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Master Project:
Climate neutral and circular buildings through digitally enabled framework

Stage 2

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1 Introduction

1.1 Context

Flexilibres is a circular, eco-friendly and flexible approach to Equilibres, a building to be constructed at Höngg, ETH Zürich.
The aim of this project is to create an inspiring, out of the box case study of how to optimize Equilibres for circularity. The design shall integrate innovative market solutions and technologies. The focus was set on zero energy systems and indoor comfort (role 1), zero embodied emissions and material sourcing (role 2), circular industrialized system and product integration (role 3), and digital asset management and BIM visualization (role 4).
The aesthetics and economic viability of the design were not major focuses of this project.

1.2 Vision

To understand circularity applied to the building context, we started with analysing the supply chain of Equilibres and identified two maijor aspects:

1. The materialization of components is crucial for circular applications in the building context.

2. Components need to integrate flexibility to enable reuse.

These two aspects are outlined in the material flow diagram in figure 1.1. The smallest reuse cycle (reuse within Flexilibres) is preferred over the larger reuse cycles (reuse within the built environment). Additionally, the building shall fulfill the requirements for a Net Zero Carbon Building.

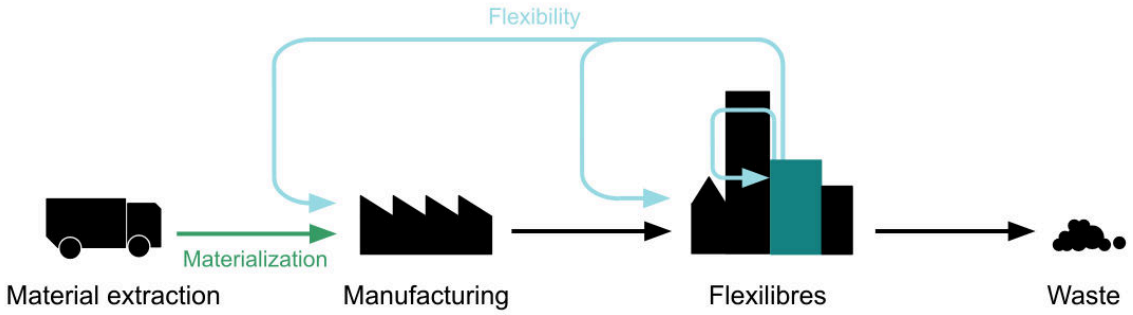


Figure 1.1: Vision of circularity and their aspects for the design of Flexilibres.

The resulting vision is:
We introduce circularity to a Net Zero Carbon Building, by maximizing environmentally beneficial materialization, and the flexibility of the design.

1.3 Framework for design choices

The three major aspects of our vision, Net Zero Carbon Building, materialization, and flexibility were researched. The findings were collected to form specific criteria for design decisions. The result is a framework, that was used for design choices (Figure 1.2).

Aspects	Criteria
Net Zero Carbon Building	**Negative or zero emissions** ability to store or offset more carbon emissions than produced for the construction and operation of the building
Materialization	**Dematerialization and organic material use** ability to minimize the usage of materials with net negative environmental impacts and maximize the usage of materials with a net positive environmental impact
	Material lifespan ability to maximize the lifespan of the material, prefered in the following order: reused and designed for reuse, refurbished, remanufactured, recycled
Flexibility	**Separation of building layers** ability to provide a functionality within one of the following building layers only: structure, skin, service, spaceplan, stuff
	Simplicity of system ability to provide a functionality with as little components as possible
	Network design ability to add new nodes or make new connections between nodes
	Building design ability to adapt to the complex and changing requirements of the users

Figure 1.2: The Framework for design choices, based on the vision.

2 Working Process (collaboration)

Collectively, we designed a framework of an iterative design process to follow (Figure 2.1). In each phase we would increase the level of detail (LOD), starting with an LOD100 model. Each phase would start with the development of superior concepts, followed by the development of detailed concepts, a discussion on the concepts, an analysis of how to integrate the concepts in the model, the model creation, a validation, and finish with an analysis of the model.

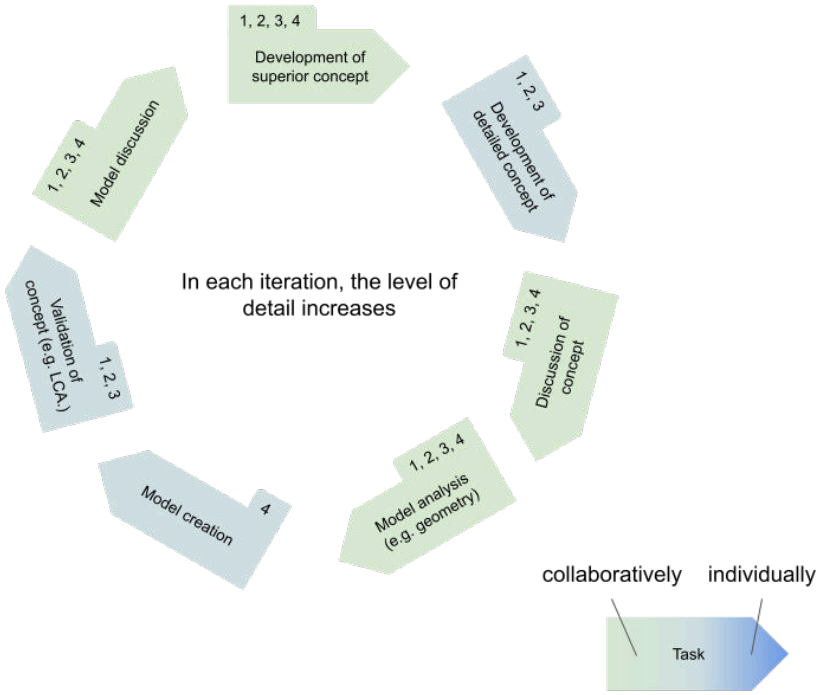


Figure 2.1: Framework for the iterative design process the team decided to follow. The numbers correspond to the roles (from 1 to 4) involved in the process.

The framework guided us through the project and clarified on the contribution of each role. Furthermore, it reinforced the collaboration where we agreed on its importance. In figure 2.2 the overall design process is mapped to the process of the framework.

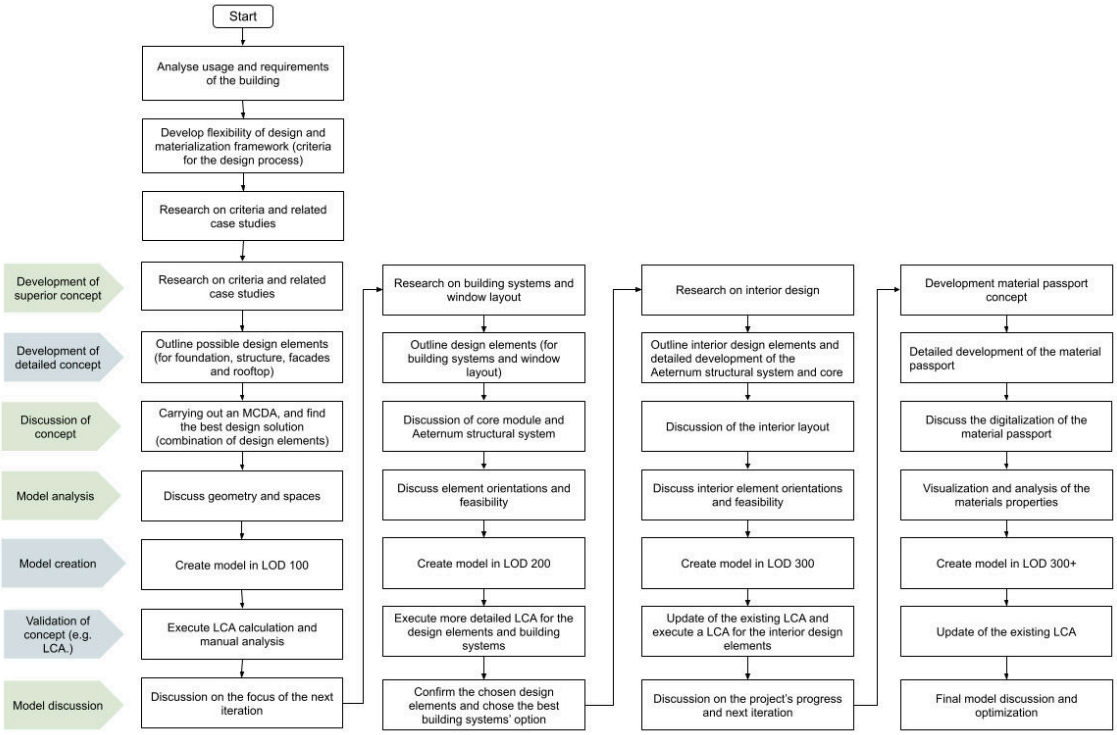


Figure 2.2: Documentation for the design process, following the framework. The four design phases build one column each.

Already in the first phase, it became apparent that the framework oversimplifies the design process for the following reasons:

1. Some concepts could not be planned with a top-down approach, starting with lower LOD and adding details in future phases. Therefore, at some points, processes were started prematurely or finished with delay.
2. The design process included multiple iterations of one to a few processes. This way, not only the overall process in figure 2.1 was repeated for each phase, but processes were repeated within one design phase.

During the design process, following the framework, we identified synergies and compromises of the four roles. An explanation of each role's perspective is outlined in the following sub chapters.

2.1 Collaboration: Perspective of Role 1 (Alex Albertini)

Collaboration was one of the major aspects of this project, also for the role of the "Energy Systems & Indoor Comfort". Having four roles and therefore also four different points of view allowed us to integrate our backgrounds and come up with innovative and very detailed solutions thanks to everyone's contribution.

Each choice could not be made by analysing only the own role and scope, but had to be analysed and discussed with the other members in order to make the best possible decision in

the overall picture. This process, as can be imagined took much more time and effort than a standard decision-making mechanism, because as the details increased, so did the analysis and collaboration with the other roles, but I personally find that the result was worth the effort.

My role in particular was in close contact with Role 2 of Matteo Jochum, as every choice or decision had to be based on a careful analysis covering a whole Life Cycle Analysis (LCA), so with the increased detail, during the project, the collaboration increased considerably and system choices were influenced not only by operational aspects but also taking into account embodied emissions.

Another key aspect was the collaboration with Role 4, as the simulations on the cove.tool software, which we will see later, require a BIM model with some adjustments due to the software. This required dialogue and modifications to the model in order to have the most accurate simulations possible, e.g. the implementation of different window-to-wall ratios configurations and the associated different operating results.

Finally, the collaboration with Role 3 was mainly based on the implementation of a material passport, which naturally depends on the choices made during the simulation and modelling phase. In addition, I must personally thank Florian Schmid, from Role 3, for his help with his knowledge of building systems, as this was a completely new subject for me and we always had very constructive discussions when questions arose.

2.2 Collaboration: Perspective of Role 2 (Matteo Jochum)

On behalf of role 2 "material sourcing and zero embodied emissions" collaboration was the key to success. After an initial phase based on collection of ideas and consequently sourcing materials whose would suit our needs the most, I had to face assessment and further optimization phases with the previously collected ideas. In order to get the best out of it, I constantly needed inputs from the others team's member. By doing so each member's perspective of the project was considered equally and it was possible to design a building that would be equilibrated and respect every aspect, avoiding perhaps to involuntary favouring the own preferences. Even if the dialogue with the other roles was luckily characterized by constancy and continuity during the whole duration of the project, there were some key moments that I would like to highlight in the following lines.

The collaboration with role 1 (Alex Albertini) was essential for the initial material sourcing phase since we were both in search of the best materials for the construction and the building systems available, as well as later during the life cycle assessment and optimization of the building systems. Role 3 (Florian Schmid), after being crucial in setting up a common understanding and strategy of the project, he provided the additional properties of the materials and design elements that we had to maximize. These material properties were then integrated into the material passports, therefore we had to take them into consideration already during the early stages of the project. For example, not only consider the embodied emissions as parameter for the material choice but also the life span or the reusability potential. Finally, the collaboration with role 4 (Parham Z. Nobari) resulted decisive at the final stages of the project, where the design elements and components had to be adapted to the BIM model. Hence, there was the

possibility to carry out the final optimization of the components and to assure that nothing was missing.

2.3 Collaboration: Perspective of Role 3 (Florian Schmid)

Generally, I see the collaboration of the different roles as an important part for the success of the project. The different perspectives made the project more interesting, and reasoned. Responsible for the integration of circular industrialized systems and products, I had frequent touch points with all three other roles. Working with the other roles, I identified multiple synergies between the roles, of which the most important are listed as follows:

1. With the different perspectives on the project, each role brought different insights to the team. Therefore, decisions would take more time, but are at the same time better thought through.

2. All four roles seemed to be interested in reducing the complexity through a repetitive, and modular design. As a result, the other roles took up my ideas for the integration of circular industrialized products and systems and often saw benefits for their own perspectives too. Additionally, the repetitive and modular approach simplified the collaboration with role 4, since a Revit-family based modelling approach could be used.

3. The different roles felt responsible for different aspects of the design. As a result, a more realistic building was designed without major components of functionalities missing.

However, some compromises of the roles and their perspectives occurred too, of which the most important are listed as follows:

1. The expertise of each role was not needed evenly distributed over the four design phases. Instead, the interests of each role was concentrated to one or more phases. Therefore, at different stages of the project, different team members formed a bottleneck.
   As an example, my contribution was needed especially in the LOD100 phase, to set up a common understanding and strategy of the project, and in the LOD300+ phase, to create the material passport. In the LOD200 phase on the other had, the energy performance analysis of role 1 and the LCA of role 2 were much more time-consuming then the tasks I was responsible for.

2. The roles needed different levels of detail for their analysis. Even in the phase LOD300+ there was a discussion between the roles on the level of detail certain components should be defined for.
   As an example, the timber frame filled with straw, which is part of the facade component, was defined as two materials. However, in discussion with role 2, we decided to model it as one material only because the manufacturer provided accurate LCA data for the compound of the two materials.

3. During the project I needed information from all my teammates and I provided information to all my teammates at the same time. This bidirectional flow of information sometimes lead to miscommunication and errors in the design process.

The following strategies helped me to manage the complexity of the project, and the compromises of the roles in a structured way:

1. Our vision and the framework helped me to streamline the design criteria from all the roles. At the same time it was a method for me to stress out the importance of circular industrialized product and system integration and its benefits for the other roles.

2. The material passport Excel file was a collaborative effort to collect data. I asked the other roles to add information to the file where they felt responsible, following the predefined scheme of the table. This method streamlined our understanding of the components and served as a template for the LOD300+ model.

2.4 Collaboration: Perspective of Role 4 (Parham Z. Nobari)

Collaboration was my central task as a digital asset manager. In essence my job boiled down to two main tasks and deliverables: translation and communication.

1. Translation: Throughout all design phases I was tasked with creating a centralized digital model in order to capture the design decisions our team came up with. This translation of implicit and explicit design decisions was not a one-way road but as the level of detail (LOD) increased throughout the design phases, it demanded an on-going dialogue and close coordination. The translation task was mainly carried out in the Autodesk Revit commercial BIM software, either through imported families or through manual family creation.

2. Communication: The concrete benefits of a realistic, detailed and information-rich digital model are contingent on how clearly that model is communicated. Therefore, my second task which was built upon the previous task was to create a platform which accommodated the clear communication of the design to all team-members and involved stakeholders. Communication of the model was accomplished on the Autodesk Forge platform which offers APIs and services that facilitate access and use of the BIM model's design and engineering data via the cloud.

Given how the work process discussed in section 2 was structured around the LOD levels, the work-load and the level of input that I had to extract from my teammates in order to be further incorporated in the model kept increasing in an over-proportional manner with higher LOD levels. The following is a ranking of the roles I most collaborated with:

1. Role 3 (Florian Schmid): Florian's input was instrumental in the first and last design phase and happened to be the role I most collaborated with. In the first design phase, Florian and I layed the ground-work for how we envisioned the working process structure to be, and also how we intended to use the BIM model for further analyses. In the last design phase, Florian constructed the material passport excel file and kept track of the changes to the material passport and communicated them to me so I could update the BIM model. Florian was also the main architect of the Autodesk Forge visualization and filtering parameters and organized our thoughts surrounding our vision communication.

2. Role 1 (Alex Albertini): Alex provided a lot of input in the second design phase and throughout the third design phase. There was a continuous exchange of ideas about the choice of energy and indoor comfort systems in the second design phase, which were not represented in the LOD200 model. Furthermore, in the second design phase, I modified the LOD200 model to create different variants with differing window to wall ratios on each side. Alex ran an energy optimization analysis on these variants and came up with the optimal window to wall ratio. In the third design phase, Alex provided me with external Revit families for the energy systems which minimized the need to manually create Revit families from scratch. I also played an active role in the definition of a few indoors comfort systems, namely the lighting and elevator systems.

3. Role 2 (Matteo Jochum): Matteo's input was mostly understood through the third and last design phases in which I was focused on creating and configuring the building interior and exterior elements in higher detail. He would have an oversight over the material choices within each element and would give me guidelines regarding component and family design. Furthermore, given his structural engineering background he would also provide me with valuable input regarding the structural feasibility of some of the Aeternum system components whenever there was an architectural and space constraint imposed on the design, for example, the arrangement of the columns in the underground levels of the LOD200 model and in the third level (OG3) of the LOD300 model. Matteo also played a central role in providing me with highly detailed wall panel (both interior and exterior), module box and foundation structure schematics.

3 First Design Phase

3.1 Analysis of the proposed building

At the beginning of the first design phase the proposed project "Equilibres" was accurately analysed, keeping in mind the vision formulated in chapter 1. Since flexibility was one of the main team's goal, it was noted that the internal space could be optimized. As a matter of fact, the internal space is going to be used by many different institutions but nevertheless not all the time and especially not all at the same time. A reduction of the internal surface resulted therefore feasible if the internal space could be used in a more flexible way. A great example is the design of the two big lecture halls, whose can be used as an open-space room for the student for studying whenever they are not needed for teaching, simply by rotating their internal walls. As it is to be seen in figure 3.1 the biggest change to the proposed project is the removal of the cantilever section of the building, which implies the biggest reduction in walkable internal surface as well.



Figure 3.1: On top the proposed building, below the modified one, without the cantilever.

3.2 Finding design elements

After having formulated the vision and the working strategy of the team's member in the previous chapters 1 and 2 and having briefly modified the main shape of the building, the first design phase went on by studying the architect's plans of the proposed building. The plans have been critically analysed and the elements which composed the proposed building were divided into four main categories, mainly: Foundation, structure, facades and rooftop. For each category the following feasible solutions (which are called " Design Elements" for the sake of this project) were proposed. In order to be feasible, design elements had to respect all the flexibility and materialization criteria accordingly to the framework developed.

3.2.1 Foundation

Since there are no infinite suitable materials to use for the foundations, for both initial proposals the idea consisted of foundations made of concrete. In particular an option which presented the use standard in-place concrete and an alternative with the use of precasted concrete elements. After further research the team decided that the combination of the two concrete foundation system suited the best the needs of the building, also given the availability of the materials and the vast customization that the combination of the two can provide. A great solution could be the use of in-place poured concrete for the lower part of the foundations and precasted elements for the upper par, as the one showed in figure 3.2 below.



Figure 3.2: Left: in-place poured concrete for the strip foundation. (Source: wlbau.ch) Right: precasted concrete wall elements. (Source: knecht.de)

3.2.2 Structure

Similarly to the "Equilibries" building, the concept of building the superstructure made of timber was well appreciated. This construction method would guarantee a lightweight structure and therefore less materials (concrete) would be needed in the foundations, sustainable and local material choice with low production and transport emissions and finally, the possibility to reach carbon negativity due to the high quantities of CO_2 stored in the timber elements. The first proposed design for the structure of the building was Aeternum. It is basically a modular

construction method which involves the use of only two main elements for the whole structure: timber columns and grid-made timber slabs, whose are displayed in figure 3.3.

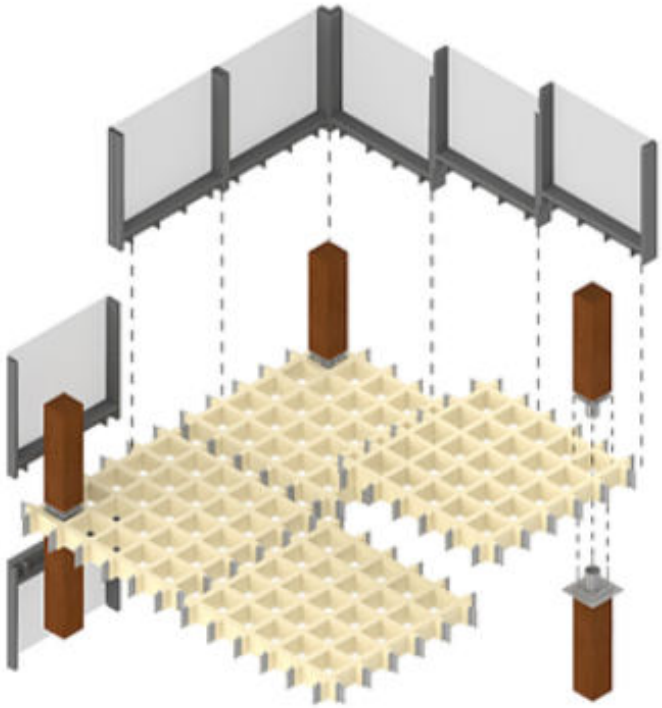


Figure 3.3: Aeternum structural system. (Source: aeternum-tech.com)

The second design option proposed was a standard timber frame structure (figure 3.4) which could host timber modules.



Figure 3.4: Timber prefabricate modules that ca be hosted in a timber frame structure. (Source: lehmann-gruppe.ch)

3.2.3 Facades

Again, also for the façade two design options were proposed: EcoCocon and EcoCell panels. Both are innovative prefabricated facade elements. EcoCocon, as it can be seen in figure 3.5 consists of a timber frame panel with straw insulation. The panel is than coated with clay plasters and wood fibre board. The second façade design element, EcoCell, is composed of two wood boards and in between the insulation is provided by a honeycomb made of recycled paper. An image of EcoCell can be seen below in figure 3.6.



Figure 3.5: EcoCocon timber-straw panel. (Source: ecococon.eu)

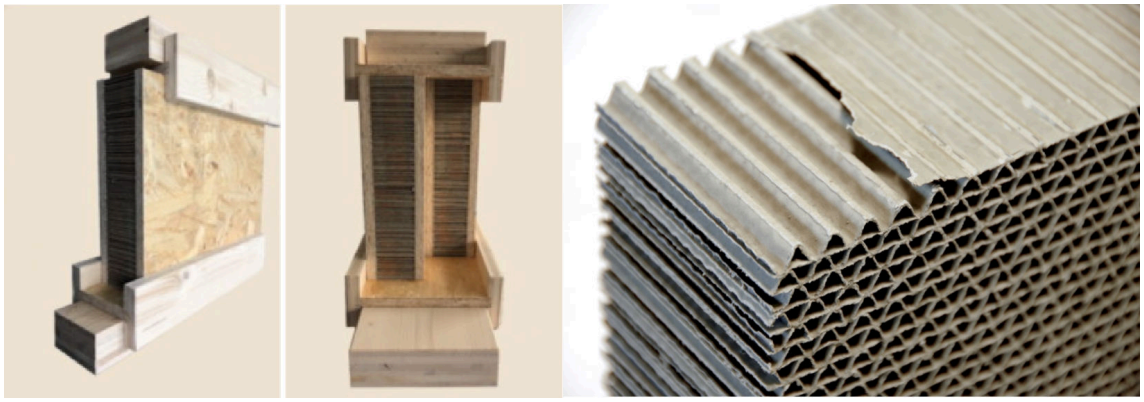


Figure 3.6: EcoCell timber-recycled paper panel. (Source: ecocell.ch)

3.2.4 Rooftop

The rooftop is designed as an open-space and outdoor floor, suitable for enjoying the break time in between the lecture hours. Being outdoor there is the need of having a pergola, which additionally to shading and protecting from the rain can be used as support for a photovoltaic system as well. On the ETH campus of Hönggerberg there are provisional buildings with drawing

rooms for the architects whose are soon going to be dismantled. Therefore, there is the great opportunity to reuse the timber elements of those buildings for the construction of the pergola. An example of the timber element to be reused can be seen in figure 3.7. The chosen alternative to this first option is a prefabricated pv-pergola made of steel, where the pv-panels are integrated in the roof of the pergola. In figure 3.8 the components of this design element are represented.

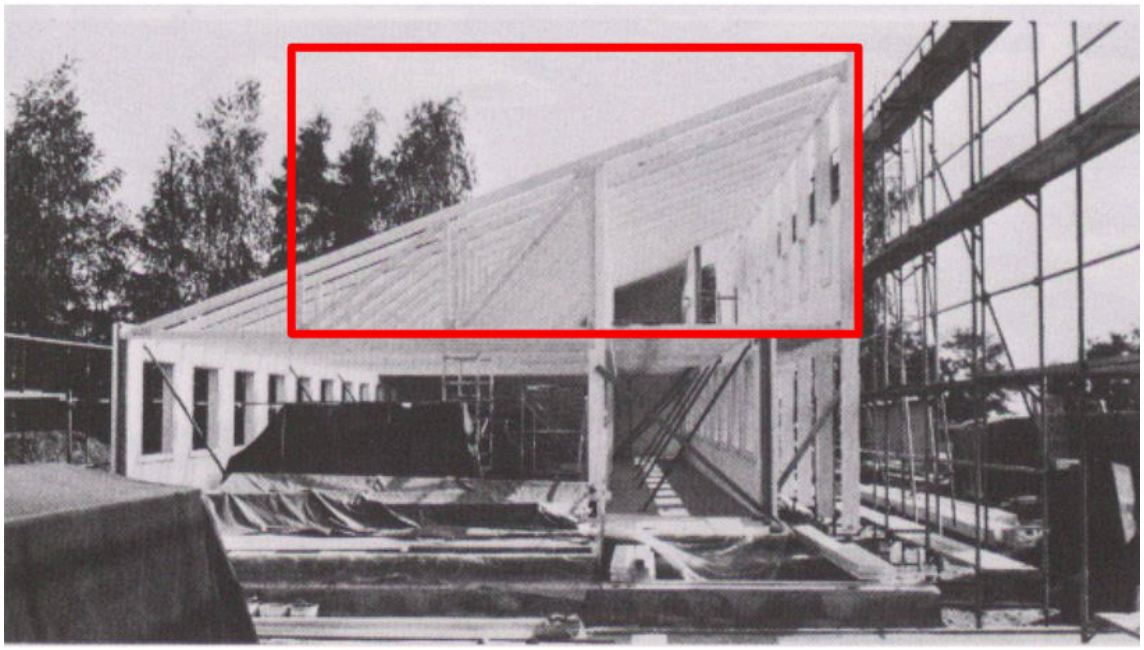


Figure 3.7: Timber frame from the old architecs' buildings to be reused as pergola. (Source: ETH [4])



Figure 3.8: Prefabricated modular pv-pergola. (Source: solarinnova.net)

3.3 MCDA: Evaluation of the Framework criteria combined with the proposed design elements

The first approach to the decision of the best design solution was to develop a weighting factor for the criteria in the framework. Since all the proposed design elements already respected all the criteria, they were equally viable options. Given that the solution space was large and the combinations were varied, we decided to systematically reduce the solution space size and try to choose the best design solution in an unbiased and all-inclusive way. This is why the team members were therefore asked to prioritize the framework criteria and all possible design solutions by means of a Multiple Criteria Decision Analysis (MCDA). An MCDA is a framework that evaluates multiple conflicting criteria and the probable alternatives to a solution in the decision-making process. There are many such frameworks and our team opted for the Analytical Hierarchy Process (AHP) [12] since it was easier to implement and devise. Throughout AHP, a hierarchical network made of three levels is constructed which can be seen in figure 3.9.

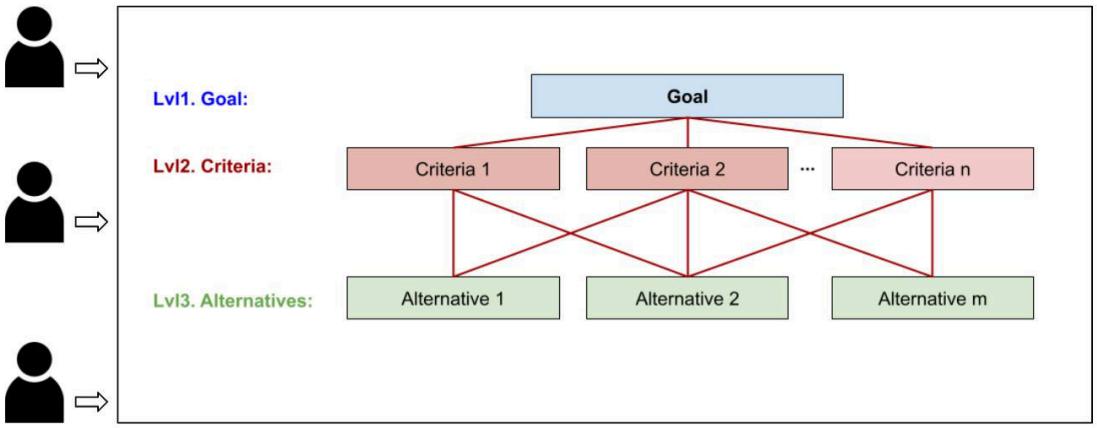


Figure 3.9: AHP hierarchy structure and expert inputs

These three levels include:

- Goal: The overarching goal of the AHP analysis was the selection of a circular and sustainable design from the design space.
- Criteria: The criteria are the basis of the decision-making and in our case correspond to nearly all of the criteria defined in the framework for design choices under section 1.3. A list of the relevant criteria and their definition can be found in 3.10.
- Alternatives: The alternatives are all the design solutions within the design space. The design space is constructed from all the possible design solution combinations for all potential structure, facade and rooftop design elements that we found in the previous steps. Figure 3.11 exhibits the design space and all possible design element combinations.

The weighting was carried out through pairwise comparison of the different criteria, simply by applying our personal opinion and knowledge which was represented by a scale. The relative

importance scale shown in figure 3.12 is a standard way of weighting elements of the AHP framework against each other and is a measure of how important one element is perceived over another from an expert's point of view.

Cluster	Criteria	MCDA Score
Flexibility	**Separation of building layers** ability to provide a functionality within one of the following building layers only: structure, skin, service, spaceplan, stuff	11.5 %
	Simplicity of system ability to provide a functionality with as little components as possible	12.0 %
	Network design ability to add new nodes or make new connections between nodes	15.2 %
	Building design ability to adapt to the complex and changing requirements of the users	32.4 %
Materialization	**Dematerialization and organic material use** ability to minimize the usage of materials with net negative environmental impacts and maximize the usage of materials with a net positive environmental impact	16.2 %
	Material lifespan ability to maximize the lifespan of the material, prefered in the following order: reused and designed for reuse, refurbished, remanufactured, recycled	12.7 %

Figure 3.10: Framework of the project with the criteria MCDA score

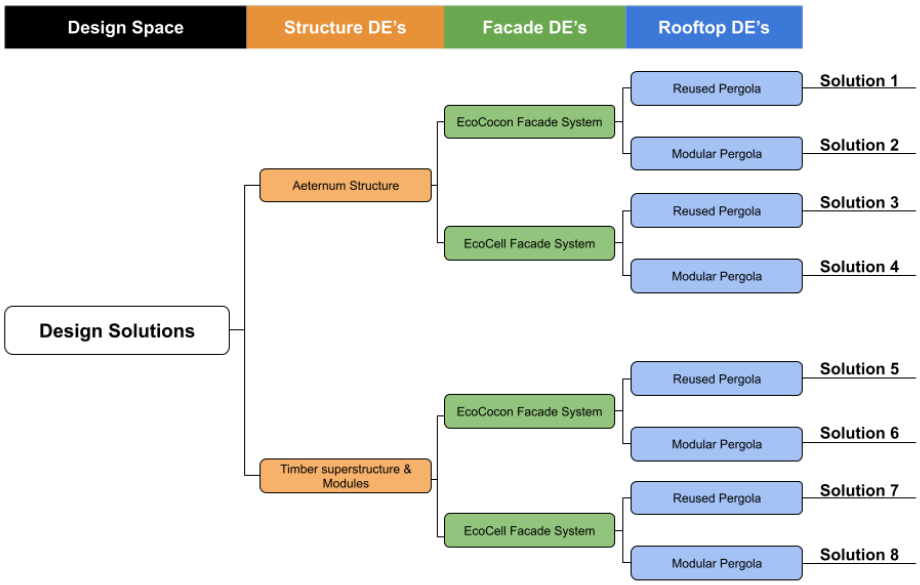


Figure 3.11: All possible combinations of the design elements.

Intensity of Importance	Definition
9	When one activity is extremely important than the other one
8	Very strongly to extremely
7	Very strong or demonstrated importance
6	Strongly to very strongly
5	Strong or essential importance
4	Moderately to strongly
3	Moderate importance of one over another
2	Equally to moderately
1	When two criteria are of equal importance to the objective

Figure 3.12: The importance intensity scale (Source: [12]).

After completing the pairwise comparison of each criteria one by one, the pairwise comparison matrix or PCM was constructed:

$$PCM_{n\times n} = \left[r_{i,j} = \frac{C_i}{C_j}\right] \tag{3.1}$$

Where $r_{i,j}$ is the relative importance of criterion C_i over criterion C_j.After this step, each PCM in equation 3.1 is synthesized into a new matrix shown in equation 3.2 and using this synthesized PCM, the weight vector is determined according to equation 3.3.

$$PCM^{synth}_{n\times n} = \begin{bmatrix} s_{1,1} = \frac{r_{1,1}}{\sum_{i=1}^{n} r_{i,1}} & s_{1,2} = \frac{r_{1,2}}{\sum_{i=1}^{n} r_{i,2}} & \dots & s_{1,n} = \frac{r_{1,n}}{\sum_{i=1}^{n} r_{i,n}} \\ s_{2,1} = \frac{r_{2,1}}{\sum_{i=1}^{n} r_{i,1}} & s_{2,2} = \frac{r_{2,2}}{\sum_{i=1}^{n} r_{i,2}} & \dots & s_{2,n} = \frac{r_{2,n}}{\sum_{i=1}^{n} r_{i,n}} \\ \vdots & \vdots & \dots & \vdots \\ s_{n,1} = \frac{r_{n,1}}{\sum_{i=1}^{n} r_{i,1}} & s_{n,2} = \frac{r_{n,2}}{\sum_{i=1}^{n} r_{i,2}} & \dots & s_{n,n} = \frac{r_{n,n}}{\sum_{i=1}^{n} r_{i,n}} \end{bmatrix} \tag{3.2}$$

$$w_{n\times 1} = \frac{1}{n}\begin{bmatrix} \sum_{j=1}^{n} s_{1,j} \\ \sum_{j=1}^{n} s_{2,j} \\ \vdots \\ \sum_{j=1}^{n} s_{n,j} \end{bmatrix} = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \tag{3.3}$$

Subsequently, the consistency of the PCMs is checked through the extraction of the principle eigenvalue which is calculated through algebraic operations on the multiplication of matrices shown in equation 3.1 and equation 3.3 as shown in equations 3.4 and 3.5:

$$\begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_n \end{bmatrix} = PCM_{n\times n}.w_{n\times 1} \tag{3.4}$$

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{p_i}{w_i} \tag{3.5}$$

Furthermore, the consistency index and the consistency ratio are calculated using equations 3.6 and 3.7 respectively:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3.6}$$

$$CR = \frac{CI}{RI} \tag{3.7}$$

Where RI is the random consistency index as put forth by L.Saaty in figure 3.13. The consistency ratio or CR of any PCM should always be below 10% and if this condition is not satisfied, the PCM must be modified.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Figure 3.13: Random consistency index as a function of PCM size

As a last step, The AHP was then also performed on all the possible combinations of the design elements (alternatives), in order to find out based on the personal opinion and knowledge of the team members, which design solution (combination of design elements) would be the most suitable with respect to the vision and framework criteria. An overview of the entire AHP process can be seen in figure 3.14. This process was done using an online AHP tool, and three experts (Florian, Matteo and Alex) participated in filling out the pairwise comparison questionnaire. Figure 3.15 illustrates the decision framework and all the nodes within the AHP which represent a pairwise comparison.

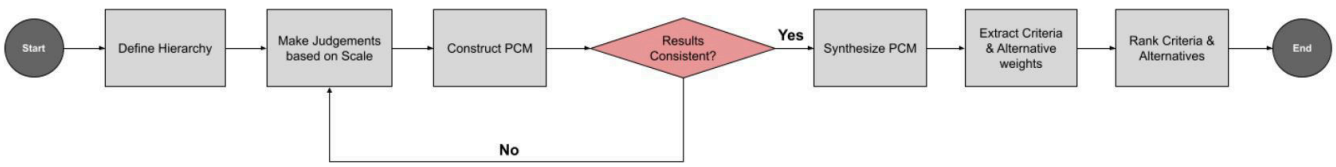


Figure 3.14: The AHP process

Finally, the results of the MCDA are presented in figure 3.16, as it can be noted the design solution that features Aeternum structure, EcoCocon façade and the reused pergola was the preferred one.

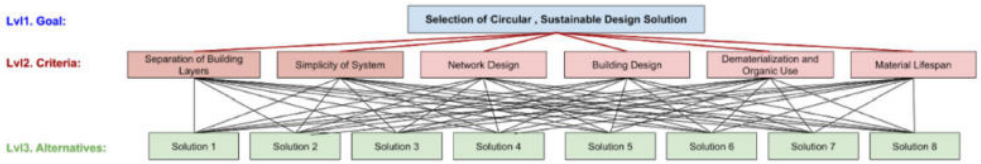


Figure 3.15: Linking the design solutions to the criteria.

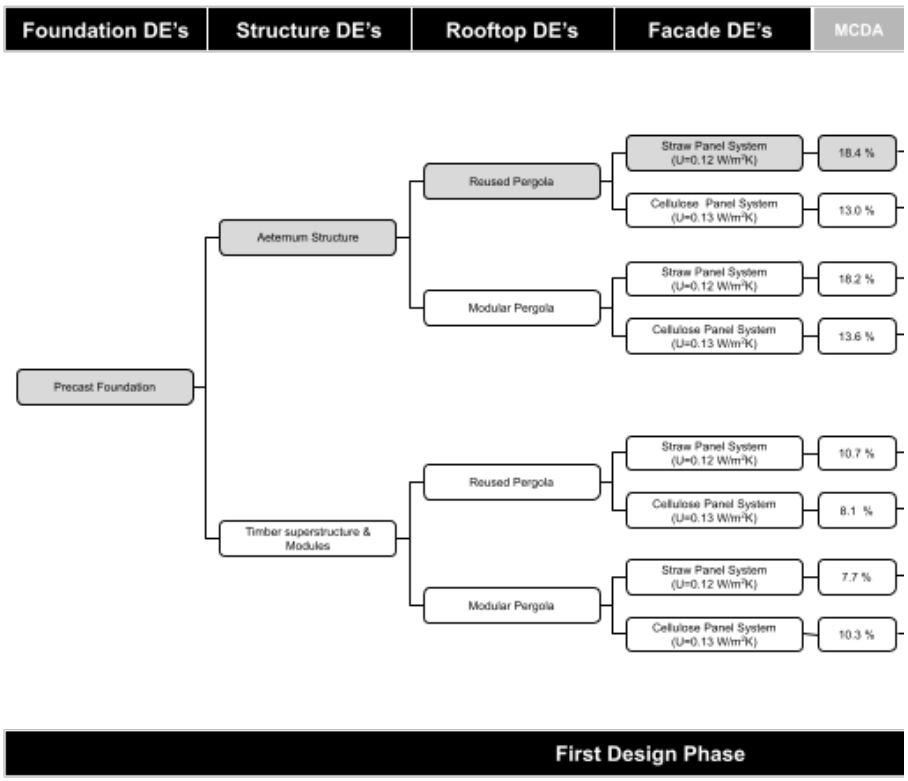


Figure 3.16: MCDA score of the design solutions.

3.4 Model LOD100

In the first design phase, the BIM manager's task was to examine and critically assess already existing plans of the Equilibres project which were provided to us as a starting point together with the team. The plans were in PDF format and provided little to no annotations and measurements, so we had to manually measure the dimensions of the building and calculate the real dimensions using the scales on the plan sheets. As discussed in section 3.1, we decided to reduce the building footprint and to simplify its underground profile into a rectangular prism. Subsequently we designed a volumetric LOD100 model (as observable in figure 3.17) which reflected the rough dimensions of the modified Equilibres building.

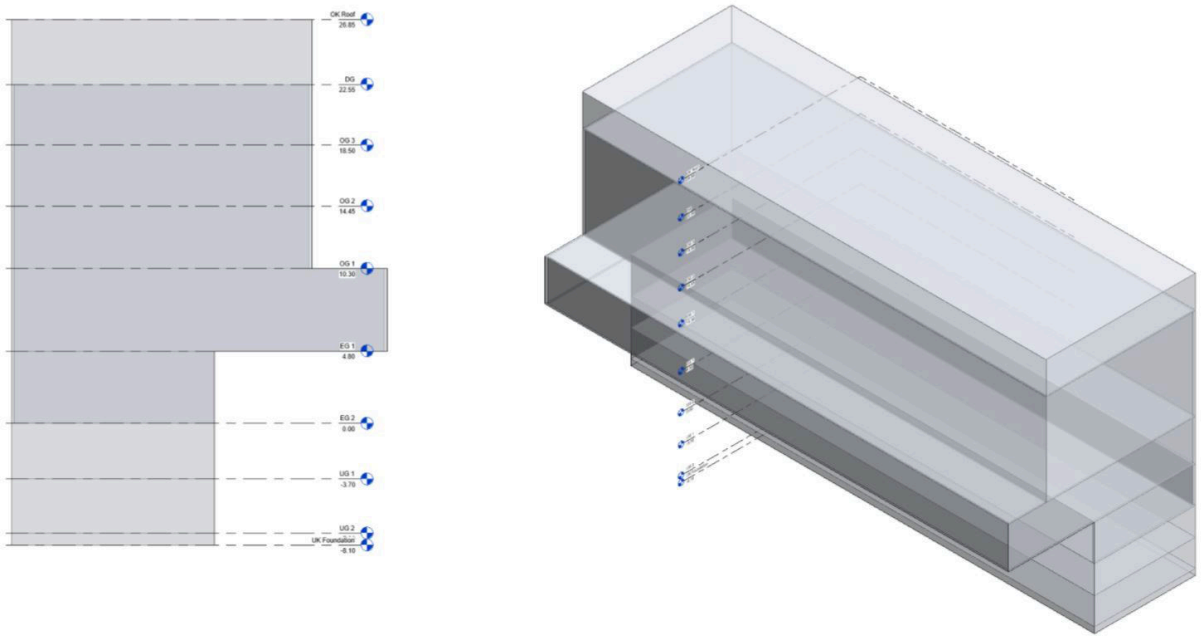


Figure 3.17: Elevation view of the LOD100 model (left), Isometric view of the LOD100 model (right).

As seen in figure 3.17, the model has 8 levels, two of which are completely under ground (UG2 - UG1), one of which is partially under ground, only it's eastern side; (EG2) and five of which are above ground (EG1 - OG1 - OG2 - OG3 - DG). Moreover, levels OK Roof and UK foundation were added in order to define and constrain the top and bottom levels of the building respectively. As a result of the above-mentioned modifications to the original design, UG1 and UG2 are flush to the building exterior. The protrusion of ground level EG1 in the original design is kept, which is the reason why the LOD100 is shaped like a piano. At this point in time we were discussing the rough space utilization and functional separation of layers within the building using the volumetric model. This is why the LOD100 model has a thin shell encompassing its core volumes which represents the detachable facade volume. Consult figure for a rundown of all the designated volumes in the model.

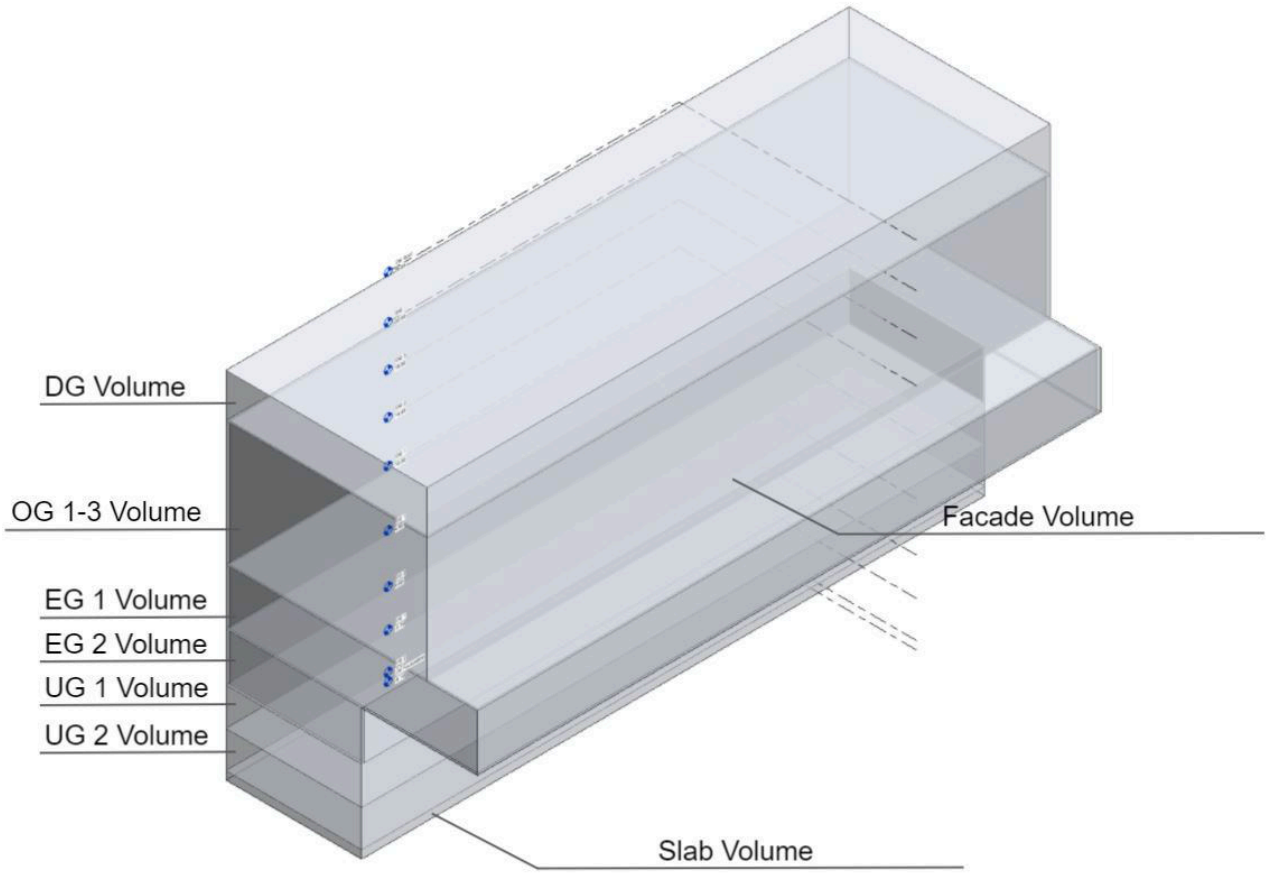


Figure 3.18: Volumetric composition of the LOD100 model.

As a next step, the LOD100 model was used to do a first draft LCA of the embodied emissions in order to verify our design choices.

3.5 LCA: first draft of the embodied emissions of the proposed design elements

Once the initial evaluation of the best design solution by mean of a MCDA was completed, the results were tested again with a simple Life Cycle Assessment (LCA) based on the LOD100 detailed model. This assessment would allow to evaluate the combinations of the design elements in terms of their embodied emissions. The LCA was carried out manually, this means that it was created an Excel file containing the design elements and the respective single elements. All the data concerning embodied emissions is taken from the KBOB. (The first draft of the LCA with the respective results can be found in the Appendix at the end of this document. See 8.1.1 .) The level of detail of the LCA corresponded for the first phase of the project to the LOD100 digital model, nevertheless it increased its level of detail during the development of the project The design solution chosen with the MCDA was confirmed also by the first draft of the LCA be the one with the lowest carbon emissions. In the last column of figure 3.19 the results of the

LCA are summarized, further details can be seen in the appendix 8.1.2.

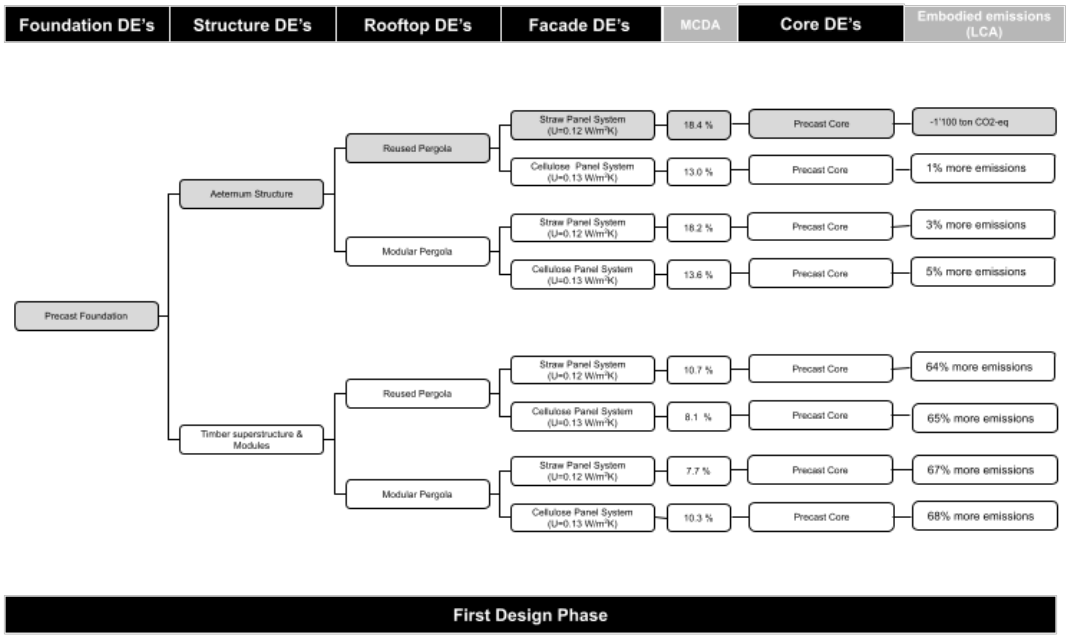


Figure 3.19: First design phase framework with the embodied emissions of the different design solutions.

3.6 Design solution of the first phase

The first design phase concluded with obtaining the design solution for the construction's materials. For the structure of the building, the Aeternum system revealed to be the best option both in terms of affinity to the project's vision and embodied emissions (figure 3.20. As already mentioned at the beginning of the first design phase, this modular structural systems consists of only two main elements whose are repetitively connected together: Aeternum slabs and Aeternum columns. Both of them are made of cross-laminated timber (CLT) and reinforced with steel bars. The grid-made slabs are equipped with steel connectors at each side so that they can easily be connected with the following slabs. The columns rely on steel connectors on both their ends as well.

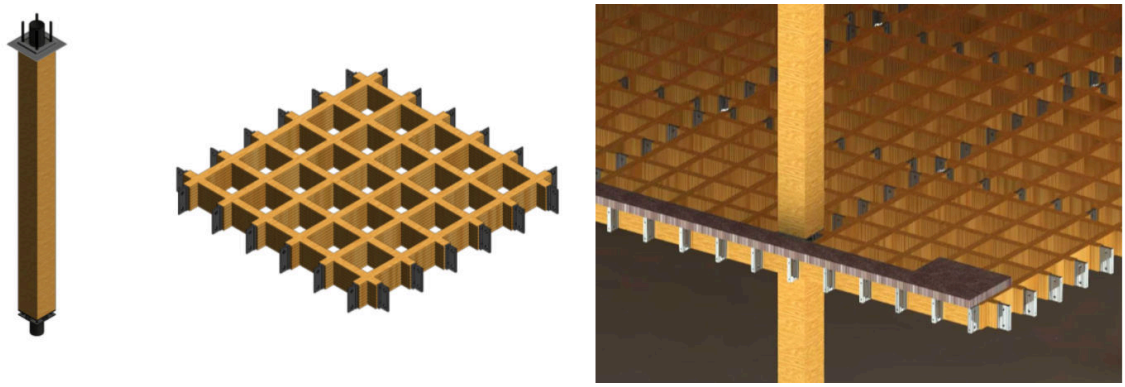


Figure 3.20: From the left: Aeternum column, Aeternum slab element and the final structure. (Source: LOD300 Model)

For what it concerns the rooftop, the pergola made with the reused timber frame from the old architect's building at the ETH campus, which will soon be demolished, has been chosen and can be visualized below in figure 3.21.

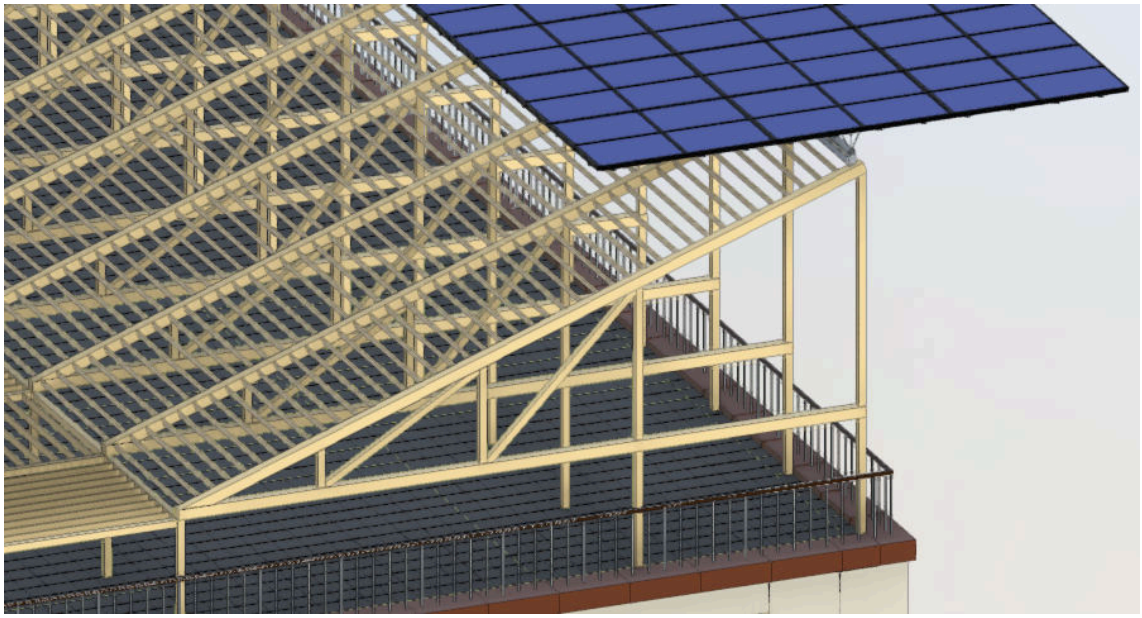


Figure 3.21: Visualization of the rooftop's pergola with the PV-panels on top. (Source: LOD300+ Model)

Finally, the facade design elements that had the best results, revealed to be the EcoCocon modules. They are made of a lean timber frame which contains straw as insulation. The timber-straw panel is then coated from the outside with a wood fiber board and in the inside with clay plasters. Below, in figure 3.22 the facades can be visualized in the LOD 300+ model.

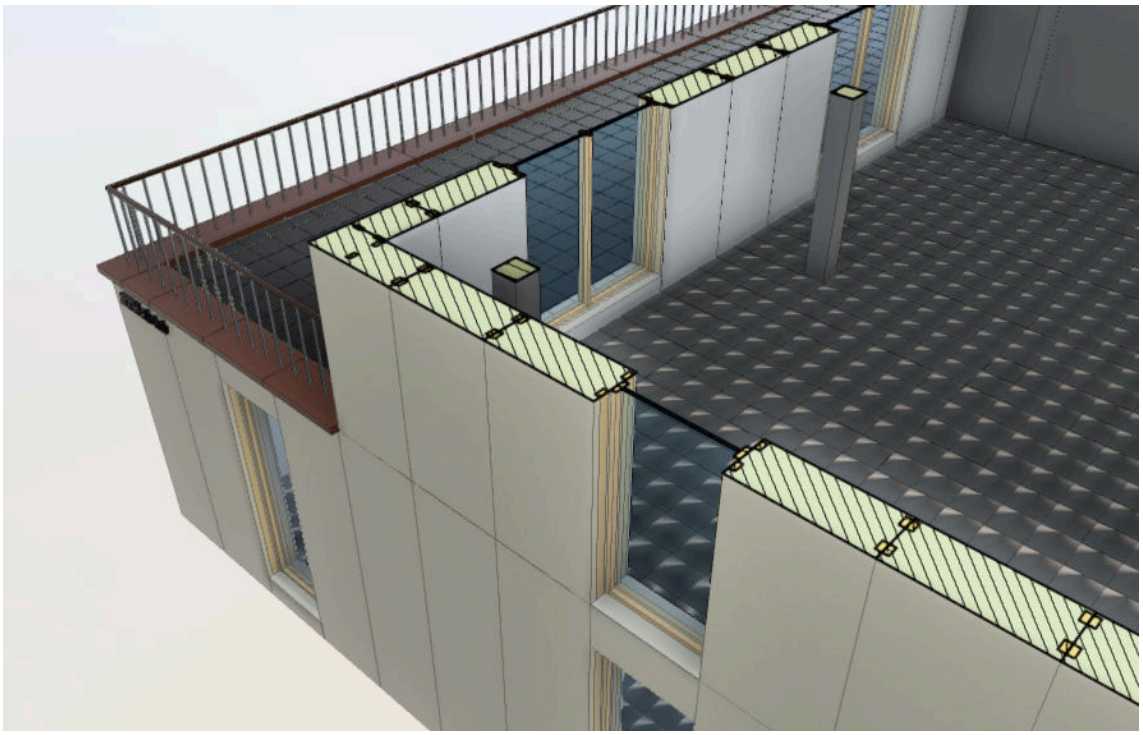


Figure 3.22: Visualization of the timber-straw facade panels. (Source: LOD300+ Model)

In the appendix 8.3 the relation between the design elements chosen and the project's vision can be seen.

4 Second Design Phase

4.1 Finding design elements

After the first iteration seen in the previous chapter 3, which dealt with the structural parts and elements present in large quantities, we moved on to a more detailed analysis focusing on the building systems, the possible window layouts, the two building cores and delving into the previously chosen components.

4.1.1 Building systems

Based on the knowledge gained in Stage 1 of this project, we created two possible initial systems configurations, the first of which could be described as more sophisticated and extensive, which we will call "Extensive Design" from now on; and the second as leaner and less sophisticated, which we will call "Lean Design" from now on. These choices led us to the following two systems chains:

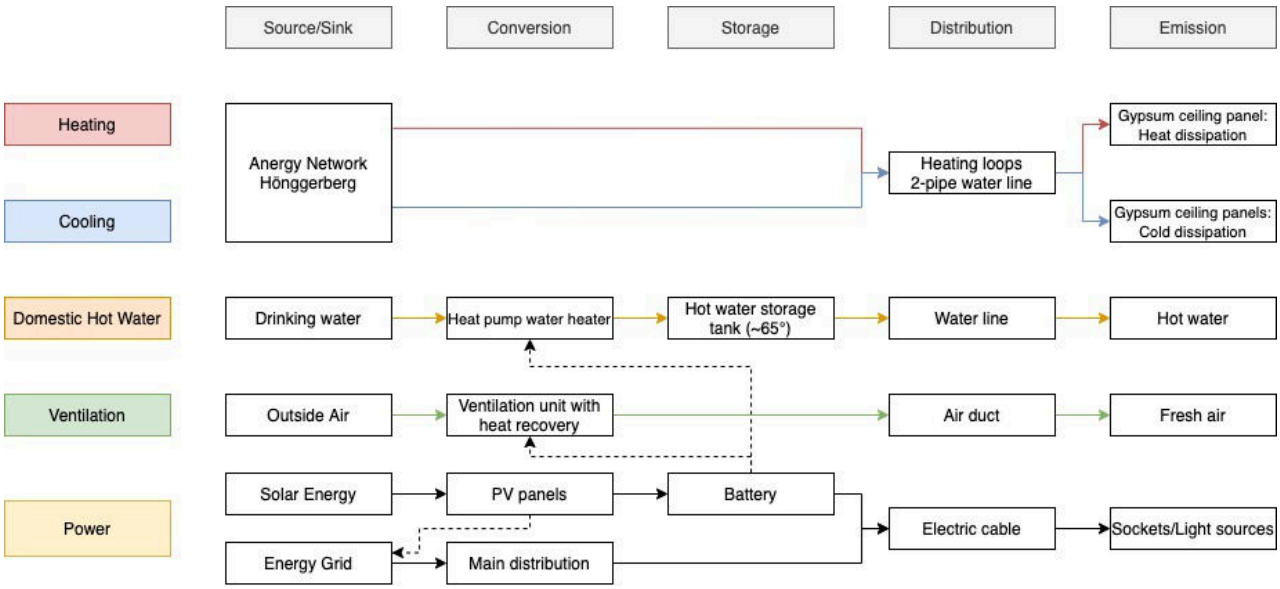


Figure 4.1: First draft of the systems chain for the Extensive Design.

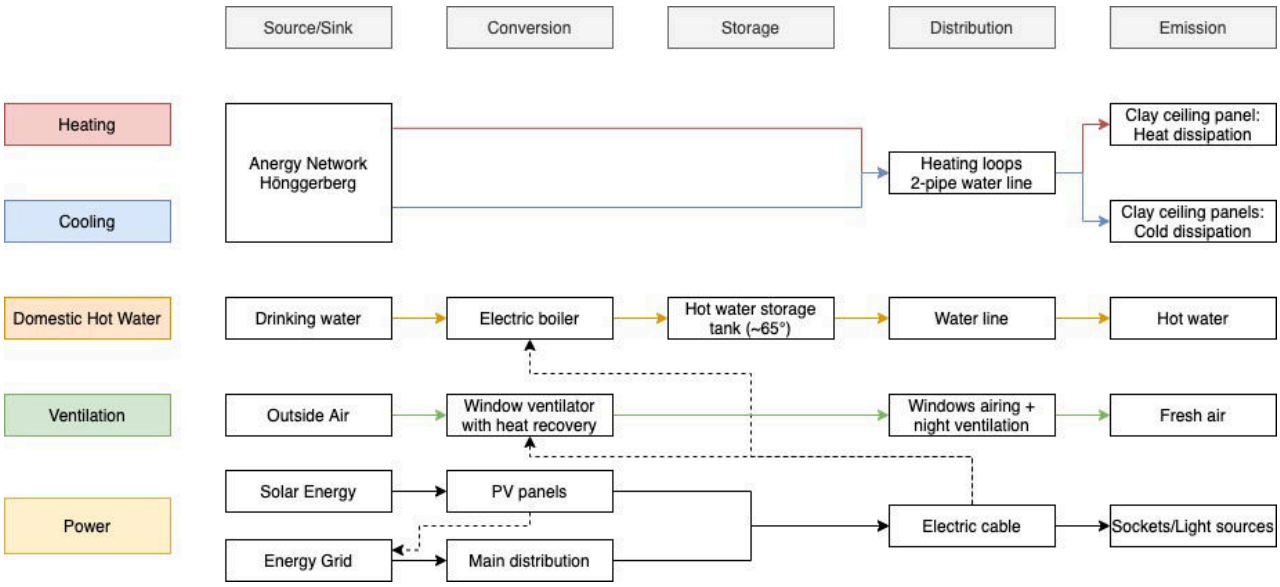


Figure 4.2: First draft of the systems chain for the Lean Design.

Looking in more detail, the main elements of the Extensive System Design are:

- for heating and cooling the building use the Anergienetz of the Campus and dissipation occurs via some gypsum ceiling panels



Figure 4.3: Gypsum panel. (Source: variotherm.com)

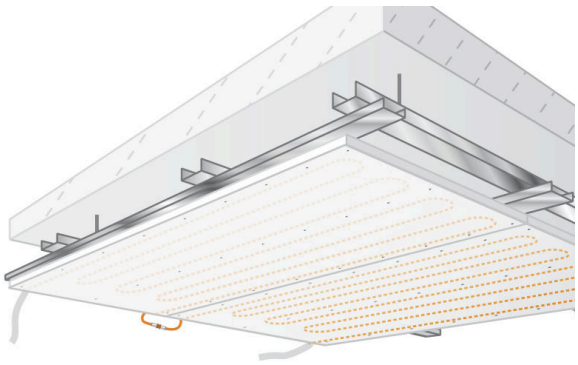


Figure 4.4: Module ceiling system. (Source: variotherm.com)

- for domestic hot water it has an heat pump water heater

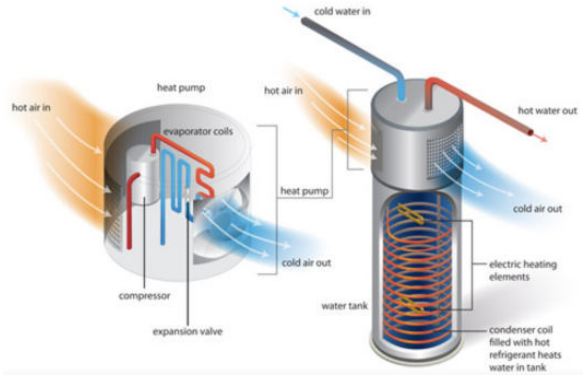


Figure 4.5: Heat pump water heater. [10]

- the ventilation occurs with ventilation units with heat recovery and the distribution with fabric air ducts



Figure 4.6: Fabric air ducts. (Source: fabricair.com)

- finally, from the energy side there are solar panels (about 500m^2) with batteries to store the surplus energy and use it during the low production moment.

The main elements of the Lean System Design are:

- For heating and cooling it use the Anergienetz of the Campus but this time the dissipation occurs via some clay ceiling panels

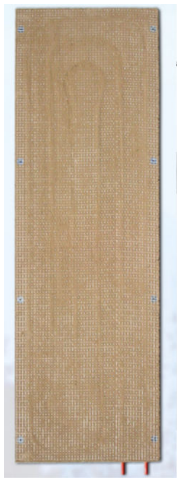


Figure 4.7: Clay panel. (Source: wem-wandheizung.ch)



Figure 4.8: Module ceiling system. (Source: wem-wandheizung.ch)

- for domestic hot water a standard electric boiler is implemented
- ventilation occurs windows airing and the implementation of windows ventilator with heat recovery

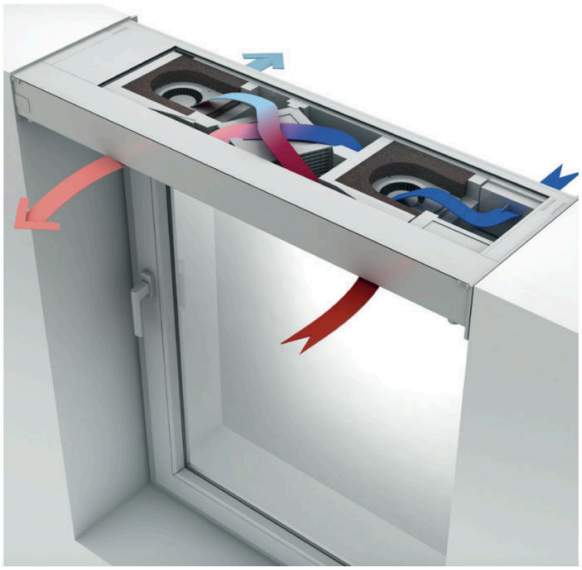


Figure 4.9: Windows ventilator with heat recovery. [9]

- from the energy side there are only solar panels (about 500m^2) and the excess energy is fed into the grid.

4.1.2 Windows layout

Window layouts and in particular Windows to Walls Ratios (WWRs), play a key role in embodied and operational emissions. In fact, the manufacture of glass has a high impact in terms of CO_2. On the operational side, windows influence thermal comfort, as they can be a source of solar heat gain that can be exploited with the implementation of heat masses. However, this can also be a disadvantage at the hottest times of the year as it will require more cooling. Finally, the visual aspect, i.e. the possibility of having an adequate light view, so as to avoid the use of artificial light, depends solely on the layout of the windows.

To remain consistent with our criteria (Figure 1.2), we opted to design only three different types of facades:

- Facade element without window
- Facade element with 80% window
- Facade element with 40% window

Having only these 3 types of facades, which are equivalent to only 2 types of windows, allows us to have a very simple stock with just a few different pieces, and their installation and layout modification is particularly easy thanks to the use of the Aeternum-system connectors (3.2.2).

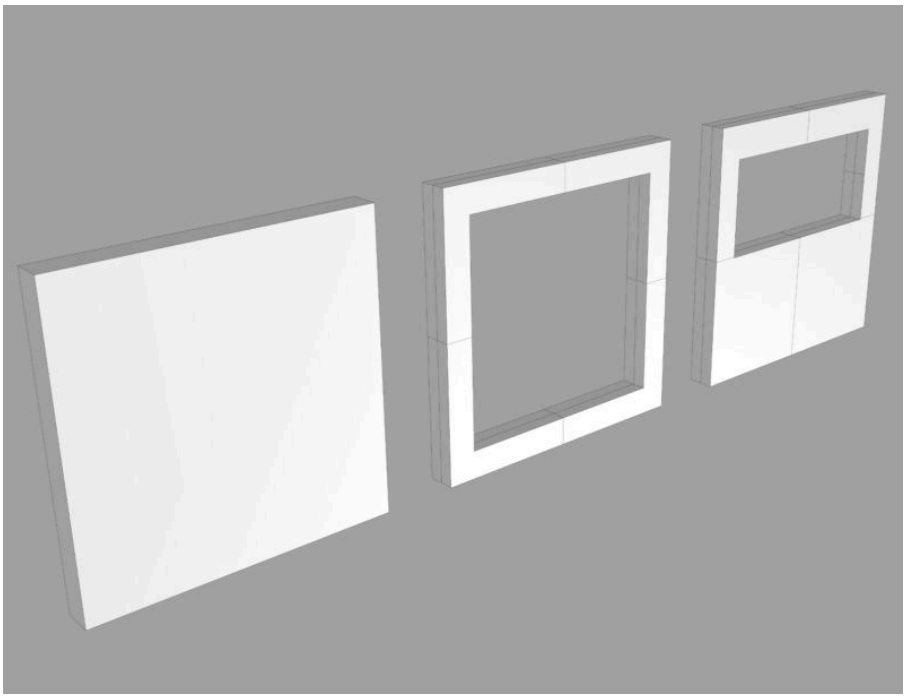


Figure 4.10: A concept of the three different windows layouts.

4.1.3 Core module

Looking in a little more detail at the core of the building, one of the main requirements is that the construction be flexible, so a core of modular elements seemed the obvious choice. At this

point two different designs emerged, a classical core with precast concrete or a timber core. A concrete core has a definite advantage in terms of fire safety, but also has a major environmental impact in terms of CO_2.



Figure 4.11: Precast concrete core.

The other option is a timber core, which has a negative embodied impact, but requires a coating to achieve the RF1 classification [14].

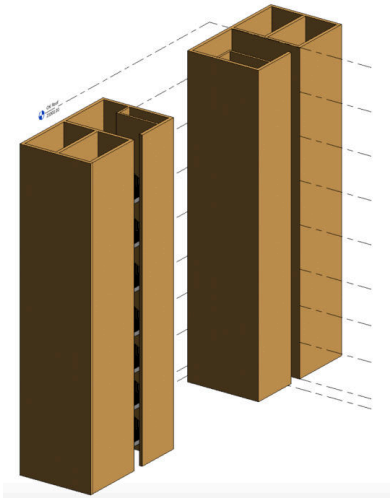


Figure 4.12: Timber core.



Figure 4.13: Timber core interior.

4.2 Model LOD200

In the second design phase, the BIM manager's task was to capture the opted design choices and to instill and graphically represent them in a model as a generic system of families or assemblies, with approximate sizes, quantities and properties. The geometric constraints of the LOD200 model were based on the volumetric design of the LOD100 model discussed in section 3.4. Since there were significant approximations present in the LOD200 model, our team decided to only focus on the main, structural and exterior layer of the building, which contained the following:

- Foundation
- Lower concrete retaining walls
- Core
- Slabs
- Structural Framing
- Facade
- Pergola

The LOD200 model can be seen in figure 4.14.

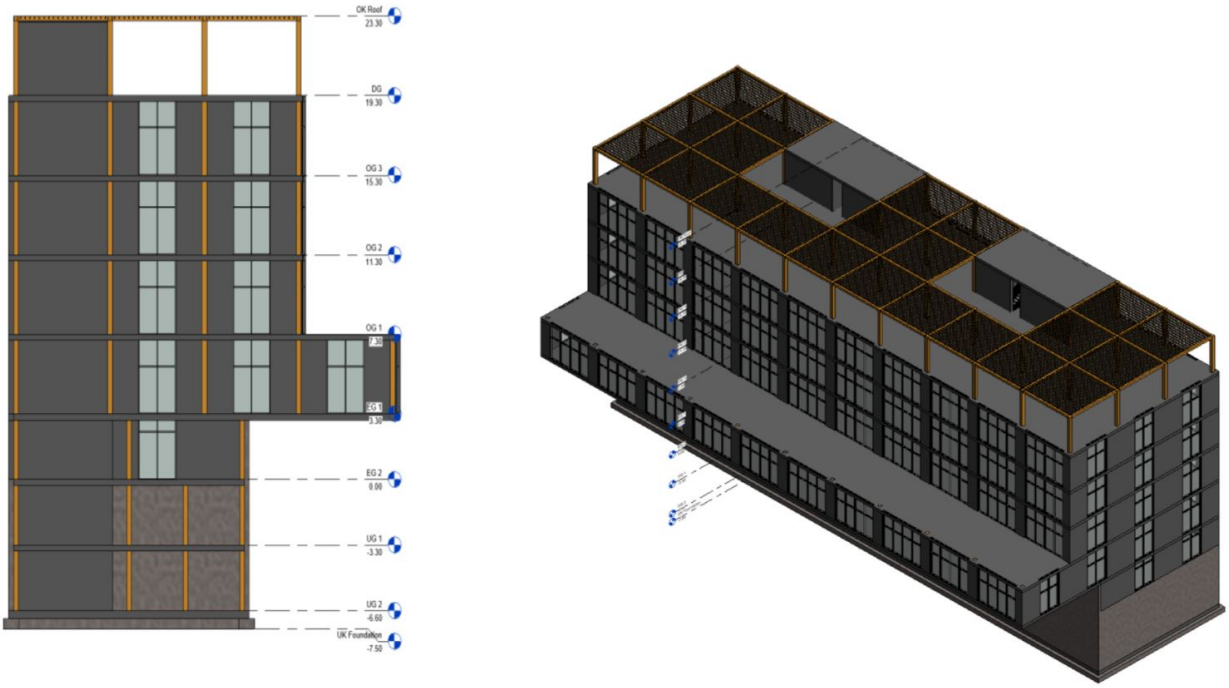


Figure 4.14: Elevation view of the LOD200 model (left), Isometric view of the LOD200 model (right).

4.2.1 Foundation

As discussed in section 3.2.1, in order to minimize the volume of in-cast concrete, we decided to go for a strip slab foundation. The strip slab foundation was 50 cm thick and ran beneath all concrete retaining walls and columns and extended 1m on each side. On top of the strip slab foundation lay a 40 cm thick slab plate which both acted as a structural element against overturning moments and an architectural slab in UG2. All of the foundation elements were modelled using the REVIT pre-defined structural concrete slabs and their thickness was modified accordingly. Figure 4.15 shows the plan and section view of the strip slab and slab plate foundations.

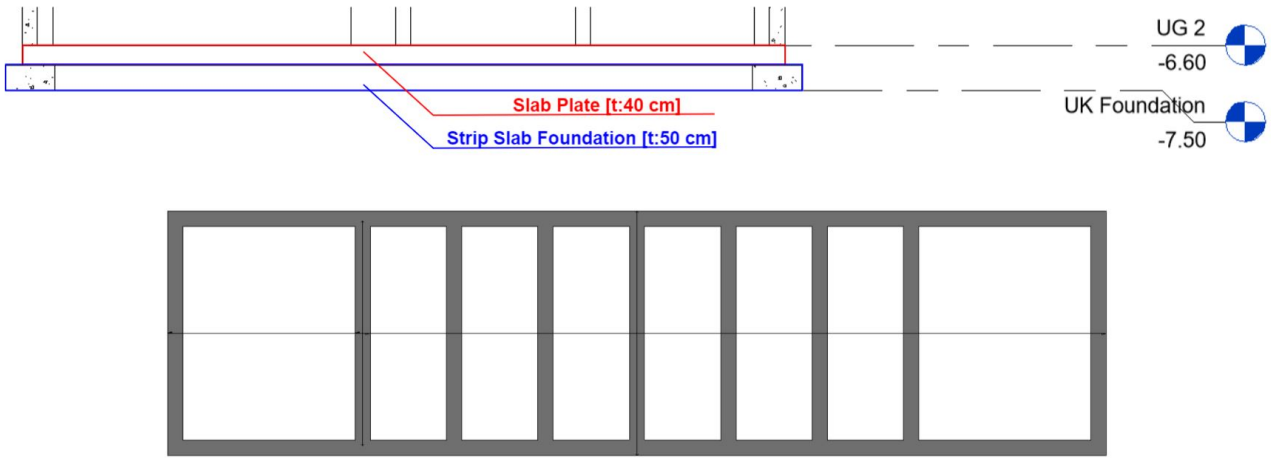


Figure 4.15: Plan view (Bottom) and Section view (Top) of the foundation elements.

4.2.2 Lower concrete retaining walls

The lower concrete retaining walls extend from the top of the foundation all the way to the ground level. Their main function is to structurally reinforce the underground levels UG1 and UG2 against underground pressure and ground-water levels. In order to minimize the negative carbon emissions impact of the lower concrete retaining walls, we decided to design them as precast retaining walls with specific dimensions which were dictated by manufacturers of such an element. As a result, levels UG1 and UG2 have are each 3.3 meters high compared to all other levels which are 4 meters high. Each precast retaining wall element is 12 meters long and 30 cm thick. The retaining walls were modelled using REVIT pre-defined structural concrete walls and their thickness was modified accordingly. Figure 4.16 exhibits a section view of the lower concrete retaining walls.

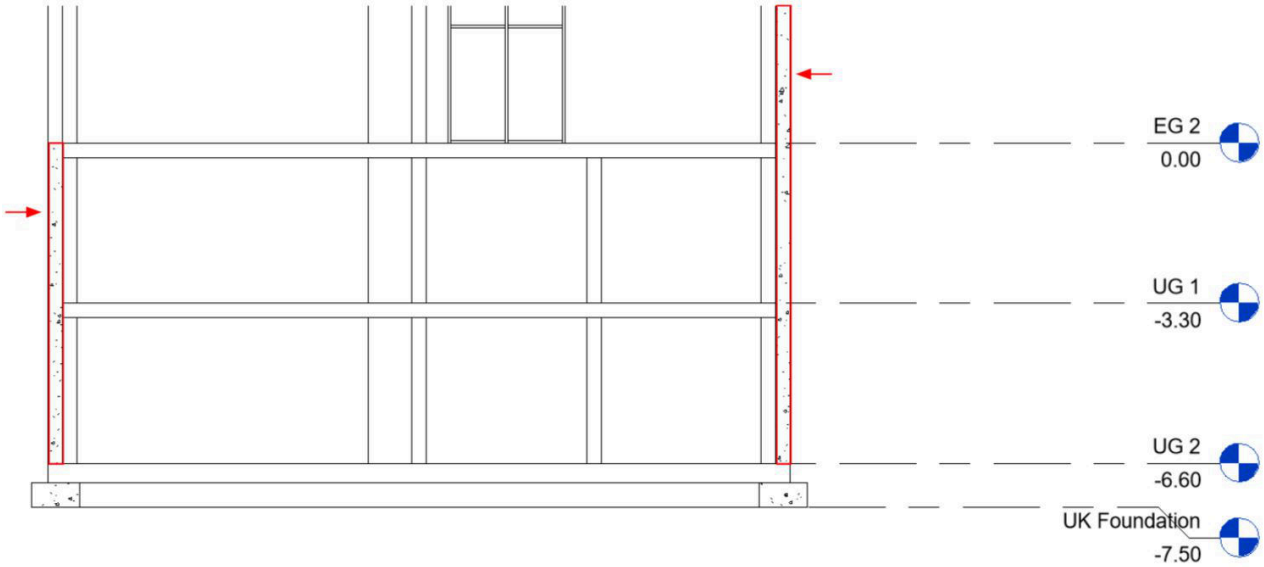


Figure 4.16: Section view of lower concrete retaining walls indicated by red arrows.

4.2.3 Core

As mentioned in section 4.1.3, we decided to go for a modular core which served as a structural backbone against shear loads. At this point in time, our decision was that of a precast concrete core, since we had concerns regarding stability and fire-safety. This design choice however underwent a change as can be seen later in the third design phase. The two cores were modules made out of 30 cm thick precast concrete walls, which contained space for an elevator shaft, a staircase and two water closets for each core. Both core modules were modelled using REVIT pre-defined architectural walls that were continuous objects which extended from level UG2 all the way to level OK Roof. Figure 4.17 illustrates a plan and section view of the core.

4.2.4 Slabs

Keeping account of the rough dimensions of the Aeternum slabs introduced in section 3.2.2, we decided to go for a generic 30 cm thick slab across all levels. All of the slabs were modelled using REVIT pre-defined architectural slabs. Visualizations of the LOD200 slabs can be seen in appendix 8.2.3.

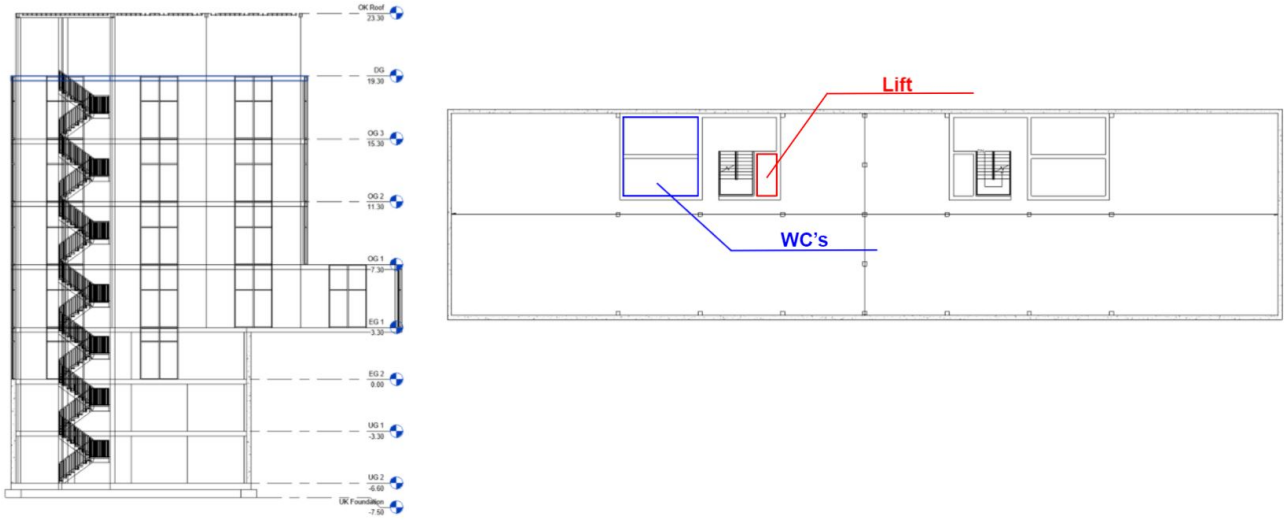


Figure 4.17: Section view of core (left) and Plan view of core with relevant compartments (right).

4.2.5 Structural Framing

With the Aeternum structural system in mind, we decided to go for rectangular 30cm×30 cm glulam timber profiles as columns. Moreover the grid spacing corresponded to the Aeternum system arrangement which dictated spans of 6 meters with 1.2 meter intervals. As a further complication, our team decided to move two large lecture halls which were situated on the ground floor to the underground level UG2, since a 6m by 6m grid would prove to be problematic in a large lecture room which demands visibility from all angles. Moreover, the structural support of the surrounding concrete retaining walls would in part offset the structural effect of omitting underground columns on the loads. This decision in turn resulted in the omission of some columns in UG2 in order to satisfy the constraints of the lecture halls which can be observed by comparing figure 4.18 with figure 4.19. This is why we decided to also structurally fortify the UG2 level with continuous 15cm×50cm lumber beam profiles (as seen in figure) that ran through places where the columns used to be and connected them to the core. As we'll see later, this decision was overturned. All of the structural framing elements were modelled using REVIT pre-defined architectural columns and beams which connect to the core and existing columns.

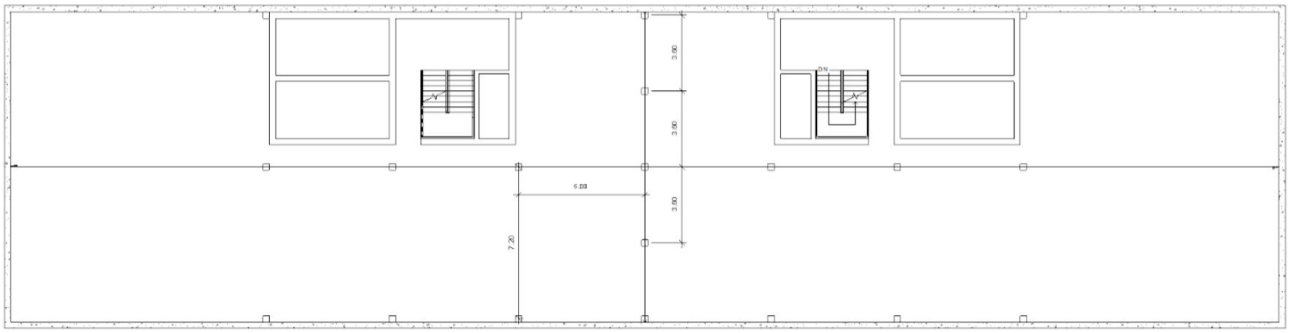


Figure 4.18: Plan view of the UG levels grid.

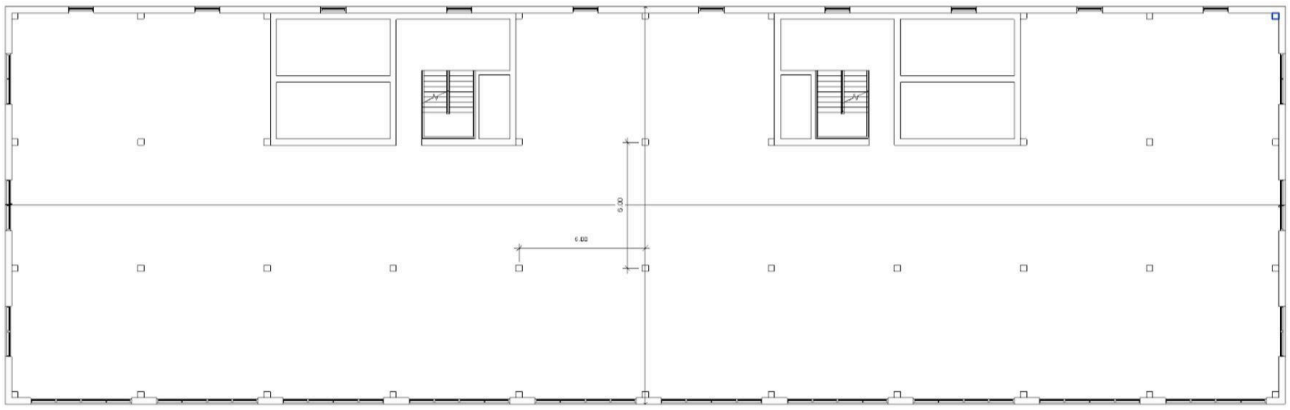


Figure 4.19: Plan view of the OG levels grid.

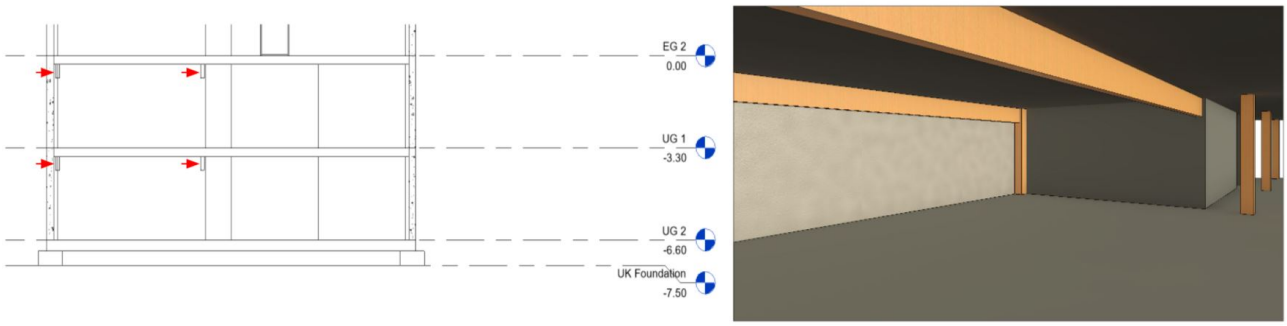


Figure 4.20: Section view of levels UG1 and UG2 fortified by beams indicated by red arrows (left), rendering of UG2 beams which connected to the core and existing columns (right).

4.2.6 Facade

The panelized facade system was modelled in order to showcase a concept for the interchangeability of facade parts. This enabled the end-user to modify the facade openings and windows in order to accommodate their changing needs throughout the building life-cycle. The following

initial window to wall ratio was chosen: S 80%, N 20%, W & E 40% as a starting point since the south and east side of the building were exposed to direct sunlight. Modelling of the facade was achieved with the aid of REVIT pre-defined architectural walls and storefronts for windows. Appendix 8.2.2 depicts a visualization of the panelized facade system on the Forge platform.

4.2.7 Pergola

A simplified version of the reused pergola system was included in the LOD200 model in order to show the space utilization of the DG volume in the LOD100 model. The pergola system consisted of the same 30cm×30cm glulam timber column profiles used on other levels, beams with 18.4cm×23.5cm glulam timber profiles and shading elements with 3.8cm×14cm lumber profiles. The pergola system was modelled using REVIT pre-defined structural elements and beam systems. Figures 4.21 and 4.22 show the reused pergola system from different views.

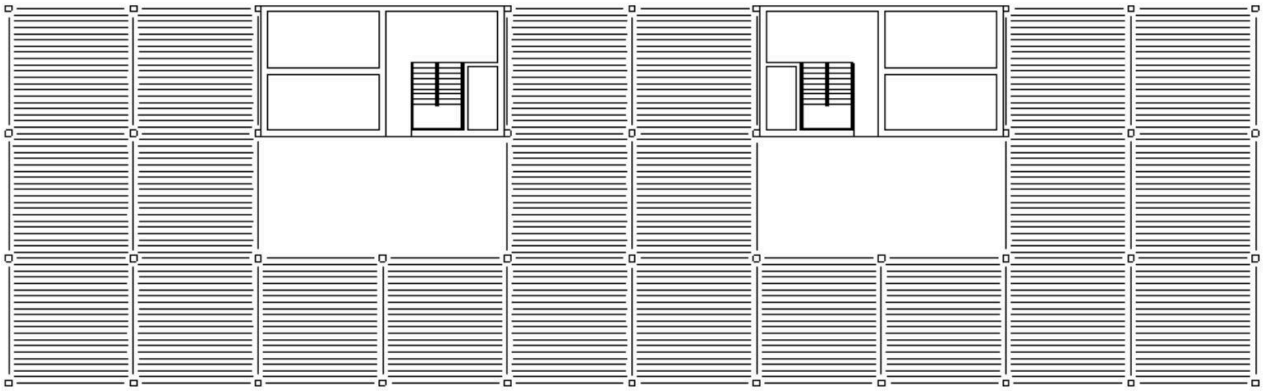


Figure 4.21: Plan view of the reused pergola system.

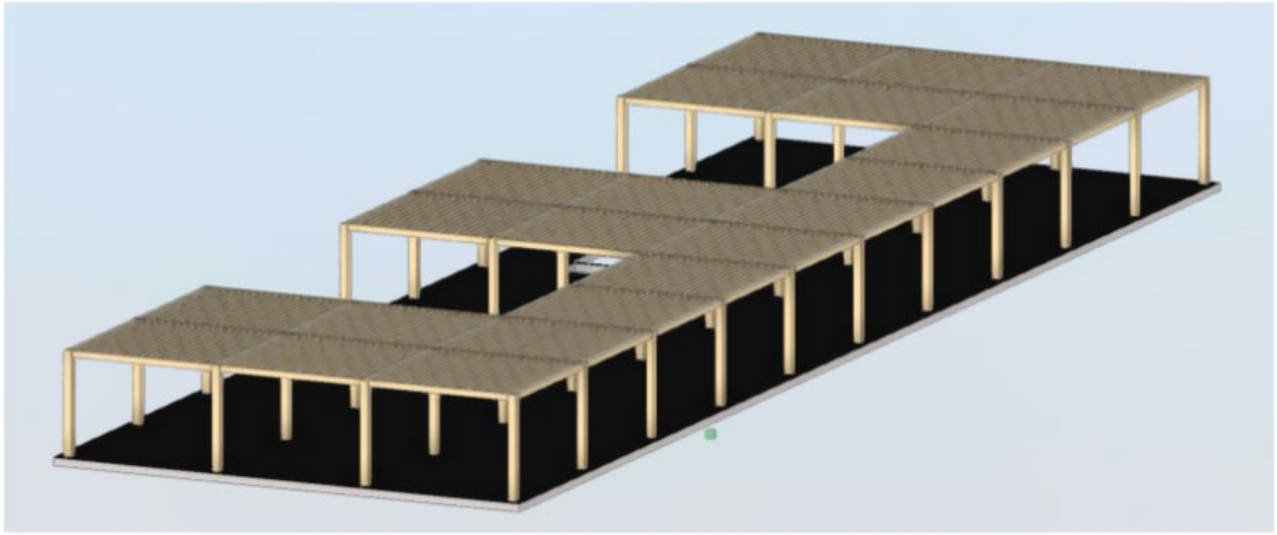


Figure 4.22: Isometric view of the reused pergola system.

4.2.8 LOD200 model on the Autodesk Forge platfrom

During this stage, the Autodesk Forge platform was set up for all three teams. Each team had their own design space with the standard Autodesk Forge UI at their disposal. The platform mainly served the purpose of visualizing and communicating our design choices and vision to the coaches. Appendix 8.2 exhibits all of the design elements introduced in sections 4.2.1 to 4.2.7 on the Autodesk Forge platform. The building blocks of our flexibility vision (according to section 1.3) were represented and visualized on the Autodesk Forge platform as follows:

- Separation of building layers: the ability to provide a functionality within on building layer only. For this visualization we used an isometric section of the building interior in order to highlight the separation of the column and facade elements as shown in figure 4.23.

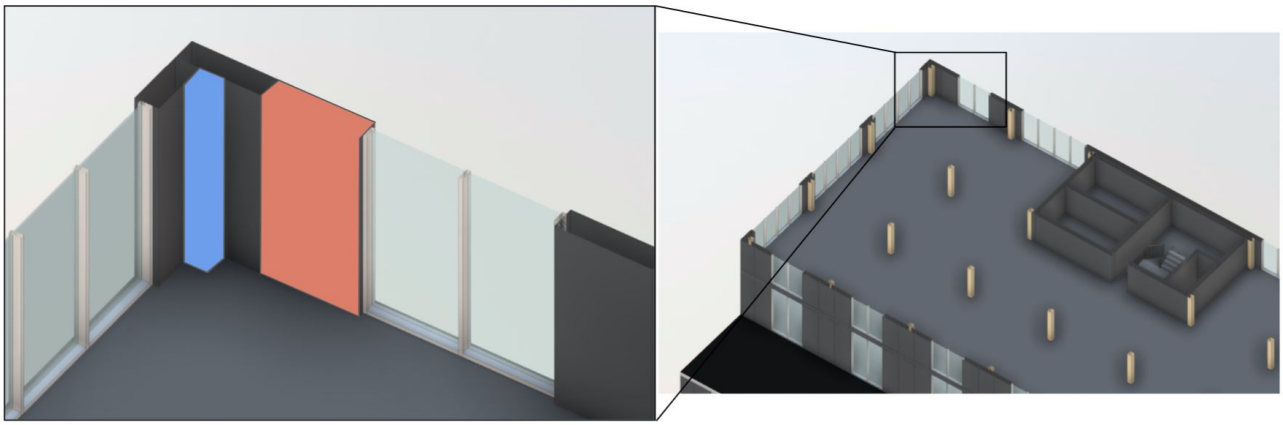


Figure 4.23: Separation of the structural layer (column) indicated in blue and the skin layer (facade) indicated in red.

- Simplicity of system: the ability to provide a functionality with as little components as possible. In order to visualize this criterion, we filtered different design elements of the model on the Forge platform. A complete list of all such instances can be found in Appendix 8.2.

- Network design: the ability to add new nodes or make new connections between nodes in 3D. The standard 3D customizable box functionality within the section analysis tab on the platform was used to illustrate the addition of new nodes in two dimensions as shown in figure 4.24.

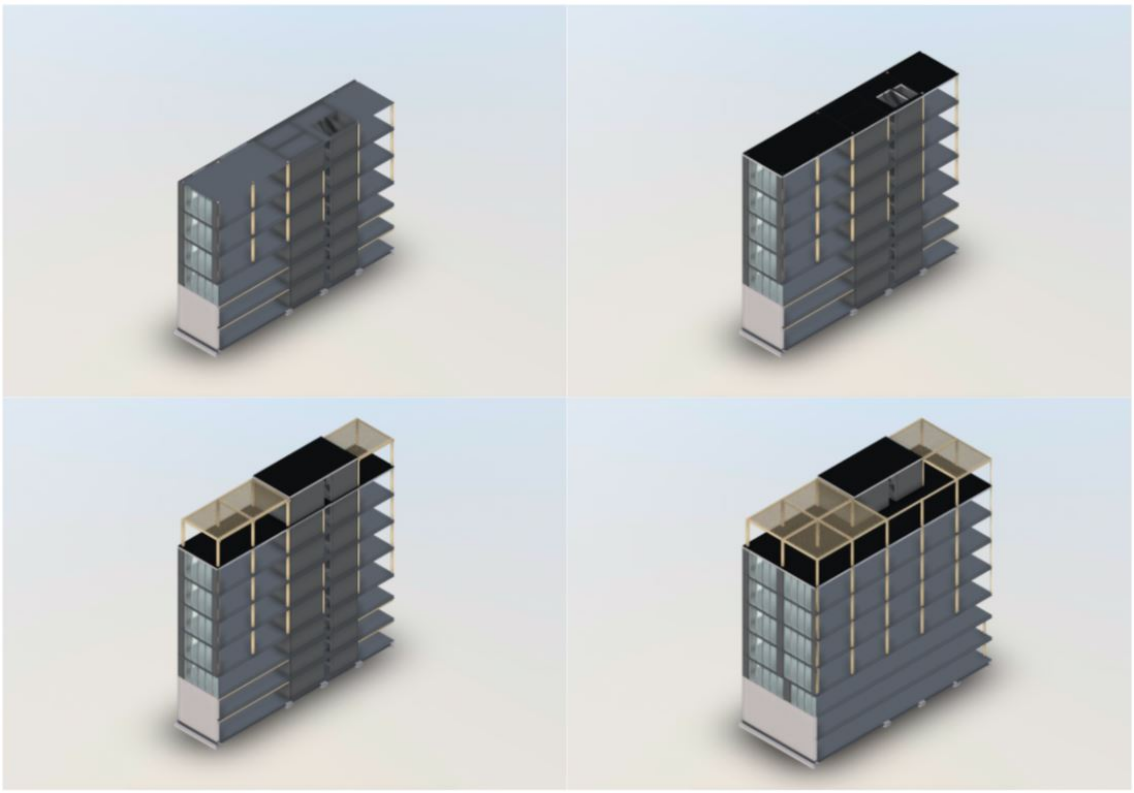


Figure 4.24: Network design of the system, end-users and architects could simply add or omit new nodes from the original design.

- Building design: the ability to adapt to the complex and changing requirements of the users. This meant that all of the design elements included in the model were re-configurable. The standard exploded view of the Forge platform was used to showcase all the design elements which could be infinitely configured as illustrated in figure 4.25.

The Autodesk Forge platform was mostly used for visualization purposes at this stage, and we did not utilize its full potential in data analytic, tagging and filtering of components of interest. This was further achieved down the line in the last design phase.

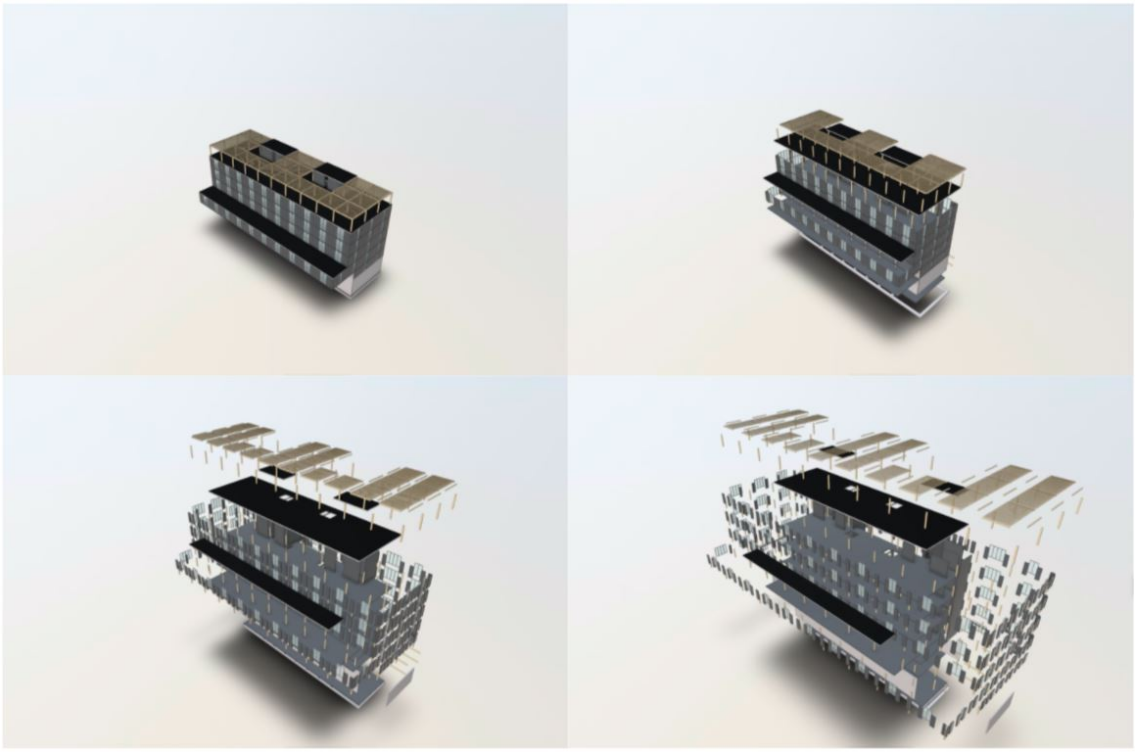


Figure 4.25: Building design of the system, each design element within the system is designed for assembly and disassembly and can be configured.

4.3 Operational energy simulation

4.3.1 Cove.tool software

For all simulations concerning comfort and operational energy we used the software cool.tool: it is a relatively young online platform based on design optimisation and automation. Their machine learning optimization algorithm allows it to become more and more powerful as the number of uses increases. Unlike many other software, cove.tool [1] has a strong graphical component, which makes it much more intuitive after only a few uses, and the online chat function and the large database they have for each tool is of great help for almost any problem.

Among its many functions, the software is able to conduct the following simulation: Energy analysis; Daylight analysis; Carbon analysis; Water analysis; Cost analysis. For our project we mainly focused on the first two analyses, Energy and Daylight. As the carbon analysis is based on US standards, we preferred not to take it into consideration and rely on Swiss data.

4.3.2 Simulation

Simulations were carried out for both building systems designs mentioned above. In both cases, the WWRs of the four facades were also varied in order to find the best value in terms of energy consumption during the lifetime of the building. The following table shows the 4 different WWRs combinations tested in this project:

Configurations	North Facade	East Facade	South Facade	West Facade
Basis	18%	37%	77%	33%
Less on South	18%	37%	57%	33%
Less on West	18%	37%	77%	28%
More on East	18%	57%	77%	33%

Figure 4.26: WWRs combinations.

The operational energy results for the Extensive Design and the operational carbon impact for a lifespan of 60 years and the current average CO_2 production of the Swiss energy mix, that is about 0.102 $kgCO_2/kWh$ [5], are as follows:

Configurations	EUI Extensive Design [kWh/m2y]	Operational Impact [tCO2]
Basis	19.38	771
Less on South	19.41	772
Less on West	19.73	785
More on East	18.95	754

Figure 4.27: Second Phase: Operational energy Extensive Design.

The following figure shows a simulation example for the combination with an higher WWR in the East facade:

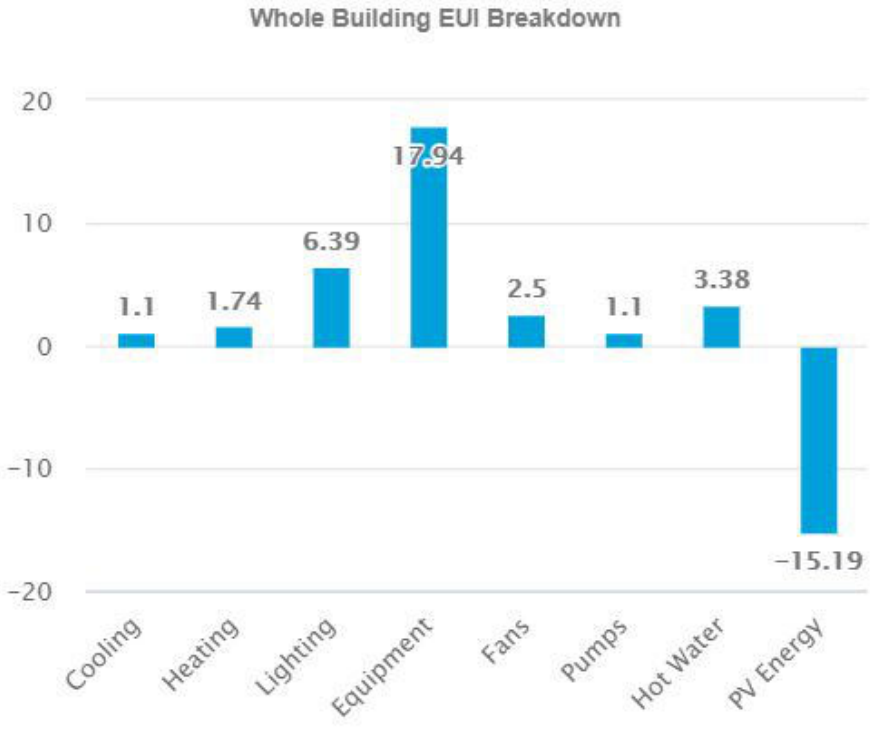


Figure 4.28: Second Phase: EUI of the Extensive configuration More on East.

The operational energy results for the Lean Design and the operational carbon impact for a lifespan of 60 years and the current average CO_2 production of the Swiss energy mix, that is about 0.102 $kgCO_2/kWh$ [5], are as follows:

Configurations	EUI Lean Design [kWh/m2y]	Operational Impact [tCO2]
Basis	20.49	815
Less on South	20.54	817
Less on West	20.64	821
More on East	20.00	796

Figure 4.29: Second Phase: Operational energy Lean Design.

The following figure shows a simulation example for the combination with an higher WWR in in the East facade:

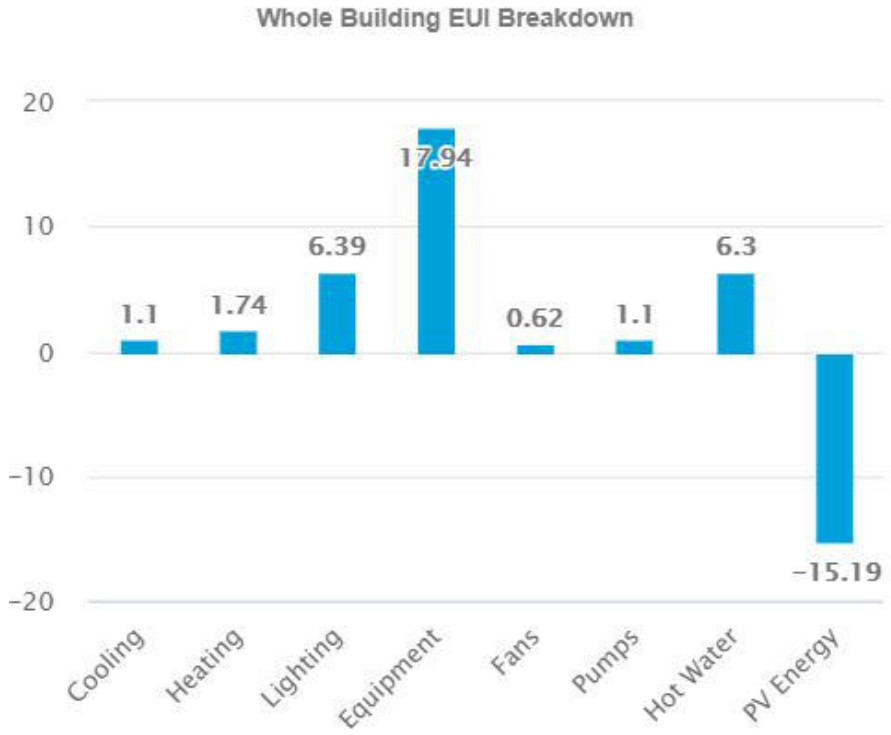


Figure 4.30: Second Phase: EUI of the Lean configuration More on East.

4.4 LCA: embodied emission of the building system

A life cycle assessment have been performed also with regard of the building systems in order to determine also in terms of embodied emission which building systems design would result as more appropriate for the scope of the building. The LCA takes account of the type of materials that compose the different building systems elements, including their fabrication, disposal at end of life, transportation emissions and possible carbon storage. The details of the calculations can be seen in the appendix 8.1.3. As it is to be seen in figure 4.31 and 4.32, the lean building system design resulted in much lower embodied emissions. This is mainly to be linked to the use of clay ceiling panel and window aeration systems that characterize the lean design. The embodied impact difference of the "less on south" configuration emerges from the reduced need of shading elements on the south facade when less windows are designed in the latter.

Configurations	EUI Extensive Design [kWh/m2y]	Operational Impact [tCO2]	Embodied Impact [tCO2]	Total Impact [tCO2]
Basis	19.38	771	956	1'727
Less on South	19.41	772	953	1'725
Less on West	19.73	785	956	1'741
More on East	18.95	754	956	1'710

Figure 4.31: Total embodied emission of the extensive building system design.

Configurations	EUI Lean Design [kWh/m2y]	Operational Impact [tCO2]	Embodied Impact [tCO2]	Total Impact [tCO2]
Basis	20.49	815	431	1'246
Less on South	20.54	817	427	1'244
Less on West	20.64	821	431	1'252
More on East	20.00	796	431	1'227

Figure 4.32: Total embodied emission of the lean building system design.

4.5 Design solution of the second phase

To recap, two different core configurations were introduced at this stage of the project: precast concrete or timber. The facades were further analysed by introducing 3 alternatives, 2 of which have two different window layouts, thanks to which different window to wall ratios can be generated which influence the embodied impact and consumption on the operational side. The latter were analysed with a more detailed one-step in the LCA.

Regarding the building systems, taking a whole LCA into account, we can clearly see from Figure 4.32 that the Lean configuration has the lowest environmental impact. Furthermore, looking at the more detailed graphs of the various configurations (Figures 4.28 and 4.30) and comparing them with the embodied emissions, we can see that the implementation of a heat pump water heater is of definite advantage in the total system analysis. These lead us to the following final Lean system chain for this phase of the project.

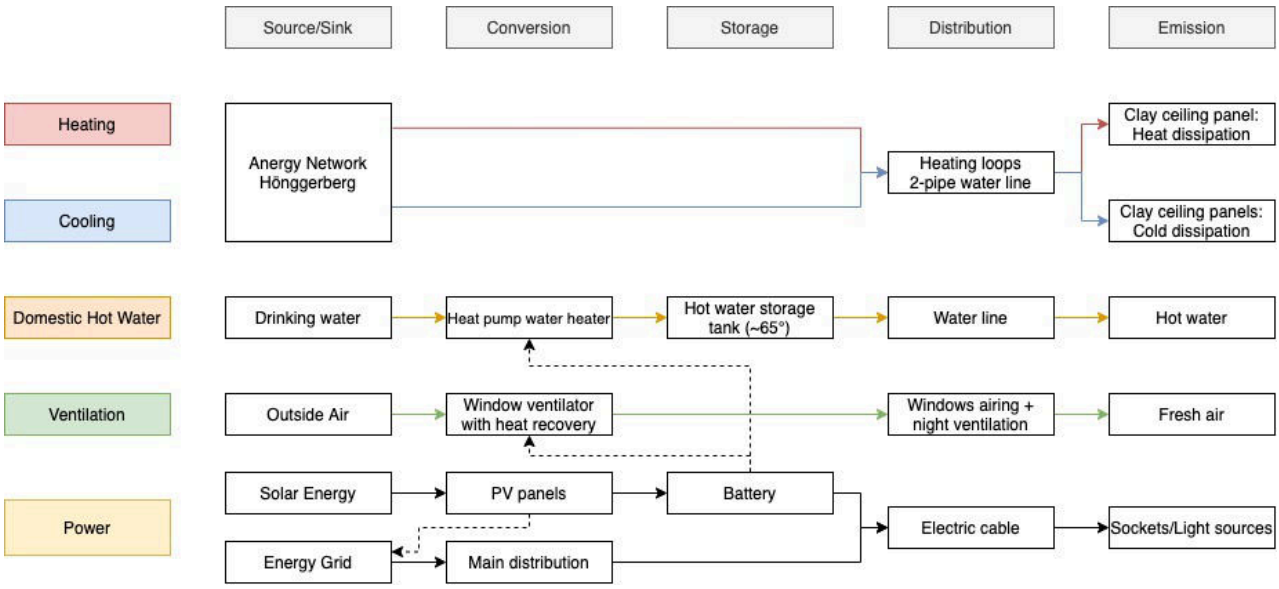


Figure 4.33: Final Lean systems chain in the second design phase.

5 Third Design Phase

5.1 Finding interior design elements

Entering in the third design phase the focus shifted on the interior design, particularly how the interior flexibility could be ensured by equipping the building with appropriate wall systems. This was made possible also by the LOD 200 model, which provided the possibility to visualize our decisions for a better understanding.

5.1.1 Interior walls

Essential for the decision of the internal walls, was at first to define, with the help of the digital model, the intended use of the internal space. This way allowed to determine which rooms would need fixed walls and which one would be better served with moving or rotating walls. In order to suit all the needs for the interdisciplinary building use the team came up with the following three different typologies of internal walls. The location of the walls within the floors can be seen in figures 5.5 to 5.9.

- Fixed walls
  Fixed walls are used principally on the two underground floors (UG 1 and UG 2) and on the first two upper floors (OG 1 and OG 2) as well as partially in EG 1 and 2, to delimit the offices and laboratories. Even though they are named "fixed walls" they are designed to be moved, maybe not on a daily basis but for example in case there will be a change in use of an office after some months or years. For these walls the technology of EcoCell have been chosen. They consist of two wooden panels with in between a layer of recycled paper insulation. The connectors are made of the same materials and can simply be screwed into the floor. The following figure 5.1 represent a visualization of a fixed wall in the digital model.

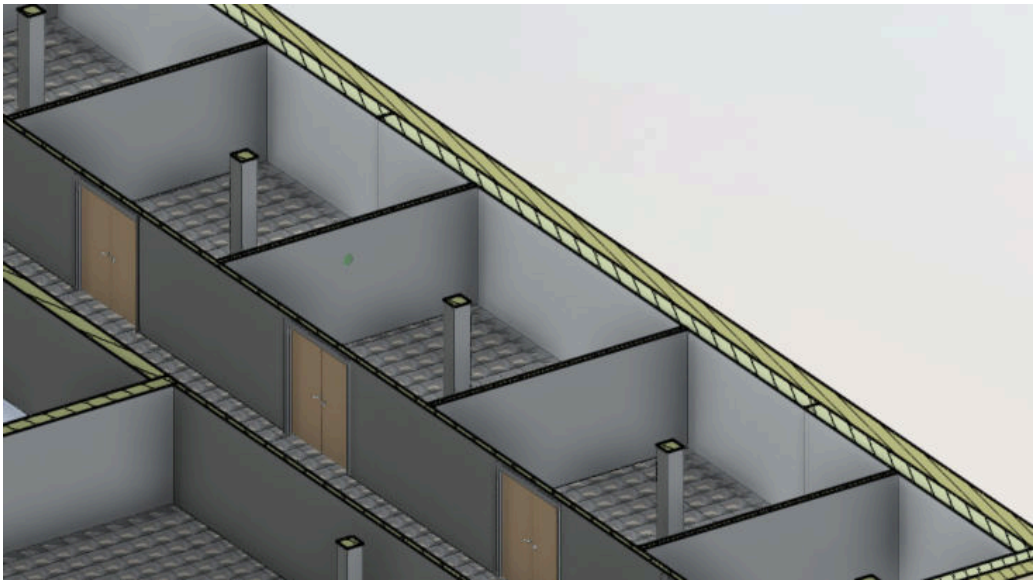


Figure 5.1: EcoCell walls on the UG 2.

- Rotating walls
  Rotating walls are dedicated to the rooms whose needs frequently to change its use. For instance on the last floor, where the lecture halls can be found. They are made with timber chipboards with steel rotating mechanisms. A rendering of their implementation in the BIM model can be seen below.

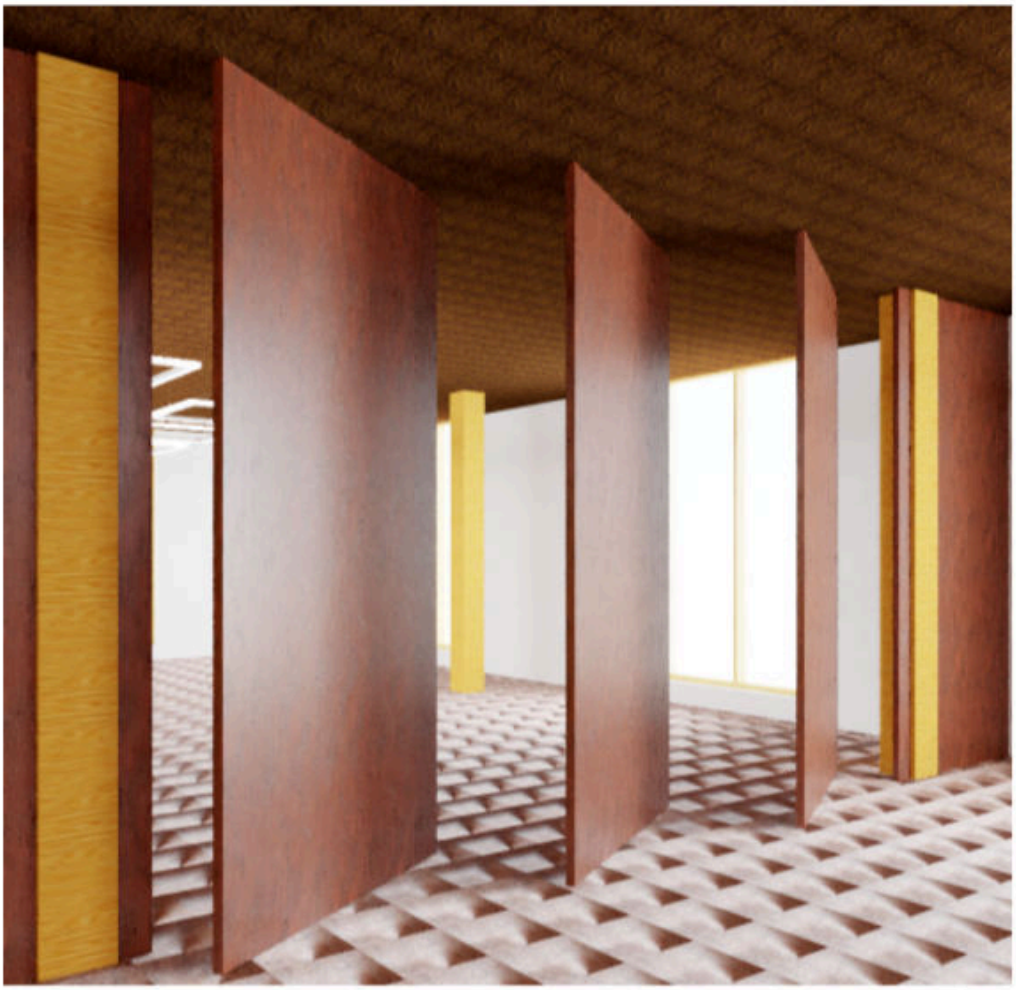


Figure 5.2: Rotating walls on the OG 3.

- Movable separation walls
  These separation walls are entirely made of reused timber and windows from the dismantled architect's buildings on the ETH campus. They are used principally in the ground floor 1 and can be easily moved around depending on the space use.



Figure 5.3: Rendering of the model with the reused timber and glass walls on the EG 1. (Source: LOD300+ Model)

Additionally to the above mentioned internal walls, on the first and second upper floor there are three meeting modules each. They allow to have small and flexible meeting spaces, whose provide the little bit of privacy that some discussion require. These modules are made with the reused windows of the dismantled buildings as well. Again, below a rendering of the model can be seen.



Figure 5.4: Rendering of the model with the meeting modules on the first two upper floors. (Source: LOD300+ Model)

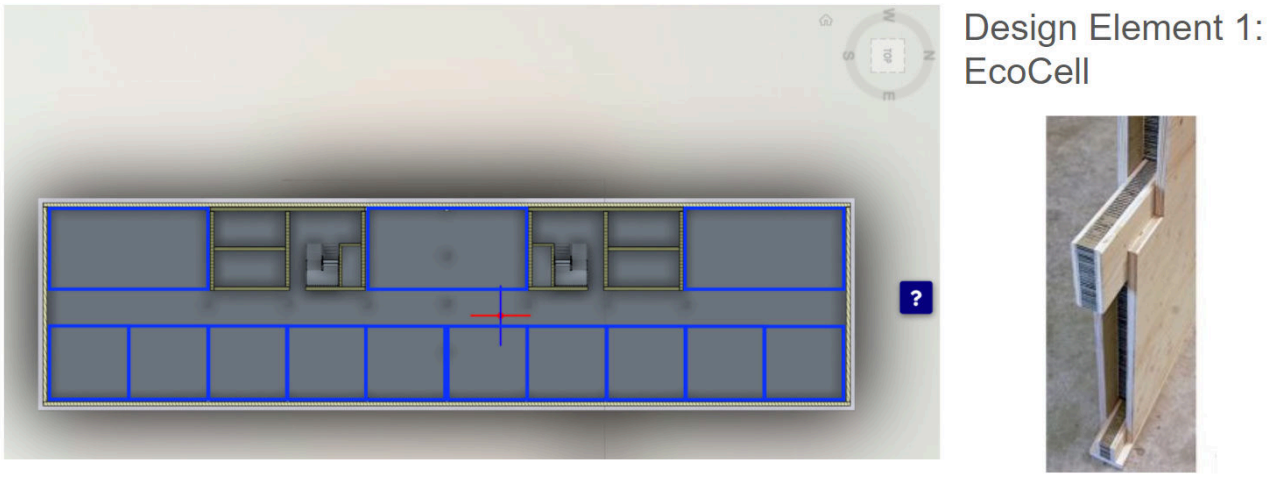


Figure 5.5: Interior layout UG 1 and UG 2.

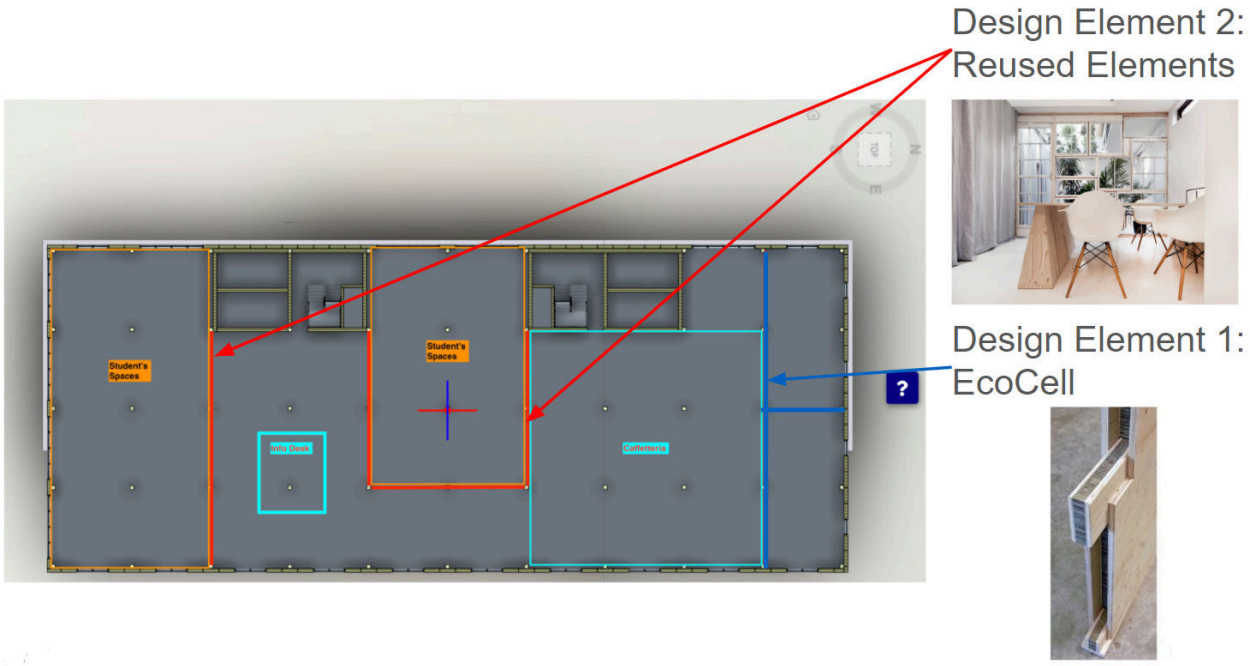


Figure 5.6: Interior layout EG 1.

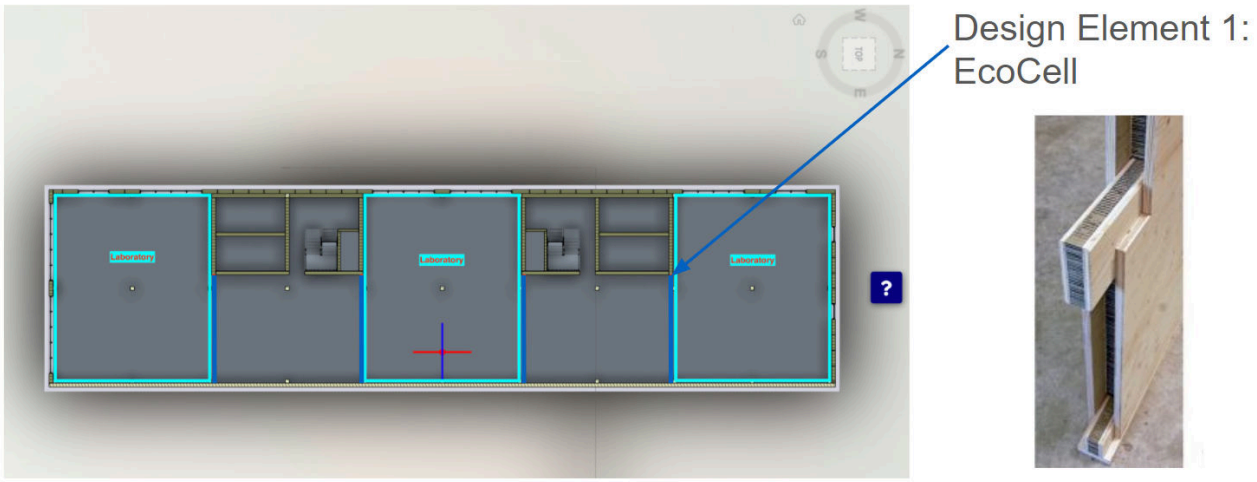


Figure 5.7: Interior layout EG 2.

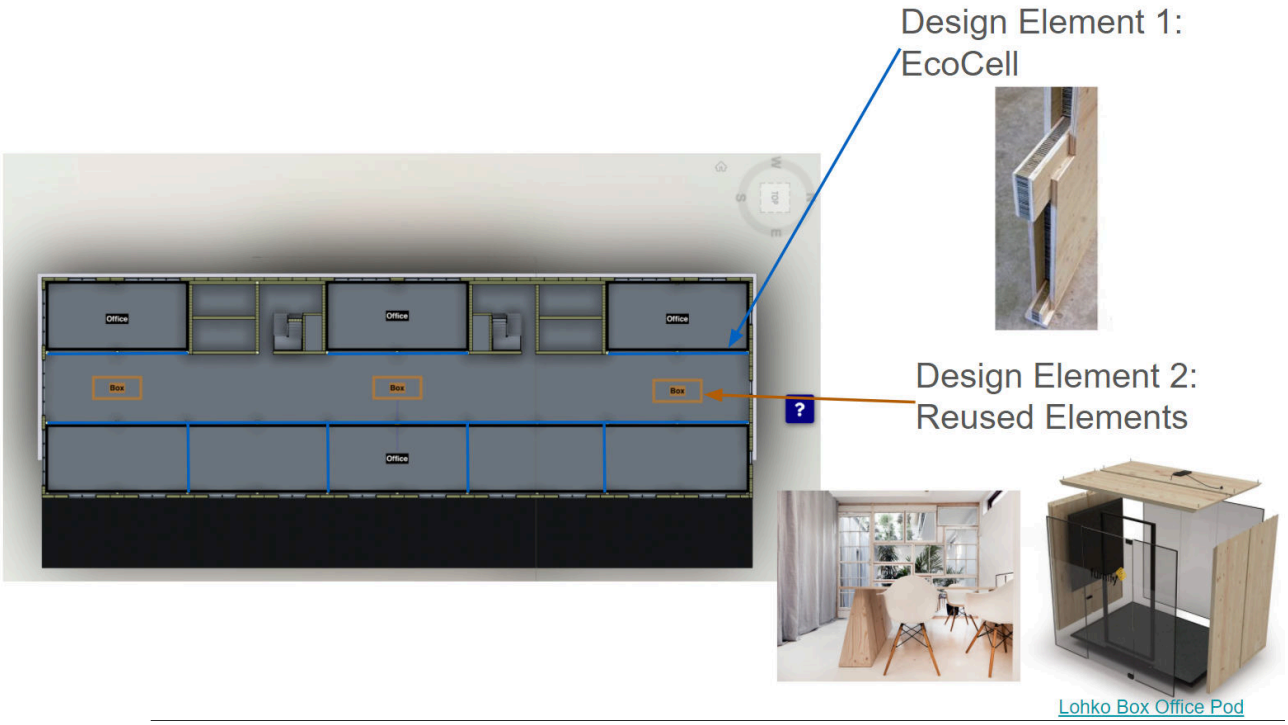


Figure 5.8: Interior layout OG 1 and OG 2.

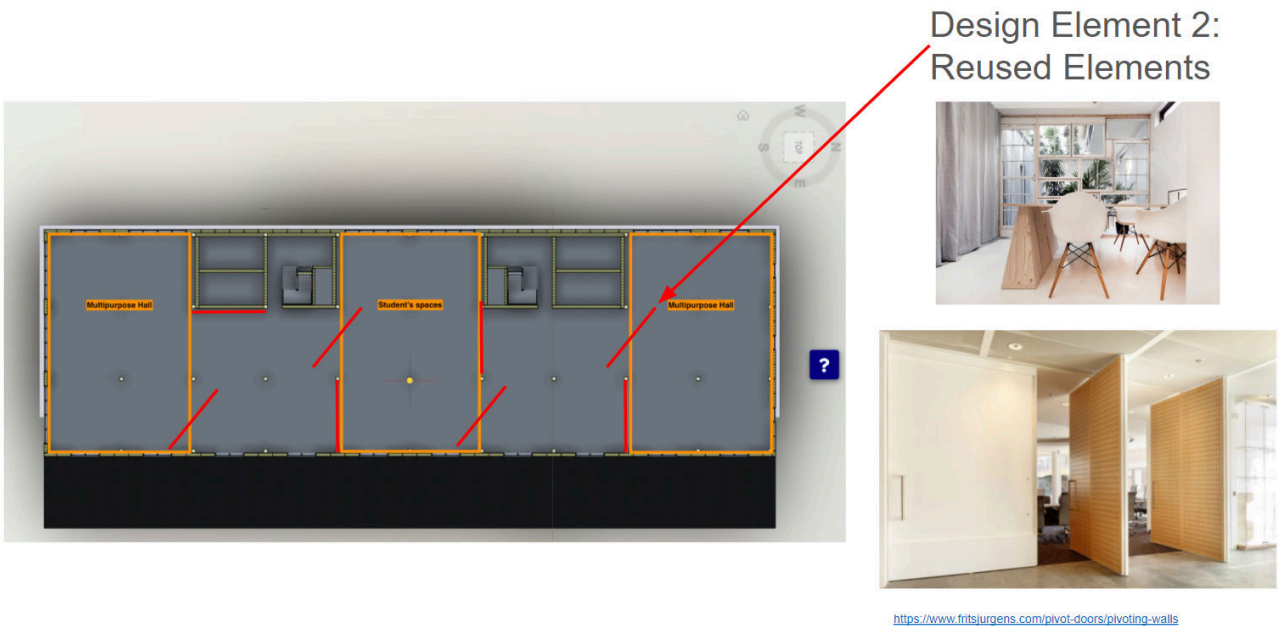


Figure 5.9: Interior layout OG 3.

5.2 Energy generation and storage

At this stage we looked in a little more detail at energy production, using solar panels, and storage of excess energy.

For energy production we decided to implement a PV uniaxial tracking systems 5.10, that follow the sun's trajectory and ensure an ideal angle of incidence, in order to have a better energy production, which can reach up to 30% more [7]. This allows us to reduce emissions on the operational side, without having to increase the area of PV, whose production has a high environmental impact, but simply by introducing a simple rotating mechanism that has a lower embodied impact compared to an equivalent panels area. From the LCA estimates, the increase in PV panels area would have resulted in an embodied impact of 57 tCO_2, on the other hand the rotating support mechanism has an estimated impact of 2 tCO_2 (more details in the LCA in the Appendix 8.1.3).

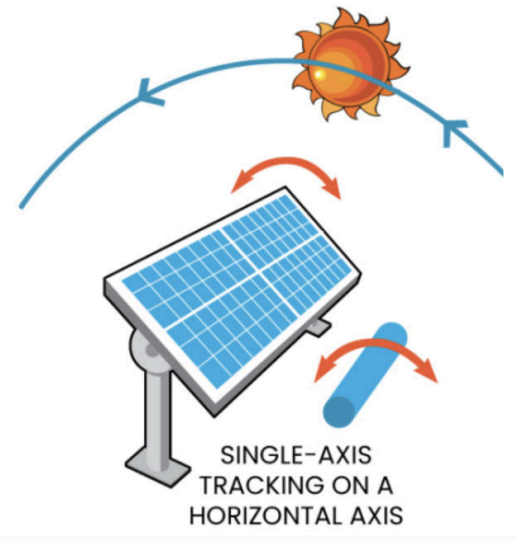


Figure 5.10: PV uniaxial tracking systems. [15]

Regarding the excess energy storage system, we tried to implement an out-of-the-box idea. Taking into consideration that the building has a very flexible concept and that it may require several modifications during its lifespan, e.g. changing the facades of the building, this involves the use of one or more cranes.

At this point the idea was to implement one or more cranes on the sides of the building and when these are not being used to make changes to the building layout, to use them as a gravity and kinetic energy based battery. The concept is very simple, tested and applied in Switzerland by Energy Vault [13], and consists of lifting masses, thus using energy, and storing it in potential form. This will then be released when needed by simply lowering the masses, transforming the kinetic energy into electricity.

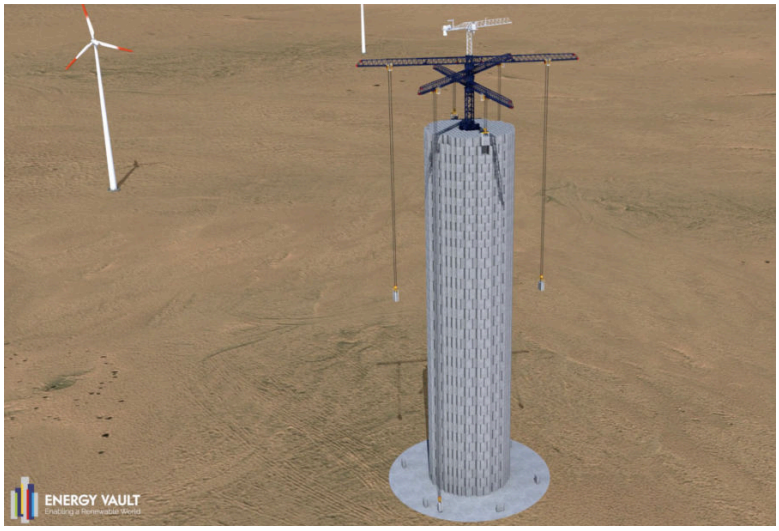


Figure 5.11: Energy Vault energy storing system. [13]

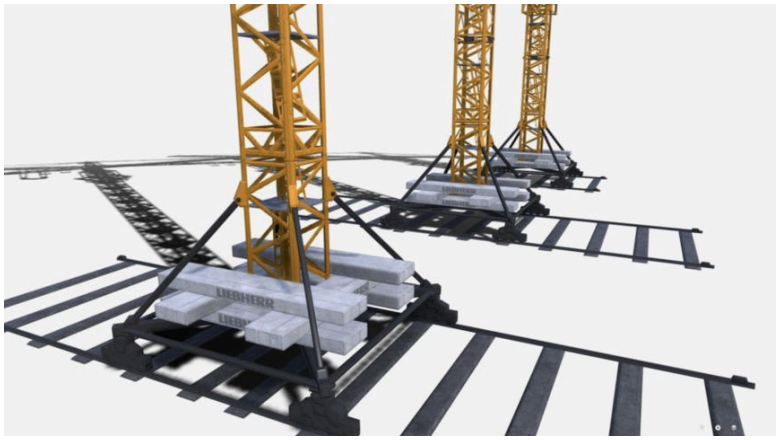


Figure 5.12: Possible implementation of mobile crane. [6]

Unfortunately, this viable alternative did not prove possible due to the high embodied impact of producing a crane, the value of which far exceeded that of a more conventional battery: the equivalent of 100 tCO_2 (for 2 cranes) against 3 tCO_2 for 6 batteries, for the same storage capacity and lifespan (more details in the LCA in the Appendix 8.1.3). In particular, the batteries chosen are 3 Tesla Powerwalls, which are currently among the best performing batteries on the market, with a capacity of 13.5 kWh, and a lifecycle of about 30 years. The production will take place near Berlin [11].

5.3 Model LOD300

In the third design stage, the BIM manager's task was to capture and showcase even more details both in the interior and exterior of the building and to represent them in a model as a specific system of families or assemblies, with accurate sizes, quantities and properties. The geometric constraints of the LOD300 model were based on the approximate dimensions and configuration of the LOD200 model discussed in section 4.2. As expected, this was the longest modelling iteration of all four phases, since it required detailed coordination of more than 70'000 elements within the model. At this point in time, our team was focused on implementing design elements accurately and we did not load any custom, non-graphic information from the material passport into the model. In contrast to the LOD200 model, the LOD300 model was mostly modelled with custom loadable families instead of REVIT pre-defined system families. 30 families have been used throughout the model, which shows the extent at which going into detail may result in an abundance of modelling elements. Figure 5.13 shows the LOD300 model.

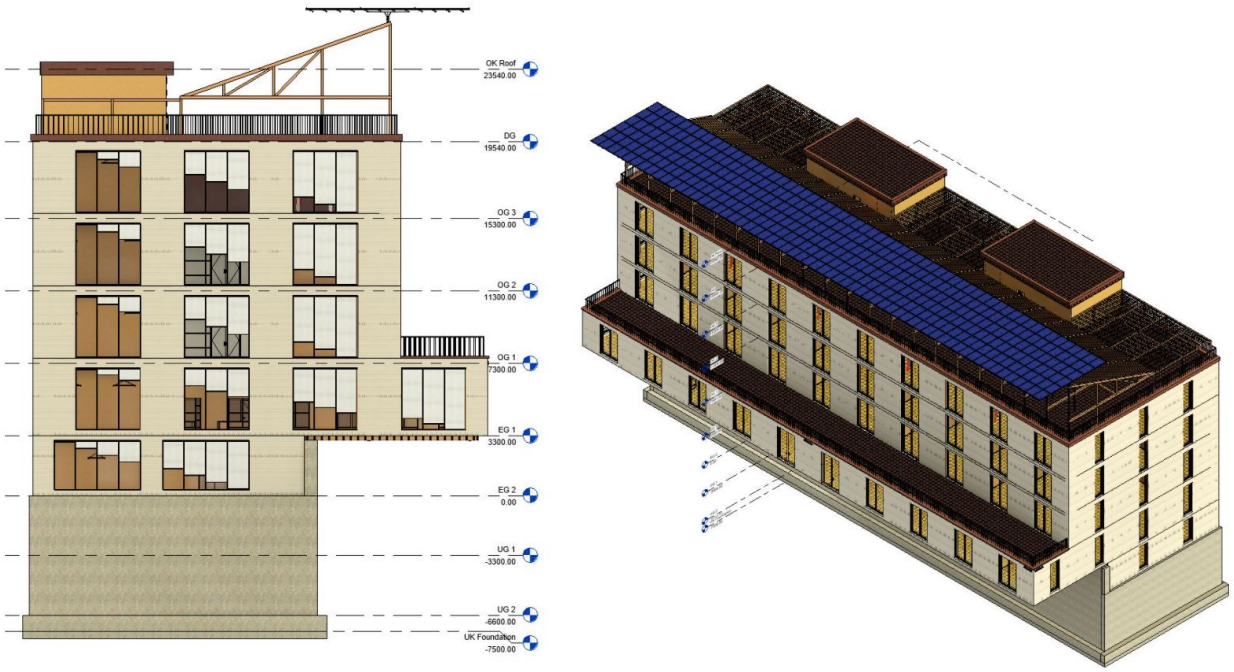


Figure 5.13: Elevation view of the LOD300 model (left), Isometric view of the LOD300 model (right).

The following sections are a detailed account of all the design elements within the LOD300 model.

5.3.1 Foundation and lower concrete retaining walls

The foundation and lower concrete retaining walls underwent minimal transformation. The only addition to this system were the 40cm thick MISAPOR foundation floor/wall insulation material which insulate the entire foundation system.

5.3.2 Core

After researching the possibilities of incorporating a CLT core in the design, our team decided to change the previous design choice. Furthermore, the dimension of the core also changed slightly in order to fit the necessary Aeternum slab angle connectors. The orientation of the stairs also changed in order for the fitting of the elevator shaft and access to both water closets to make sense. Figure 5.15 shows the core system in more detail.

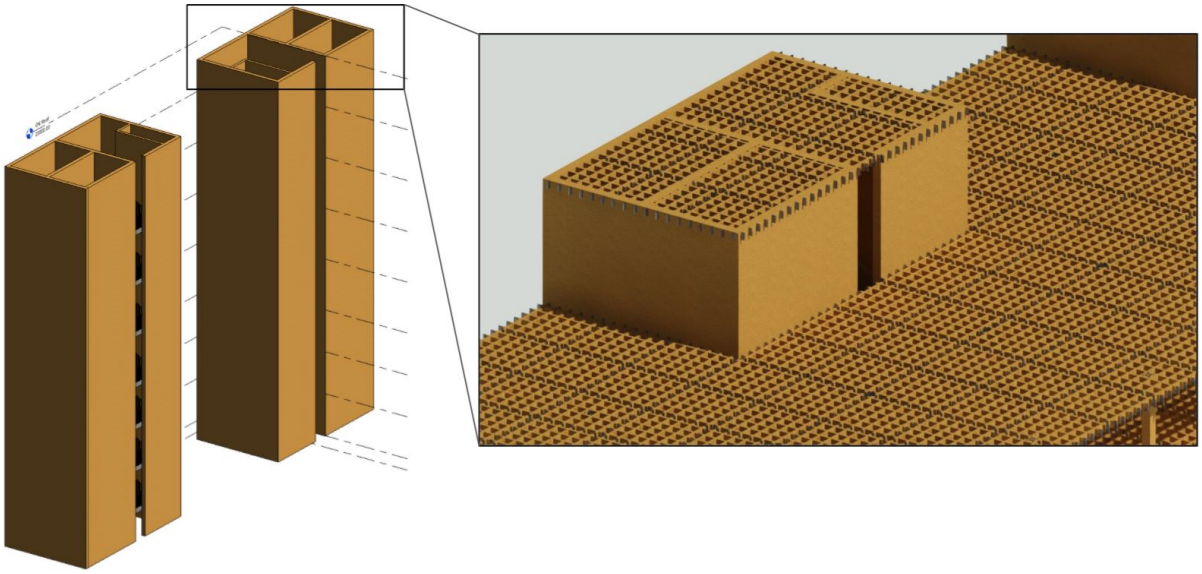


Figure 5.14: Details of the CLT core.

5.3.3 Slabs

Our team obtained Sketchup CAD files for the Aeternum structural elements after a conversation about the structural properties and limitations of the Aeternum elements with Aeternum's founder. There were however, interoperability issues since the Sketchup elements could not be directly used in a REVIT project, and exporting it into an IFC format also meant losing a lot of detail in translation. This is the BIM manager decided to manually convert the Sketchup file into a REVIT family. In doing so, layers were assigned to each material type within Sketchup and then the Sketchup file was exported into a dwg format. In the next step, the dwg file was imported into Autodesk AutoCAD and the layer coloring was set according to block. As a last step, the modified dwg file was then imported into a REVIT family template and materials from the REVIT library were assigned to each layer. Figure shows a regular Aeternum slab element. Furthermore, depending on the position of the Aeternum raster within the slab element and its connection to adjacent elements, three Aeternum slab types were created, namely: regular, one-sided side type and two-sided corner. Figure 5.16 shows the different Aeternum Slab family types.

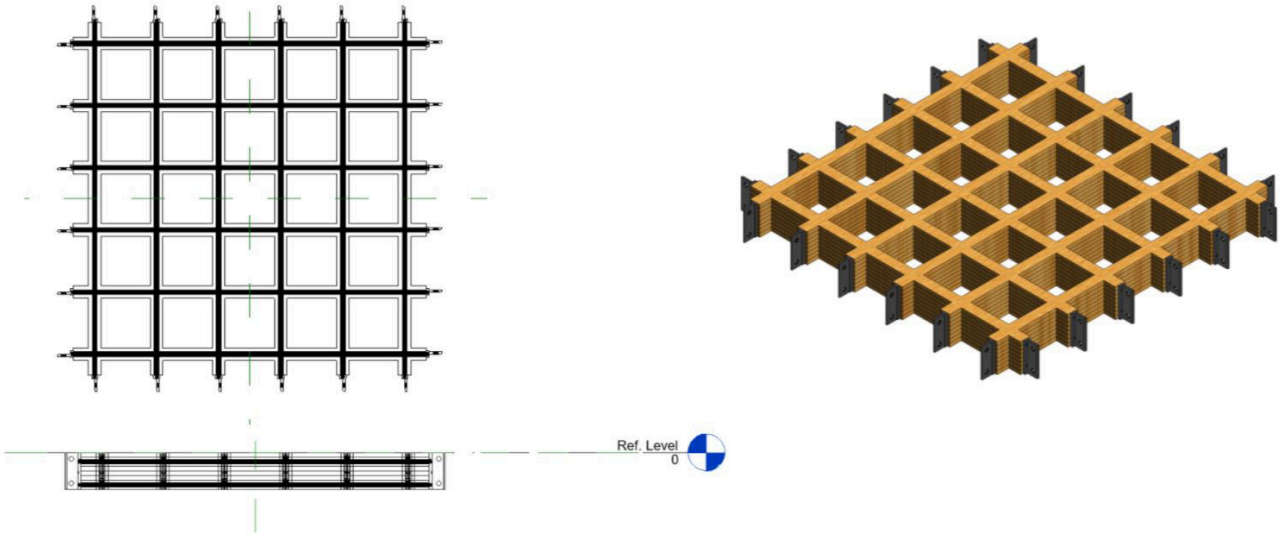


Figure 5.15: Regular Aeternum Slab structure with timber raster, inner rebars and outer steel angle connectors

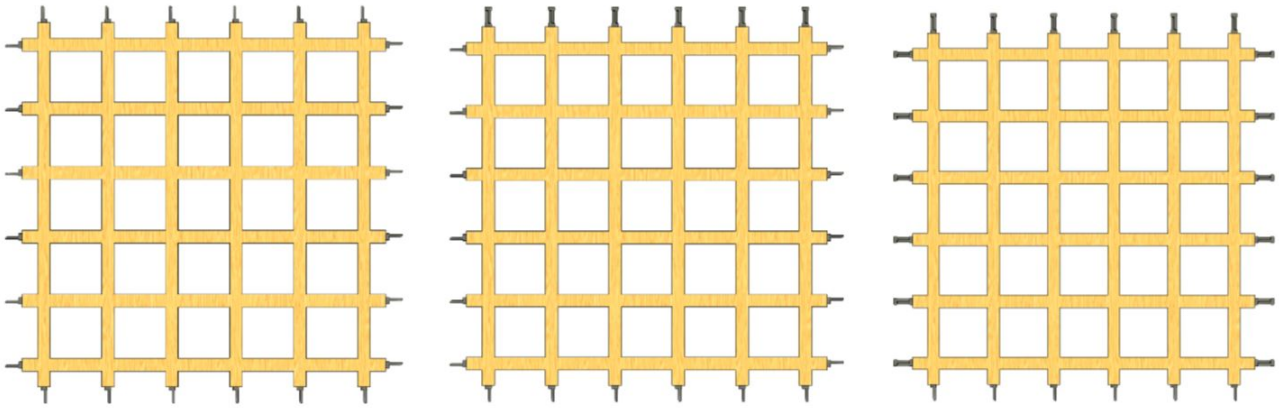


Figure 5.16: Regular Aeternum slab (left), one-sided side Aeternum slab (middle), two-sided corner Aeternum slab (right).

The floor tiles were created with the Aeternum wooden timber raster in mind. Each floor tile had an 8 cm thick clay tile with a glulam timber stem connected to it which would fit inside the raster slots. In order to take into account the geometric variation of the floor tiles in the middle, corners and sides of the floor slab, four floor tile types were created, namely: regular, side, corner and ring which are shown in figure 5.17 . The ring floor tile was placed around Aeternum columns so that the columns would go through it.

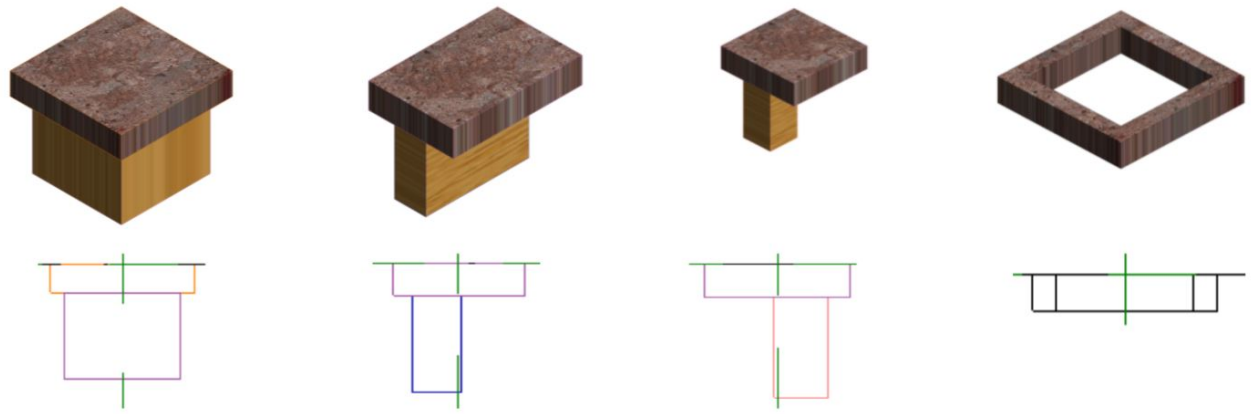


Figure 5.17: From left to right, regular, side, corner, ring floor tiles.

5.3.4 Structural Framing

As discussed in section 5.3.3, the structural framing was also obtained from the aforementioned Sketchup files. After conversion, two separate column families were created, namely: regular columns and corner columns. Each Aeternum column is connected to the column below/above through its top/bottom connector system. Corner columns have a smaller top supporting plate beneath the connector which ensures that the slab support would not stick out of the building footprint as evident from figure 5.18. This is why they were positioned along the corners and sides of the building.

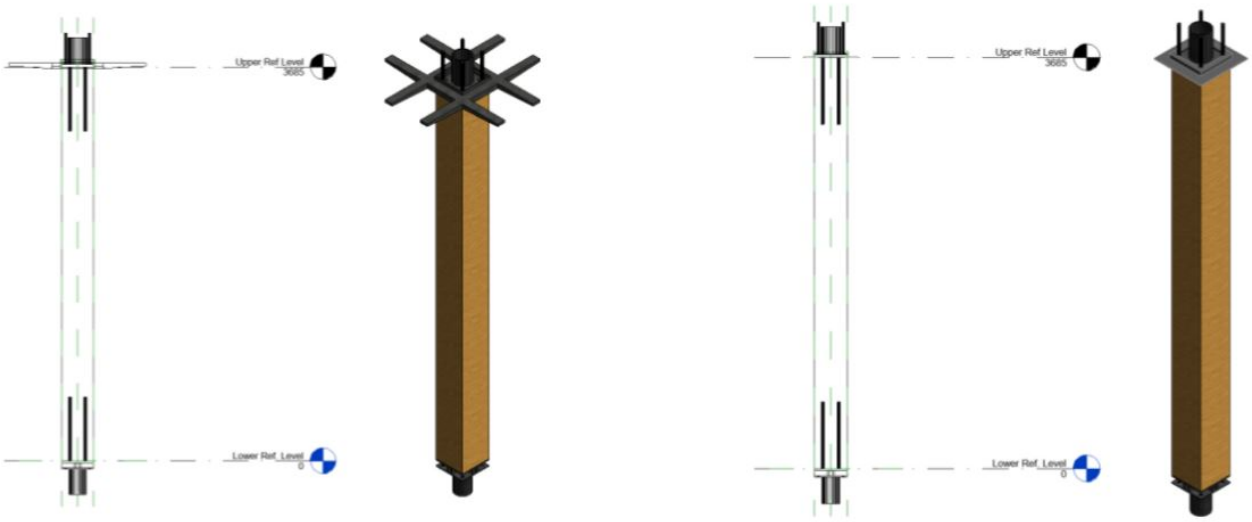


Figure 5.18: Regular Aeternum column (left), corner Aeternum column (right).

Figures 5.19 and show the complete Aeternum structural system which is an interplay of Aeternum columns, slabs and floor tiles.

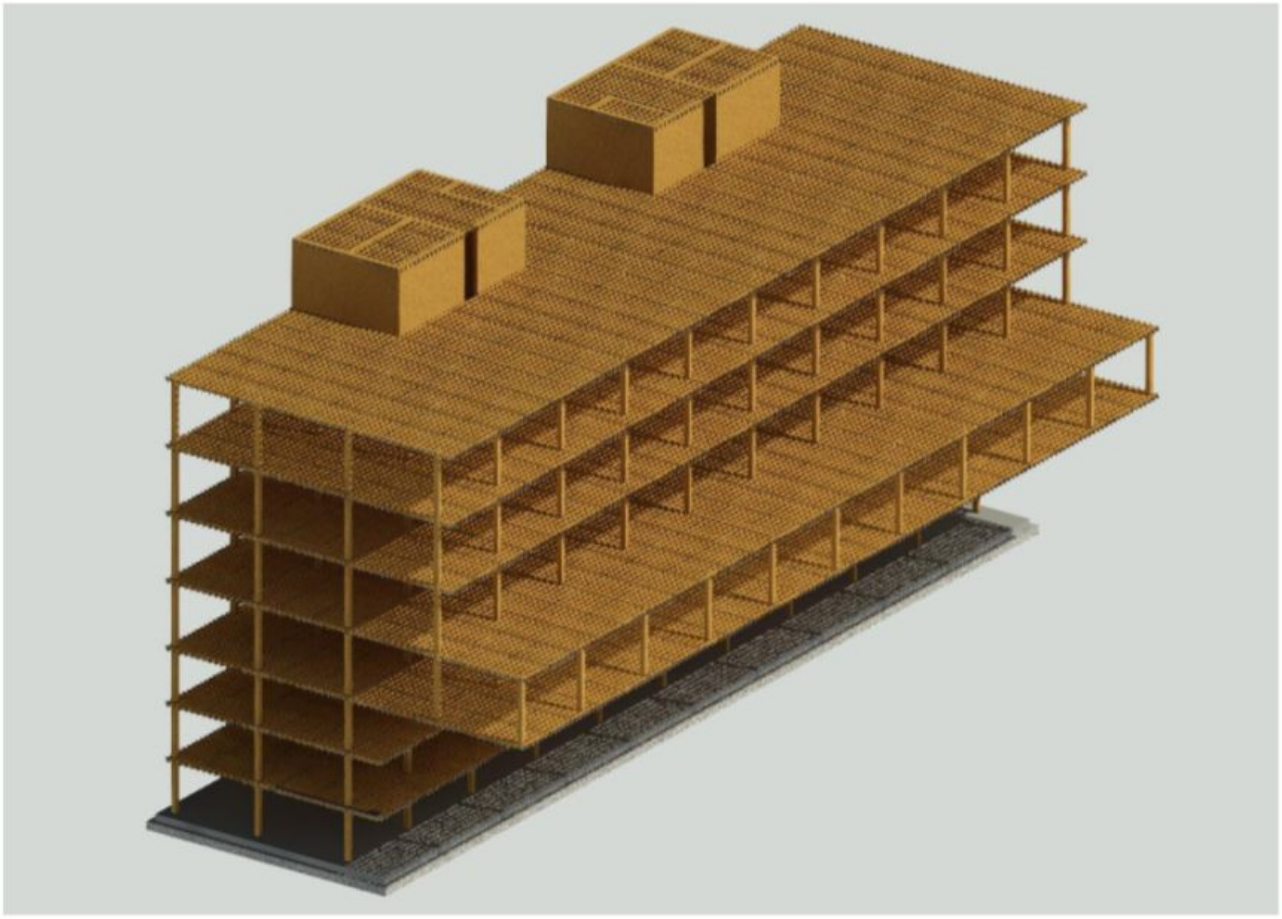


Figure 5.19: Complete Aeternum system.

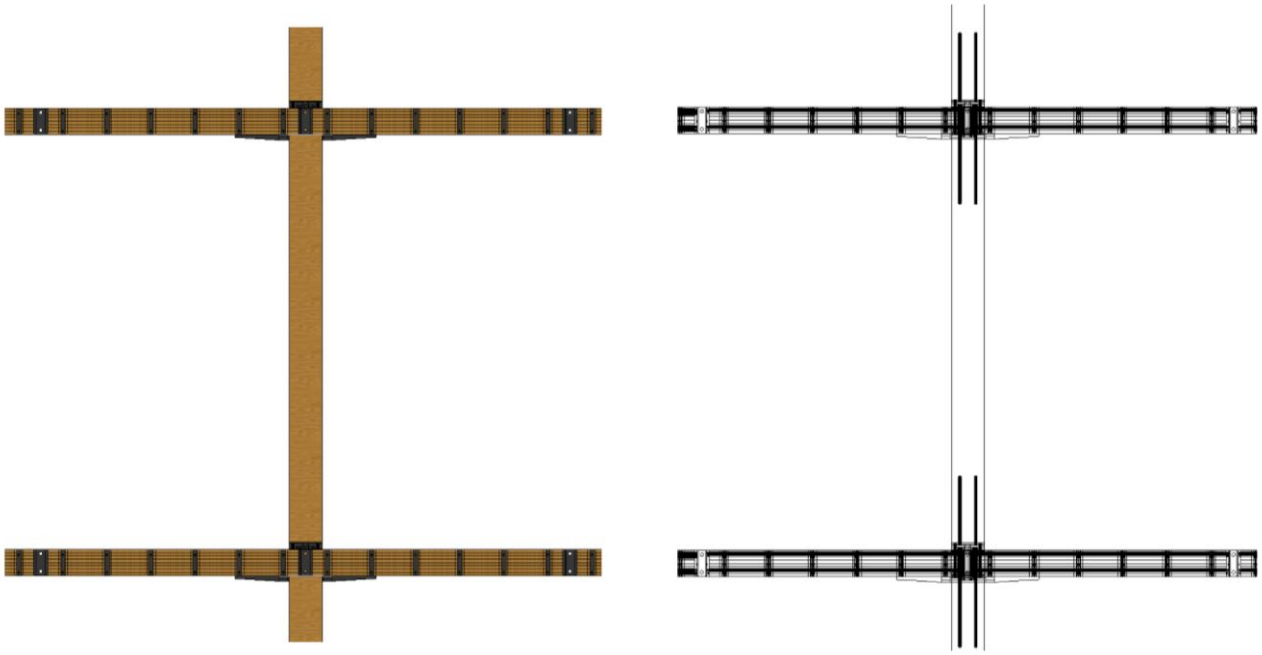


Figure 5.20: Interplay of different Aeternum system elements.

The lecture halls discussed in section 4.2.5 were relocated to the top floor (OG3) in order to allow for a continuation of load transfer from the top to the foundation and to avoid any unwanted buckling effects in the lower parts of the structure. This meant that some of the columns in on the southern and northern parts of the building were omitted. In order to keep the structural balance, another layer of Aeternum wooden slabs were added to level DG to ensure structural rigidity.

5.3.5 Facade

The facade was designed in a way which would sit flush to the Aeternum slab connectors so they could be disassembled with ease. The facade is based on a panelized system with 1.2 m panel width so that it could be adjusted to the Aeternum raster width. A REVIT pre-defined system architectural wall family was modified in order to create the layered composition of EcoCocon. The internal timber frame structure of the facade panels was created using 6 different structural assemblies. The different assembly types, arose from the differences in level heights (underground levels and above ground levels) and panel position (corner, middle). Figures 5.21 and 5.22 show the facade panel in more detail.

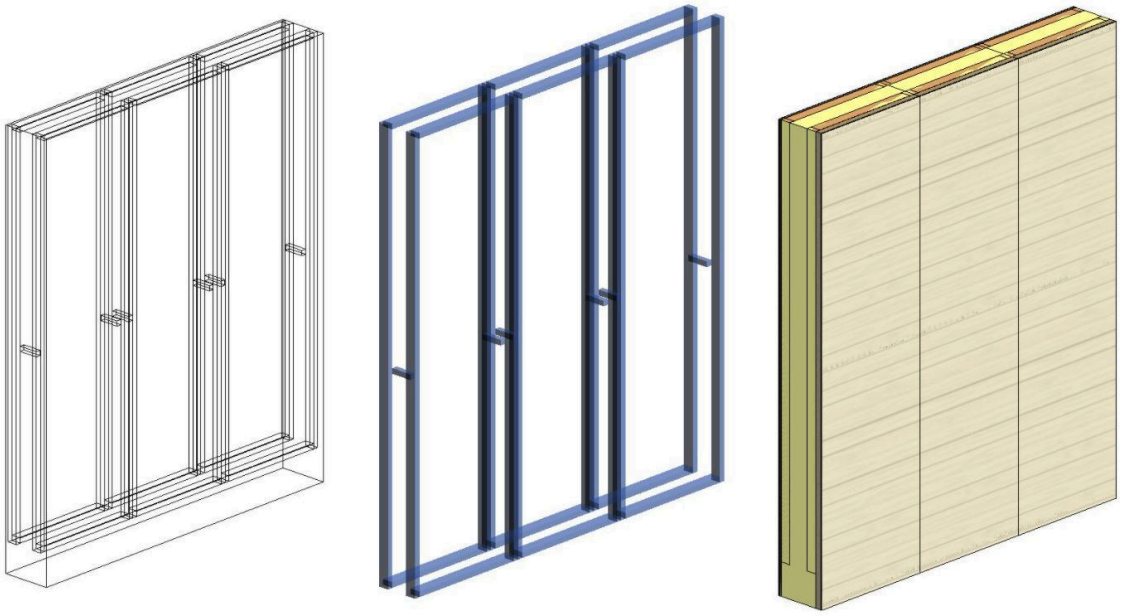


Figure 5.21: Structure and layers of the facade panel.

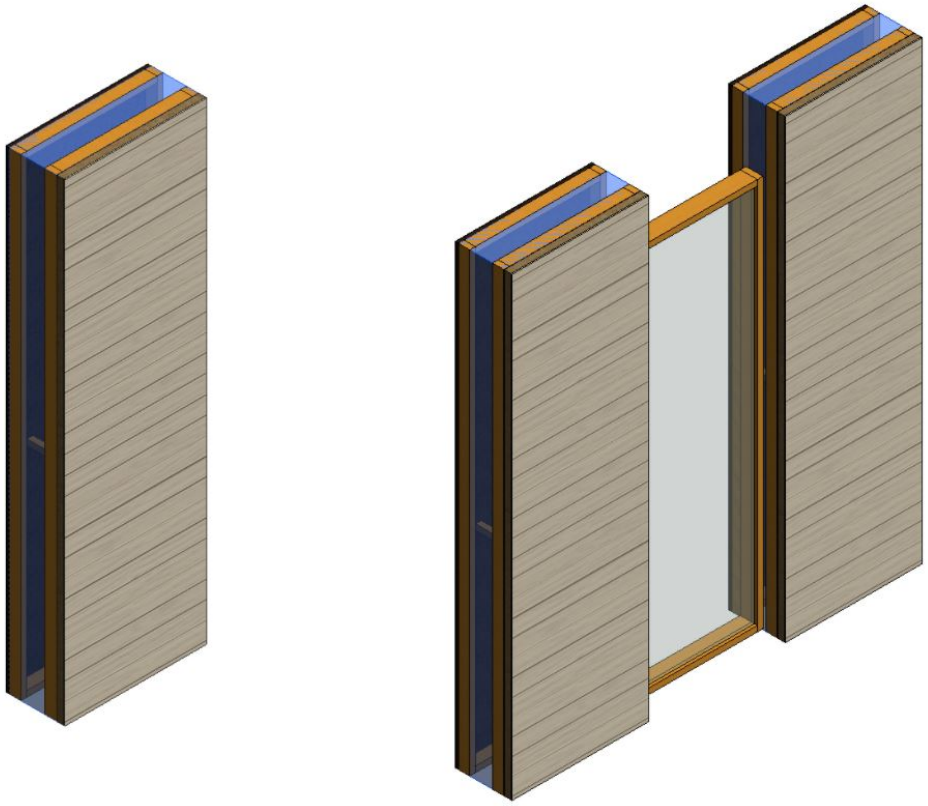


Figure 5.22: Different Assembly types of facade panels and their relation to window openings.

5.3.6 Pergola

The complete dimensions of the load-bearing trusses of the old architect's building on the ETH campus of Hönggerberg presented in section 3.2.4 were extracted from the plans and was created as a modified M_Pratt gabled truss with 8 panels. These trusses were used as the east-side pergola structure. The regular pergola structural system included a framing system made of 12cm× 12 cm rectangular glulam timber profiles. A beam system comprised of 3cm× 12 cm rectangular lumber profiles as shading elements was created with a spacing of 28.8 cm on top of the pergola structural system. These shading elements had a checkered pattern on the regular side of the pergola. Figures 5.23 and 5.24 illustrate the reused pergola system.

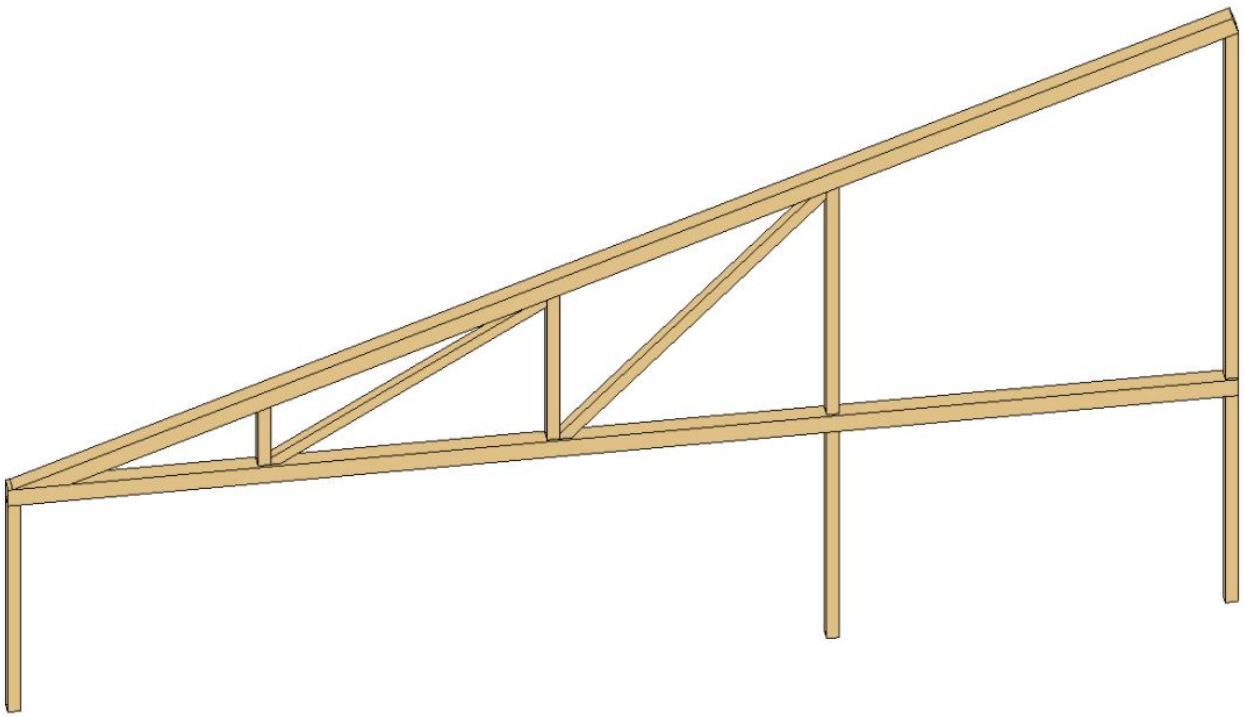


Figure 5.23: Reused pergola from the HIP building on the ETH campus of Hönggerberg.



Figure 5.24: Rendering of the rooftop's pergola with the pv-panels on top. (Source: LOD300+ Model)

5.3.7 Stairs

Being an integral part of the cores, the stair materials also resembled that of the core which was made of CLT. The stairs have steel railings and a wooden handrail. On level OG3, since the roof has two layers of the Aeternum slab system and an insulation layer that comes on top, an extra mid run was added in order to cover the height difference. As a result WC's on the DG level are smaller than the rest of the levels. Figure 5.25 and 5.26 show the stair system and the stair in OG3 respectively.



Figure 5.25: Plan view and Isometric view of the stair system.

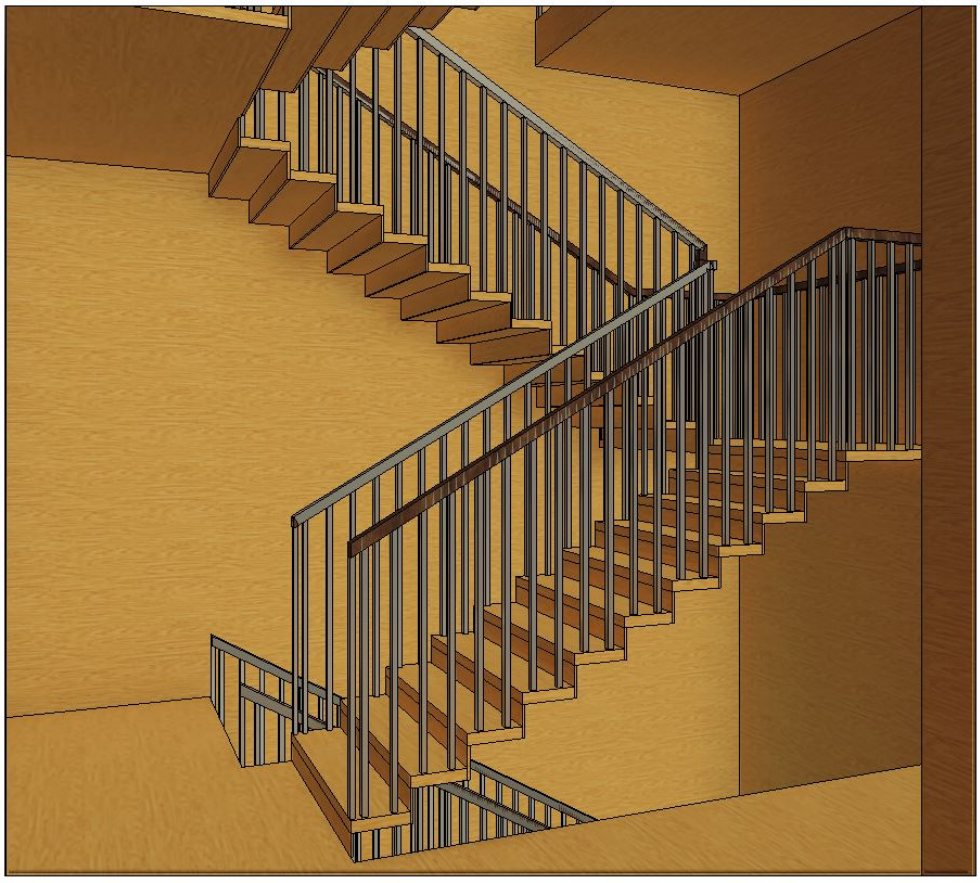


Figure 5.26: Addition of a mid-level run on level OG3.

5.3.8 Roof Insulation

An Insulation tile family was created so that in could be layed on top of the clay Aeternum flooring clay tiles such that the building was insulated against heat, sound and humidity. These insulation tiles had a 20 cm thick straw layer, followed by a thin 2 mm damp-proofing film and a 3 cm thick wooden tile on top. These tiles had the same footprint as the Aeternum flooring clay tiles, and as such had the same family types, namely: regular, side and corner insulation tiles.Figure 5.27 shows the different roof insulation family types.

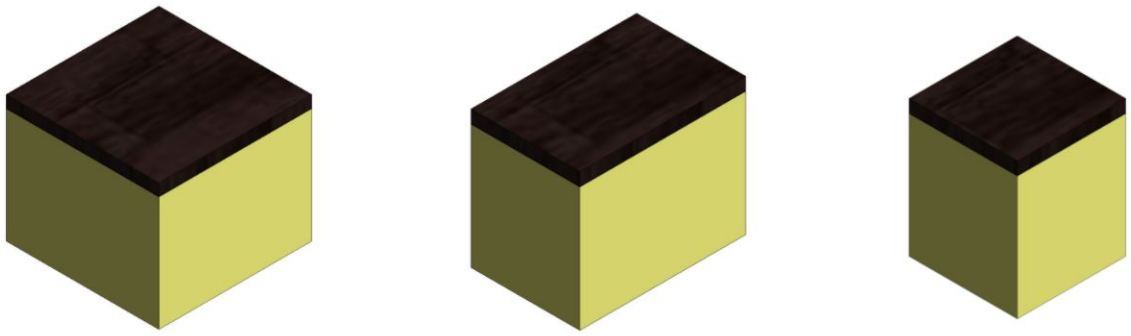


Figure 5.27: Interplay of different Aeternum system elements.

5.3.9 Interior Ecocell wall panel

The interior Ecocell wall panels were modelled using REVIT pre-defined architectural walls and the base T-connector was modelled using a line based profile family. The structure of the Ecocell wall panel is shown in figure 5.28.

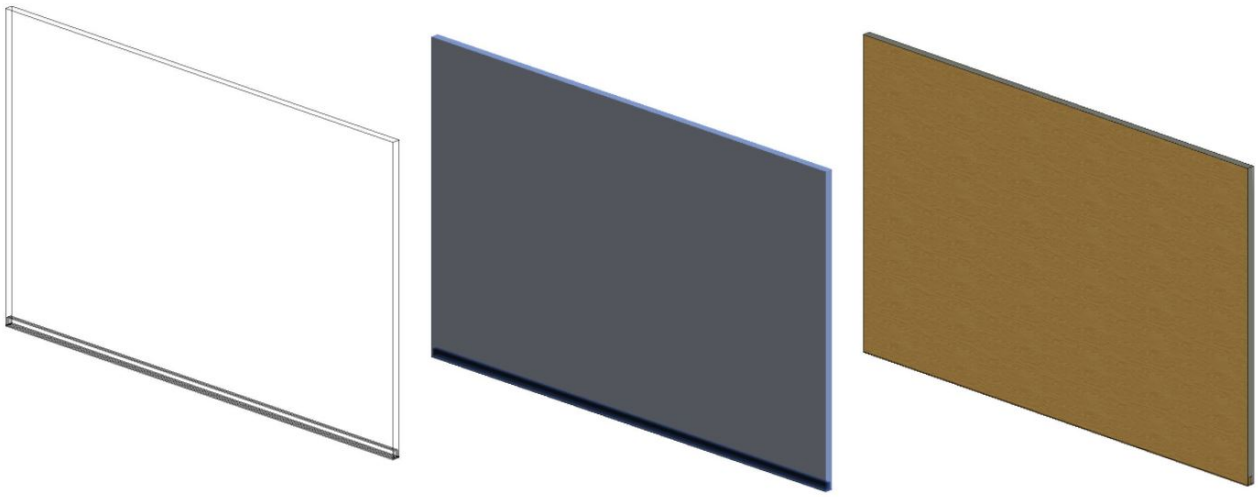


Figure 5.28: Structure and layers of the Ecocell interior wall panels.

5.3.10 Interior rotatable OSB walls

The interior rotatable OSB walls of FritsJurgens were imported from an external database. This family and its types are modelled as revolving doors. The top and bottom hinges would be mounted on the Aeternum clay flooring tile and the cooling clay panels respectively. The intrior rotatable OSB walls shown in figure 5.29 are only used in the last floor (OG3) as entrances to the main lecture halls (illustrated in figure **??**).

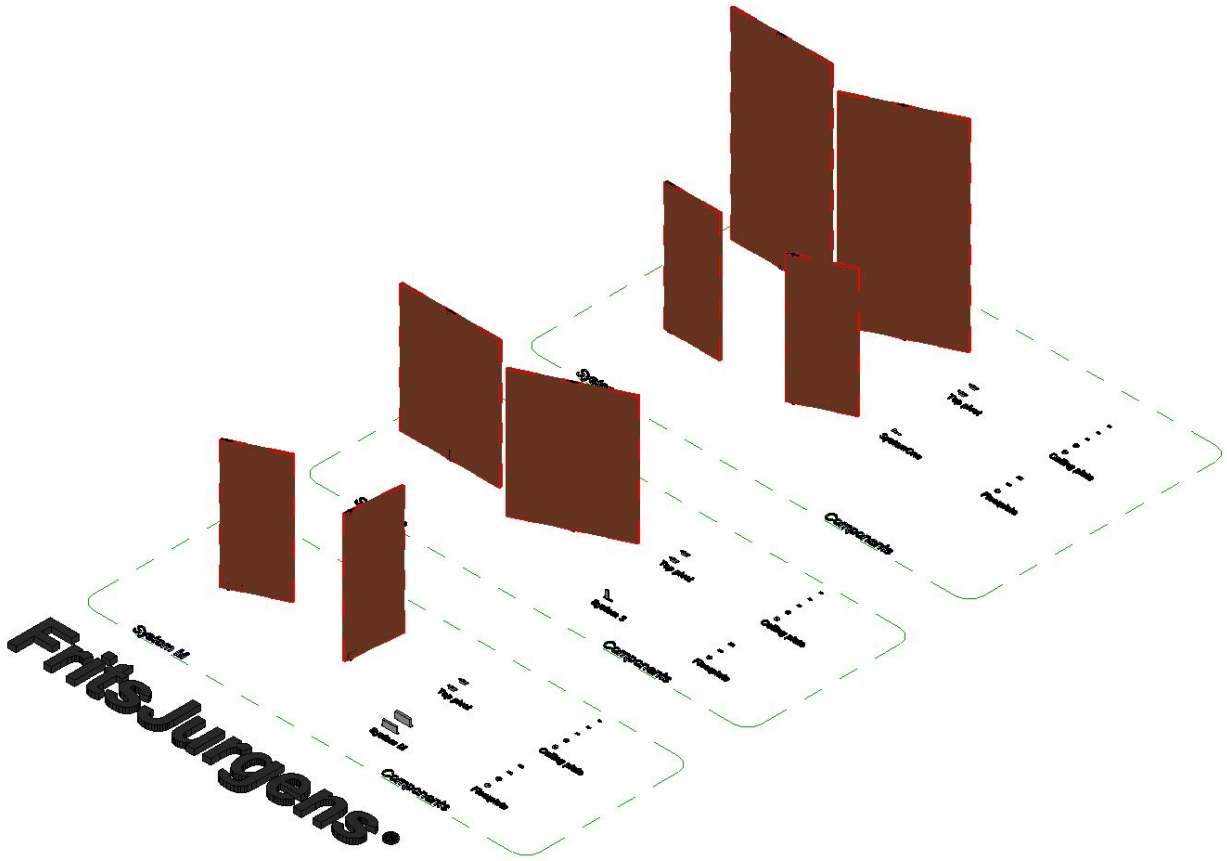


Figure 5.29: The FritsJurgens rotatable OSB wall family types.

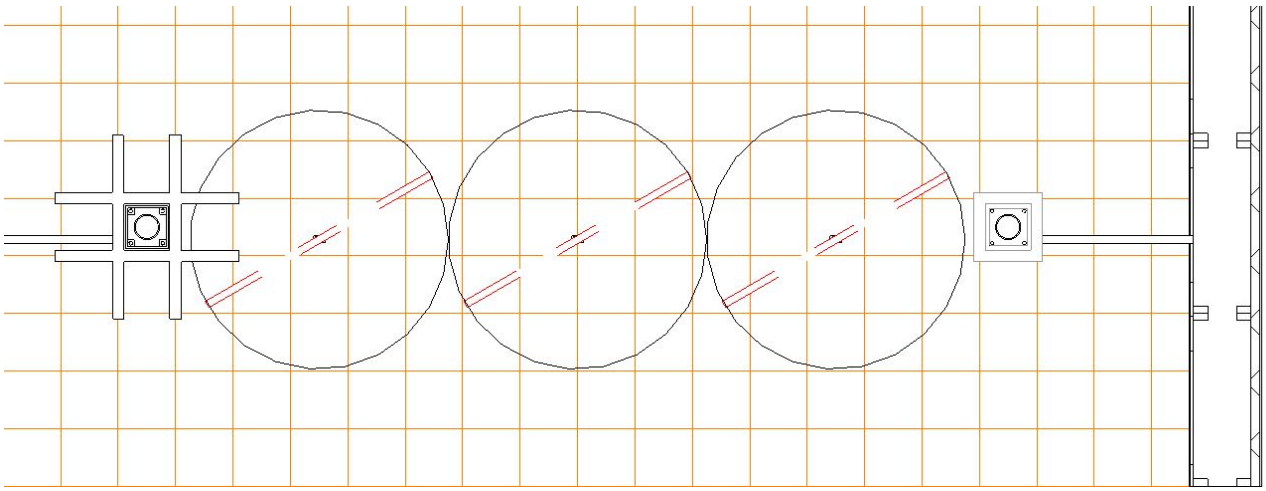


Figure 5.30: Plan view of the rotatable OSB walls on level OG3.

5.3.11 Office modules

The office modules were modelled as a 3.2m×4.8m×2.4m cube made of architectural storefront walls. One side of the office module and the roof is made of a simple gypsum plaster-board. The entire office module components were morphed into an assembly so that it could be used more easily throughout the project. The arrangement of the interior walls was altered in order to ensure at least 1 m of space between the opening on each side of the office module in the corridors where it is situated for fire-safety reasons. The office assembly is shown in figure 5.31.

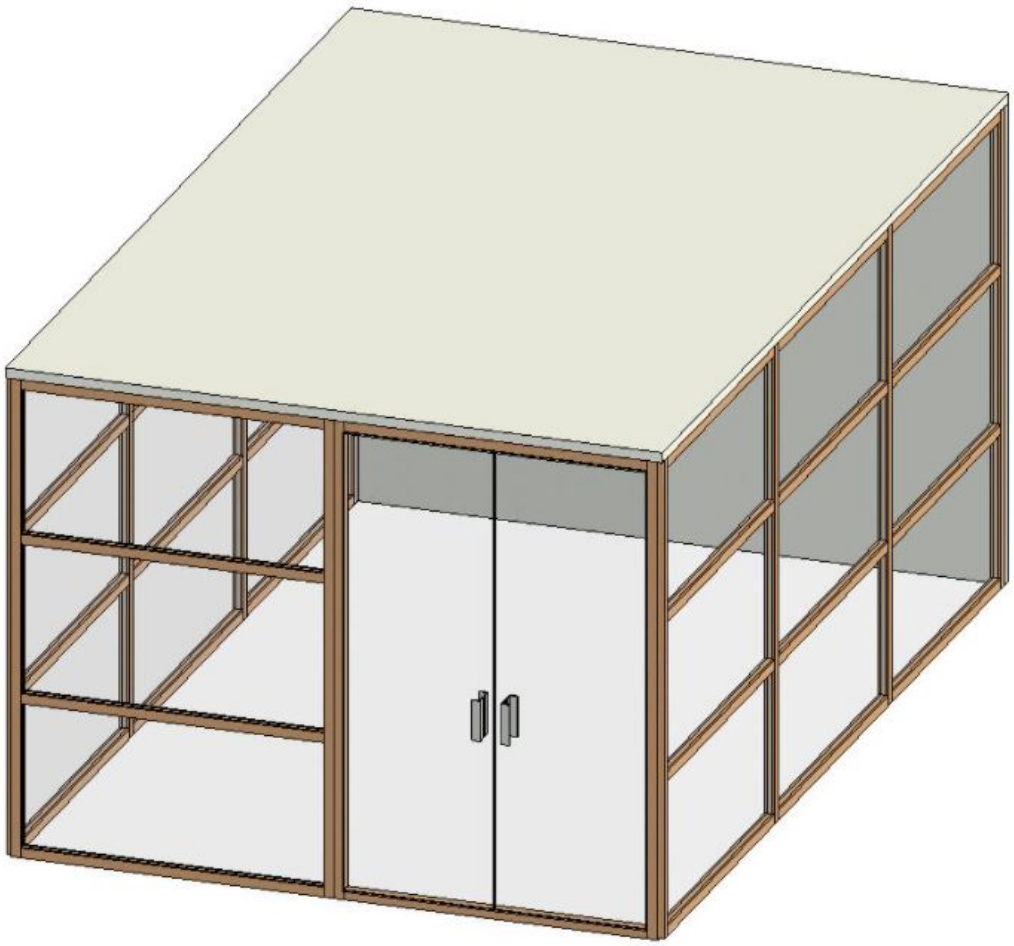


Figure 5.31: Office module assembly.

5.3.12 Interior separation walls

The interior separation walls were modelled using a modified REVIT pre-defined system storefront wall family. For each wall type, the panel composition, geometry and material was altered in order to create the unique interior separation walls made of reused windows. The first type of the separation walls has a width of 1.6 meters and a height of 2 meters. It makes use of a

large 1.6m×1.6m window and a small 1.6m×0.4m reused timber plate. The second type of the separation wall family has a width of 1 meters and a height of 2 meters. It is made of a small 1m×0.8m window and a large 1m×1.2m reused timber plate. Figure 5.32 illustrates the interior separation walls.



Figure 5.32: Interior separation wall types (left: type 2, right: type 1) made of reused windows.

5.3.13 Doors

The Doors were imported from an external database and have two types: Single flush doors and double flush doors. The single flush doors have a dimension of 900mm×2000mm as core entrances and 750mm×2000mm everywhere else. The double flush doors have a dimension of 1700mm×2000mm and are only used in the underground levels. The door types are illustrated in figure 5.33.

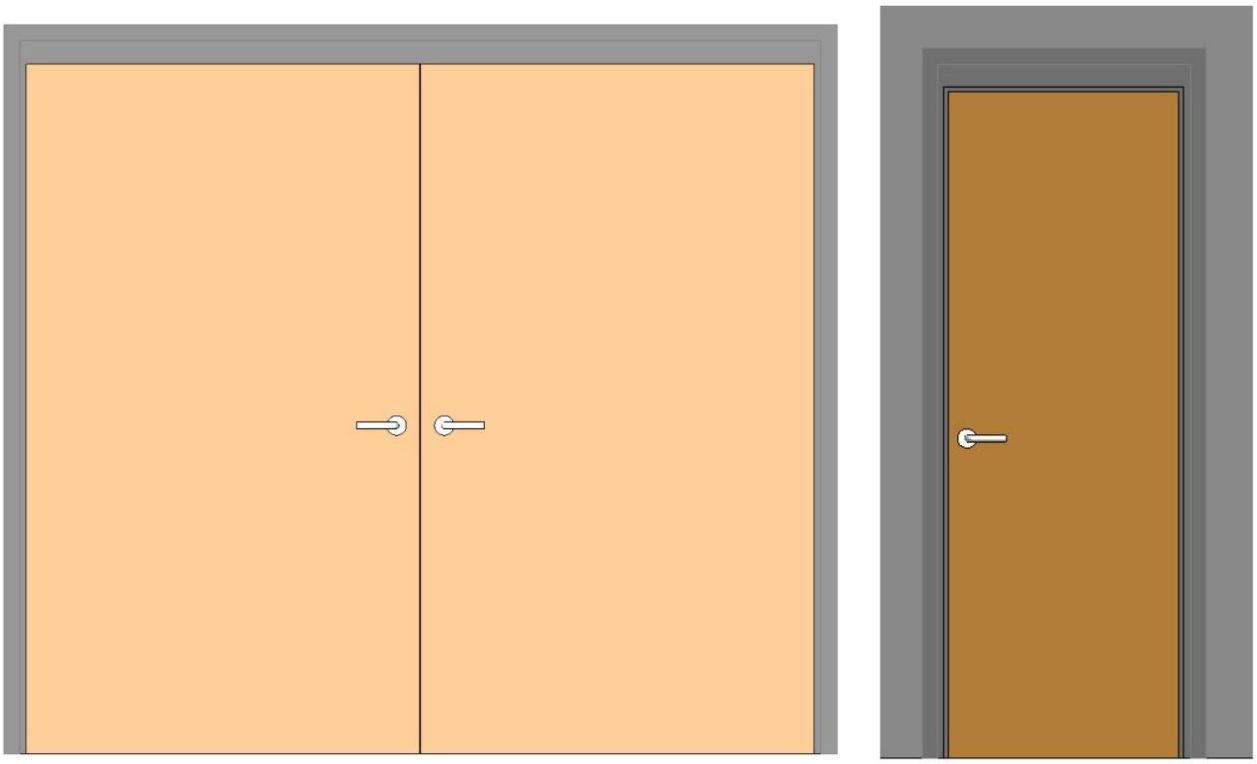


Figure 5.33: Double flush doors (left), Single flush doors (right).

5.3.14 Cooling clay panels

The cooling clay panels were modelled as a modified REVIT predefined compound ceiling with a 60cm×120cm grid. These panels are only 5 cm thick and allow for the placement of ceiling based lighting fixtures. Figure 5.34 shows a schematic of the cooling clay panels.

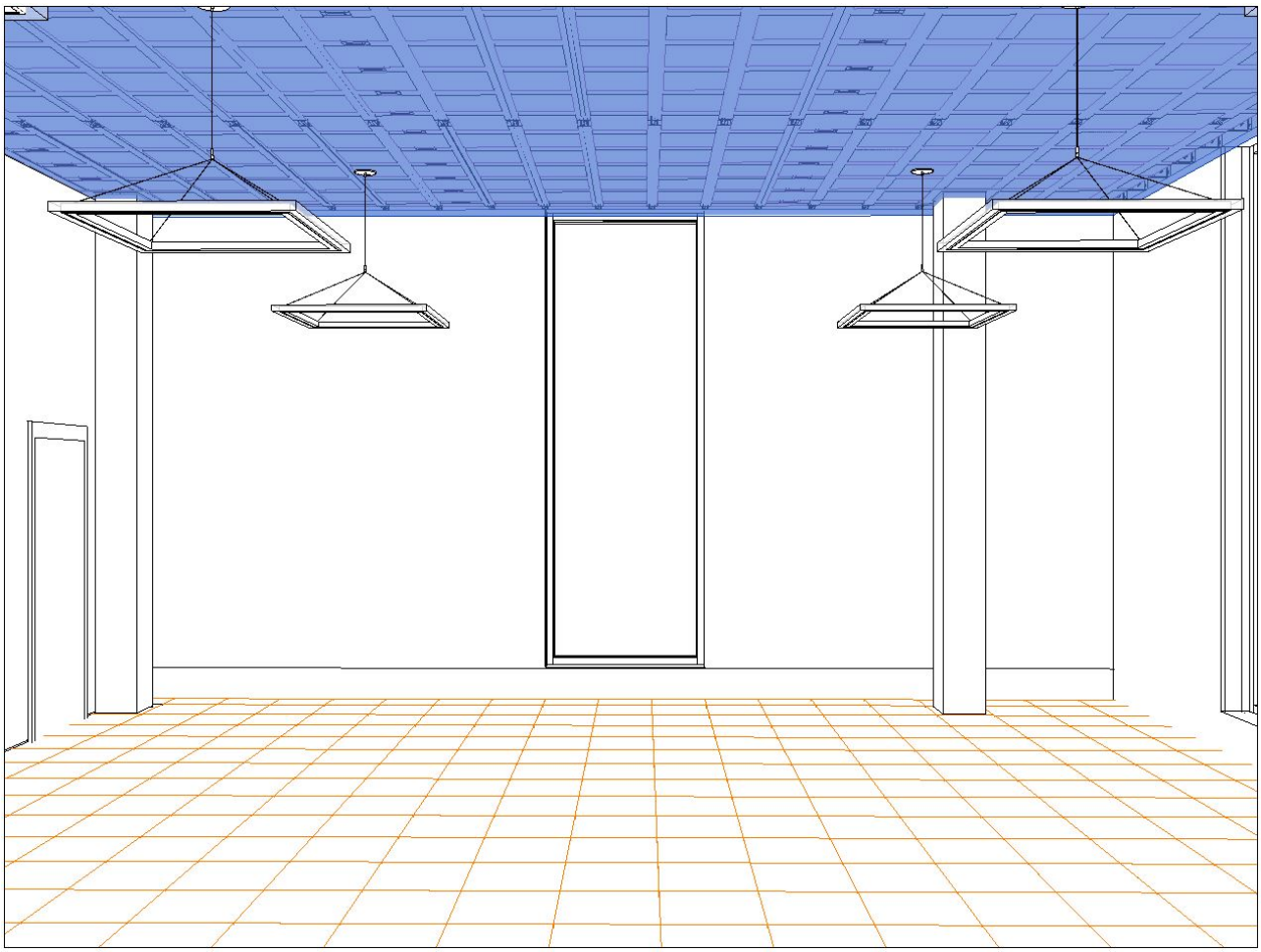


Figure 5.34: Cooling clay panels as compound ceilings.

5.3.15 Ventilation Units

The ventilation units were imported from an external database. The imported family had a configurable family parameter which controlled the length of the element. Hence two ventilation unit family types were created, one that covers the width of one window and one that covers two windows. Figure 5.35 shows a rendering of an exposed ventilation unit within the facade panel.



Figure 5.35: Rendering of exposed ventilation units above the shading system and inside the facade panels.

5.3.16 PV Modules and rotating mechanism

The PV modules shown in figure 5.36 were imported from an external database. The imported family had configurable family parameters which controlled the number of PV modules in each row and in each column. The rotating mechanism of the PV modules sits on the edge of the sloped reused pergola truss, which allows for the rotation of the PV modules mounted on top. The rotating mechanism was modelled as a generic REVIT family and without any motors installed on it. The rotating mechanism is exhibited in figure 5.37.

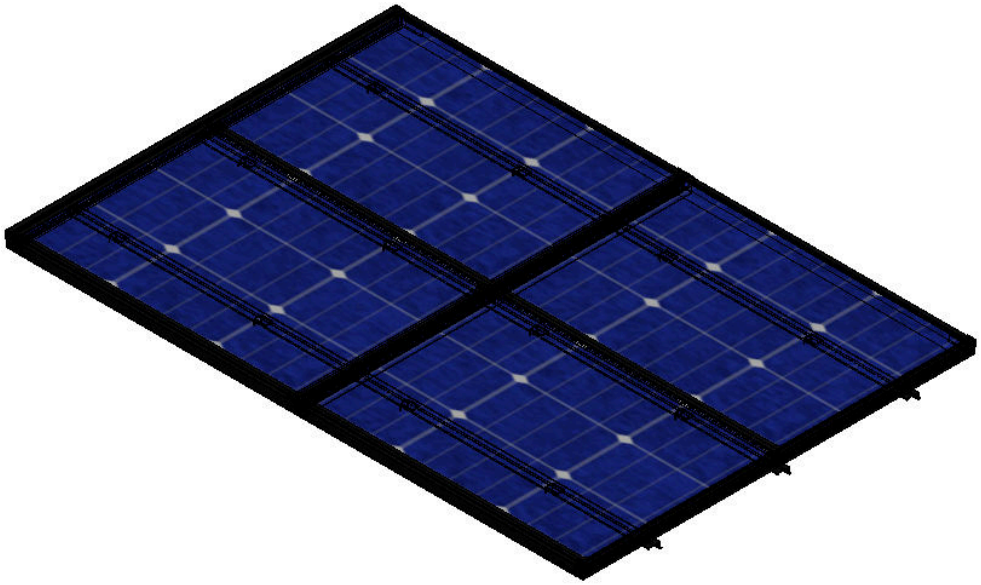


Figure 5.36: PV modules in the LOD300 model.

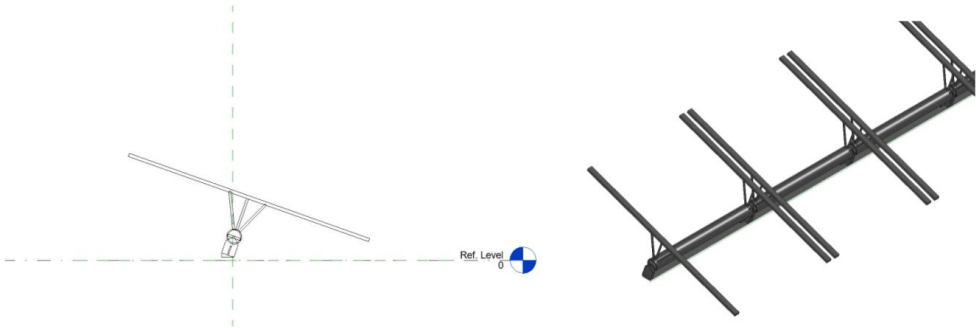


Figure 5.37: Section view of the rotating mechanism (left), Isometric view of the rotating mechanism (right).

5.3.17 Heat pump and water heater

The Heat pump and water heater was imported from an external database and is an actual HVAC family with connector points.

5.3.18 Battery

The Tesla Powerwall family was imported from an external database and it's a real electrical family with connector points. The Heat pump and all three Tesla Powerwall families can be seen in figure 5.38.



Figure 5.38: Heat Pump and Tesla Powerwall batteries on level UG2.

5.3.19 Elevator

The Elevator shaft cabin and doors were modelled automatically using the DigiPara elevator architect. We decided to go for a Schindler 5500 EU solution since Schindler is a Swiss and domestic manufacturer. This elevator type has a payload of 1600 kg (21 persons) and has a speed of 1 m/s. The car has a dimension of 2100mm×1600mm and it is a wheelchair type with no bed. The door opening is 1100mm×2100mm and the door has two panels. This elevator type suits this project since the elevator within the project has 8 stops and a travel of 26.14 meters which falls well in the design thresholds of 15 maximum stops and 45 meters of maximum travel. The elevator element can be seen in figure 5.39.

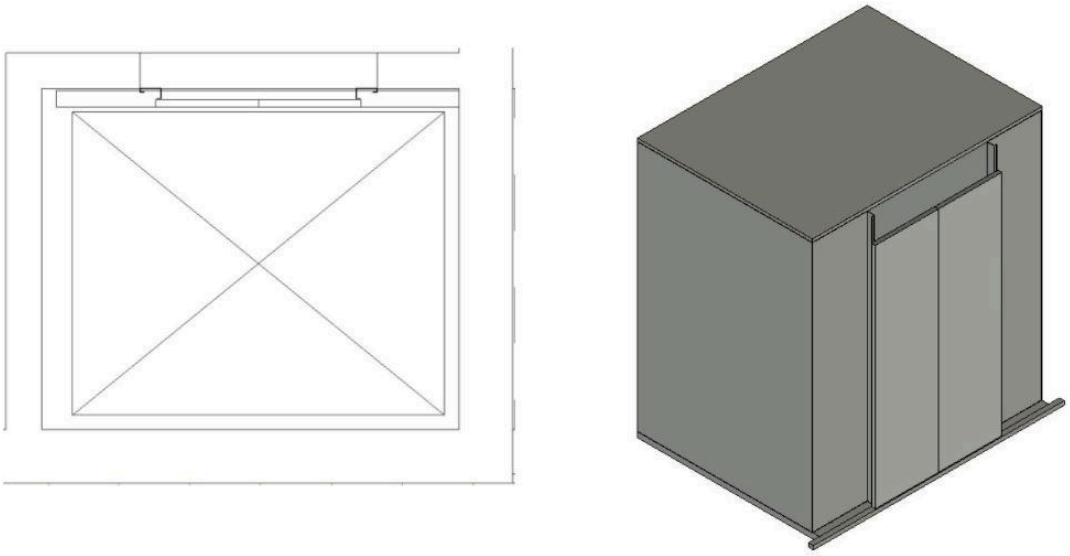


Figure 5.39: Plan view of the elevator unit (left), isometric view of the elevator unit (right).

5.3.20 Shading System

The shading system was imported from an external database and is a face-based family with geometric configurable parameters such as shading width, height and shading level in percentage. A rendering of the shading system is shown in figure 5.40.



Figure 5.40: Shading element with different shading level configurations.

5.3.21 Lighting fixtures

The lighting fixtures were imported from an external database as parametric ceiling-based families. The lighting fixture is an LED hanging lighting fixture with different sizes as types. The hanging length of the lights can be configured using the family parameter. Consult figure 5.41 for a rendering of the hanging light system.



Figure 5.41: Hanging LED lighting fixtures.

5.4 Operational energy simulation

In this phase, the simulation is again conducted with the same WWRs presented in Figure 4.26 and with both configurations: Extensive and the Lean version updated in the second phase. Furthermore, in both cases, the simulation was conducted with the new uniaxial tracking system for PVs.

The operational energy results for the Extensive Design and the operational carbon impact for a lifespan of 60 years and the current average CO_2 production of the Swiss energy mix, that is about 0.102 $kgCO_2/kWh$ [5], are as follows:

Configurations	EUI Extensive Design [kWh/m2y]	Operational Impact [tCO2]
Basis	16.58	660
Less on South	16.45	654
Less on West	16.71	665
More on East	16.62	661

Figure 5.42: Third Phase: Operational energy Extensive Design.

The following figure shows a simulation example for the combination with an higher WWR in the East facade:

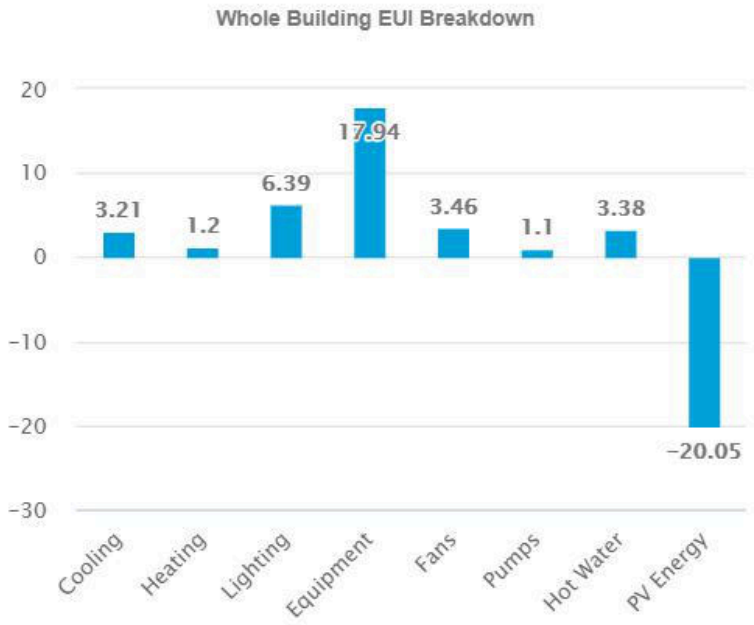


Figure 5.43: Third Phase: EUI of the Extensive configuration More on East.

The operational energy results for the Lean Design and the operational carbon impact for a lifespan of 60 years and the current average CO_2 production of the Swiss energy mix, that is about 0.102 $kgCO_2/kWh$ [5], are as follows:

Configurations	EUI Lean Design [kWh/m2y]	Operational Impact [tCO2]
Basis	14.18	564
Less on South	14.12	562
Less on West	14.26	567
More on East	14.02	558

Figure 5.44: Third Phase: Operational energy Lean Design.

The following figure shows a simulation example for the combination with an higher WWR in the East facade:

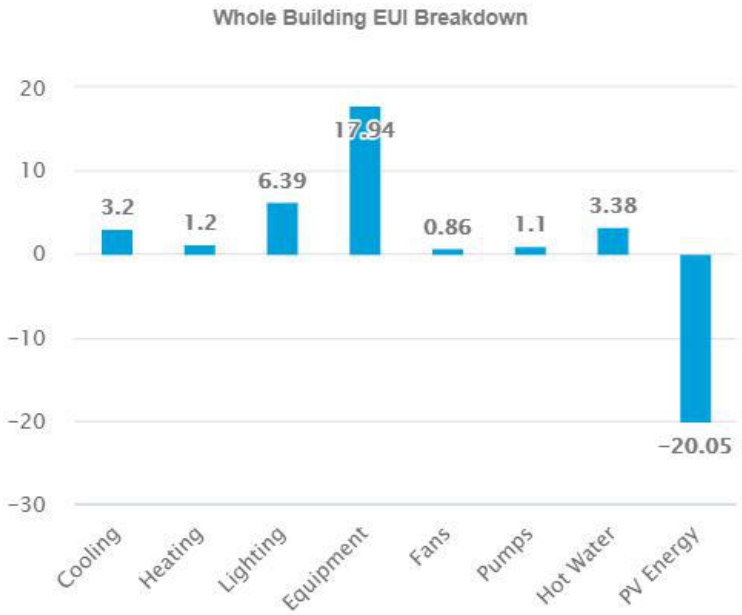


Figure 5.45: Third Phase: EUI of the Lean configuration More on East.

5.5 LCA: considering the whole building's emissions.

At this phase of the project the environmental impact of the entire building is calculated. The embodied impact of the building is obtained by adding the emissions of the construction materials to the emissions caused from the building systems before subtracting the great carbon storage potential that these two can provide. This value, which is proudly in almost all configurations negative (more carbon storage than emissions) is than added to the impact caused of the operational energy in order to finally obtain the total building impact on the environment. In figures 5.46 and 5.47 are summarized the total emissions of the building depending on the windows configurations and building system (extensive vs. lean).

Configurations	EUI Extensive Design [kWh/m2y]	Operational Impact [tCO2]	Embodied Impact [tCO2]	Total Impact [tCO2]
Basis	16.58	660	-22.04	638
Less on South	16.45	654	-40	614
Less on West	16.71	665	-32	633
More on East	16.62	661	-31	630

Figure 5.46: Total embodied emission of the building with building systems accordingly to extensive design.

Configurations	EUI Lean Design [kWh/m2y]	Operational Impact [tCO2]	Embodied Impact [tCO2]	Total Impact [tCO2]
Basis	14.18	564	-548	16
Less on South	14.12	562	-566	-4
Less on West	14.26	567	-557	10
More on East	14.02	558	-503	55

Figure 5.47: Total embodied emission of the building with building systems accordingly to lean design.

5.6 Design solution of the third phase

The design solution of the internal walls have already been presented in chapter 5.1, since there were only one option (design element) for each typology of wall.

Likewise the others design elements in the previous chapters, the choices regarding the internal walls and energy generation and storage systems are justified with respect to the vision and flexibility framework that unify the whole project as well. These can be consulted in the appendix 8.3 at the end of this report.

6 Fourth Design Phase

6.1 Material passport

The material passport of Flexilibres is a platform and repository for stroring, linking, and providing relevant information on the components with respect to circularity. The data supports various actors visualized in figure 6.1 in their decision making process and their analysis.

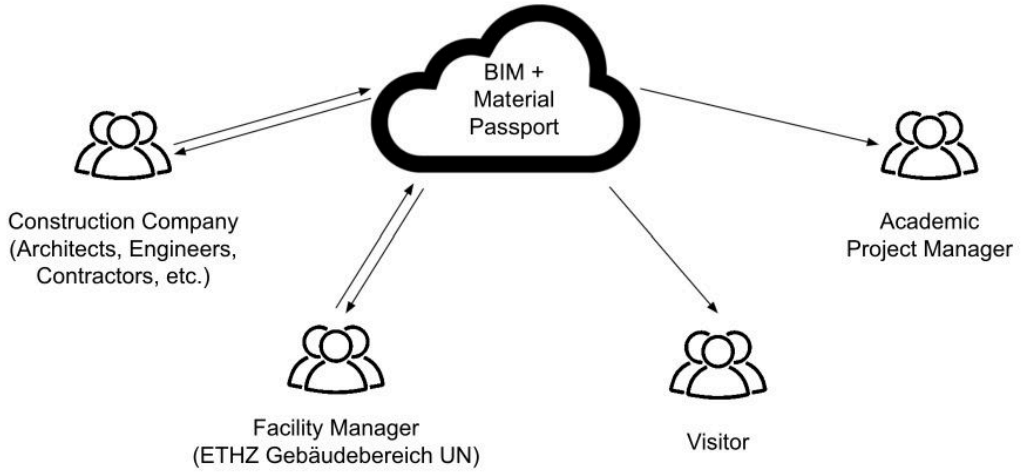


Figure 6.1: Material passport data management and roles.

Construction companies and the facility management are responsible to update the BIM model including the material passport during the lifetime of Flexilibres. This data driven approach ensures the potential of the components for reuse and recycling is harvested.

6.2 Material passport properties

An extensive list of properties is necessary for realistic material passport applications [3]. Since the workload to create a complete material passport extends the scope of this project, the material passport of Flexilibres was reduced to properties that are important for the vision of this project. Therefore, the three aspects of the vision, Net Zero Carbon Building, flexibility and materialization are represented by the material passport. Each criterion of the vision framework has a corresponding property outlined in the diagram in figure 6.2.

filtering of most important properties

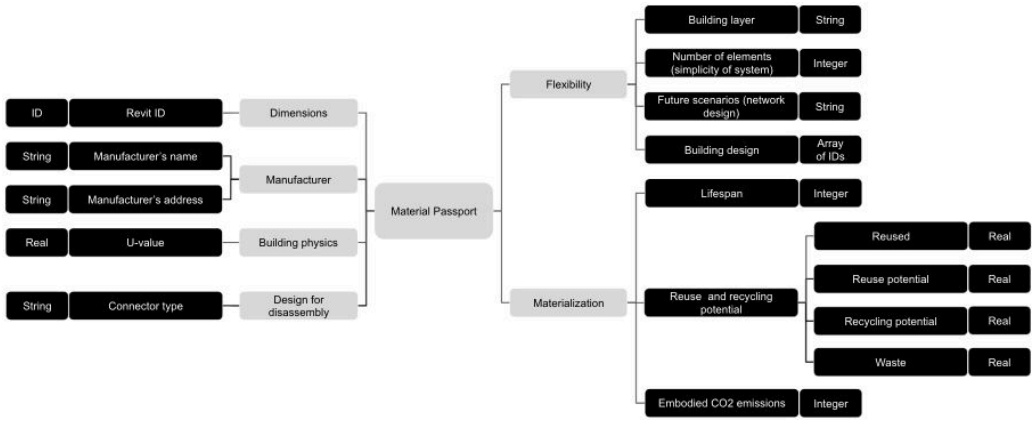


Figure 6.2: Hierarchy of the material passport properties that were identified to be most important for the aspects Net Zero Carbon Building, flexibility and materialization.

6.3 Material passport concept

The material passport adapts to the LOD300+ model. Therefore, all material passport property information is provided on a component level as outlined in figure 6.3. However, some properties need to be calculated on a material level, before they can be aggregated to a component level. Additionally, some properties can be aggregated on a building level for a more high level analysis.

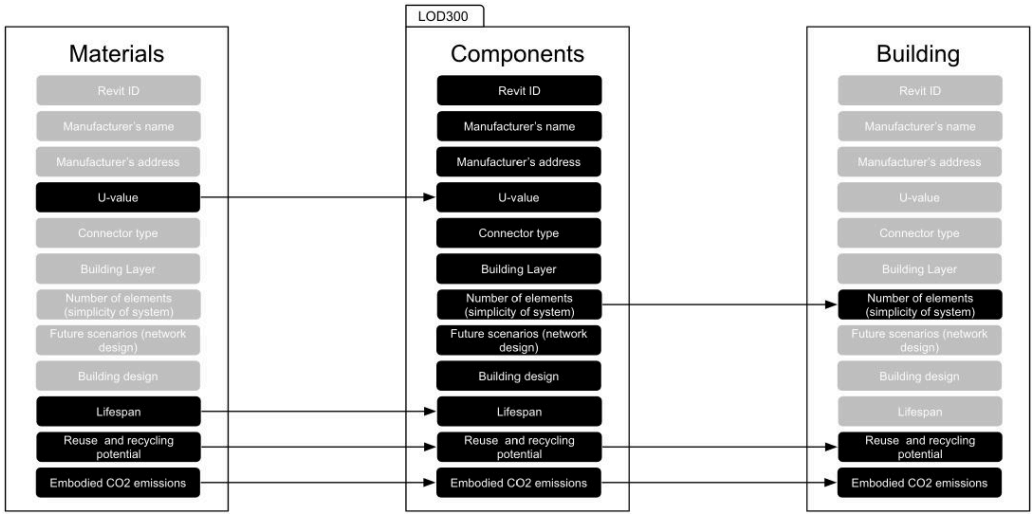


Figure 6.3: Material passport concept for the level of detail and aggregation of information. Relevant material passport properties are highlighted in black.

The aggregation of properties to a higher level of detail was calculated according to predefined roles:

1. U-value: The U-value of a component with multiple material layers can be calculated as the sum of the inverse thermal resistances of the individual layers.

2. Number of elements (simplicity of system): The number of elements on a building level is equal to the sum of all number of elements of the components.

3. Lifespan: The lifespan of the component was set to the lifespan of the material with the highest volume, or the material that provided the essential functionality of the component.

4. Reuse and recycling potential: The reuse and recycling potential of the components were calculated using the volumetric fraction of the reuse and recycling potential on a material level. The same logic was used to calculate reuse and recycling potential on a building level.

5. Embodied CO2 emissions: The embodied CO2 emissions on a component level is equal to the embodied CO2 emission on a material level. The same logic was used to calculate reuse and recycling potential on a building level.

6.4 Material passport data

The material passport data including the aggregation of the individual properties is outlined in the table in appendix 8.4. Additionally, the data can be accessed on the Autodesk Forge model by clicking on a component. A view that is similar to figure 6.4 appears.

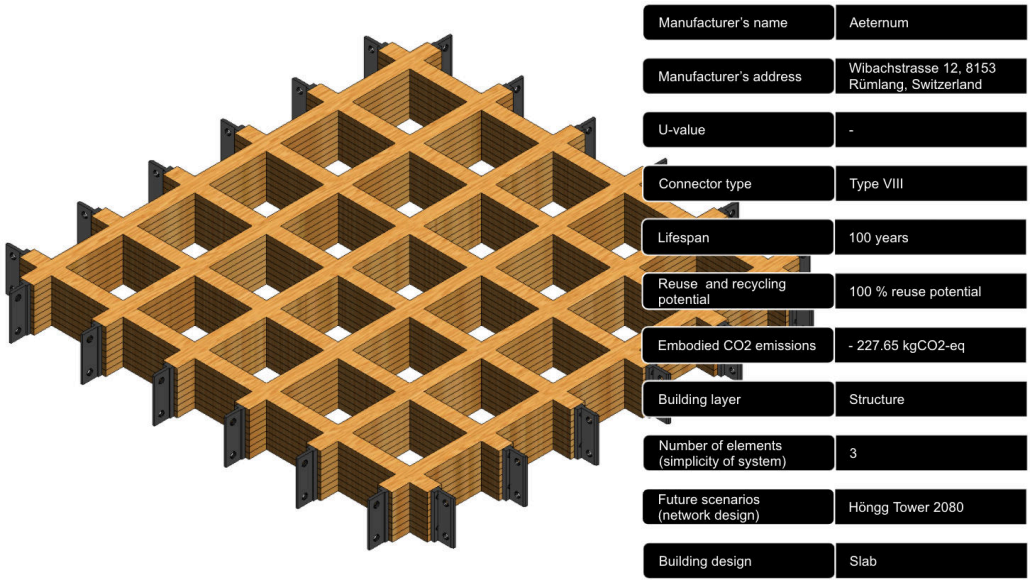


Figure 6.4: The Aeternum slab element including material passport properties as an example for all components of the LOD300+ model.

Additionally, on the Autodesk Forge platform the material passport properties that are relevant to the vision of the project are visualized as follows:

1. Color coded properties: The properties lifespan, reuse and recycling potential, embodied CO2 emissions, and number of elements (simplicity of system) can be color coded using the corresponding functionality on Autodesk Forge.

2. Filtering properties: The properties building layer and building design can be filtered for using the corresponding functionality on Autodesk Forge.

6.5 Model LOD300+

THE LOD300+ model is from a graphical point of view identical to the LOD300 model, however there is a major distinction between the two which is that the LOD300+ model is loaded on a component level with the material passport data introduced in sections 6.3 and 6.4. This enables further analyses and facilitates decision-making down the line in the future since all the required data is stored on a central model. At this point in time, the model at hand was a true BIM model since it entailed storage and communication of building-specific information. Figure 6.7 shows an example of the displayed information when clicking on any component of the LOD300+ model on the Autodesk Forge platform.



Figure 6.5: Frontal East side of the Flexilibres Building.



Figure 6.6: Corner North side of the Flexilibres Building.

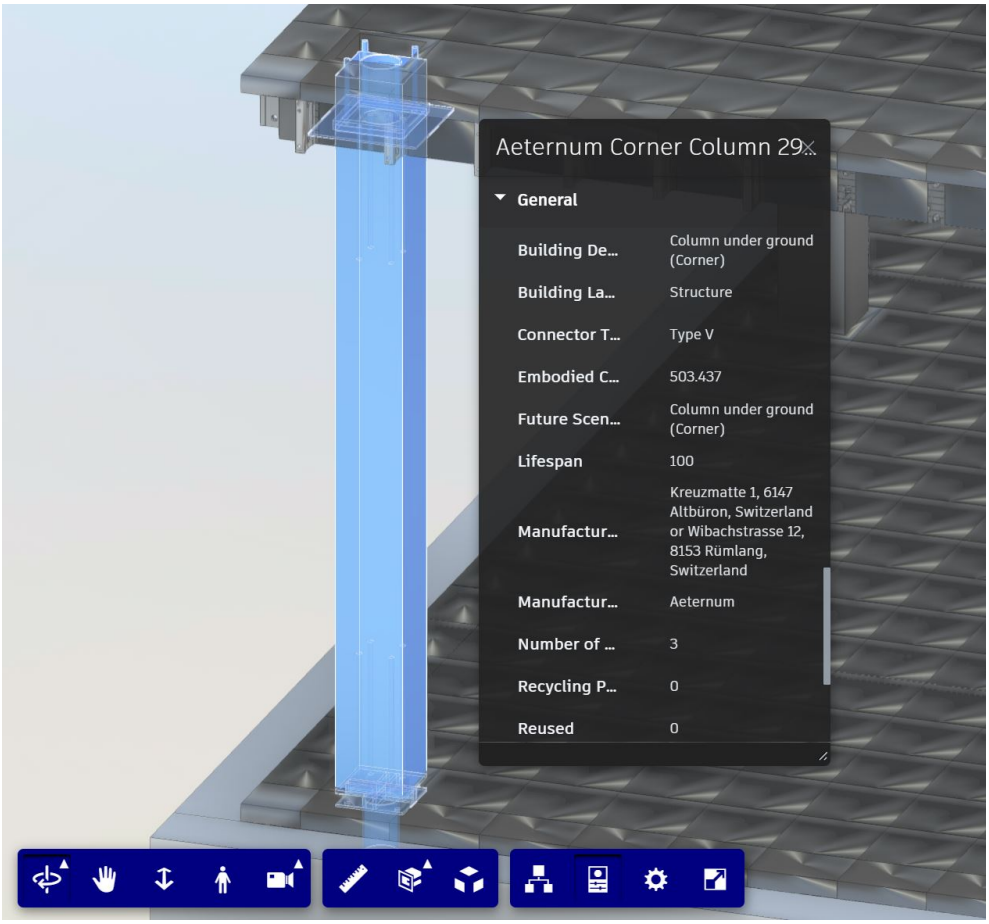


Figure 6.7: Example of component-specific information being displayed, in this case a regular Aeternum Column.

6.5.1 LOD300+ model on the Autodesk Forge platfrom

In order to leverage the power of the information loaded on the LOD300+ model, the Autodesk Forge designing space was configured for each team to provide the stakeholders some analytics and visualizations. As mentioned in section 6.4, our team decided to configure the design space with two functionalities, namely: color coded parameter visualization and filtering of elements based on building layer and building design. In this section, we are going to go through all the color coded parameter visualizations. Details of the filtering functionality can be found in appendix 8.5.

6.5.2 Color coded parameter visualization of the LOD300+ on Autodesk Forge

The color coded parameters are as follows:

- Lifespan: The following figures 6.8 and 6.9 show the visualizations for the lifespan on the building and component level respectively.

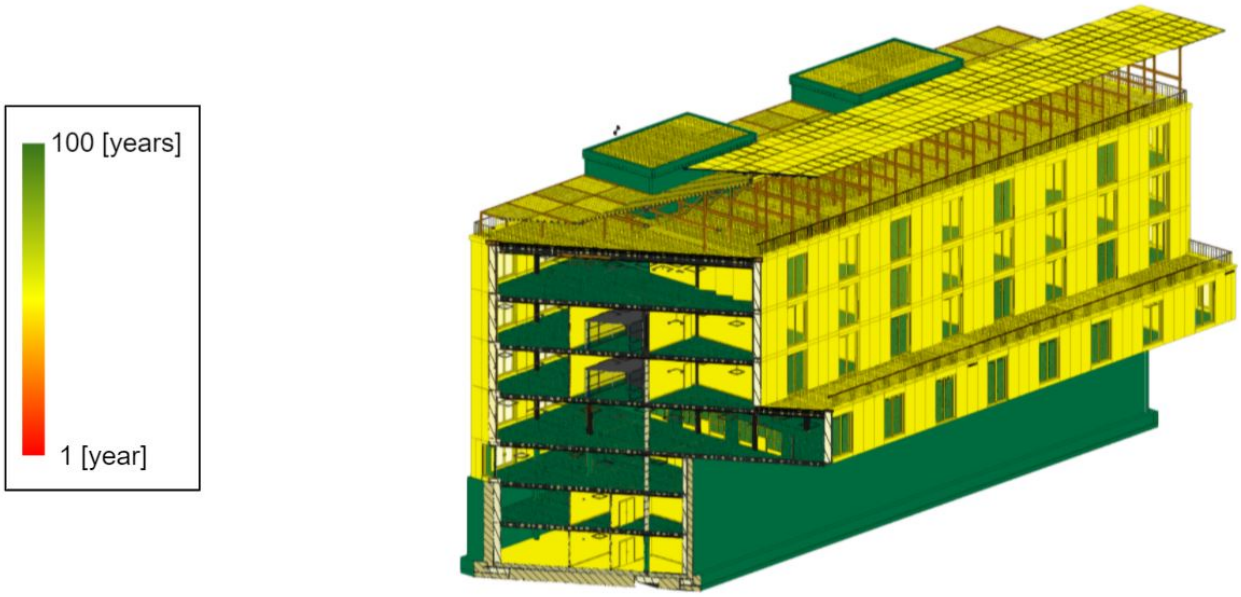


Figure 6.8: Lifespan visualization on the building level.

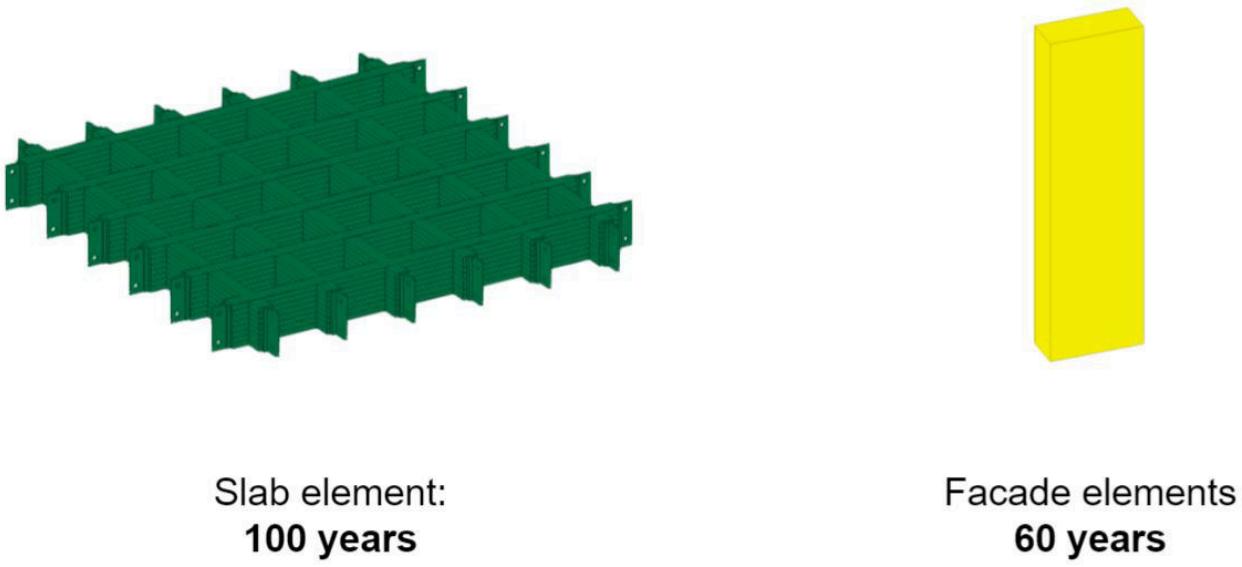


Figure 6.9: Lifespan visualization on the component level, for example an Aeternum slab (left) and a facade panel (right).

- Reuse: The following figures 6.10 and 6.11 show the visualizations for the reuse on the building and component level respectively.



Figure 6.10: Reuse visualization on the building level.

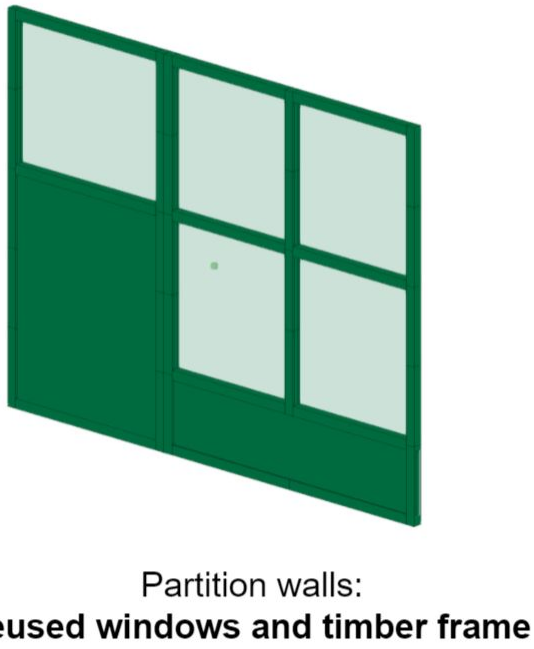


Figure 6.11: Reuse visualization on the component level, for example an interior separation wall.

- Embodied CO2 emissions: The following figures 6.12 and 6.13 show the visualizations for the reuse on the building and component level respectively.

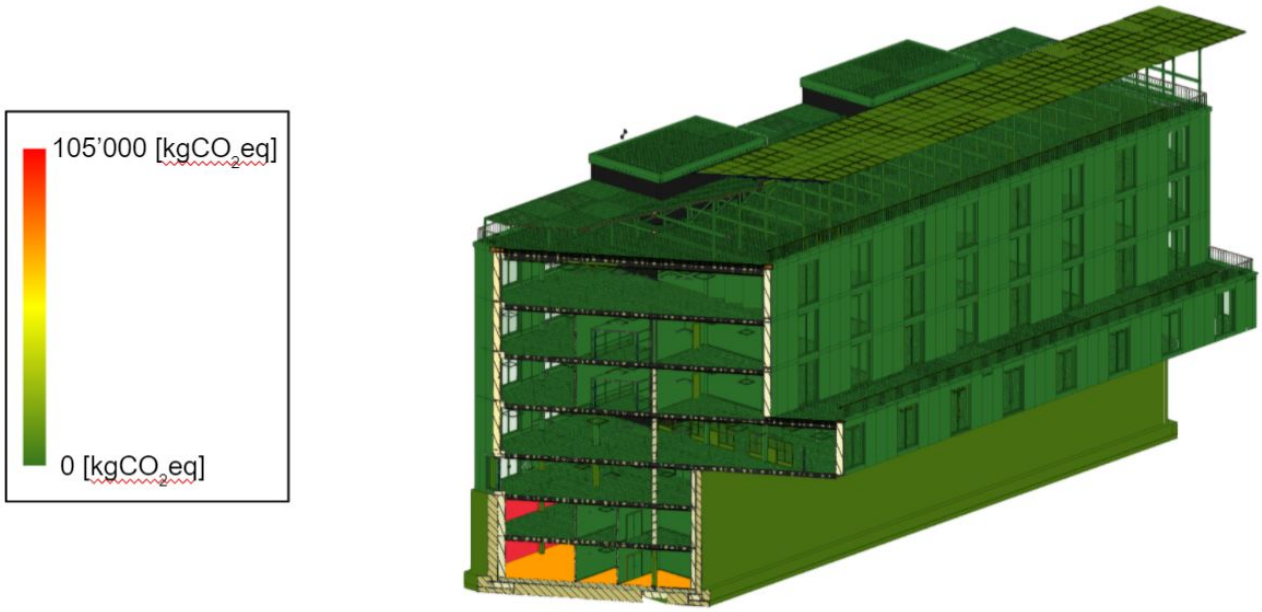


Figure 6.12: Embodied CO2 emission visualization on the building level.

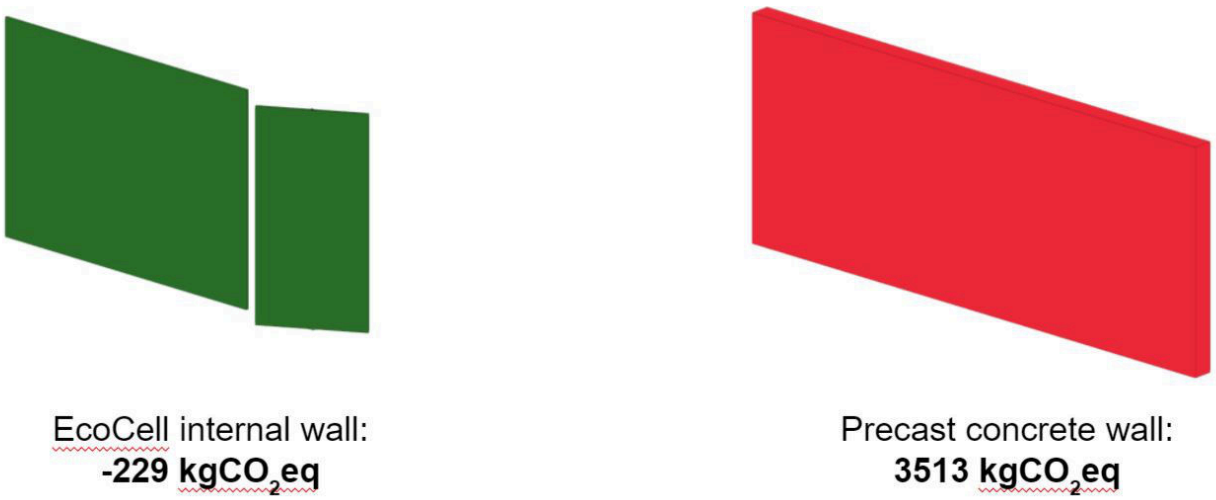


Figure 6.13: Embodied CO2 emission visualization on the component level, for example an Ecocell interior wall (left) and a precast concrete lower retaining wall (right).

- Number of elements: The following figures 6.14 and 6.15 show the visualizations for the number elements on the building and component level respectively.

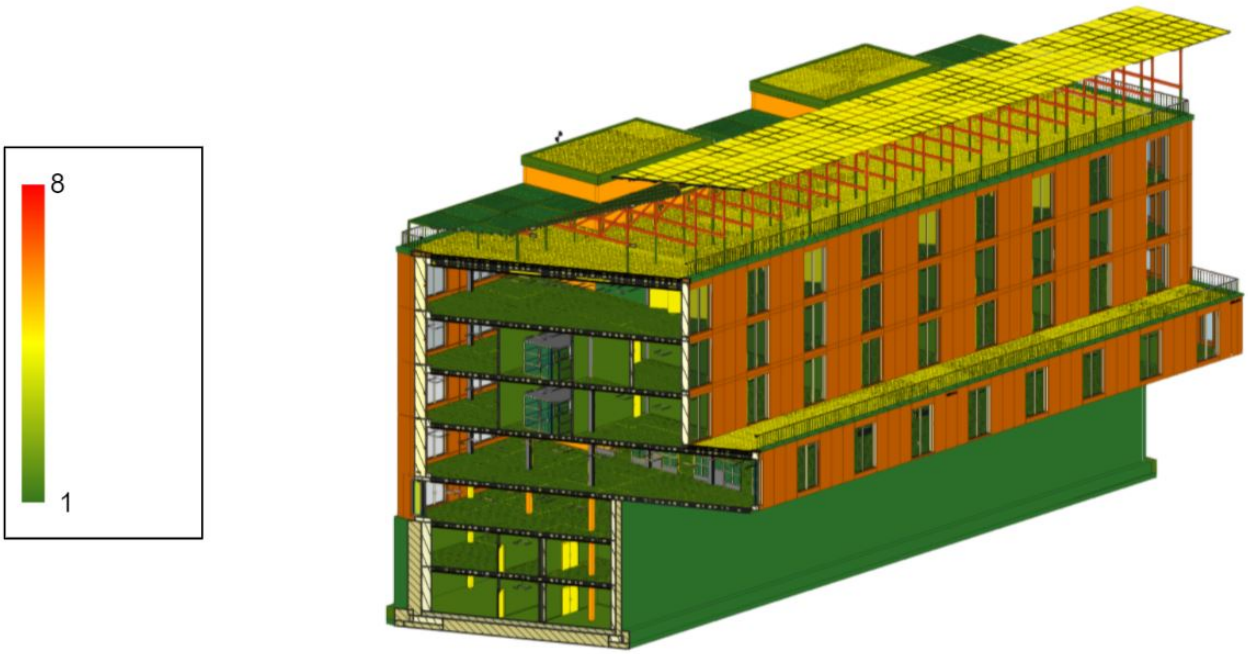


Figure 6.14: Number of elements visualization on the building level.

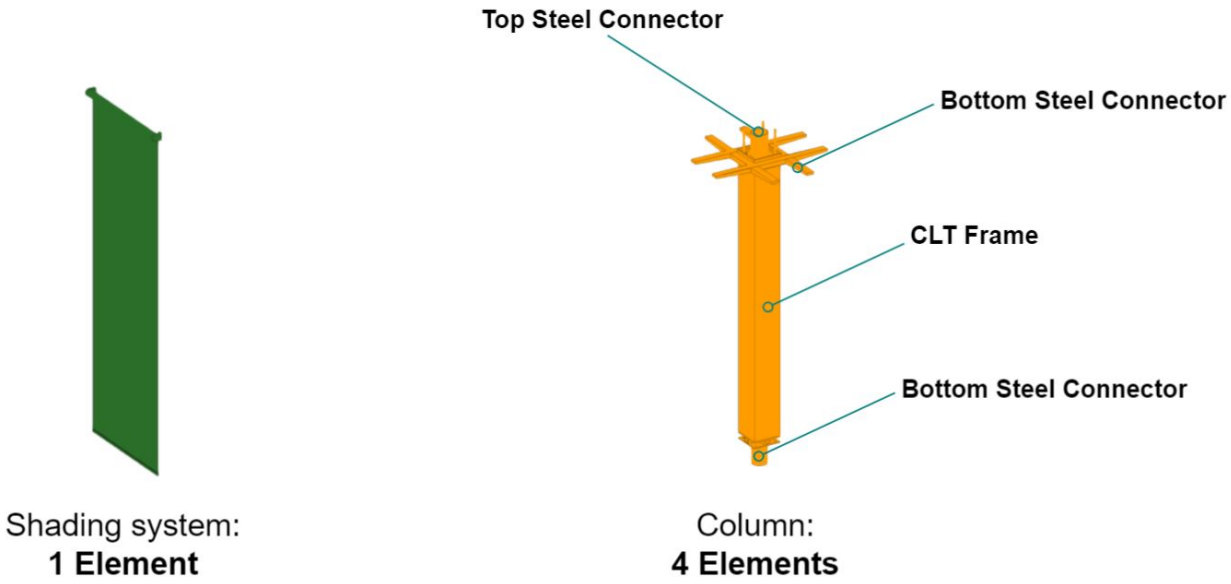


Figure 6.15: Number of elements visualization on the component level, for example a shading system (left) and an Aeternum regular column (right).

6.6 Final operational simulation

The last step on the operational side is purely the refinement and analysis of the data collected. Looking more closely at the simulations of the irradiation of the surfaces, Figure 6.16, it can be seen that the south facade receives a lot of light, what in technical terms is called Annual Solar Exposure (ASE) and refers to the percentage of space that receives too much direct sunlight (1000 Lux or more for at least 250 occupied hours per year).

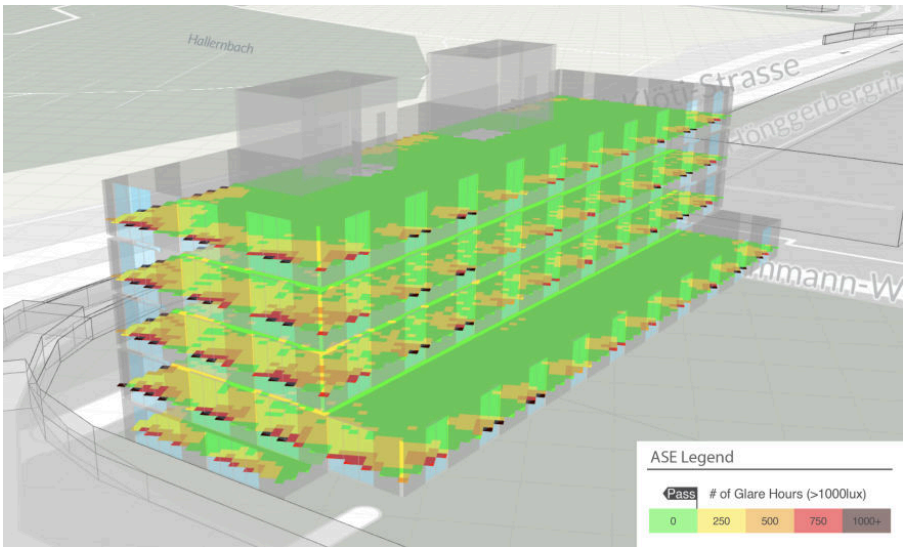


Figure 6.16: Annual Solar Exposure.

This has led us to implement a shading system, so we introduced a wooden roller blinds, so that the embodied impact can be reduced as much as possible, and with an integrated projecting arm that allows a minimum amount of light into the rooms.



Figure 6.17: Wooden roller blinds with integrated projecting arm. [2]

Finally, with the cove.tool software it is also possible to analyse the lighting of spaces. As can be seen in the Figure 6.18 all spaces with windows have good natural lighting. The daylight analysis is carried out based on the Spatial Daylight Autonomy (sDA) describes the percent of space that receives sufficient daylight. describes the percentage of floor area that receives at least 300 lux for at least 50% of the annual occupied hours (8:00-18:00). This provides optimal lighting, thanks to the use of an LED lighting system, which is equipped with occupancy and daylight sensors, so that the energy consumption is minimal.

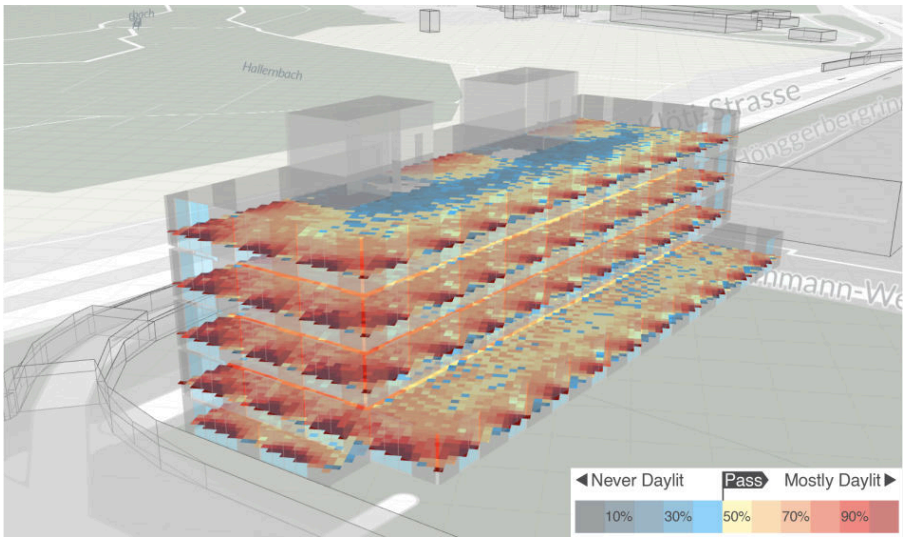


Figure 6.18: Spatial Daylight Autonomy.

In this phase, the simulation is again conducted with the same WWRs presented in Figure 4.26 and and with the implementation of the improvements mentioned above. Again the operational energy results for the Extensive Design and the operational carbon impact for a lifespan of 60 years and the current average CO_2 production of the Swiss energy mix, that is about 0.102 $kgCO_2/kWh$ [5], are as follows:

Configurations	EUI Extensive Design [kWh/m2y]	Operational Impact [tCO2]
Basis	14.52	578
Less on South	14.55	579
Less on West	14.87	592
More on East	14.09	561

Figure 6.19: Fourth Phase: Operational energy Extensive Design.

The following figure shows a simulation example for the combination with an higher WWR in the East facade:

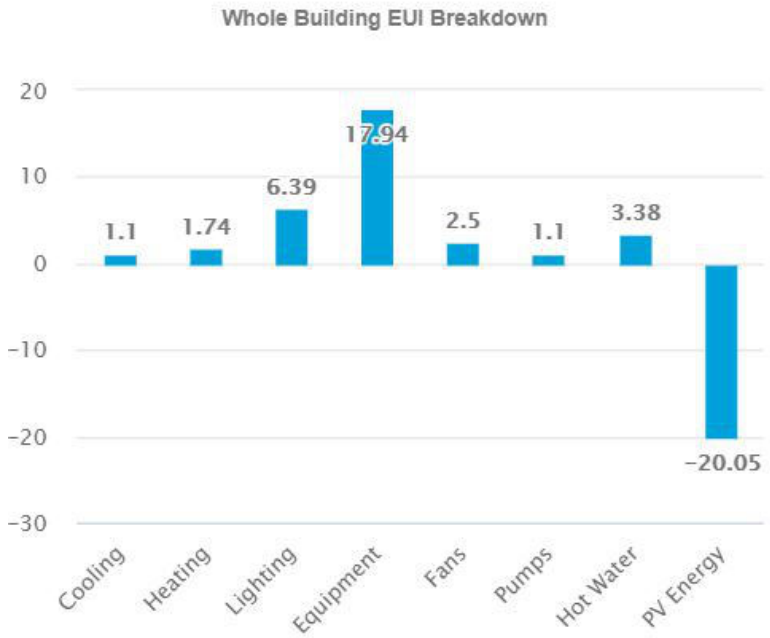


Figure 6.20: Fourth Phase: EUI of the Extensive configuration More on East.

The operational energy results for the Lean Design and the operational carbon impact for a lifespan of 60 years and the current average CO_2 production of the Swiss energy mix, that is about 0.102 $kgCO_2/kWh$ [5], are as follows:

Configurations	EUI Lean Design [kWh/m2y]	Operational Impact [tCO2]
Basis	12.71	506
Less on South	12.76	508
Less on West	12.86	512
More on East	12.21	486

Figure 6.21: Fourth Phase: Operational energy Lean Design.

The following figure shows a simulation example for the combination with an higher WWR in the East facade:

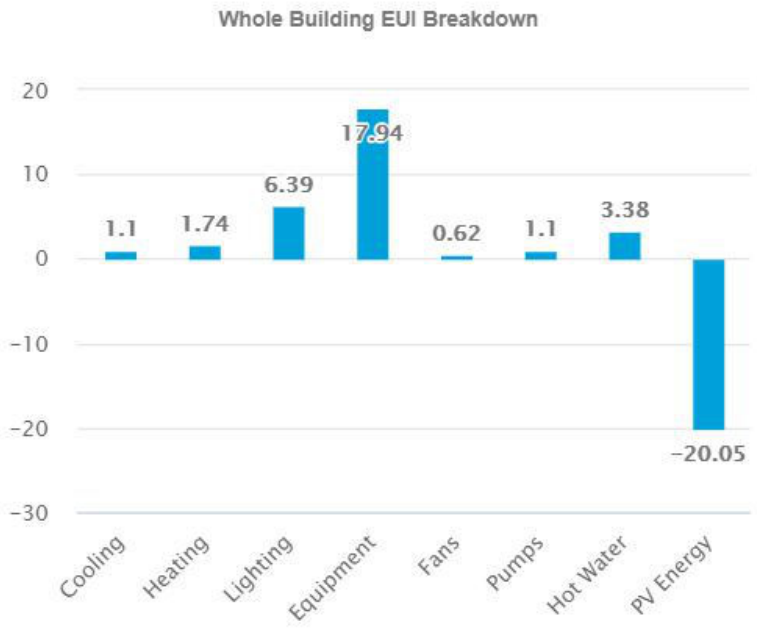


Figure 6.22: Fourth Phase: EUI of the Lean configuration More on East.

6.7 LCA: final

In the following two tables the environmental impact of the whole building is derived. As seen before, the comparison between the different building systems influenced by the different combinations of WWRs is again presented.

Configurations	EUI Extensive Design [kWh/m2y]	Operational Impact [tCO2]	Embodied Impact [tCO2]	Total Impact [tCO2]
Basis	14.52	578	-13.04	565
Less on South	14.55	579	-31	547
Less on West	14.87	592	-23	569
More on East	14.09	561	22	582

Figure 6.23: Final total embodied emission of the building with building systems accordingly to extensive design.

Configurations	EUI Lean Design [kWh/m2y]	Operational Impact [tCO2]	Embodied Impact [tCO2]	Total Impact [tCO2]
Basis	12.71	506	-536	-30
Less on South	12.76	508	-557	-50
Less on West	12.86	512	-548	-36
More on East	12.21	486	-494	-8

Figure 6.24: Final total embodied emission of the building with building systems accordingly to lean design.

Taking into account the option with the lower environmental impact, i.e. the configuration with an optimised Lean system design and fewer windows in the South façade, we derive an operational energy consumption of 12.76 kWh, which corresponds to 1.3 $kgCO_2eq/m^2y$ (Swiss energy mix: 0.102 $kgCO_2/kWh$ [5]). This value is below the SIA2040 target, which corresponds to 2 $kgCO_2eq/m^2y$ [8].

In figure 6.25 the large gap in total carbon emissions for a lifespan of 60 years can be seen graphically.

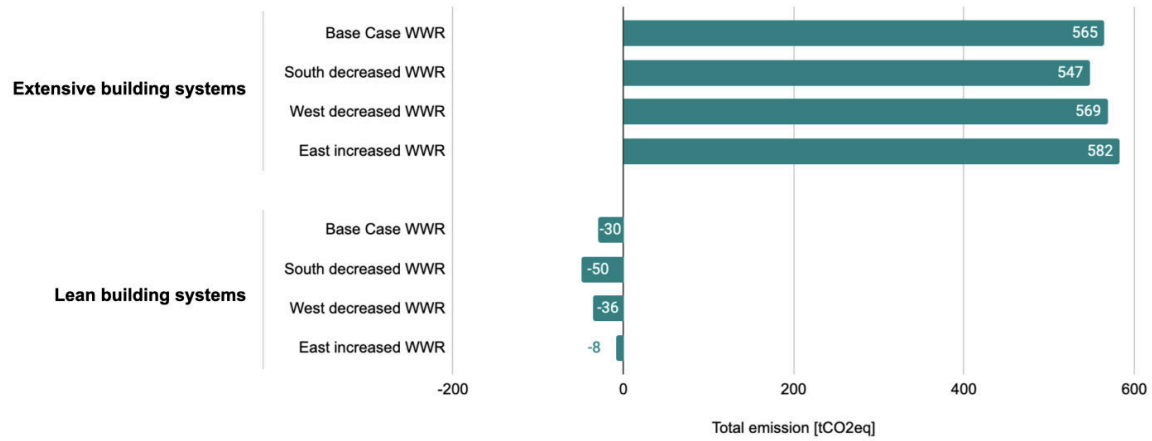


Figure 6.25: Total carbon emission for a lifespan of 60 years.

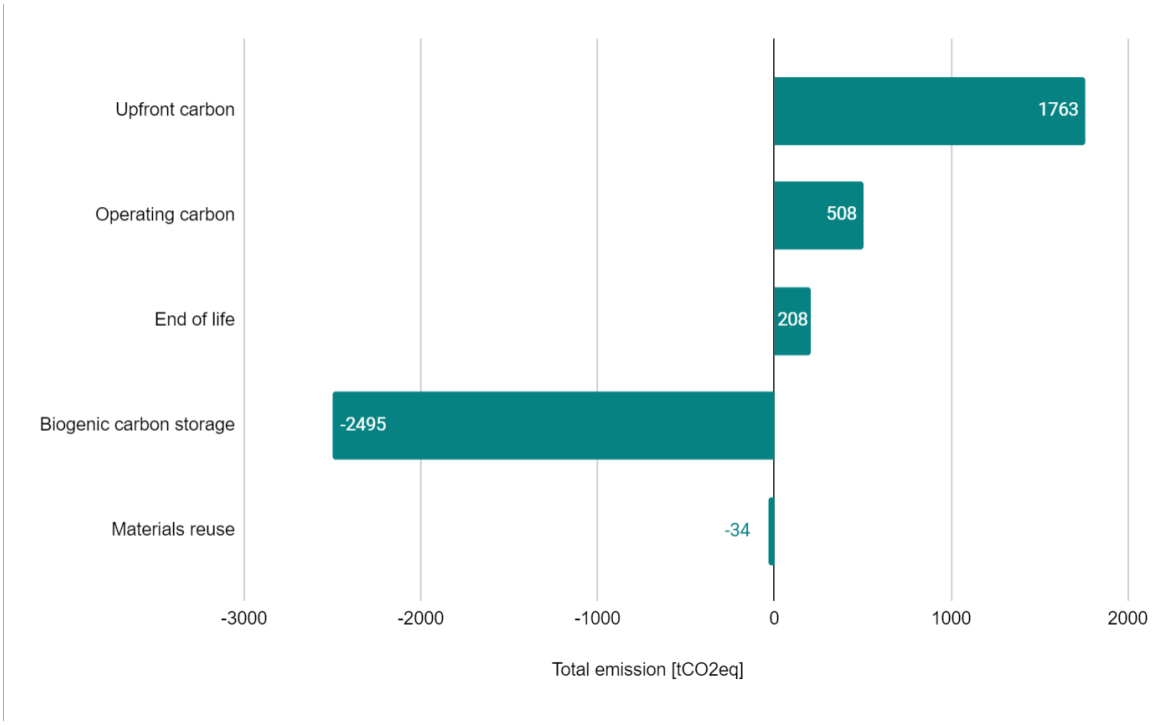


Figure 6.26: Total building emissions.

In figure 6.26 the total building emissions are divided into categories:

- Upfront carbon: Emissions that are made from the production and transport of the design elements are regrouped here.
- Operating carbon: This self-explaining term include the emissions from the building operation.

- End of life: The elements that can not be reused or recycled have to be disposed at end of life and will produce emissions as well.

- Biogenic carbon storage: The total carbon uptake of the materials, for instance timber or straw, are summed in here.

- Materials reuse: Reusing materials produces emissions only trough its transportation, from the original location to the new building site.

Summing up these values a total of -50 tons $CO_2 - equivalent$ can be reached, this means the building will be carbon negative and therefore store more carbon than what it is produced during its realization.

In figure 6.27 the volume of the main materials used are displayed. It can be noted the successful maximization of the materials whose could provide great values in terms of the properties defined in the material passport, for example timber, straw and clay. The use of steel as reinforcement or for the connectors, concrete in the foundation and glass, on the other hand, was kept to the minimum necessary.

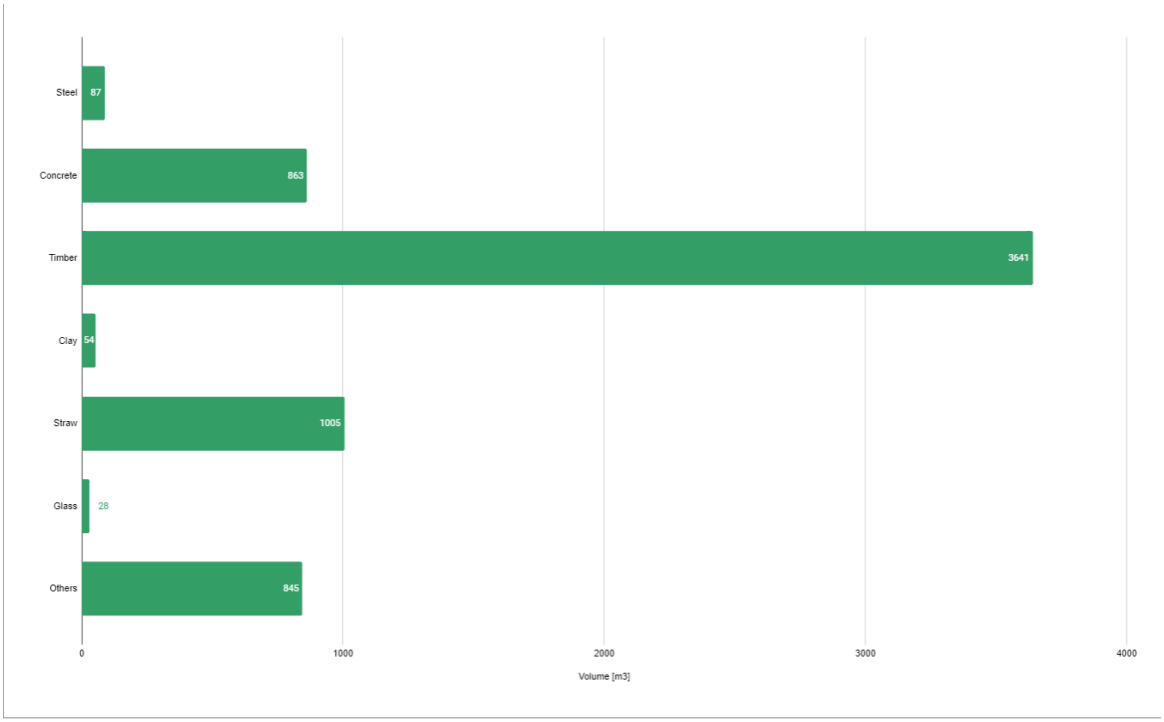


Figure 6.27: Total material's volume.

Finally, figure 6.28 below shows the effort made in maximizing recycle and reuse potential during the choice and the design of the building elements. With more than a total of 70'000 components in the building, it was essential to avoid waste as much as possible by extending their lifespan.

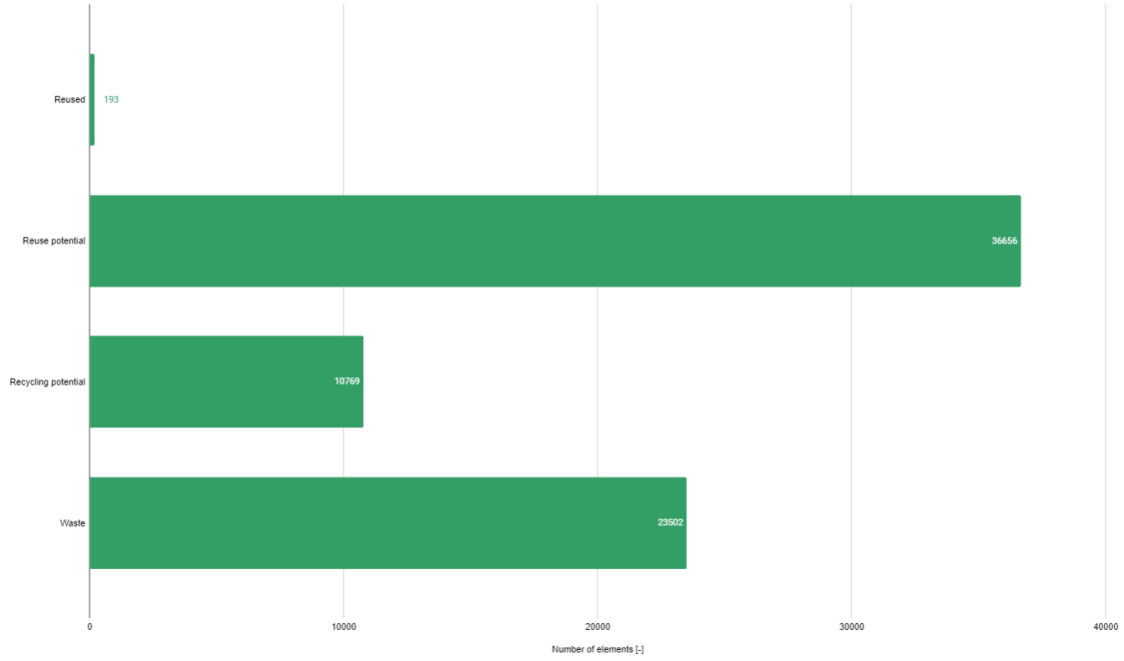


Figure 6.28: Number of elements whose can be reused, have recycle or reuse potential or must be eliminated at end of life.

7 Conclusion

This project is based on three major aspects, Net Zero Carbon Building, Materialization and Flexibility, with the iterative approach used in this project, these three requirements have been completely fulfilled. In fact we have a building with a negative carbon footprint for the next 60 years, thanks to a careful choice of components and materials, a highly modular and flexible configuration that can respond to future new needs, and components whose life will not end with that of the building, but rather can be used further in the future.

As is often said, there is no single recipe for a carbon-neutral building, but it can only be achieved by exploiting the different properties of different materials and components, so it is necessary to have a total and lasting vision and not just dwell on the level of the present and the individual component.

In addition, in our view, cooperation is a fundamental aspect of achieving a circular society. Only by analysing and setting, from the very beginning, clear common goals and by using different skills, backgrounds and knowledge a circular society can be achieved and sustained from all the different aspects. Furthermore, it is precisely this extensive collaboration that made the project fascinating and pushed our personal boundaries.
This close collaboration sometimes has its disadvantages, for example conflicts arose between the necessary different level of details, some parts were needed in great detail, others not. Additionally, whenever we went into details, more problems arose. But it is precisely by solving these problems and details that the best solutions were found, even if the used iterative approach did not revealed as the most time-efficient way to develop our project.

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8 Appendix

8.1 First Design Phase

8.1.1 First draft of the Life Cycle Assessment

Type	Design element	Materials	Material density	Dimensions			Volume of one element	Number elements	total volume	GHG emission (KBOB) Fabrication	GHG emission (KBOB) elimination	GHG emission (KBOB) Fabrication + elimination	Distance Transport: truck/train		GHG emission (KBOB) transport	Total GHG emission	Total GHG emission	Suppliers CH	Assumption
-	-	-	kg/m3	Height/ Width [m]	Lenght [m]	Thikness [m]	m3	-	m3	kg CO_2-eq/ m3	kg CO_2-eq/ m3	kg CO_2-eq/ m3	truck [km]	train [km]	kg CO_2-eq/ m3	kg CO_2-eq/ m3	kg CO_2-eq	-	-
Foundation																			
	Strip foundation	Concrete, Susteno EviopactZero/Plus XC1/2	2350	1	267.2	0.5	133.6	1	133.6	192.56	24.44	217.00	5	0	1.59	218.59	29202.99	Holcim, Glattbrugg	KBOB tiefbaubeton; recycled concrete -15% emissions for fabrication
	Concrete ground plate	Concrete, Susteno EviopactZero/Plus XC1/2	2350	16	61.6	0.4	394.2	1	394.2	192.56	24.44	217.00	5	0	1.59	218.59	86175.05	Holcim, Glattbrugg	KBOB tiefbaubeton; recycled concrete -15% emissions for fabrication
	Precasted concrete core	Concrete, Susteno EviopactZero/Plus XC1/2	2500	3.5	17.6	0.2	12.3	14	172.5	344.25	25.00	369.25	62	0	20.93	390.18	67297.38	MÜLLER-STEINAG Gruppe	25m is perimeter of one core element; 7 floors; 2 each floor
	precasted concrete walls	Concrete, Susteno EviopactZero/Plus XC1/2	2500	3	372	0.2	223.2	1	223.2	344.25	25.00	369.25	125	0	42.19	411.44	91832.85	Peter Bausysteme AG	KBOB tiefbaubeton; recycled concrete -15% emissions for fabrication
	Reinforcement >= 0.2%	steel B500B	7850						1.1	5761.90	0.00	5761.90	5	0	5.30	5767.20	6088.32	HANS KOHLER AG	0.2% reinforcement steel in the foundations
Structure																			
	Timber structure	Timber column, Spruce	485	4	0.3	0.3	0.4	126	45.4	56.26	4.49	60.75	8.8	70.00	1.05	61.80	2803.37	Blumer-Lehmann AG, Gossau	Massivholz Fichte / Tanne / Lärche, luftgetr., gehobelt; 7 floors 3 x 6 columns per floor;
		Timber beam, Spruce	485	0.5	12	0.8	4.8	189	907.2	56.26	4.49	60.75	8.8	70.00	1.05	61.80	56067.30	Blumer-Lehmann AG, Gossau	Massivholz Fichte / Tanne / Lärche, luftgetr., gehobelt; 7 floors 3 x5 beams long side 6 x 2 beams short side per floor;
	Aeternum slab	Timber, spruce	242.5	2.4	2.4	0.3	1.7	1460	2522.5	28.13	2.25	30.38	10	50	0.50	30.87	77876.94	Aeternum	Slab has a grid form: only 50% is wood; 7 floors
	Aeternum column	Timber column, Spruce	485	4	0.3	0.3	0.4	251	90.4	56.26	4.49	60.75	10	50	0.99	61.75	5579.31	Aeternum	Aeternum column are positionated every 6 m in all the 7 floors
Modular elements																			
	Timber modular elements	Timber pavement/ceiling panels	485	5	10	0.15	7.5	72	540.0	56.26	4.49	60.75	8.8	70	1.05	61.80	33373.39	Blumer-Lehmann AG, Gossau	Massivholz Fichte / Tanne / Lärche, luftgetr., gehobelt; 3 floors (OGs) 50% modular timber and 50% openspace-rooms; 5x10x4 m modules; walls 10cm and pavements/ceiling 15 cm thick; transport distance of aeternum assumed
		Timber walls	485	4	10	0.1	4.0	36	144.0	56.26	4.49	60.75	8.8	70	1.05	61.80	8899.57	Blumer-Lehmann AG, Gossau	
Facade																			
	Ecococon	Timber, front/back	485	2	0.4	0.02	0.0	934.5	15.0	46.75	5.04	51.80	800	0	52.38	104.18	1557.67	Ecococon	windows/wall = 0.5 (0.8 south and 0.4 rest): measures of elements are all divided by 2, lifespan 30years (have to be replaced once); nr. Elements = tot. Perimeter / 0.8 m; glass: Isolierverglasung 2-fach, Ug-Wert 1.1 W/m2K, Dicke 24 mm; Timber: spruce ; staw: Strohballenwand
		Timber frame	485	0.095	19.2	0.045	0.1	934.5	76.7	46.75	5.04	51.80	800	0	52.38	104.18	7990.84	Ecococon	
		Straw	215	2	0.4	0.4	0.3	934.5	299.0	19.35	0.00	19.35	800	0	23.22	42.57	12730.13	Ecococon	
		Glass	2500	2	0.4	0.024	0.0	934.5	17.9	1658.33	9700.00	11358.33	10	0	3.38	22723.42	407712.63	Glas Müller AG	
	EcoCell	Timber	485	2	1.2	0.05	0.1	311.5	37.4	46.75	5.04	51.80	15	100	1.66	53.46	1998.30	EcoCell, Uttwil	
		Recycled paper	150	2	1.2	0.35	0.8	311.5	261.7	0.00	0.00	0.00	15	100	0.51	0.51	134.43	EcoCell, Uttwil	
		Glass	2500	2	1.2	0.024	0.1	311.5	17.9	1658.33	9700.00	11358.33	10	0	3.38	22723.42	407712.63	Glas Müller AG	
Pergola																			
	Modular PV-pergola	steel, beam and colums	7850	0.1	3	0.1	0.03	128	3.8	5761.90	0.00	5761.90	5	0	5.30	5767.20	22146.04	HANS KOHLER AG	assume ca. 8 modules (each 4 steel column and 4 steel beam)
		PV-panels [m2]	25	6	6		36.0	8	288.0			2788.99	10	0	0.03	5578.05	5578.05	PREISIG AG	120 kWh/m2 (https://www.uvek-gis.admin.ch/), Replace after 30 years (twice the emissions are calculated)
	Reused timber pergola	Timber	400	0.1	9.6	0.1	0.1	130	12.5	0.00	4.00	4.00	0	0	0.00	4.00	49.92	ETH	dimensions are estimated

8.1.2 Results of the first draft of the Life Cycle Assessment

Type	Design Element	total volume	Co2 storage	Total Co2 storage	Total GHG emission	Difference
		m3	kg CO_2/ m3	kg CO_2	kg CO_2-eq	kg CO_2-eq
Foundation	Strip foundation	134	-	-	29’203	29’203
	Ground concrete plate	394	-	-	86’175	86’175
	reinforcement	1	-	-	6’088	6’088
	Precasted concrete core	172	-	-	67’297	67’297
	Design element 1: Precast foundation	223	-	-	91’833	91’833
				-		-
Structure	Design Element 1: Aeternum Structure	2’613	700	1’829’016	83’456	-1’745’560
	Design Element 2: Timber Superstructure	1’637	700	1’145’592	101’144	-1’044’448
						-
Facades	Design Element 1: EcoCocon Panel	391	145	56’651	429’991	373’340
	Design Element 2: EcoCell Element	299	75	22’428	409’845	387’417
					(windows= 218000)	
Rooftop	Design Element 1: Pergola Reused	12	700	8’736	-	-8’736
	Design Element 1: PV-Pergola Modular	4	-	-	27’724	27’724

Design solution	Embodied emissions		
	kg CO_2-eq		
(Sol.1) Aeternum structure, EcoCocon façade, reused pergola	-1’100’359	Choosed	
(Sol.2) Aeternum structure, EcoCocon façade, modular pergola	-1’063’899	3%	More emissions
(Sol.3) Aeternum structure, EcoCell façade, reused pergola	-1’086’282	1%	More emissions
(Sol.4) Aeternum structure, EcoCell façade, modular pergola	-1’049’822	5%	More emissions
(Sol.5) Timber superstructure & modular units, EcoCocon façade, reused pergola	-399’247	64%	More emissions
(Sol.6) Timber superstructure & modular units, EcoCocon façade, modular pergola	-362’787	67%	More emissions
(Sol.7) Timber superstructure & modular units, EcoCell façade, reused pergola	-385’170	65%	More emissions
(Sol.8) Timber superstructure & modular units, EcoCell façade, modular pergola	-348’710	68%	More emissions

Timber carbon storage
1 kg timber = 1.44 kg co2
spruce = 485 kg/m3 = 1.44*485 = 700kg co2
Holzbau I Vorlesunng

8.1.3 Final Life Cycle Assessment

Type	Design element	Materials	Material density	Dimensions			Volume 1 element	Number elements	total volume	GHG emission (KBOB) Fabrication	GHG emission (KBOB) elimination	GHG emission (KBOB) Fabrication + elimination	Distance Transport: truck/train		GHG emission (KBOB) transport	Co2 storage	Total GHG emission	Total GHG emission	Lifespan	Lifespan factor	Total GHG emission for 60 years	Suppliers CH	Assumption	GHG KBOB DATA: Herstellung	GHG KBOB DATA: Entsorgung	reference
-	-	-	kg/m3	Height/ Width [m]	Length [m]	Thickness [m]	m3	-	m3	kg CO_2-eq/ m3	kg CO_2-eq/ m3	kg CO_2-eq/ m3	truck [km]	train [km]	kg CO_2-eq/ m3	kg $CO_{2,unit}$	kg CO_2-eq/ m3	kg CO_2-eq	(years) (for LCA max 60y)	-	kg CO_2-eq	-	-			
Foundation																										
	Strip foundation	Concrete, Susteno EviopactZero/ Plus XC1/2	2170	1	267.2	0.5	133.600	1	133.6	97.65	22.57	120.22	5	0	1.46	0.00	121.68	16256.82	60	1.00	16256.82	Holcim, Glattbrugg	recycled concrete (see calculation at the right)	0.045	0.010	kg
	Concrete ground plate	Concrete, Susteno EviopactZero/ Plus XC1/2	2170	16	61.6	0.4	394.240	1	394.2	97.65	22.57	120.22	5	0	1.46	0.00	121.68	47972.21	60	1.00	47972.21	Holcim, Glattbrugg	recycled concrete (see calculation at the right)	0.045	0.010	kg
	ground plate insulation	MISAPOR(0.4m), Schaumglasschotter	150	16	61.6	0.4	394.240	1	394.2	22.20	1.06	23.26	150	0	3.04	0.00	26.30	10368.31	60	1.00	10368.31	MISAPOR AG, Zizers		0.148	0.007	kg
	Precasted timber core	Timber, Glulam (brettschichtholz)	470	3.5	48	0.2	33.600	14	470.4	153.22	56.87	210.09	100	0	6.35	700.00	-483.57	-227468.98	60	1.00	-227468.98	MÜLLER-STEINAG Gruppe	48m is perimeter of one core element; 7 floors; 2 each floor	0.326	0.121	kg
		Steel	7850				9.408	1	9.4	5761.90	0.00	5761.90	100	0	105.98	0.00	5867.88	55204.97	60	1.00	55204.97	Aeternum	0.2% steel reinforcement	0.734	0	kg
	precasted concrete walls	Concrete, Susteno EviopactZero/ Plus XC1/2	2500	3	372	0.3	334.800	1	334.8	405.00	25.00	430.00	125	0	42.19	0.00	472.19	158088.38	60	1.00	158088.38	Peter Bausysteme AG	recycled concrete (see calculation at the right)	0.162	0.010	kg
	Concrete wall insulation	MISAPOR(0.4m), Schaumglasschotter	150	3	372	0.4	446.400	1	446.4	22.20	1.06	23.26	150	0	3.04	0.00	26.30	11740.10	60	1.00	11740.10	MISAPOR AG, Zizers		0.148	0.007	kg
	concrete walls airtight membrane	Polyethylen (PE)	920	3	372	0.001	1.116	1	1.1	2539.20	2373.60	4912.80	10	0	1.24	0.00	4914.04	5484.07	60	1.00	5484.07		kbob: Dampfbremse Polyethylen (PE)	2.76	2.58	kg
	Reinforcement >= 0.2%	steel B500B	7850						1.1	5761.90	0.00	5761.90	5	0	5.30	0.00	5767.20	6088.32	60	1.00	6088.32	HANS KOHLER AG	0.2% reinforcement steel in the foundations	0.734	0	kg
																				total:	**83734.19**					
Structure																										
	Aeternum slab	Timber, Glulam (brettschichtholz)	470	2.4	2.4	0.3	0.864	1451	1253.6	153.22	56.87	210.09	100	0	6.35	700.00	-483.57	-606172.91	60	1.00	-606172.91	Aeternum	Slab has a grid form: only 50% is wood (volume/2); 7 floors	0.326	0.121	kg
		Rebar, steel	7850				0.001	34821	26.1	5761.90	0.00	5761.90	100	0	105.98	0.00	5867.88	153243.22	60	1.00	153243.22	Aeternum		0.734	0	kg
		Connections, steel	7850	0.3	0.1	0.02	0.001	34821	20.9	5761.90	0.00	5761.90	100	0	105.98	0.00	5867.88	122594.58	60	1.00	122594.58	Aeternum		0.734	0	kg
	Aeternum column	Timber, Glulam (brettschichtholz)	470	4	0.3	0.3	0.360	175	63.0	153.22	56.87	210.09	100	0	6.35	700.00	-483.57	-30464.60	60	1.00	-30464.60	Aeternum	Aeternum column are positionated every 6 m in all the 7 floors	0.326	0.121	kg
	Aeternum column	Timber, Glulam (brettschichtholz)	470	3	0.3	0.3	0.270	95	25.7	153.22	56.87	210.09	100	0	6.35	700.00	-483.57	-12403.44	60	1.00	-12403.44	Aeternum	Aeternum column are positionated every 6 m in all the 7 floors	0.326	0.121	kg
		Connections, steel	7850				0.054	540	29.2	5761.90	0.00	5761.90	100	0	105.98	0.00	5867.88	171107.24	60	1.00	171107.24	Aeternum		0.734	0	kg
	Aeternum floor	Timber, Glulam (brettschichtholz)	470	0.32	0.32	0.24	0.025	52231	1283.6	153.22	56.87	210.09	100	0	6.35	700.00	-483.57	-620721.06	60	1.00	-620721.06	Aeternum		0.326	0.121	kg
		Fine clay plaster	1800	0.4	0.4	0.08	0.013	44988	575.8	32.76	8.51	41.27	100	0	24.30	0.00	65.57	37760.13	60	1.00	37760.13	Aeternum		0.018	0.005	kg
		Roof straw insulation	110	0.4	0.4	0.2	0.032	7244	231.8	9.90	0.00	9.90	100	0	1.49	163.83	-152.44	-35336.70	60	1.00	-35336.70	Aeternum		0.090	0	kg
		Roof airtight membrane	920	19	61	0.001	1.159	1	1.2	2539.20	2373.60	4912.80	10	0	1.24	0.00	4914.04	5695.37	60	1.00	5695.37		kbob: Dampfbremse Polyethylen (PE)	2.76	2.58	kg
		Roof parkett	470	0.4	2	0.02	0.016	1449	23.2	193.64	52.17	245.81	100	0	6.35	700.00	-447.85	-10381.05	60	1.00	-10381.05	Aeternum	KBOB: Parkett 3-Schicht werkversiegelt, 15 mm	0.412	0.111	kg
		Roof glulam plaster	470	0.4	0.4	0.08	0.013	7244	92.7	153.22	56.87	210.09	100	0	6.35	700.00	-483.57	-44836.15	60	1.00	-44836.15	Aeternum		0.326	0.121	kg
																				total:	**-869915.35**					
Facade																										
2972	Ecococon	Wood fiber board	640	4	1.2	0.06	0.288	402	115.9	332.16	81.28	413.44	800	0	69.12	630.00	-147.44	-17089.48	60	1.00	-17089.48	Ecococon	kbob: Spanplatte, PF-gebunden, Feuchtbereich	0.519	0.127	kg
		Airtigtht membrane (Polyethylen (PE))	920	4	1.2	0.001	0.005	402	1.9	2539.20	2373.60	4912.80	800	0	99.36	0.00	5012.16	9682.49	60	1.00	9682.49	Ecococon	kbob: Dampfbremse Polyethylen (PE)	2.76	2.58	kg
		Base clay coat	1800	4	1.2	0.025	0.120	402	48.3	32.76	8.51	41.27	800	0	194.40	0.00	235.67	11381.88	60	1.00	11381.88	Ecococon	kbob: lehmputz	0.018	0.005	kg
		Fine clay plaster	1800	4	1.2	0.003	0.014	402	5.8	32.76	8.51	41.27	800	0	194.40	0.00	235.67	1365.83	60	1.00	1365.83	Ecococon	kbob: lehmputz	0.018	0.005	kg
1634.6		Straw with timber frame	150	4	1.2	0.4	1.920	402	772.7	7.00	0.75	7.75	800	0	16.20	244.00	-220.05	-170036.65	60	1.00	-170036.65	Ecococon	EcoCocon panel (timber frame + straw) = 2.8kg/m2 for production; tot.perimeter facades=(9*61+6*19+2*15+2*25); total facades surface = 2972 m2; nr. Elements = tot. Perimeter / 1.2 m; 55% of facade surface is not covered by windows	0.047	0.005	kg
1337.4		Glass	2500	4	1.2	0.024	0.115	217	25.0	1658.33	161.67	1820.00	10	0	3.38	0.00	1823.38	45520.19	30	2.00	91040.38	Glas Müller AG	windows/wall = 0.38 (0.18/0.77/0.37/0.33); glass: Isolierverglasung 2-fach, Ug-Wert 1.1 W/m2K, Dicke 24 mm (replacement after 30 years, nr.elements *2)	39.8	3.88	m2
		Windows timber frame	470	0.08	10.4	0.08	0.067	217	14.4	153.22	56.87	210.09	800	0	50.76	630.00	-369.15	-5324.66	60	1.00	-5324.66	Ecococon		0.326	0.121	kg
	Curb (Rooftop + small roof OG1+core roofs)	Timber, Glulam (brettschichtholz)	470	0.06	1.2	0.034	0.002	254	0.6	153.22	56.87	210.09	5	0	0.32	700.00	-489.59	-304.62	60	1.00	-304.62	Saxer Holzbau GmbH	nr. Of elements = (perimeter rooftop+ per. Small roof og EG + per. Roof of the cores)/1.2m	0.326	0.121	kg
																				total:	**-79284.83**					
Internal walls																										
	EcoCell, TRENNWANDSYSTEM EI-60	Timber and cellulose	250	4	1.2	0.095	0.456	543	247.4				15	100	0.86		-314.93	-77908.18	60	1.00	-77908.18	EcoCell, Uttwil	from productor: total production + disposal emissions inkl. Storage = -30 kg CO2-eq / m2	30.0		m2
	Rotating walls fritsjurgens	Timber, chipboard	640	4	6	0.05	1.200	8	9.6	332.16	81.28	413.44	150	0	12.96	630.00	-203.60	-1954.56	60	1.00	-1954.56	fritsjurgens		0.519	0.127	kg
		Steel	7850				0.027	8	0.2	5761.90	0.00	5761.90	100	0	105.98	0.00	5867.88	1267.46	60	1.00	1267.46	fritsjurgens	assumed quantities	0.734	0	kg
	Separating wall with reused windows	Glass	2500	1.6	1.6	0.01	0.026	34	0.9	0.00	388.00	388.00	0	0	0.00		388.00	335.23	60	1.00	335.23	ETH?		0	3.88	m2
		Timber frame	400	0.4	1.6	0.02	0.003	34	0.1	0.00	4.00	4.00	0	0	0.00	700.00	-696.00	-60.13	60	1.00	-60.13	ETH		0.00	0.01	kg
	Box meeting rooms	Glass	2500	2.4	1.6	0.01	0.038	48	1.8	0.00	388.00	388.00	0	0	0.00		388.00	715.16	60	1.00	715.16	ETH?	2 floors x 3 box x 12.8m perimeter per box	0	3.88	m2
		Timber frame	400				0.004	48	0.2	0.00	4.00	4.00	0	0	0.00	700.00	-696.00	-128.29	60	1.00	-128.29	ETH	dimensions are estimated 10% of the glass surface	0.00	0.01	kg
		OSB panel as roof + small wall	640	3.2	7.2	0.03	0.691	1	0.7	332.16	81.28	413.44	0	0	0.00	630.00	-216.56	-149.69	60	1.00	-149.69	fritsjurgens		0.519	0.127	kg
	Doors	Timber panel, glulam	470	1	2	0.04	0.040	100	4.0	153.22	56.87	210.09	5	0	0.32	700.00	-489.59	-1958.37	60	1.00	-1958.37	Saxer Holzbau GmbH		0.326	0.121	kg
		Steel elements	7850				0.004	100	0.4	5761.90	0.00	5761.90	5	0	5.30	0.00	5767.20	2306.88	60	1.00	2306.88	Saxer Holzbau GmbH		0.734	0	kg
																				total:	**-77882.99**					
Pergola																										
	Reused timber pergola	Timber frame	465				1.084	21	22.8	0.00	4.65	4.65	0	0	0.00	700.00	-695.35	-15828.95	30	2.00	-31657.89	ETH	Reused from the architect's buildings HIP,...	0.00	0.01	kg
		steel screws	7850				0.000	1530	0.0	0.00	0.00	0.00	0	0	0.00	0.00	0.00	0.00	30	2.00	0.00	ETH	Reused from the architect's buildings HIP,...	0	0	kg
		Pergola Shading Element	465	0.03	3	0.12	0.011	1038	11.2	61.85	4.70	66.54	5	0	0.31	700.00	-633.14	-7097.80	60	1.00	-7097.80	Saxer Holzbau GmbH	0.3m = distance between shading elements; each rectangular pergola has 10 elements; each reused pergola has 38 shading elements	0.133	0.010	kg
		Pergola beam	470	0.12	3	0.12	0.022	60	1.3	0.00	56.87	56.87	0	0	0.00	700.00	-643.13	-833.50	30	2.00	-1666.99	eth	Reused from the architect's buildings HIP,...	0	0.121	kg
		pergola column	470	0.12	2	0.12	0.014	30	0.4	0.00	56.87	56.87	0	0	0.00	700.00	-643.13	-277.83	30	2.00	-555.66	eth	Reused from the architect's buildings HIP,...	0	0.121	kg
		Railing																				ETH	Reused from the architect's buildings HIP,...			

GHG emission (KBOB) transport: truck/train [kg CO2-eq /(kg*km)]		Assumption
Truck	0.000135	KBOB: Lastwagen durchschnitt
Train	0.000014	KBOB: Güterzug

																				total:	-40978.36								
																				total building:	-984'327.35								
Type	**Design element**	**Materials**	**Material density**	**Dimensions**			**Volume 1 element**	**Number elements**	**total volume**	**GHG emission (KBOB) Fabrication**	**GHG emission (KBOB) elimination**	**GHG emission (KBOB) Fabrication + elimination**	**Distance Transport: truck/train**		**GHG emission (KBOB) transport**	**Co2 storage**	**Total GHG emission**	**Total GHG emission**	**Life span**	**Lifespan factor**	**Total GHG emission for 60 years**	**Suppliers CH**	**Assumption**			
-	-	-	kg/m3	Height/ Width [m]	Length [m]	Thickness [m]	m3	-	m3	kg CO_2-eq/ m3	kg CO_2-eq/ m3	kg CO_2-eq/ m3	truck km	train km	kg CO_2-eq/ m3	kg CO_{2} unit	kg CO_2-eq/ m3	kg CO_2-eq	Years	-	kg CO_2-eq	-	-			
Systems																													
Heating/cooling																													
opt2	WEM Klimaelement, heating/cooling clay panel	Clay	1376	2	0.625	0.025	0.03125	6637.6	207.425	22.43	9.74	32.17	100	400	26.28	0.00	58.45	12124.51	30	2.00	24249.01	WEM Gmbh, Germany	all ceilings are covered with clay panels	0.016	0.007	kg
opt1	The Variotherm Modular Ceiling	gypsum fibre	1200	0.6	2	0.02	0.024	6914.167	165.94	632.40	11.11	643.51	250	500	48.90	0.00	692.41	114898.85	30	2.00	229797.69	Variotherm Heizsysteme Gmbh, Austria		0.527	0.009	kg
Ventilation																													
opt2	Windows ventilation, AEROMAT VT mit Wärmerückgewinnung	Aluminium and others [per pieces]	1				1	217		38.00	5.48	43.48	520	0	35.10	0.00	78.58	17028.94	30	2.00	34057.88	Siegenia, Germany	KBOB: Einzelraumlüfer Fenstermodell 10-30 m^3/h, ohne Montage; only considered the floors with windows	38.0	5.48	stk.
op1	Lüftungsanlage, spez. Luftmenge 4 m^3/hm^2 EBF	[m2]							6832	25.20	0.76	25.96					25.96	177379.22	30	2.00	354758.43		only considered the floors with windows	25.2	0.763	m2
Power																													
	PV-Panels	[m2]	25	1.7	1.1		1.9	270	504.9			180873.00	80	0	13.50	0.00	6816.15	187689.15	60	1.00	185818.86	Megasol AG, Solothurn	kWp for 1 panel = 0.33 (from Megasol ag);	2'030		kWp
		steel supports	7850				0.027	12	0.3	5761.90	0.00	5761.90	10	0	10.60	0.00	5772.50	1870.29	60	1.00	1870.29		1 support every 5 m; data used for the material passport, since in the embodied emissions of the pv the supports of the systems is already included. Therefore this value is subtracted from the embodied emissions of the pv	0.734	0	kg
	Battery [13.5 kWh]		1000				0.1	3				1201.50	450	450	67.05	0.00	1268.55	490.93	10	6.00	2945.57	Tesla	quantity=3, lifespan 10 years (6 replacements); data from tesla battery 13.5 kWh; 89kgCO2/Kwh Forbes.com;			
	Electrical installation	per m2							6832	63537.60	23228.80	86766.40						86766.40	60	1.00	86766.40		average Elektroanlagen Wohnen from KBOB	9.30	3.40	m2
	crane	Steel	7850				8.000	2	16.0	5761.90	0.00	5761.90	100	0	105.98	0.00	5867.88	93886.00	60	1.00	93886.00		assumed quantities	0.734	0	kg
Boiler																													
opt1	Sanitäranlagen, Büro, einfach, inkl. Apparate und Leitungen (electric boiler)	[m2]							6832	3.33	1.15	4.48					4.48	30607.36	30	2.00	61214.72		considered tot. Floor surface	3.33	1.15	m2
opt2	Sanitäranlagen, Büro, einfach, inkl. Apparate und Leitungen (air-heatpump boiler)	[m2]							6832	3.36	1.16	4.52					4.52	30913.43	30	2.00	61826.87		considered tot. Floor surface	3.36	1.16	m2
Shading system																													
	Rolling shading system	wood[m2]						62	207.047	23.83	0.14	23.97					23.97	4962.77	30	2.00	9925.55		only on south facade, possibility to add them to the desired windows; KBOB: Sonnenschutz, Rollladen motorisiert	23.8	0.136	m2
Elevator																													
		Steel	7850				0.834	4	3.3	5761.90	0.00	5761.90	150	0	158.96	0.00	5920.86	19752.00	60	1.00	19752.00	Schindler, Luzern	assumed volume of 1 element, probably it will be less than it, nevertheless the used value will contain all the elevator system as well	0.734	0	kg
																				total systems:	427'212.43								

Facade	m^2	WWR [%]			
North	363.24	18	18	18	18
South	363.24	77	77	57	77
East	950	37	57	37	37
West	1157.1	33	33	33	28
tot	**2833.35**	**38**	**45**	**35**	**36**

total:	-557'114.9

8.1.4 Calculation of the embodied emissions of concrete

Here the calculation sheet of the embodied emissions of concrete are presented. Option 1 have been chosen to be used in this project, it is characterized by the high recycled content and presents the properties of Susteno cement, produced by Holcim AG.

KBOB
Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren
Conférence de coordination des services de la construction et des immeubles des maîtres d'ouvrage publics
Conferenza di coordinazione degli organi della costruzione e degli immobili dei committenti pubblici
Coordination Group for Construction and Property Services

Stadt Zürich
Amt für Hochbauten

Betonsortenrechner für Planende

	Variante 1	Variante 2	Variante 3
Beton			
Anwendungsbereich	Hochbaubeton, NPK-A	Hochbaubeton, NPK-A	Hochbaubeton, NPK-A
Zusammensetzung Betonsorte			
Zementtyp	CEM III/B	CEM II/B CH-Mix	CEM III/A
Zusammensetzung Zuschlagstoffe	100.00%	100.00%	100.00%
Anteil natürliche Gesteinskörnung R_n	40%	100%	50%
Anteil Betongranulat R_c	50%	0%	50%
Anteil Mischgranulat R_b	10%	0%	0%
Betonbezeichnung	Recyclingbeton RC-M	Beton aus Primärrohstoffen	Recyclingbeton RC-C
Umweltindikator			
Treibhausgasemissionen (THG-E)			
Rohdichte	2170 kg/m³	2240 kg/m³	2190 kg/m³
Herstellung	88 kg CO2-eq/m³	190 kg CO2-eq/m³	140 kg CO2-e
Zement	89 kg CO2-eq/m³	179 kg CO2-eq/m³	130 kg CO2-e
Gesteinskörnung	3 kg CO2-eq/m³	4 kg CO2-eq/m³	3 kg CO2-e
Übriges (Energie, Wasser, Zusatzmittel)	8 kg CO2-eq/m³	8 kg CO2-eq/m³	8 kg CO2-e
Entsorgung	23 kg CO2-eq/m³	23 kg CO2-eq/m³	23 kg CO2-e
Total	121 kg CO2-eq/m³	213 kg CO2-eq/m³	152 kg CO2-e

Version 2.5, Juni 2020

Mit dem Betonsortenrechner können Sie die Umwelteinwirkungen von einem m³ Beton Ihrer Wahl berechnen. Legen Sie den Anwendungsbereich, den Betontyp sowie den Zementtyp fest und geben Sie die Anteile an natürlicher Gesteinskörnung, Beton- und Mischgranulat ein. Für die Quantifizierung der Umwelteinwirkungen wählen Sie den gewünschten Umweltindikator aus. Welche Betonsorten in der Schweiz gemäss Norm SN EN 206:2013 freigegeben sind, entnehmen Sie bitte dem SIA Register der frei gegebenen Zemente und Kombinationen von Zementen und Zusatzstoffen. Die Bezeichnungen der Zusammensetzung beziehen sich auf das SIA Merkblatt 2030 Ausgabe 2010 Recyclingbeton (v.a. Tabellen 1 und 2).

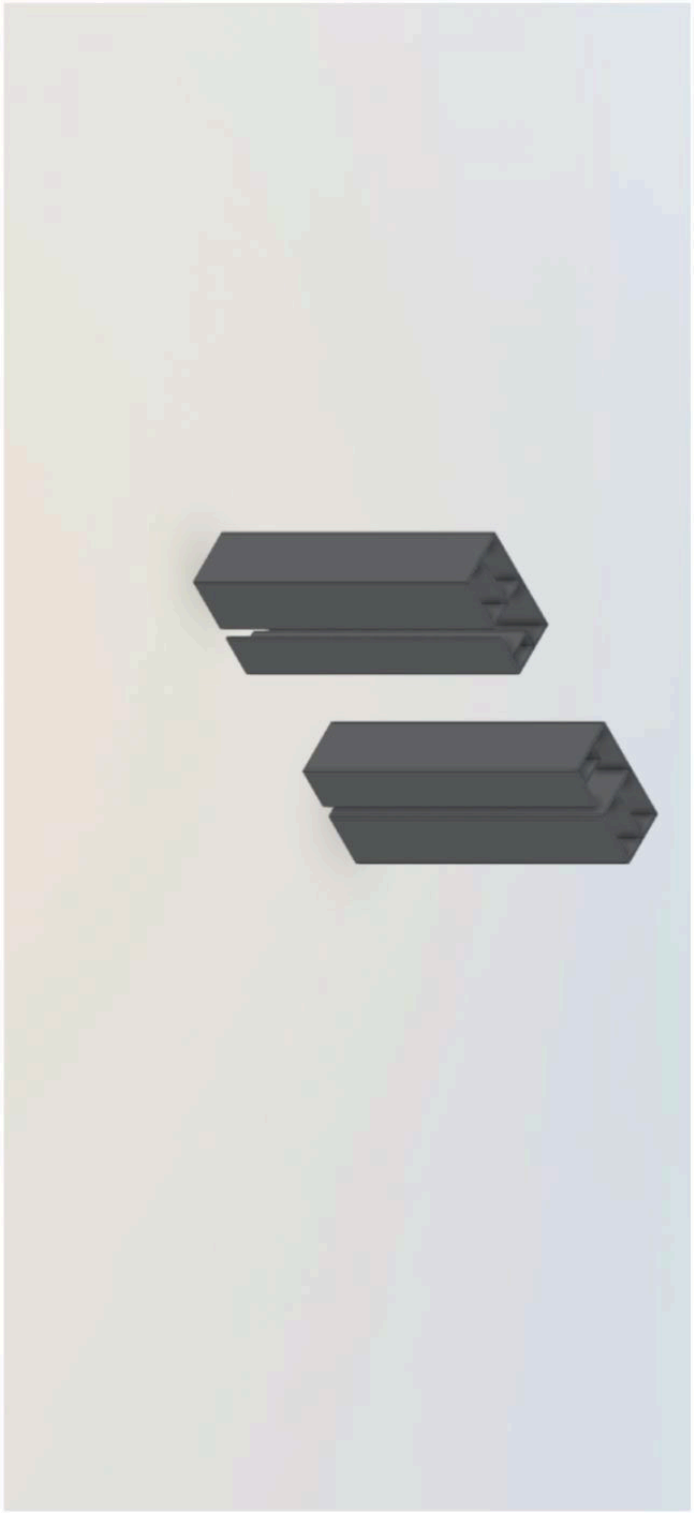
Der Betonsortenrechner sowie dessen zugrundeliegenden Annahmen werden im "Hintergrundbericht Betonrechner" beschrieben.

Die dem Rechner zugrunde liegenden Ökobilanzen wurden mit dem KBOB Ökobilanzdatenbestand v2.2:2016 (basierend auf dem ecoinvent Datenbestand v2.2) berechnet. Die Sachbilanzen zur Herstellung von Recycling-Gesteinskörnung sowie von CEM I, CEM II/A, CEM II/B CH-Mix, CEM II/B-LL, CEM III/A, CEM III/B und CEM V/A/D Zementen sind in der Studie "Ökobilanz ausgewählter Betonsorten" von Tschumperlin et al. (2020) dokumentiert.

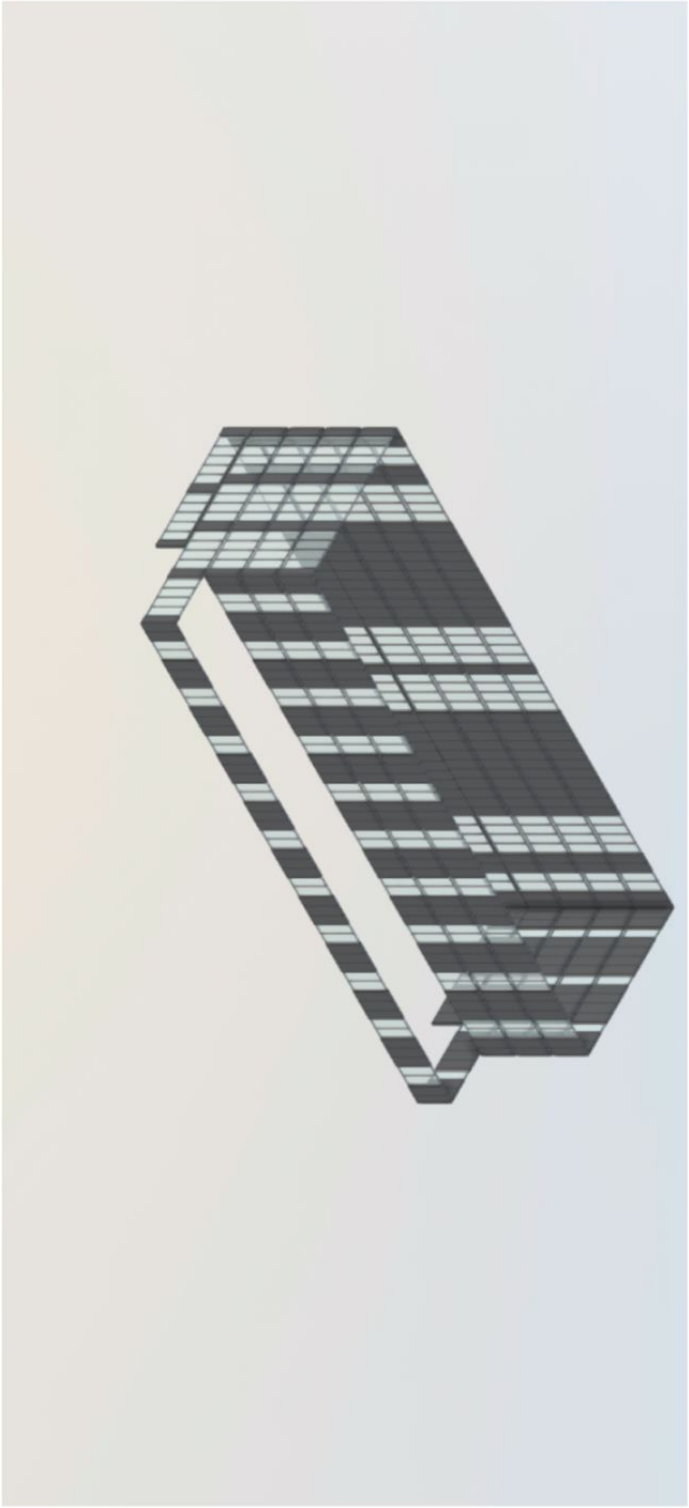
SIA 262 - Register der freigegebenen Zemente und Kombinationen von Zementen und Zusatzstoffen
"Hintergrundbericht Betonrechner" herunterladen
Studie "Ökobilanz ausgewählter Betonsorten" herunterladen
Zurück zur Kreisa Website

8.2 Autodesk Forge LOD200 Visualizations

8.2.1 Cores



8.2.2 Facade



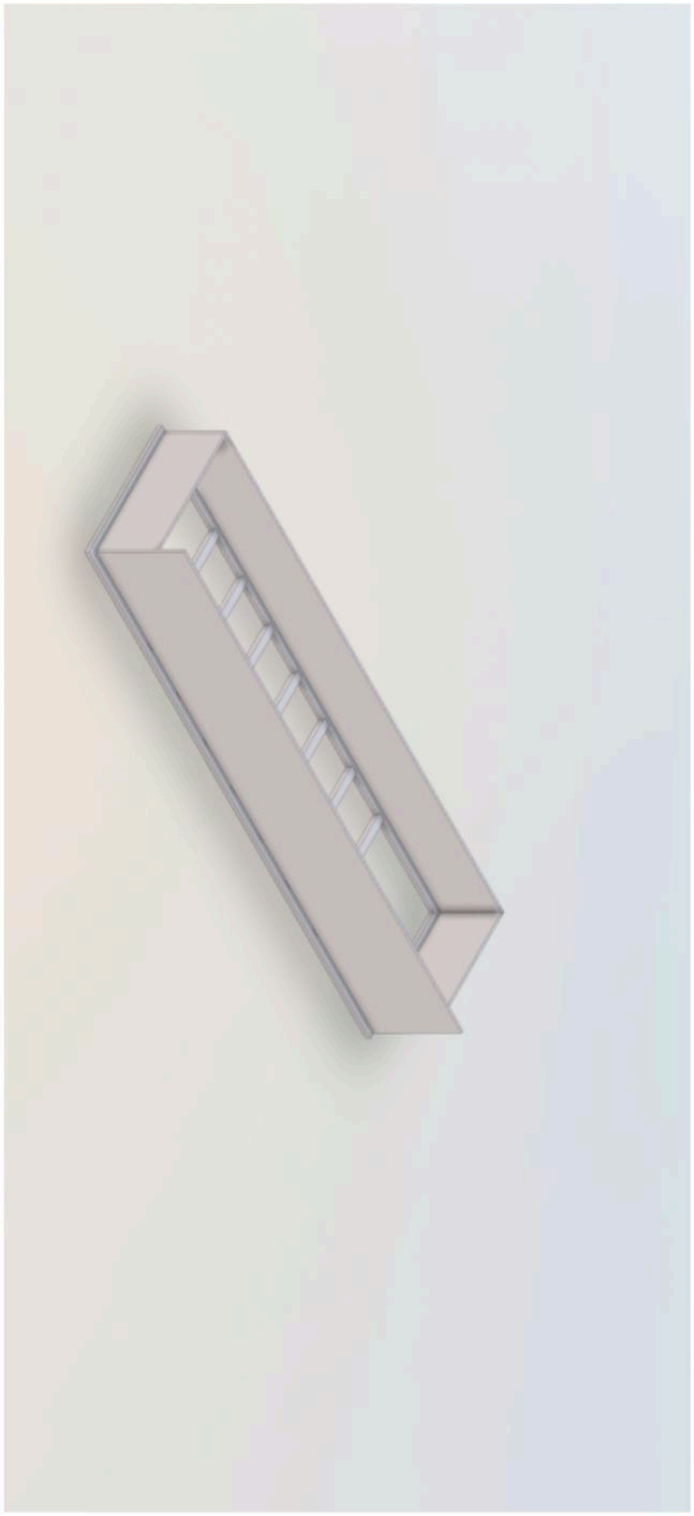
8.2.3 Slabs



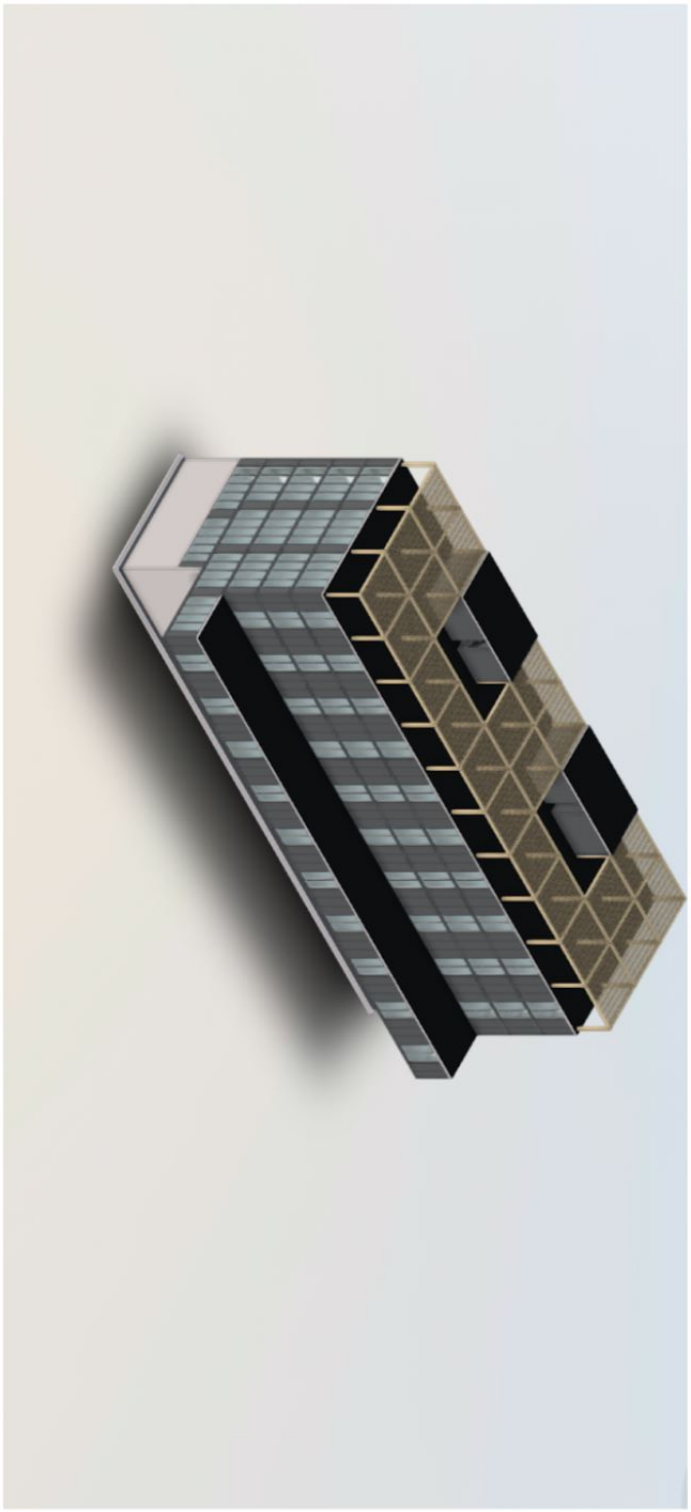
8.2.4 Columns



8.2.5 Foundation & Retaining Walls



8.2.6 Model



8.3 Design Elements Catalogue

Foundation - Design Element 1: Precast Foundation

Cluster	Criteria
Flexibility	**Separation of building layers** The foundation made with precast concrete elements is clearly separated from the structure and the rest of the building, also by the fact that they are made from a different material. However, there are multiple different connection systems that provide a simple and effective connection to the rest of the structure of the building.
	Simplicity of system The simplicity of the system is provided by the use of precast concrete elements with identical dimensions only.
	Network design It is possible to add new elements to the foundation in case a building expansion is planned.
	Building design The precast concrete elements will provide enough stability and safety for the multiple use of the building.
Materialization	**Dematerialization and organic material use** No alternative to concrete foundation could be found. However, the use of sustainable and recycled concrete such as Susteno by Holcim will ensure lower CO2 emissions and short transportation distance. Due to the precision of the industrialized precast production process concrete waste is minimized.
	Material lifespan Precast concrete elements are durable with lifespans larger than on-site casted concrete. Additionally, the precast elements can be reused for other foundations, due to their connectors.

Structure - Design Element 1: Aeternum Structure

Cluster	Criteria
Flexibility	**Separation of building layers** Aeternum's column and slab element build a primary structure. Other building layers can be connected to the structure, using the standardized reversible connectors.
	Simplicity of system The structural system contains of three main components, the column, a slab grid, and slab blocks (for the slab grid).
	Network design The structure only contains two types of connectors, enabling infinite different network designs. The connectors at the slab's edges can be used for other building layers (e.g. the facade) to connect it to the structure.
	Building design The skeleton structure guarantees great flexibility for the space layout. Interior walls don't need to be load bearing and therefore can be treated similar to furniture.
Materialization	**Dematerialization and organic material use** The main element is built from timber only. The connectors are from steel.
	Material lifespan Aeternum's system is build for re-adaptability. The concept is designed to maximize the lifespan of each component.

Structure - Design Element 2: Timber Superstructure

Cluster	Criteria
Flexibility	**Separation of building layers** The timber superstructure is clearly separated from the rest of the building. The individual units on the other hand, need to integrate functionalities from different building layers. Therefore, the design of the units has a great impact on this criterion.
	Simplicity of system The timber superstructure is based on a simple and repetitive column and slab structure.
	Network design Modules can be attached in X- and Y- direction. The space grid (volume in between the columns) is the only limitation.
	Building design The building design is part of the modules. However, due to production and logistic requirements, the modules are expected to be less adaptable to users needs than an open space.
Materialization	**Dematerialization and organic material use** The superstructure is built from CLT. The separation of the superstructure and the structure needed for the module to be transported results in additional material use.
	Material lifespan The lifespan of the superstructure can only be maximized as a whole. If individual components of the superstructure reach the end of their lifespan before others, the whole superstructure might be affected.

Rooftop - Design Element 1: Pergola Reused

Cluster	Criteria
Flexibility	**Separation of building layers** The pergola made with reused timber, laying on the rooftop, is clearly separated from the rest of the building, also because it is not part of the structural system of the building.
	Simplicity of system The timber pergola is made with a repetitive structure, using only beams with a few different measures.
	Network design Since the timber elements are reused, their dimensions are already given, small changes can however be done.
	Building design The supports of pergola allow to maintain an open-space underneath, which can be used for multiple purposes.
Materialization	**Dematerialization and organic material use** The entire pergola is made with reused timber elements of the dismantled architects' buildings on the ETH campus.
	Material lifespan The already reused timber can not guarantee an addition reusability when they are no more needed on this building. Nevertheless by reusing them the first time, a prolonged lifespan is guaranteed.

Rooftop - Design Element 1: PV-Pergola Modular

Cluster	Criteria
Flexibility	**Separation of building layers** The pergola made with a steel structure, laying on the rooftop, is clearly separated from the rest of the building, also because it is not part of the structural system of the building.
	Simplicity of system The frame of the pergola is made with a simple structure, using only three different steel beams. The PV-modules are nicely integrated in the frame by using a steel grid.
	Network design Moving or expanding/reducing the pergola can be easily done just by adding/removing parts of the frame.
	Building design The supports of pergola allow to maintain an open-space underneath, which can be used for multiple purposes.
Materialization	**Dematerialization and organic material use** The entire pergola is made with newly produced steel elements with high expected emissions. The use of a PV-system provide clean energy. The emissions saved by using solar energy instead of electricity from the grid can partially compensate the emissions of steel production.
	Material lifespan The steel beams can guarantee a long lifespan, which can be prolonged by reusing the frames elements.

Facade - Design Element 1: Straw Panel

Cluster	Criteria
Flexibility	**Separation of building layers** The straw panel facade can be integrated into the structure or separated from the rest. In our case, to adhere to the concept of separation of the layers and as suggested by the manufacturer, for buildings above 3 floors, it is better to separate them from the structural part.
	Simplicity of system Straw panel facades are particularly simple and made up of just few modular elements, composed by only few materials, the timber framework, the straw insulation and two external breather elements.
	Network design Each element can be connected to other elements in any direction using the integrated timber frame.
	Building design Having a modular design, the facade elements can be detached and reattached to the structure in different configurations (e.g. to have several windows in a facade at a given location for given comfort needs).
Materialization	**Dematerialization and organic material use** Each module is composed practically only of carbon-negative materials (with the exception of the reinforcement mash and the screws). One m^3 of a straw panel core stores 145 kg of atmospheric CO_2.
	Material lifespan The facade, being composed of modules, is easily disposable and these can then be reused in other contexts. In addition, each module can be easily dismantled and all elements either re-used, recycled, used as biomass or safely composted.

Facade - Design Element 2: Cellulose Panel

Cluster	Criteria
Flexibility	**Separation of building layers** The cellulose facade can be integrated into the structure or separated from the rest. In our case, to adhere to the concept of separation of the layers, it is better to separate them from the structural part.
	Simplicity of system Cellulose panel facades consist of modules composed by only two composites, OSB plates and recycled paper covered with a mineral coating, that are stick together.
	Network design Each module can be inserted into I-shaped joints or the existing OSB plates can be used to connect it to other elements.
	Building design Having a modular design, the facade elements can be detached and reattached to the structure in different configurations (e.g. to have several windows in a facade at a given location for given comfort needs).
Materialization	**Dematerialization and organic material use** Each module is made of timber and recycled paper, the only process with a negative impact in terms of CO_2 is the process of paper mineralisation. However, he manufacturer guarantees, that every m^2 stores 30 kg of CO_2.
	Material lifespan The facade, being composed of modules, is easily disposable and these can then be reused in other contexts.

WWR - Design Element 1: Ecococon Window

Cluster	Criteria
Flexibility	**Separation of building layers** Non-loadbearing panels with integrated windows, like all facade elements, can be easily separated from the rest of the building.
	Simplicity of system With only three different facade elements, the facade can be designed including the flexibility to change the design.
	Network design Thanks to the timber frame with standardized dimensions, the elements can be installed in any position of the facade.
	Building design There are three different modules: One with a large window (ca. 80% of the facade element), one with a small window (40% of the element), and one without windows. With different configurations of these modules the facade layout can be changed.
Materialization	**Dematerialization and organic material use** Each module is composed of organic materials, with the exception of windows, the percentage of which depends on the element in question.
	Material lifespan The facade, being composed of modules, can easily be disassembled and reassembled in another place of the building. In addition, each module can be easily dismantled and all elements either re-used, recycled, used as biomass or safely composted.

Core - Design Element 1: Precast Concrete Core

Cluster	Criteria
Flexibility	**Separation of building layers** The precast core contains the staircase and lift only. It is part of the structure and therefore directly connected to the rest of the structure.
	Simplicity of system The precast elements are from reinforced concrete only. No additional coating is necessary for fire safety regulations (Aufzugsschächte aus brennbaren Bauprodukten sind schachtseitig mit Baustoffen der RF1 zu bekleiden).
	Network design For the core to be compatible with the rest of the structure, the connectors of the rest of the structure need to be integrated to the precast core.
	Building design The space of the two cores in the center of the building (low daylight availability) is only suited for limited building functionalities.
Materialization	**Dematerialization and organic material use** Thanks to the use of concrete, fire safety regulations are met without additional coatings. The use of sustainable and recycled concrete such as Susteno by Holcim ensures low CO_2 emissions and a short transportation distance. Due to the precision of the industrialized precast production process concrete waste is minimized.
	Material lifespan Precast concrete elements are durable with longer lifespans than on-site casted concrete. The elements can be reused in other buildings, once the majority of the building components has reached its lifespan but not the core.

Core - Design Element 2: Timber Core

Cluster	Criteria
Flexibility	**Separation of building layers** The timber core contains the staircase and lift only. It is part of the structure and therefore directly connected to the rest of the structure.
	Simplicity of system The precast elements are from CLT timber. Additional coating is necessary for fire safety regulations (Aufzugsschächte aus brennbaren Bauprodukten sind schachtseitig mit Baustoffen der RF1 zu bekleiden).
	Network design For the core to be compatible with the rest of the structure, the connectors (Aeternum connectors) of the rest of the structure need to be integrated to the precast core.
	Building design The space of the two cores in the center of the building (low daylight availability) is only suited for limited building functionalities.
Materialization	**Dematerialization and organic material use** The main element is built from timber only. The connectors are from steel. For fire safety an additional coating is needed
	Material lifespan The timber core as a long lifespan, like the aeternum system. The elements can be reused in other buildings, once the majority of the building components has reached its lifespan but not the core.

Building Systems - Design Element 1: Extensive

Cluster	Criteria
Flexibility	**Separation of building layers** All the distribution and emission systems are external/detached from the structural system. That's why their configuration can be easily changed (bolted elements).
	Simplicity of system Due to the complexity of the system, a lot of components of state of the art technology are necessary.
	Network design The configuration of the fabric air ducts can easily be changed and extended. The ceiling panel connections are made from reversible bolts.
	Building design The path of the air ducts can easily be modified, but this system requires a lot of space. The ceiling modules can also be exchanged and require little space.
Materialization	**Dematerialization and organic material use** A lot of carbon intensive materials are used due to the complex state of the art technological system (e.g. battery). The ceiling panels are also made of organic materials, with the exception of the plastic pipes and connections.
	Material lifespan All components are designed to be easily separated from the rest of the building, giving them excellent opportunities for reuse. However, the state of the art technologies involve risks and unreliable information on lifespan.

Building Systems - Design Element 2: Lean

Cluster	Criteria
Flexibility	**Separation of building layers** All the distribution and emission systems are external/detached from the structural system, so their configuration can be easily changed (bolted elements)
	Simplicity of system Due to the simplicity of the system, little components are needed and well established technologies are used.
	Network design The ceiling panel connections are made from reversible bolts.
	Building design Only little space is needed for the systems, the ceiling modules can be exchanged and require little space. For the window airing no additional space is needed.
Materialization	**Dematerialization and organic material use** The systems are reduced to a minimum. Consequently the need for materials drops dramatically. The ceiling panels are also made of organic materials, with the exception of the plastic pipes and connections.
	Material lifespan All components are designed to be easily separated from the rest of the building, giving them excellent opportunities for reuse. In addition, the well established technologies involve fewer risks and have a longer lifespans.

Interior Walls - Design Element 1: Rotating Walls

Cluster	Criteria
Flexibility	**Separation of building layers** The rotating internal walls do not serve as structural element, they just separate and insulate the rooms, therefore they are also separated from the rest of the building.
	Simplicity of system Rotating walls are composed by only two components, a wooden chipboard and the rotating hinges.
	Network design Each rotating wall can be easily installed everywhere, since the rotating mechanisms just need to be attached to the ceiling and floor without any predisposition of the latter.
	Building design Rotating walls can radically change the use of the hall or room simply by open up the earlier enclosed space.
Materialization	**Dematerialization and organic material use** Each wall panel is made of timber therefore it has the capability to store CO_2. The steel connectors instead have a negative impact on the environment, nevertheless the impact is almost neglectable if the benefit of timber is considered.
	Material lifespan The internal walls can easily be dismantled and these can then be reused in other contexts.

Interior Walls - Design Element 2: Fixed Walls

Cluster	Criteria
Flexibility	**Separation of building layers** The cellulose (recycled paper) internal walls do not serve as structural element, they just separate and insulate the rooms, therefore they are also separated from the rest of the building.
	Simplicity of system Cellulose walls consist of modules composed by only two composites, OSB plates and recycled paper covered with a mineral coating, that are stick together.
	Network design Each module can be inserted into I-shaped joints or the existing OSB plates can be used to connect it to other elements.
	Building design Having a modular design, the internal wall elements can be detached and reattached together in different configurations (e.g. if the room use changes or new office rooms have to be created).
Materialization	**Dematerialization and organic material use** Each module is made of timber and recycled paper, the only process with a negative impact in terms of CO_2 is the process of paper mineralisation. However, he manufacturer guarantees, that every m^2 stores 30 kg of CO_2.
	Material lifespan The internal walls, being composed of modules, can easily be dismantled and these can then be reused in other contexts.

Interior Walls - Design Element 3: Reused walls and meeting modules

Cluster	Criteria
Flexibility	**Separation of building layers** The separating internal walls and meeting modules do not serve as structural element, they just separate the internal space. Therefore they are also separated from the rest of the building.
	Simplicity of system Reused walls and meeting modules are composed by only two composites, reused windows and a lean timber frame.
	Network design These kind of walls are just layed on the floor, they can be located basically everywhere.
	Building design The separating wall elements can be putted together in different configurations, depending on the needs, they simply need to be moved around without any fixing system.
Materialization	**Dematerialization and organic material use** The separating walls and meeting modules are entirely made of reused materials from old dismantled building on the ETH campus.
	Material lifespan Being inside they will last during the entire lifespan of the building, even if they are made of reused materials.

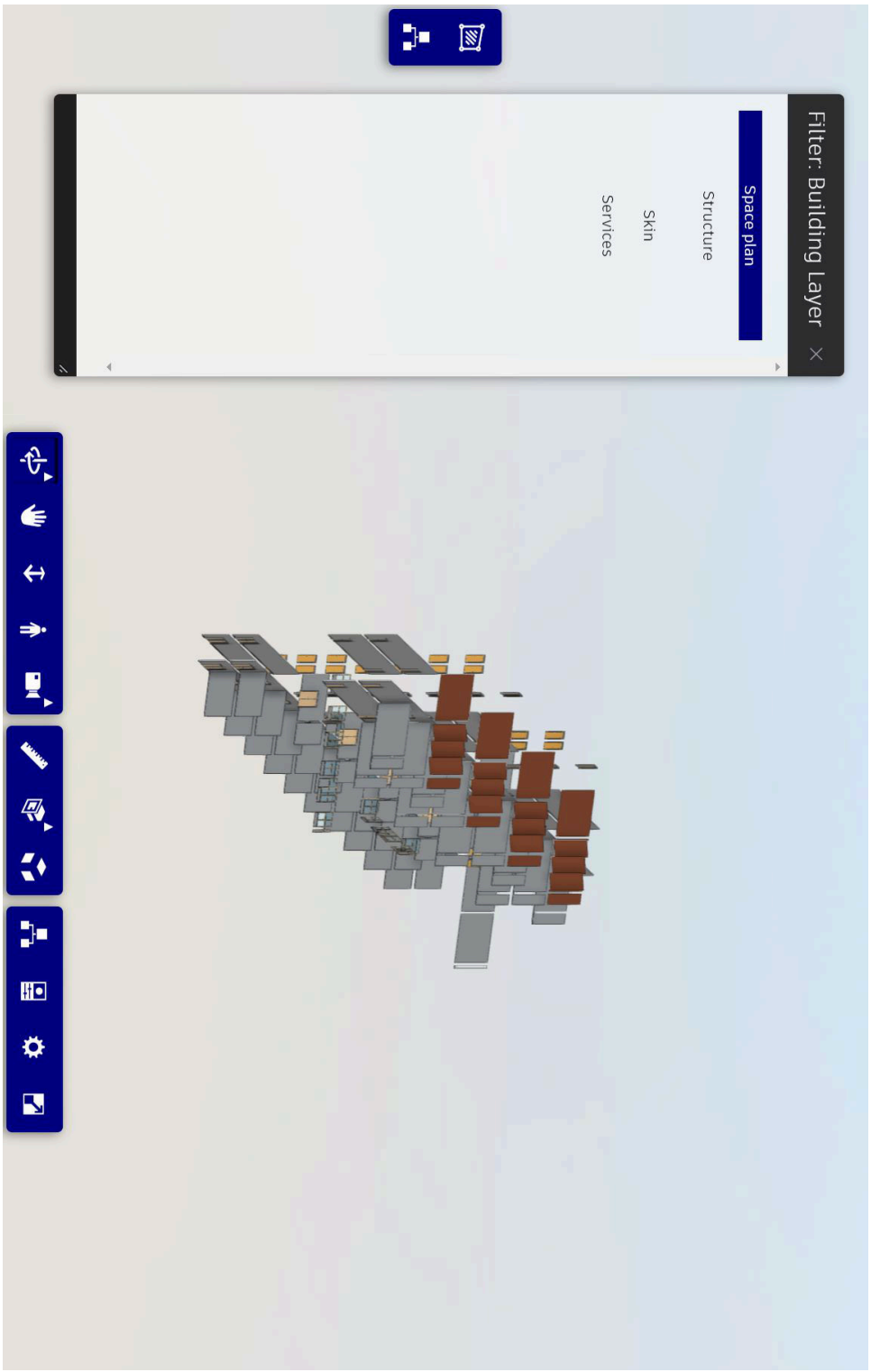
8.4 Material Passport Table

Component			Dimensions	Manufacturer		Building physics	Design for disassembly	Flexibility									
Component category	Component name	Material	Revit Family [picture]	Manufacturer's name	Manufacturer's address	U-value [W/m2K]	Connector type	Building layer	Number of elements (simplicity of s	Future scenarios (network design)	Building design	Lifespan [years]	Reused [-]	Reuse potential [-]	Recycling potential [-]	Waste [-]	Embodied CO2 emissions [kg CO2-
Method						Utotal = 1/R1 + 1/R2 + ... + 1/Rn			Number of elements modeled in Re	Possible future use of components	Category of interchangable components	Ltotal = L1 * f1 + L2 * 0 + ... + Ln * 0 where L1 is the material with the hig	Volumentric fraction: Fx = (Vx * Fx) / (V1 * F1 + V1 * F2 + ... + Vn *fn)				
		Concrete										60	0.000	0.000	1.000	0.000	16256.820
		Steel rebar										60	0.000	0.000	1.000	0.000	1541.000
	Foundation strips (600 mm)	Total		Holcim Kies und Beton AG	Bäulerstrasse 8, 8152 Glattbrugg, Switzerland	3.80	Type I	Structure	2	Construction industry internal recyc	Foundation strips	60	0.000	0.000	1.000	0.000	17797.820
		Concrete										60	0.000	0.000	1.000	0.000	47972.000
		Steel rebar										60	0.000	0.000	1.000	0.000	4544.900
	Foundation plate (400 mm)	Total		Holcim Kies und Beton AG	Bäulerstrasse 8, 8152 Glattbrugg, Switzerland	4.75	Type I	Structure	2	Construction industry internal recyc	Foundation plate	60	0.000	0.000	1.000	0.000	52516.900
Fondation floor	Foundation floor insulation MISAPOR (400 mm)	Foam-glass granulate		MISAPOR AG	Rosenstrasse 2, 7205 Zizers, Switzerland	0.20	Type IX	Skin	1	Hönggi Tower 2080	Foundation floor insulation	100	0.000	1.000	0.000	0.000	10368.000
	Precast foundation wall (300 mm)	Reinforced Concrete		Peter Bausysteme AG	Dorfstrasse 35, 8155 Niederhasli, Switzerland	9.50	Type VIII	Structure	1	Hönggi Tower 2080	Precast fondation wall	100	0.000	1.000	0.000	0.000	105392.000
		Foam-glass granulate bags										100	0.000	1.000	0.000	0.000	11740.000
		Airtight membrane										60	0.000	0.000	1.000	0.000	5494.070
Foundation wall	Foundation wall insulation MISAPOR Wall-Bag (400 mm)	Total		MISAPOR AG	Rosenstrasse 2, 7205 Zizers, Switzerland	0.20	Type IV	Skin	2	Hönggi Tower 2080	Foundation wall insulation	100	0.000	0.998	0.000	0.002	17224.070
		Glulam timber										100	0.000	1.000	0.000	0.000	-417.741
		Steel rebar										100	0.000	1.000	0.000	0.000	105.697
		Steel connector			Kreuzmatte 1, 6147 Altbüron, Switzerland							100	0.000	1.000	0.000	0.000	84.485
	Slab	Total		Aetemum	or Witbachstrasse 12, 8153 Rümlang, Switzerland	-	Type VIII	Structure	3	Hönggi Tower 2080	Slab	100	0.000	1.000	0.000	0.000	-227.649
		Glulam timber										100	0.000	1.000	0.000	0.000	-130.563
		Steel connector			Kreuzmatte 1, 6147 Altbüron, Switzerland							100	0.000	1.000	0.000	0.000	634.000
	Column under ground (Corner)	Total		Aetemum	or Witbachstrasse 12, 8153 Rümlang, Switzerland	-	Type V	Structure	3	Hönggi Tower 2080	Column under ground (Corner)	100	0.000	1.000	0.000	0.000	503.437
		Glulam timber										100	0.000	1.000	0.000	0.000	-130.563
		Steel connector			Kreuzmatte 1, 6147 Altbüron, Switzerland							100	0.000	1.000	0.000	0.000	824.200
	Column under ground (Regular)	Total		Aetemum	or Witbachstrasse 12, 8153 Rümlang, Switzerland	-	Type V	Structure	4	Hönggi Tower 2080	Column under ground (Regular)	100	0.000	1.000	0.000	0.000	693.637
		Glulam timber										100	0.000	1.000	0.000	0.000	-174.083
		Steel			Kreuzmatte 1, 6147 Altbüron, Switzerland							100	0.000	1.000	0.000	0.000	634.000
	Column above ground (Corner)	Total		Aetemum	or Witbachstrasse 12, 8153 Rümlang, Switzerland	-	Type V	Strucure	3	Hönggi Tower 2080	Column above ground (Corner)	100	0.000	1.000	0.000	0.000	459.917
		Glulam timber										100	0.000	1.000	0.000	0.000	-174.083
		Steel			Kreuzmatte 1, 6147 Altbüron, Switzerland							100	0.000	1.000	0.000	0.000	824.200
	Column above ground (Regular)	Total		Aetemum	or Witbachstrasse 12, 8153 Rümlang, Switzerland	-	Type V	Strucure	4	Hönggi Tower 2080	Column above ground (Regular)	100	0.000	1.000	0.000	0.000	650.117
		Glulam timber										100	0.000	1.000	0.000	0.000	-11.894
		Clay			Kreuzmatte 1, 6147 Altbüron, Switzerland							60	0.000	0.000	1.000	0.000	0.839
	Floor tile (Regular)	Total		Aetemum	or Witbachstrasse 12, 8153 Rümlang, Switzerland	-	Type IX	Structure	2	Hönggi Tower 2080	Floor tile (Regular)	100	0.000	0.658	0.000	0.342	-11.045
		Glulam timber										100	0.000	1.000	0.000	0.000	6.942
		Clay			Kreuzmatte 1, 6147 Altbüron, Switzerland							60	0.000	0.000	1.000	0.000	0.420
	Floor tile (Side)	Total		Aetemum	or Witbachstrasse 12, 8153 Rümlang, Switzerland	-	Type IX	Structure	2	Hönggi Tower 2080	Floor tile (Edge)	100	0.000	0.658	0.000	0.342	-6.522
		Glulam timber										100	0.000	1.000	0.000	0.000	-2.971
		Clay			Kreuzmatte 1, 6147 Altbüron, Switzerland							60	0.000	0.000	1.000	0.000	0.210
	Floor tile (Corner)	Total		Aetemum	or Witbachstrasse 12, 8153 Rümlang, Switzerland	-	Type IX	Structure	2	Hönggi Tower 2080	Floor tile (Corner)	100	0.000	0.658	0.000	0.342	-2.761
		Glulam timber										100	0.000	1.000	0.000	0.000	-22.7469.000
		Steel			Kreuzmatte 1, 6147 Altbüron, Switzerland							100	0.000	1.000	0.000	0.000	52205.000
	Core (cross laminated timber)	Total		Aetemum	or Witbachstrasse 12, 8153 Rümlang, Switzerland	-	Type V	Structure	2	Hönggi Tower 2080	Core	100	0.000	1.000	0.000	0.000	-17264.000
		Glulam timber			Kreuzmatte 1, 6147 Altbüron, Switzerland							100	0.000	1.000	0.000	0.000	-172.344
		Steel			or							100	0.000	1.000	0.000	0.000	5980.108
	Stairs	Total		Aetemum	Witbachstrasse 12, 8153 Rümlang, Switzerland	-	Type V	Structure	2	Hönggi Tower 2080	Stair	100	0.000	1.000	0.000	0.000	5807.763
					Kreuzmatte 1, 6147 Altbüron, Switzerland												
Structure	Core Curb	Glulam timber		Aetemum	or Witbachstrasse 12, 8153 Rümlang, Switzerland	-	Type V	Structure	2	Hönggi Tower 2080	Core closing	100	0.000	1.000	0.000	0.000	-71.824
		Glulam timber										60	0.000	0.000	1.000	0.000	6.296
		Straw			Kreuzmatte 1, 6147 Altbüron, Switzerland							60	0.000	0.000	1.000	0.000	-4.878
		Airtight membrane			or							60	0.000	0.000	1.000	0.000	0.786
	Insulation tile (Regular)	Total		Aetemum	Witbachstrasse 12, 8153 Rümlang, Switzerland	0.18	Type IX	Skin	1	Construction industry internal recyc	Insulation tile (Standard)	60	0.000	0.000	0.289	0.711	-10.378
		Glulam timber										60	0.000	0.000	1.000	0.000	-3.143
		Straw			Kreuzmatte 1, 6147 Altbüron, Switzerland							60	0.000	0.000	1.000	0.000	2.439
		Airtight membrane			or							60	0.000	0.000	1.000	0.000	0.393
	Insulation tile (Side)	Total		Aetemum	Witbachstrasse 12, 8153 Rümlang, Switzerland	0.18	Type IX	Skin	1	Construction industry internal recyc	Insulation tile (Edge)	60	0.000	0.000	0.289	0.711	-4.189
		Glulam timber										60	0.000	0.000	1.000	0.000	-1.572
		Straw			Kreuzmatte 1, 6147 Altbüron, Switzerland							60	0.000	0.000	1.000	0.000	-2.439
		Airtight membrane			or							60	0.000	0.000	1.000	0.000	0.393
	Insulation tile (Corner)	Total		Aetemum	Witbachstrasse 12, 8153 Rümlang, Switzerland	0.18	Type IX	Skin	1	Construction industry internal recyc	Insulation tile (Corner)	60	0.000	0.000	0.289	0.711	-3.618
Roof	Railing	Reused steel		ETH Zürich	Wolfgang-Pauli-Strasse 17-19-21, 8049 Zürich, S	-	Type V	Skin	1	Hönggi Tower 2080	Railing	60	1.000	0.000	0.000	0.000	0.000
		Reused timber		ETH Zürich	Wolfgang-Pauli-Strasse 17-19-21, 8049 Zürich, S							30	1.000	0.000	0.000	0.000	-754.455
		Reused Steel connector										30	1.000	0.000	0.000	0.000	0.000
	Pergola Framework	Total		Megert und Frutiger Holzbau AG	Töpferweg 16, 3613 Steffisburg, Switzerland	-	Type V	Structure	2	Construction industry internal recyc	Pergola Framework	30	1.000	0.000	0.000	0.000	-754.455
		Reused timber										30	1.000	0.000	0.000	0.000	-14.146
		Reused Steel connector										30	1.000	0.000	0.000	0.000	0.000
	Pergola Beam (120 x120)	Total		Megert und Frutiger Holzbau AG	Töpferweg 16, 3613 Steffisburg, Switzerland	-	Type V	Structure	2	Construction industry internal recyc	Pergola Beam	30	1.000	0.000	0.000	0.000	-14.146
		Reused timber										30	1.000	0.000	0.000	0.000	9.032
		Reused Steel connector										30	1.000	0.000	0.000	0.000	0.000
	Pergola Column (120 x120)	Total		Megert und Frutiger Holzbau AG	Töpferweg 16, 3613 Steffisburg, Switzerland	-	Type V	Structure	1	Construction industry internal recyc	Pergola Column	30	1.000	0.000	0.000	0.000	9.032
Pergola	Pergola Shading Element (30x 120) new	Glulam timber		Megert und Frutiger Holzbau AG	Töpferweg 16, 3613 Steffisburg, Switzerland	-	Type V	Structure	1	Construction industry internal recyc	Pergola shading element	60	0.000	0.000	1.000	0.000	-8.953
		Wood fiber board (60 mm)										60	0.000	0.000	1.000	0.000	-44.100
		Airtight membrane										60	0.000	0.000	1.000	0.000	24.058
		Panel: Timber frame with Straw (400 mm)										60	0.000	0.000	1.000	0.000	-418.000
		Base clay coat (25 mm)			Zahradnicka 60, 821 08 Bratislava, Slovakia							60	0.000	0.000	1.000	0.000	28.294
		Fine clay plaster (3 mm)			and							60	0.000	0.000	1.000	0.000	3.394
	Straw panel without window	Total		EcoCocon s.r.o. and SHIFT (Swiss partner)	R. de l'Indépendance 10, 1096 Cully, Switzerland	0.12	Type VIII	Skin	2	Biodegradation and incineration	Facade	60	0.000	0.000	0.000	1.000	-406.364
		Wood fiber board (60 mm)										60	0.000	0.000	1.000	0.000	-26.460
		Airtight membrane										60	0.000	0.000	1.000	0.000	14.435
		Panel: Timber frame with Straw (400 mm)										60	0.000	0.000	1.000	0.000	-250.800
		Base clay coat (25 mm)			Zahradnicka 60, 821 08 Bratislava, Slovakia							60	0.000	0.000	1.000	0.000	16.970
		Fine clay plaster (3 mm)			and							60	0.000	0.000	1.000	0.000	2.036
	Straw panel with small window (WWR: 40%)	Total		EcoCocon s.r.o. and SHIFT (Swiss partner)	R. de l'Indépendance 10, 1096 Cully, Switzerland	0.12	Type VIII	Skin	2	Biodegradation and incineration	Facade	60	0.000	0.000	0.000	1.000	-243.819
		Wood fiber board (60 mm)										60	0.000	0.000	1.000	0.000	-8.820
		Airtight membrane										60	0.000	0.000	1.000	0.000	4.812
		Panel: Timber frame with Straw (400 mm)										60	0.000	0.000	1.000	0.000	-83.600
		Base clay coat (25 mm)			Zahradnicka 60, 821 08 Bratislava, Slovakia							60	0.000	0.000	1.000	0.000	5.657
		Fine clay plaster (3 mm)			and							60	0.000	0.000	1.000	0.000	0.679
	Straw panel with large window (WWR: 80%)	Total		EcoCocon s.r.o. and SHIFT (Swiss partner)	R. de l'Indépendance 10, 1096 Cully, Switzerland	0.12	Type VIII	Skin	2	Biodegradation and incineration	Facade	60	0.000	0.000	0.000	1.000	-81.273
				EcoCocon s.r.o. and	Zahradnicka 60, 821 08 Bratislava, Slovakia and												
	Facade curb (120 mm)	Glulam timber		SHIFT (Swiss partner)	R. de l'Indépendance 10, 1096 Cully, Switzerland	-	Type V	Skin	1	Construction industry internal recyc	Facade curb (120 mm)	60	0.000	0.000	1.000	0.000	-0.120
				EcoCocon s.r.o. and	Zahradnicka 60, 821 08 Bratislava, Slovakia and												
Facade	Facade curb (66 mm)	Glulam timber		SHIFT (Swiss partner)	R. de l'Indépendance 10, 1096 Cully, Switzerland	-	Type V	Skin	1	Construction industry internal recyc	Facade curb (66 mm)	60	0.000	0.000	1.000	0.000	-0.066
	Interior wall panel (9.5 cm) (incl. T-connector)	Timber with Recycled paper		Ecocell	Dorfstrasse 18, 8592 Uttwil, Switzerland	0.56	Type V	Space plan	1	Hönggi Tower 2080	Interior wall panel	60	0.000	1.000	0.000	0.000	-143.477
		Rivet Hinges		FritsJurgens	Zelgstrasse 95, 3661 Uetendorf, Switzerland							60	0.000	0.000	1.000	0.000	158.375
		OSB Board (60 mm)										60	0.000	0.000	1.000	0.000	-244.320
	Rotatable wall (Pivot in center)	Total		Saxer Holzbau GmbH	Riedenhaldenstrasse 270, 8046 Zürich, Switzerland	-	Type V	Space plan	3	Construction industry internal recyc	Rotatable wall	60	0.000	0.000	1.000	0.000	-85.945
		Reused windows		ETH Zürich	Wolfgang-Pauli-Strasse 17-19-21, 8049 Zürich, S							60	1.000	0.000	0.000	0.000	14.896
		Reused timber										60	1.000	0.000	0.000	0.000	-46.333
	Office module	Total		Saxer Holzbau GmbH	Riedenhaldenstrasse 270, 8046 Zürich, Switzerla	-	Type IX	Space plan	6	Construction industry internal recyc	Office module	60	1.000	0.000	0.000	0.000	-31.438
		Reused windows		ETH Zürich	Wolfgang-Pauli-Strasse 17-19-21, 8049 Zürich, S							60	1.000	0.000	0.000	0.000	9.853
		Reused timber										60	1.000	0.000	0.000	0.000	-2.098
	Partittion wall (little)	Total		Saxer Holzbau GmbH	Riedenhaldenstrasse 270, 8046 Zürich, Switzerla	-	Type IX	Space plan	1	Construction industry internal recyc	Partittion wall	60	1.000	0.000	0.000	0.000	7.755
		Reused windows		ETH Zürich	Wolfgang-Pauli-Strasse 17-19-21, 8049 Zürich, S							60	1.000	0.000	0.000	0.000	9.853
		Reused timber										60	1.000	0.000	0.000	0.000	-2.098
	Partittion wall (big)	Total		Saxer Holzbau GmbH	Riedenhaldenstrasse 270, 8046 Zürich, Switzerla	-	Type IX	Space plan	1	Construction industry internal recyc	Partittion wall	60	1.000	0.000	0.000	0.000	7.755
		Glulam timber										60	0.000	0.000	1.000	0.000	-19.560
		Steel										60	0.000	0.000	1.000	0.000	23.088
	Door single flush	Total		Saxer Holzbau GmbH	Riedenhaldenstrasse 270, 8046 Zürich, Switzerla	-	Type V	Space plan	1	Construction industry internal recyc	Door single flush	60	0.000	0.000	1.000	0.000	3.528
		Glulam timber										60	0.000	0.000	1.000	0.000	-39.120
		Steel										60	0.000	0.000	1.000	0.000	46.176
Interior design	Door duble flush	Total		Saxer Holzbau GmbH	Riedenhaldenstrasse 270, 8046 Zürich, Switzerla	-	Type V	Space plan	2	Construction industry internal recyc	Doorduble flush	60	0.000	0.000	1.000	0.000	-32.704
	WEM klimaelement, heating/cooling clay panel	Clay		WEM Wandheizung CH	Zentweg 17c, 3006 Bern, Switzerland	-	Type V	Services	1	Construction industry internal recyc	WEM klimaelement	30	0.000	0.000	1.000	0.000	3.653
		Aluminium		SIEGENIA AG	Duisburger Straße 8, D-57234 Wilnsdorf, Deutsch							30	0.000	0.000	1.000	0.000	190.946
		Glass										30	0.000	0.000	1.000	0.000	84.022
		Windows Timber frame										30	0.000	0.000	0.000	1.000	-12.269
	Small window, incl. window ventilation unit AEROMAT	Total		Glas Müller AG	Lättenstrasse 31, 8952 Schlieren, Switzerland	-	Type III	Skin and services	1	Construction industry internal recyc	Small window	30	0.000	0.000	0.632	0.368	228.700
		Aluminium		SIEGENIA AG	Duisburger Straße 8, D-57234 Wilnsdorf, Deutsch							30	0.000	0.000	1.000	0.000	190.946
		Glass										30	0.000	0.000	1.000	0.000	168.045
		Windows Timber frame										30	0.000	0.000	0.000	1.000	-24.538
	Large window, incl. window ventilation unit AEROMAT	Total		Glas Müller AG	Lättenstrasse 31, 8952 Schlieren, Switzerland	-	Type III	Skin and services	1	Construction industry internal recyc	Small window	30	0.000	0.000	0.632	0.368	380.453

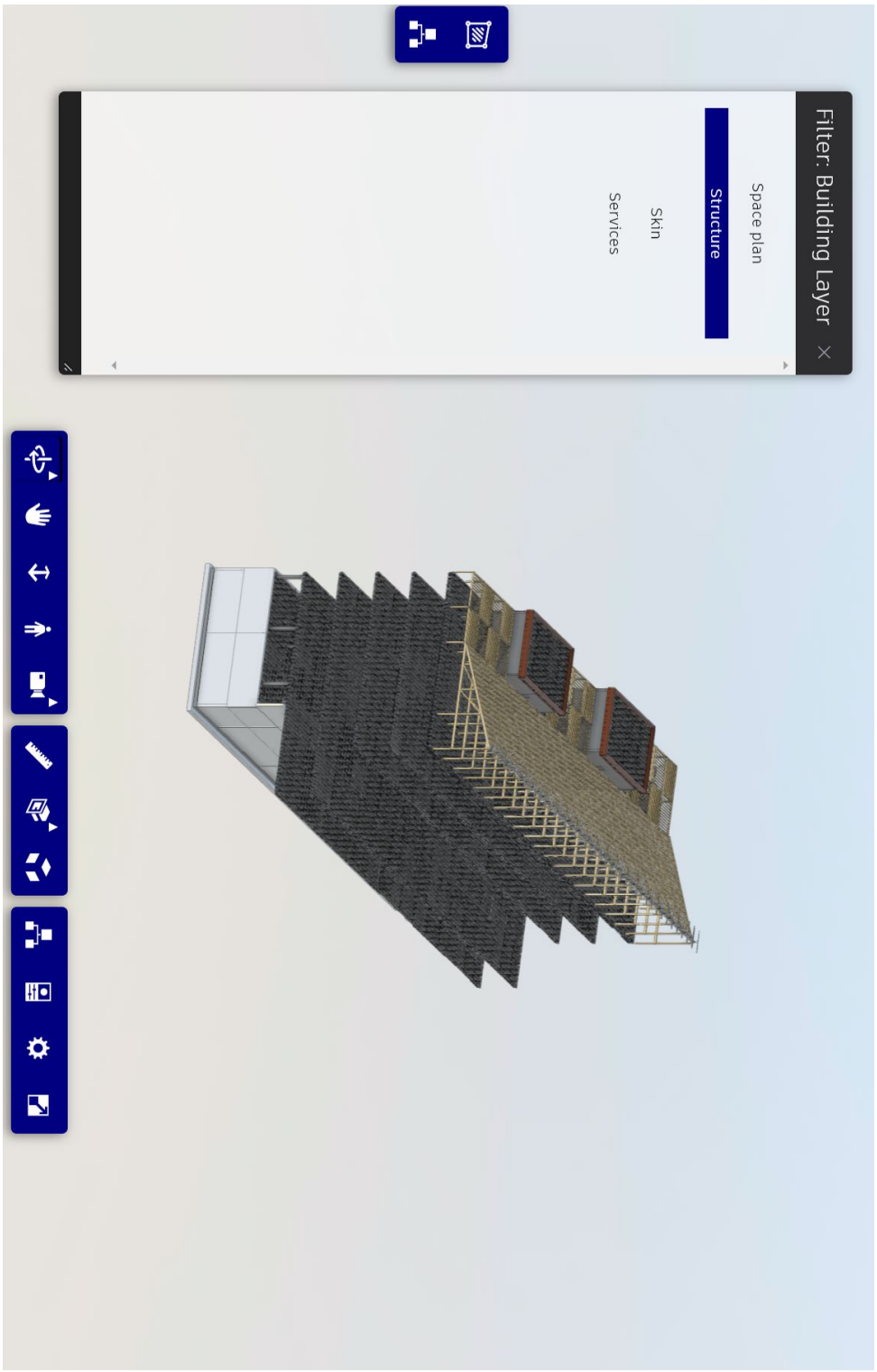
Component			Dimensions	Manufacturer		Building physics	Design for disassembly	Flexibility										
Component category	Component name	Material	Revit Family [picture]	Manufacturer's name	Manufacturer's address	U-value [W/m2K]	Connector type	Building layer	Number of elements (simplicity of s	Future scenarios (network design)	Building design	Lifespan [years]	Reused [-]	Reuse potential [-]	Recycling potential [-]	Waste [-]	Embodied CO2 emissions [kg CO2-
Method						Utotal = 1/R1 + 1/R2 + ... + 1/Rn			Number of elements modeled in Re	Possible future use of components	Category of interchangable components	Ltotal = L1 * 1 + L2 * 0 + ... + Ln * 0 where L1 is the material with the hi	Volumentric fraction: Fx = (Vx * Fx) / (V1 * F1 + V1 * F2 + ... + Vn *Fn)					
	PV module	PV panel, M330-60-b GG LEVEL		Megasol AG	Industriestrasse 9, 4543 Deitingen, Switzerland	-	Type VII	Services	1	Construction idustry internal recycl	PV module	60	0.000	0.000	1.000	0.000	695.144
	Rotatable construction for PV modules	Steel		HANS HOHLER AG	Claridenstrasse 20, 8022 Zürich, Switzerland	-	Type VII	Structure	1	Construction idustry internal recycl	Rotatable construction for PV modules	60	0.000	0.000	1.000	0.000	155.833
	Heat pump water heater	Heat pump water boiler		Solar GmbH	Lindenhofstrasse 6, 8180 Bülach, Switzerland	-	Type VII	Services	1	Construction idustry internal recycl	Heat pump water heater	10	0.000	0.000	1.000	0.000	0.000
	Battery	Battery		Tesla AG	Tesla Str. 1, 15537 Grünheide (Mark), Germany	-	Type VII	Services	1	Recycling in other industries	Battery	10	0.000	0.000	1.000	0.000	163.667
	Elevator	Steel		Schindler AG	Zugerstrasse 13, 6039 Ebikon, Switzerland	-	Type V	Services	1	Recycling in other industries	Elevator	60	0.000	0.000	1.000	0.000	9876.000
Building Systems	Shading system	Wood		Schenker Storen AG	Stauwehrstrasse 34, 5012 Schönenwerd, Switzer	-	Type V	Services	1	Construction idustry internal recycl	Shading system	30	0.000	0.000	1.000	0.000	160.090

8.5 Autodesk Forge LOD300+ Visualizations

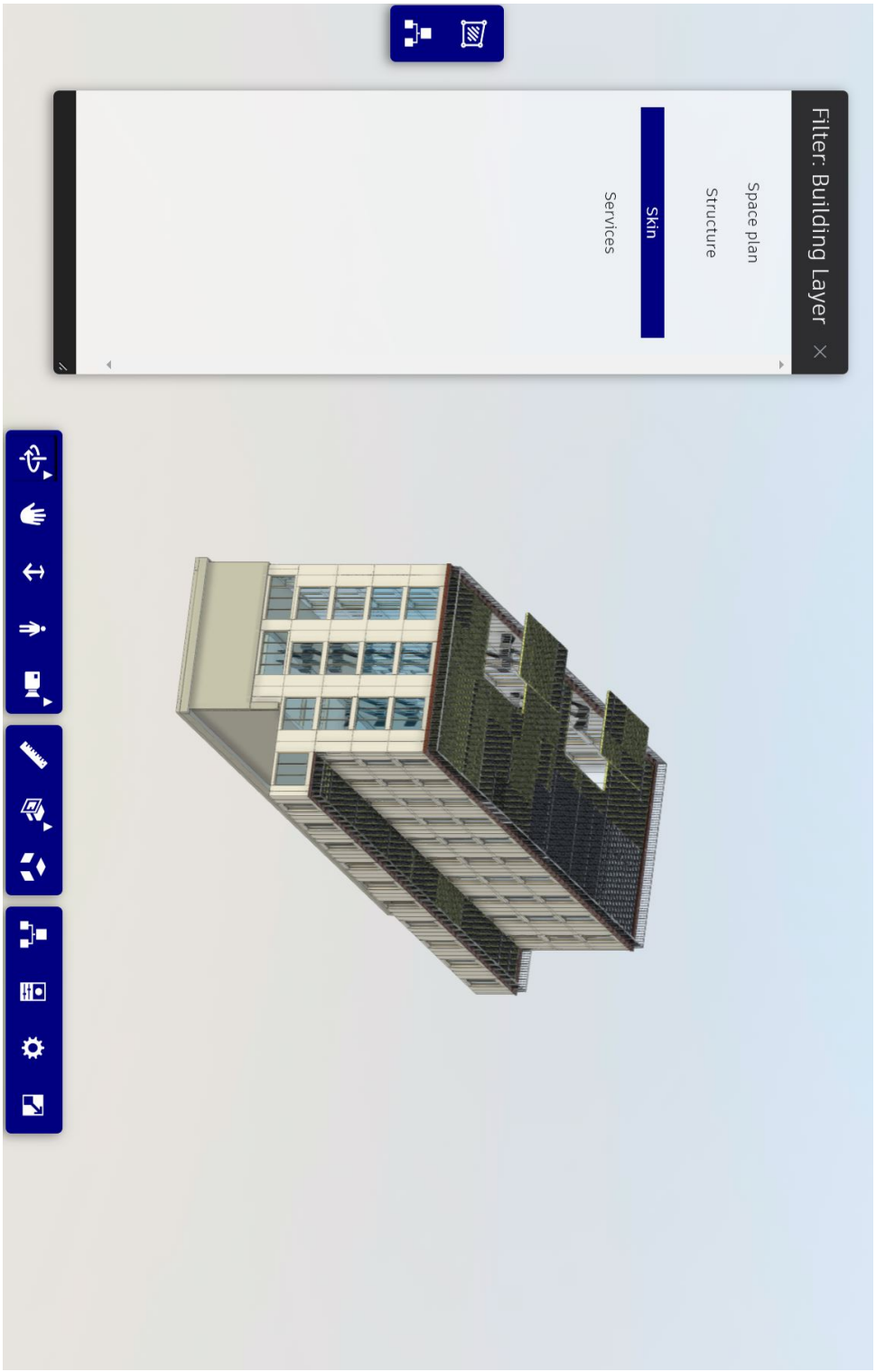
8.5.1 Building Layer 1



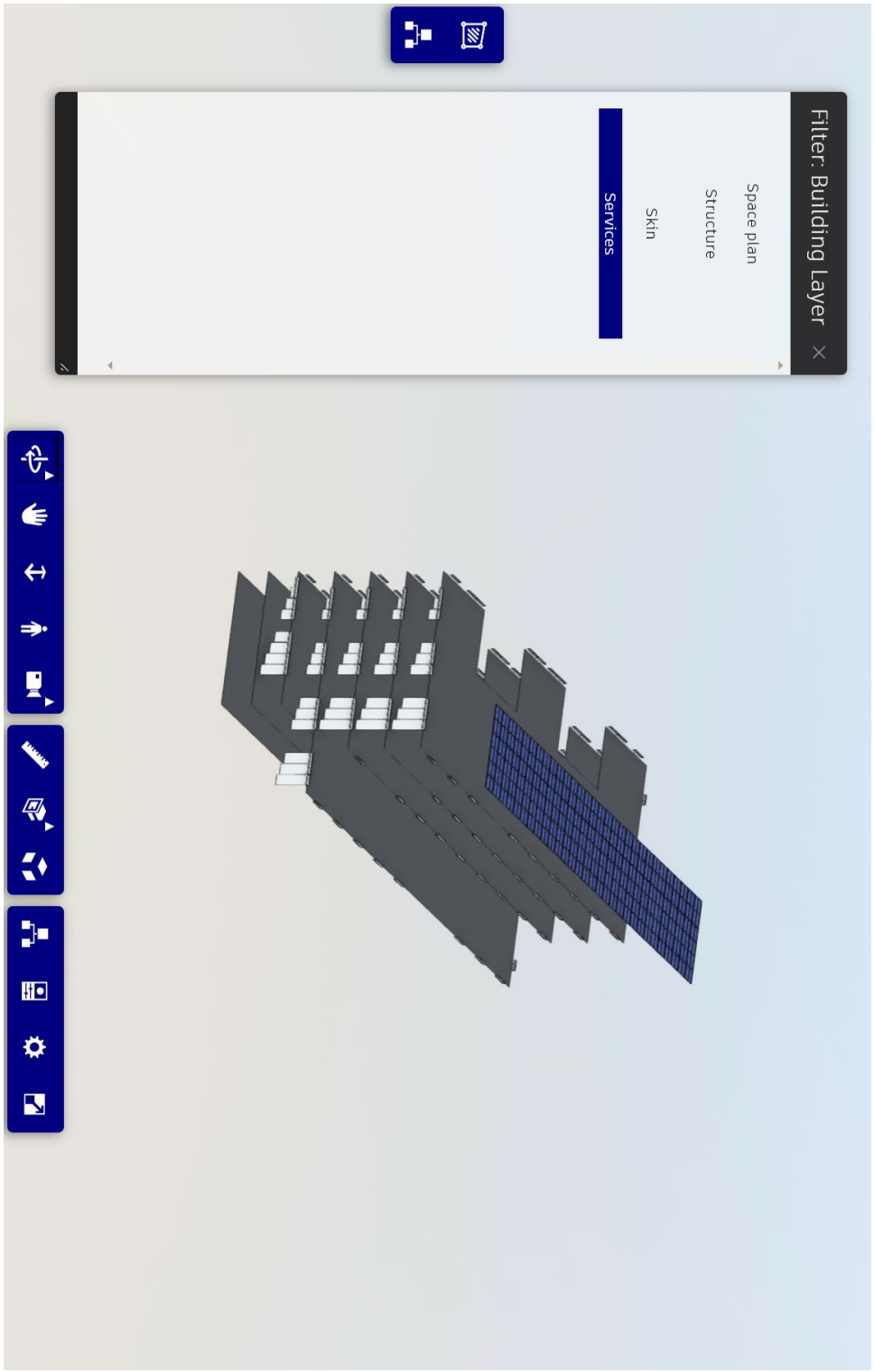
8.5.2 Building Layer 2



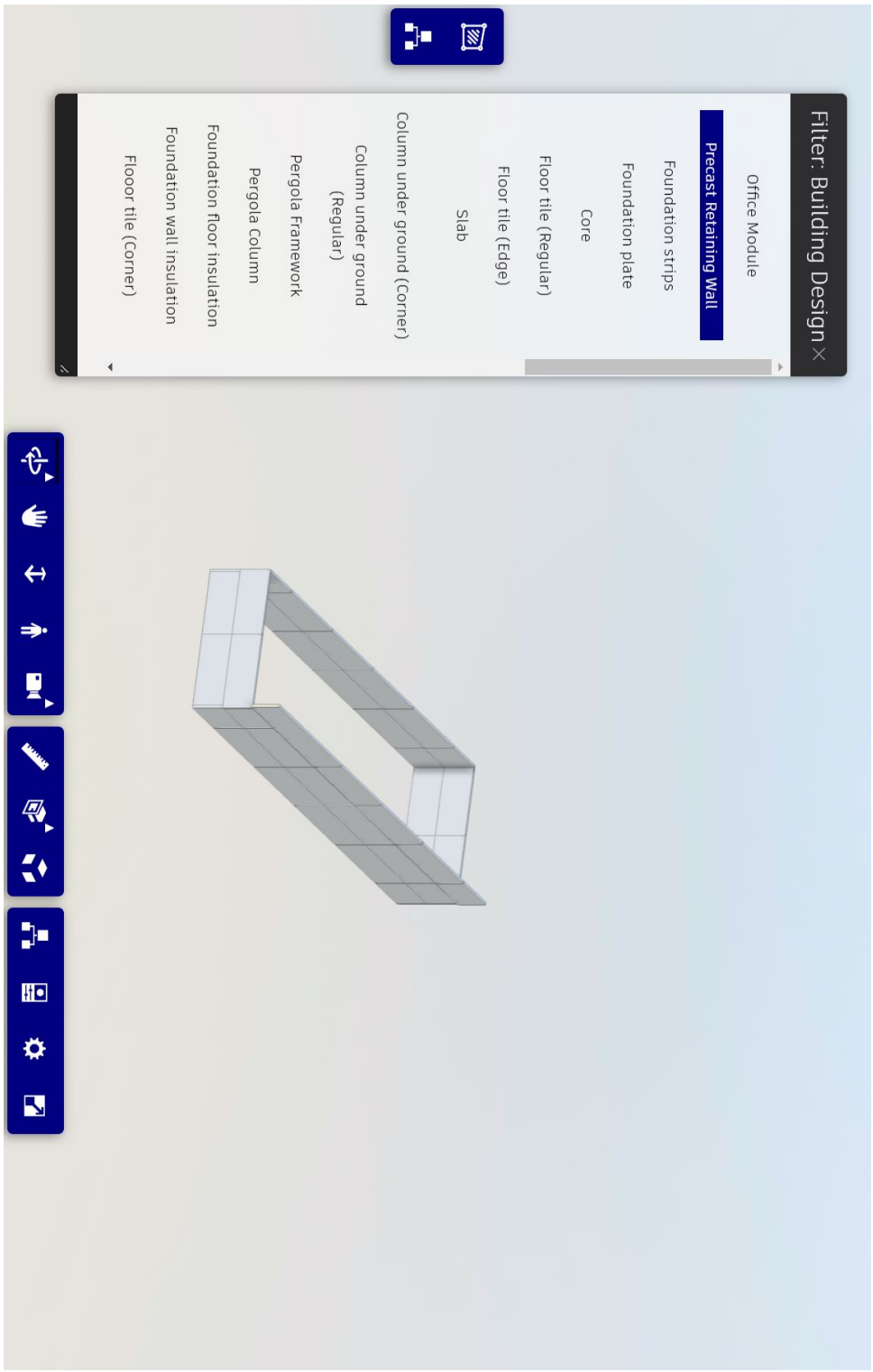
8.5.3 Building Layer 3



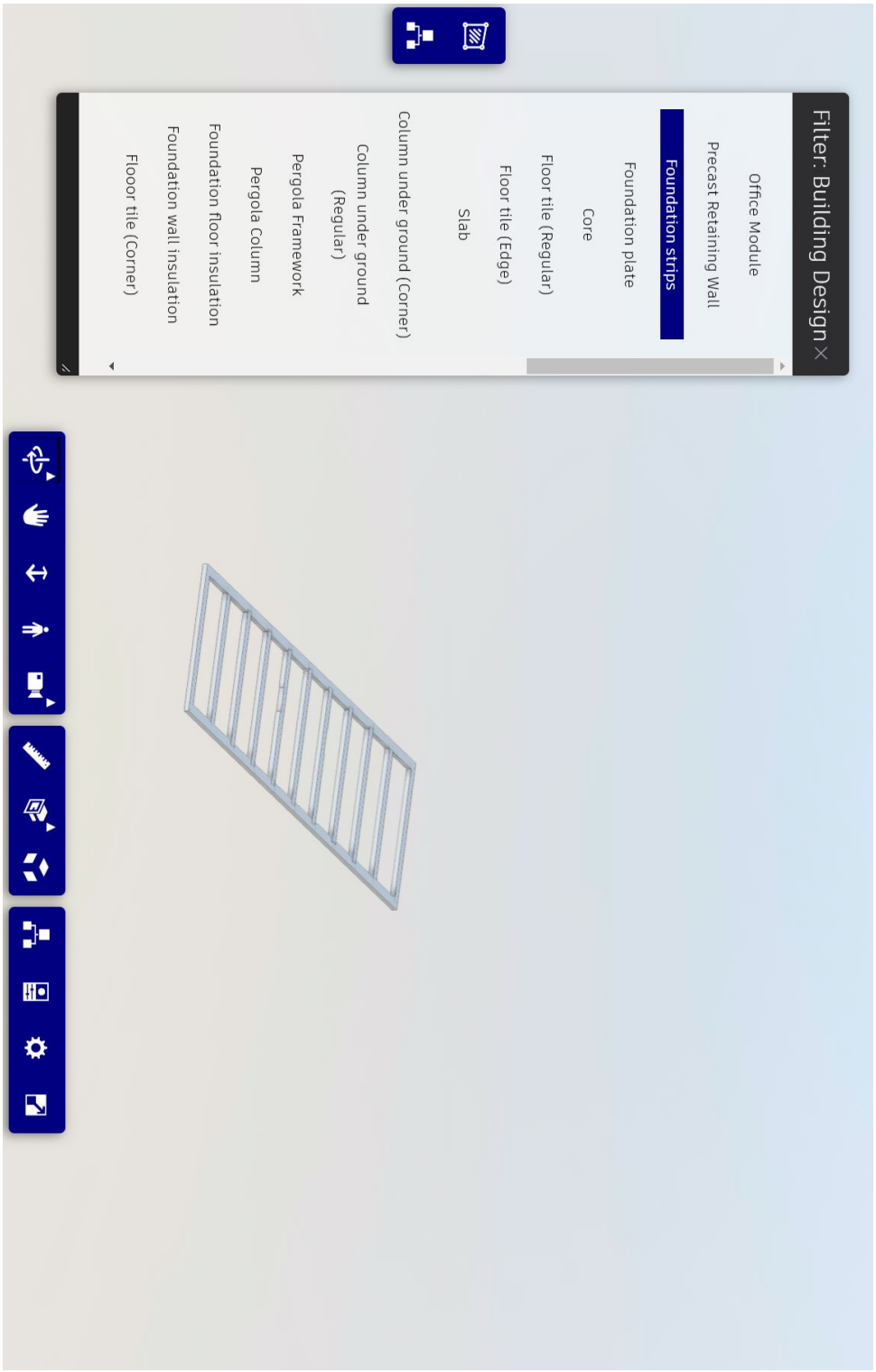
8.5.4 Building Layer 3



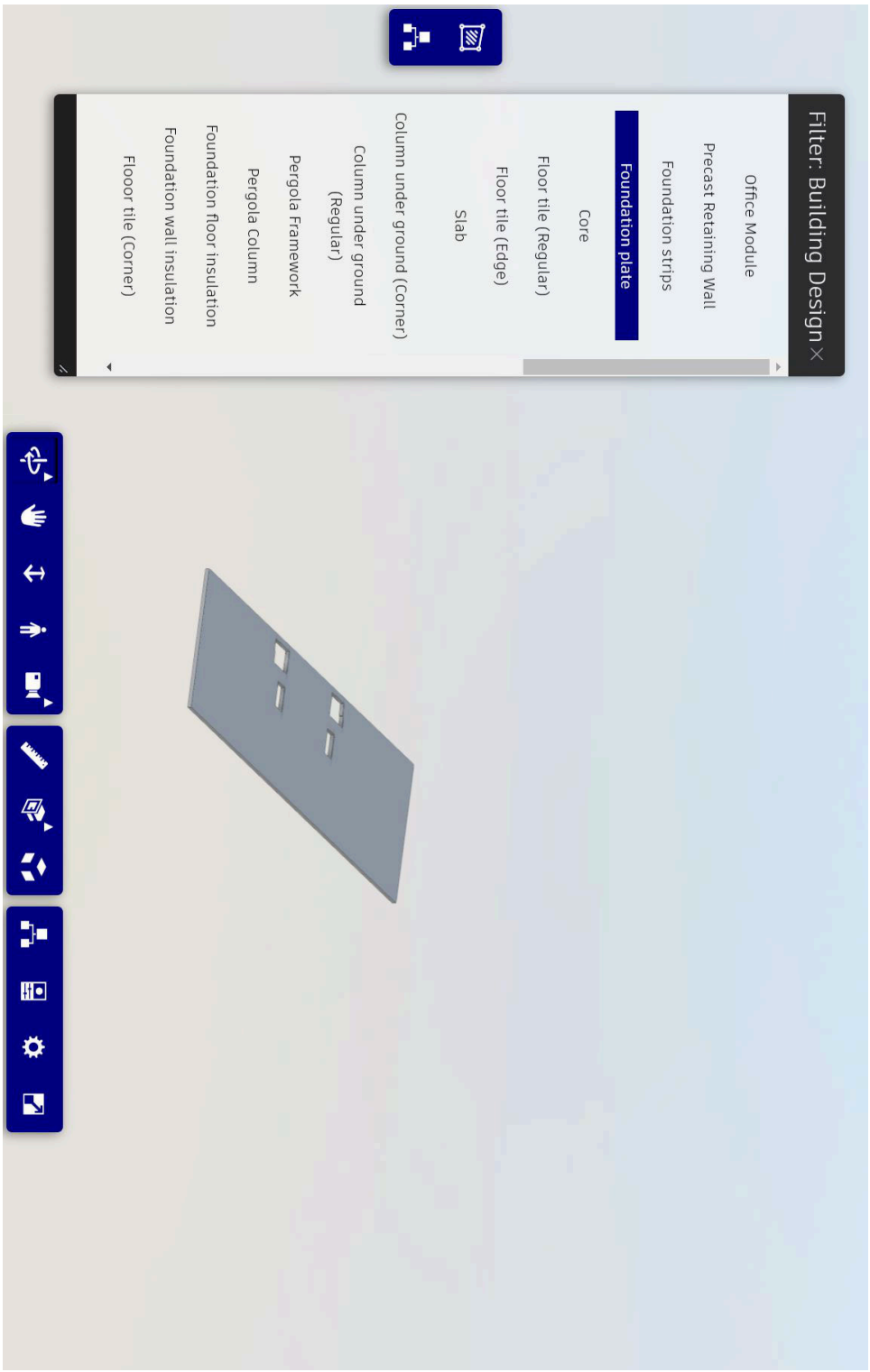
8.5.5 Building Design 1



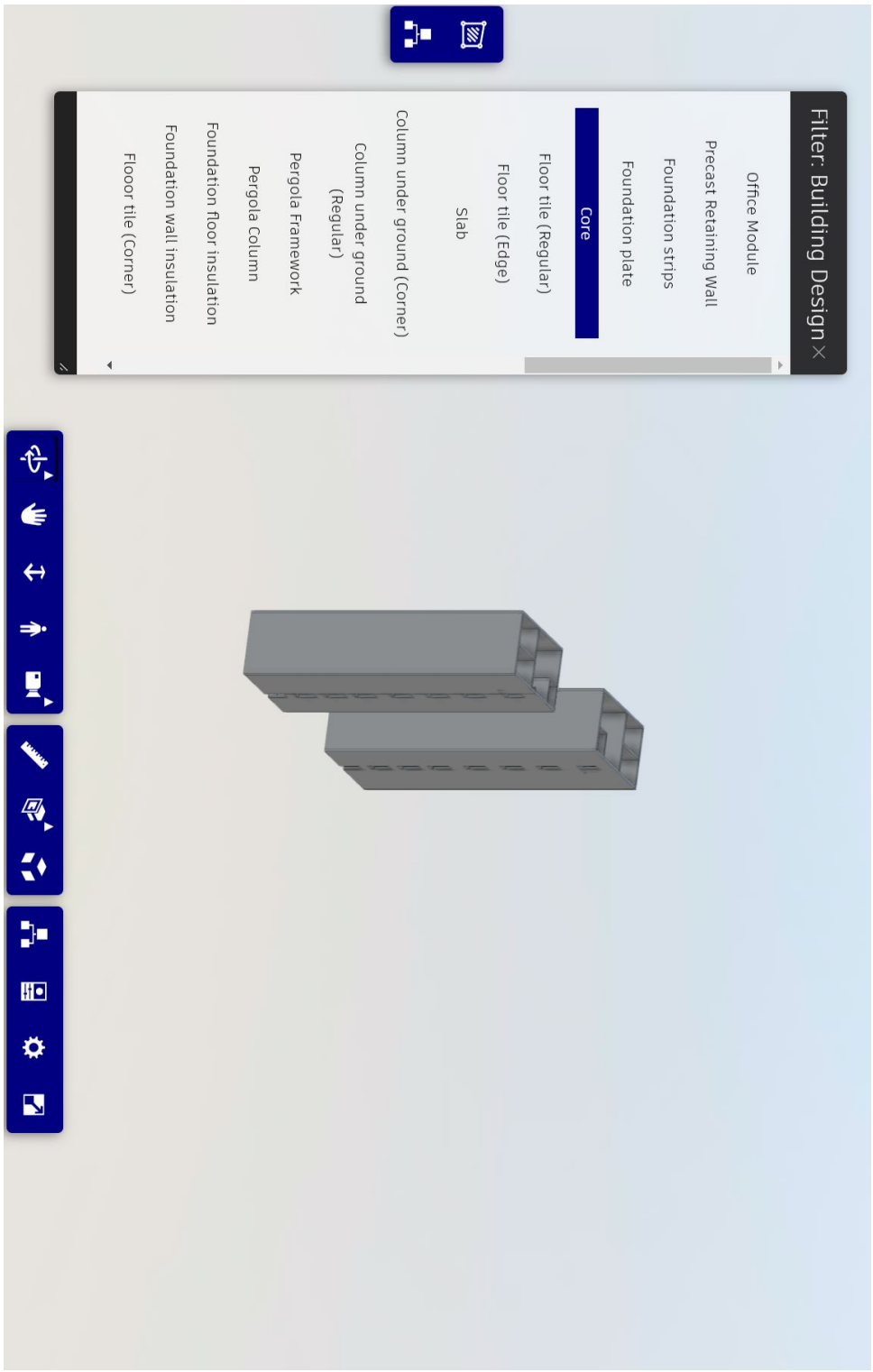
8.5.6 Building Design 2



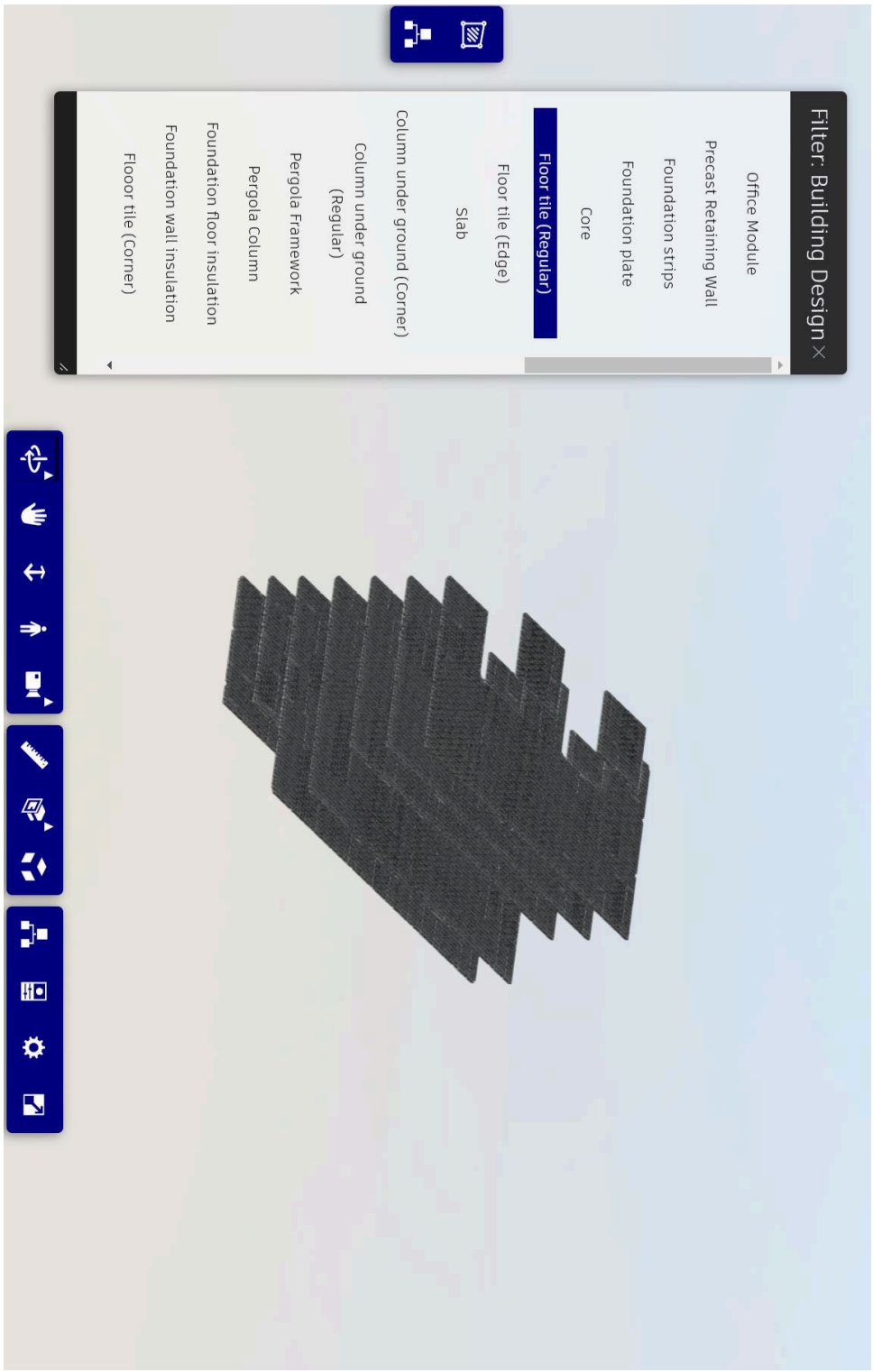
8.5.7 Building Design 3



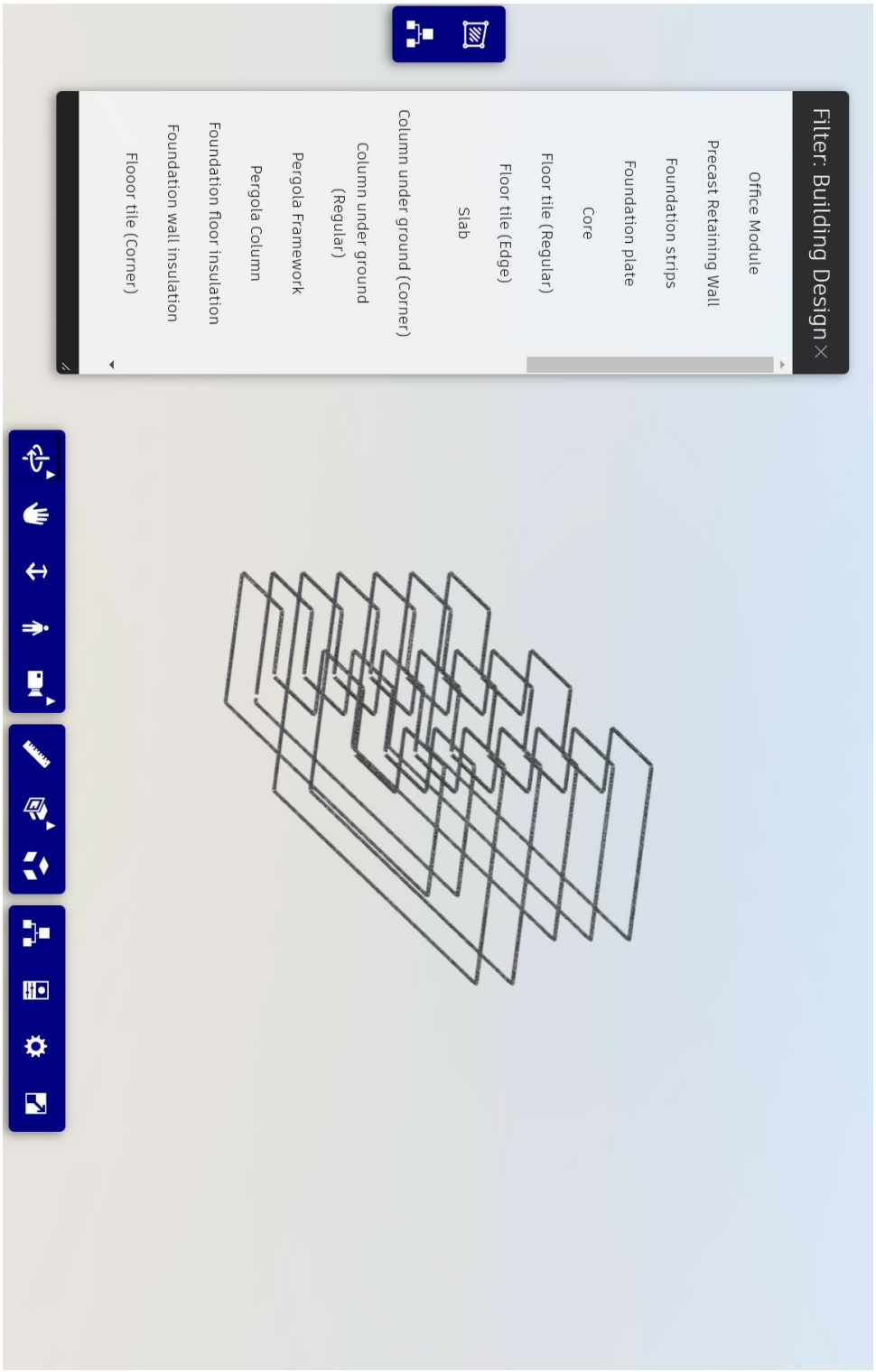
8.5.8 Building Design 4



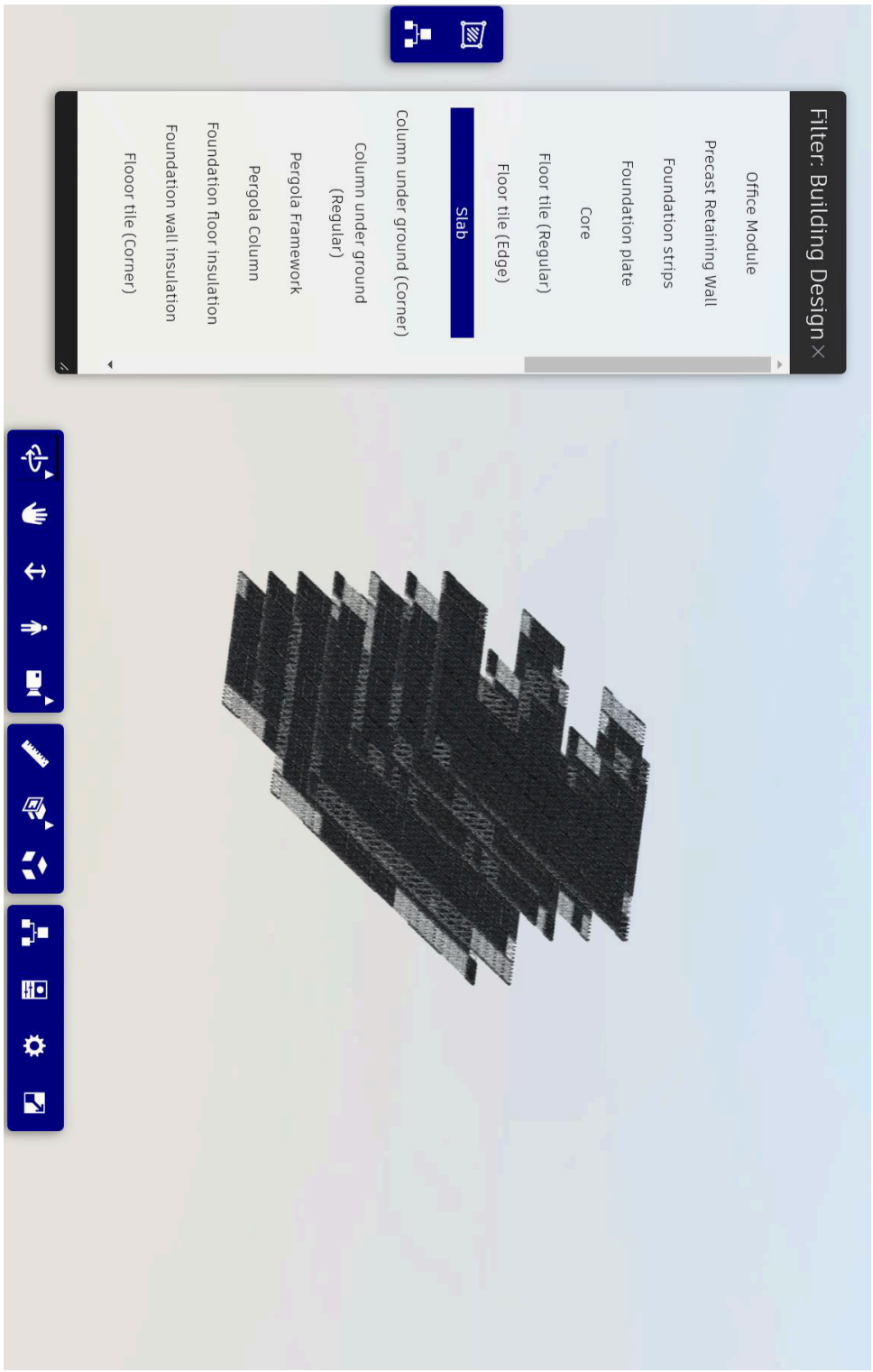
8.5.9 Building Design 5



8.5.10 Building Design 6



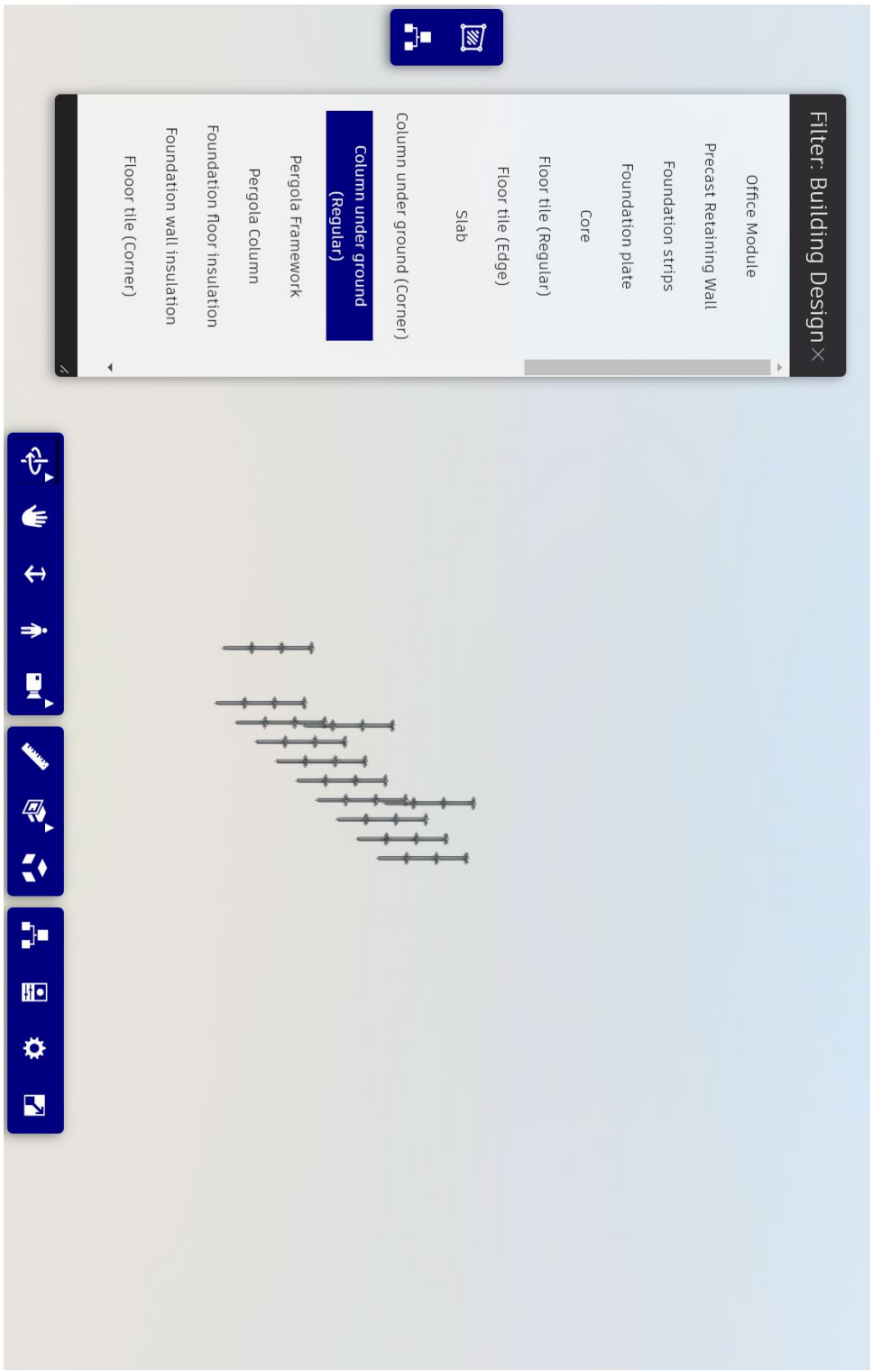
8.5.11 Building Design 7



8.5.12 Building Design 8



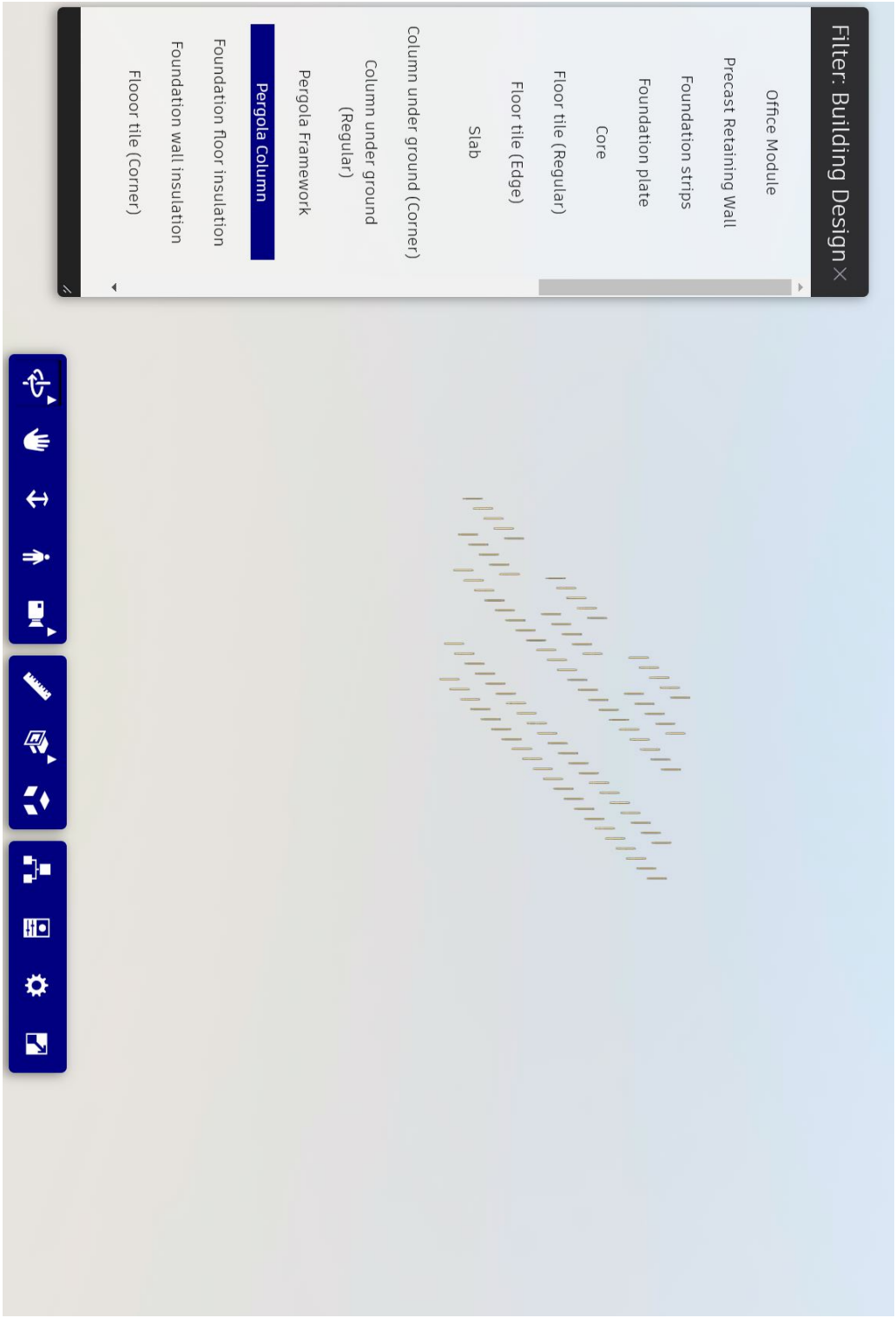
8.5.13 Building Design 9



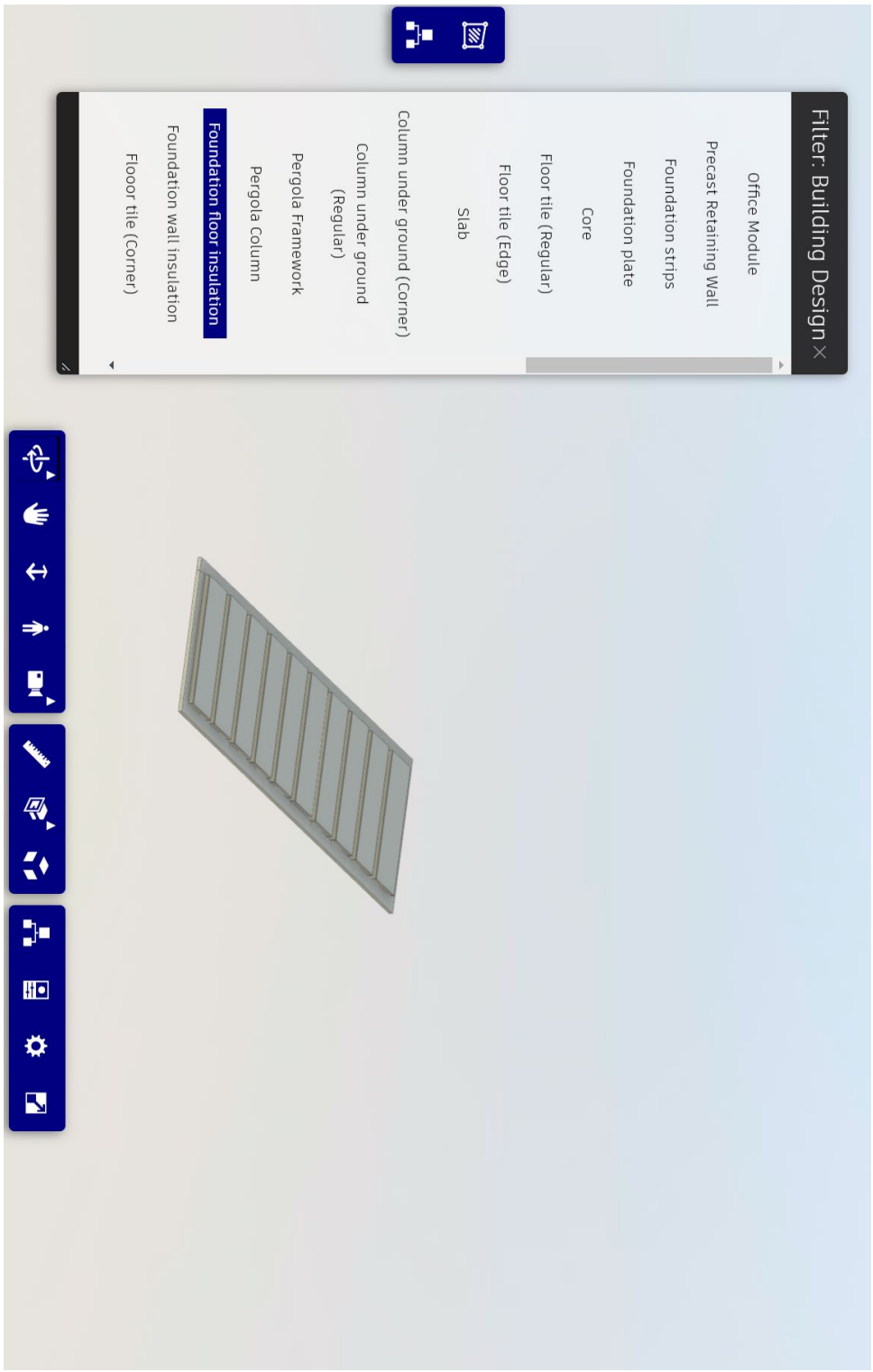
8.5.14 Building Design 10



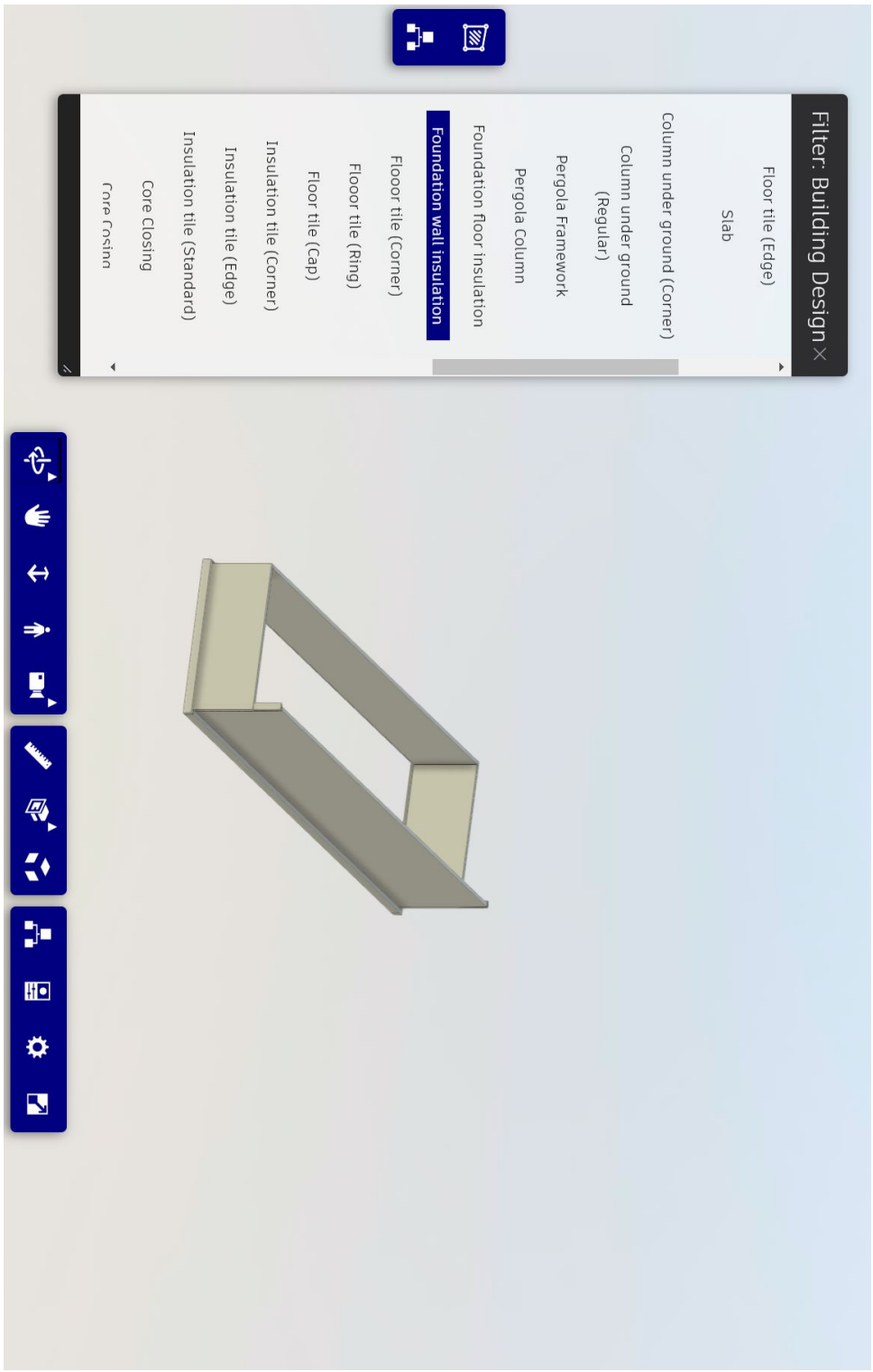
8.5.15 Building Design 11



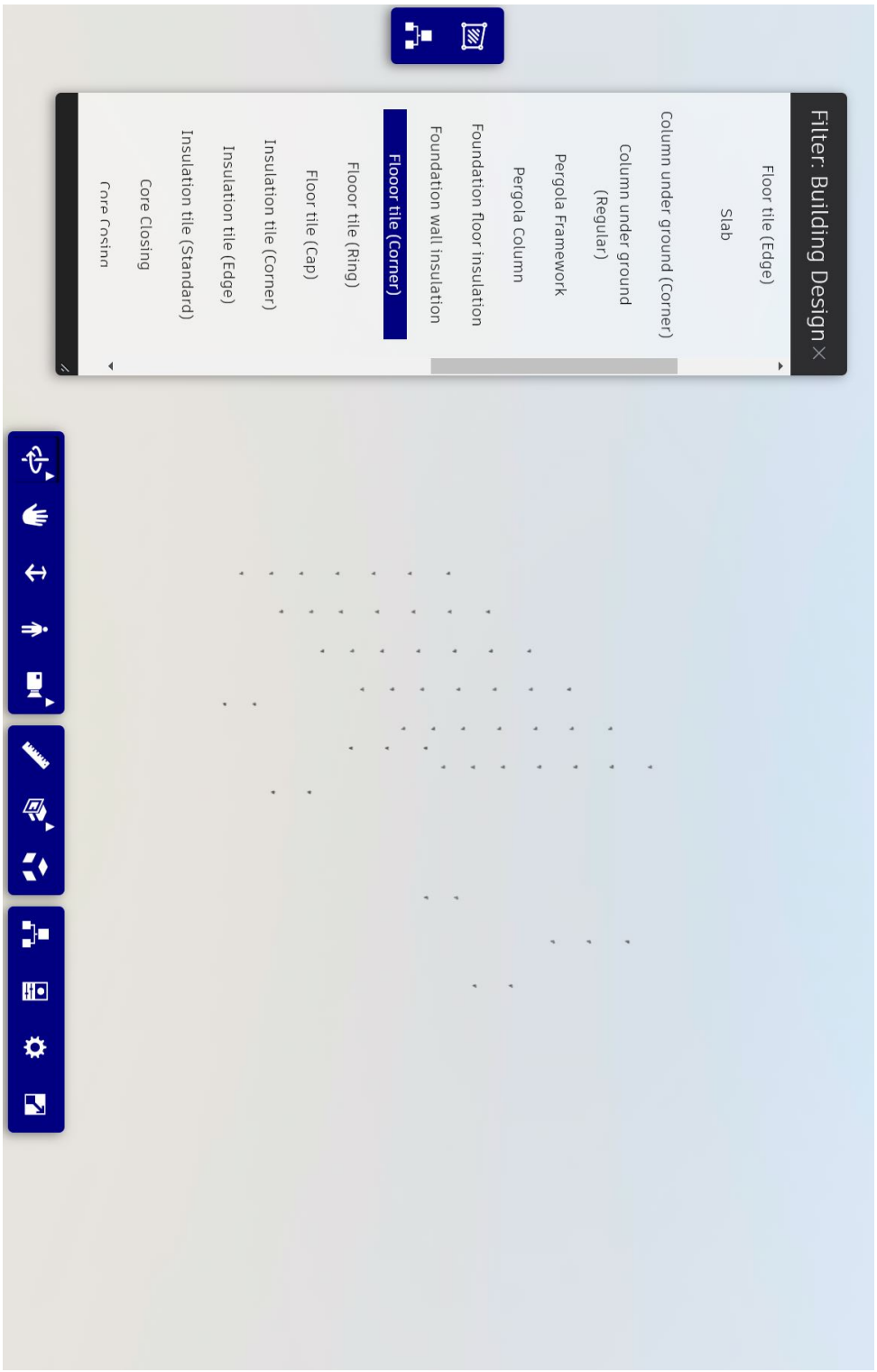
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8.5.17 Building Design 13



8.5.18 Building Design 14



8.5.19 Building Design 15



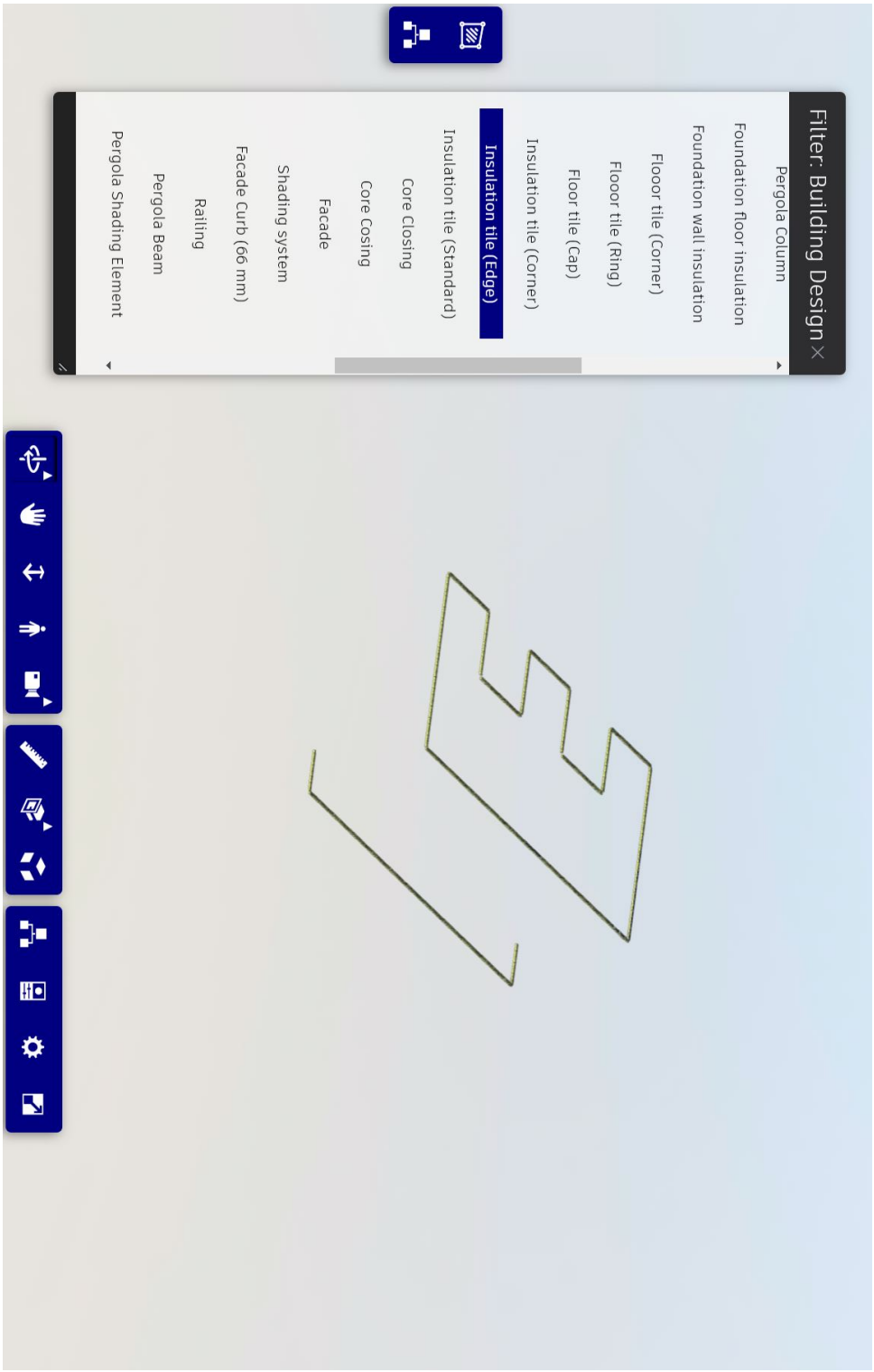
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8.5.21 Building Design 17



8.5.22 Building Design 18



8.5.23 Building Design 19



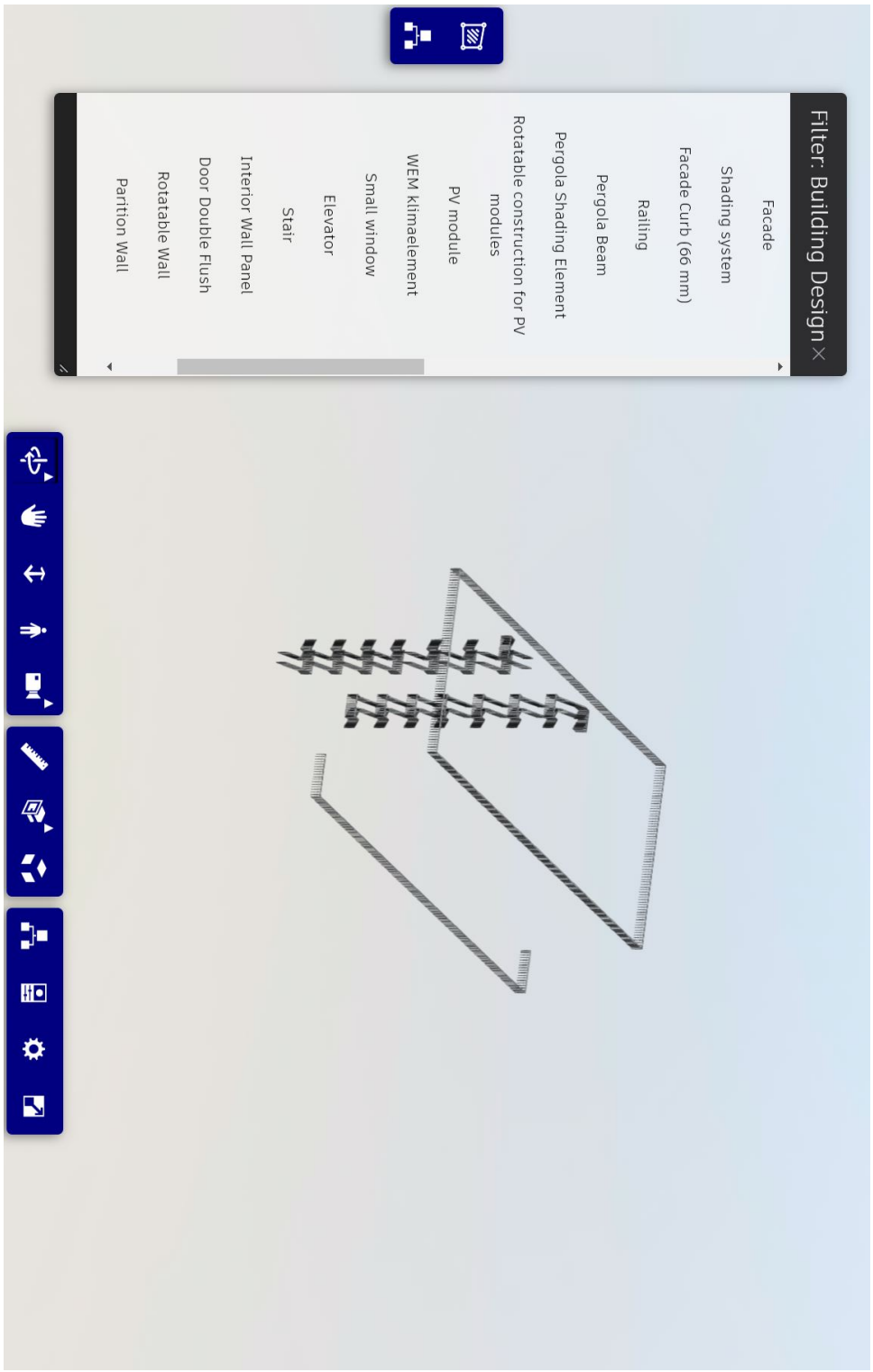
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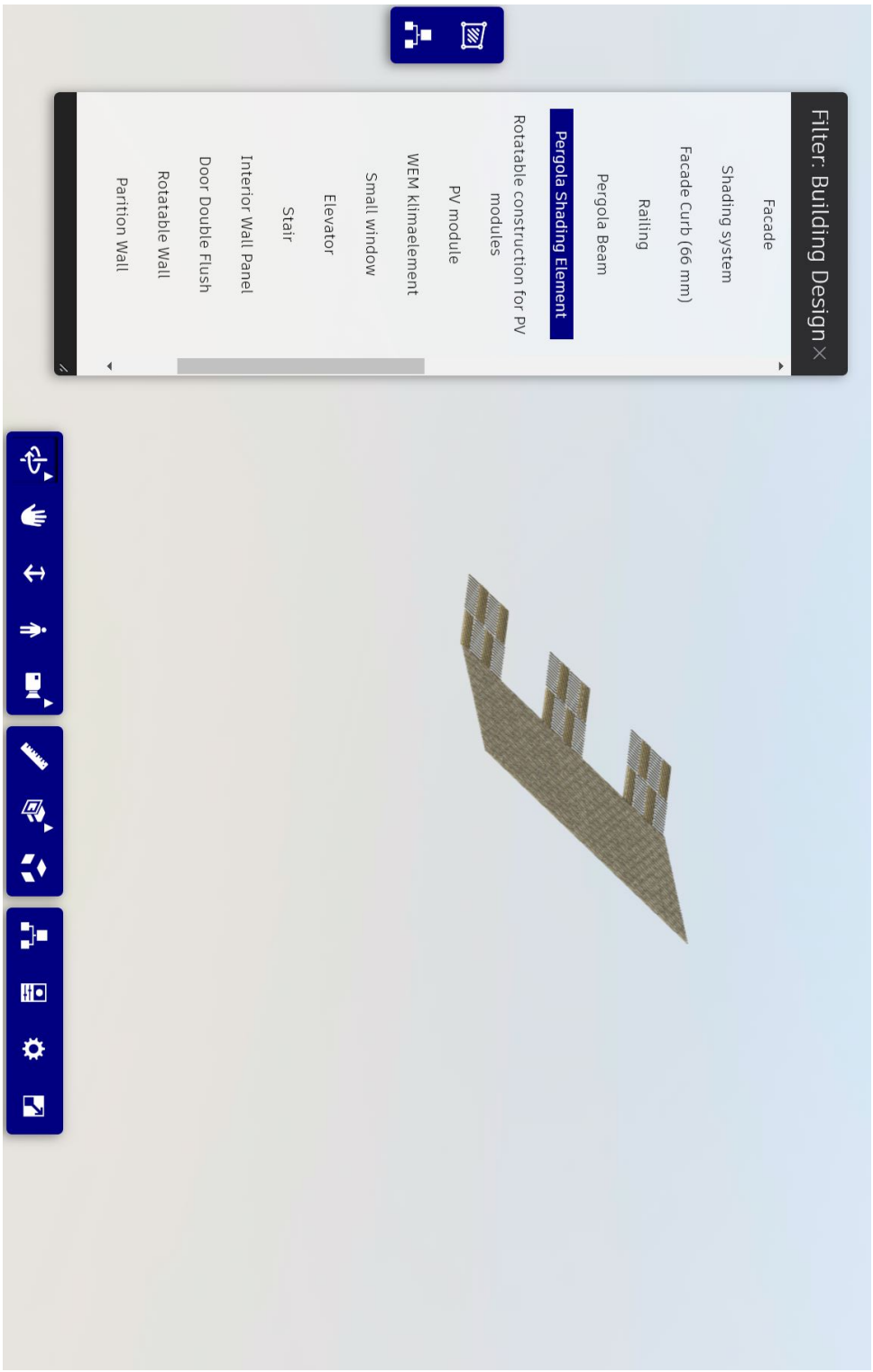
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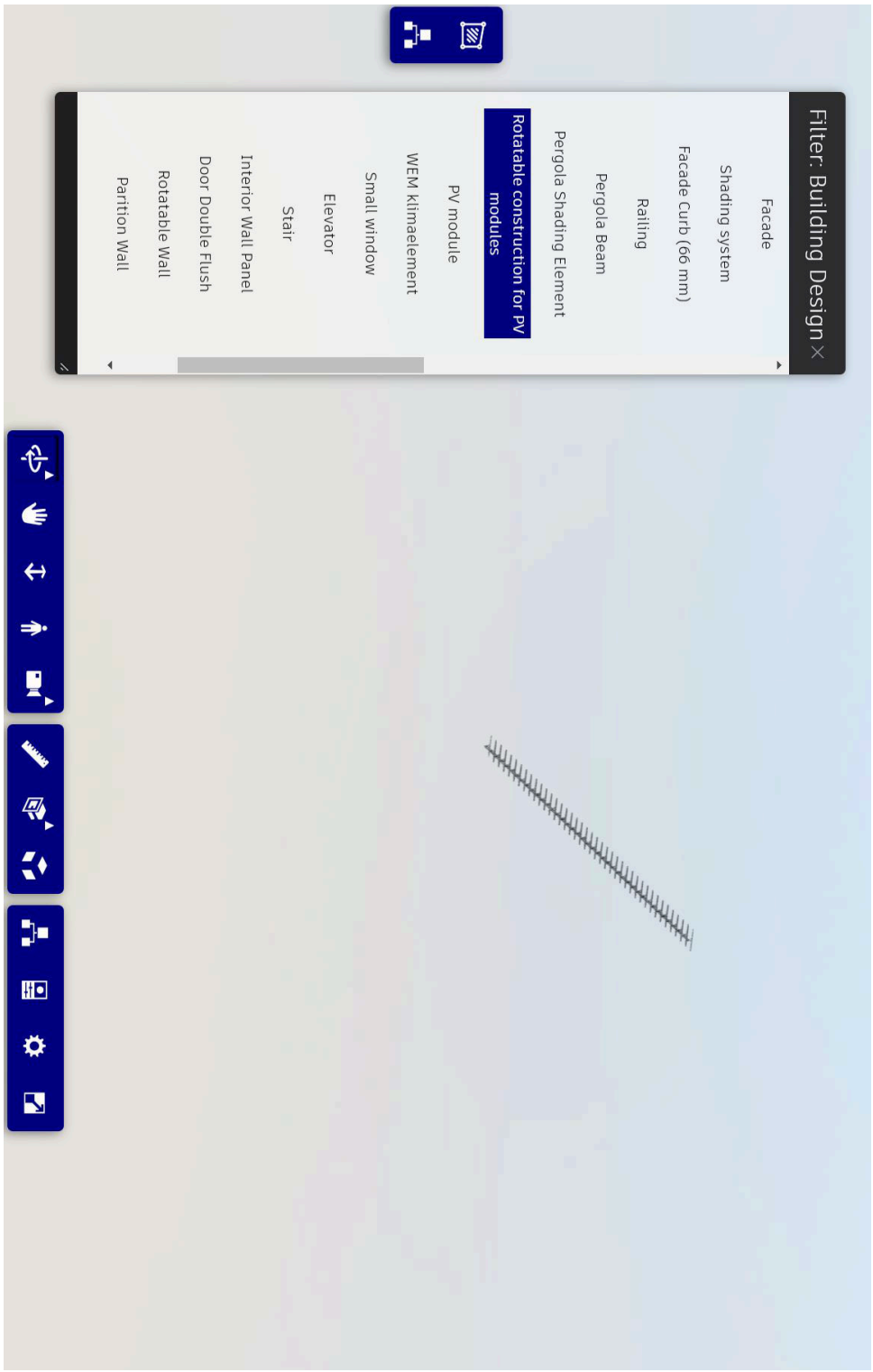
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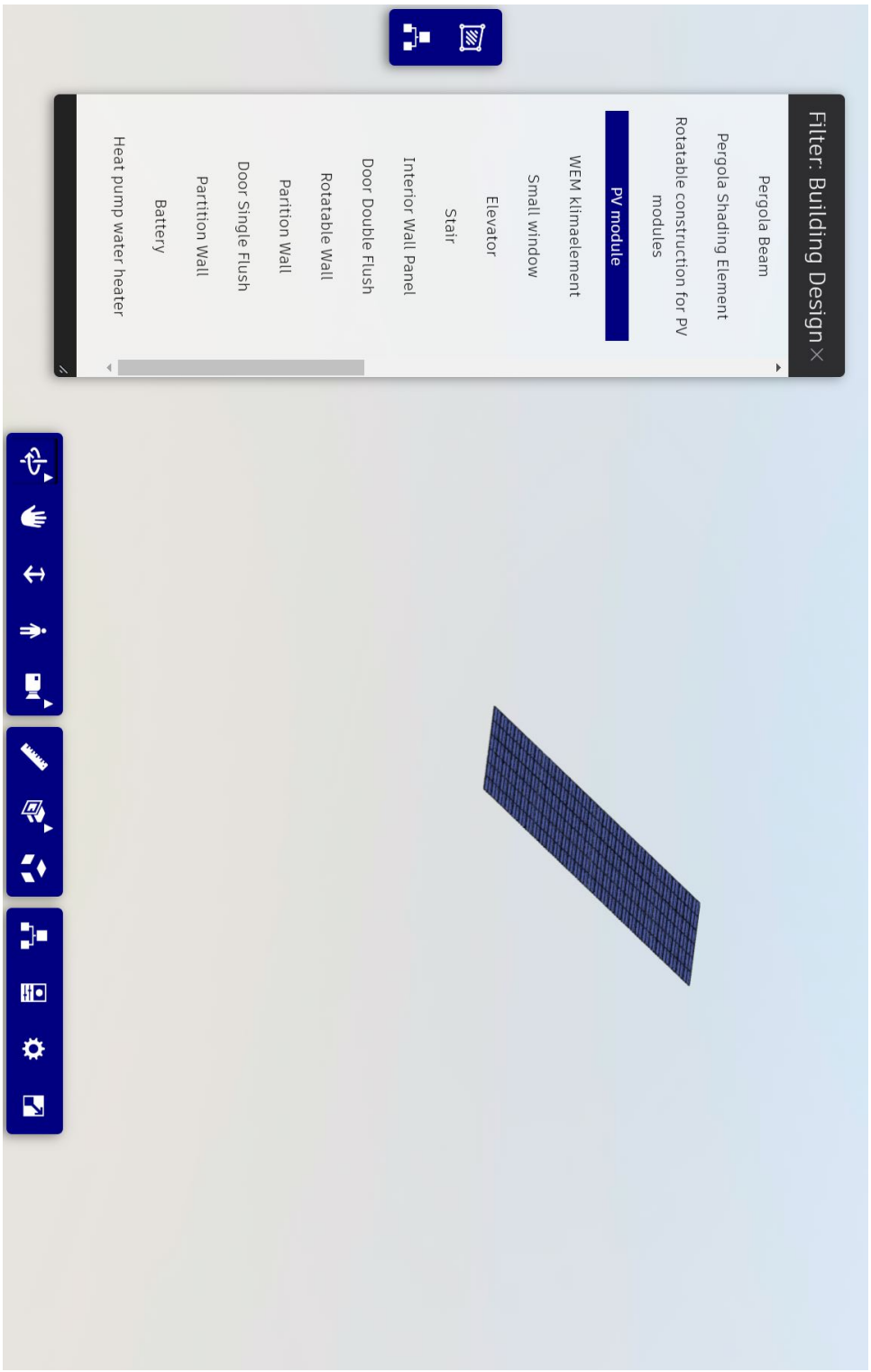
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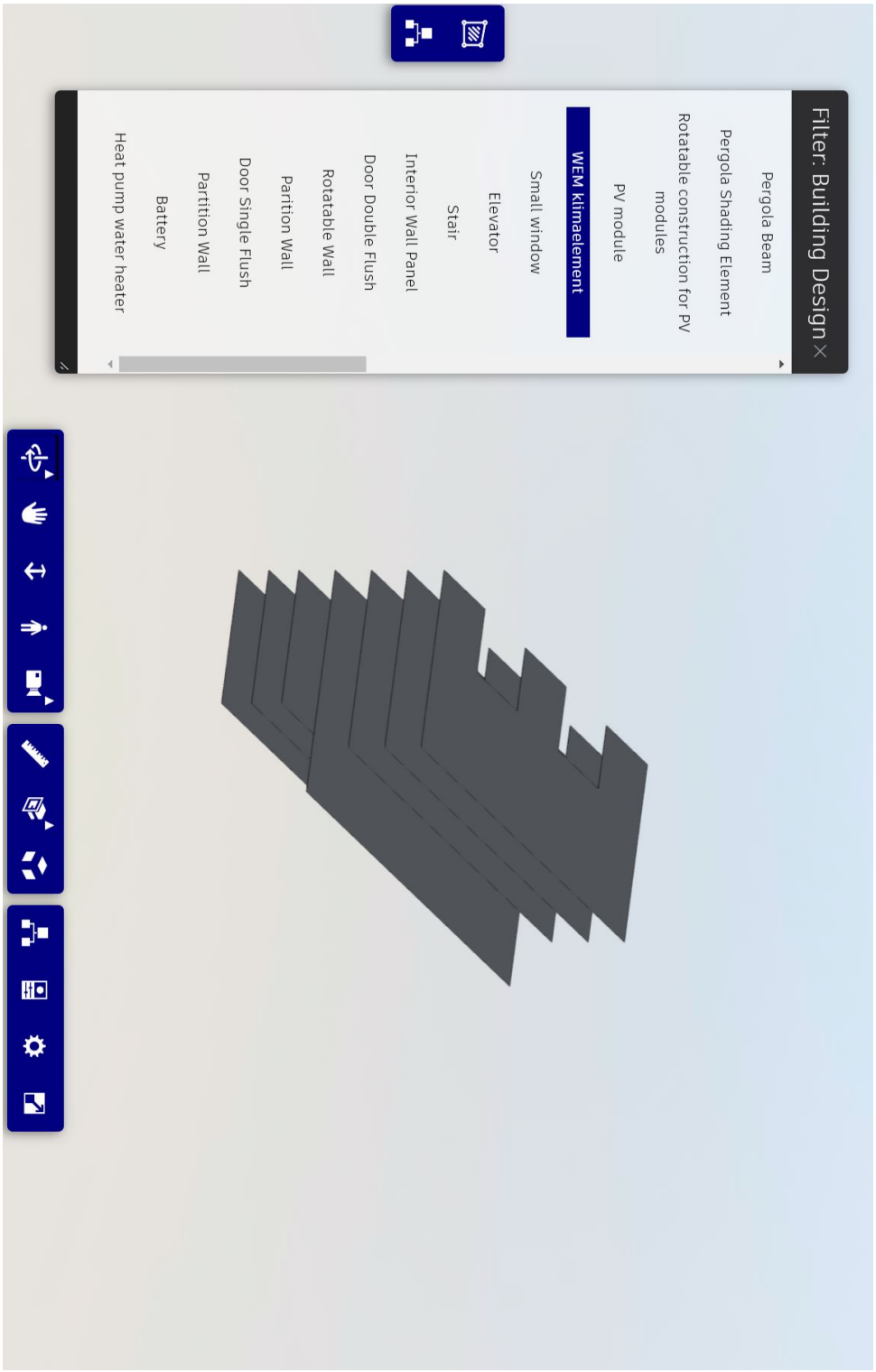
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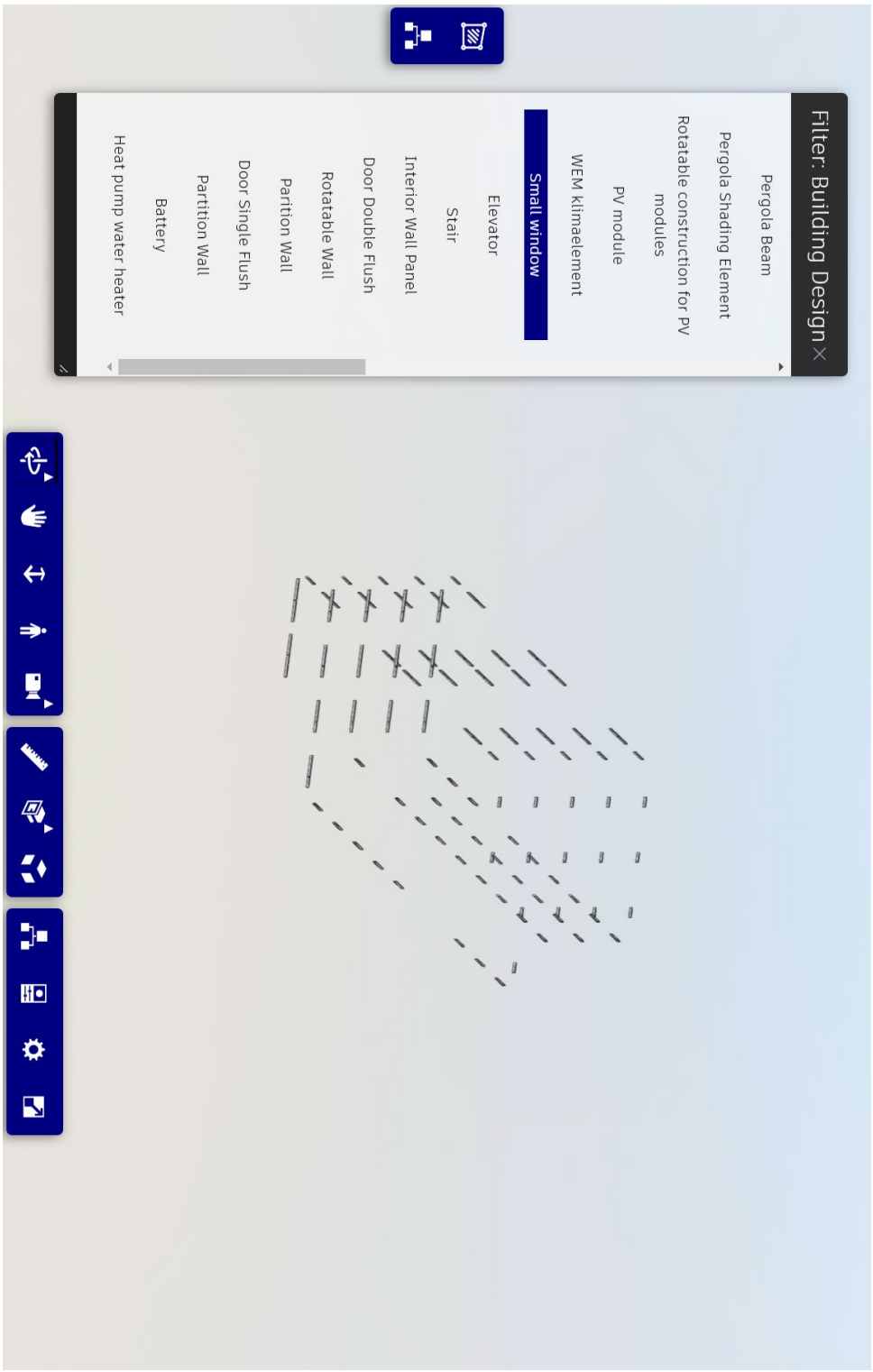
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8.5.30 Building Design 26



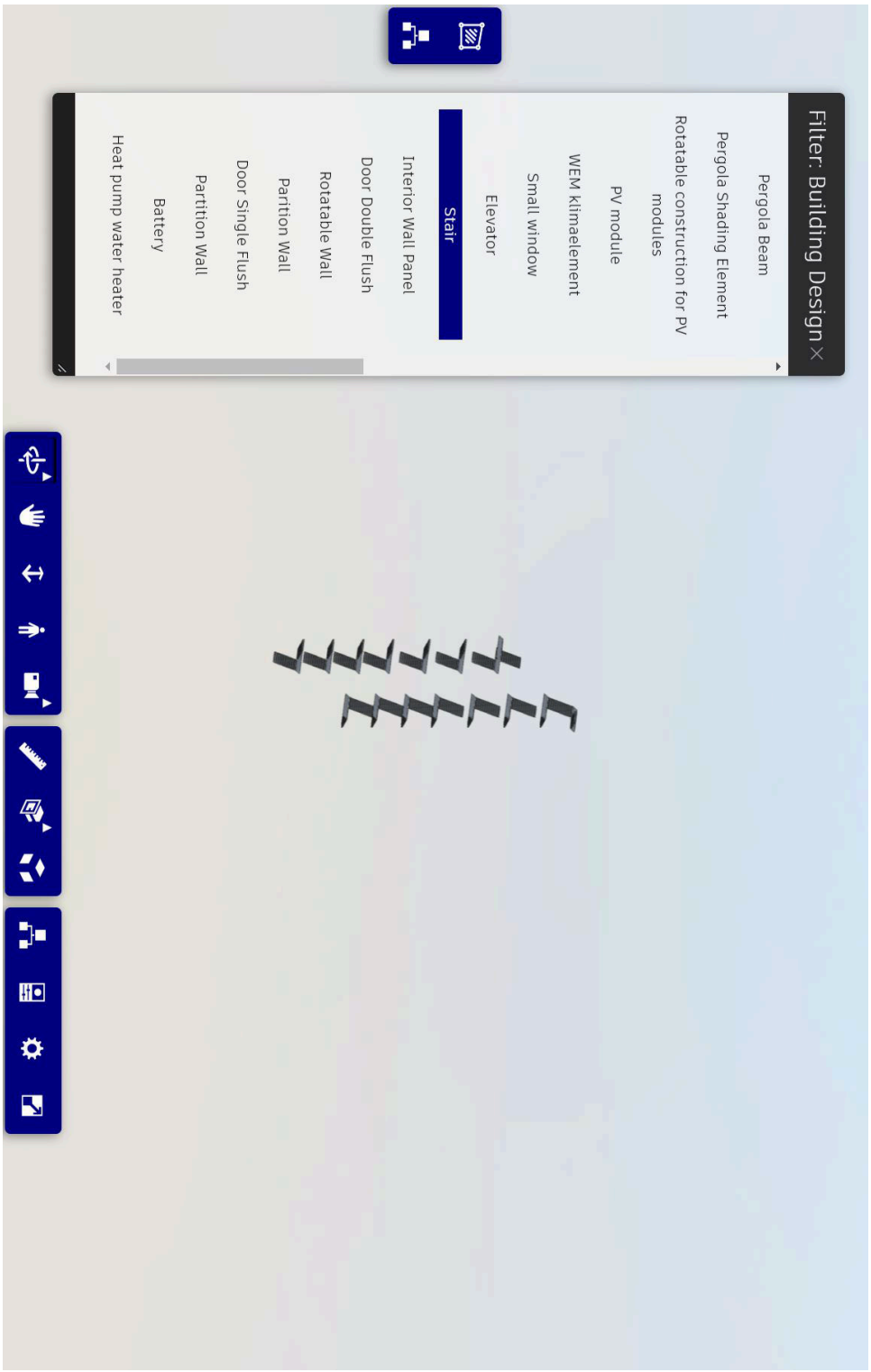
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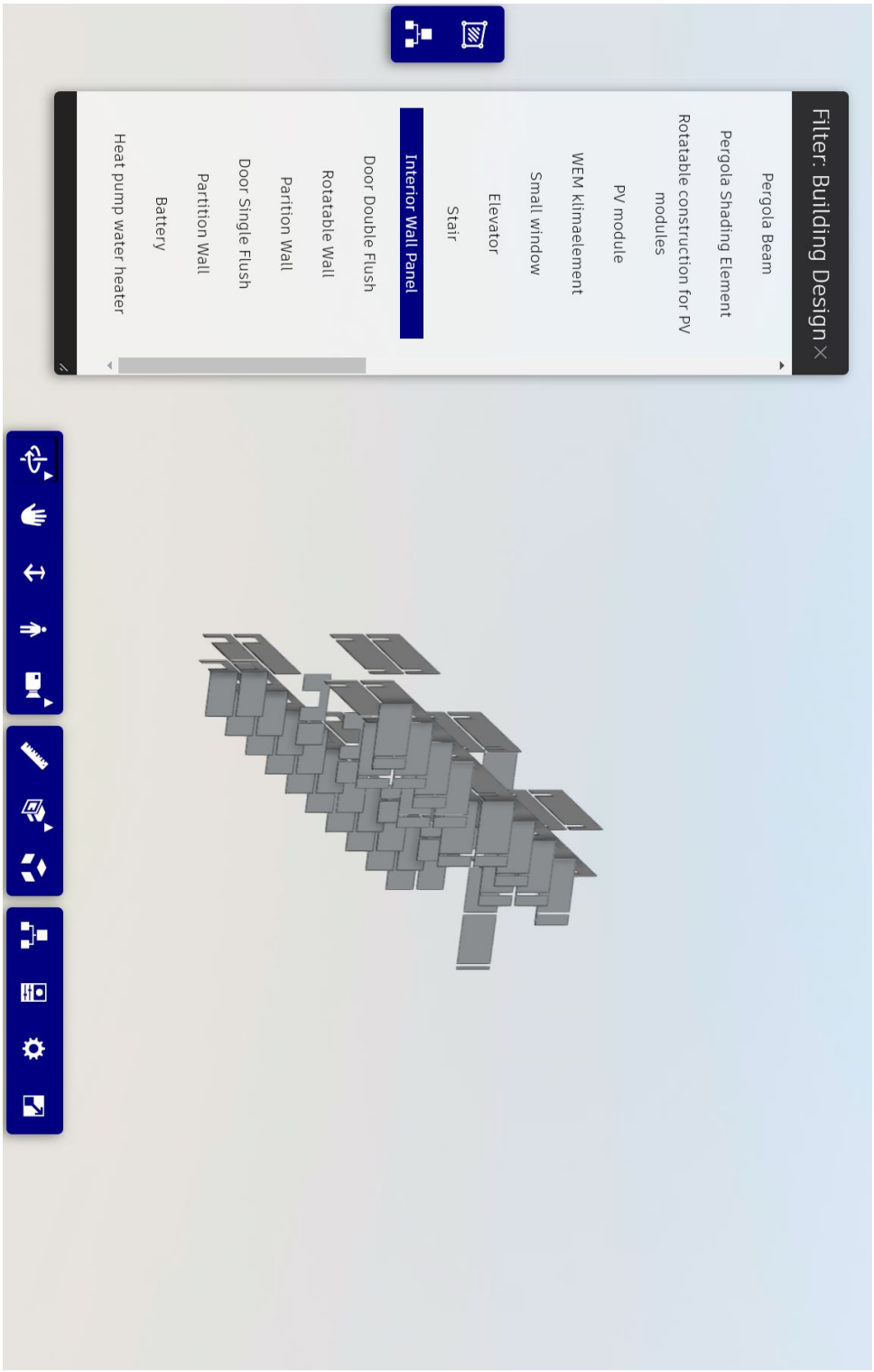
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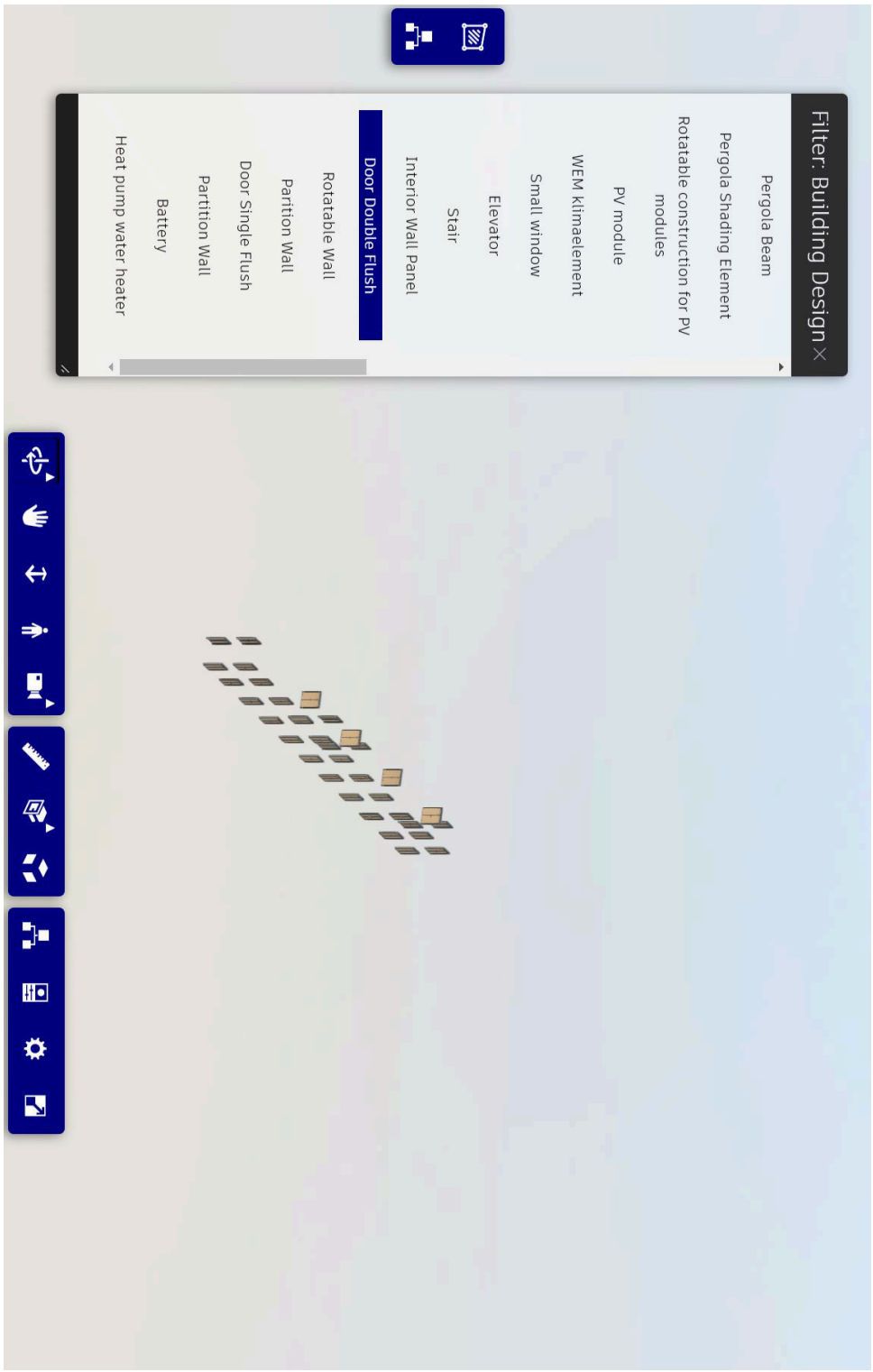
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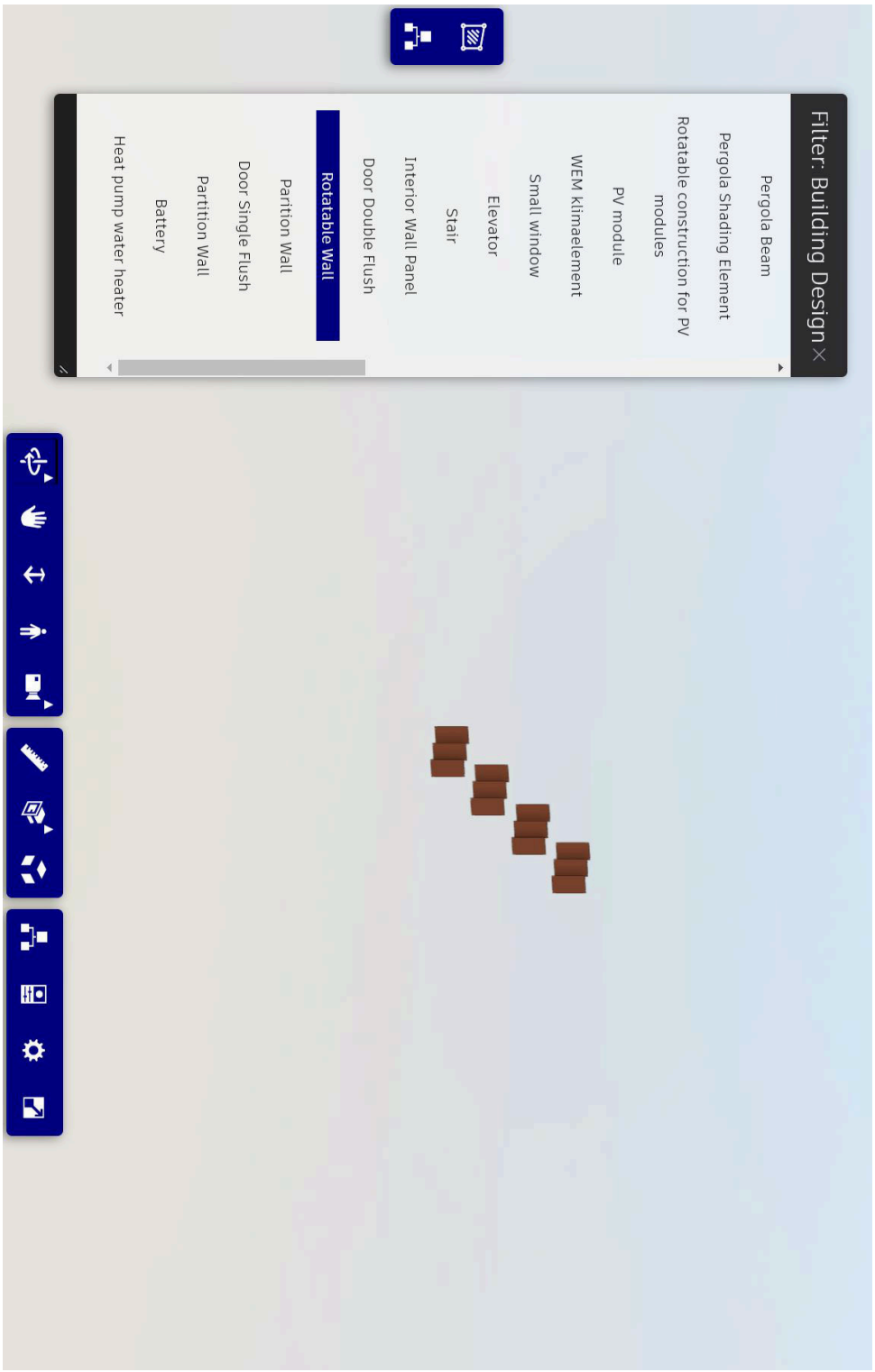
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8.5.35 Building Design 31



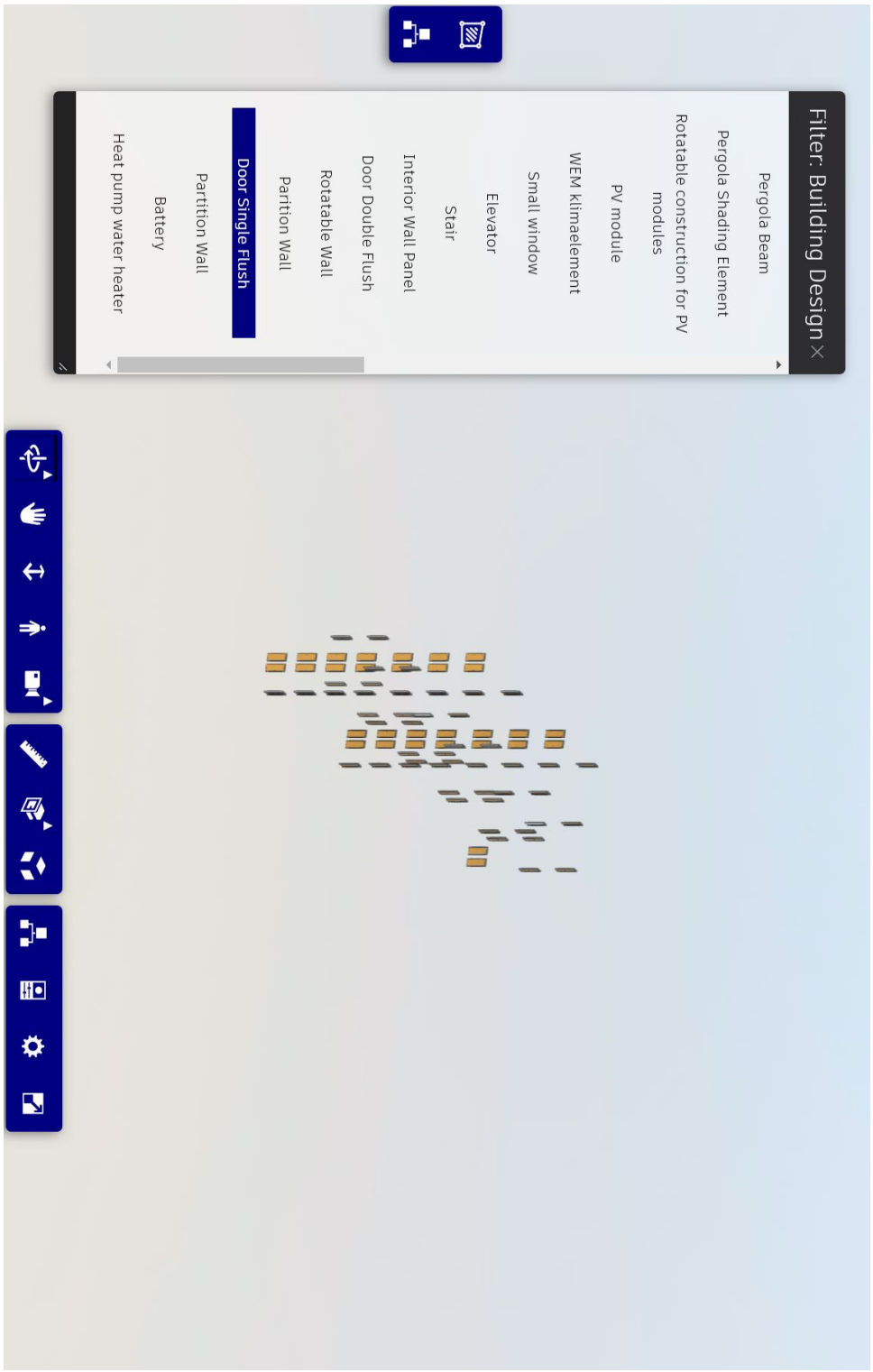
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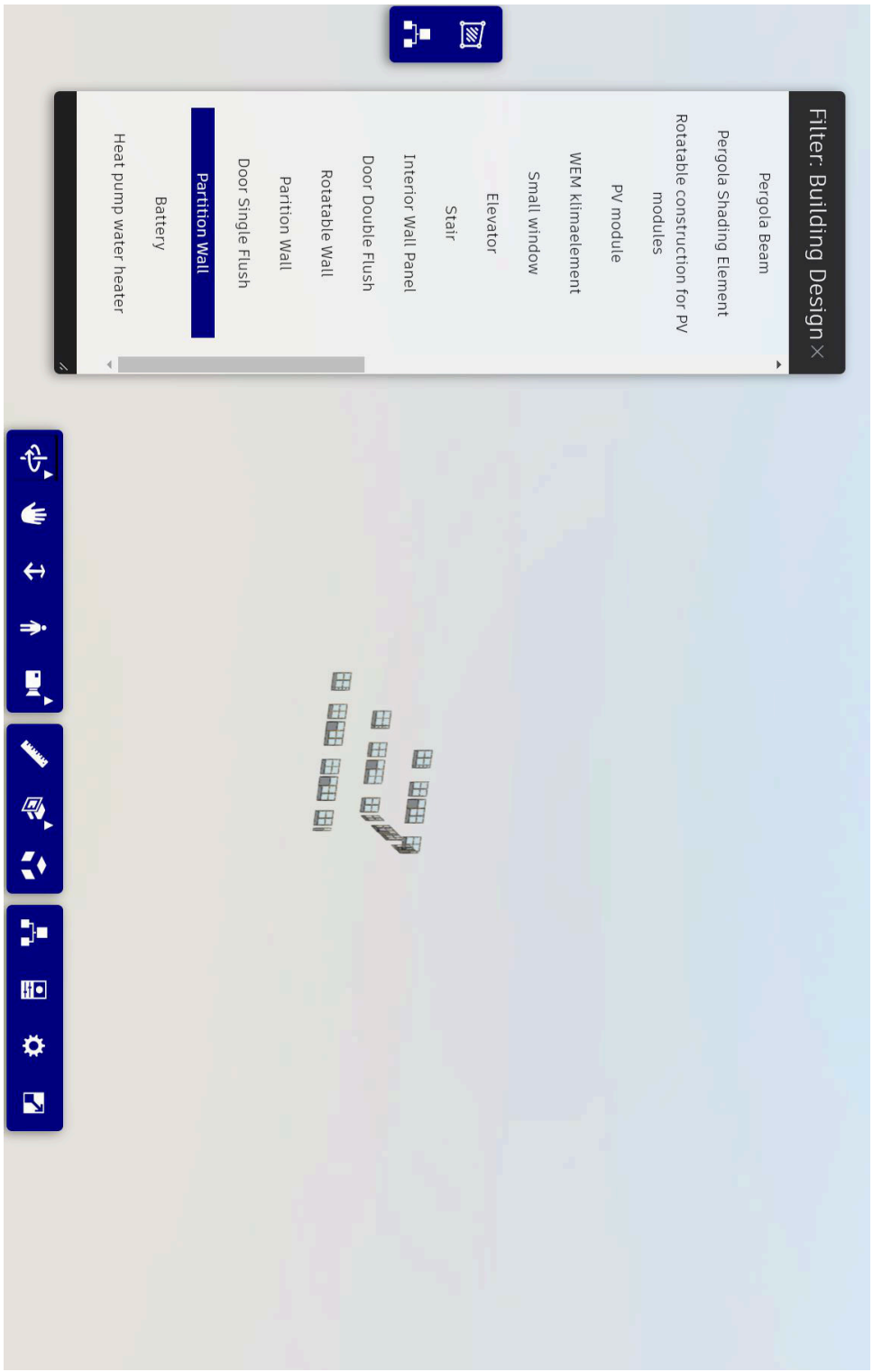
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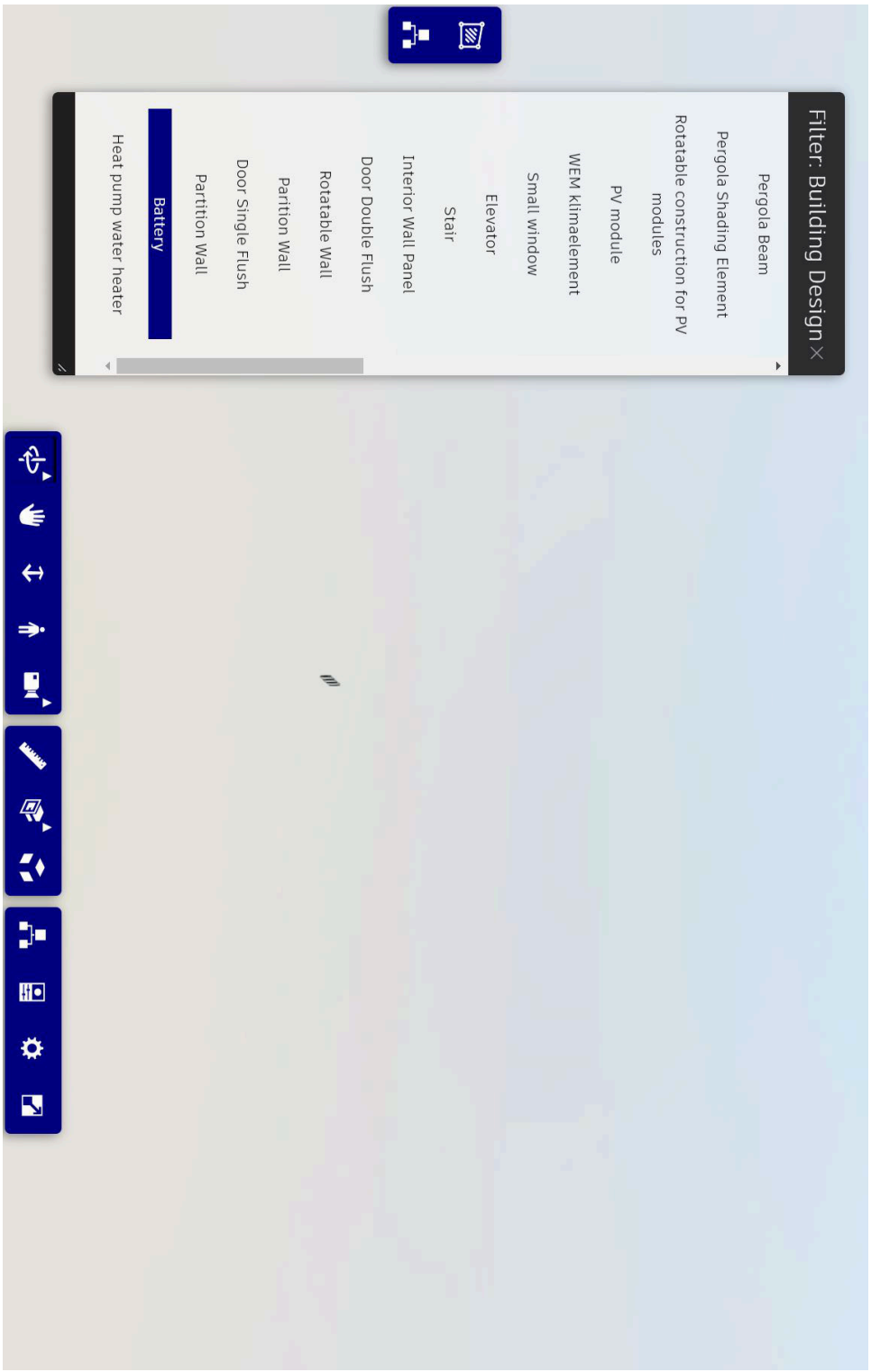
8.5.38 Building Design 34



8.5.39 Building Design 35



8.5.40 Building Design 36



8.5.41 Building Design 37

