	kg
Cooling	857	kg
Heating	1,363	kg
Lighting	634	kg
Embodied carbon facade element	1,625	kg
Embodied carbon outer layer	581	kg
Total of 75 years	5,060	kg

Inputs facade element 2		
Building parameters	Orientation	360
	Compactness	1.5
Facade parameters	WWR	0.5
	G-value window	0.65
	U-value window	1.5
	RC-value closed	6
Building technique	Facade element	HSB Element
	Outer layer	Aluminium 7

Outputs facade element 2		
Total Operational carbon	2,854	kg
Cooling	857	kg
Heating	1,363	kg
Lighting	634	kg
Embodied carbon facade element	634	kg
Embodied carbon outer layer	581	kg
Total of 75 years	4,068	kg



Scenario’s

To take it one step further an attempt is made to lower the operational carbon. The thermal performance of the window is increased by lowering the U-value from 1.5 to 1.0.

In the results it´s found that the cooling demand is increased from 857 to 905 but the heating demands are decreased from 1363 to 975kg Carbon.

In the end, the total carbon emissions were reduced from 5,060 kg to 3,728 kg, which represents a reduction of approximately 26.3%.

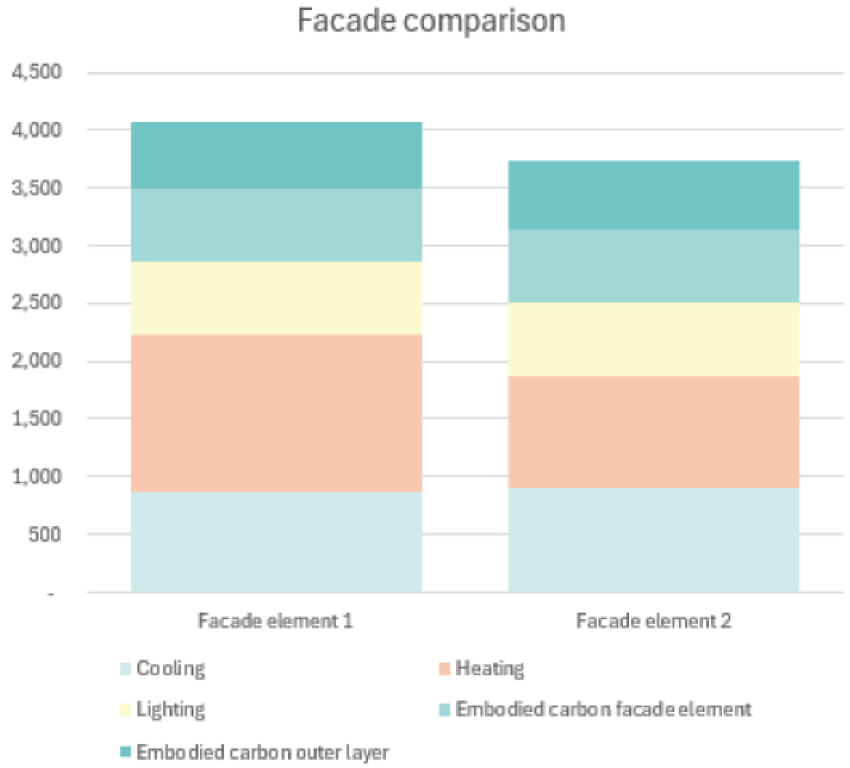
The next step would be to consult with the contractor to assess how these changes affect costs and construction time

Inputs facade element 1		
Building parameters	Orientation	360
	Compactness	1.5
Facade parameters	WWR	0.5
	G-value window	0.65
	U-value window	1.5
	RC-value closed	6
Building technique	Facade element	HSB Element
	Outer layer	Aluminium 7

Outputs facade element 1		
Total Operational carbon	2,854	kg
Cooling	857	kg
Heating	1,363	kg
Lighting	634	kg
Embodied carbon facade element	634	kg
Embodied carbon outer layer	581	kg
Total of 75 years	4,068	kg

Inputs facade element 2		
Building parameters	Orientation	360
	Compactness	1.5
Facade parameters	WWR	0.5
	G-value window	0.65
	U-value window	1
	RC-value closed	6
Building technique	Facade element	HSB Element
	Outer layer	Aluminium 7

Outputs facade element 2		
Total Operational carbon	2,514	kg
Cooling	905	kg
Heating	975	kg
Lighting	634	kg
Embodied carbon facade element	634	kg
Embodied carbon outer layer	581	kg
Total of 75 years	3,728	kg



Conclusion

"How do different dynamic façade variables influence the embodied and operational carbon of mid to high-rise residences during the early design phase, and what optimal combinations can be identified to minimize environmental impact while meeting regulatory standards?"

Façade Design & Carbon Impact

- Material selection, WWR, and glazing performance significantly influence both **embodied & operational carbon**.
- Optimizing these factors in early design stages can **minimize environmental impact**.

Comparing Façade Typologies

- **Aluminum unitized façades** → **Highest embodied carbon** due to carbon-intensive production of the materials.
- **Timber façades** → **Lowest embodied emissions** with added **carbon sequestration benefits**.
- **Concrete façades** → **Intermediate embodied carbon**, but WWR variations affect emissions uniquely.

Operational Carbon & Energy Performance

- **Façade orientation matters**:
  - **North-facing** → Higher heating demand.
  - **South-facing** → Passive heating but increased cooling loads.
- **Reducing glazing U-values** is the most effective strategy for lowering operational carbon.
- **Grid decarbonization trends** → Over 75 years, operational emissions are expected to **halve**, making **embodied carbon even more important**.

Optimized Façade Strategies

- **Timber façades + efficient glazing & insulation** = **most sustainable** option.
- **Aluminum façades** → Highest total carbon footprint, even in optimized setups.
- **Concrete façades** → WWR adjustments can have **counterintuitive effects** on emissions.

An integrated approach to façade design is key: balancing materials, insulation, glazing, and orientation to achieve **the lowest total carbon footprint**.

Discussion

Validity

- **Proven simulation models** ensure accurate assessment of façade-related carbon impacts.
  - Also tested in other simulation software
- **Findings align with literature**, confirming embodied carbon's increasing significance in a decarbonized energy grid.

Limitations:

- Focused on specific materials, climates, and building types.
- Single simulation tool used; real-world validation needed.
- Excluded smaller façade components
- Excluded material aging
- Excluded transport emissions.
- Excluded optimal material use
- Future energy grid decarbonization scenarios are uncertain due to unpredictable policy and technological developments.

Key Findings & Interpretation

- **Embodied carbon will dominate long-term impacts** as operational carbon decreases due to grid decarbonization.
- **WWR significantly affects energy demand**, with higher WWR increasing heating loads (especially north-facing façades).
- **Unexpected results**: Thermal resistance (Rc-value) has a **smaller effect than assumed**, while **WWR, g-value & U-value interactions are more important**. highlighting the need for tailored solutions for each façade orientation.

Discussion

Suggestions for Future Research

- Occupant Behavior: Incorporate adaptive behavior to improve thermal comfort and energy use predictions in simulations.
- Shading and HVAC: Investigate the inclusion of passive/active shading, more realistic HVAC systems, and renewable energy sources in simulations.
- Material and Façade Expansion: Broaden the study's scope by including a wider variety of materials and façade configurations for improved carbon reduction strategies.
- Database and Climate Models: Develop a more comprehensive embodied carbon database and refine climate models to understand the impact of different decarbonization scenarios and regions.
- Add lifecycles to the materials and elements.
- Material use optimization

Reflection

Effective Approach:

- The combination of computational design and sustainability-focused research provided valuable insights into the impact of façade typologies on embodied carbon and energy usage in mid- to high-rise buildings.
- Gained a deeper understanding of façade design optimization through dynamic modeling and energy simulations, recognizing the importance of material choices and facade parameters in minimizing environmental impact.

Mentor Feedback:

- Simplified the number of parameters in simulations for clearer results and more efficient analysis.
- Focused on conducting exploratory simulations first and then optimization for better clarity and focus.
- Emphasized the importance of a clear, strong narrative and explaining the reasoning behind design decisions and limitations.

Learning and Skill Development:

- Improved computational design skills, including learning Grasshopper and Python coding, which enhanced simulation efficiency and the ability to tackle complex problems.
- Gained the ability to balance technical constraints with sustainable design goals, improving iterative methods and outcomes.

Relevance to Master’s Program:

- The research aligns with the Master of Science in Architecture, Urbanism, and Building Sciences (AUBS) focus on sustainability, energy efficiency, and computational design.
- The study directly connects to the Building Technology track, addressing concerns on reducing carbon emissions through innovative façade designs.

Reflection

Practical Applications:

- The research provides guidelines for optimizing energy efficiency and reducing embodied carbon in façades, offering a framework for informed decision-making in design.
- Findings are context-dependent, suggesting the need for similar simulations in specific situations to understand optimal façade designs.

Methodology Success:

- The use of computational simulations, and dynamic modeling was successful in meeting research objectives, offering valuable insights into the environmental implications of façade design.
    - There could be made an extra step to find the sweet spots
- The integration of parametric design tools enabled quick optimization of façade variables, providing a foundation for both academic and practical sustainable design solutions.

Reflection Questions:

- **What would I do differently?**
  Start with a more focused plan and aim to conduct deeper computational exploration. Finish the literature review early to allow more time for research and refine the conclusion and discussion.

- **Am I satisfied with my work?**
  Satisfied with the results, as the project offered new perspectives and was a valuable learning experience. Improved academic skills and learned to approach projects with a critical academic mindset.

Dynamic Façade Design for Sustainability: A Computational Approach to Reducing Embodied and Operational Carbon in Façade Elements

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