Modeling Civil Engineered Systems

Parametric Modeling of an RC Cantilever Retaining Wall

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1. Objective and Scope

Reinforced concrete cantilever retaining walls are widely used engineering solutions to ensure the stability of road embankments and various infrastructure structures. The behavior of these walls is an integrated problem affected by many parameters, such as geometry, material usage, soil pressure, and soil-structure interaction. Therefore, even small changes in geometric dimensions can significantly alter both structural safety and environmental impacts.

Within the scope of this study, a parametric model of a reinforced concrete cantilever retaining wall was created in the Dynamo environment. Two fundamental geometric variables were examined in the model: stem height (H) and heel length (L_h). These two parameters were selected because they directly affect the magnitude of lateral earth pressure, overturning moment, distribution of counterweight base mass, and moment arm. The ranges of H and L_h used and the other geometric parameters kept constant are consistent with the dimensions recommended in the study by Mohammad & Ahmed (2018), which examines Eurocode-based optimal wall designs, aiming to keep the model within realistic engineering limits.

This study focuses on analysing how the two selected high performance criteria respond to the variation of the two geometric design variables.

1. a global structural stability performance index, combining overturning, sliding, and soil bearing capacity safety, and
2. the embedded material mass and CO_2 emissions per unit area.

The goal of this study is not to perform any optimization, but to investigate how the selected performance indicators vary across the design space when the geometric parameters H and $L_h$change. For this purpose, three representative design alternatives were selected to span the range of admissible parameter combinations. These alternatives correspond to:

1. Alternative 1: A configuration with a large stem height H and a small heel length L_h, representing one end of the design space.
2. Alternative 2: A configuration with intermediate values of H and L_h, representing a mid-range point within the design space.
3. Alternative 3: A configuration with a small stem height H and a large heel length L_h, representing the opposite end of the design space.

These alternatives were intentionally selected to cover the lower, intermediate, and upper regions of the parameter domain. This systematic selection allows the parametric model to clearly illustrate how both structural performance indicators and material& CO_2 based indicators vary across the range of possible geometric configurations.

2. Parametric Geometry and Design Parameters

The reinforced concrete cantilever retaining wall has been created as a three-dimensional geometric model in a parametric manner within the Dynamo environment. The model focuses on two fundamental design variables that determine the system's behavior: stem height and heel length. Other geometric dimensions were kept constant to ensure the model remained understandable and controllable. These are toe length, stem thickness, base thickness, and the the wall's length. Thus, by changing only H and L_h, the wall cross-section and three-dimensional geometric mass are automatically updated.

Table 1. Geometric Design Parameters

Parameter	**Symbol**	**Value / Range**
Stem height	H	3.5 – 7.5 m
Heel length	L_h	1.65 – 2.75 m
Toe length	L_t	1.20 m
Wall length	L_x	6.00 m
Base thickness	t_b	0.35 m
Stem thickness	t_s	0.30 m

H and L_h values are controlled using slider nodes in Dynamo. When these values are changed, both the three-dimensional wall geometry and the submodules that perform the performance calculations are simultaneously rebuilt. This enables different design alternatives to be generated quickly, and the effects of geometric variables on performance can be clearly observed.

3. High Performance Criteria

This study evaluates the performance of the reinforced concrete cantilever retaining wall using two key indicators: structural stability and the embedded material mass and CO_2 emissions per unit area. Both measures are computed parametrically in Dynamo as functions of the design variables H and L_h. Detailed formulations are provided in Appendix A.

3.1 Structural Stability Performance

Structural stability performance is based on three fundamental safety checks commonly used in retaining wall design: overturning, sliding, and bearing capacity. The following assumptions and methods were used in calculating these checks:

In the structural stability assessment, active earth pressure based on Rankine theory was used, taking into account the typical soil parameters given in Prof. Kemal Önder Çetin's 2022 Soil Mechanics – Soil Properties lecture notes. In the overturning control, the overturning moment induced by this pressure was compared with the resisting moments generated by the wall and soil components; the sliding control was performed based on the sliding resistance derived from the base-soil friction coefficient at the base-soil interface, while the soil bearing capacity control was performed by comparing the bearing stresses beneath the base with the allowable bearing capacity. These three checks were normalized with target safety factors to obtain a Global Performance Index, a combined structural performance indicator.

Table 2. Input Parameters Used in the Stability Calculation

Parameter	Symbol	Value	Unit
Internal friction angle	φ	30	°
Soil unit weight	γ_{soil}	18	kN/m³
Reinforced concrete unit weight	$\gamma_{concrete}$	25	kN/m³
Base soil friction coefficient	μ_{base}	0.50	–
Allowable bearing capacity	q_{allow}	300	kN/m²

3.2 Embodied Material and CO_2 Performance

The second performance criterion evaluates the amount of concrete and steel required to produce the wall and the CO_2 emissions from these materials. For this purpose, the body and base concrete volumes were calculated, the steel area and volume were determined using Eurocode minimum reinforcement ratios, and CO_2 emission factors were applied for both concrete and steel. The material and environmental impact coefficients are based on typical parameters presented in the sustainable design study by Akbay Arama, Kayabekir, and Bekdaş (2021). The CO_2 emissions obtained from the total concrete and steel mass were normalized by the area retained by the wall to obtain the indicators material mass per unit retained area (kg/m²) and CO_2 per unit retained area (kgCO₂/m²). This normalization ensures a fair and comparable assessment of the environmental performance of walls of different heights.

Table 3. Input Parameters Used in Material and CO_2 Calculations

Parameter	**Symbol**	**Value**	**Unit**
Yield strength of steel	f_{yk}	420	MPa
Mean tensile strength of concrete	f_{ctm}	2.90	MPa
Concrete density	$\rho_{concrete}$	2549.29	kg/m³
Steel density	ρ_{steel}	7850	kg/m³
Concrete CO_2 emission factor	$e_{concrete}$	376	kgCO₂/m³
Steel CO_2 emission factor	e_{steel}	3.01	kgCO₂/kg

4. Design Alternatives and Results

4.1 Geometric Definition of the Alternatives

Three representative geometric alternatives were selected to examine how the high performance criteria vary with changes in the design parameters stem height, heel length. These alternatives cover different points within the admissible design space and are not associated with any predefined level of optimality or safety; their purpose is solely to illustrate parametric variation. Below, the 3D geometries of Alternative 1, Alternative 2, and Alternative 3 generated in Dynamo are presented.

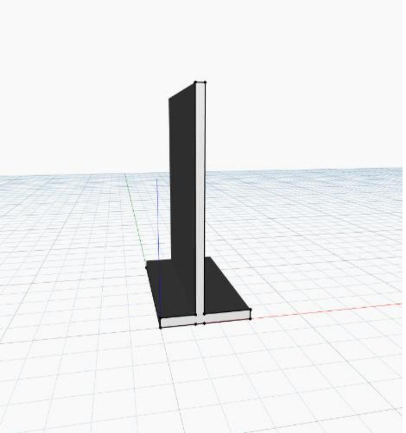


Figure 1. Alternative 1
(H = 7.5 m, L_h = 1.65 m)

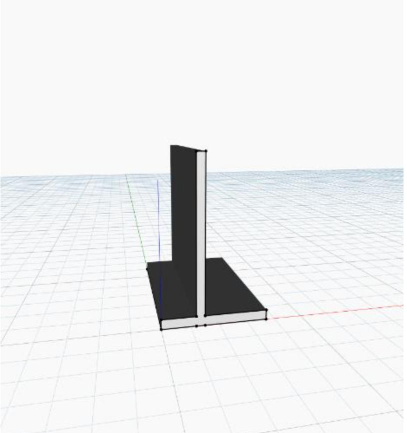


Figure 2. Alternative 2
(H = 5.5 m, L_h= 2.20 m)

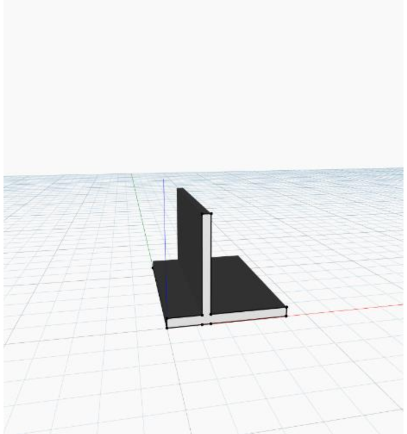


Figure 3. Alternative 3
(H = 3.5 m, L_h = 2.75 m)

4.2 Structural Stability Results

Overturning, sliding, and bearing capacity checks were evaluated for the three design alternatives, and their safety factors were compared. To summarise how well each alternative performs relative to the target safety factors (1.5 for overturning and 1.3 for sliding), a Global Performance Index was used. This index represents the average normalised performance of the three checks.

Table 4. Structural Performance Indicators for Design Alternatives

Alternative	H (m)	L_h (m)	**FS Overturning**	**FS Sliding**	**Bearing Utilization**	**Global Performance Index**
Alt. 1	7.5	1.65	1.511	0.908	0.759	1.008
Alt. 2	5.5	2.20	4.098	1.606	1.016	1.650
Alt. 3	3.5	2.75	14.287	3.220	0.816	4.409

As can be seen in Table 4, the stability results obtained from three different geometric alternatives clearly demonstrate the effects of changes in stem height H and heel length on structural behavior. In general, as the stem length increases and the heel length decreases, the system exhibits weaker structural performance. To examine these behaviors in detail:

In overturning behaviour, the overturning moment generated by the active earth pressure is compared with the stabilizing moment provided by the self-weight of the wall and the soil resting on the heel. In high walls, the moment arm of the active pressure increases, causing the overturning moment to increase rapidly. In addition, in short heel configurations, the weight arm that balances this moment is also limited. Therefore, Alternative 1 offers a marginal safety factor in terms of overturning, while Alternative 3 achieves very high overturning safety factors thanks to the combination of low stem height and long heel.

In terms of sliding behavior, the friction resistance between the base and the ground is the determining factor. This resistance depends on the normal force acting on the base and the interface friction. As the stem height increases, the active earth pressure grows faster than the stabilizing vertical load, and a shorter heel reduces the effective sliding resistance at the base. As a result, the sliding safety factor tends to decrease for tall walls with short heels. Therefore, it is not surprising that the FS value in Alternative 1 falls below 1.0. In contrast, Alternative 2 and especially Alternative 3 produced quite safe values in terms of sliding, thanks to the increase in heel length and lower active thrust levels.

It is also not incorrect that the bearing capacity utilisation differs between the three alternatives, even though the same soil parameters are used. This is because the stress distribution under the foundation depends not only on soil properties, but also on the total wall weight, the base width and the eccentricity from moment equilibrium. For this reason, Alternative 2 yields a higher bearing capacity utilisation than the two extreme cases is not interpreted as an error. The maximum contact stress is influenced by both the load level and how eccentrically this load is transferred at the base. When H and $L_h$change together, these effects can combine, and an intermediate geometry may produce the highest stress

Finally, the global Performance Index is the average of the normalized results of the three different stability checks according to their target safety factors and provides a summary for evaluating general trends. From this perspective, the index accurately reflects the significant increase in stability as we progress from Alternative 1 to 3. However, it should be noted that, due to its average value, a weak control can be masked by other strong controls. Indeed, the fact that the Global Performance value is approximately 1 in Alternative 1, despite the insufficient slip safety factor, is a very good example of this situation.

4.3 Embodied Material and CO_2 Results

The examination of the material and CO_2 performance across the three alternatives reveals how the geometric design variables influence both the total resource consumption and the environmental impact per unit of retained area.

Table 5. Material Use and CO_2 for All Alternatives

Alternative	H **(m)**	L_h **(m)**	**Concrete Volume (m^3)**	**Steel Mass (kg)**	**CO_2 concrete (kg)**	**CO_2 steel (kg)**	**CO_2 total (kg)**	**Material Mass per Stem Area (kg/m^2)**	**CO_2 per Stem Area (kgCO_2/m^2)**
Alt. 1	7.5	1.65	20.04	615.82	7533.74	1853.62	9387.36	1148.77	208.61
Alt. 2	5.5	2.20	17.60	540.97	6618.01	1628.31	8246.32	1376.10	249.89
Alt. 3	3.5	2.75	15.17	466.11	5702.27	1403.00	7105.28	1863.22	338.35

Among the alternatives, a decrease in stem height while increasing heel length creates opposing effects on volume components. While the decrease in stem height reduces the body volume, the increase in heel length enlarges the base area and prevents the total volume from decreasing rapidly. Therefore, although the total concrete volume and total CO_2 emissions decrease steadily among the three alternatives, this decrease occurs more slowly compared to the decrease in the area retained. Furthermore, when examining the material components, it is seen that, due to being the main structural element within the system, the vast majority of CO_2 in all three alternatives is concrete related, while steel is a smaller but still significant component of the total environmental impact.

The use of normalized indicators based on retained area in the evaluation of material performance aims to provide a comparison that is more appropriate for the engineering purpose of retaining walls. The primary function of such walls is to safely retain the ground up to a certain height, and therefore the area retained can be considered the fundamental engineering gain provided by the system. In contrast, the amount of concrete and steel, and the associated CO_2 emissions, represent the resources expended to achieve this gain. Therefore, evaluating performance based on expenditure per unit area retained provides a much more logical approach. When looking at total concrete or total CO_2 amounts, high walls naturally appear more negative because they consume more material, but the fact that these walls stabilize a larger area is overlooked. Therefore, area-based normalization reveals the true efficiency of the design. The trend that emerges after normalization clearly shows the divergence between total quantities and efficiency indicators. Alternative 1, which has the highest concrete volume and total CO_2 emissions, produces the lowest material and CO_2 intensity per unit area because it is the design with the largest area retained. In contrast, Alternative 3, which has the lowest total concrete volume and CO_2 values, is the design with the highest material and CO_2 intensity per unit area because it has the smallest area retained. This table shows that although a short and wide-based wall uses less material overall, it becomes a more material-intensive system due to its structural inefficiency. Indeed, the structural performance evaluation also revealed that this configuration exhibits a significant degree of overdesign.

5. Conclussion

This study utilized a parametrically defined reinforced concrete cantilever retaining wall model to investigate the interaction between geometric design variables and two fundamental performance criteria: structural stability and material/CO_2 efficiency per unit area. Three alternatives were evaluated by systematically varying the stem height and heel length.

The structural stability results revealed that increasing the stem height significantly increased the overturning and sliding effects; conversely, increasing the heel length strengthened stability by increasing the stabilizing moment arm. In this context, Alternative 3 yielded the best results. However, these excessively high safety factors indicate that the structure is overdesigned; that is, the system offers a load-bearing capacity far beyond what is required, which is not desirable in terms of engineering efficiency. Material and CO_2 performance provided a complementary perspective. Although the total amount of concrete and steel decreased steadily as the wa height decreased, the indicators normalized over the area showed the opposite. The shortest wall used the least material overall, but because it occupied much less area, it produced the highest material and CO_2 intensity per unit area. This result demonstrates that material efficiency in retaining structures is only meaningful when evaluated based on the area retained; because total material consumption alone does not reveal whether the design is efficient or sustainable.

When both performance criteria are considered together, a clear trade-off between structural safety, total material consumption, and environmental efficiency is evident. A design that maximizes stability may not be environmentally efficient; low total material usage does not always mean efficient resource utilization per unit area. Therefore, the parametric model not only revealed the effect of geometric variables on wall behavior but also highlighted critical engineering issues such as sustainability and overdesign risks.

In conclusion, this study has demonstrated that effective retaining wall design is not possible by optimizing a single criterion, but rather by developing a balanced solution between geometry, structural requirements, and environmental impacts. It has emphasized the importance of evaluating all these criteria in a proportional and balanced manner.

6. References

Akbay Arama, Z., Kayabekir, A. E., & Bekdaş, G. (2021). *Sustainable Optimum Design of RC Retaining Walls: The Influence of Structural Material and Surrounding Soil Properties*.

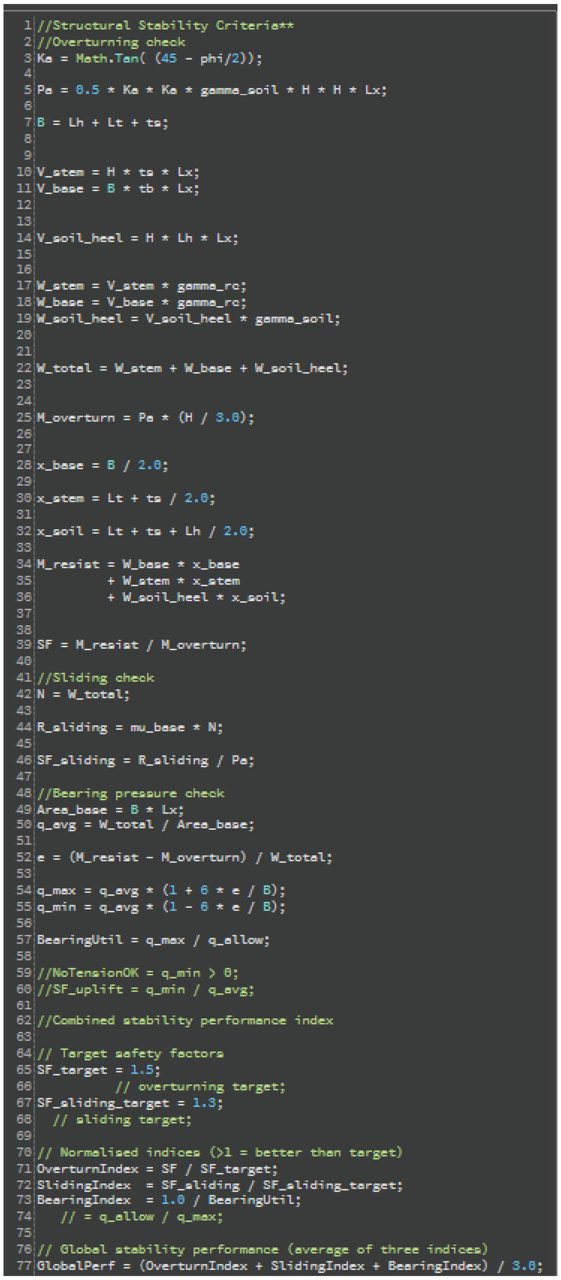
Çetin, K. Ö. (2022). *Soil Mechanics – Soil Properties (Lecture Notes).* Middle East Technical University, Department of Civil Engineering.

Mohammad, F. A., & Ahmed, H. G. (2019). *Optimum design of reinforced concrete cantilever retaining walls according to Eurocode 2 (EC2)*. Athens Journal of Technology and Engineering, 5(3), 277–296.

7. Appendices

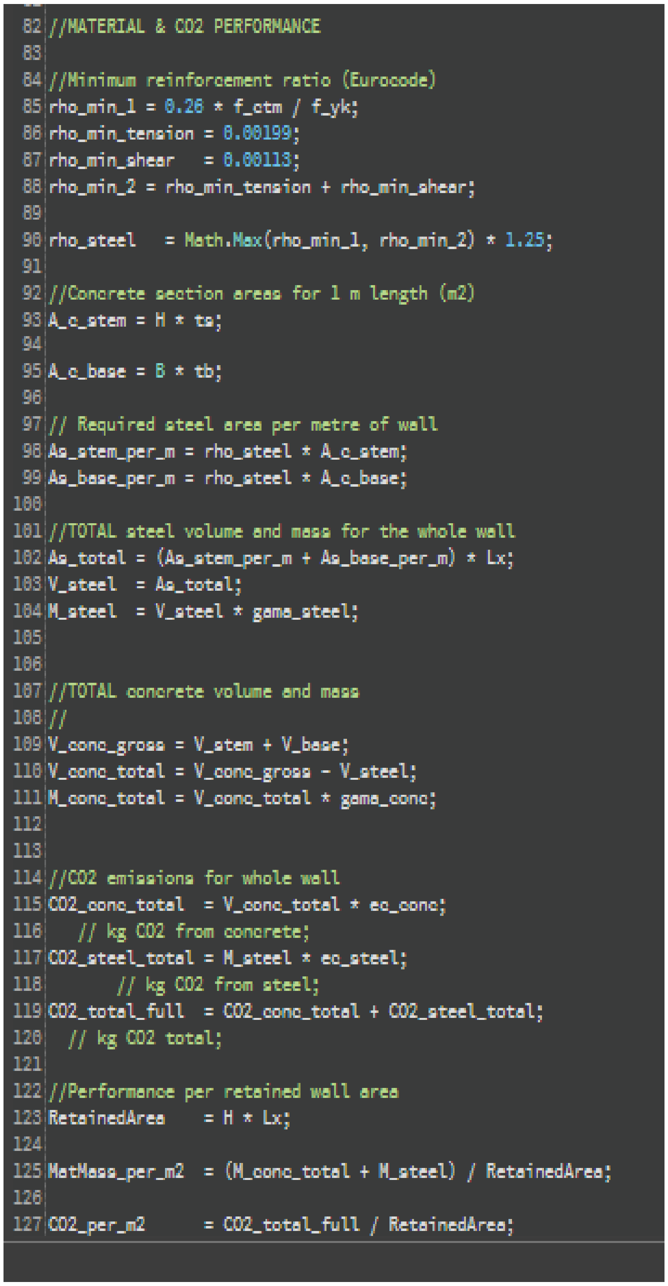
Appendix A –Formulations

This appendix presents the mathematical expressions used to compute the structural stability checks and the material and embodied CO_2 indicators.



```
//Structural Stability Criteria**
//Overturning check
Ka = Math.Tan( (45 - phi/2));

Pa = 0.5 * Ka * Ka * gamma_soil * H * H * Lx;

B = Lh + Lt + ts;


V_stem = H * ts * Lx;
V_base = B * tb * Lx;


V_soil_heel = H * Lh * Lx;


W_stem = V_stem * gamma_rc;
W_base = V_base * gamma_rc;
W_soil_heel = V_soil_heel * gamma_soil;


W_total = W_stem + W_base + W_soil_heel;


M_overturn = Pa * (H / 3.0);


x_base = B / 2.0;

x_stem = Lt + ts / 2.0;

x_soil = Lt + ts + Lh / 2.0;

M_resist = W_base * x_base
         + W_stem * x_stem
         + W_soil_heel * x_soil;


SF = M_resist / M_overturn;

//Sliding check
N = W_total;

R_sliding = mu_base * N;

SF_sliding = R_sliding / Pa;

//Bearing pressure check
Area_base = B * Lx;
q_avg = W_total / Area_base;

e = (M_resist - M_overturn) / W_total;

q_max = q_avg * (1 + 6 * e / B);
q_min = q_avg * (1 - 6 * e / B);

BearingUtil = q_max / q_allow;

//NoTensionOK = q_min > 0;
//SF_uplift = q_min / q_avg;

//Combined stability performance index

// Target safety factors
SF_target = 1.5;
          // overturning target;
SF_sliding_target = 1.3;
  // sliding target;

// Normalised indices (>1 = better than target)
OverturnIndex = SF / SF_target;
SlidingIndex  = SF_sliding / SF_sliding_target;
BearingIndex  = 1.0 / BearingUtil;
   // = q_allow / q_max;

// Global stability performance (average of three indices)
GlobalPerf = (OverturnIndex + SlidingIndex + BearingIndex) / 3.0;
```

Figure A.1 – Structural Stability Calculation Script



```
//MATERIAL & CO2 PERFORMANCE

//Minimum reinforcement ratio (Eurocode)
rho_min_1 = 0.26 * f_ctm / f_yk;
rho_min_tension = 0.00199;
rho_min_shear   = 0.00113;
rho_min_2 = rho_min_tension + rho_min_shear;

rho_steel   = Math.Max(rho_min_1, rho_min_2) * 1.25;

//Concrete section areas for 1 m length (m2)
A_c_stem = H * ts;

A_c_base = B * tb;

// Required steel area per metre of wall
As_stem_per_m = rho_steel * A_c_stem;
As_base_per_m = rho_steel * A_c_base;

//TOTAL steel volume and mass for the whole wall
As_total = (As_stem_per_m + As_base_per_m) * Lx;
V_steel  = As_total;
M_steel  = V_steel * gama_steel;


//TOTAL concrete volume and mass
//
V_conc_gross = V_stem + V_base;
V_conc_total = V_conc_gross - V_steel;
M_conc_total = V_conc_total * gama_conc;


//CO2 emissions for whole wall
CO2_conc_total  = V_conc_total * ec_conc;
   // kg CO2 from concrete;
CO2_steel_total = M_steel * ec_steel;
        // kg CO2 from steel;
CO2_total_full  = CO2_conc_total + CO2_steel_total;
  // kg CO2 total;

//Performance per retained wall area
RetainedArea    = H * Lx;

MatMass_per_m2  = (M_conc_total + M_steel) / RetainedArea;

CO2_per_m2      = CO2_total_full / RetainedArea;
```

Figure A.2 – Material and Embodied CO_2 Calculation Script

Appendix B – Dynamo BIM Model

The parametric model was implemented in Dynamo BIM. The geometric variables H and L_h were defined as slider inputs, automatically regenerating the 3D geometry and all dependent performance calculations. Below, sample screenshots of the visual programming environment are provided.

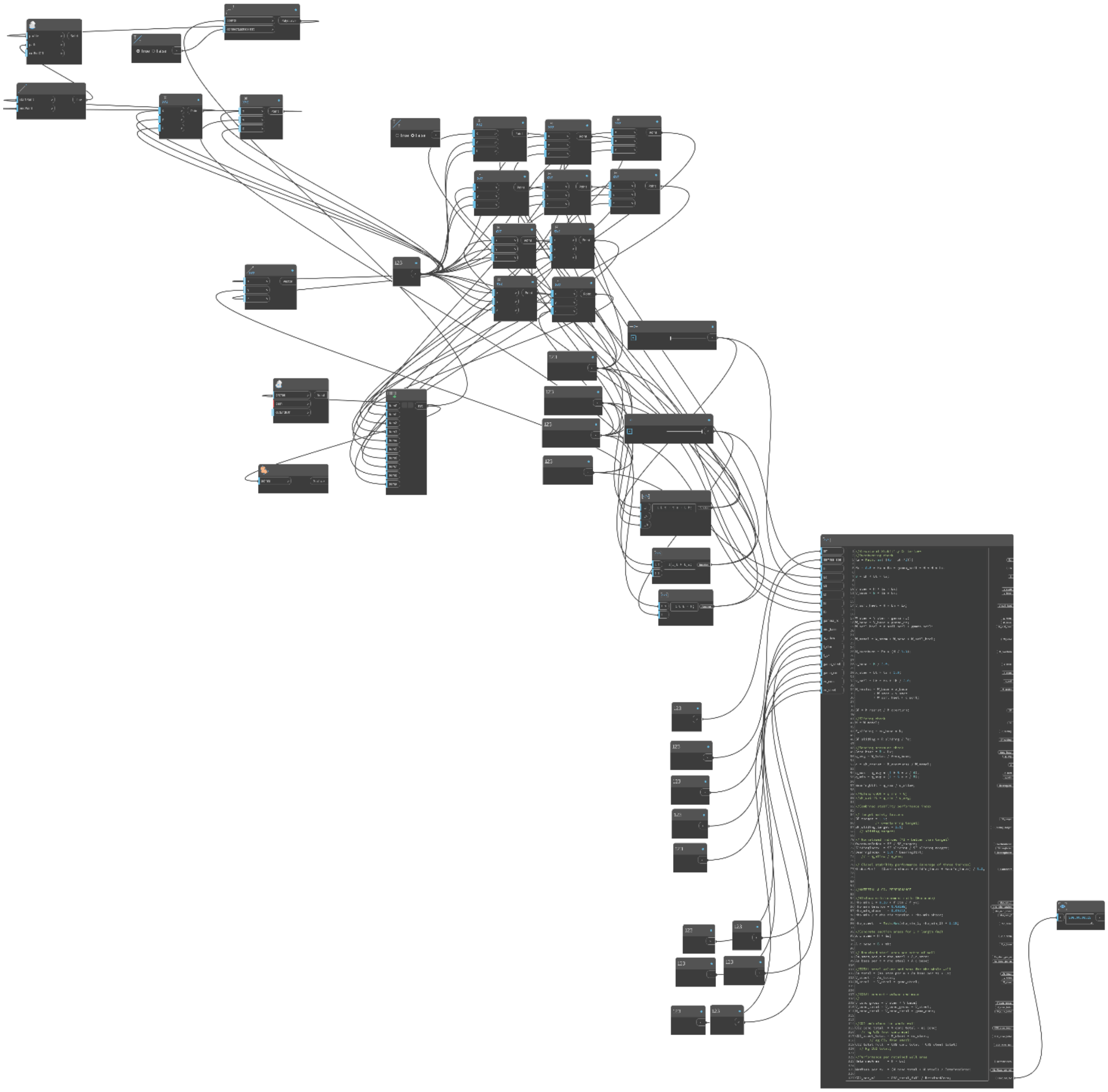


Figure B.1 – Overall Dynamo script implementing geometry generation and performance calculations