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Article

Generative Design for Dimensioning of Retaining Walls

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Abstract: The design of retaining walls follows a classic structure. The engineer proposes certain dimensions that will be modified until they comply with the regulatory and site restrictions presented by the project. This is an iterative process that can be optimized through a new method called generative design. The designer codes the characteristics and restrictions of the project so that the system creates the most appropriate solutions to the problem presented. In this research, a computer program was created to build the dimensions of retaining walls using generative design. For this purpose, Design Science Research (DSR) was used, complemented with the incremental software development method. A program that delivers multiple retaining wall design alternatives in a short time was constructed. The evaluation of this program was performed through usability tests, giving as main perceptions the program's ease of use and the time savings concerning the traditional design.

Keywords: generative design; retaining walls; optimization; design science research (DSR)

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1. Introduction

Retaining walls support the lateral thrusts produced by the retained material. To fulfill this purpose, these walls use their weight and the weight of the material placed on their foundation to stabilize themselves [1]. The designs of retaining walls have to meet requirements of functionality, safety, strength, and economy [2] that depend on the regulations of each country. The most commonly used types of retaining walls are gravity and cantilever retaining walls, where the latter are also called cantilever or bracket retaining walls [3]. Gravity walls (Figure 1a) are usually massive walls of great thickness, without steel reinforcement, and they are generally used for moderate heights of up to approximately 3.5 [m]. Cantilever walls (Figure 1b), on the other hand, are usually used to contain soil up to 6 [m] in height and work thanks to the resistance produced by a vertical cantilevered screen embedded to its horizontal base [1,4,5] Cantilever walls are commonly used to reduce the volume of material used compared to gravity walls [6].

Consequently, the design of retaining walls seeks to guarantee the stability of the structure in the face of the forces that converge on it, such as soil thrust, self-weight, backfill weight, and overloads [7]. In seismic countries, for example, in Chile, the guidelines of the Highway Manual, volume 3, are followed as a reference, where it is indicated that, as a compliment, the provisions of the American Association of State Highway and Transportation Officials (AASH-TO), Section 5, should be followed [8]. The Chilean highway manual proposes gravity and cantilever walls, given their good performance in a seismic country such as Chile [8].

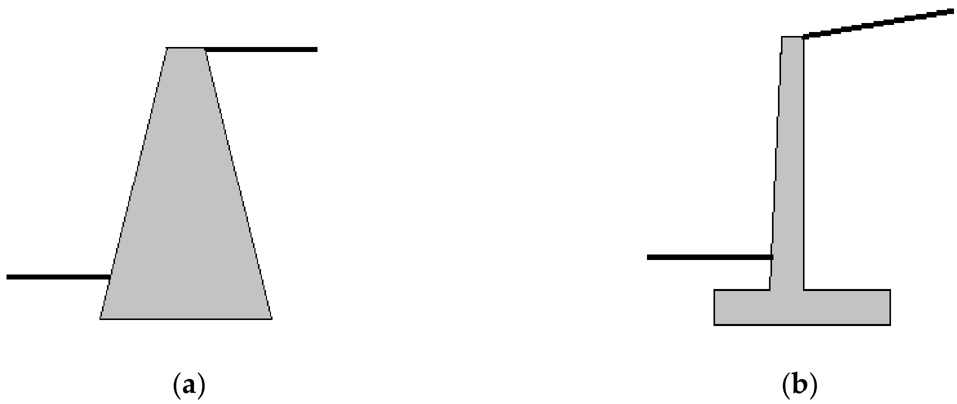


Figure 1. Cross-section of some types of retaining walls: (**a**) Gravity wall; (**b**) Cantilever wall. Adapted from [4].

For designs to achieve compliance with all technical and regulatory requirements, engineers need to assume the initial geometry of the wall (called dimensioning) and check if the solution satisfies the established requirements. In case of non-compliance, the wall geometry is modified and revised again [7]. This way of dimensioning corresponds to a traditional design process, where the designer creates a solution (based on an idea) to solve a problem. Subsequently, this solution is evaluated to decide whether it satisfies what is expected. If it does not, the designer modifies it and evaluates it again until it satisfies the problem for which it was created, as shown in Figure 2. This iterative design process is programmable through computer software [7]. It is worth mentioning that, although there are recommendations with the proportions that the different parts of each retaining wall should have [9], this is a procedure that depends mostly on the engineer's experience and vision; however, this form of dimensioning does not guarantee that the final design will be the best solution [10,11].

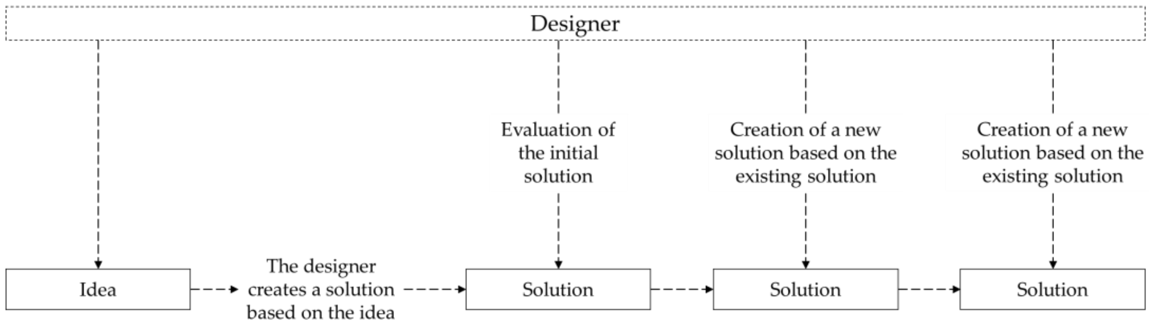


Figure 2. Traditional design process. Adapted from [10].

In this perspective, some optimization techniques can be useful to reduce the design time and the volume of material to be used in the retaining wall [11]. Currently, there is another design process called *generative*, where the designer has an idea that is translated into a set of rules or algorithms to make a code that will create the solution to the problem [12], as schematized in Figure 3. The importance of this last process is that, in contrast to traditional design, the solution or solutions obtained can be modified by changing the rules and code, and it is not necessary to go back to the beginning [10]. According to Hesselgren [10], generative design is not about designing the infrastructure but about designing the system that will create the infrastructure.

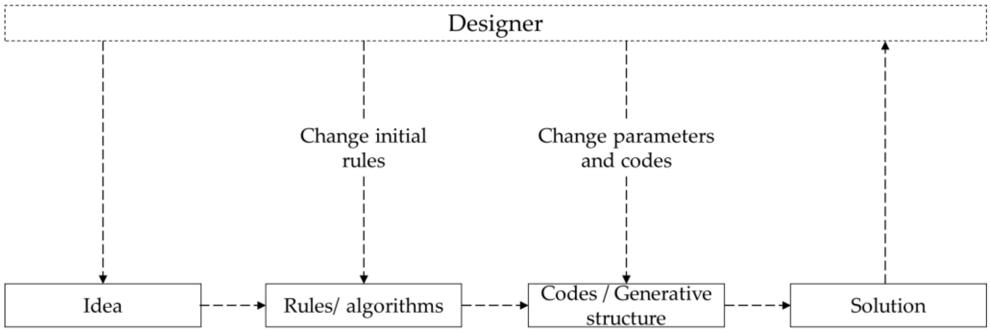


Figure 3. Generative design process. Adapted from [10].

Generative design is a process that allows designers and engineers to define parameters such as materials, spatial constraints, manufacturing methods, or cost constraints to create sets of rules or algorithms to automatically explore various permutations of the model, where the software generates the best design alternatives according to the previously proposed objectives [12]. This process often generates designs that would otherwise have been difficult to imagine under the premise of traditional design. Hence, its forms are unique since they are created to adapt to particular needs [13]. Some applications where this method has been applied are: to optimize the distribution of material within a space; to maximize or minimize compliance with certain parameters, such as the weight of an element or the temperature of a building; and to limit the volume, displacement, or stress, both of a specific component and the whole building [14]. As a result of these qualities, generative design has been used in fields as diverse as art, music, literature, fashion, design, architecture, and engineering [10].

In structural engineering (as part of civil engineering), generative design has been used to optimize elements based on mathematical, size, shape, and topology constraints [15]. Some examples found in the literature are: the modification of the central structure of a building for deformation control [16], cantilever beam optimization with 3D printing [17], the optimization of slab material [18], characteristics of the materials as a criterion for the design of a grid plan [19], and material optimization for reinforced concrete deep beams [20]. As observed, the systematization of the structural design is focused on specific subsystems that minimize the cost and weight of such elements; therefore, it is not common that this optimization is applied to the complete structural design of the building [15]. In addition, most of the studies focused on studying structural elements of buildings and infrastructure; however, no applications of generative design have been made to soil-retaining structures, such as retaining walls.

Based on the previous analysis, this research developed a retaining wall dimensioning program to help engineers optimize the design process of these structures through generative design to allow them to quickly conceive different wall alternatives that fulfill the most suitable characteristics for each project. This application had to comply with current regulations so that its results can be implemented, and its proposal is easy to use so that professionals can use the program.

2. Materials and Methods

The Design Science Research (DSR) method was used to develop this research, which according to Hevner [21], has three main cycles: relevance, design, and rigor. Within these cycles, we followed the procedure proposed by Hevner and Chatterjee [22], as it provides a specific separation for research requiring software testing, as was the case here. Based on Hevner and Chatterjee [22], the research has been structured in four stages: (1) problem/solution identification; (2) solution design and development; (3) verification and validation; and (4) research dissemination. Figure 4 shows the workflow schematically, and the tools, activities, and deliverables of each stage are also shown.

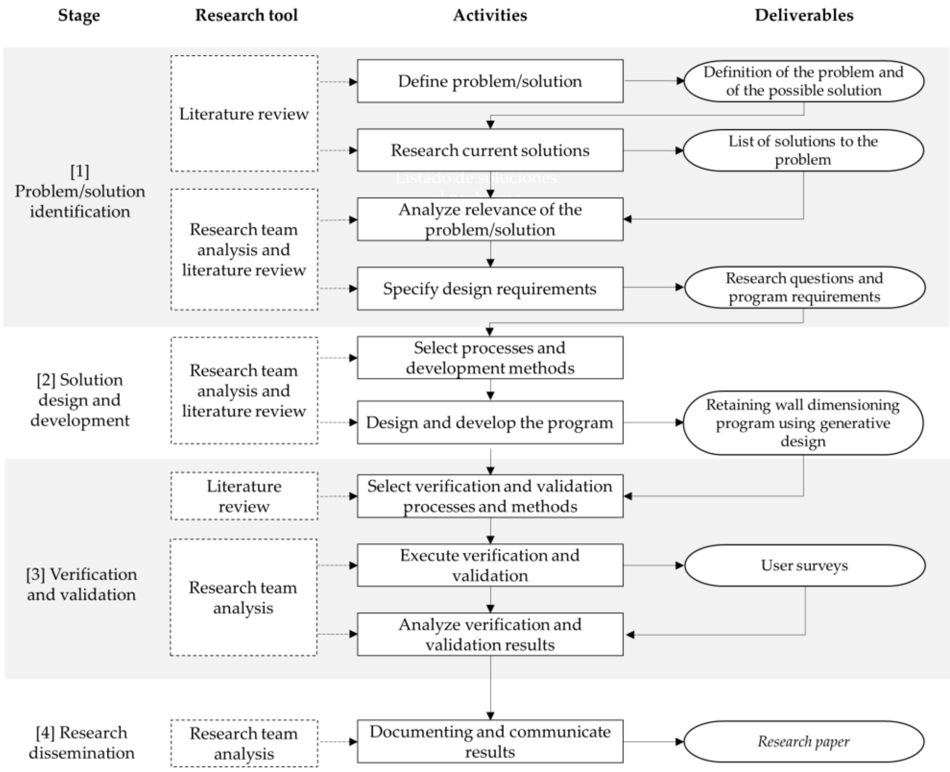


Figure 4. Research method.

In the first stage of the research, the problem and its potential solution were identified, which allowed us to characterize the problem and its opportunities for improvement through the state-of-the-art review, thus determining the importance of solving the problem through DSR. Based on the above, a literature review was carried out, consisting of a search in the databases Web of Science, Scopus, Scielo, and Google Scholar, using as key concepts "generative design," "retaining wall," and finally "retaining wall optimization." Finally, 26 documents published between 1993 and 2021 corresponding to books, theses, papers, conference proceedings, and manuals were used.

Then, in the design and development stage of the solution, the incremental method of software construction was chosen. The code was created and iterated to produce the retaining wall dimensioning program with a generative design. For the design of the solution, a technology framed within the Building Information Modeling (BIM) methodology was chosen. BIM is a methodology that combines 3D modeling with parameterized information and intelligence, which allows the management and modification of architectural, structural, and other specialty elements in an agile manner. Additionally, an application was chosen that would allow a design to be carried out through coding, which would also be interoperable with the modeling software. Finally, a third technology was selected to allow iterations through an optimization algorithm.

For the third stage, verification and validation, usability tests were performed to observe in a controlled manner how people interacted with the program. Given the health contingency conditions of COVID-19, these tests were performed remotely in a synchronous manner using the TeamViewer application to have direct communication between the user and evaluator. For these tests, an entry survey (Table 1) consisting of closed-ended questions was conducted to characterize the participants' age and academic background, learn about their previous experience with the software to be tested, discover their knowledge of generative design, and determine their ability to design retaining walls. In addition, they were asked for permission to use the data obtained from experience academically. Finally, in the dissemination stage of the research, this paper was created so that the interested community can learn about and use the program created and, consequently, receive specialized feedback.

Table 1. Entry survey.

Stage	Name	Description
1	Confidentiality agreement	Agreement to participate in the user test and disclosure of results.
2	General information	Explanation about the program being evaluated and not its skills. In addition, the following steps were described.
3	Preliminary questionnaire	Identification of the participant: age, educational level, knowledge of generative design, familiarity with the software to be used, and capacity to design retaining walls.

3. Results and Discussions

The following is the detailed breakdown of the first three stages presented in Figure 4, that is, (1) problem/solution identification; (2) solution design and development; (3) verification and validation.

3.1. Problem/Solution Identification

About the problem of the traditional design of retaining walls described in the introduction, and to the proposed solution of creating a program for the dimensioning of these structures with generative design, there were surveys conducted in 2020 where civil engineers mostly (77%) declared as "feasible" or "very feasible" the use of generative design in their professional practice and proposed to use it for pre-designs of structural elements, foundations, and steel structures, among others [12]. In addition, it was decided that the problem and the solution could be approached using DSR for two reasons: no programs were found that provide multiple alternatives for retaining wall dimensioning, according to current standards, and also, creating a generative design code is not routine, since, although this process is generally defined (Figure 3), few programs were found that use this form of design in structural engineering. Moreover, creating this program opens the way for the use of generative design in other civil engineering applications.

For the development of the program, the technical considerations defined by the regulations (in this case, the highway manual) were applied [8], such as:

- Work with the active condition, equivalent to using a retention coefficient equal to unity (Cr = 1,0) [8].
- Define the static soil thrusts, with their respective variables and the correction of retained soil parameters, depending on whether an imaginary line of 45º to the horizontal passes only through the fill or, on the contrary, also crosses the existing natural soil or fill. In the latter case, the cohesion and friction angle must be weighted to an equivalent cohesion and friction angle, c^* and ϕ^*, respectively [8].
- Consider a triangular distribution and the different parameters to calculate the static soil thrusts in both a gravity wall and a cantilever, including the respective static thrust coefficient (Ke) [8].
- Ensure that the static slip factor of safety (FSED) and the static overturning factor of safety (FSEV) are greater than or equal to 1.5 (Equations (1) and (2)); for this purpose, Ke based on Coulomb theory was used [8].
- For the seismic soil thrusts, expressions based on Mononobe and Okabe were used, which were superimposed on the static thrusts, according to a pseudo-static approximation [8].
- An inverted triangular distribution for the backfill and a rectangular distribution for the overburden (conservative assumption) were considered, as well as the different parameters to calculate the seismic soil thrusts in both a gravity wall and a cantilever, including the seismic thrust coefficient (Ks) [8].

- In addition, it was verified that the seismic slip factor of safety (FSSD) was at least 1.1, and the seismic overturning factor of safety (FSSV) was greater than 1.15 times the FSSD [8].
- Finally, it was estimated that the area in compression of the foundation seal should exceed 80% [8].

$$\text{FSED} = \frac{\sum \text{Resisting horizontal forces}}{\sum \text{Applying horizontal forces}} \geq 1.5, \quad (1)$$

$$\text{FSEV} = \frac{\sum \text{Resisting overturning moments}}{\sum \text{Applying overturing moments}} \geq 1.5, \quad (2)$$

For the above calculations, the passive thrust generated by the soil at the front foot of the wall was not considered since it is a force that cooperates with the stability of the wall, of which there is no certainty that the soil that generates it will remain there, so we worked more conservatively without it [23]. Considering the problem and its potential solution, at the end of this stage, the research questions that were used to evaluate the wall dimensioning program with the generative design were planned:

- Does the program fulfill the design of retaining walls?
- Does it deliver solutions that satisfy the requirements of the corresponding regulations?
- Is the program user-friendly?
- Does it work for people who are not familiar with generative design?
- Does the program have advantages over traditional retaining wall design (according to the users' opinion)?

Complementarily and linked to the previous questions, the following requirements of the program were defined as: dimensioning the retaining walls, considering the regulatory requirements (in this case, those defined by the highway manual), and guiding the user within the same interface. Finally, the characteristics to evaluate the program were user satisfaction, whether it meets the appropriate output data, and the speed with which these users obtained these results. The evaluation strategy was through usability testing.

3.2. Solution Design and Development

Once the research questions and the requirements to be met by the program were defined, the incremental software development method was chosen for the creation of the program since it allows the artifact to be improved progressively, which increases the understanding of the problem and its solution, by refining it progressively [24]. This approach to software creation consists of developing the project in incremental stages, where each stage adds functionality to the whole project, as shown in Figure 5. The specific iterations for the development of this program are detailed in Table 2, where we go from a parametric model of a 3D wall to one that, after entering the respective input data, can take the constraints imposed by the user and generate the dimensions of a retaining wall that meets those conditions.

It should be noted that among the generative design software that can host the proposed program and according to the literature review carried out in the area of structural engineering, the most used are Grasshopper and Refinery [12]. Refinery was chosen for this research since its interface is derived from Dynamo, which is a complement to Revit—software widely used in the professional practice of the Architecture, Engineering and Construction (AEC) industry [12]. The interaction between the software is detailed in Figure 6, where Revit served only as an interface to open its Dynamo add-in, in which the whole program was coded. Subsequently, this code searches for the appropriate solutions with the other Refinery add-in, which exports the wall model created with the generated dimensions to Dynamo. A simplified schematic of the code created in Dynamo is shown in Figure 7, which already considered all iterations performed during the process (and mentioned in Table 2). Figure 8 shows the complete code implemented in Dynamo. Each area of the code has been marked according to Figure 7.

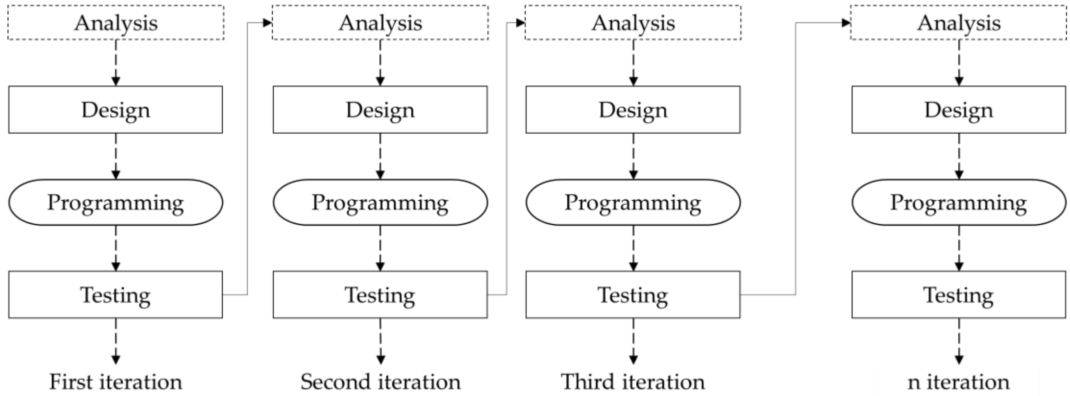


Figure 5. Incremental life cycle model. Adapted from [24].

Table 2. The development process of a wall dimensioning program through generative design.

Iteration	Activity
First	Development of the 3D parametric model of the retaining wall
Second	Enter inputs
Third	Internal calculations (mathematical algorithm)
Fourth	Transform parametric model into a generative model

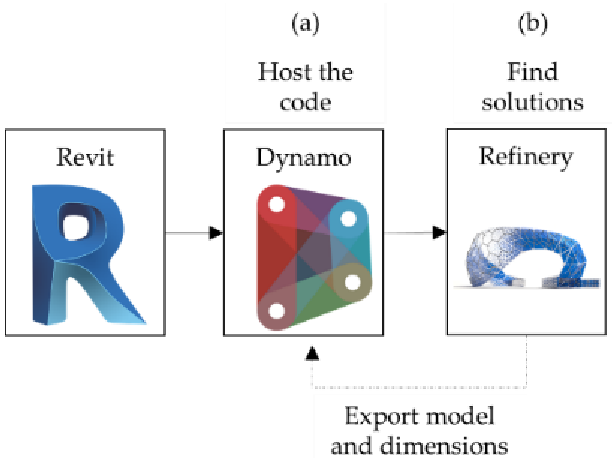


Figure 6. Revit-Dynamo-Refinery relationship diagram.

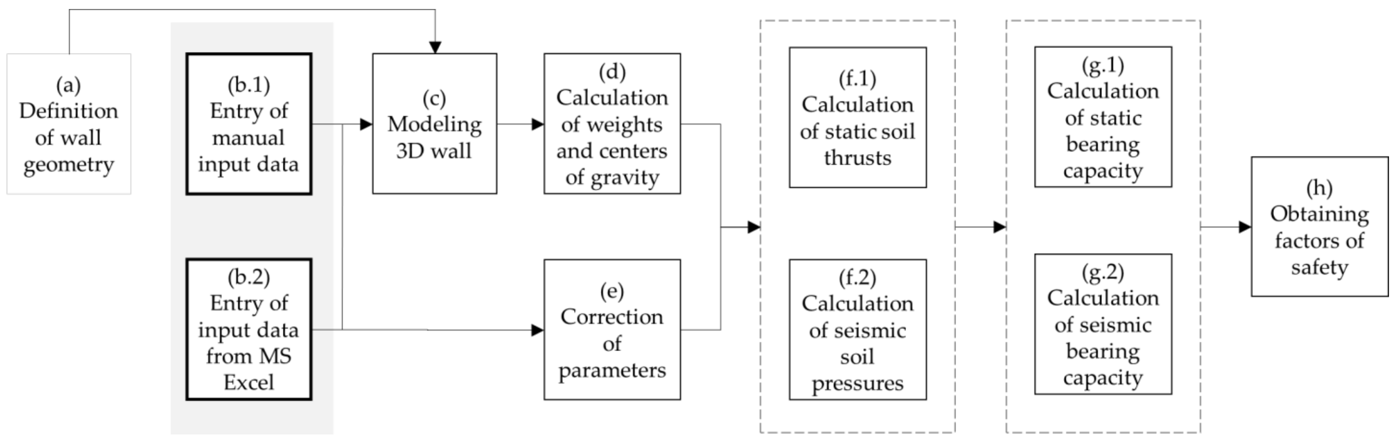


Figure 7. Proposed code scheme.

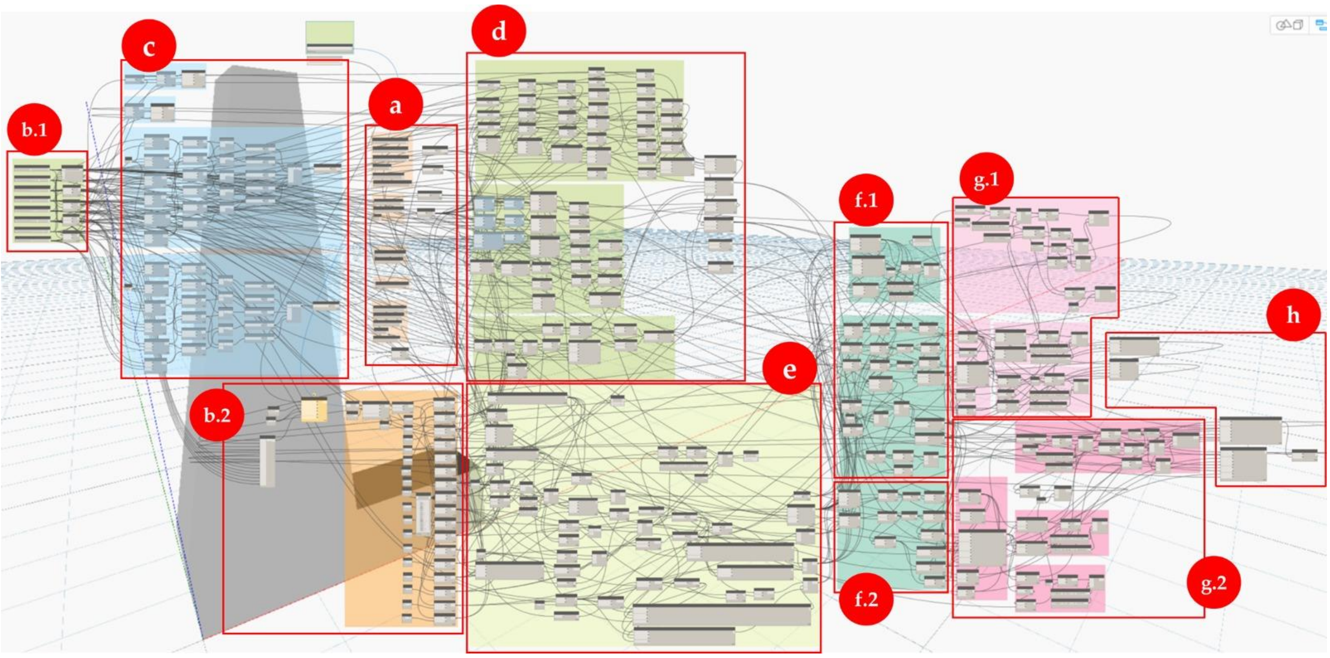


Figure 8. Developed code in Dynamo.

In the first iteration (as indicated in Table 2), the 3D model of the wall was created in Dynamo. For this purpose, certain dimensions were assigned to its parts (Figure 7, box (a). Code in Figure 9) where, in addition, each variable was restricted both below and above, also defining its increment, so that later Refinery could select different values in that interval and iterate the solutions.

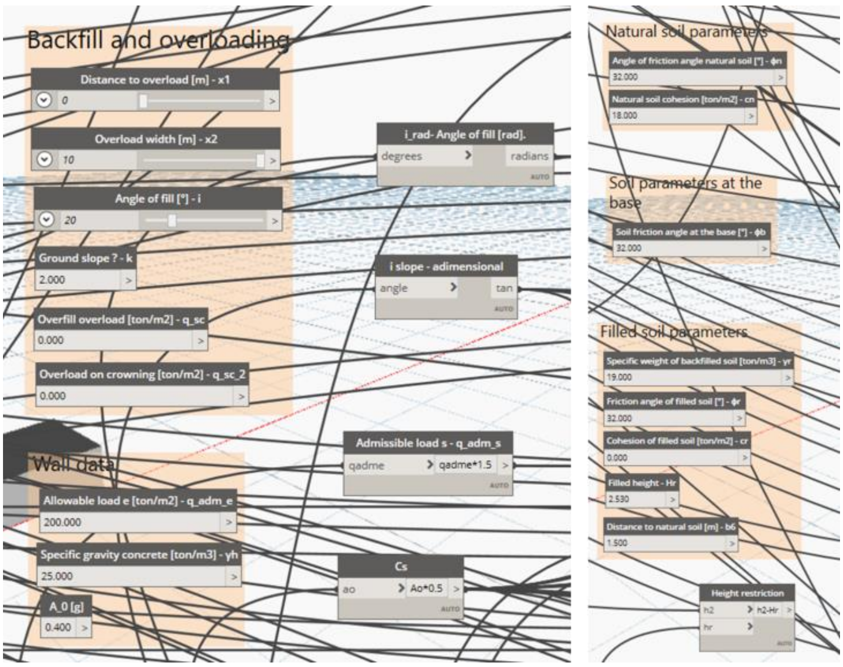


Figure 9. Code "(a) Wall geometry definition" in Dynamo.

Then, with these measurements, the model was built from the vertices, passing through the edges, to subsequently form the planes which, when joined together, formed the wall itself (Figure 7, box (c). Code in Figure 10). One linear meter of the wall was considered. Although this value can be modified, it was not considered input data for the user since the volume is easily expandable by the total number of meters of the project.

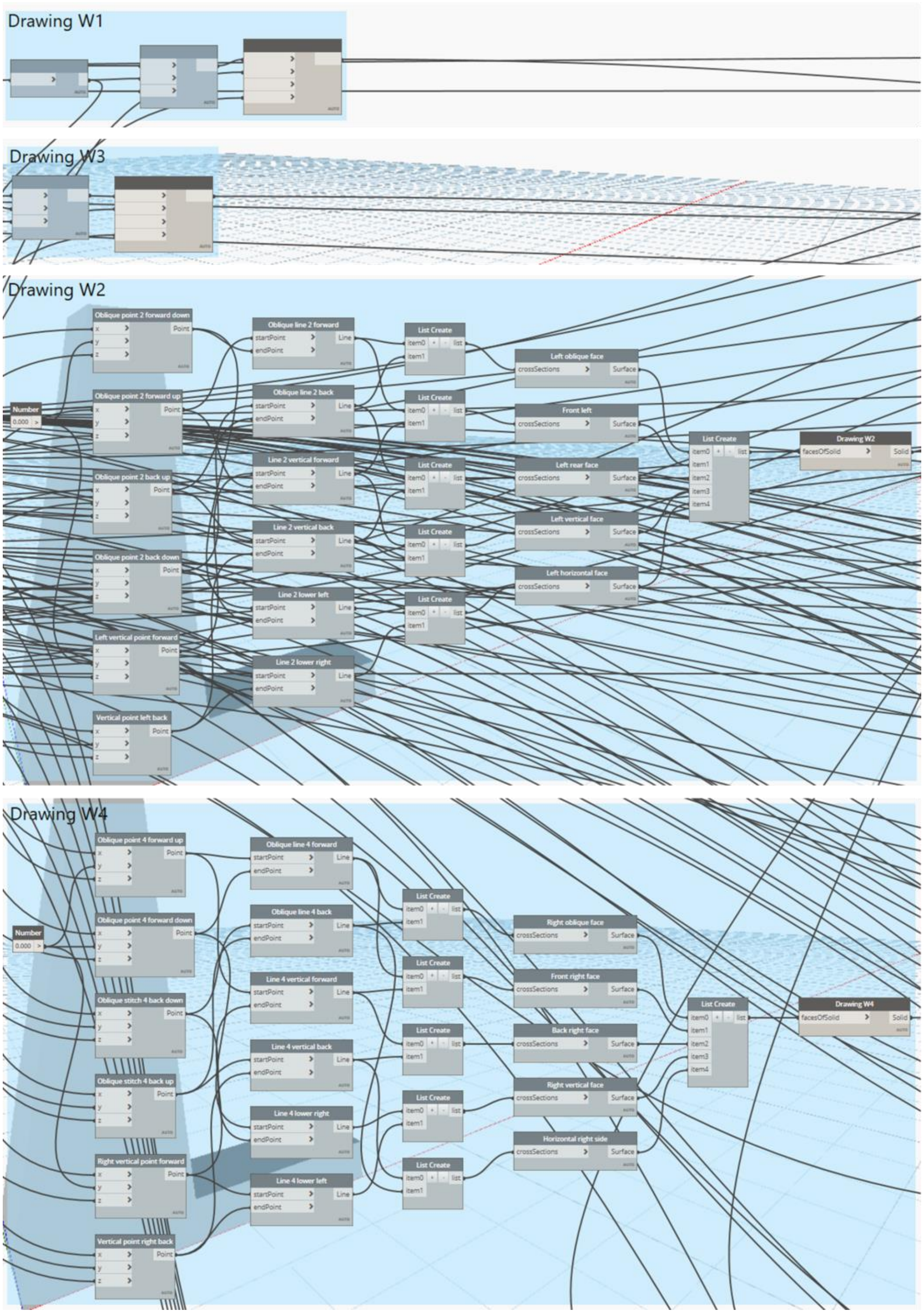


Figure 10. Code "(c) Modeling 3D wall" in Dynamo.

To finish this iteration, the code was checked to ensure that it worked parametrically, varying each dimension so that the 3D model would adjust according to these changes, as shown in Figure 11. Of the wall dimensions, the crown was restricted to a minimum of 0.30 [m] [25] with 0.05 [m] offsets for constructive reasons, while the other dimensions were proposed with a minimum of 0 and maximums between 2 and 5 [m].

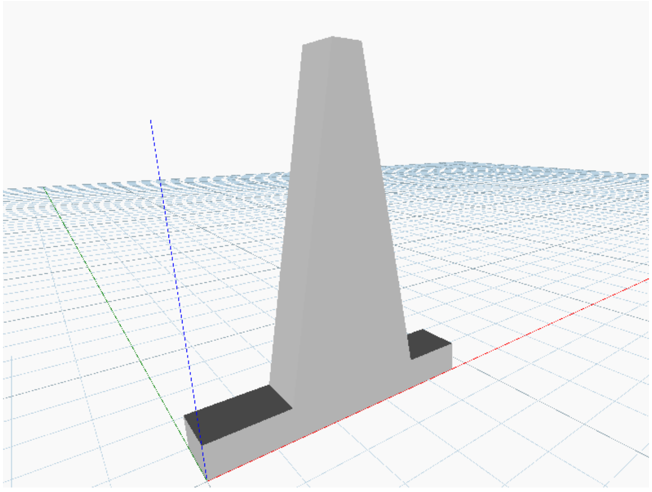
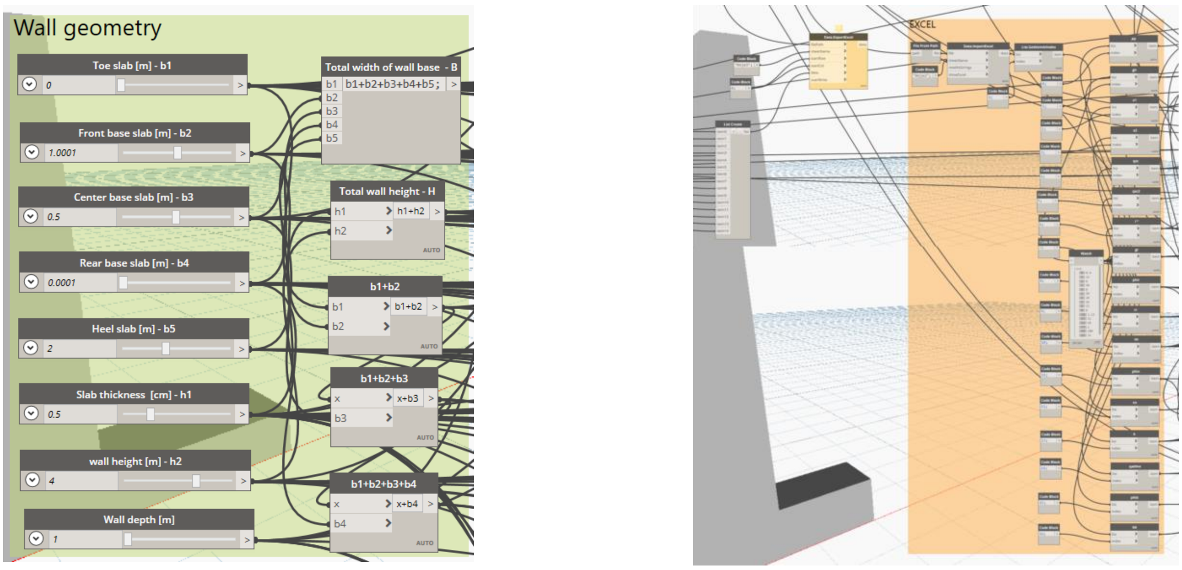


Figure 11. Building Information Model (BIM) of retaining wall at Dynamo.

Then, in the second iteration, the nodes representing the inputs that the user must fill in to start the program were integrated (Figure 7, box (b.1). Code in Figure 12a). It is worth mentioning that in order to make the code in Dynamo, an Excel file provided by a specialist engineer was used as a reference, which replicates the considerations of the current regulations and whose input data are (in brackets appears the denomination of the Excel file itself): seismic zone (A0), specific weight of concrete (γ_h), distances and value of overburden (x_1, x_2, q_{sc} and q_{sc2}), backfill angle (i), specific weight of backfill (γ_r), backfill friction angle (ϕ_r), cohesion of backfill (c_r), backfill height (H_r), natural soil friction angle (ϕ_n), natural soil cohesion (c_n), natural soil inclination (k), allowable base soil load, base friction angle (ϕ_b) and distance to fill (b_6). After an internal evaluation, these nodes were replaced by an Excel file (called "Inputs") that is derived from the same code and imports the data into Dynamo (Figure 13). The latter makes the system more user-friendly since, through the image shown in the spreadsheet, it is easy to understand what each variable represents (as well as its respective units), which makes it easier to use (Figure 7, box (b.2). Code in Figure 12b).



(**a**) (**b**)

Figure 12. (**a**) Code "(b.1) Entry of manual input data" in Dynamo. (**b**) Code "(b.2) Entry of input data from MS Excel" in Dynamo.

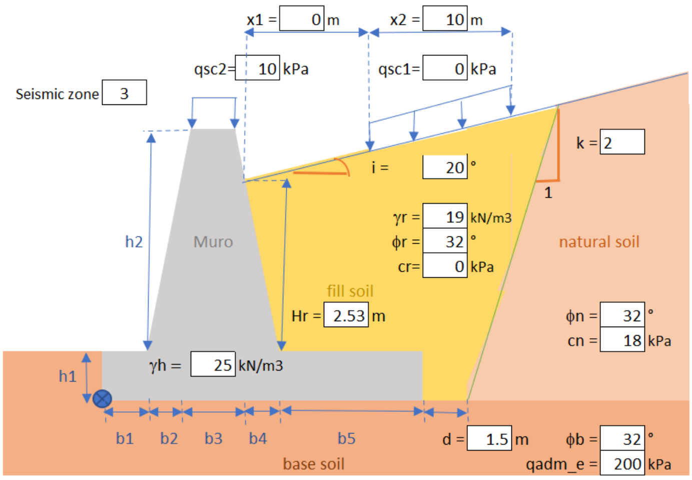


Figure 13. MS Excel "Inputs" to fill in the input data.

Once the model was completed, the third iteration was performed. In this one, the volumes were extracted from the same code to calculate the wall's weights and centers of gravity (using the data imported from Excel). The same procedure was performed with the backfill and the overburden (Figure 7, box (d). Code in Figure 14).

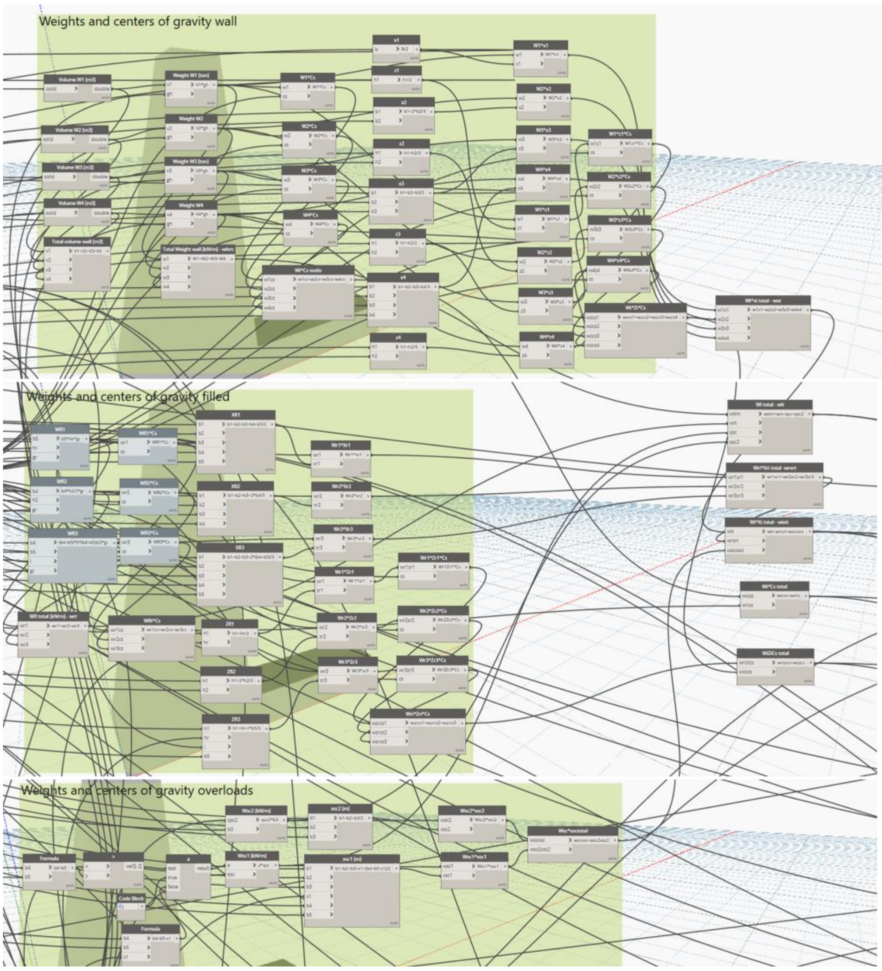


Figure 14. Code "(d) Calculation of weights and centers of gravity" in Dynamo.

At the same time, the parameters were corrected, and the K_e and K_s coefficients were calculated, in addition to indicating whether the slope where the wall will be built will present dynamic stability problems or not (Figure 7, box (e). Code in Figure 15). This parameter correction was performed to obtain the base cohesion (c*), base friction angle (ϕ*), unit weight of retained fill (γr), mobilized cohesion in the fictitious plane (Cf, which for design purposes was considered to be zero), and mobilized friction angle in the fictitious plane (δf), which was conservatively considered to be $\frac{1}{2}$*ϕr. With all these data, static and seismic soil thrusts were calculated, in addition to the presence or absence of tension crack (Figure 7, boxes (f.1) and (f.2). Codes in Figure 16).

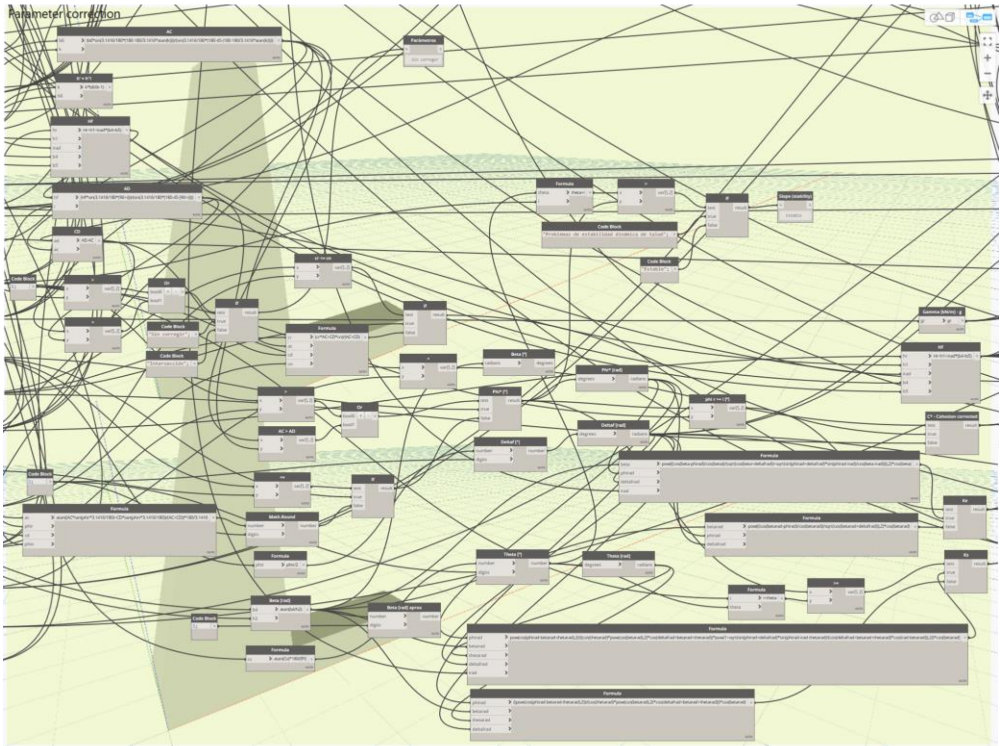
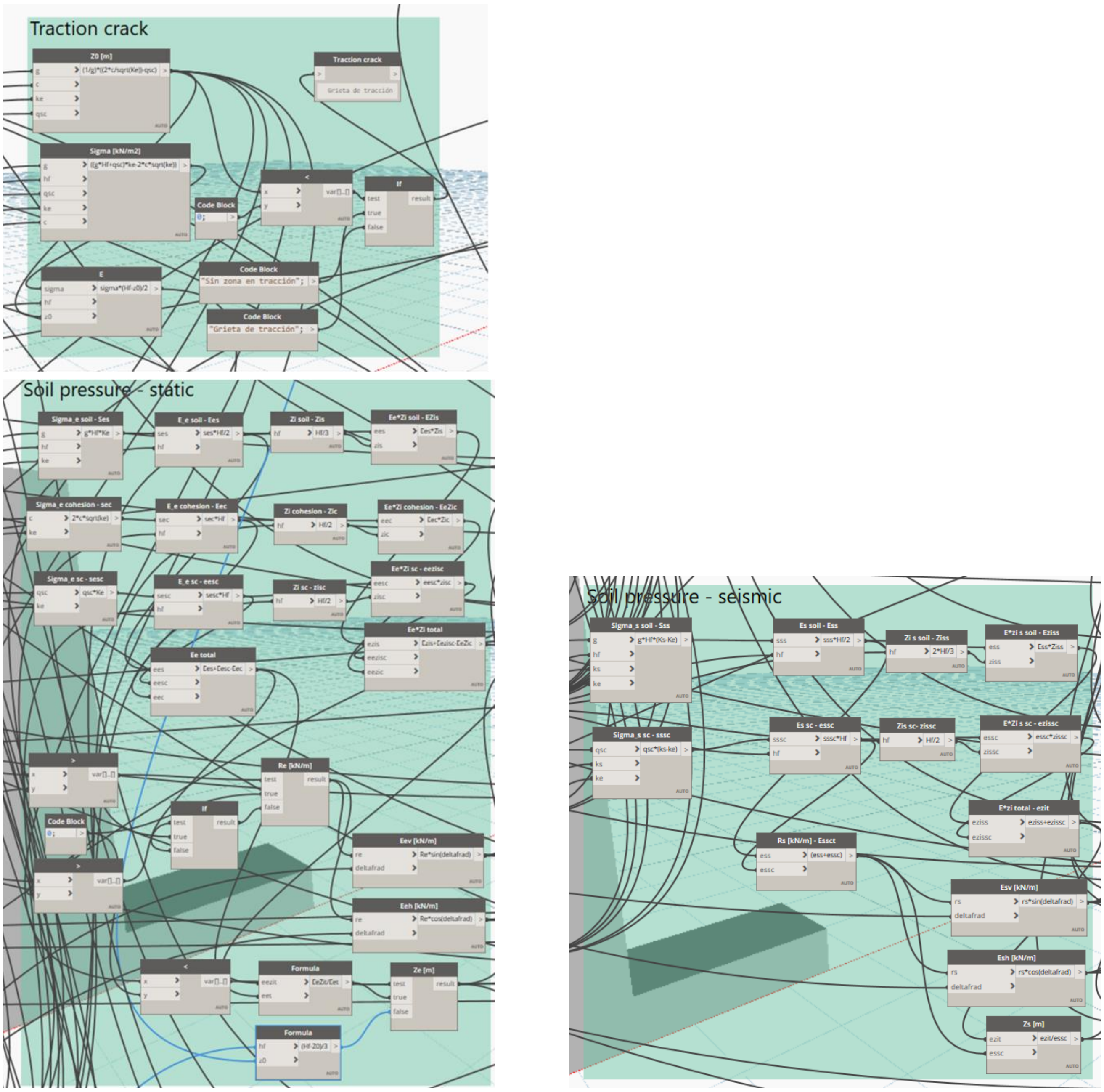


Figure 15. Code "(e) Correction of parameters" in Dynamo.



(**a**) (**b**)

Figure 16. (**a**) Code "(f.1) Calculation of static soil thrusts" in Dynamo. (**b**) Code "(f.2) Calculation of seismic soil pressures" in Dynamo.

The above variables are the base parameters to determine the thrust, resultant, and active soil pressure coefficient (K_e) according to Coulomb theory, as shown in Equation (3), where K_e is the active soil pressure coefficient; β is the angle generated between the wall and the vertical of the backfill.; ϕ is the design soil friction angle; i is the angle of inclination of the backfill soil; and δ_f is the mobilized friction angle in the fictitious plane.

$$K_e = \left[\frac{\frac{1}{(\cos\beta)} \cdot \cos(\beta - \phi)}{\sqrt{\cos(\beta + \delta_f)} - \sqrt{\frac{\sin(\phi+\delta_f)\cdot\sin(\phi-i)}{\cos(\beta-i)}}} \right]^2 \cdot \cos\beta, \quad (3)$$

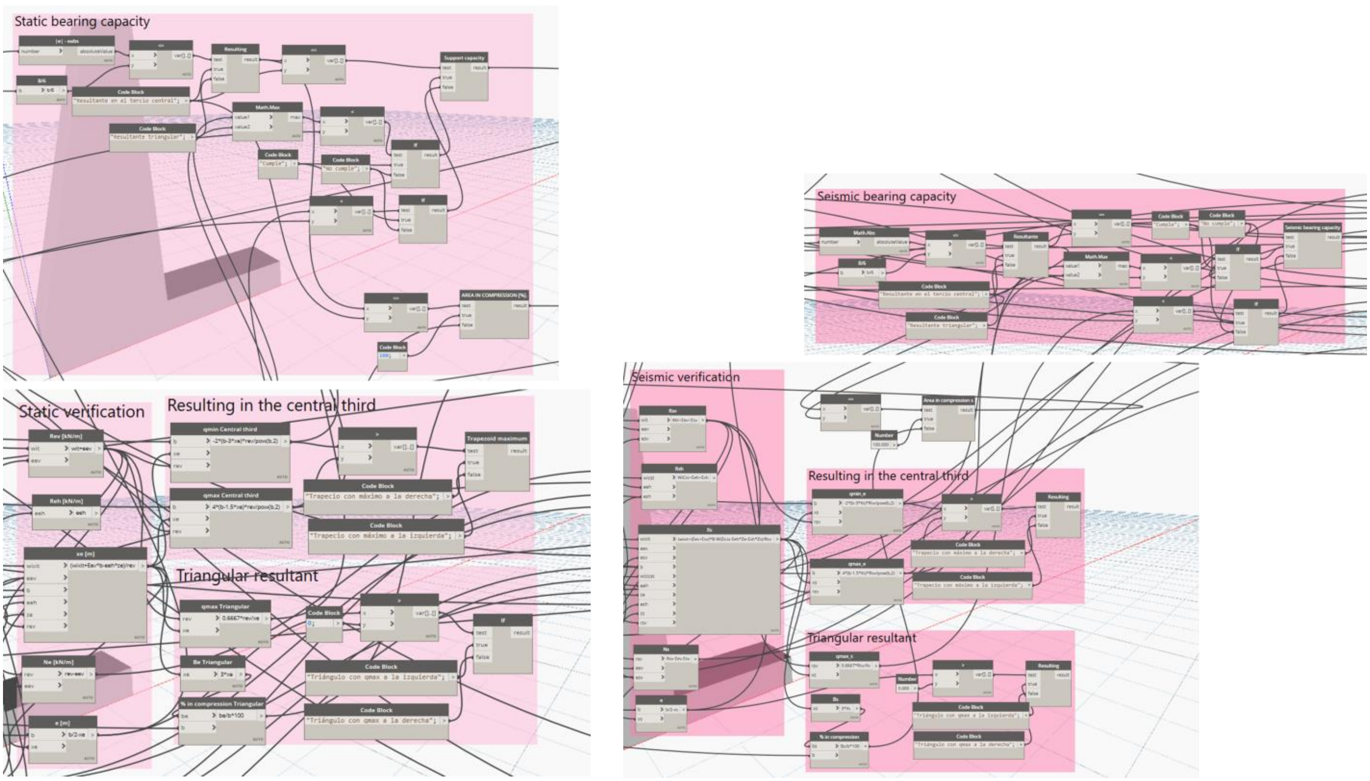
The design soil friction angle (ϕ) is calculated through Equation (4), where ϕ_o is the equivalent friction angle for zero displacement condition, ϕ^* is the equivalent base friction angle, and C_r is the retention coefficient (if $C_r > 1.0$, we used in the equation Cr = 1.0).

$$\phi = \phi_0 + C_r(\phi^* - \phi_0), \tag{4}$$

Additionally, Ks was calculated according to the Mononobe–Okabe methodology, as shown in Equation (5), where Ks is the seismic thrust coefficient; β is the angle generated between the wall and the vertical of the backfill.; ϕ is the design soil friction angle; i is the angle of inclination of the backfill soil; and δ_f is the mobilized friction angle in the fictitious plane.

$$K_s = \left\{ \frac{\cos^2(\phi - \beta - \theta)}{\cos\theta \cdot \cos^2\beta \cdot \cos(\delta_f + \beta + \theta) \cdot \left[1 + \sqrt{\frac{\sin(\phi+\delta_f)\cdot\sin(\phi-i-\theta)}{\cos(\delta_f+\beta+\theta)\cdot\cos(i-\beta)}}\right]} \right\}^2 \cdot \cos\beta, \tag{5}$$

Then, the static and seismic bearing capacity was verified with their respective areas in compression (currently equivalent to 80%, modifiable in the code according to the regulations), considering whether the resulting base soil was of the triangular or trapezoidal type (Figure 7, boxes (g.1) and (g.2). Codes in Figure 17). Finally, the different safety factors were coded; FSED, FSEV, FSSD, and FSSV (Figure 7, box (h). Codes in Figure 18). The evaluation of this iteration was carried out by comparing the results obtained by the reference Excel and the Dynamo code, whose differences in the safety factors were of the order of 1.4%.



(**a**) (**b**)

Figure 17. (**a**) Code "(g.1) Calculation of static bearing capacity" in Dynamo. (**b**) Code "(g.2) Calculation of seismic bearing capacity" in Dynamo.

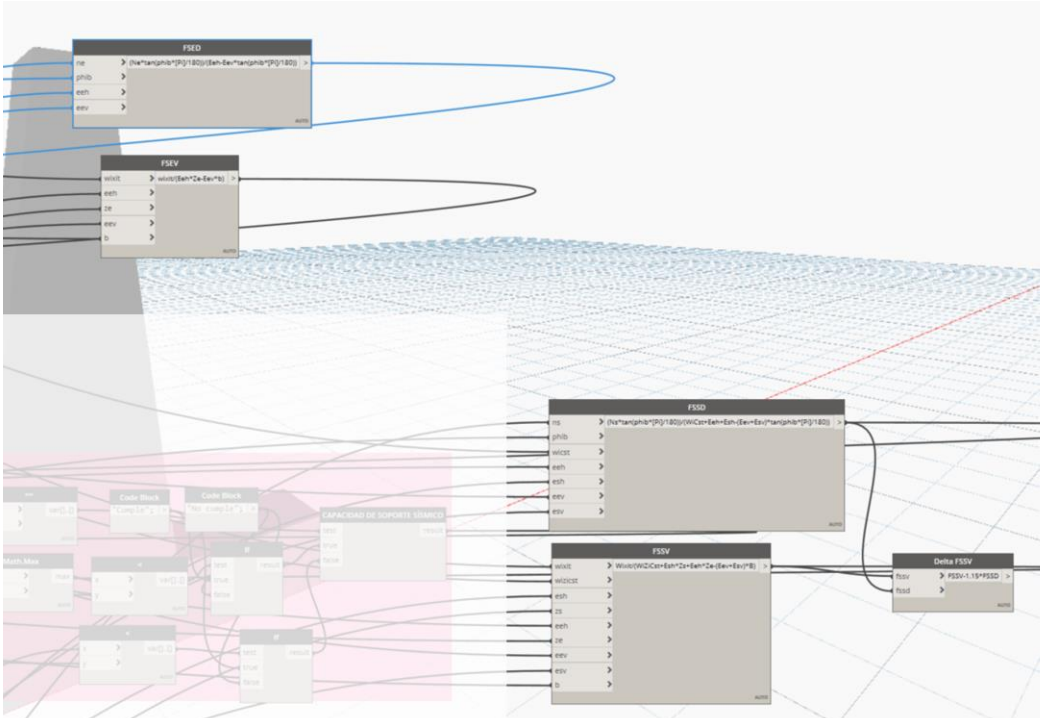


Figure 18. Code "(h) Obtaining factors of safety" in Dynamo.

The code developed in Dynamo up to this point could be used in the same way as the base Excel used, where the user entered the input data in the Excel " inputs" to obtain the safety factors, bearing capacity, and areas under compression (in addition to displaying the 3D model of the proposed wall itself). This would only be a parametric code that would follow the premise of the traditional design (Figure 2). It had to be transformed into a generative code to achieve the proposed objective. In line with this, in the fourth iteration, modifications were made to the Dynamo code to change the function of the nodes that involve wall dimensions (b1, b2, b3, b4, b5, h1, and h2), as illustrated in Figure 13, by the denomination of "Is input" so that these nodes would not function only as fixed numbers and, on the contrary, would be considered by the program as variables that it would modify to meet the goals proposed by the user (within the values that were already restricted in the construction of each one). The target values defined for this program were the safety factors, the total volume of the wall, and the area under compression since it is these variables that the sizing must meet to optimize. The target values defined for this program were the safety factors, the total volume of the wall, and the area under compression. These are the variables that the design must necessarily comply with to be optimized. For these targets to be considered, their function in the code was modified by the option "To be generated" since, in this way, the user will be able to restrict them later and use them as output data.

The first problem detected when evaluating this last iteration was the FSSV, since it does not have a constant minimum as the other safety factors because it corresponds to 1.15 times the FSSD; given this, the solution was to create another node that would serve to restrict this factor by subtracting the FSSV with 1.15*FSSD and then requesting that it be greater than zero. After some tests, it was seen that the program delivered solutions of low height walls, which, although they satisfied the mathematically established goals, did not fulfill the physical task of containing the fill since it passed over the screen. This was fixed with another node that restricted the situation where the screen height (h2) was at least the height of the fill (Hr).

With this, the code in Dynamo was finished, so it was passed to its Refinery complement, where it is possible to choose whether to optimize, randomize, or combine products.

For this study, the optimize tool was more useful since it allows us to minimize and maximize variables. Refinery uses a multi-objective optimization approach where the optimal solution is refined over series of generations for the defined population size. Then, it is asked which input data should be varied, and to this it is proposed to leave all the options already marked by default, which correspond to the dimensions of the wall that were defined as "Is input" (b1, b2, b3, b4, b5, h1, and h2). There may be a situation where the value of some of these variables is already known in advance (due to a site constraint), so they should be deselected in this step, and their dimension should be set in the Dynamo code. The program then asks what output data should be used as targets to be reached, giving as options everything defined as "Generated." At this point, it is recommended to minimize both the total volume and the four safety factors, as shown in Table 3. However, as in the previous step, another variable may need to be maximized or minimized.

Table 3. Input data to be restricted.

Variable	Select	Minimize	Maximize
Total volume	✓	✓	-
FSED	✓	✓	-
FSEV	✓	✓	-
Area under compression	-	-	-
FSSD	✓	✓	-
Delta FSSV	✓	✓	-
Height restriction	-	-	-

Finally, the program asks for the output data to be restricted, having to be filled in as indicated in Table 4. Additionally, the program by default asks how many "Population size," "Generations," and "Seed" it should work with. The first one by default comes in 20 but can be increased, always in multiples of four, and implies that in each iteration of "generation," which will be the number of alternatives that the program will consider, the second one is predetermined as ten and is the number of iterations that will be performed. The second is predetermined as ten and is the number of iterations that will be performed, and it can also be increased (depending on the capacity of the computer on which the program is run) in order to refine the results further. Finally, "Seed" refers to a number or vector from which pseudo-random values that will generate the options that will be evaluated in each iteration will be output; this number can be increased so that the delivered solutions vary more from each other. This information is relevant since, in internal tests, when modifying certain parameters, the program did not achieve satisfactory results, so that, to solve this problem, the default values (especially the number of generations) had to be increased so that the program could find solutions that complied with the restrictions proposed in each case.

Table 4. Output data to be restricted.

Variable	Select	Minimize	Observations
Total volume	-	-	-
FSED	✓	1.5	According to Highway Manual, vol. 3 [8]
FSEV	✓	1.5	According to Highway Manual, vol. 3 [8]
Area under compression	✓	80	According to Highway Manual, vol. 3 [8]
FSSD	✓	1.1	According to Highway Manual, vol. 3 [8]
Delta FSSV	✓	0	FSSV − 1.15* FSSD > 0
Height restriction	✓	0	The height of the screen must be greater than the fill height

Then, some input data values were proposed for one of the case studies tested by the research team, resulting in 12 retaining wall designs (Figure 19).

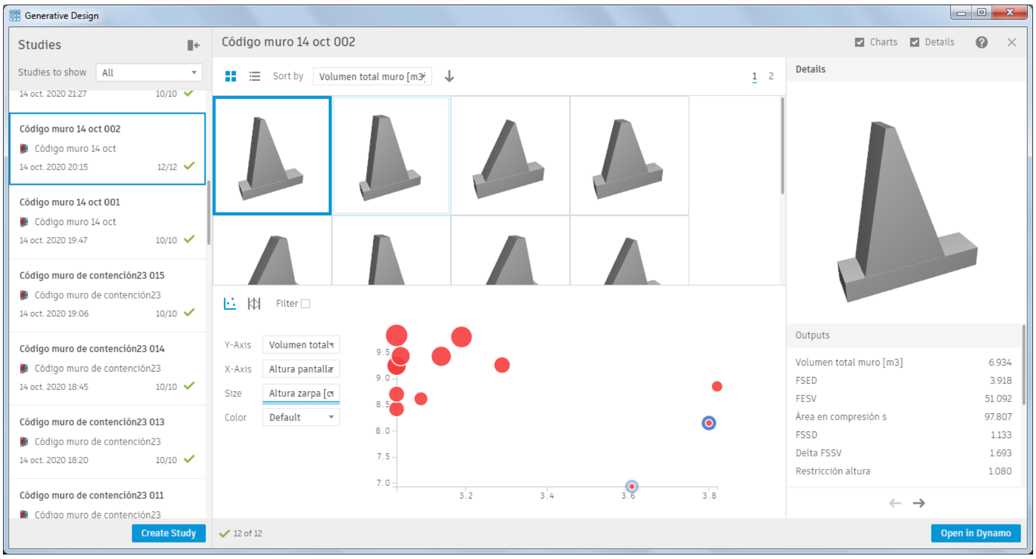


Figure 19. Optimization results with Refinery.

To complete the cycle, the Dynamo code was modified, adding certain nodes so that after selecting the most appropriate option in Refinery, the program could export the important data to the original MS Excel file where the input data were loaded, as shown on the right of Figure 20 (right); on the left of the image is the interface for filling in the input data.

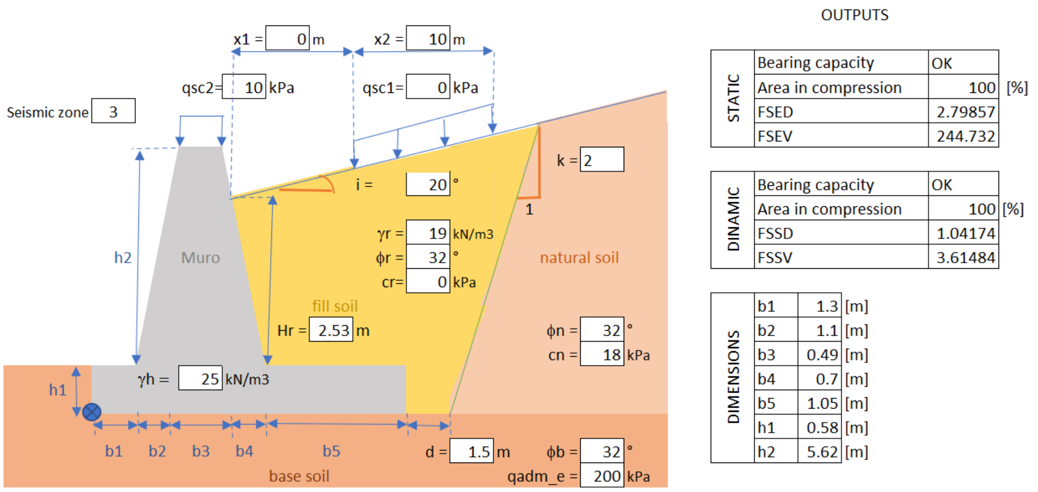


Figure 20. MS Excel Inputs/Outputs modified.

As a result of the iterations of the incremental software development process, and by adding the Excel "Inputs," the structure that had been proposed at the beginning (Figure 6) was modified, resulting in Figure 21, where the Excel file served as an intermediary between the different interfaces. Furthermore, it can be observed that this figure follows the same structure of the generative design presented in Figure 3, which indicates that, if the solutions obtained do not comply with what they should, the code or the rules that gave rise to it would have to be changed and not the original idea. In addition to what is presented here, a user's manual for the program was prepared to support the following stage. This manual presents the general operation of the program, how to open it, how to enter the data, and how to obtain the solutions. In the Supplementary Materials, three files are provided to use this methodology: first, the Excel file to import and export data; second, the Dynamo code for the design of the retaining wall; and third, a user's manual to apply the methodology.

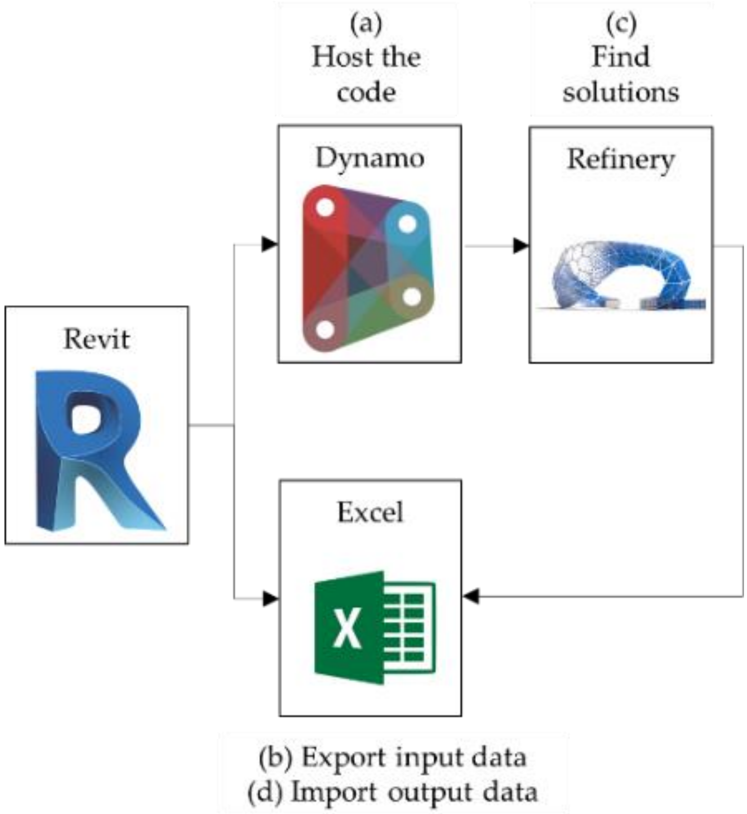


Figure 21. Modified Revit-Dynamo-Refinery link diagram.

3.3. Verification and Validation—Usability Tests

Before performing the actual user tests, the program was evaluated with two users (different from those of the post-test), where the most significant problems of the program were detected and fixed early on. Then, the authors conducted usability tests that were performed with five users, since with this number, 90% of the usability problems of the program can be discovered [26]. First, we conducted a previous survey to understand the basis features of the group of users. The survey's results reported that the test users are civil engineering graduates; all of them had used Excel, 80% Revit, and only 20% Dynamo. None of them were familiar with the use of Refinery. Regarding generative design, 80% had limited knowledge of it, while the remaining 20% were completely unfamiliar with it. Regarding the design of retaining walls, 60% rated their skill as "basic" and the remaining 40% as "average."

For the tests, users were asked to perform seven tasks that represent fundamental parts of the program, which are indicated in Table 5 and were: open the corresponding Revit, enter input data in the Excel "Inputs," create the generative design study, choose design goals, choose the appropriate constraints (regarding Tables 3 and 4), create solutions, and finally, obtain output data. Before this, participants were asked to verbalize the entire mental process as they performed the requested tasks to account for how complicated or easy each task would be for them. The results of how long it took on average for users to complete the seven tasks are presented in Table 5. It should be noted that these times include how long the software took to open, change tabs, and process any action in example 1 of an equation.

Table 5. Average execution time for each task—user test.

Task	Average Execution Time [minutes]
Open corresponding Revit file	5
Enter input data MS Excel	2
Create generative design study	2
Choose design goals	1
Choose appropriate constraints	2
Create solutions	5
Obtain output data	6
Total	23

The users, through their comments, expressed feeling well guided by the program throughout the process, highlighting as the only complication the absence of more specific indications in some tasks (a problem that was solved at the end of the tests). It is worth mentioning that, in the five tests performed, only one participant had problems in finding the final data, since, with the number of iterations that the program brings by default, it was not possible to reach a valid proposal; in response to this, the evaluator explained how to change this limitation to finish the process. Finally, this section was included in the user's manual, as discussed in Section 3.2 of this research.

After these user tests, an exit questionnaire was carried out, with both open and closed questions, to find out their opinions about the program, with the result that 60% of the participants were able to complete the tasks set "very easily," while 40% were able to do so "easily," and 60% of them felt "oriented" while navigating within the program. In comparison, 40% felt "very oriented." The satisfaction with the program made 80% consider it "very satisfactory," while the other 20% thought it was "satisfactory." When asked if they would use the generative design retaining wall sizing program again, 100% responded that they "strongly agree".

On the other hand, in the open questions, they were asked to share what they found most difficult about the program, finding as a common concept in the answers the fact that there was no particularly difficult task to perform. It is suggested that some functions could be better signaled since many windows and tabs are open to work (Revit, Dynamo, and Excel), in addition to the fact that it was the first time that some were in front of these interfaces. On the other hand, in the aspects they liked most about the program, they highlighted the delivery of the different results in a clear and visually pleasing way. In addition to the dimensions, the 3D model of the options provided by the program can be observed. When asked about what aspects the program lacks, it was suggested that it should be more detailed about what each of the processes represents. It should try to combine all these interfaces into a single one to avoid moving from one to another.

Concerning the advantages of designing walls over the traditional ones, the saving in the manual iterations that should be performed to reach satisfactory results was highlighted, including the fact of being able to choose among several options according to the situation of each project. On the other hand, as disadvantages were highlighted, on the one hand, the fact that, in order to choose among these options, an engineering criterion must be developed, and on the other hand, concern was expressed about the software that houses the program, since it is believed that not all companies can afford it or have adequate computational capacity.

4. Conclusions

First, regarding the research methodology, DSR was considered adequate to clarify the processes involved in developing a program. In conjunction, the incremental method was established as a relevant complement to creating a generative program, of which no clear information was found on its development, as we only found research on its direct application. Therefore, this research serves as a basis for others to develop their applications with generative design, regardless of the area in which they work.

Through this research, it was possible to show how generative design emerges as an alternative to the traditional design of retaining walls, since it showed a concrete use of generative design in civil engineering, with advantages such as saving design time, the multiplicity of alternative solutions, and also the option of choosing the shape of the wall that needs the least amount of material possible to be built and meet the restrictions proposed by the user, which will cause a decrease in the cost of the structure and CO_2 emissions by the generation of the same. Additionally, the authors can conclude that it is possible to apply generative design for the design of structural elements in the AEC industry; however, this requires a high compatibility between analysis and modeling software, which can be solved using visual programming tools that include software aligned with the BIM methodology. In addition, with this methodology, it is possible to evaluate different options delivered through complex optimization methods, which should be complemented with multi-criteria decision-making analysis.

Responding to the research questions presented, it can be said that the developed software complies with the requirements of the current Chilean regulations (highway manual, volume 3) [8]. This design is performed in a fast and user-friendly way, considering the fundamental parameters of each project, and obtaining, as a result, the complete dimensioning of the wall and the necessary verifications to guarantee its stability—in this case, safety factors, support capacity, and areas in compression (both static and seismic). This program is adaptable to the requirements of each country or a specific project since the general structure of the wall design is already established in the code; therefore, to modify, eliminate, or add any variable, it is not necessary to redo the whole program, but only that specific part.

The above aspects were validated in user tests. The participants of these tests positively highlighted the fact that the program is easy to use even for people who do not know or know very little about generative design and Revit, Dynamo, and Refinery software. Likewise, for the users, this way of dimensioning retaining walls does present an improvement over the traditional one, mainly because of the savings in the manual iterations necessary to arrive at an adequate solution, given that, on average, the process was completed in 23 min, as well as in the variety of these proposals. These last characteristics are the main advantages of the generative design found in the literature and are confirmed in the initial evaluation. Even though this research was based on the dimensioning of retaining walls, it favors the understanding of this new design process in general. On the other hand, one of the negative aspects mentioned by the users is the cumbersome use of several windows in the use of the program. This could cease to be a complication since, during this study, the Revit software (version 2021) included a generative design section in its interface without the need to jump to Dynamo and Refinery.

The program created will be useful for civil engineers and construction companies with little experience in designing walls to optimize the dimensioning process and quickly find an adequate solution. It is worth mentioning that, in order to use the program developed in this research, it is necessary to have the license of the Excel and Revit programs (either student or professional) and download the Dynamo and Refinery add-ins (which can be obtained for free if you already have the Revit license); in addition, you must have the files that are attached in the supplementary material: Dynamo code, Excel "Inputs", and the user's manual.

To further validate the developed program, it should be tested with more experienced retaining wall design professionals to see whether it improves their professional practice. This was not conducted because, in this case, given their advanced knowledge, it would be appropriate to teach these users to modify the code for each of their projects (and not only explore it) and thus demonstrate the adaptability of the program to people with different levels of expertise in retaining wall design.

As future lines of research, it is recommended to include steel reinforcements in the presented model, which in a seismic country such as Chile are indispensable. This aspect is easily programmable in the code, functioning as a new variable to be considered in the analysis. In addition, this design process should be explored and analyzed to see its possibilities, limitations, and possible connections with the BIM methodology. Likewise, it is recommended to use generative design in other civil engineering applications that depend on traditional iterative design, such as steel connections, whose characteristics are suitable for coding, or other aspects, such as the optimal positioning of buildings in previously realized topologies. In addition, from the point of view of usability, it is recommended to perform an exhaustive analysis based on heuristics, both with those of Nielsen and some of our own created specifically for generative design, since, at the time of this study, no heuristics were found in the literature.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/math9161918/s1, Excel inputs-and outputs—retaining wall; Dynamo code—retaining wall; and User manual—retaining wall.

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