Alive; Making buildings more intelligent for a sustainable future

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Contents

Abstract

Buildings are responsible for more than a third of the global carbon emission, and this number will increase unless there are some significant breakthroughs in the way they are built and managed. In addition, most sustainable buildings are also not performing as well as expected. For such reasons, it is crucial to make buildings more intelligent from their construction to their end of life. The number of factors affecting a building efficiency, sustainability, and performance is so numerous that it is essentially impossible to consider all of them during the design process and even if it is achievable to optimize the design with the most accurate assumptions; over the lifespan of the building, many of these factors might alter or act unpredictably.

This project aims to demonstrate different factors that a building should follow to be considered intelligent. It focuses on an intelligent algorithm that reacts to real-time activities and behaviors. This algorithm provides the foundation for future adaptations in response to new needs and functions. Such an algorithm could be easily applied to existing buildings and increase their performance by offering a real-time management method of the resources and systems. This is necessary considering that many relatively new buildings are not performing efficiently worldwide. Although this algorithm can increase the performance of the building and help them to adapt to the real-time condition, other design factors are still essential to achieve a fully sustainable building, such as minimizing the material use, simplifying the construction, and designing for disassembly. In the end, The only way to achieve higher sustainability in buildings is to utilize intelligent management systems, AI, and behavior prediction to minimize human errors, the negative impact of unexpected events, and the unpredicted behavior of users.

Introduction

We produce as much as 51 million tons of CO_2 each year, and despite all the efforts to lessen this number, the quick expansion of developing countries means that this number will push up unless we find some breakthrough innovations in all the main things we do (Gates, 2021). The harsh consequences of global warming are almost well accepted. For example, in the last century, 38 heatwaves occurred in Europe; eleven were after 1990 and six after 2000 (IPCC, 2007). Urban areas suffer even more from climate change due to phenomena like Urban Heat Island (UHI). Considering the building sector is accountable for 38% of global CO2 emissions (Global ABC Global Report, 2020), and as a result, the current direction in the architecture sector is designing and operating buildings increasingly "sustainable" and "smart" (Chiesa, 2020).

Nevertheless, these techniques are not always robust because of the restrictions of elevating city skylines, limited urban spaces, and already well-structured urban tissues (He, 2019). Therefore, we need some new thinking to tackle these concerns regarding the complexity of the issue. One way forward is to explore cutting-edge technologies and find the solutions to apply them on a large scale. Knowing that most developing countries do not have the resources to invest a lot of money and time in new solutions and technologies, developed countries are responsible for doing these experiments and then exporting them to other parts of the world (Gates, 2021).

Computational Design in Architecture

Even though computers are one of the non-separable elements of today's world, they hardly go beyond a representation tool in architecture and urban design. For many architects, computers are advanced gadgets for a faster and more controllable design reproduction (Chiesa, 2020). By itself, it is not an incorrect approach, but the rapid progress in AI, Machine Learning, Neural Networks, and other advance computational methods provides the opportunity to expand their application in architecture and urban design. It means that the AEC industry is going through one of the most important and most disruptive transformations in history, from being a document-based sector to evolving into an information-based system of interconnected tools, processes, and actions (Kocaturk, 2019). This rapid evolution of information and communication technology (ICT) has been a catalyst for transforming human-made environments into "smart" environments, which engage with users through sensors and digital devices (Lee et al., 2021).

For years, designers have used computational methods to determine the best feasible options and optimize potential design choices. It is due to the capability of parametric design applications in automating the generation and evaluation of an extensive range of alternative design solutions (Haidar, 2019). Nevertheless, as the trend of becoming more sustainable and smarter advances, we should focus equally on designing buildings that predict, adapt, and respond to changing scenarios (e.g., user behavior) through intelligent systems (Kocaturk, 2017). Hence, these innovations in sustainable design should be an equal use of computational and data-driven approaches both in the design process and during the building's life cycle. Accomplishing this task requires a method that allows building professionals to resolve conflicts between different segments of a design project; visual and thermal comfort, energy demands, and life-cycle costs (Jalilzadehazhari et al., 2019).

Another critical fact about so-called sustainable buildings is that most buildings are not performing as well as planned or expected (Bordass et al., 2001). Some of the leading underlying causes of disparities between detailed energy modeling predictions and in-use performance of occupied buildings are related to the use of unrealistic input parameters (assumptions), inefficient and superficial use of the modeling/simulation technologies (tools), unpredictable occupancy behaviors, and inefficiencies in facility management (Menezes et al. 2011). To close this gap, it is crucial to reevaluate our approach to sustainable design and decision making and utilize the right tools, processes, and mindset to interpret and make sense of the gathered data to develop an efficient and appropriate real-time reaction (Kocaturk, 2017). BIM 2050 identifies and describes four distinct and progressive waves, referring to our digital state's improved degree of maturity in the coming 30–40 years (CIC BIM2050 Group, 2014). Digital Decisions (2020–2030) identifies with an improved state of integrated processes and technology platforms to allow the efficient collation of design, construction, and operational data. It will then enable the progressive development of data sets from real-time building use and allow other technologies to incorporate them more readily for more efficient and precise decision-making (Kocaturk, 2017).

The significance of designing smart buildings capable of data-driven real-time response to the conditions is further evident as Evans et al., and later Hughes et al. manifest a third and hidden cost indicator: the cost of the people who utilize the building, including their wages and productivity. Assuming that the first two indicators are capital and operational costs, the third indicator overtakes them combined over the lifetime of a building (Kocaturk, 2017). By respecting the demands of inhabitants in a real-time situation, it is possible to optimize this indicator and achieve a more sustainable building.

Goals and Approach

To control the enormous amount of CO_2 emission, all the industries need to undergo some massive changes in the coming years. As one of the significant sources of global emission, buildings have to enhance dramatically, not only in how they are built but also in how they are operated. If the efficiency of buildings can be increased by 2.5 percent per year while the electrification of buildings also increases by 25 percent, in 2050, CO_2 emissions will be reduced by 3.48 gigatons and 16.05 gigatons in 2100 (climateinteractive.org). These numbers show how slight increases in the performance of new and existing buildings can have an enormous and essential effect on global CO_2 emissions, which will be necessary for the battle against climate change.

Considering that there are many different criteria involving buildings' performance and efficiency, and the fact that many of the already existing buildings are low performance and it is impossible to demolish and rebuild most of them shortly, improving efficiency requires some new thinking and advanced computational processes for a real-time approach in a predictive method. In this way, while new buildings can be designed around this vision, the existing buildings can also undergo a minor intervention to use such methods quickly.

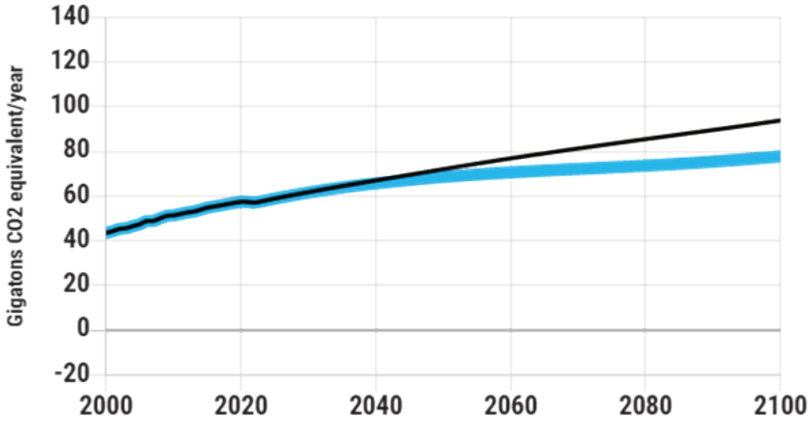


Image 01. This graph shows the result of increasing the efficiency of the buildings by 2.5% per year and their electrification by 25% (climateinteractive.org).

1- A hybrid strategy of passive and active sustainability

There is a fine line between overdoing the active elements in a design and having the correct amount. Active elements from moving facades and shaders to more complex mechanical systems provide a more comprehensive range of control on the building performance during its life, though they also have higher maintenance costs and usually a higher carbon footprint. To find the best ratio between active and passive elements in a design requires full awareness of all the different aims and needs of the project.

2- Predict, adapt, and respond to change

It is well known that most buildings are not performing as planned or expected. This difference is mainly related to the use of unrealistic input parameters during the design, changes in the environment during the building's life, changes in the function of the building. Having an intelligence building that can comprehend these changes in a real-time scenario and adapt to them can guarantee high performance and sustainability during its whole life cycle.

3- Minimizing the cost of people

The cost of the people who use the building refers to their wages and productivity. In many so-called sustainable buildings, residences are substantially unsatisfied or uncomfortable. This unsatisfaction comes from a single perspective design approach that only considers energy efficiency and sustainability and does not consider residences' social and mental requirements or real-time needs. As a result, people use other ways to answer their physical needs like desk lights, fans, and heaters, or get annoyed and lose their mental well-being, which reduces their overall productivity. A proper sustainable building should react to its residence needs in real-time and answer those demands while maintaining its high efficiency.

4- Feasibility of reimplementation

As mentioned, to have a meaningful positive impact on the most severe threat to our planet, there should be an increasing efficiency trend for all new buildings and most of the existing ones each year. With some minor interventions, a real-time computational method can be reimplemented in existing buildings. As it is an algorithm with some physical elements to control the environment and some sensors and devices to get the data, executing it on already existing buildings is more reasonable than fitting a whole new system from the ground up or demolishing and constructing new buildings. At the same time, the result can be highly prominent.

Case Studies

1- Pulse

Delft, The Netherlands

Ector Hoogstad Architecten, 2018

After reviewing many projects, case studies are chosen regarding their location, similarity of function, general idea and concept, and overall sustainability and circularity of design. Each of the following case studies represents one or more ideas regarding this project, helping to understand real-world implementations of these concepts better.

Image 02. The location of Pulse is in close contact with IDE and emE and makes it an ideal place to spend time and meet others (campusdevelopment.tudelft.nl).

General Information. Pulse is an education building and a meeting center between the Industrial Design Engineering (IDE) and 3mE facilities. Its central location brings students and lecturers together and, alongside educational spaces, provides meeting points, relaxing areas, and food and beverage facilities (campusdevelopment.tudelft.nl).

With an A++++ energy label, Pulse is the first energy-neutral building on the TU

Delft campus. The close cooperation between architects, students, and lecturers resulted in an optimized layout of spaces while considering sustainability and architectural aspects (campusdevelopment.tudelft.nl).

The education spaces are located in the center and vary in capacity from 60 to 100 people. There are also two terraced rooms for 125 people that can be used for instruction and project work. In addition, there are three other rooms, each with a particular theme for approximately 50 people. In total, these rooms support up to 1025 seats which can be used as quiet study spaces during the evenings and exam periods (ectorhoogstad.com).

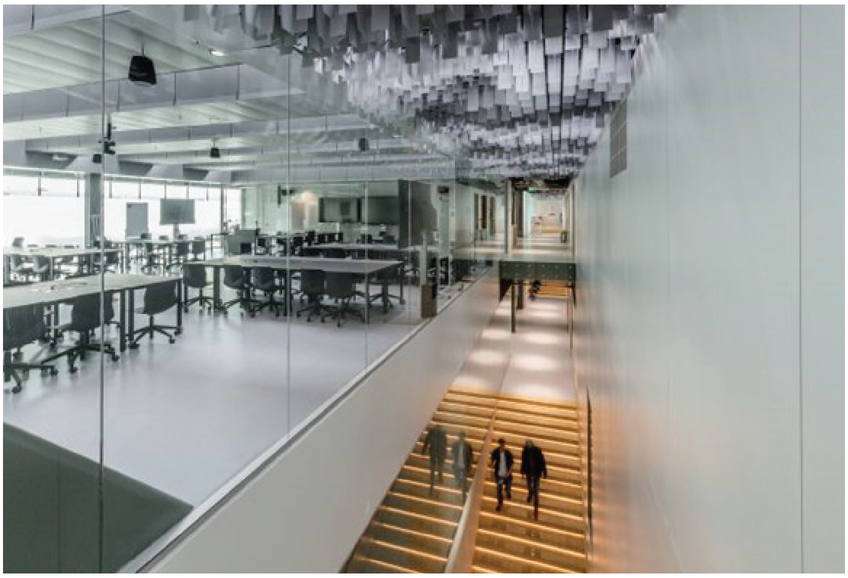


Image 03. The teaching spaces support new types of education like interactive seminars, a flipped classroom and video conferencing (campusdevelopment.tudelft.nl).

To follow TU Delft's new vision for food and beverage provision, on the ground floor, diverse food and beverage concessions are joined together in a 'Foodmarket' concept. This space creates a pleasant environment for all the people to gather and spend time, making it one of the bustling places on the campus (campusdevelopment.tudelft.nl).

Achieving Full Sustainability. The first step to achieving energy-neutrality is to optimize the layout of the interior spaces. To enhance the use of natural sunlight and optimize the heating and cooling needs, the classrooms and educational spaces are placed in the middle and the northeast of the building, while the hallways and public spaces to rest and study are located on the southwest part.

The other step is making sure that the building can adapt to change in demands and usage. Flexibility in construction and layout provides multifunctional operability over time and assures a future-proof design. Thanks to flexible dividers, many of its rooms can be increased or decreased in size, and even the facade can be partially opened, making the ground floor cafeteria merge with the square.

Image 04, Many rooms in Pulse can change their size and dimensions to insure a future sustainable building (campusdevelopment.tudelft.nl).

The final step of sustainability in Pulse is its efficiency and energy production. While many design choices, like the layout and the facade openings, are essentially static, an intelligent building management system controls the air-conditioners, ventilators, and lights in various Pulse spaces in line with their use. This active solution, in line with 490 solar panels (750 m2) with an annual yield of 150,000 kWh on the roof and an underground thermal storage system, makes Pulse a proper energy-neutral building.

2- The Green House

Utrecht, The Netherlands

Cepezed Architectenbureau

Image 05. The indoor vertical farm dominates the main façade (cepezed.nl).

General Information. The Green House is a small urban farm, restaurant, and meeting point located between the Knoopkazerne and the adjacent head office of Rabobank. This location would not be filled with permanent construction for another 15 years, so The Green House is entirely circular, which means all its components and construction parts can be recycled or be reused after its disassembly. Having a temporary structure could make the area that would otherwise remain vacant livelier, and when it is time for a permanent solution, it can be easily taken apart and rebuilt elsewhere (cepezed.nl).

In addition to being fully disassemblable, vertical farming is the other main characteristic of the building. This 80 m² vertical greenhouse is located on the first floor, next to the meeting rooms. Here, vegetables and herbs are grown to be used as fresh ingredients for the restaurant. Thanks to a void in the pavilion, visitors can see the freely accessible greenhouse from the restaurant below. Furthermore, the large green wall contributes significantly to the experience of The Green House (cepezed.nl).

The roof of the pavilion is packed with solar panels. The Green House has an ac-plug-free kitchen in which food is prepared without electricity but with energy-efficient ovens fired with renewable fuels. A large part of the interior has been found through urban mining, and all the new furniture is made from recycled materials (cepezed.nl).

Image 06. The vertical farm is directly next to the meeting rooms (cepezed.nl).

Image 07. The Green House creates a lively environment in an otherwise vacant space (cepezed.nl).

3- Building D(emountable)

Delft, The Netherlands

Cepezed Architectenbureau

Image 08. Building D’s façade is mostly transparent and its frameless structure reduces the material use (cepezed.nl).

General Information. Cepezed acquired this site in the center of the Dutch city of Delft with former laboratories from the Delft University of Technology in 2012. While Cepezed transformed the monumental buildings on this site to its own offices and studios and some other creative companies, the only non-monumental building on the site was still in poor condition. It made way for the construction of Building D(emountable), a modern, sustainable, and fully demountable structure housing companies in the knowledge-intensive creative industry (cepezed.nl).

The Netherlands aims to execute all construction activities fully circular by 2050, and Building D is an excellent example of such a building. Its components are easy to reuse or recycle, while the whole building can be reassembled in an entirely different place in the future. To achieve this, supreme simplicity has been an essential principle in the design. The structure is made of prefabricated super lightweight steel, and for all the other parts, the use of materials is held to an absolute minimum. The floor is made from prefabricated Laminated Veneer Lumber (LVL), and the glass facade is mounted directly onto the steel structure without frames.

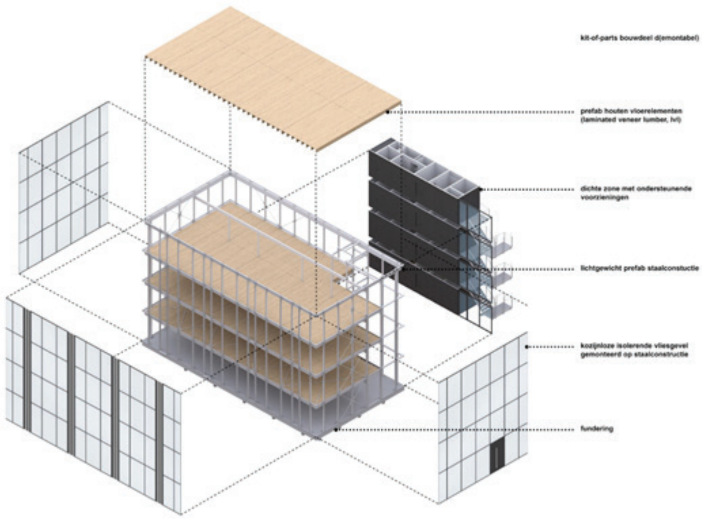


Image 09. The simplicity is construction has minimized the material need and reduces the cost and environmental effects (cepezed.nl).

To ensure a future sustainable design, each floor is fully flexible in its arrangement, has no gas pipes, and is equipped with heat recovery. Furthermore, the entire building functions as one large fire compartment and little material was needed for fire-resistant standards; only the stairwell has a fire-resistant barrier. In addition to heat exchangers, air conditioners that also take care of heating are integrated into the ceiling, while roller blinds provide sun and light protection.

Building D is an exceptional model of a sustainable building from the design process to its end of life. A well-thought-out preparation and close relationships and communications between specialists from different divisions made it possible for the construction to be finished in 6 months, reducing the cost of construction and its environmental effects.

Image 10. Part of aesthetics of the building is its simple prefabricated LVL floor structure (cepezed.nl).

Image 11. The Contrast between the Building D and its old surrounding is one of the characteristics of the project (cepezed.nl).

4- ShareCuse

New York, The USA

Architecture Office

Image 12. The cubicles devide the space into semi-private and open spaces for gatherings (architectureoffice.org).

General Information. ShareCuse is a 3,200-square-foot coworking space that prompts a simultaneously interactive and private work environment. It is characterized by freestanding black cubicles and a kitchen island that define a series of interstitial lounge spaces. Unlike the traditional enclosed cubicle, the ShareCuse cubicles are crafted from black mesh screens that filter the appearance of the spaces behind rather than creating an opaque separation layer. The surfaces turn into layers of translucent scrim that manifest the offices and personnel within when looked closer. The cubicles act as minimal objects occupying, framing, and defining regions by populating a larger room (architectureoffice.org).

To allow for moments of engagement and interaction between spaces and invite people to share across workspaces, these cubicles are deployed with 0.9 by 2.1-meter openings. Some openings are gates for entry, while others serve as possibilities for members working in teams to pass information or share desks. Although the cubicles and their openings are all of the uniform

Image 13. The mesh surface of cubicles filters the view while keeping the space light and open (architectureoffice.org).

sizes, the placement of the openings is different, making variety and different interactions with their adjacent spaces. The modular cubicle can appear simultaneously open and closed, efficient and playful (architectureoffice.org).

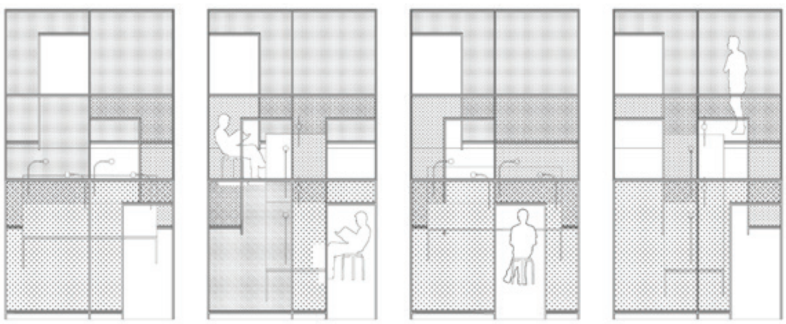


Image 14. Different types of design and combinations are possible by placing the openings differently (architectureoffice.org).

Design Scenario

TU Delft is working on a diverse and inspiring setting for students, scientists, employees, entrepreneurs, and visitors. Considering that student numbers have been steadily rising for years and there is high demand for startups, research, companies, and visitors, TU Delft is investing in high-quality spaces for new forms of teaching, working, and research to achieve a sustainable and CO_2 neutral campus.

The ambition of TU Delft for a carbon-neutral campus by 2030 is visible through their latest projects in the development of the campus. The recently built education building Pulse is an excellent example of this. It is the first energy-neutral building on campus and was developed closely with the Architecture faculty. The strategy behind this goal is by thinking about whether a building is needed (refuse), by reducing the energy and material use (reduce), by generating as much renewable energy as possible (produce), and finally by reusing the materials and products as long as possible (reuse).

Over the years, TU Delft has gradually moved away from the city further towards the south. This new area creates the space required for new small companies, startups, and research labs. In TU Delft Science Park, besides new buildings and facilities for some faculties, there is massive planning for new offices, labs, and especially co-working spaces. Some of these co-working and startup spaces have already been realized (Yes! Delft), while others are under construction (Next). Alongside some offices in this area, these workspaces create a startup-focused region in the northeast of Science Park.

As described, the master plan of the TU Delft campus provides exciting opportunities to propose co-working spaces for young graduates and startups. While there are other co-working spaces on the campus, the rising number of graduates and the enormous need for innovation in today's world create the demand for a small but highly advanced co-working space focusing on indoor and vertical farming.

This building includes a co-working space and its related labs and workshops with a small vertical farm for experiencing the newest innovations and is located in the under-development TU Delft Science Park in front of Yes! Delft co-working space.

Image 15. TU Delft Science Park

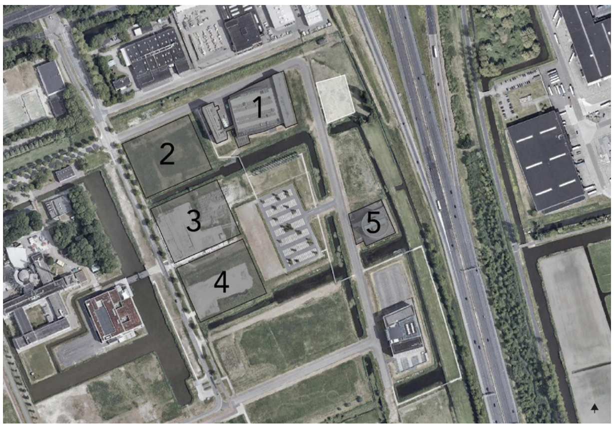


Image 16. Location of the proposed building. 1) Yes! Delft 2) Next 3, 4) TNO Delft 5) 3M Office

Concept Principles

To eliminate the carbon footprint of buildings, they should become fully sustainable. A sustainable building should respect all the sustainability criteria, from its concept and design methods to its end of life and disassembly. A building is neither considered intelligent nor sustainable if it is only intelligent or sustainable in one or two sectors.

Even though the focus of this design project is on the real-time response and adaptiveness of the building to the condition and its inhabitants' behavior, it is still essential to have a clear idea about other sustainability measures of the building. To make the matter clear regarding this project, the sustainability criteria can be defined in three main categories. Achieving sustainability in these categories ensures a final sustainable and circular building without sacrificing the users' comfort and other architectural aspects of the building.

1- Design Approach in Different Levels

Buildings are built to create a livable space for users, protect them from the harsh environment and aid them to reach their best productivity and efficiency. However, while buildings try to make their interior as comfortable as possible, they sometimes negatively affect their surroundings and decrease comfort in open spaces or adjacent buildings. As a result, one of the goals of an intelligent design should be to consider and minimize these adverse effects through passive or active elements on the building's skin.

While some of these unfavorable effects have been well studied, for example, the urban heat island, others are relatively new and also quite unpredictable, for example, the effect of the reflection of the skin on adjacent buildings. Using an active facade can allow the designers to use sensors and intelligent algorithms to tackle these unpredictable effects when they happen while maintaining the high performance and the comfort of the building. In this criterion, the goal is to understand the comfort needs of the users while considering other factors such as environmental impact and the effects on the surrounding. In other words, the design approach should consider all the future requirements of the building from small to large scale. It must enable the building to be fully adaptive to changes and be real-time responsive to conditions.

Image 17. The design approach in different levels

2- Real-time Adaptiveness and Intelligent Responsiveness

As mentioned earlier, most buildings perform less efficiently than anticipated. One of the main reasons behind this difference is that most buildings are designed without considering the users' actual behavior. To minimize this difference, the main focus of this project is to present a real-time algorithmic method that can adapt the building performance based on the actual condition and users' behaviors and needs at any given time. This algorithm can be fed with data and numbers to provide different levels of comfort and efficiency based on each area, function, and condition. To write such an algorithm, it is necessary to have a clear idea about the priorities, data inputs, extent of automation, and the number of changing factors.

Such an algorithm intends to make buildings more intelligent, aware of the condition, and responsive to changes to lessen their carbon footprint while extending their lifespan.

Image 18. Real-time Adaptiveness and Intelligent Responsiveness

3- Circular Design

No matter how optimized and sustainable a building is, it nonetheless requires a considerable amount of resources to be constructed. From extraction to transportation, these materials contribute hugely to global CO_2 emissions, negatively impact the environment, and increase the construction cost.

To have a fully sustainable building, one step is to minimize the required material for construction by removing all the unnecessary parts and optimizing what remains. Having a simple approach toward the construction reduces the construction time and material significantly. The other step is to design and construct the building so that most of its constructing elements are disassemblable by its end of life to be directly reused or at least recycled.

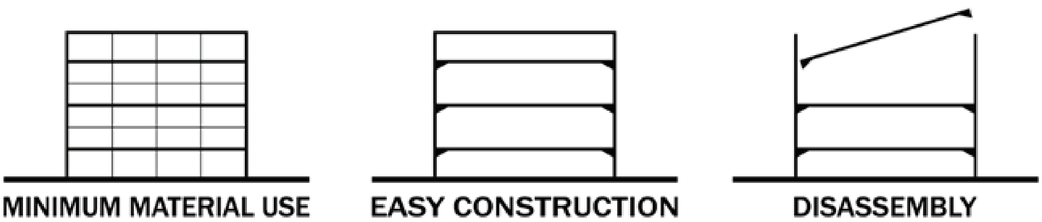


Image 19. Circular Design

These three sustainability measures work together, and it is impossible to apply one of them to achieve a sustainable design. Although the focus is on the second criterion in this project, the others are also discussed and considered throughout the process. For example, having a building capable of real-time and automated adaptation based on the condition requires a fair number of active elements, and as these active elements increase the material use and construction costs, it is essential to find a balance between passive and active systems.

The other critical fact is that although this intelligent algorithm only results in a fully sustainable design when applied with other steps, it should still be a fully open and adaptive algorithm that can be implemented on existing buildings to increase efficiency. One of the primary purposes of this project is to create a method that can be used in different buildings regardless of their function, shape, and location. In making such an algorithm, it is essential to be entirely parametric and use high-tech active elements as little as possible to make it applicable to other buildings with the least cost and effort.

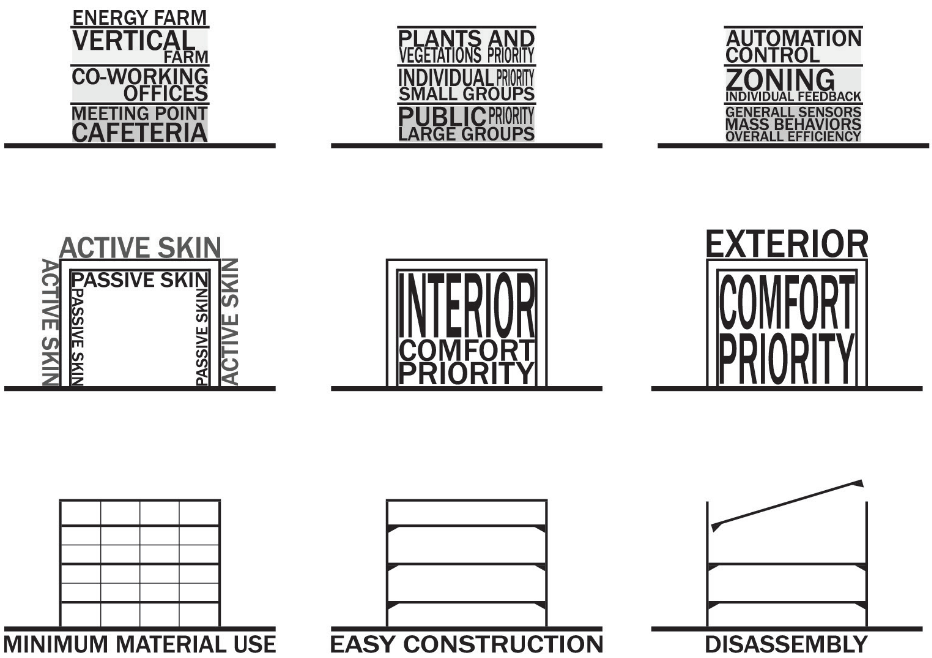


Image 20. Concept Principles

Design Principles

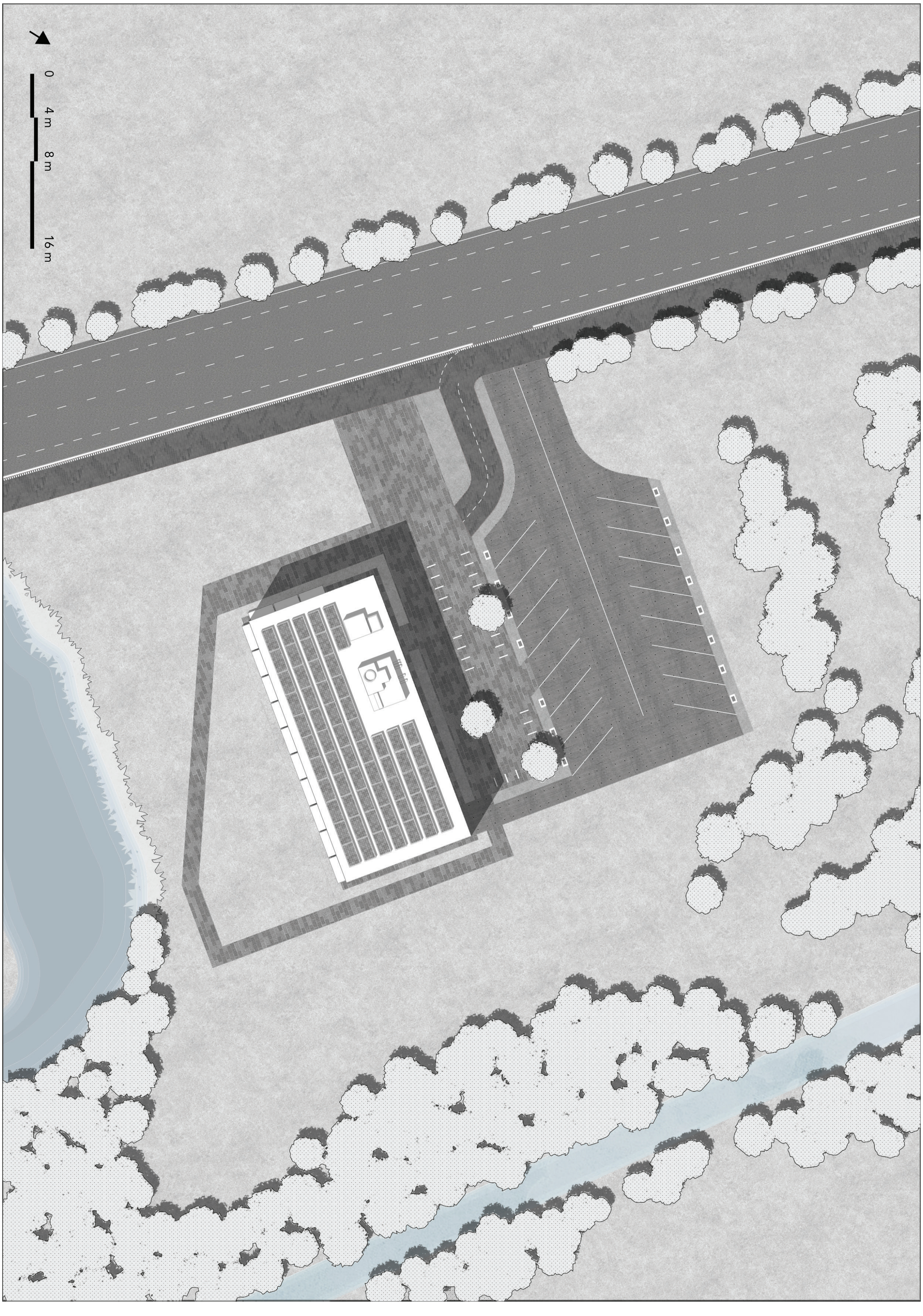
In the first steps of the design, it is essential to ensure that it respects the foremost criterion mentioned earlier. The design should follow simple rules and guidelines to guarantee the building can respond in real-time and adapt to future changes. On the other hand, too many moving elements and a complex kinetic facade should be avoided to reduce the cost and material use. Following this, the design avoids unnecessary elements and only keeps what is necessary for the users' function and comfort. In addition, having a well thought and easy to set up structure allows using prefabricated elements and easy joints between the structural elements. These characteristics secure a circular and disassemblable building when its lifespan is over.

In the following pages, these design approaches and criteria will be illustrated in detail before presenting this project's main subject, which is the intelligent real-time algorithm.

1- Form and Placement

Having a simple form helps to retain easy construction and less material use, while it also facilitates creating the intelligent algorithm. Nevertheless, to achieve this simplicity, nothing is sacrificed. All the regular optimization, consideration, and design principles are assessed during this design phase.

The orientation of the building is in a way that it can receive most light during the cold seasons. As the data suggest, the sun is needed most of the time to achieve a comfortable environment. Considering that the footprint of the building is little compared to its site, there is a massive opportunity to dedicate a large scale of it to vegetation and greenery, car charging stations, and bike parking.



Drawing 01. Master Plan. The building is located on an open lot which provides adequate light and airflow.

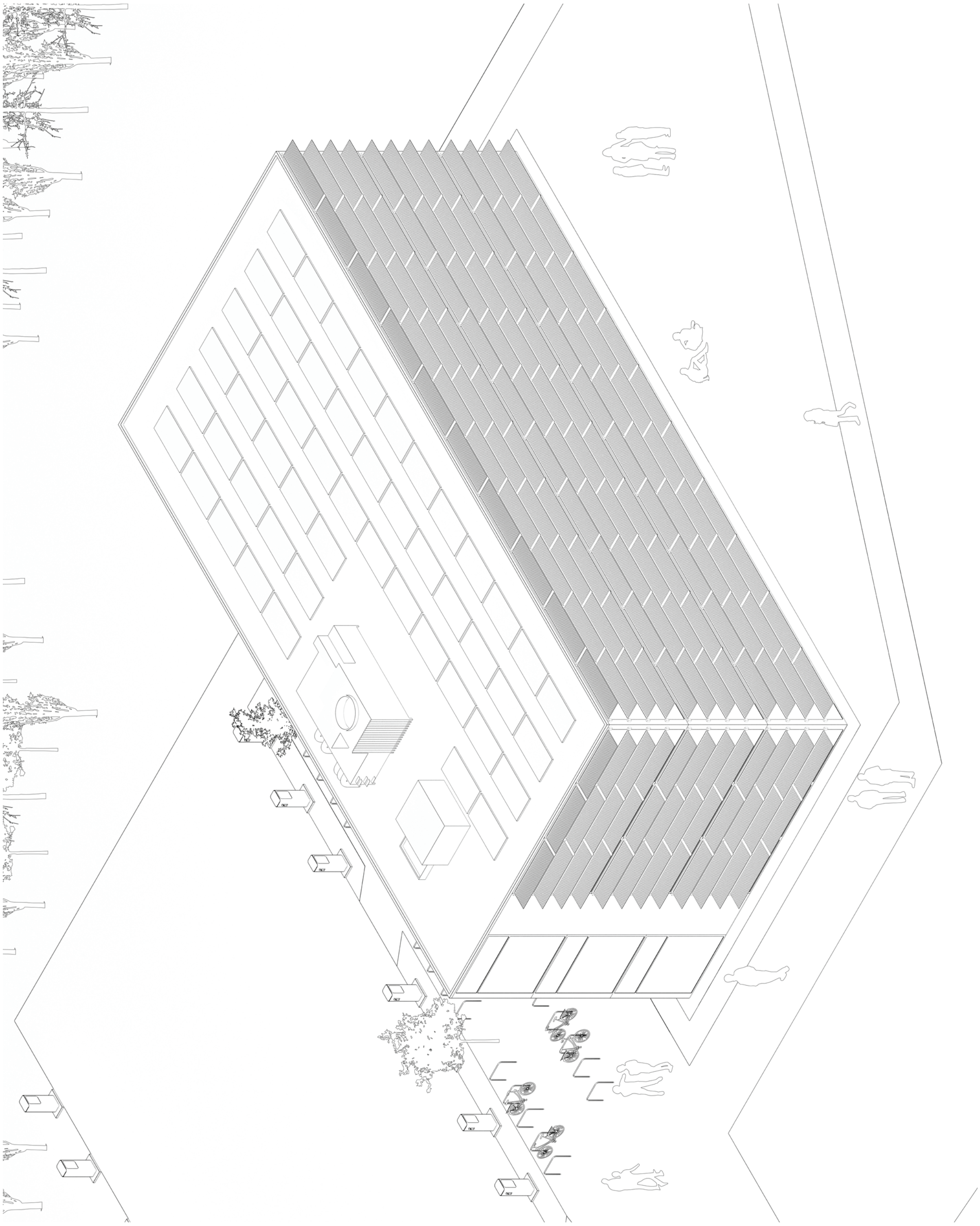


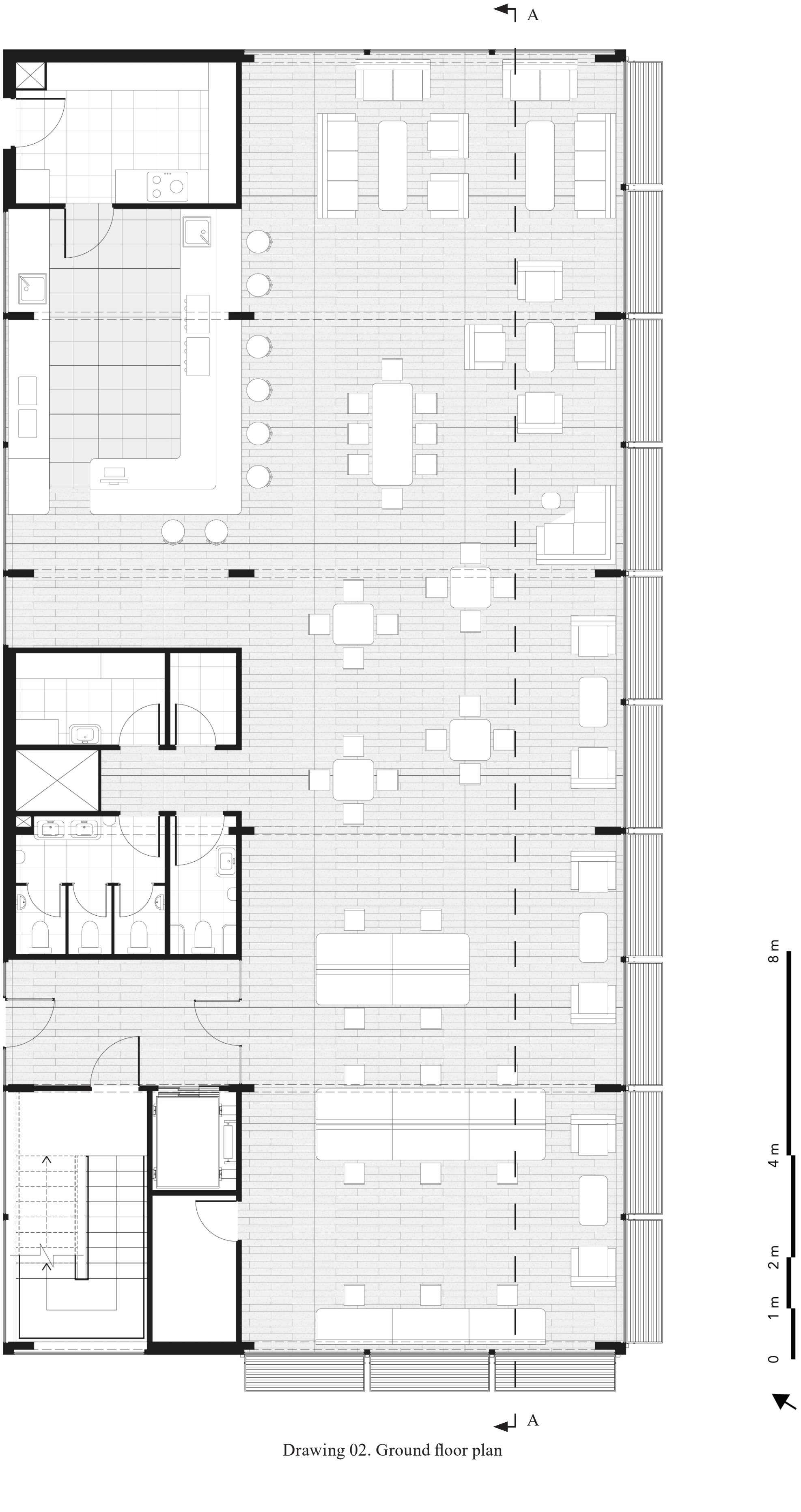
Diagram 01. Bird-eye view from southwest

2- Design and Layout

The simple design also allows for an open layout that can be changed easily at any time. However, the general idea is to provide an All in One function system, even on a small scale. Having an All in One layout allows more unified service management, more efficient and circular resource usage, and better social interactions between diverse types of users. It also showcases how the same algorithm can be used for various functions, layouts, and needs by changing inputs and minor changes. In the algorithm chapter, all these possibilities will be explained in depth.

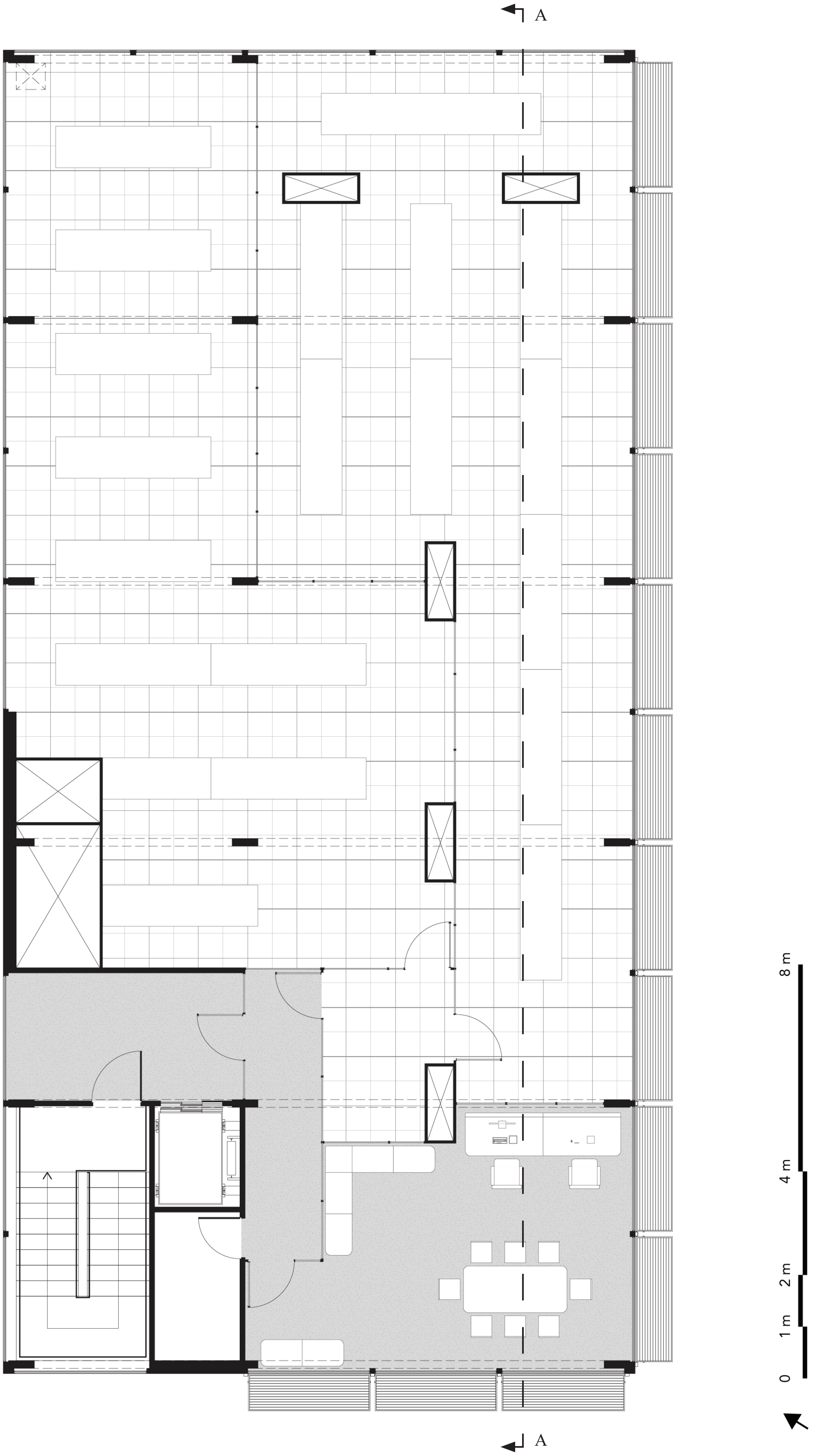
The building consists of three open layout floors. The ground floor is a public meeting space, with some work desks and a cafeteria. This space works as a meeting and working hub focusing on larger groups of users and large-scale comfort priorities. The first floor is a co-working space with two individual offices hosting two teams. This area focuses on individual comfort and priorities users' productivity, and the last floor is dedicated to vertical farming and one small laboratory to monitor and control the farms.

The design features a largely transparent façade to ensure strong sightlines and connections between the internal and external environments. Each window frame has one opening on top that can be controlled through the algorithm. Furthermore, each frame also features two diffuse rolling blinds, one for the top third part and one for the bottom part. Four shading louvers cover each frame from outside; the top one moves individually while the other three work together. These moving elements of the facade, together with the passive measures and other active mechanical and electrical systems like the interior lighting grid and sensors, ensure real-time response to the condition using the intelligent algorithm.

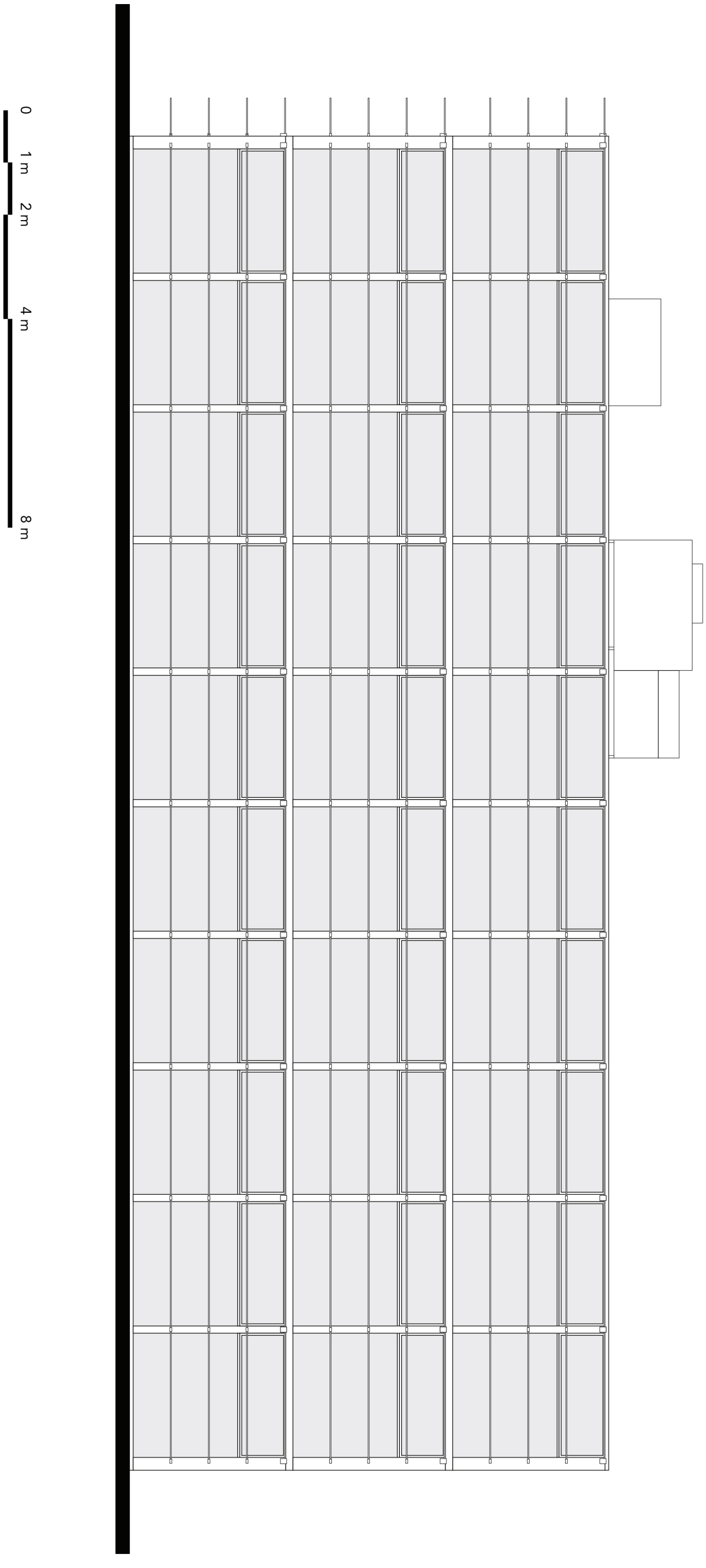


Drawing 02. Ground floor plan

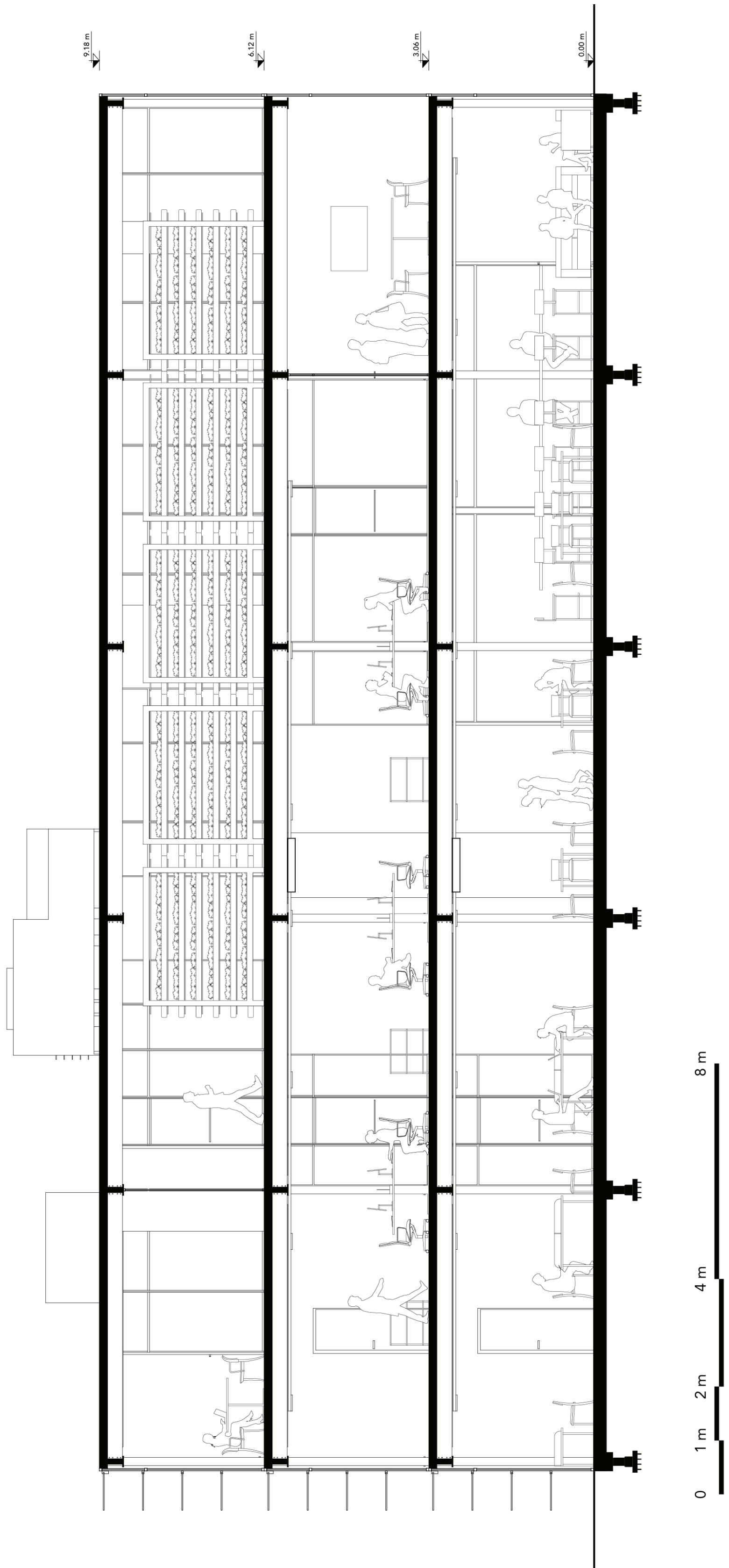
Drawing 03. First floor plan. The plan is modifiable as there are no fixed walls. All the piping systems are also exposed and located on the roof. This flexibility ensures a future-proof design.



Drawing 04. Second floor plan. All the required mechanical systems for the vertical farm are delivered from the roof using a set of ducks.

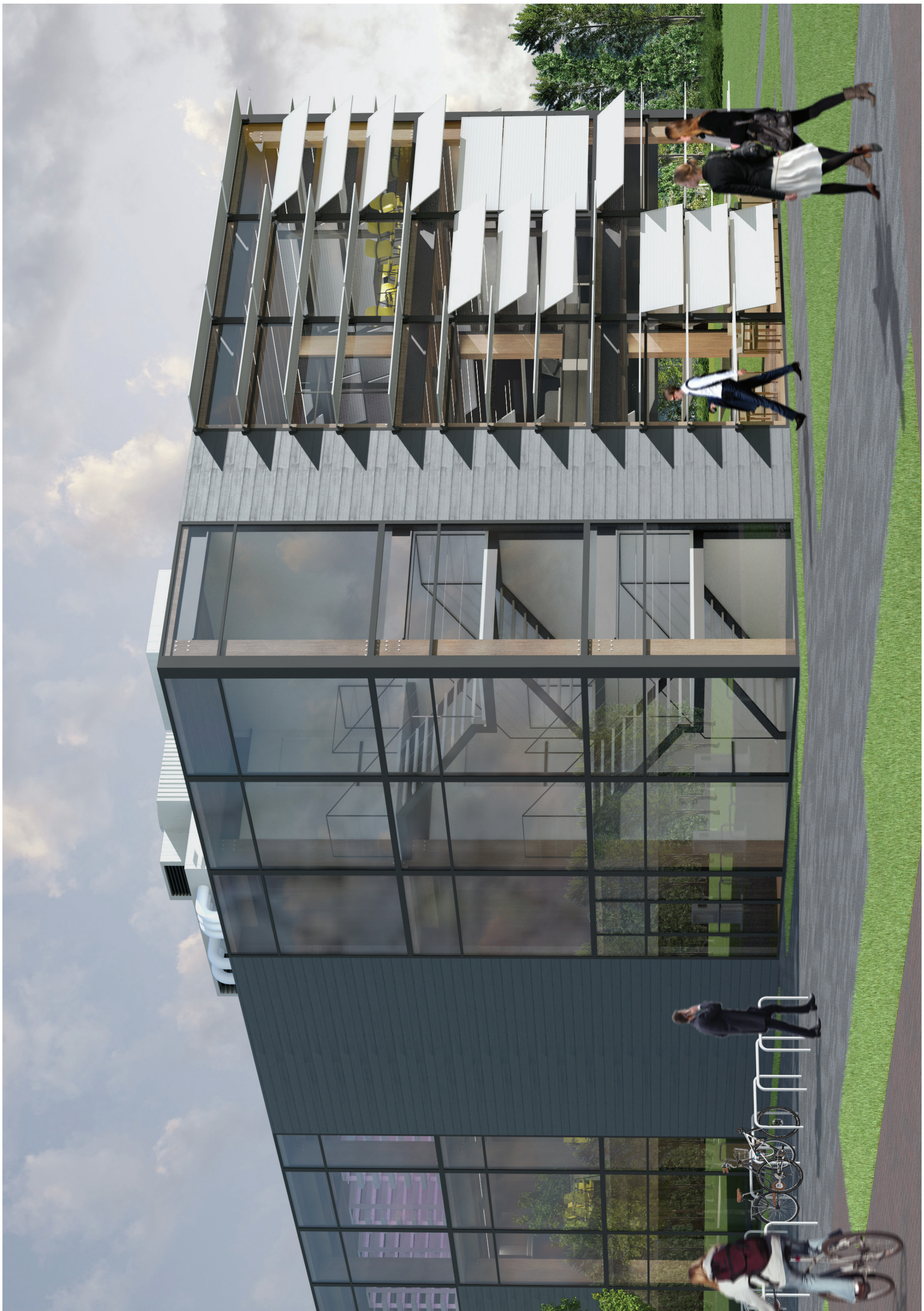


Drawing 05. South Elevation. The minimal design helps to reduce construction costs, material use, and end-of-life disassembly.



Drawing 06. A-A Section. Most spaces are fully changeable.

Render 01. South Facade. White exterior shades are reacting in real-time to provide the users with their desired conditions.



Render 02. View from the street. Exterior shades are removed on the north facade and unnecessary openings like the staircase.

Render 03. A view from the co-working office. All the structural and mechanical elements are exposed to increase flexibility and reduce construction costs.

Render 04. Public meeting area on the ground floor.

Render 05. A view from the co-working office.

Render 06. Vertical farm. This space needs different conditions from other floors, provided by the algorithm and the facade system.

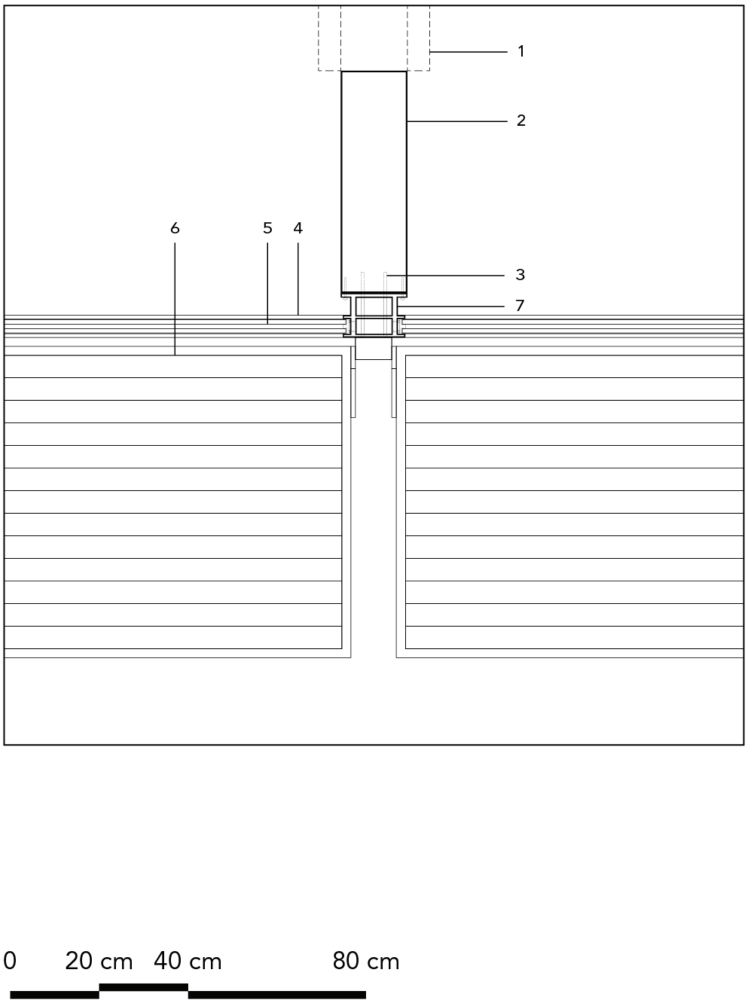
3- The Circular Design and Disassembly

Constructing a building requires resources and materials. Many of these materials are from rare-earth elements and have a considerable carbon footprint. While it is necessary to minimize material usage by finding more straightforward approaches to design, an intelligent building also needs wise material choices and construction techniques to reduce the carbon footprint and scrap material.

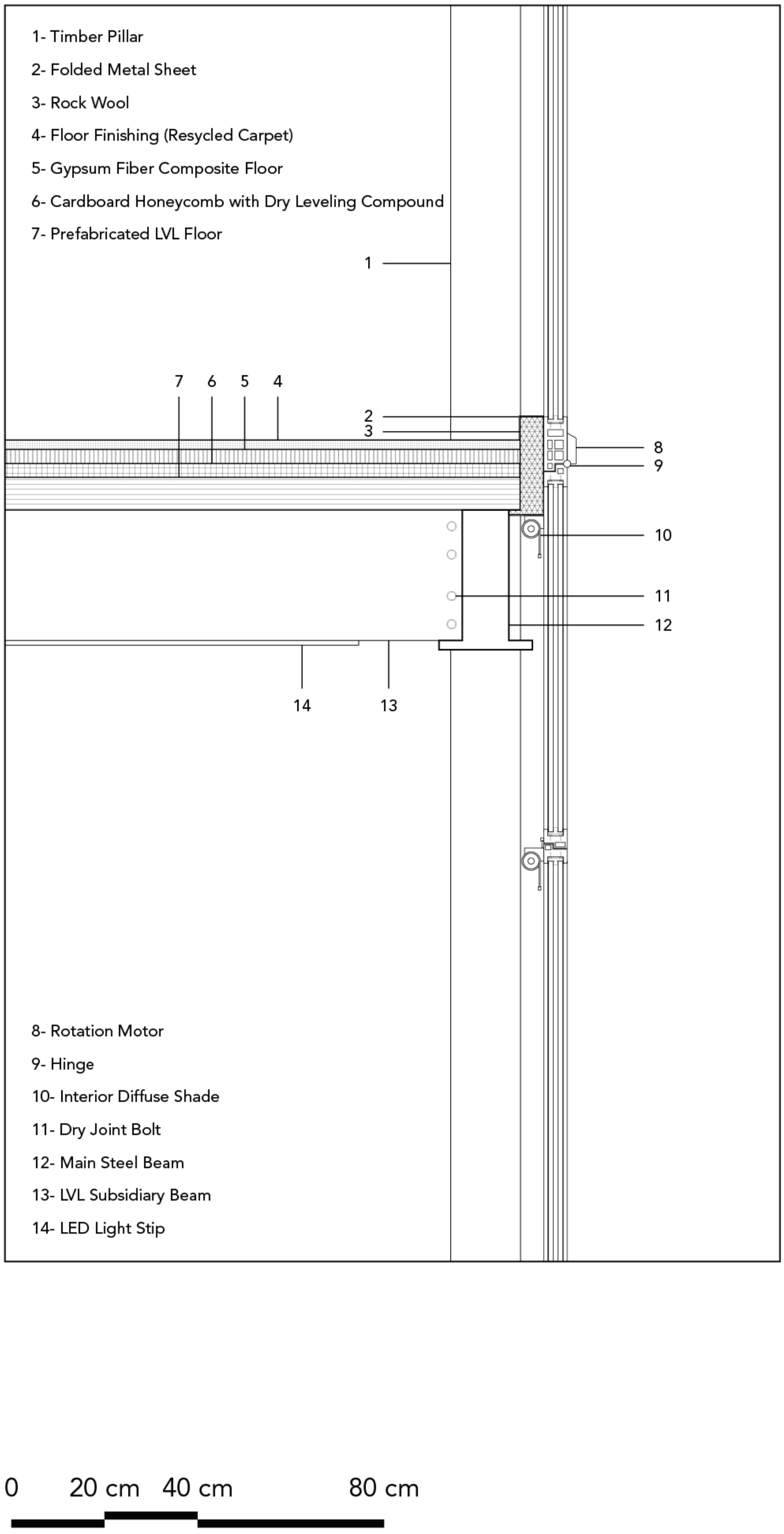
In this project, the structure is extremely lightweight, and the use of materials is kept to an absolute minimum. The open layout means that the building is entirely flexible in its configuration, it has no gas connection, and all the mechanical and electrical connections are passed through the roof's exposed beam system. Ultimate simplicity has been an essential principle in the design, with steel, wood, and glass as the only materials in the construction. All building components are modular and dry mounted, making them easy to disassemble to be reused elsewhere.

The main supporting structure is prefabricated wooden pillars with steel beams. The floors and roofs are made of fully exposed prefabricated lightweight Laminated Veneer Lumber (LVL). The screed is constructed from metal sheets structure, sustainable insulation, and partly recycled PVC and carpet finish.

1- Main Steel Beam
2- Timber Pillar
3- Dry Joint Bolt
4- Aluminum Frame
5- Double Glazed Glass
6- Exterior Rotary Shade
7- Hollow Structure

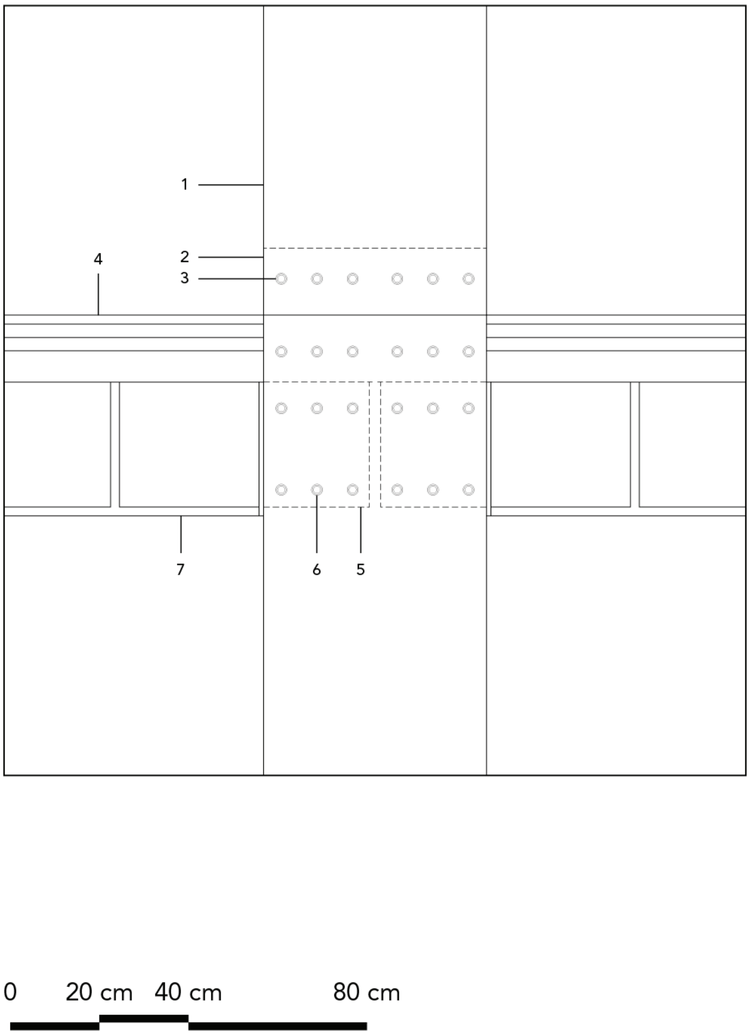


Drawing 07. Construction detail of exterior frames and their connection to the structure.



Drawing 08. Vertical section of the exterior frame, floor and structure.

1- Timber Pillar
2- Steel Plate
3- Dry Joint Bolt
4- Floor Structure
5- Main Steel Beam Extension
6- Dry Joint Bolt
7- Main Steel Beam



Drawing 09. Construction detail of pillars connections and main beams.

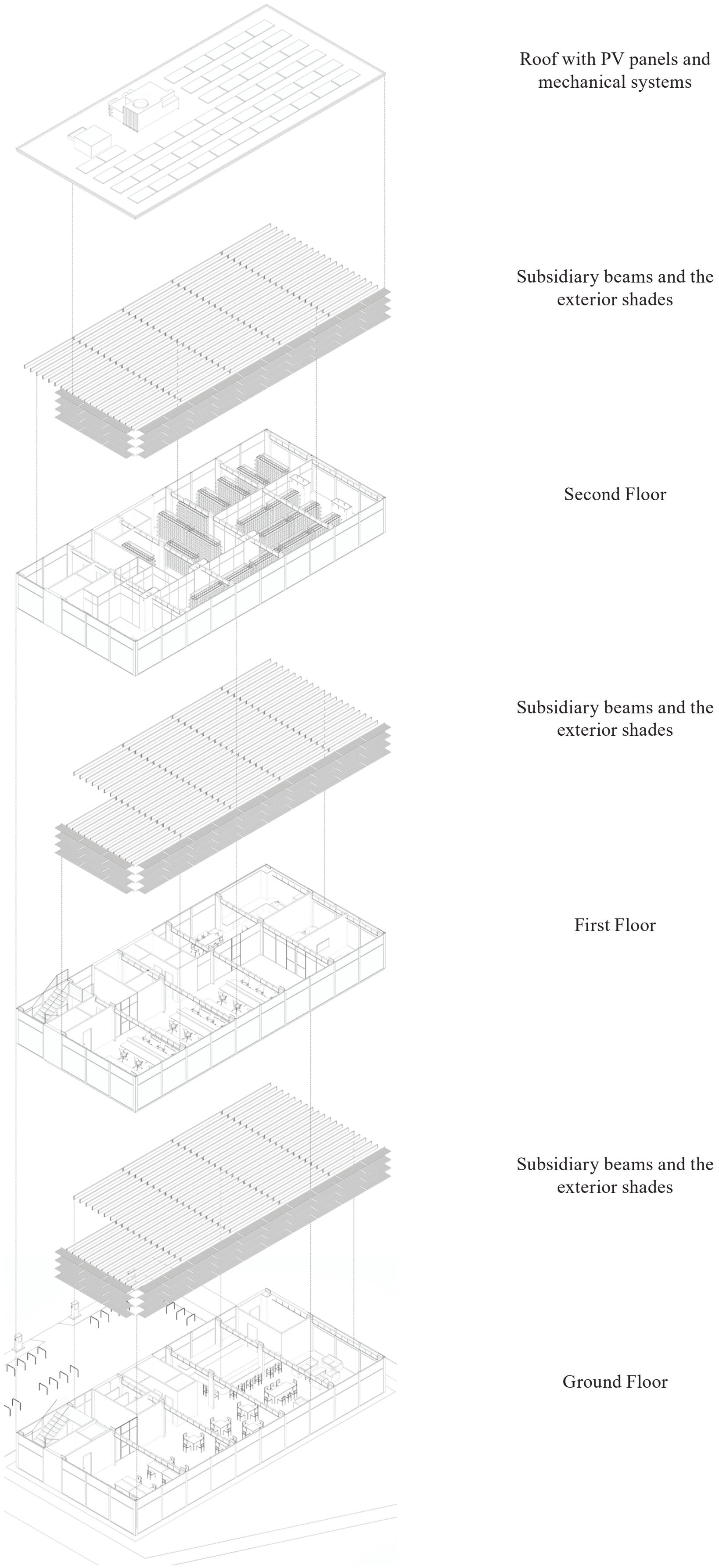


Diagram 02. Exploded isometric view of the different levels. This diagram shows the simplicity of the structure, open floor design, and the connection between the facade and the building.

The Algorithm

1- Principles

The primary part of the project is to develop a real-time responsive algorithm that can enhance the efficiency of the buildings throughout their lifespan by evaluating the real-time conditions and users' behaviors and needs. The other important fact about this algorithm is that it should be fully applicable in other projects despite their various scale or function, with minor tweaks to their facade or mechanical systems. While the principle and the structure of the algorithm are extensive enough to support all the sustainable related factors, in this project, the main focus is to design the strategies and showcase an example of how the algorithm can work intelligently in real-time to control light and ventilation through changes in the facade, interior lighting, and other available systems.

As debated in the earlier chapters, an intelligent building with real-time responsiveness should improve efficiency by lessening the users' cost and adjusting itself to the actual condition while providing a comfortable environment. Thus, such an algorithm should be based on the presence of the users, their behavior and particular needs, outdoor conditions, and the comfort level in each space. Each of these factors is discussed and considered to achieve this algorithm.

Each floor's footprint is the first input for the algorithm. It defines the active boundary of the project. Next, it is separated into different subzones. These zones define some general requirements and minimum comfort and efficiency levels. It defines whether it is a public, private or semi-private space. For example, caféteria is considered a public space for small and large groups of people, and as it is public, there is less personalization of the comfort level than in more private spaces like offices. Using this primary zoning system, it is possible to feed the algorithm with the minimum comfort levels, like lumens, dry bulb temperature, CO2 level, and humidity for each zone. These numbers act as guidelines for the algorithm, and it always tries to keep the real-time numbers from the sensors close to input values.

To ensure that all the inhabitants have a pleasant experience, they can control their desired condition using an app on their smartphones to provide the algorithm with more inputs. For example, they can express whether they want sunlight or diffuse light in any subzones, and the algorithm attempts to deliver them with their needs. Combining this personalization system with the minimum comfort requirements related to each subzone, the algorithm can calculate how each building element needs to react to deliver the desired condition while keeping the efficiency at its highest.

The following scheme illustrates a simplified overall view of the algorithm process. Each node describes a set of programs and functions. The process can become even more accurate and flexible by introducing new nodes and inputs depending on the needs while the general concept stays the same. It is easily achievable due to the generative nature of such programs and algorithms. These nodes work hand to hand to deliver a real-time reaction to the actual condition. In this case, Grasshopper and Python were used to write such an algorithm, but it is evident that these tools can be different, and the concept and the general idea are the principal matter.

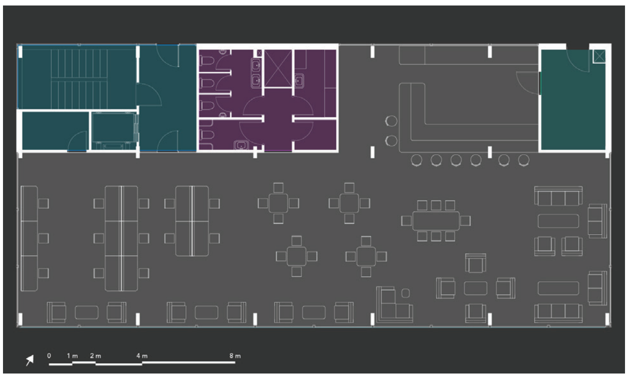


Image 21. Ground floor sub zoning system

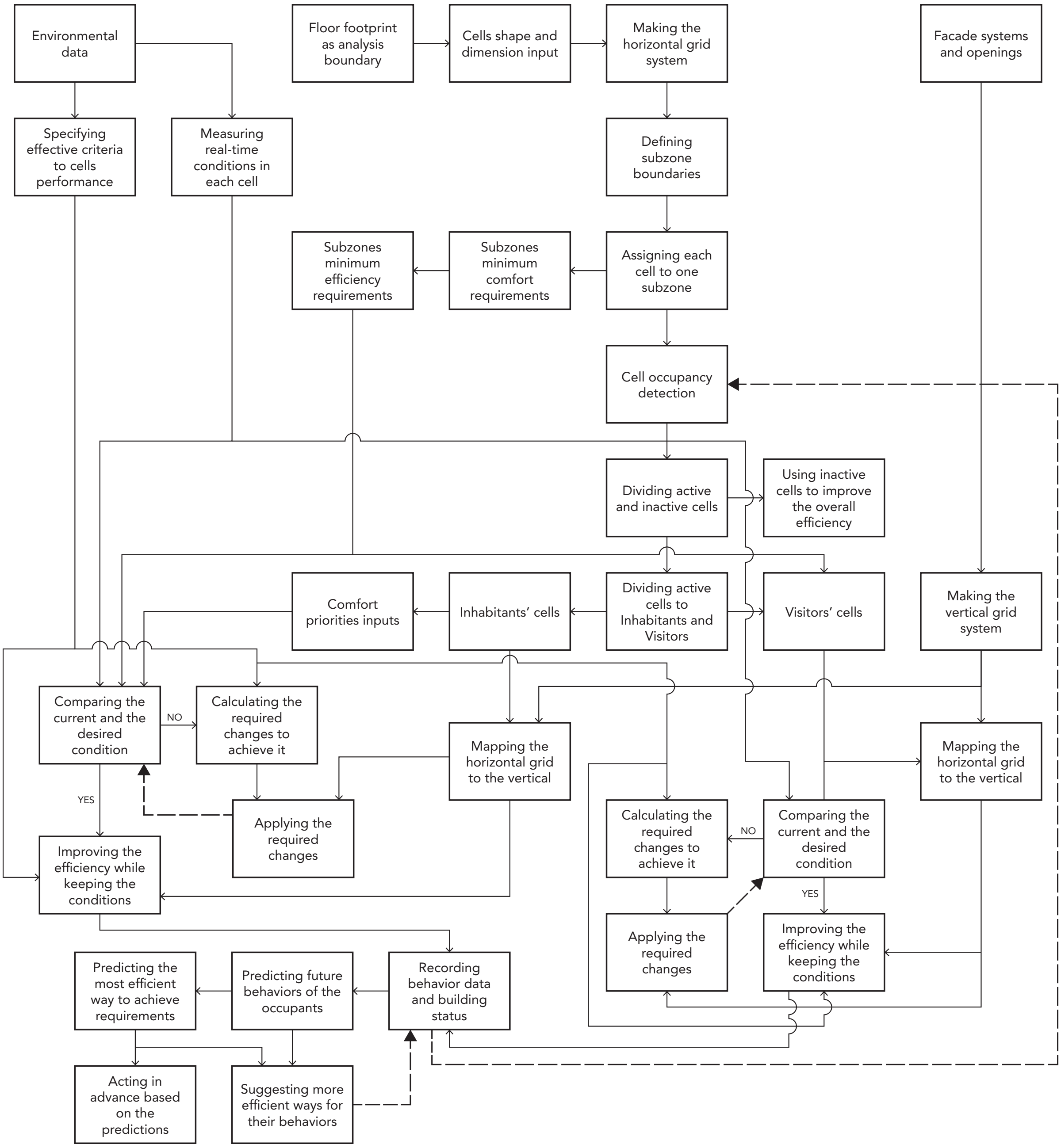


Image 22. Simplified Overview of the Algorithm

The following primary step is defining a grid system that works as the logic behind the algorithm. As with other steps, this part of the algorithm is fully parametric. Each cell's dimension can be changed to define a grid that works nicely with different designs. It is even possible to define different grids for different days and hours as in many cases, users' behaviors are fundamentally different depending on the time. In this case, the cells are 1.5m by 1.5m. This tiling system works perfectly for the co-working space, restrooms, and kitchen area. While it is possible to have different grids for each space, all the floors have the same grid system to keep the topic more precise.

The next step is to connect the last two parts to realize which cells belong to which subzone. To do so, rather than creating an extended algorithm, a simple python program is written. This simple program looks for the center of each cell and checks if that point is within the specific subzone border. The result is a fully adaptive algorithm that can work with any cell and subzone configuration. The advantage of this method rather than computing individual tiling for each subzone is that all of these cells are part of a more extensive tiling system that fills the whole plan, and it is possible to identify each cell using their indices. In other words, they can be divided into as many different lists as needed while knowing their place in the initial list is always the same. This way, it is guaranteed that the whole process stays linked from the start to the end, making the algorithm fully flexible and intelligent.

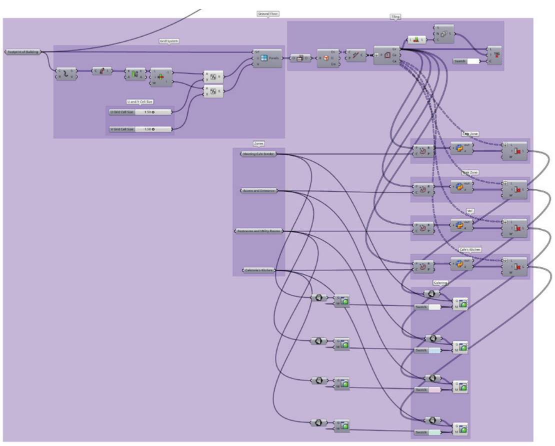


Image 23. The Algorithm behind the grid system and subzoning

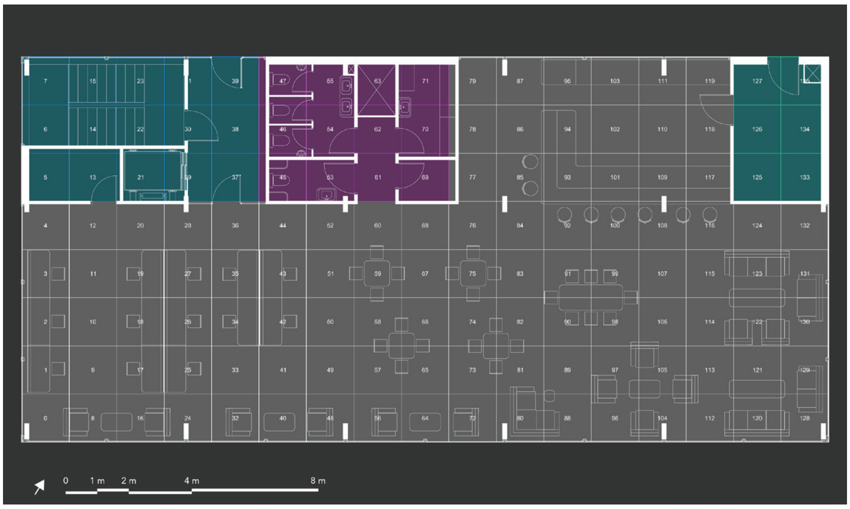


Image 24. Grid system of the ground floor

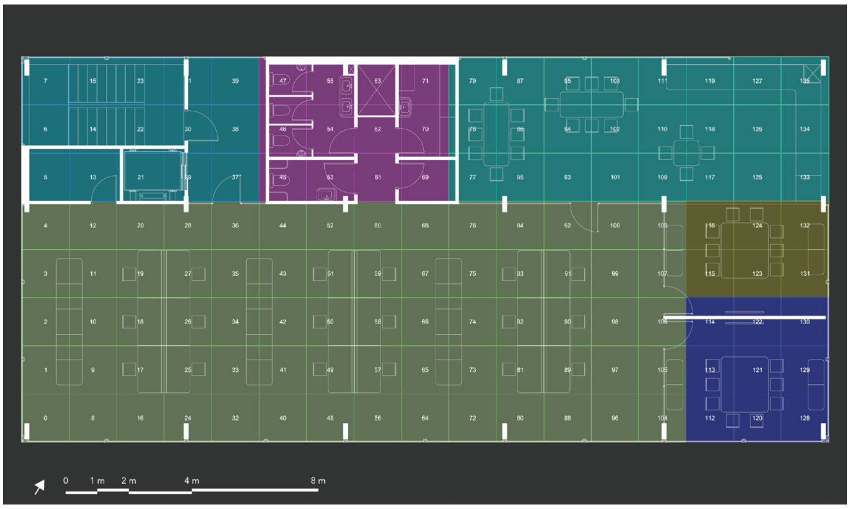


Image 25. Grid system of the first floor

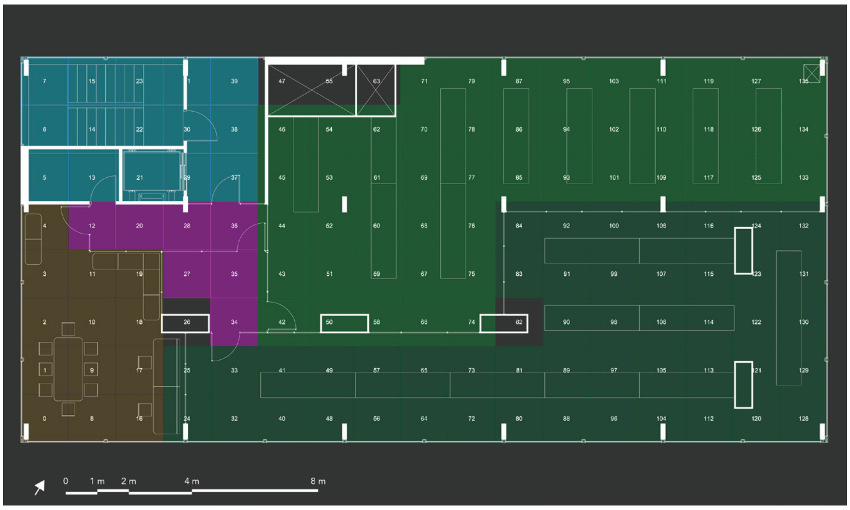


Image 26. Grid system of the second floor

2- Computation Process of the Algorithm

The core element of the algorithm intelligence and its real-time awareness is based on users presence recognition. This simple criterion defines the status of each cell at any given time. The algorithm can have different levels of intelligence based on the amount of information it receives. On the first level, all the empty cells are considered inactive, while all the cells with users are active

Regarding their status, they can accept different functions. To ensure the complete adaptability of the algorithm, it is possible to input the number of neighboring cells for each active cell to be also considered active. In this case, in the subzone of the cafeteria, the two closest cells to each dot are considered active, while in other subzones, just the cell with a user inside is active. Finally, as the cells in different subzones are still part of the more extensive initial grid system, the index of each active cell in the initial list is available after this process.

A fully randomized group of points represents the users' location in this project. Their presence will be recognized using sensors in a real-world scenario.

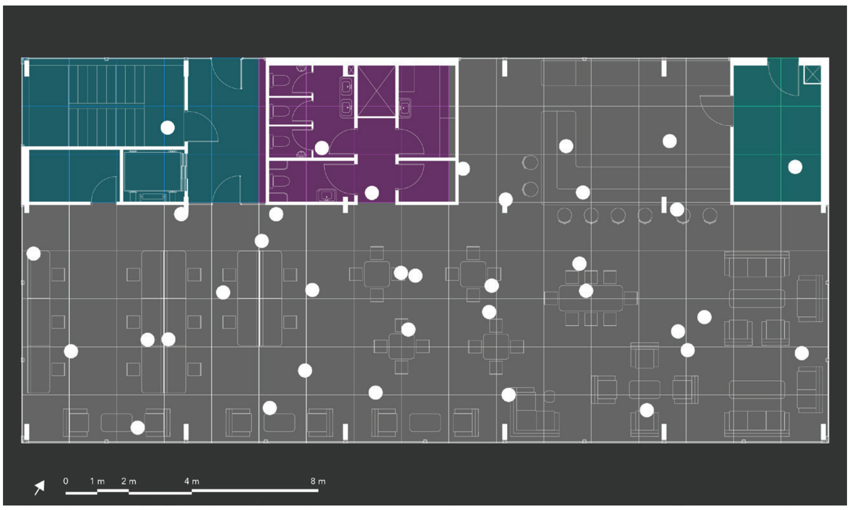


Image 27. Random points are representing the location of users

The algorithm has to check for each point first their corresponding subzone and then separate each subzone's active and inactive cells based on the presence of users. A higher number of people in one cell means that cell is of a higher priority.

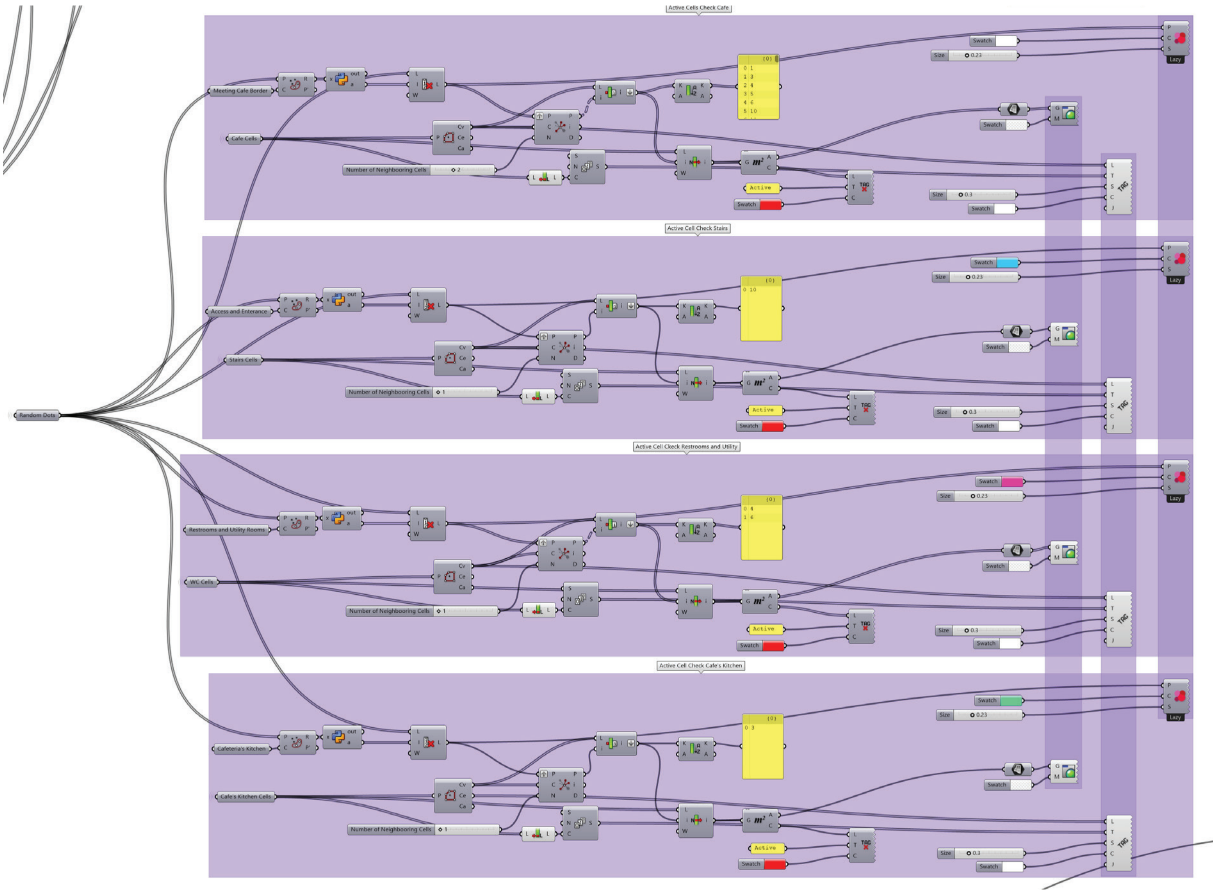


Image 28. The logic behind the presence recognition for each subzone of the ground floor

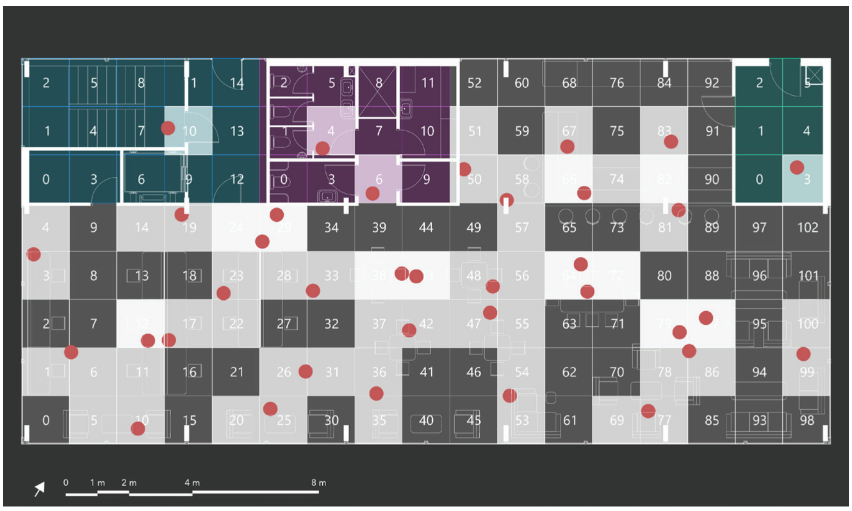


Image 29. Active cells of the ground floor. Intensity of the highlight shows the higher priority.

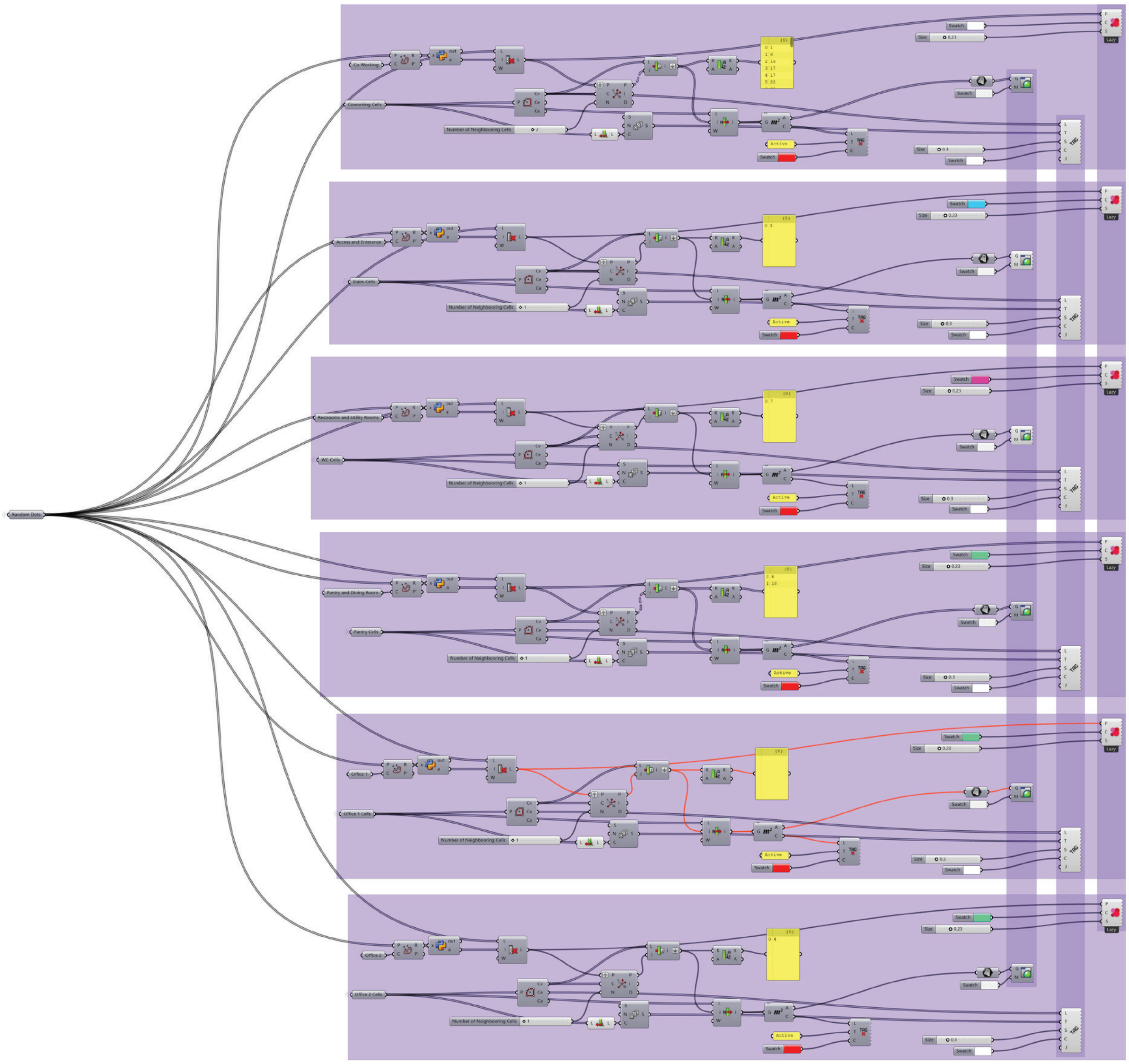


Image 30. The logic behind the presence recognition for each subzone of the first floor

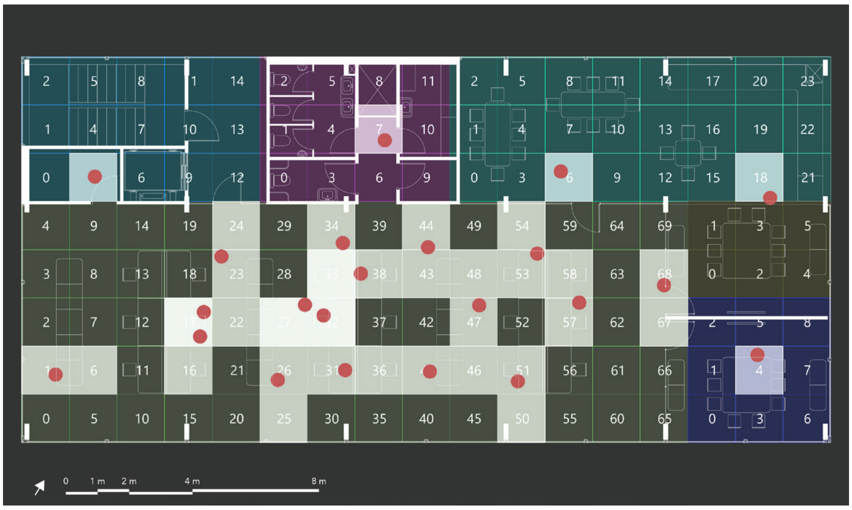


Image 31. Active cells of the first floor. Intensity of the highlight shows the higher priority.

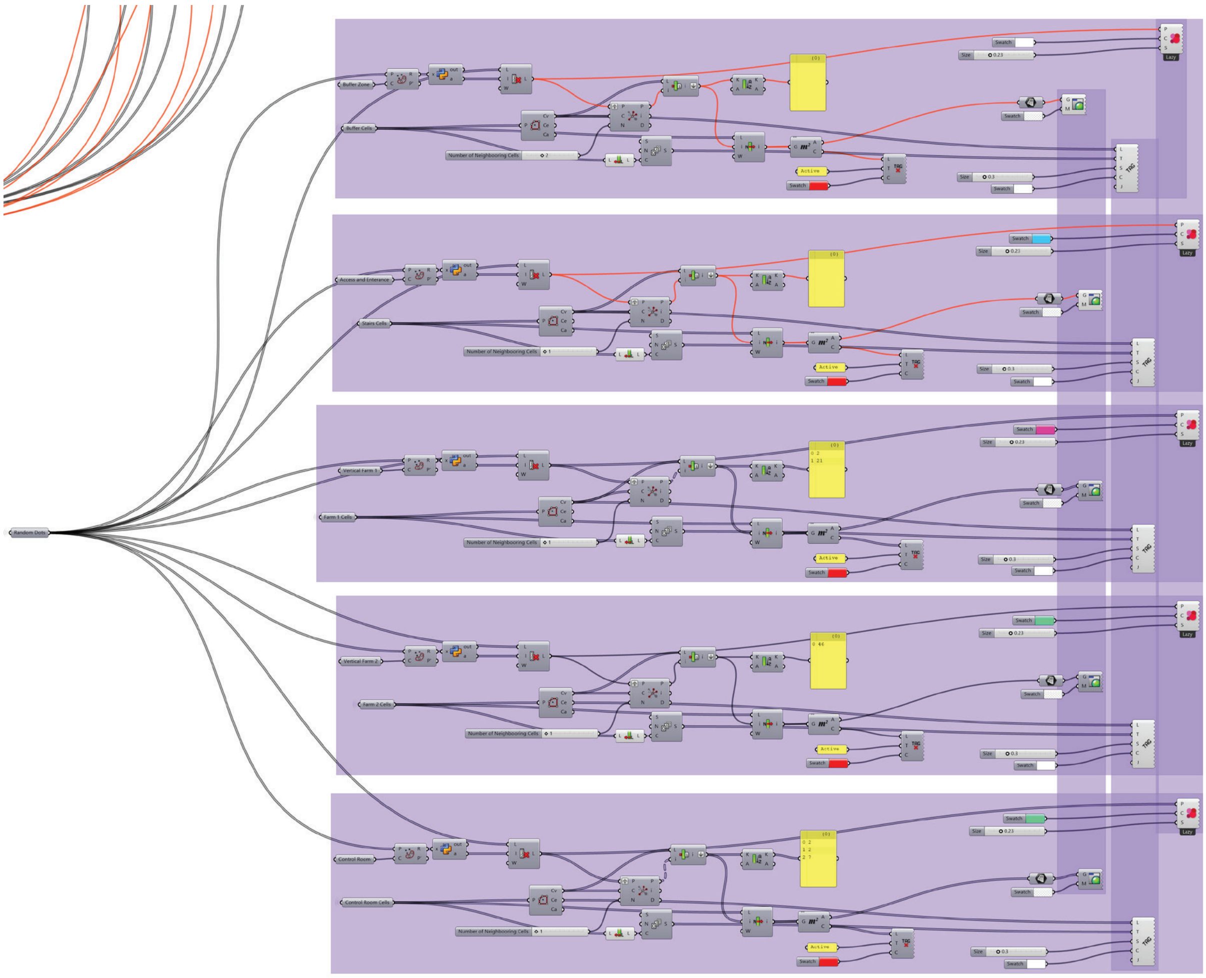


Image 32. The logic behind the presence recognition for each subzone of the second floor

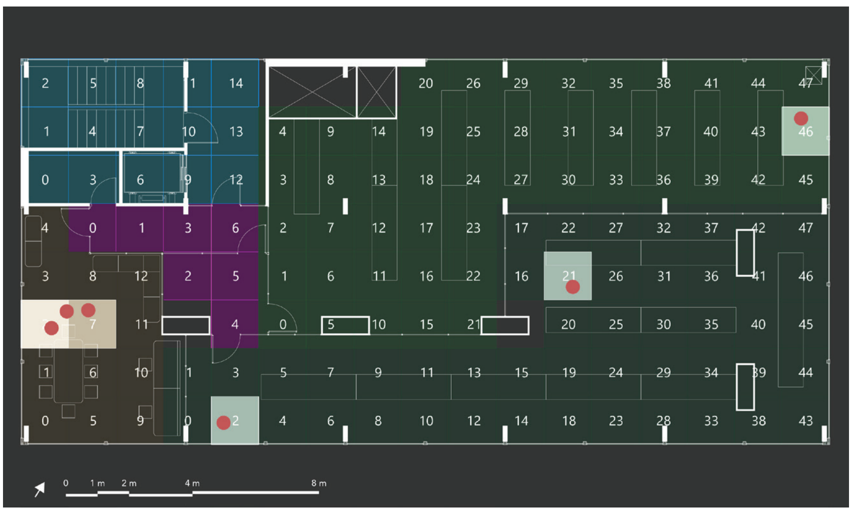


Image 33. Active cells of the second floor. Intensity of the highlight shows the higher priority.

At this point, each of the following steps provides the algorithm with additional data sets to be more intelligent and aware of its surroundings. These data can be from the exterior environment such as wind speed and direction, interior conditions like dry-bulb temperature, or the users' behavior and inputs.

On the users' side of the algorithm, the next step after the presence recognition is to separate the visitors and inhabitants. In this definition, inhabitants are those who use the building continually and have access to the building control app through their smartphones. In this way, they can provide the algorithm with additional data regarding their preferences and needs at any given time or set some presets for particular activities. The algorithm then can track their activities and prioritize their desired condition. However, a threshold of sustainability and efficiency should be respected based on the initial data sets of each subzone. These thresholds represent the limits of the algorithm's responsiveness to the users' inputs.

Moreover, it is possible to deactivate any personalization input for each subzone. In some cases, it is not necessary to personalize the level of comfort in a particular subzone. For example, while a user is in the staircase subzone, their presence and movement direction are the only critical data to perform the required actions. In the other case, some subzones have highly restricted thresholds. In the vertical farm, the algorithm's sole purpose is to measure the well-being of the plants and provide each of them with their specific requirements to grow and yield so that the thresholds might be very restricted for individual comfort. The other factor in this step is that inhabitants have a higher priority than visitors. So when a cell contains both, the algorithm only considers the inhabitant in its calculations.

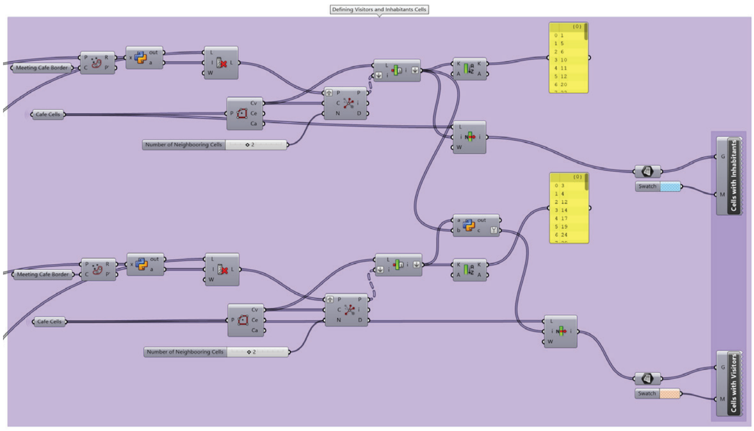


Image 34. The logic behind the separation of visitors and inhabitants in the cafeteria subzone.

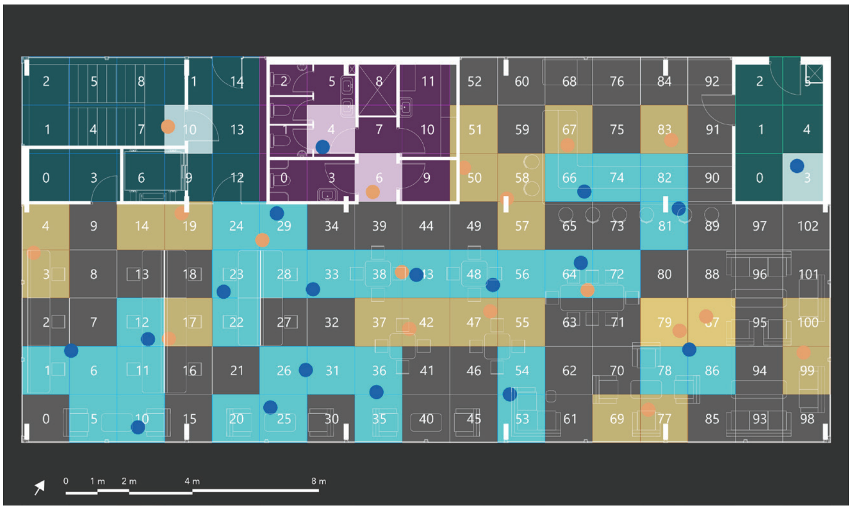


Image 35. Visitors (orange) and Inhabitants (blue) on the ground floor. At some spaces like restrooms, there is no personalization, as a result the cells are just white, meaning active cells regardless of the type of user.

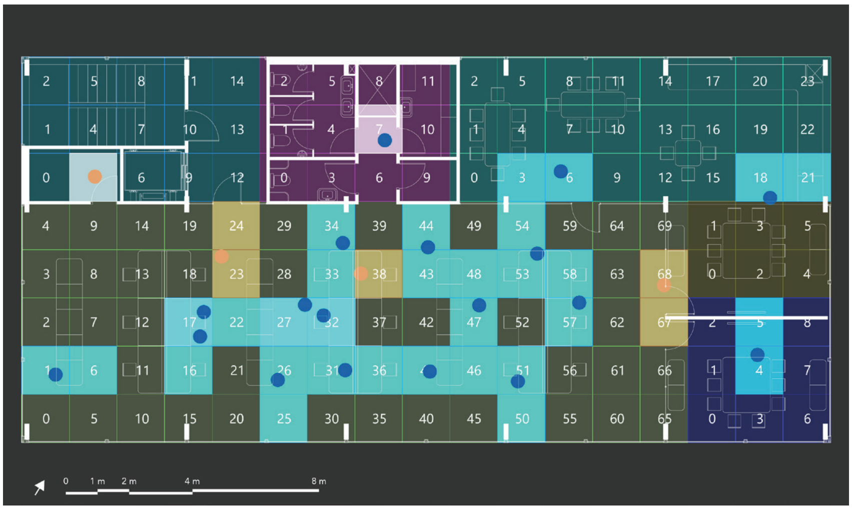


Image 36. Visitors (orange) and Inhabitants (blue) on the first floor. At some spaces like restrooms, there is no personalization, as a result the cells are just white, meaning active cells regardless of the type of user.

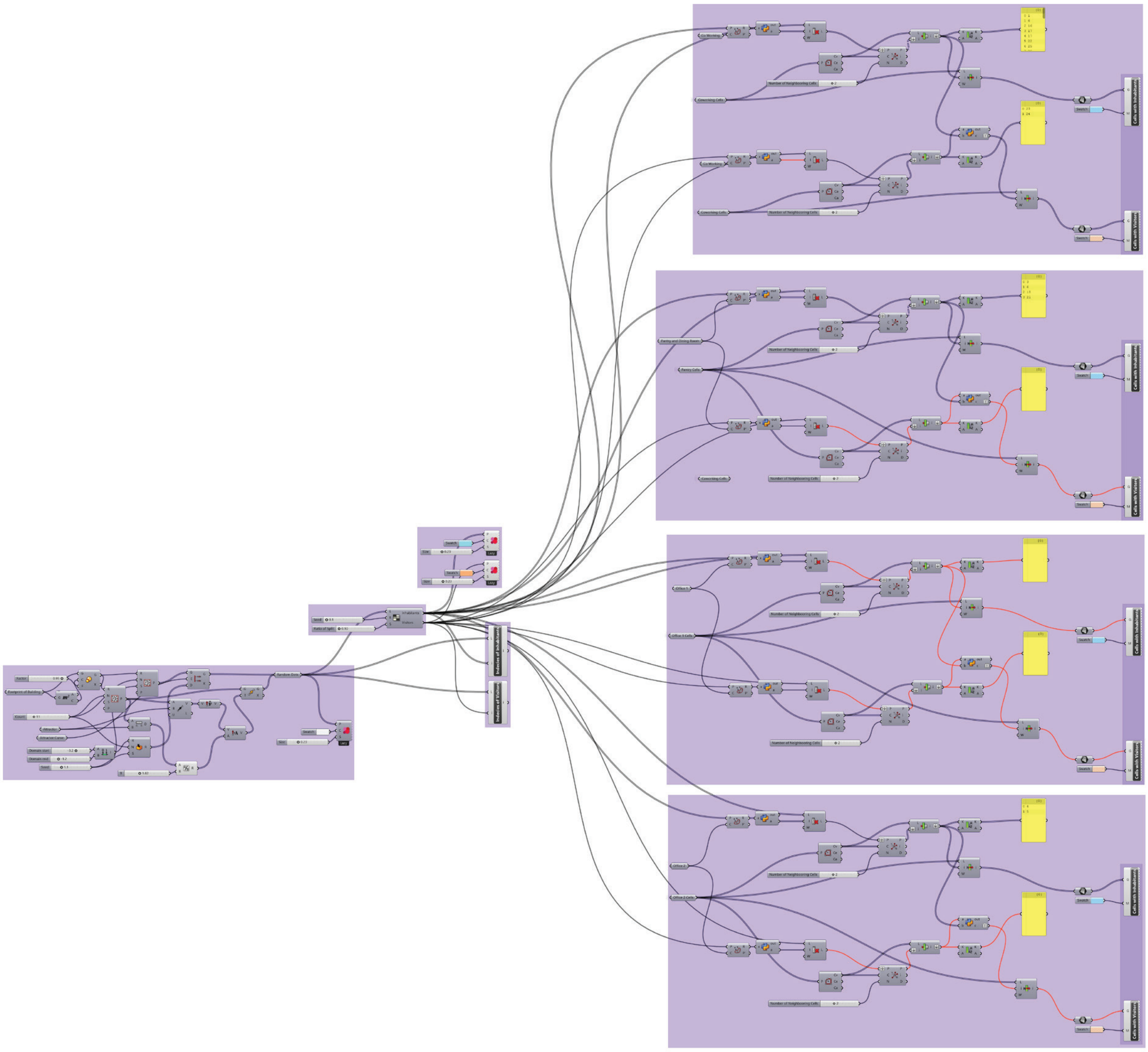


Image 37. The logic behind the separation of visitors and inhabitants on the first floor.

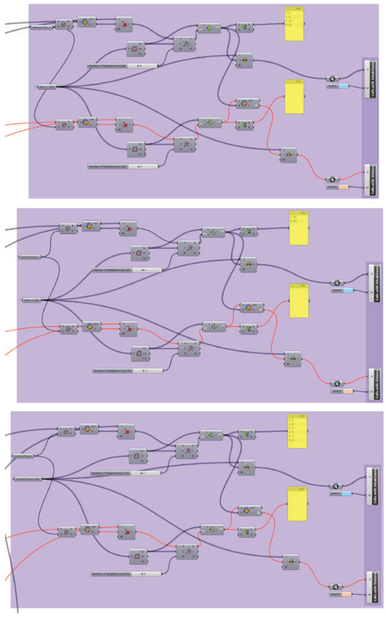


Image 38. The logic behind the separation of visitors and inhabitants on the second floor.

While the active cells receive the most engagement, many aspects of sustainability and efficiency are only feasible by considering larger groups of cells together. Thus, the inactive cells are just as important as the active ones in achieving the best efficiency while providing the users with their needs.

Regarding their status, each cell can execute a set of functions. While the active cells provide their occupying users with their required needs, the inactive ones execute other sets of programs to contribute to the overall efficiency of the building while helping their surrounding active cells in their responsibility. These sets of functions can be defined differently for each period. For example, during congested hours, the functions can be different for active and inactive cells by defining a threshold for the number of occupants in each subzone.

As mentioned, each inhabitant can provide the algorithm with their desired condition in various subzones for different periods, situations, and days. The algorithm can run more accurately and give better results by adding more inputs either from the users or the environment through sensors and actual data. One of the primary desires for most users is the demand for direct sunlight, which can range from no to maximum direct sunlight. Users can feed the algorithm with their desired amount of direct sunlight for any situation in each subzone, and the algorithm provides them with their desired condition as much as possible while considering all the other inputs and thresholds.

In this example, the algorithm is fed with a group of visitors and inhabitants in the cafeteria subzone. While the visitors do not have the chance of feeding the algorithm with their desired condition (white cells), the inhabitants are divided randomly into two clusters, those who desire direct sunlight (yellow cells) and those who do not (blue cells). Inactive cells are also highlighted in black.

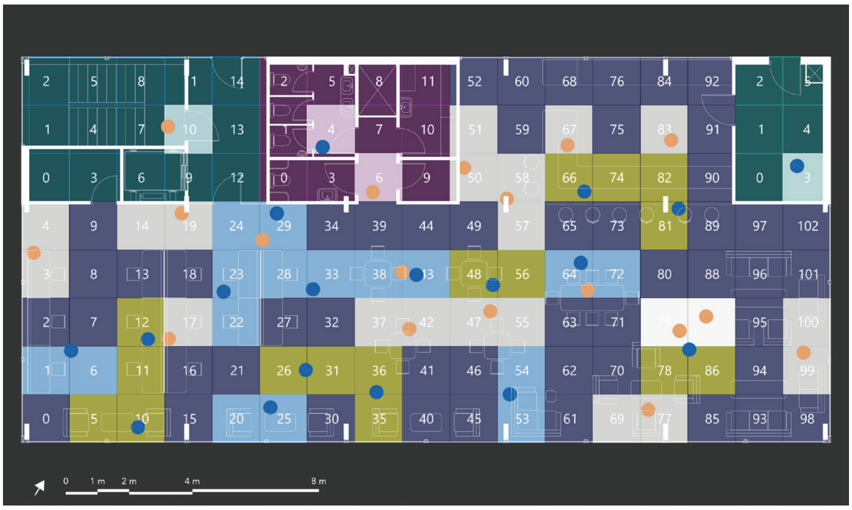


Image 39. Clusters of users based on their direct sunlight desire. Yellow cells desire direct sunligh while the blue ones do not. White cells represent the visitors and the black cells are inactive cells.

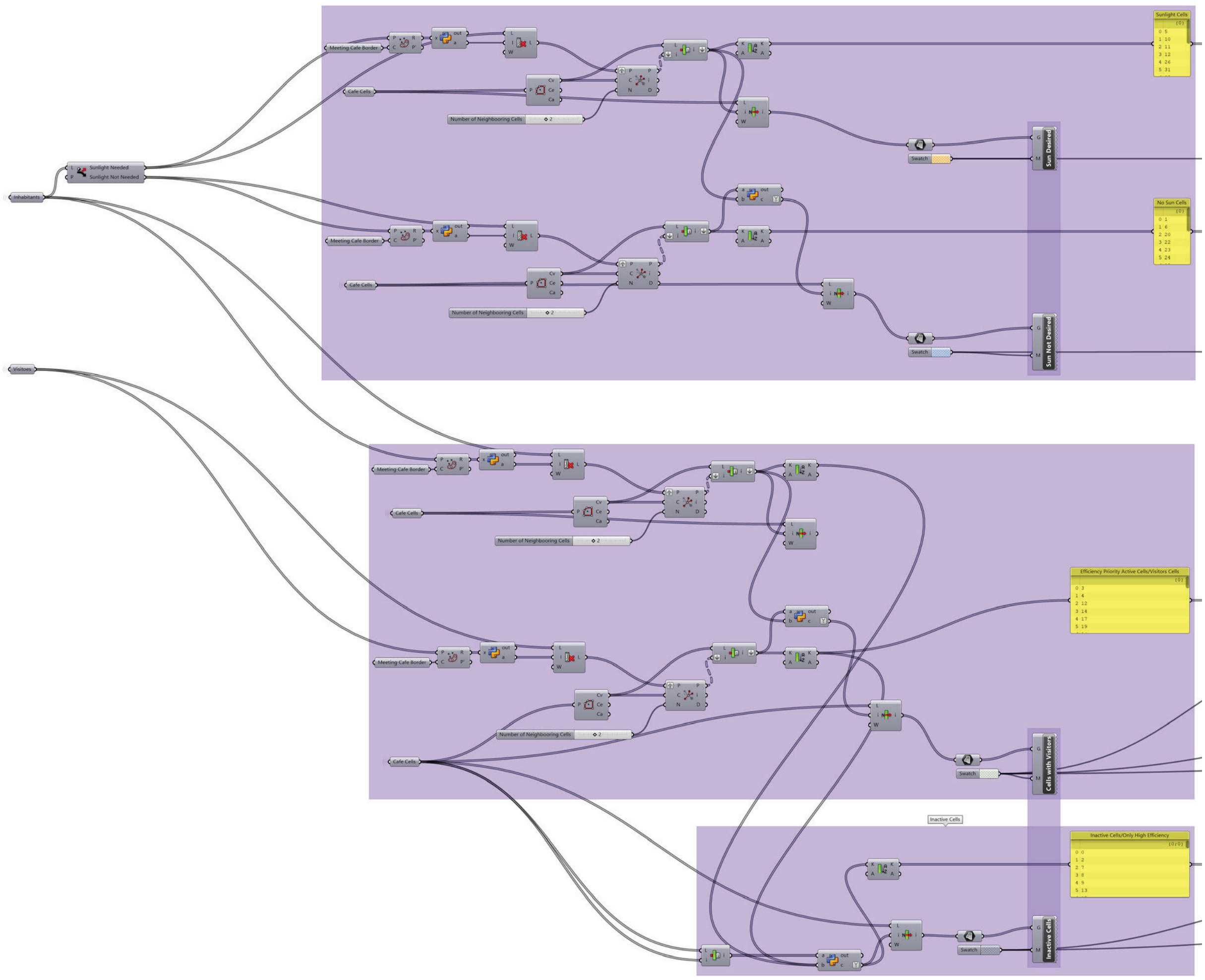


Image 40. This algorithm clusters the cells based on their direct sunlight desire. It also separates visitors cells and inactive ones.

The next step is to define a vertical grid system for each facade. Like the horizontal grid of the floors, these are also fully parametric and can be applied to different types of facades with distinct features. As mentioned in the earlier chapters, in this project, the facade is made of rectangular glass frames with an openable upper part. Each frame also utilizes a set of interior diffuser blinds and a set of exterior shades on the south and west facades. This configuration means that each frame has two separate active regions, and using the algorithm, it is possible to match the grid precisely on the building's facade. After this, it is possible to map the vertical grid on the horizontal one to find all the corresponding cells and run the proper actions.

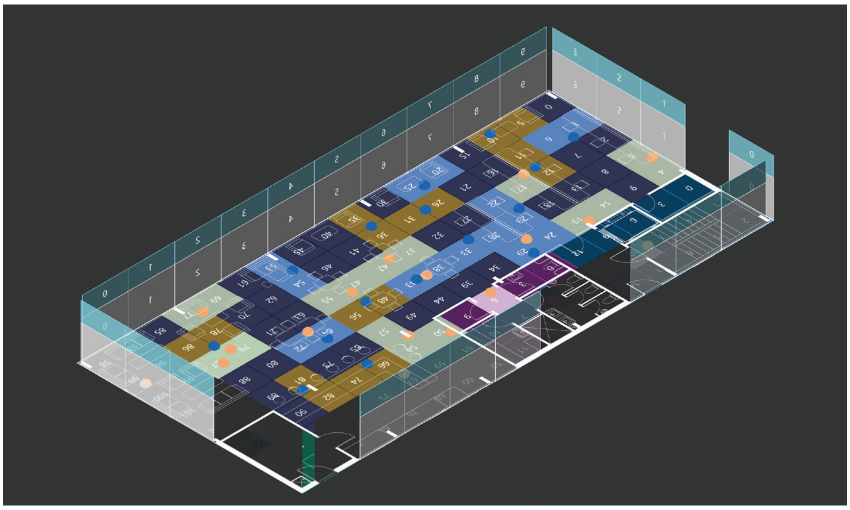


Image 41. Vertical grid systems representing the facade and its functions

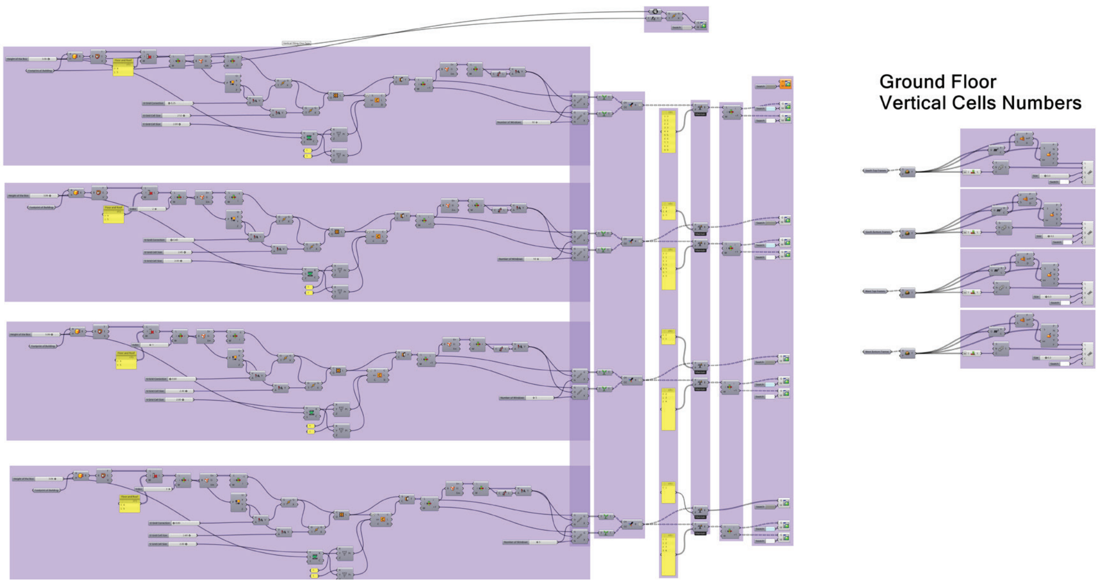


Image 42. The vertical grid system algorithm is fully intelligent and adaptive

Next, based on the actual weather data from the sensors located on the building, the algorithm is constantly fed with sets of data, in this case, the direct sunlight. The assessment of these data with other data sets from interior conditions like the dry-bulb temperature, glare, and lumen indicates how much direct sunlight is essential for the general efficiency and the comfort of the building. These outcomes are applied to each active and inactive cell, respecting other restrictions based on their subzone and type.

The algorithm is also provided with some comfort requirements from inhabitants. These requirements will affect the initial outcomes, which were based only on the efficiency and the actual weather condition. As was shown in image 39, in this step, the algorithm will consider the necessities of direct sunlight provided by inhabitants.

Using sensors and weather data, the sun's direction is available at any moment of the year. The algorithm then simplifies these data by drawing representing vectors for each sunray for all the demanded cells. As a result, when the grid system is denser, the calculation's accuracy will be higher; thus, the number of moving elements needs to increase to provide the algorithm with flexibility. Drawing sunray vectors for each cell makes it possible to group them based on their importance and necessity.

The following case shows the sun location on the first day of November at 2 p.m. and all the sun rays hitting cafeteria cells. Next, the algorithm divides each sunray based on its related cell. Inactive cells' rays are shown in black while the visitors' rays are white. These rays may be desired or undesired based on calculating the efficiency and the minimum comfort. These rays' necessity depends on the other conditions, but at the same time, the rays impacting cells with inhabitants who prefer direct sunlight and those who do not desire it have a different situation. The algorithm does its best to satisfy their desire while respecting sustainability thresholds. In the following images, blue rays are undesired and yellow ones are desired ones.

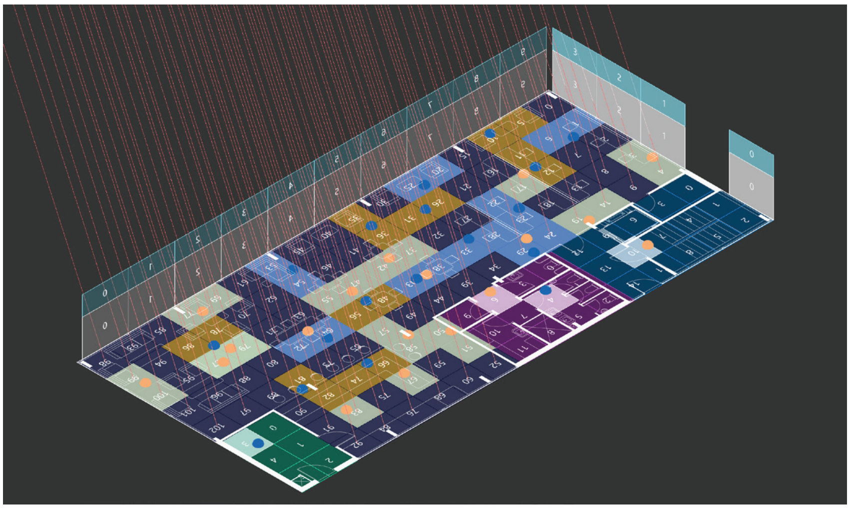


Image 43. All the rays hitting the cafeteria grid

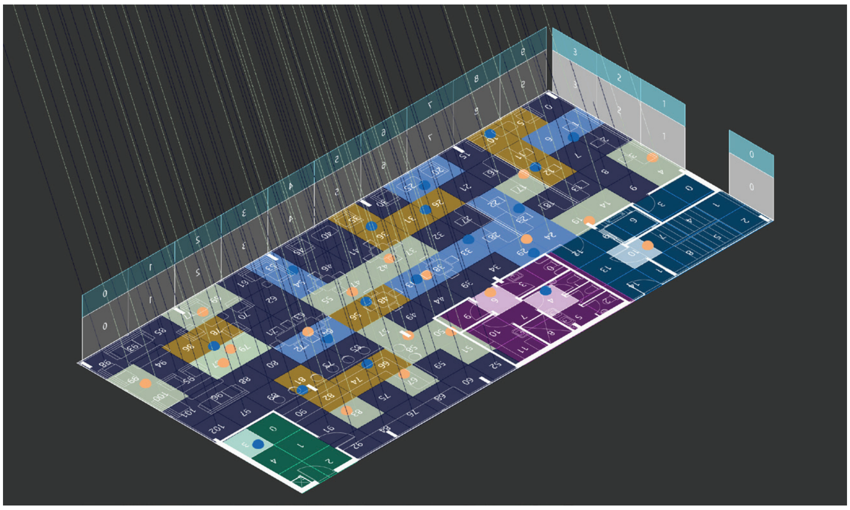


Image 44. All the rays affecting inactive cells (black) and visitors cells (white)

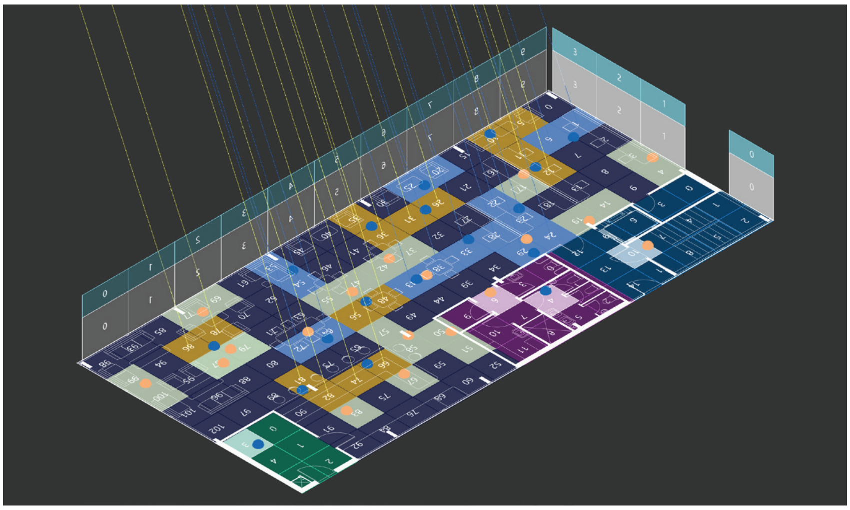


Image 45. All the desired rays (yellow) and undesired ones (blue)

Nonetheless, not all of these rays are valid. Some of them pass through walls and the roof, while external obstacles might block some. A short addition to the algorithm is required to remove these invalid rays.

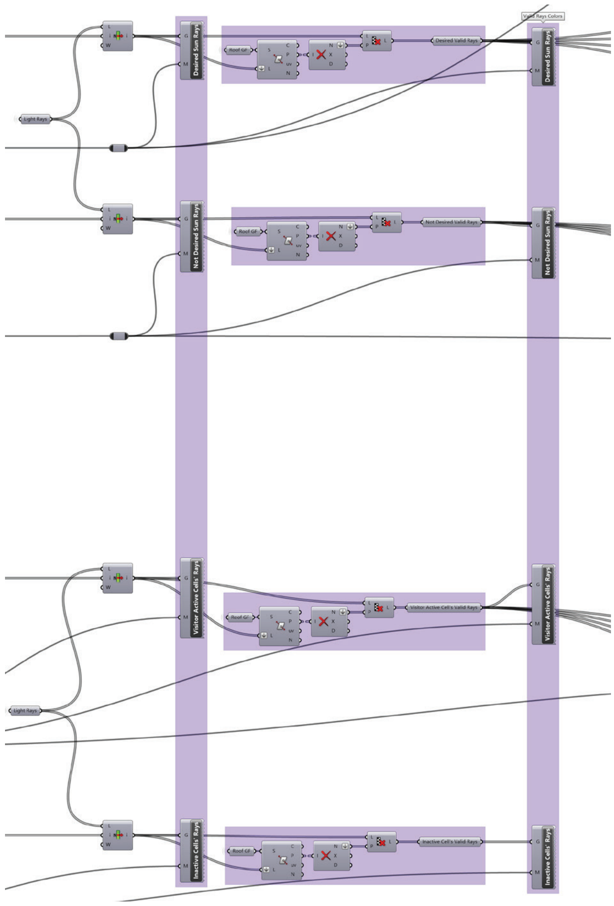


Image 46. This algorithm removes invalid rays

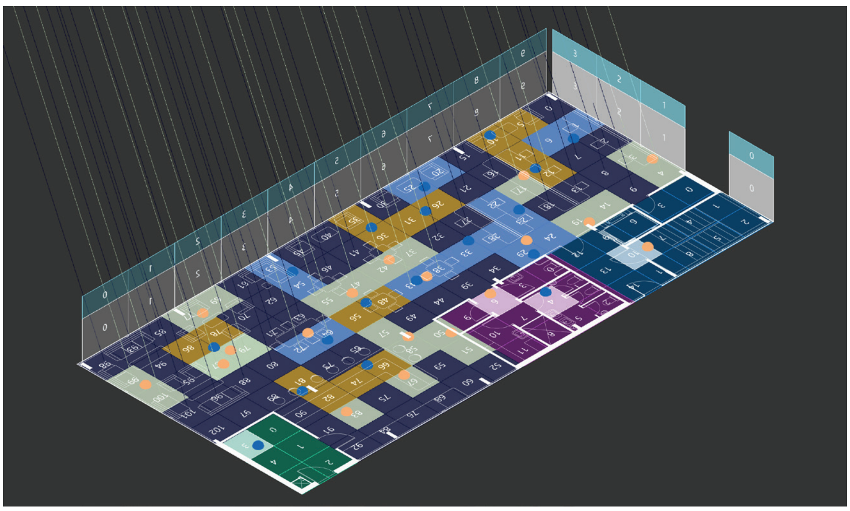


Image 47. All the valid rays affecting inactive cells (black) and visitors cells (white)

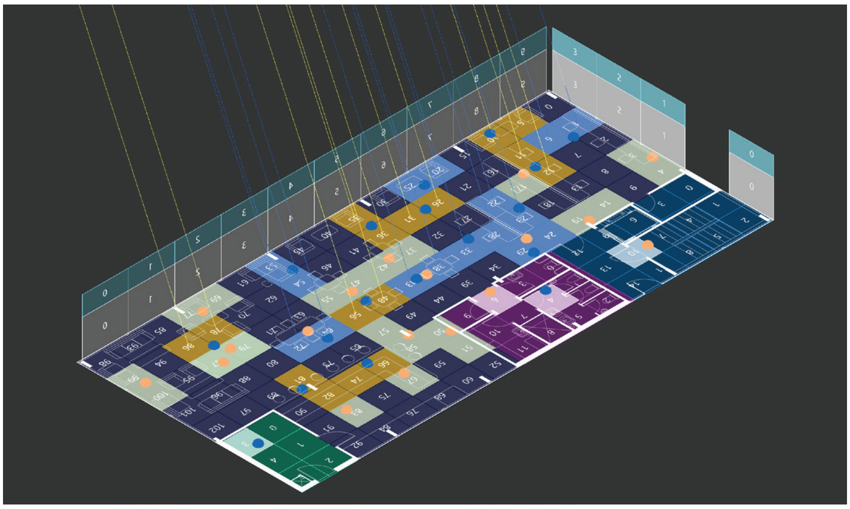


Image 48. All the valid desired rays (yellow) and undesired ones (blue)

Next, the algorithm finds the intersection of each ray with vertical grids to find the relation between the vertical and horizontal cells. Each ray already belongs to one predetermined group, and the corresponding vertical cells also proceed to that group. If rays from different groups intersect with the same vertical cell, the priority is always in favor of inhabitants, and between the inhabitants, the priority is always for the more efficient solution.

Each frame has two types of shades: exterior shades and internal diffuser. The algorithm can decide which shades should be open and closed regarding the necessities. In this case, the yellow ones are fully open as they provide direct sunlight and the blue ones have to close external shades to avoid direct sun. The white ones are those affecting the visitors' cells, and therefore their state depends on the minimum requirements of the subzone and the actual real-time condition in their respective cells. The remaining vertical cells are those affecting the inactive cells, and their functions only depend on the general efficiency of the building. If different types of openings overlap, the algorithm chooses the most efficient option.

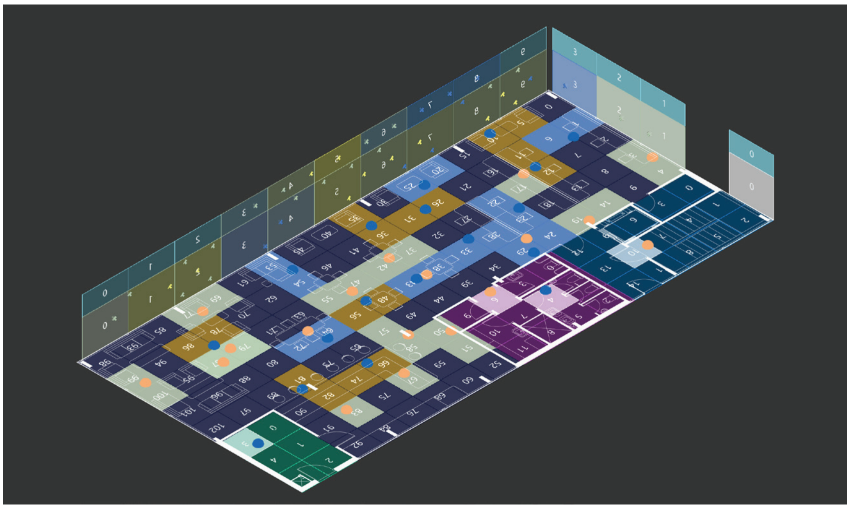


Image 49. Intersection points and vertical cells clustring based on their respective horizontal cells

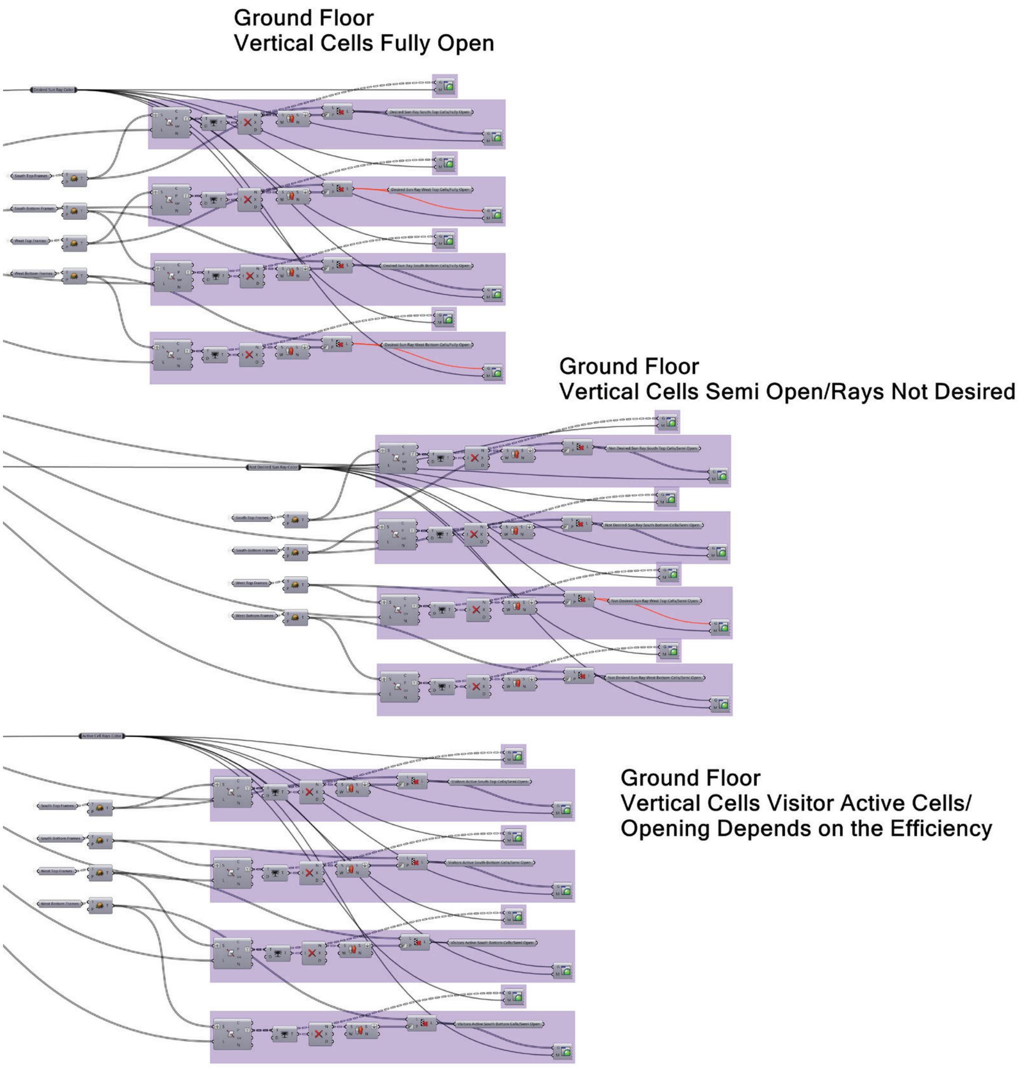


Image 50. The logic behind the finding corresponding cells of vertical and horizontal grids

From the beginning, the idea behind writing such an algorithm was to create a system that could be easily adapted for new situations and requirements. To showcase this capability, the following example, which concerns direct wind and ventilation, is laid on the principles of the previous example, and with some minor tweaks, it results in a real-time understanding of the condition and the required action. In this example, the average wind direction on the first day of August at 2 p.m. in 2021 is used, but these data are achievable from the sensors located on the building in the real-world scenario.

As before, each inhabitant can feed the algorithm with their desired condition. Here blue cells represent those who wish to receive direct wind, and the red ones are against the direct wind. The white cells represent the visitors, and the black ones are inactive cells. To calculate which openings are impacting each cell, two lines represent the border of each opening in the direction of the wind vector at that moment. These rectangles represent the direct line of the wind entering from each opening in a simplified manner. Each cell inside these rectangles is considered under the influence of that specific opening. As a result, based on the condition of cells, the algorithm can create a set of clusters for the openings.

Image 51. Dividing the cells based on their ventilation preferences. Blue cells favor the wind, and the red ones are against it. Black cells are inactive while the white ones are visitors.

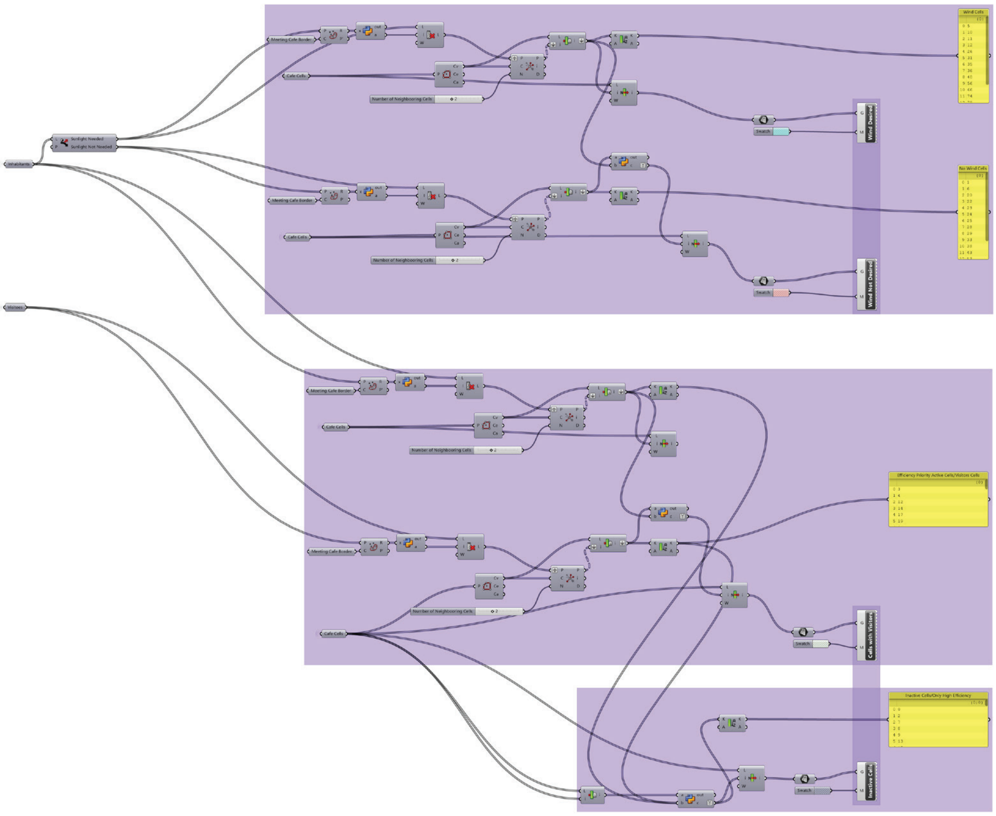


Image 52. Separating the cells based on the desire for wind

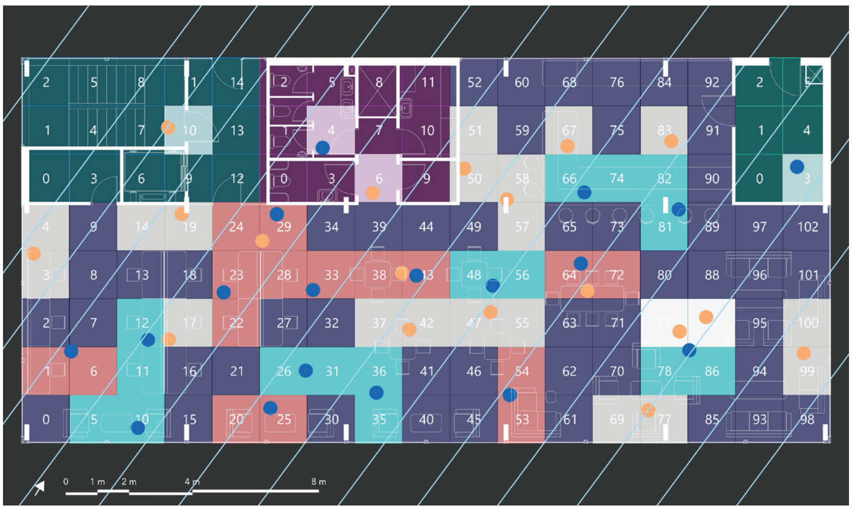


Image 53. Wind direction vectors

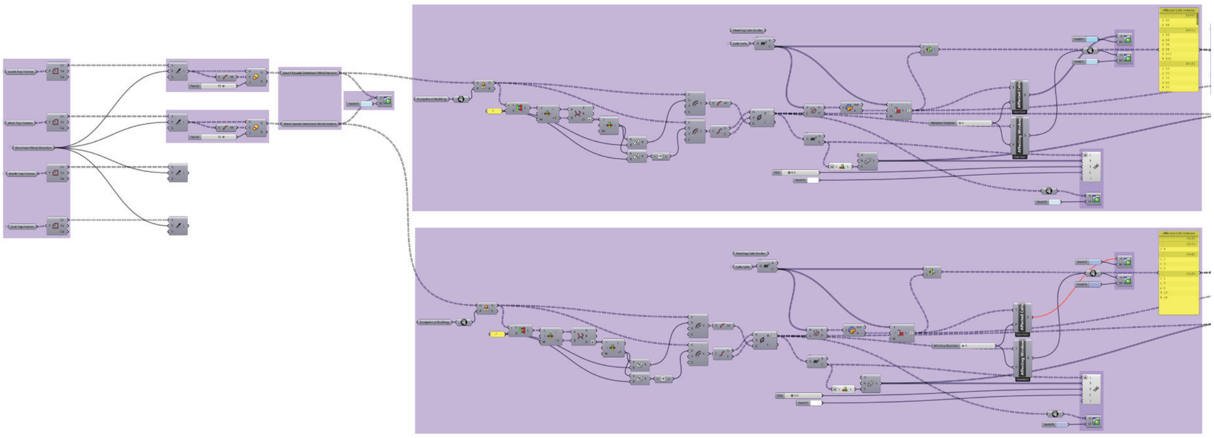


Image 54. The logic behind difining the opening's impact area based on the actual wind data

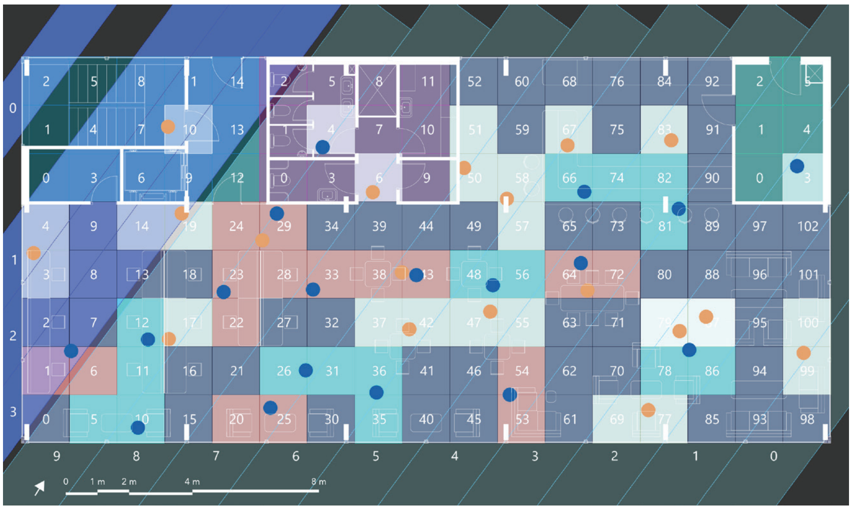


Image 55. South facade openings imapct zones in blue and the west facade's in dark blue

Each opening affects different cells from different groups. Hence, to calculate the state of each opening, the algorithm considers efficiency, sustainability, and, particularly, the dominant type of cells within each opening impact zone. This process has been accomplished by writing a python program. For example, if an opening impacts five wind preferring cells and only two cells against the direct wind, the algorithm favors the first group and then calculates the best ways to fulfill the sustainability requirements based on their need.

Image 56. South facade openings with dominant wind preferring cells. These openings should be open.

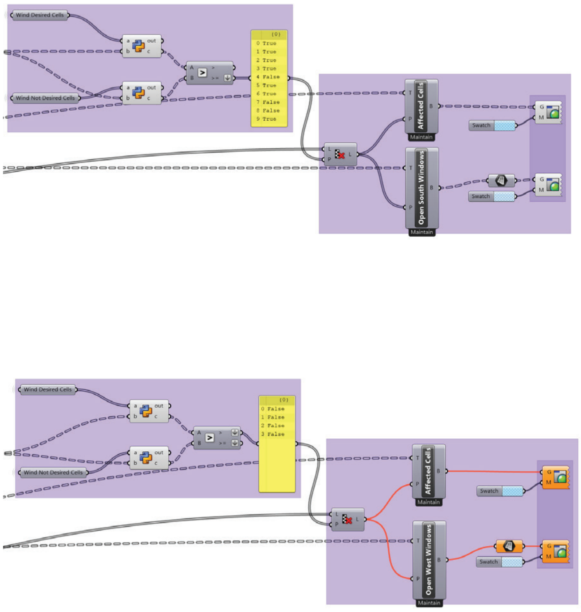


Image 57. The logic behind finding the dominant cell type for each opening using python programming

3- Future Improvments, Prediction, Optimization, and Flexibility

During these two showcases, the procedure was illustrated during one single moment. Nevertheless, this is just a simplified way to demonstrate the algorithm's feasibility and methodology. In reality, the users are constantly moving, the exterior and interior conditions are frequently changing, and each inhabitant feeds the algorithm with different demands. In this situation, it is irrational to write an algorithm that constantly changes the building's states. To address this issue, a threshold is defined, which indicates the minimum time requirement for each user to keep its existing state in order for the algorithm to include it in the calculations. However, this threshold does not affect all the algorithm's factors. To make it clear, imagine that a user is walking throughout the hallway to reach a sitting position. While the user is moving, the algorithm only computes its presence to execute the necessary actions, like turning the lights on, but it does not check for the wind, direct sunlight, temperature, or other specific requirements. When the user sits and the time threshold is passed, their needs and demands are included in the calculations.

This leads to the other important concept regarding a data-based algorithm. The fact that all the movements, activities, desires, and behaviors of the users, including visitors and inhabitants, are observed and recorded means that after a while, it is possible to use them as a data set for a machine learning procedure to find patterns in the general and individual behaviors and needs. These patterns can lead the architects to optimize the interior design to better match the real-world behaviors, but more importantly, it gives the ability to the algorithm to predict and suggest certain functions and behaviors in advance.

For example, assume an inhabitant always prefers to receive direct sunlight in the cafeteria. In this case, the algorithm suggests them with locations to sit based on the other users' preferences and conditions, so their needs are answered better while keeping the efficiency at the highest. With prediction, the algorithm can also slowly perform specific actions to make the desired condition in space before the user arrives or input the demands.

In general, this project only presents underlying ideas behind an intelligent algorithm to improve the real-time response of buildings. Such an algorithm can be improved by adding more functions and ideas, increasing its intelligence and ability to predict behavior based on machine learning techniques to propose options for users. This algorithm is based on the data, and it gets smarter as more data are fed for calculation and predictions over time. However, the overall limitation in this experiment is the lack of real-world data sets. To fully comprehend the capabilities and flaws of this algorithm, it is necessary to feed it with real-world data sets from sensors, cameras, and smartphone apps. The next step of developing this project should be applying it to real-world scenarios and recording the results carefully to understand its shortcomings and reliability in different circumstances.

4- Privacy and User's Policy

As mentioned throughout the process, the users can interact with the algorithm using their smartphones or smart screens in the building. They contribute to the better performance of the algorithm by providing more data sets for it to execute the computations more accurately. It also allows users to personalize their surroundings based on their desires and personal preferences. This personalization varies from more uncomplicated measures like the lumen intensity to more advanced measures like the sightline or direct sunlight. In the end, the algorithm can learn their behavior and suggest better solutions or act in advance to better provide them with their needs.

Despite all these advantages, some might find it against their privacy to participate in this process. In this case, they can decide how much information they want to share with the algorithm. Some might want to limit the algorithm access only to their location and basic desires, while some may not want to participate at all. In this can, the algorithm considers them as visitors and, in case of their presence, it only provides them with the minimum comfort requirements while prioritizing the efficiency all the time.

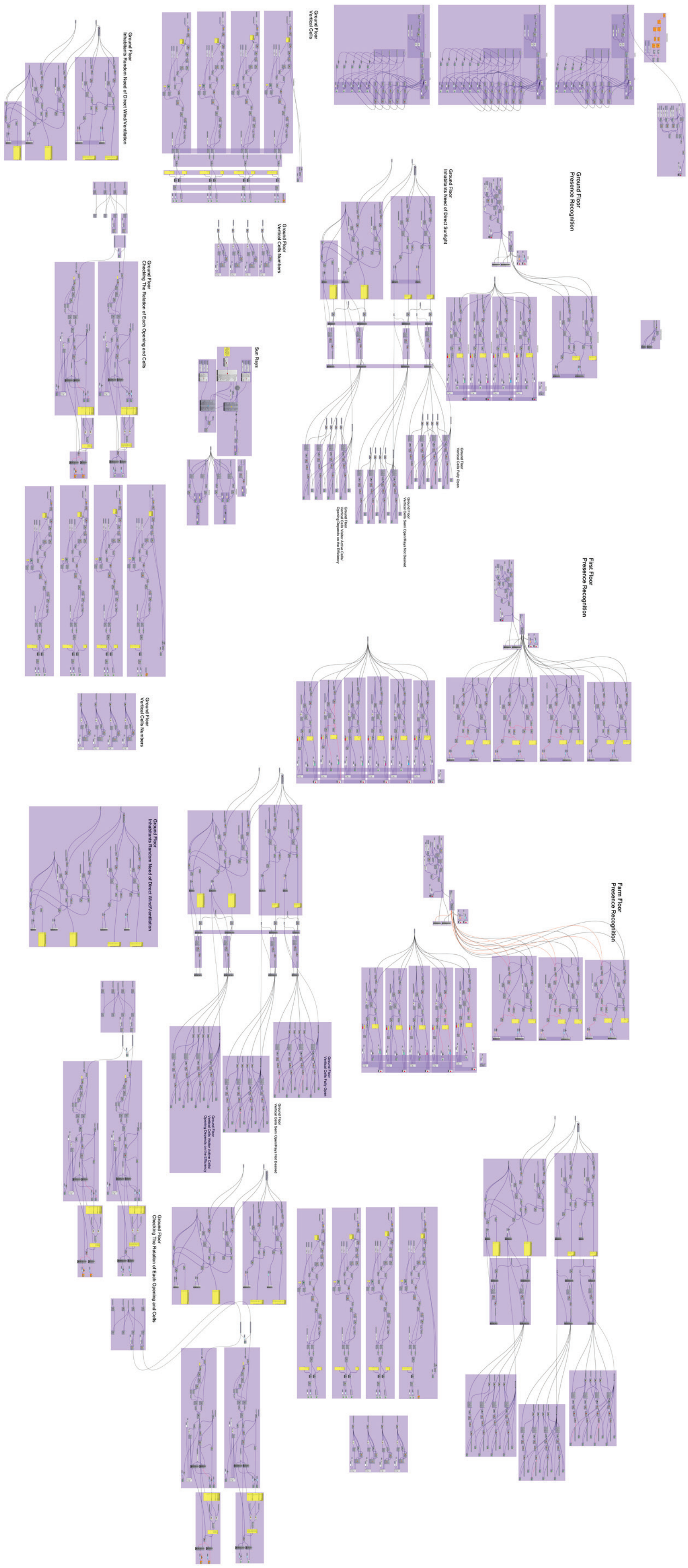


Image 58. Overall view of the algorithm, calculating all the explained factors and criteria for all three floors.

Conclusion

The number of factors affecting a building efficiency, sustainability, and performance is so numerous that it is essentially impossible to consider all of them during the design process and even if it is achievable to optimize the design with the most accurate assumptions; over the lifespan of the building, many of these factors might alter or act unpredictably. These unexpected circumstances or behaviors decrease the buildings' efficiency and shorten their lifetime. To address this issue, it is necessary to make buildings more intelligent and responsive while making sure they are designed as optimized as possible during the design process.

This project aimed to demonstrate different factors that a building should follow to be considered intelligent, from the simplicity of design and smart material choices to being disassemblable and having a circular design. However, the main focus was to propose an algorithm that can enhance the building efficiency and sustainability by making it aware of the condition and responsive to the real-time behavior of its users. As demonstrated, such an algorithm can be written in different languages or software, but the idea behind it matters. It was also illustrated that as this algorithm is fully parametric, it could be easily applied to existing buildings and increase their performance by offering a real-time management method of the resources and systems. In addition to the real-time management of the building, this algorithm can be added to improve the design of the building by introducing the pattern of the behaviors to the designers and helping them improve the design based on the needs of the users.

The only way to achieve higher sustainability in buildings is to utilize intelligent management systems, AI, and behavior prediction to minimize human errors, the negative impact of unexpected events, and the unpredicted behavior of users.

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Table of Images, Drawings and Diagrams

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