Politecnico di Milano
School of Architecture Urban Planning Construction Engineering
Polo Territoriale di Lecco

Master of Science in Building and Architectural Engineering
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Master's degree Dissertation:

Bridging Biophilia and Energy Efficiency within High-Performance Building Design

The Innovation Center at University City in Philadelphia

Supervisor: Prof. Giuliana Iannaccone

Co-supervisor: Prof: Eugenia Victoria Ellis

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BRIDGING BIOPHILIA AND ENERGY EFFICIENCY WITHIN HIGH-PERFORMANCE BUILDING DESIGN
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Master's degree Dissertation:
Co-authored by: Jose Angel Arcila Gonzalez, and Riccardo Bornati
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ABSTRACT

This project formulates the proposal of an Innovation Center building for Drexel University, inside a new complex that covers one urban block in University City, Philadelphia, United States. The development process follows a holistic approach, linking strategies for energy efficiency with principles of biophilic design aimed to promote well-being in occupants; both attributes are organized into the broader concept of high-performance building design, which is studied and shaped by objective criteria taken from different building standards and certifications. This project is organized in three stages: a first diagnostic phase where the context physical and legal conditions are analysed, considering the plans already defined by local stakeholders for the growth of the area; a second exploratory phase in which design concept, strategies and relevant standards are investigated through extensive bibliography; and a third proposal phase, covering the massing and landscape configuration of a site masterplan for the building complex at the urban block scale, while using performance analysis tools to develop the architectural layout and technical design of the Innovation Center at the building scale, and assess its results.

Keywords: High performance building, Energy efficiency, Biophilic design, Biophilia, Sustainable design, Innovation center.

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Tesi di Laurea Magistrale:
Co-autori: Jose Angel Arcila Gonzalez e Riccardo Bornati
Relatori: Giuliana Iannaccone, e Eugenia Victoria Ellis

ABSTRACT

Il lavoro proposto in questa tesi consiste nella progettazione di un Centro di Innovazione per la Drexel University, posto all'interno di un nuovo complesso di edifici che occupa un intero lotto della zona universitaria di Filadelfia, USA. Lo sviluppo ha seguito un processo olistico, che ha combinato strategie atte all'efficientamento energetico, con i principi della progettazione biofilica, creando soluzioni che migliorano il benessere degli occupanti. Entrambi i concetti sono stati organizzati seguendo le regole della progettazione di edifici ad alte prestazioni, che sono state studiate e realizzate utilizzando criteri obiettivi presi da differenti standard costruttivi e certificazioni. Questo progetto è stato suddiviso in 3 fasi: una prima diagnostica, dove le condizioni fisiche e legali del contesto sono state analizzate, considerando anche i piani per lo sviluppo dell'area già studiati dagli enti locali; una seconda esplorativa, dove i concetti di progettazione, le strategie e gli standard più rilevanti sono stati analizzati con il supporto di un'ampia bibliografia; ed una terza di progettazione dei volumi degli edifici nel lotto, con anche la configurazione di un masterplan che rispetta la scala del contesto urbano. In quest'ultima fase, utilizzando software per l'analisi delle performance degli edifici, si è inoltre sviluppato il layout architettonico ed il progetto tecnologico, con anche una valutazione dei risultati, per un solo edificio del Centro di Innovazione.

Keywords: Edificio ad alte prestazioni, Efficienza energetica, Progettazione biofilica, Biofilia, Progettazione sostenibile, Centro di innovazione.

DEDICATIONS/ ACKNOWLEDGMENTS

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Gracias a todos / Thank you all / Grazie a tutti

Jose Angel.

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INTRODUCTION

Along human history, building have constituted a way of modifying immediate context to provide protection from natural phenomena and reflect individual and societal values, and as human groups became sedentary and technology evolved, man-made indoor spaces gained a higher proportion of the "time budget" of individuals and groups, at the expense of time spent outdoors; this evolution provided increased control of the inhabited environment characteristics (dimensions, light, temperature), but also increased the influence that buildings have in shaping the physical environment, the amount of resources to keep them functioning, and the impact design decisions would have in the well-being of occupants.

By today, in developed countries people spend up to 86% of their time indoors, however, humans were hunter-gatherers for most of its evolutionary history, living in the savanna for millennia before reaching other habitats, and only very recently staying in artificially controlled spaces; so, humans evolved adapted to sensorial stimuli from natural phenomena, and have an important attachment to natural elements for psychological health and well-being, i.e. biophilia. Modern urban life presents a very different situation, where dense occupation and overlayed dynamics can expose the body to many stressors (noise, pollution, sustained glare) while separating it from relaxing stimuli (moderate breezes, sunlight, views of plants); the overall result has allowed to increase quality of life to today's high standards, but there is still an underused set of regenerative benefits that can be enhanced by biophilic design.

The increased role that buildings have as part of the human habitat, also translates to higher need for resources to ensure they provide proper conditions: buildings consume 36% of the total energy used globally, a proportion that is expected to increase due to a rapid urbanization process in developing countries. Most of the used energy is currently extracted by burning fossil fuels, which carry negative effects in the local scale as small particulate matter can produce respiratory problems at high concentrations, and have even more problematic consequences at a global scale due to the release of greenhouse gases (GHG), responsible for climate change.

Given the already increased exposure to extreme weather events and the estimated risk of long-term disruption of natural cycles human groups are dependent on, efforts are being made globally to progressively reduce the negative impact human activities have on the balance of natural processes, specially by reducing GHG emitted for energy generation and consumption. Regarding the built environment, the focus has been mainly in increasing the efficiency on the use of resources (electricity, water, heat) while keeping and improving the well-being of occupants; this approach has been broadly described as *high-performance design*, referring to an optimized behavior of a building with respect to the performance of other buildings, and the specific criteria to define it is dependent on the targets it is evaluated for, used in building standards.

Most of the efforts to create high-performance built environments are being done in cities, as the agglomeration of economic resources, development and innovation can be used for increased impact. In the United States, Philadelphia is one of the cities with the highest rate of growth on innovation and research, specially focused on life sciences and mainly driven by its strong corporative and academic sector; this has increased the demand for facilities and the involvement of educational institutions in the development of new building projects. In particular, Drexel University is already involved in the project for development of Schuylkill Yards neighborhood, inside the University City area, where major transit connections, professional talent availability and closeness to existing business districts have boosted the growth of start-ups and enterprises related to the life-sciences innovation industry.

This project proposes the design of an Innovation Center building for Drexel University to provide much needed space for the rapidly growing life-science industry of the city and works as a continuation of the already outlined guidelines for the creation of Schuylkill Yards neighborhood and the broader 30th Street Station District. Centrally, the proposal is developed according to the attributes of high-performance building design, specifically linking the underlying principles of energy efficiency and biophilic design; the hypotheses is that these two approaches can be enhanced by the interaction with one another and applied into the design of common buildings to reduce energy consumption and improve user’s well-being. The resulting objectives of the research project are the following ones:

Table 1: Project general and specific objectives

General objective	*Design* a multi-purpose building for Innovation and Research from Drexel University, in Philadelphia; focusing on the use of energy efficiency strategies and biophilic principles to guarantee high performance.
Specific objectives	1. *Analyze context* constraints and opportunities given by the current regulation, urban dynamics, climatic conditions, and expected future developments. 2. Identify objective criteria and attributes for the development of *high-performance* building design process and assessment of results. 3. Identify general *biophilic design principles* and strategies, their potential and feasibility in the project area. 4. Generate a *spatial Masterplan* for the intervention area (~20000m2), following the guidelines of the Schuylkill Yards masterplan and applying biophilic design principles to the local scale. 5. Design an *architectural project* for the Innovation Center building (up to 6000m2), a portion of the complex dedicated to education and research, using selected strategies to guarantee energy efficiency and occupant well-being.

To comply with the project objectives this document is organized in five chapters: ***a)*** *Site analysis* dedicated to objective 1, ***b)*** *Theoretical framework* where chapters 2 and 3 are explored, ***c)*** *Methodology*, where the structure and tools used are explained, ***d)*** *Site Masterplan*, covering objective 4, and ***e)*** Innovation Center Building, that goes into detail of the proposal from objective 5. Throughout the project development a holistic and horizontal approach has been taken, however both co-authors had different degrees of involvement in specialized aspects of the process.

Jose Angel Arcila Gonzalez focused on the analysis of legal context, investigation of high performance and energy efficiency criteria, masterplan massing and use allocation, design of shading elements, lighting, and solar analysis (for roof shape, PV, shadings, and peak loads optimization), sizing and selection of building services, and verification of certification.

Ricardo Bornati specialized on the climate analysis, investigation of biophilic design principles, definition of masterplan's strategic guidelines, design of open areas and green features, energy modelling (peak loads simulation and energy use analysis), design of structure, opaque and transparent envelope assemblies, internal partitions, furniture, and rendering.

CHAPTER 1: SITE ANALYSIS

Philadelphia is the largest city of Pennsylvania, and one of the most populous in the United States; it represents a major business, transit, and educational hub in the east coast of U.S. and has experienced an important growth in its business and research sector during last years, around the field of life sciences, centered on medicine and biology. This growth has been heavily supported by the presence and activities of important universities located in West Philadelphia: University of Pennsylvania and Drexel University, the latter of which is seeking to expand its operations and provide more support for life sciences research, by creating a new Innovation Center on the campus terrains, inside University City.

1.1 Urban context

The available site for the new Innovation Center building is located in the easternmost portion of University City, close to the Schuylkill River, comprising an area of approximately 21320m²; delimited by Market Street on the north, 30th Street on the east, 31st Street on the west, and Chestnut Street on the south. It is divided in two rectangular blocks by Ludlow Street, which directly connects to the main buildings of Drexel University to the west, and to a service road that runs under the elevated 30th Street in direction north-south.

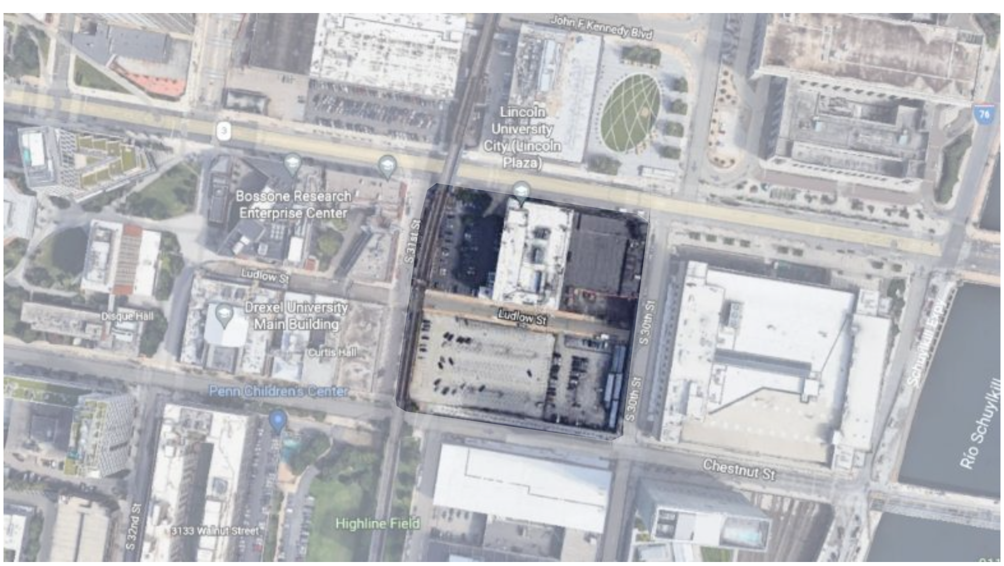


Figure 1: Satellite view of the project site (Source: Google Earth)

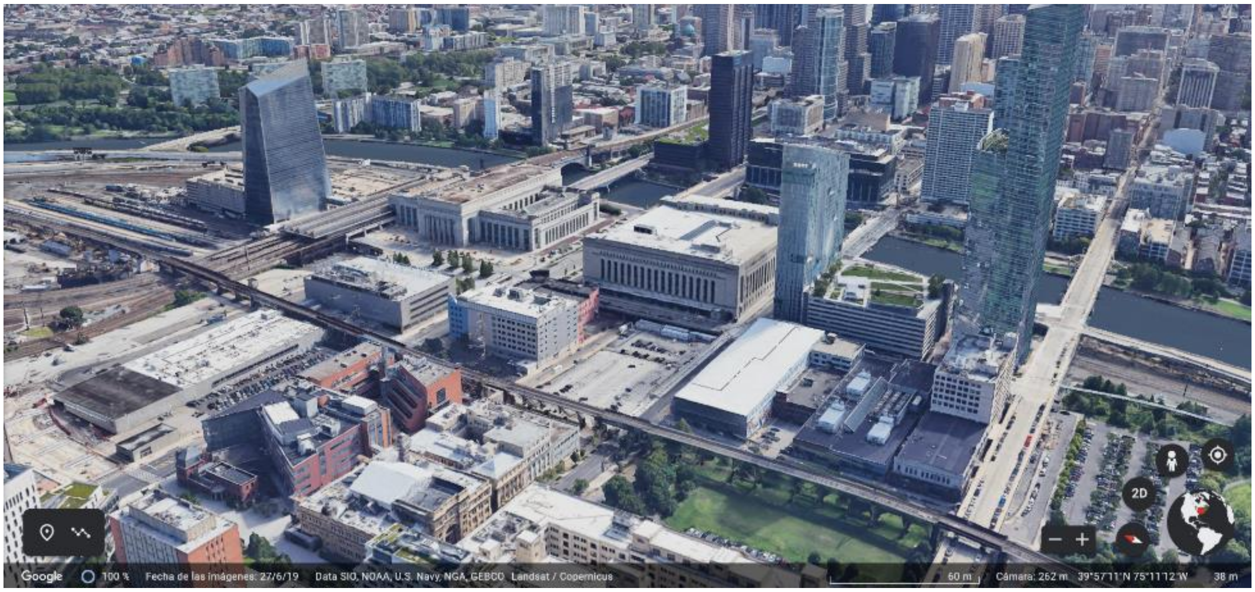


Figure 2: 3D view of project site and surroundings (Source: Google Earth)

The site is located right next to Philadelphia's 30th Street Station, an important intermodal transit hub that serves as a node of several regional rail links, like the Keystone Corridor (that extend to the west of Pennsylvania towards Pittsburgh), and the Northeast Corridor (that connects Boston and New York in the northeast with Washington D.C. in the southwest); the station also has many direct connections to the rest of the city via the subway's Market-Frankford Line, bus/tram lines, the suburban bus network, and commuter rails. Drexel and Penn University are also important attractors on the area and determine part of its demographics and development, focused on technology and innovation.

In fact, its location and characteristics have made University City a thriving participant of the Real State Market in Philadelphia on recent years, sharing with Center City business district (located across the Schuylkill river) a rhythm of office space development seven times higher than the historical average, apart from a high demand for residential units, and great potential for retail and hotel facilities (Skidmore, Owings & Merrill LLP, 2016, p. 87); such growth has been fueled in part due to the increased rate of venture capital funding and industry development on Life Sciences companies (focused in research, therapeutics and diagnostics) during the last five years (Brandywine Realty Trust, p. 4).

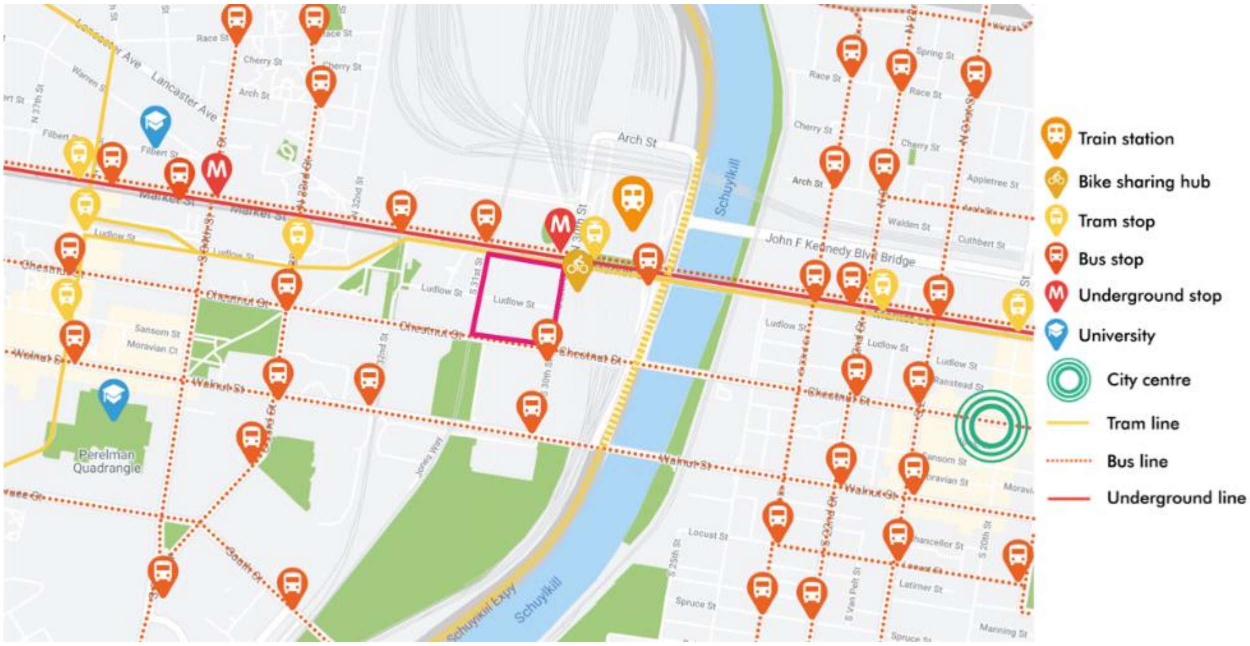


Figure 3: District transit connections and main facilities

Educational uses are the predominant ones to the west of the project site, due to the university campus facilities; however, closer to the Schuylkill river, a mixture of uses defines the urban dynamics: the train station acts as an urban services hub that activates the district, and several administrative/office buildings attract an important group of workers to the area every day, like the Internal Revenue Service (IRS) building to the east, the recently renovated One Drexel Plaza (former Bulletin Building) to the north, and the new mixed residential/office development of Cira Centre South, southeast of the project site; further south several recreational and sport facilities complete the mix of uses in the district.

Figure 4: 30th Street Station District building uses

Despite the opportunities offered in the area, more than half of the project site remains underused, hosting non-structural level-grade vehicle parking, only its northeast portion contains commercial/office 3-6 story buildings facing Market Street. However, its development potential has been recognized by several local public and private stakeholders, and the project site was included into a broader development plan that revolves around the renovation and expansion of 30th Street Station, and its consolidation as the core of a revitalized district.

Figure 5: View of the project site from its southwest corner (Google Street View, 2014)

Figure 6: View of the project site from its southeast corner (Google Street View, 2019)

Figure 7: Projected shading on project site during solstices

Philadelphia 30th Street Station District Plan

This thesis project is inscribed inside the much broader Philadelphia 30th Street Station District Plan prepared by Skidmore, Owings and Merrill, and to be developed in a joint enterprise by several of the main landowners of the area: Amtrak, Brandywine Realty Trust, Drexel University, Pennsylvania Department of Transportation, and Southeastern Pennsylvania Transportation Authority (SEPTA). The Plan mainly focuses on the retrofit and expansion of the train station and extends its influence over a broader area called Station District, a projected new diverse and vibrant neighborhood that agglutinates several communities, including the education-driven campuses of Drexel and Pennsylvania University, and the residential areas of Mantua and Powelton Village; and creating new developed areas above the train yards that give service to the train station (Skidmore, Owings & Merrill LLP, 2016, p. 86).

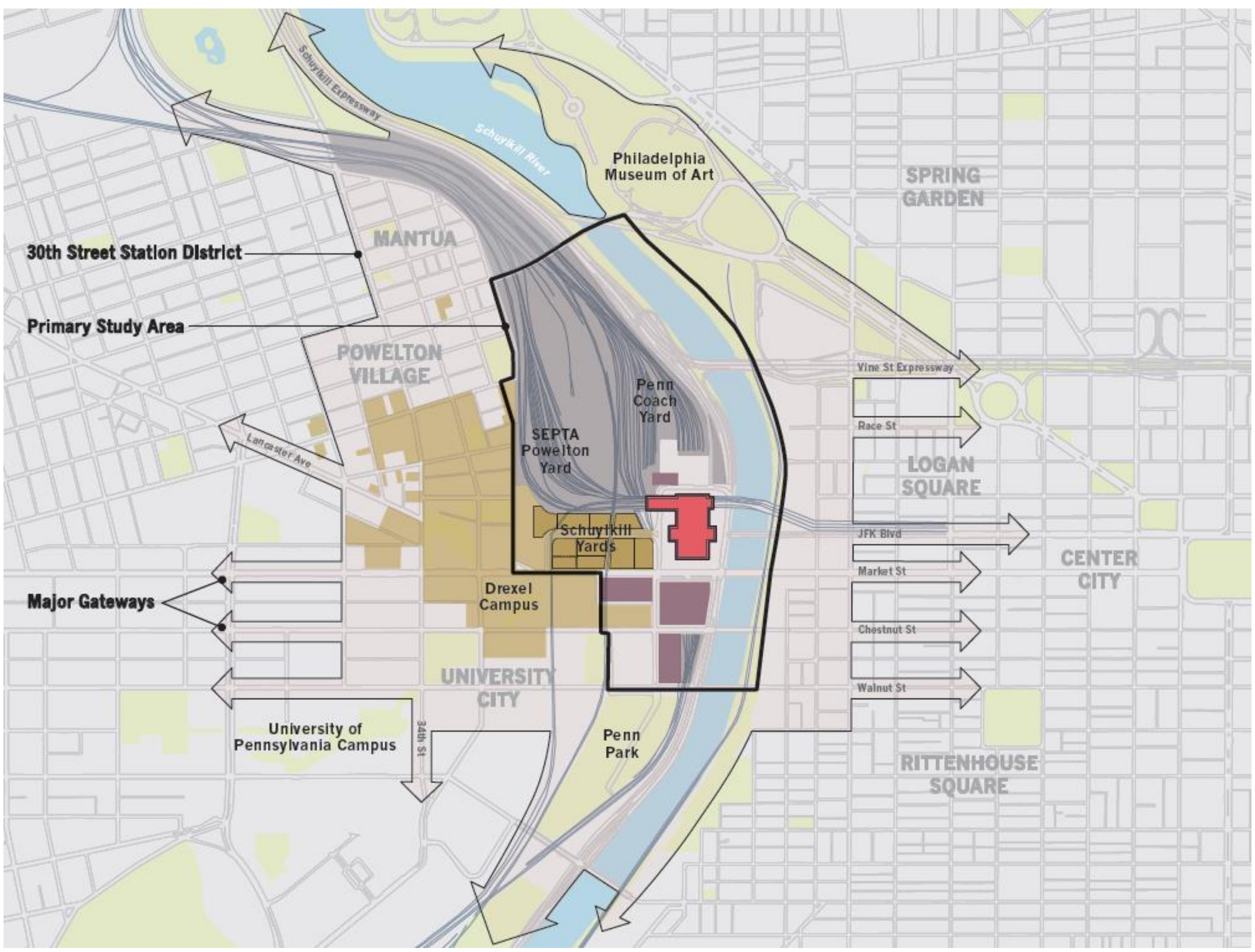


Figure 8: 30th Street Station District Plan area (Skidmore, Owings & Merrill LLP, 2016)

The District Plan targets the previously stablished sustainability goals of the City of Philadelphia, and Amtrak, further adding several specific objectives (**Error! Reference source not found.**), with some of their strategies that are applicable to the project area, which will be taken into account during the development of this project's proposals:

Table 2: Goals of the 30th Street Station District Plan (Skidmore, Owings & Merrill LLP, 2016, pp. 142-147)

Goal	**Applicable strategy**
Minimizing Energy Use and Greenhouse Gas (GHG) Emissions	Designing green buildings (LEED, Living Building Challenge, Passivhaus) High-performance landscapes
Improving Air Quality	Use of vegetation to reduce pollutant concentrations
Mitigating Noise Pollution	Use of physical barriers (berms, sound walls) along noisy transport infrastructure
Restoring Natural Habitats	Offer continuous green areas for improved animal habitats
Improving Access to Parks and Nature	Provide extensive open space networks and parks
Promoting Access to Healthy Food	Provide civic spaces for farmer markets, and small-scale agriculture
Using Sustainable Materials	Use responsibly-sourced, locally-available and low-embedded carbon materials
Managing and Treating Stormwater	Increase permeable landscape surfaces for water infiltration
Protecting from Flooding and Sea Level Rise	Control the vulnerability of constructions on 500-year floodplain areas

Among the different areas of operation, one of the cores of the district development, included in its first phase of implementation, is Schuylkill Yards, a neighborhood projected to cover seven blocks directly west of the train station, intended to bolster the already accelerated innovation pace of the city, and take advantage of its proximity to both the educational and economic centers of the city. Drexel University plays a major role in the development, as it owns parts of the land, including the southern block of the project site, together with Bradywine Realty Trust which owns the northern block (City of Philadelphia, n.d.).

Figure 9: Schuylkill Yards vision (Skidmore, Owings & Merrill LLP, 2016)

1.2 Legal and normative context

The project area is under jurisdiction of Philadelphia City, so the main set of regulations to be considered for new construction development are inscribed into the Philadelphia Code, inside Title 4: Building Construction and Occupancy Code, and Title 14: Zoning and Planning.

The site is in reality comprised by three different lots, two of them (3001, and 3020-52) are zoned as *I2: Medium Industrial*, while the remaining one (3000-18) is *CMX-5: Center City Core Commercial Mixed-Use*, changed from its original industrial status after the District Plan definition (Philadelphia Building Code, pp. § 14-402.1.c.6). Both zones are subjected to the following standard requirements expressed in Table 3: Dimensional standards applicable to project site , a particular exception is applicable to the northeast lot, as it is a CMX-5 and lies inside the Center City/University City area, so according to code §14-701.(3).(a).(2) its maximum FAR can be increased to 1600% of the lot area.

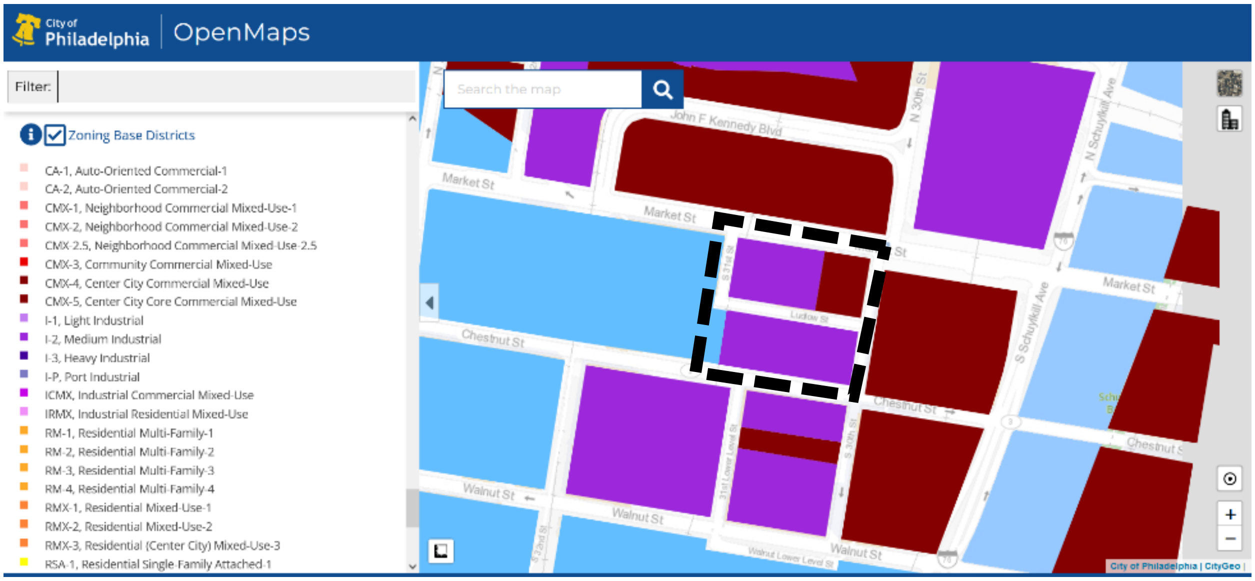


Figure 10: Zoning of the site and surroundings (City of Philadelphia, n.d.)

Table 3: Dimensional standards applicable to project site (Philadelphia Building Code)

			CMX-5	I-2	Notes
Dimensional standards	Code reference		§ 14-701.3	§ 14-701.4	
	Max. occupied area		100%	100%	
	Min. Yards	Front	0	0	
		Side	2.44m (8ft)	1.83m (6ft)	
		Rear	0	2.44m (8ft)	
	Max. height		~~-~~	-	
	Floor to Area Ratio (FAR)		~~1200%~~	500%	
	Increased FAR (§ 14-701.3.a.2)		1600%	-	Inside the boundaries of Center City/University City

Apart from zoning dimensional standards, CMX-5 lot is subjected to Bulk and Massing regulations that limit the sky coverage in the edge of the street or the lot coverage towards Market Street and 30th Street, to guarantee enough Solar Access to the buildings. These regulations are expressed together with parking requirements in Table 4.

Table 4: Bulk and Massing controls applicable to project site (Philadelphia Building Code)

			CMX-5	I-2	Notes
Bulk and massing controls (§ 14-701.5)	Sky Plane Standards		Setbacks above 38m (125ft)		Towards Market Street
	Max. lot coverage by height	<19.8m	100%		Towards 30^{th} Street
		<91.4m	75%		
		<152.4m	50%		
Parking requirements (§14-802.3 and (§14-802.4)	Min. Parking	Retail	0	1lot/1000sq.ft. ($93m^2$)	First $232m^2$ excluded
		Office			
		Assembly	1lot / 10 seats*		First $371m^2$ excluded
	Preferential parking		≥ 5% for carpool, hybrid/alternative fuel vehicles		If total parking lots > 30
	Bicycle parking		1 bicycle parking space can replace 1 carparking lot		Up to 10% of the total required by code

Regarding risk mitigation policies, the Federal Emergency Management Agency (FEMA) indicates that around one third of the site is on a 500 year floodplain, due to its proximity to the Schuylkill river; more importantly a Special Flood Hazard Area, delimited by the Base Flood Elevation (BFE), reaches the edge of the site, in which case the Code requires a minimum extra-elevation of 457mm above BFE for all habitable or non-structurally flood-proofed spaces. (Philadelphia Building Code, pp. B-1612.2.1)

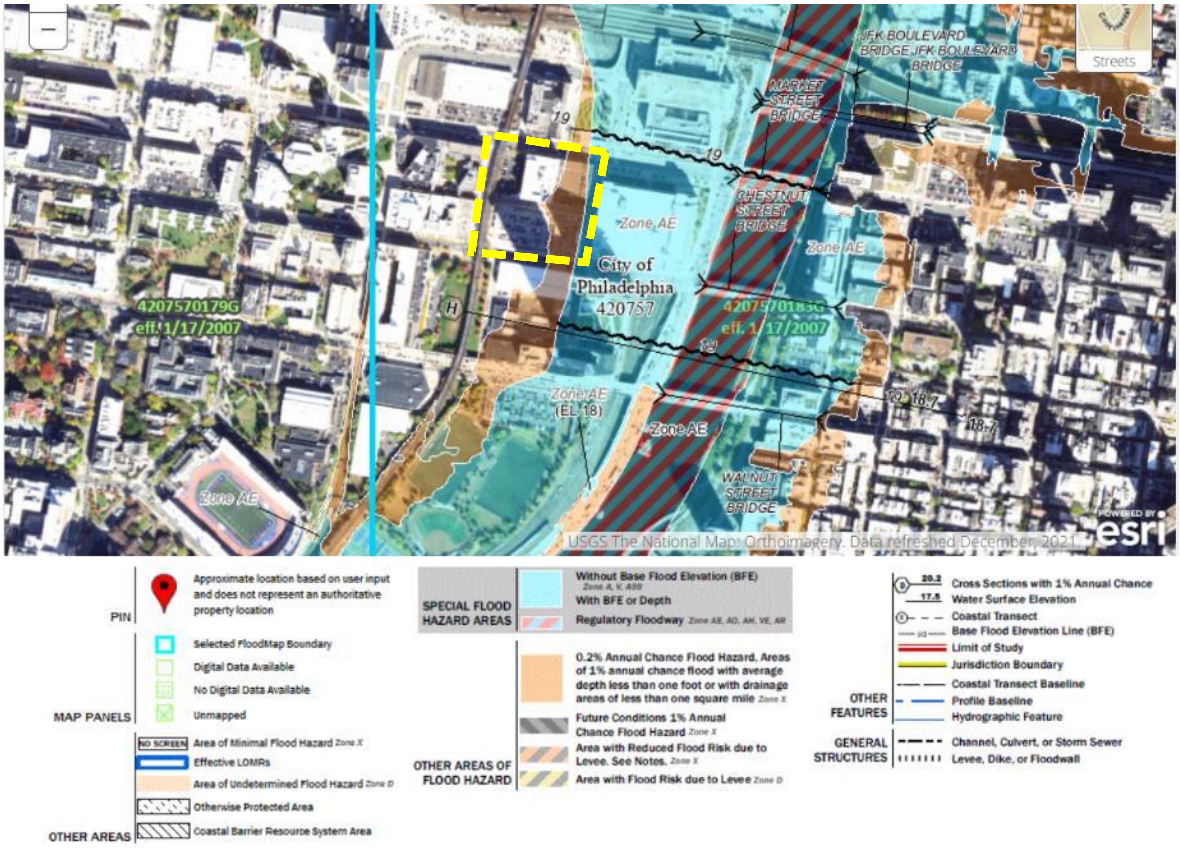


Figure 11:Flood Hazard Map around project site (Federal Emergency Management Agency, 2021)

Besides local regulations, the Philadelphia Building Codes adopts as mandatory complying with the requirements for energy efficiency contained in the International Energy Conservation Code (IECC), which establishes performance prescriptions for building components and configuration, based on the project's location; in this case in a Climate Zone *4A: Mixed Humid*; additional information regarding climate is presented in the next subchapter.

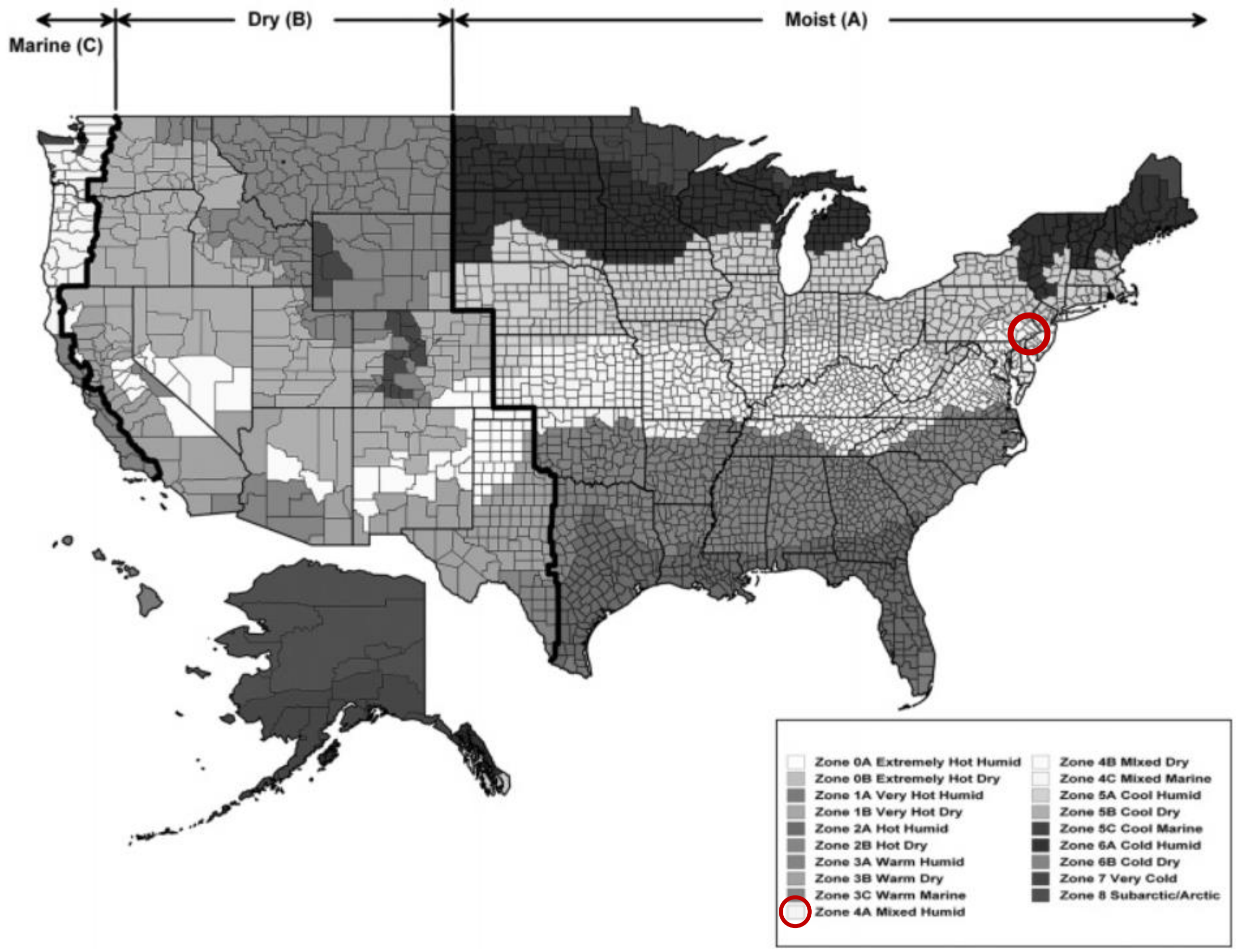


Figure 12: U.S Climate Zones map (International Code Council, 2021, p. C301.1)

1.3 Climate analysis

To evaluate the climatic conditions of the site, weather data was extracted from EnergyPlus database, corresponding to Station 724080, located in the Philadelphia International Airport, 10km southwest of the site; TMY3 dataset was chosen for the analysis, as it is the most recent dataset based on the period between 1976 and 2005.

Philadelphia is included inside *Cfa* category of the Köppen-Geiger climate classification system, featuring a four-season *moist subtropical mid-latitude climate, wet year-round with hot summers* (National Weather Service). July is the hottest month with a mean dry bulb temperature of 25.33

°C and a maximum of 36.70 °C, heat waves with high humidity levels are relatively frequent. Conversely, January is the coldest month, with an average mean temperature of -1.59 °C and a minimum of -13.9 °C, with a window for freezing temperatures between November and April.

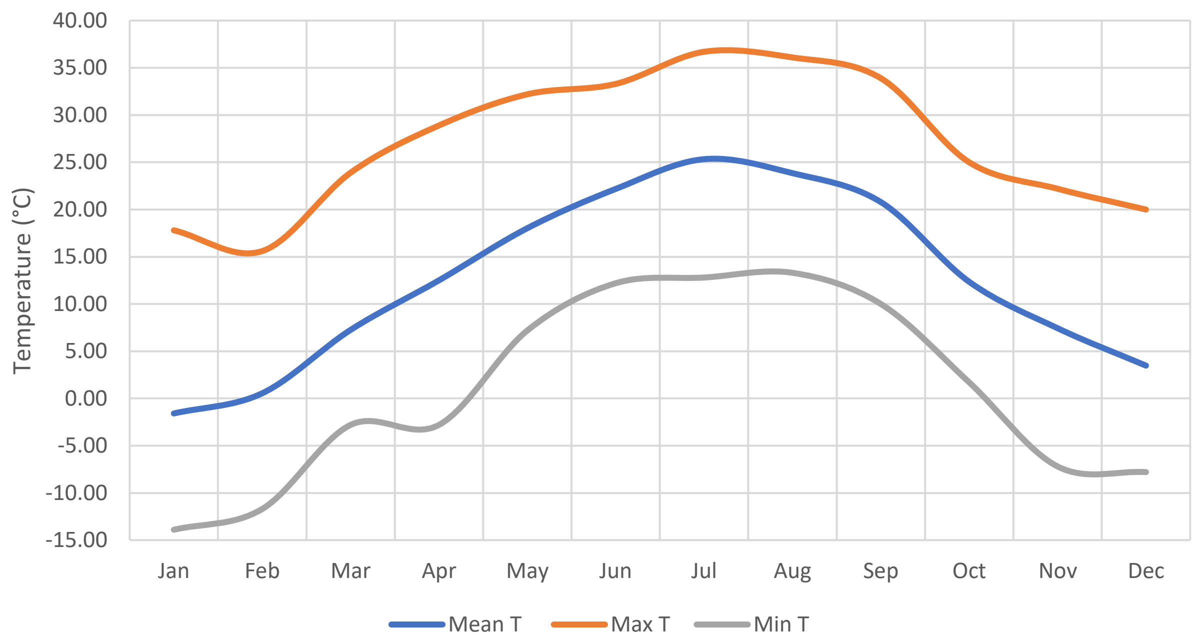


Figure 13: Monthly mean, maximum and minimum dry-bulb temperature in Philadelphia (EnergyPlus)

Sky coverage varies greatly around the year, with a mean value between 50.71% and 71.25% in March. Precipitation is relatively frequent, with a range between 3.06mm of rainfall in February and 5.54mm in June. Snowfall is greatly variable throughout the years, ranging from years with minimal snowfall and no sustained snow cover to occasional heavy snowstorms; the seasonal average is 57cm.

Recorded wind speeds have reached 18m/s in November, but the mean values range between 3.5 and 5 m/s throughout the year, generally higher when closer to midday across the whole year, in a consistent pattern with the variation of temperature (Figure 14).

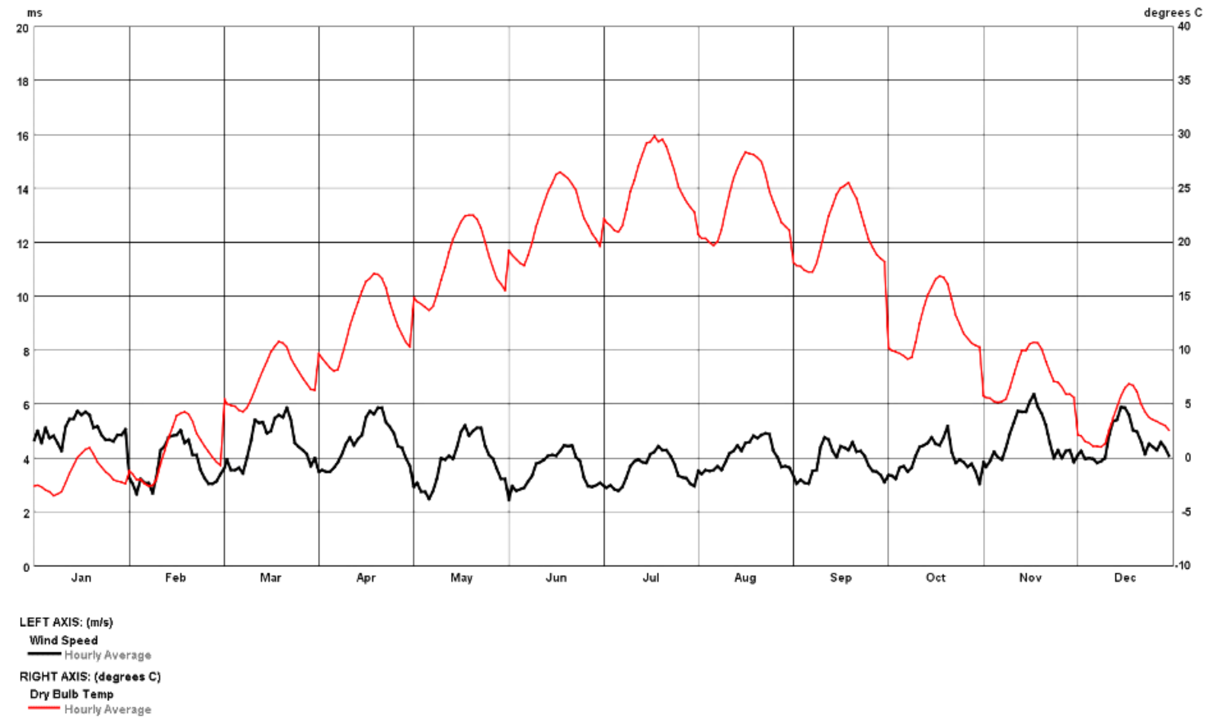


Figure 14: Mean hourly temperature and wind speed variation in Philadelphia (EnergyPlus)

Air quality in Philadelphia has been progressively increasing in recent years: short term particle pollution (average number of days with high $PM^{2}_{.5}$ concentration) is at safe levels (between "good" and "moderate") during most of the year; while long term particle pollution (annual average $PM^{2}_{.5}$ concentration) has remained under the safe threshold of 12 µg/m3 since 2011. High ozone levels can be found at an average of 6.8 days per year, a figure that is higher than the acceptable threshold (3.8 days/year) but has been in progressive reduction in recent years (American Lung Association, 2022).

The analyzed data shows climatic conditions that require mechanical air conditioning during winter and summer season, but with a great potential for natural ventilation during mid-season due to air temperatures inside comfort range, generally low pollution levels and wind patterns that make cross-ventilation possible during working hours. The likelihood of eventual freezing temperatures and heat waves at some points of the year, might be tackled by provisioning semi-public internal spaces able to provide shelter in case of extreme weather events; landscaping features, like water bodies and trees canopy could also be beneficial.

Finally, the frequent precipitation pattern throughout the year provides a steady source of rainwater able to be harvested, collected, and used to satisfy part of the water demand of the buildings and irrigation systems, without the need for big storage facilities to cope with the time offset between supply and demand.

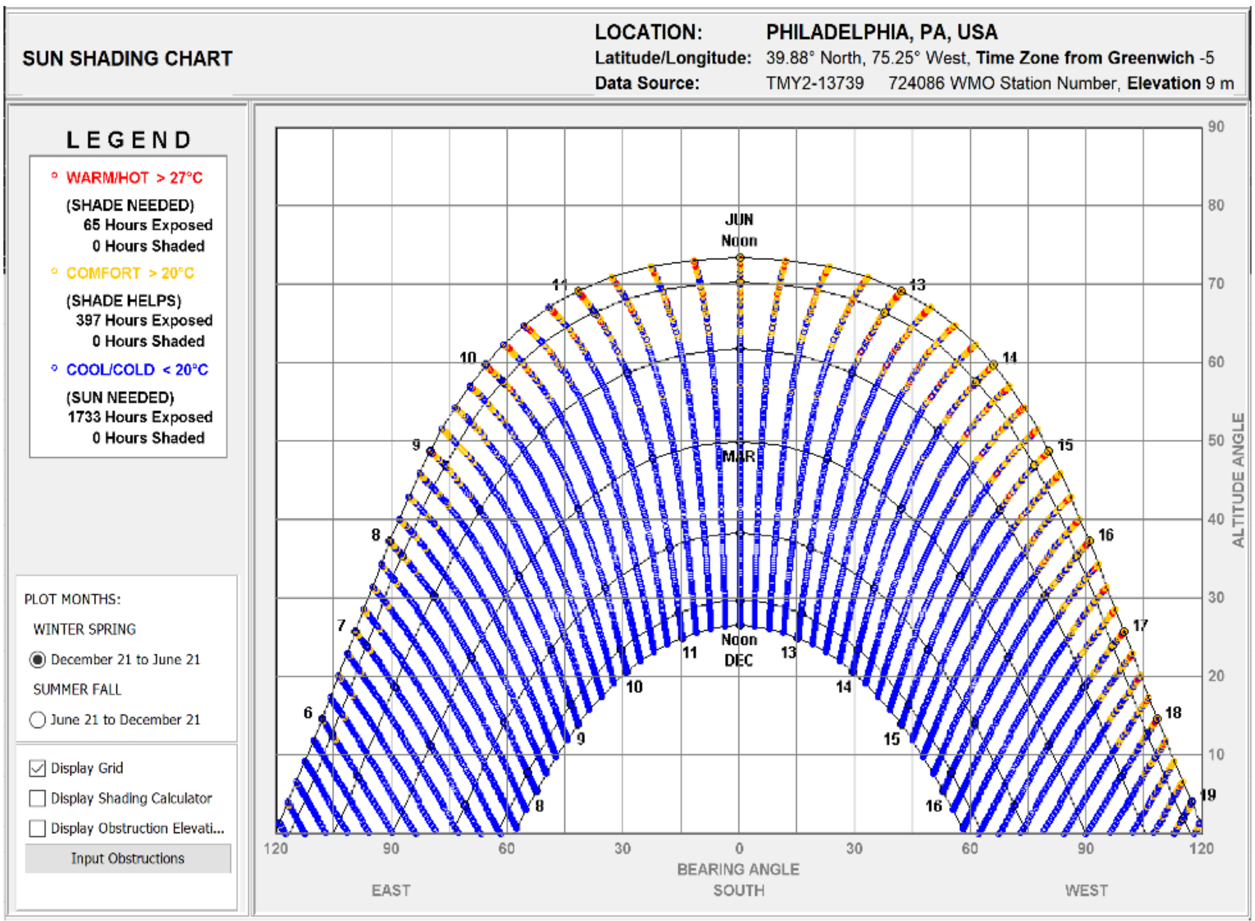


Figure 15: Sun shading chart from winter to summer solstice (Climate consultant 6.0, EnergyPlus)

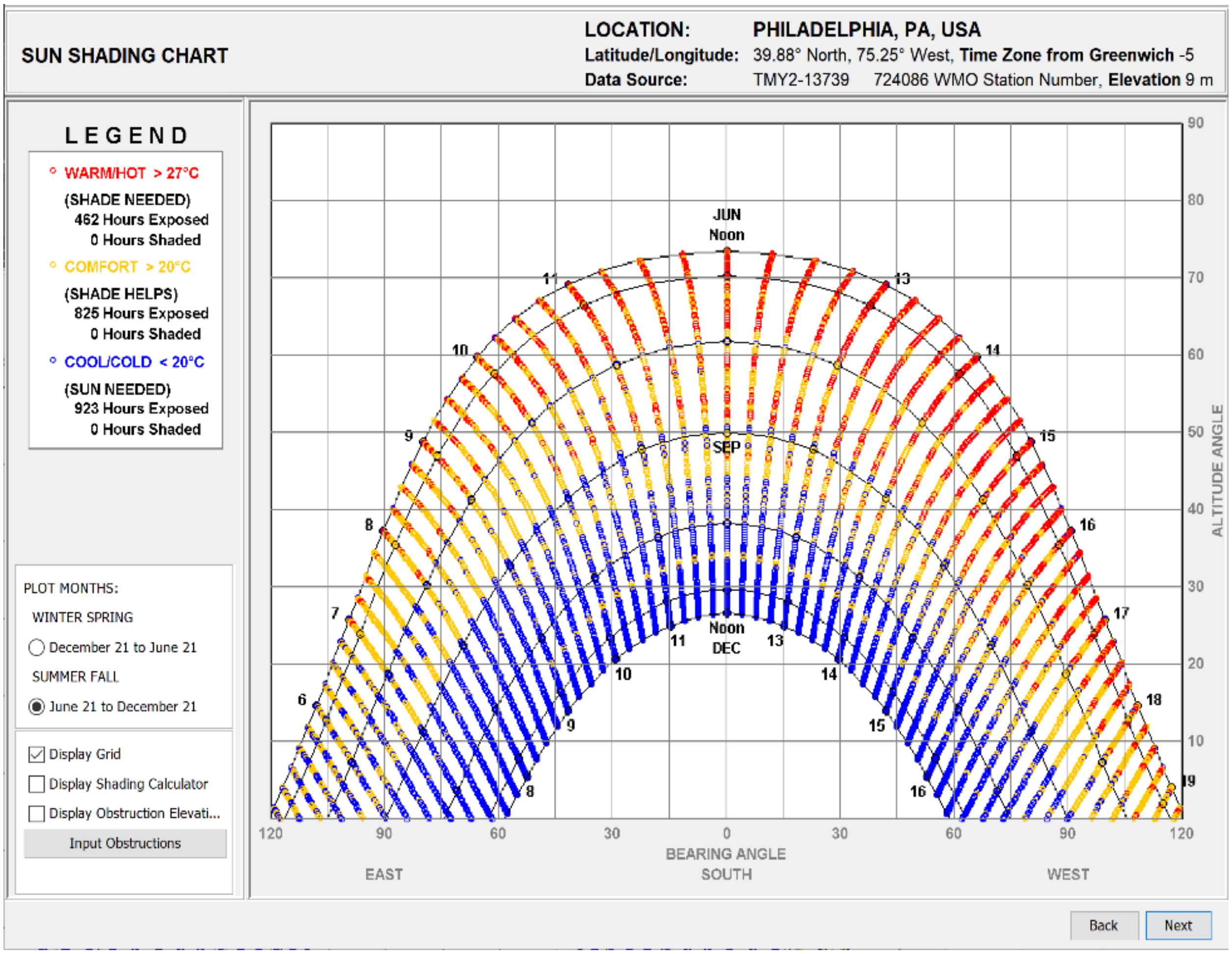


Figure 16: Sun shading chart from summer to winter solstice (Climate consultant 6.0, EnergyPlus)

CHAPTER 2: THEORETICAL FRAMEWORK

This project is inscribed into the broader notion of high performance, and specifically targets energy efficiency and biophilic design as guiding principles in the process of design. This chapter sets the theoretical basis and explains the definitions and relationships between the main concepts investigated during the analysis and design of the project.

2.1 High performance

In its broadest definition, the word *performance* is described as "the ability to perform… the manner in which a mechanism performs" (Merriam-Webster Dictionary, 2022) or more specifically as "how well a person, machine, etc. does a piece of work or an activity" (Cambridge Dictionary, 2022), so for the purposes of this research project, it can be understood as the degree at which an entity (in this case, a built environment component) is able to carry out its intended task; a *high performance*, then, refers to the capacity to perform at a higher standard and deliver better results for an intended task.

In a narrower spectrum, particularly related to buildings, high performance refers to the capacity to provide safety, comfort and especially, energy efficiency; in fact, the definition of high performance building is described in the U.S. Code, as part of the Building Standards section of the Energy Policy Act (2005) as "…a building that integrates and optimizes all major high-performance building attributes, including energy efficiency, durability, life-cycle performance, and occupant productivity" (U.S. Code, Chapter 149- National Energy Policy and Programs, p. §16194) . So, high performance in buildings can be taken as a rather broader umbrella term that covers a variety of attributes, in particular concerning energy efficiency and user well-being.

2.1.1 High-performance building standards

It is possible to notice that all previous definitions refer to high performance as determined by a particularly enhanced capacity to produce expected results, which implies a) relative improvement with respect to a previous state or base case, and b) a set of expected results or conditions to be fulfilled by the building; both conditions are variable, constantly evolving and dependent on technological and economic capabilities, societal expectations, and political priorities. As a result, different standards are used nowadays, each one working from a different approach and covering separate topics and/or regions:

2.1.1.1 Passivhaus

Passivhaus, or passive house, is a concept and a standard for construction of energy efficient buildings developed in Germany in 1988, and used as certification since 1991; it aims to drastically reduce the energy consumption of buildings by restricting unwanted heat transfer between interior and exterior, maximize the use of free heat from internal sources and regulate the exposure to direct sunlight through the use of shadings to promote solar heat gains in winter and avoid them in summer. It is based in five main principles (Passive House Institute, 2015):

A) *Thermal insulation of opaque components*: Envelope walls, roof and slabs must have a maximum heat transfer coefficient (u-value) of 0.15 W/(m²K), achieved by thick layers of insulation. to minimize conduction heat gains and losses

B) *Passive House windows:* Heat transfer coefficients of window assemblies must be lower than 0.80 W/(m²K), usually fitting very well insulated framing, low emissivity glass, and argon/krypton filled cavities; also, the solar heat gain coefficient (SHGC) must be around 0.5

C) *Ventilation heat recovery:* Ventilation air that enters or exit the house must flow through a heat exchanger that ensures a minimum of 75% of heat from exhaust air to be transferred to the fresh air, avoiding thermal losses.

D) Airtightness: Leakage through envelope gaps must be lower than 60% of the total house volume per hour, when subjected to a pressure test with the interior at 50 Pascal above and under external pressure levels.

E) *Absence of thermal bridges:* Ensuring that all edges and connections between envelope elements are well designed and constructed to minimize point heat gains or losses.

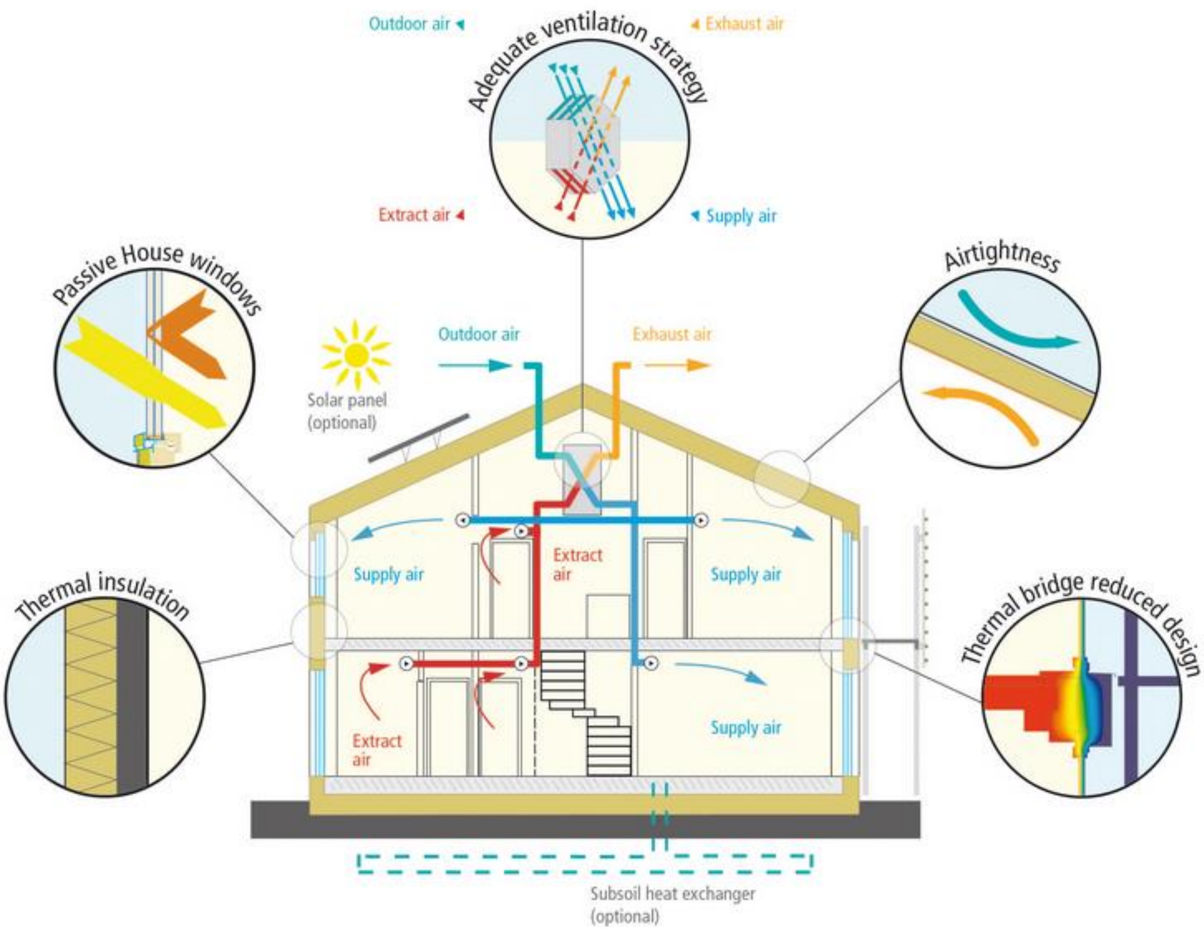


Figure 17: Key principles of Passive House design (Passive House Institute, 2015)

The specific values for heat transfer and solar heat gains coefficients can vary according to the location of the building, the aforementioned requirements are applicable to Central European region and similar climates.

By applying passive house strategies, it is expected for the building to be able to meet most of its HVAC demands by heating and cooling ventilation air, without any further conditioning device, and provide high thermal comfort by keeping regular radiant temperature across internal surfaces. To obtain official certification, the building must have a space heating energy demand lower than

15kWh/m² per year, and a maximum peak demand of 10W/m², this limitation is mainly driven by the technical constraint of safely providing all required heat through a limited amount of air without producing side effects like smells or high temperatures differences in the rooms. Additionally, the total energy consumption, measured through Primary Energy Demand, of all building systems and appliances must be lower than 60 kWh/m² per year (Energy Use Intensity); and still be able to guarantee thermal comfort at least 90% off all year hours above 25 °C. (Passive House Institute, 2015)

Due to its nature, heavily focused on the energy efficiency component of a high-performance building, Passivhaus standard is very effective on curbing energy consumption during building use, especially on residential units, and its impact on CO_2 emissions, however it has some limitations in its application:

The restriction on maximum peak demand of 10W/m² for space conditioning can be more difficult or impossible to achieve in spaces with higher internal gains due to relatively high occupation densities or elevated levels of heat production (e.g. offices, meeting rooms, gyms), and where higher rates of ventilation are required; also, the strict requirements on insulation greatly limits window size and connection to the exterior, compromising views and light conditions, being appropriate lighting a primary requirement in offices and usually their main electricity-consuming component. Finally, the limitation in total energy consumption is hard to meet when a great amount of energy (particularly electrical) is necessary to run the main activities of the building, like electronic devices in offices, which can be very variable during its lifetime.

2.1.1.2 Active House

Active House is a concept defined in 2011 that has a holistic approach to building design, it puts a stronger emphasis on the creation of healthy and comfortable spaces while reducing negative impact in the natural environment. Since 2016 it acts also as a certification label awarded to buildings that meet the standard criteria, based on qualitative and quantitative aspects inside three key principles: comfort, energy, and environment (Active House Alliance, 2020):

2.1.1.2.1 Comfort

Buildings must ensure healthy and comfortable indoor conditions for their occupants, providing good IAQ, adequate thermal conditions, lighting levels and acoustic comfort. Individual rooms must be analyzed, scored, and weighed according to their hours of use and number of occupants. Inside comfort criteria, three elements are considered: daylight, thermal environment, and Indoor Air Quality (IAQ)

a) *Daylight* quality, together with views, has an important influence on the well-being of occupants, natural light is preferred and electric lighting use during daytime must be minimized. The standard considers as qualitative criteria the quality of external views, visual transmittance of external glazing, how glare is managed, if daylight is guaranteed in secondary rooms, reflectance levels of internal surfaces, number of openings and how simulations have been carried out. Inside the quantitative criteria, daylight performance is evaluated based on the results of lighting analysis, using Daylight Factor (which compares the amount of light in the interior with respect to the exterior under overcast skies), or Daylight Autonomy (preferred, as it considers climate conditions too).

b) *Thermal environment* must be kept at comfortable temperature levels, particularly avoiding over-heating. Qualitatively the building prioritizes individual and intuitive control of indoor conditions during winter and summer (as ability of control increases the sense of comfort), night cooling to allow heat removal, other means to prevent overheating in winter, and proper design of the ventilation system to avoid air drafts and other forms of local discomfort. Quantitatively, the standards take into consideration the maximum threshold of operative temperature per room during warm periods, and the minimum one during cold periods; again, the points are weighed by room use levels.

c) *Indoor Air Quality* ensures proper conditions to avoid respiratory problems, allergies, or irritation due to dust, bacteria, viruses, and mold; control of humidity levels is critical and natural ventilation is preferred. Qualitative criteria include possibility of individual control on ventilation levels, presence of extraction devices to avoid dampness, use of low emitting building materials, and filters. Quantitative evaluation es made based on the CO_2 concentration levels inside the building as a measurement of fresh air supply.

d) *Acoustic quality* is enhanced by protecting users from noise and unwanted sounds, that can cause annoyance, stress, and affect daily activities. Attention to internal mechanic systems, acoustic privacy between rooms and protection of external spaces are qualitative aspects. Quantitative evaluation is carried out measuring the noise levels in decibels (dB) of mechanical systems, outside sources and coming from adjacent rooms.

2.1.1.2.2 Energy Efficiency

It is a key point of Active Houses; they must use responsibly sourced energy and prioritize renewable sources integrated on-site or nearby; the aim is to minimize energy demand, promote local renewable energy production and limit the release of greenhouse gas emissions due to fossil fuels use. It is evaluated through the building's energy demand, energy supply and primary energy use, (Active House Alliance, 2020):

A) Energy demand is expected to be kept as low as possible, mainly focusing on the reduction of building-coupled consumption (space heating, ventilation, air conditioning) by minimizing unwanted heat losses and gains through the envelope, after that the reduction of user-coupled demand (appliances) consist mainly of equipment efficiency. Qualitative attributes include the use of architectural solutions that reduce energy requirements, and use of passive cooling strategies. Quantitative analysis is made using the building Annual Energy Demand for HVAC, hot water and lighting, per unit of area; also called Energy Use Intensity (EUI).

B) Energy supply must target renewable and CO2-neutral energy sources, ideally produced within the building lot. Priority must be given to cover the building-coupled energy demand (HVAC and other services), user-coupled energy demand comes second (lighting, appliances) and covering other non-building related uses (like electric mobility) is optional. Qualitative criteria consider the inclusion of renewable energy sourcing into the building, and the evaluation of costs. Quantitative evaluation is based on the percentage of energy produced in the plot / nearby site.

C) Primary Energy Performance takes into consideration the use of non-renewable sources taking into consideration efficiencies in the conversion and transmission process between energy carriers; this is highly dependent on the characteristics of the national grid and energy mix. Quantitatively, it is evaluated measuring the Annual Primary Energy Use (non-renewable) per unit of area.

2.1.1.2.3 Environment

Positive interaction with surrounding environment is a primary goal, evaluating impact of the building and the material resource it uses during its lifecycle to avoid ecological damage, and the effect it has on the cultural landscape. They key aspects in this principle are related to the environmental loads of the construction materials, and the freshwater consumption (Active House Alliance, 2020):

A) Sustainable construction: Prioritize reused, recycled, or recyclable content, and evaluate the impact of materials, construction, use and decommissioning, using a Life Cycle Analysis (LCA). Qualitatively, it accounts for the use of LCA, use of responsibly sourced wood, management of construction, possibility of disassembly and respect for biodiversity in the use of materials and techniques. Quantitative criteria are subdivided in the assessment of sustainable construction, which measures the percentage of recycled content and recyclable content, use of wood, and the percentage of material that possess an Environmental Product Declaration (EPD); the second assessment is focused on environmental loads, measuring the Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Photochemical Ozone Creation Potential (POCP), Acidification Potential (AP) and Eutrophication Potential (EP) during the building's life cycle.

B) Freshwater consumption: must be reduced to mitigate pressure on freshwater sources and wastewater treatment, this can be done by improving efficiency of water fixtures, use grey and rainwater. Qualitatively, this section assesses if saving fixtures have been used, water is reused, and stormwater runoff is controlled. Quantitative evaluation is performed calculating the volume of water used in toilets, showers, and taps.

The sum of points earned under each category is quantified in a radar graph that allows for the comparison of buildings performance with diverse focus; in this way the results are reflected in a concise graph while being able to show the strengths and weaknesses of each building project. Finally, an Overall Score is obtained from the average of scores in all 9 parameters, which must be lower than 2.5 to be considered certified under the Active House Standard (3.5 in the case of renovation projects)

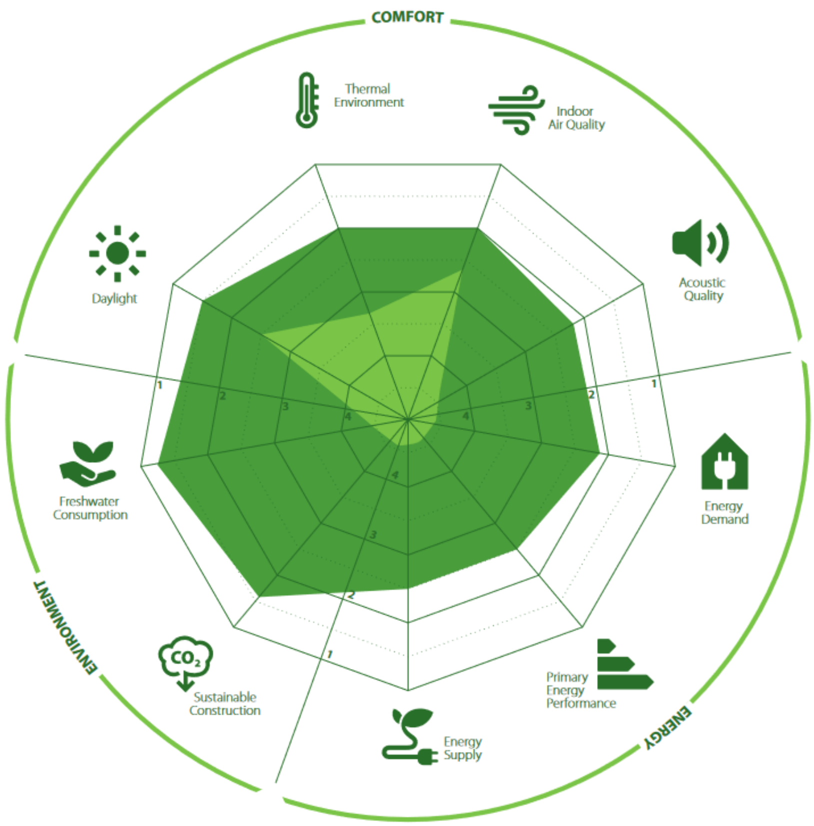


Figure 18: Example of Active House Radar Diagram (Active House Alliance, 2020)

2.1.1.3 Leadership in Energy and Environmental Design (LEED)

LEED is a green building certification program managed by the U.S. Green Building Council (USGBC) formed in 1993. It consists of a rating system that evaluate buildings according to their carbon footprint, energy and water consumption, waste production, impact of transportation and materials, health of occupants and IAQ; if positive, the resulting level of certification can be: Certified, Silver, Gold or Platinum, depending on the number of earned points. (U.S. Green Building Council, 2021)

The certification has a holistic approach, and its aim is to promote building construction patterns that reduce contribution of built environment to climate change, enhance human health, protect natural resources and biodiversity, and strengthen social ties inside communities. The criteria and thresholds for classification are adapted to different project characteristics: Building Design and Construction (BD+C) which has separate requirements depending on use, Interior Design and Construction (ID+C), Building Operations and Maintenance (O+M), Neighborhood Development (ND), Homes, Cities and Communities, LEED Recertification, and LEED Zero.

As the criteria is very dependent on the type of development, the reference to be revised in this chapter is the one related to the type of building to be designed in this project, taking as a reference the LEED v4.1 for Building Design and Construction (BD+C) for New Construction and Major Renovation, as the building type doesn’t fit inside the other subclassifications (data centers, healthcare, hospitality, retail, schools, warehouses and distribution centers).

The most recent version (v4.1) of LEED BD+C certification assess the performance of the building based on a set of 16 prerequisites and 51 credits applicable to different types of building, totalizing up to 110 achievable points, the credits are grouped in 9 groups: Integrative process, Location and transportation, sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation, and regional priority. (U.S. Green Building Council, 2021)

LEED certification is already required or encouraged by several public agencies and governments in the U.S., it is also the most widely used certification around the globe. It is one of the certifications with wider coverage of different sustainability aspects inside the building, thus the contribution of energy efficiency in the overall scoring is relatively lower than in other standards.

		New Construction	Core and Shell	Schools	Retail	Data Centers	Warehouses and Distribution Centers	Hospitality	Healthcare
INTEGRATIVE PROCESS		1	1	1	1	1	1	1	1
Prerequisite	Integrative Project Planning and Design								P
Credit	Integrative Process	1	1	1	1	1	1	1	1
LOCATION AND TRANSPORTATION		16	20	15	16	16	16	16	9
Credit	LEED for Neighborhood Development Location	16	20	15	16	16	16	16	9
Credit	Sensitive Land Protection	1	2	1	1	1	1	1	1
Credit	High-Priority Site and Equitable Development	2	3	2	2	2	2	2	2
Credit	Surrounding Density and Diverse Uses	5	6	5	5	5	5	5	1
Credit	Access to Quality Transit	5	6	4	5	5	5	5	2
Credit	Bicycle Facilities	1	1	1	1	1	1	1	1
Credit	Reduced Parking Footprint	1	1	1	1	1	1	1	1
Credit	Electric Vehicles	1	1	1	1	1	1	1	1
SUSTAINABLE SITES		10	11	12	10	10	10	10	9
Prerequisite	Construction Activity Pollution Prevention	P	P	P	P	P	P	P	P
Prerequisite	Environmental Site Assessment			P					P
Credit	Site Assessment	1	1	1	1	1	1	1	1
Credit	Protect or Restore Habitat	2	2	2	2	2	2	2	1
Credit	Open Space	1	1	1	1	1	1	1	1
Credit	Rainwater Management	3	3	3	3	3	3	3	2
Credit	Heat Island Reduction	2	2	2	2	2	2	2	1
Credit	Light Pollution Reduction	1	1	1	1	1	1	1	1
Credit	Site Master Plan			1					
Credit	Tenant Design and Construction Guidelines		1						
Credit	Places of Respite								1
Credit	Direct Exterior Access								1
Credit	Joint Use of Facilities			1					
WATER EFFICIENCY		11	11	12	12	11	11	11	11
Prerequisite	Outdoor Water Use Reduction	P	P	P	P	P	P	P	P
Prerequisite	Indoor Water Use Reduction	P	P	P	P	P	P	P	P
Prerequisite	Building-Level Water Metering	P	P	P	P	P	P	P	P
Credit	Outdoor Water Use Reduction	2	3	2	2	2	2	2	1
Credit	Indoor Water Use Reduction	6	4	7	7	6	6	6	7
Credit	Optimize Process Water Use	2	3	2	2	2	2	2	2
Credit	Water Metering	1	1	1	1	1	1	1	1
ENERGY AND ATMOSPHERE		33	33	31	33	33	33	33	35
Prerequisite	Fundamental Commissioning and Verification	P	P	P	P	P	P	P	P
Prerequisite	Minimum Energy Performance	P	P	P	P	P	P	P	P
Prerequisite	Building-Level Energy Metering	P	P	P	P	P	P	P	P
Prerequisite	Fundamental Refrigerant Management	P	P	P	P	P	P	P	P
Credit	Enhanced Commissioning	6	6	6	6	6	6	6	6
Credit	Optimize Energy Performance	18	18	16	18	18	18	18	20
Credit	Advanced Energy Metering	1	1	1	1	1	1	1	1
Credit	Grid Harmonization	2	2	2	2	2	2	2	2
Credit	Renewable Energy	5	5	5	5	5	5	5	5
Credit	Enhanced Refrigerant Management	1	1	1	1	1	1	1	1
MATERIALS AND RESOURCES		13	14	13	13	13	13	13	19
Prerequisite	Storage and Collection of Recyclables	P	P	P	P	P	P	P	P
Prerequisite	Construction and Demolition Waste Management Planning	P	P	P	P	P	P	P	P
Prerequisite	PBT Source Reduction – Mercury								P
Credit	Building Life-Cycle Impact Reduction	5	6	5	5	5	5	5	5
Credit	Building Product Disclosure and Optimization – EPD	2	2	2	2	2	2	2	2
Credit	Building Product Disclosure and Optimization – Sourcing of Raw Materials	2	2	2	2	2	2	2	2
Credit	Building Product Disclosure and Optimization – Material Ingredients	2	2	2	2	2	2	2	2
Credit	PBT Source Reduction – Mercury								1
Credit	PBT Source Reduction – Lead, Cadmium, and Copper								2
Credit	Furniture and Medical Furnishings								2
Credit	Design for Flexibility								1
Credit	Construction and Demolition Waste Management	2	2	2	2	2	2	2	2
INDOOR ENVIRONMENTAL QUALITY		16	5	16	15	16	16	16	16
Prerequisite	Minimum Indoor Air Quality Performance	P	P	P	P	P	P	P	P
Prerequisite	Environmental Tobacco Smoke Control	P	P	P	P	P	P	P	P
Prerequisite	Minimum Acoustic Performance			P					
Credit	Enhanced Indoor Air Quality Strategies	2	2	2	2	2	2	2	2
Credit	Low-Emitting Materials	3	3	3	3	3	3	3	3
Credit	Construction Indoor Air Quality Management Plan	1	1	1	1	1	1	1	1
Credit	Indoor Air Quality Assessment	2		2	2	2	2	2	2
Credit	Thermal Comfort	1		1	1	1	1	1	1
Credit	Interior Lighting	2		2	2	2	2	2	1
Credit	Daylight	3	3	3	3	3	3	3	2
Credit	Quality Views	1	1	1	1	1	1	1	2
Credit	Acoustic Performance	1		1		1	1	1	2
INNOVATION		6	6	6	6	6	6	6	6
Credit	Innovation	5	5	5	5	5	5	5	5
Credit	LEED Accredited Professional	1	1	1	1	1	1	1	1
REGIONAL PRIORITY		4	4	4	4	4	4	4	4
Credit	Regional Priority	4	4	4	4	4	4	4	4
		110							

Figure 19: LEED v4.1 BD+C Scorecard (U.S. Green Building Council, 2021)

2.1.1.4 Energy Star

Energy Star is a certification, backed by the U.S. government, through the Environmental Protection Agency and the Department of Energy, that assesses and identifies the energy efficiency of products (appliances in general), buildings and industrial plants, so it can be easily compared by consumers and public administration. It is widely used in the United States, and particularly used in the performance benchmarking system of Philadelphia for its buildings.

The calculation estimates the Source Energy consumed by a building with the same location, occupants, and type, in the best and worst-case scenario, using an algorithm that takes data of the energy mix and utility grid characteristics, and compares the estimation with the metered data of site energy demand of the real building, to identify how well-performing it is relative to the standard cases.

This certification has the advantage of assessing the real behavior of buildings after construction, and the possibility of comparing performances with similar or neighboring buildings, given its widespread use; however, this means that the program is not useful to guide the design process of the building before construction, and focuses only on energy efficiency component of high performance; excluding other aspects like comfort and lifecycle impact.

2.1.2 Attributes of high-performance building design

As previously described, high performance in buildings can be understood as an overall optimized behavior, driven by several interrelated attributes that determine the functioning of the building as a system; the key attributes would depend on the chosen standard and general aim of the building; inside the scope of this project and following the criteria established in the Active House standard (given its holistic but synthesized approach), three attributes are particularly influential inside the scope of this project, so are separately described in the following paragraphs.

2.1.2.1 Energy efficiency

In many contexts, high performance and energy efficiency are terms used interchangeably, being the latter understood as "…the use of less energy to perform the same task or produce the same result. Energy-efficient homes and buildings use less energy to heat, cool, and run appliances…" (Office of Energy Efficiency & Renewable Energy); however, to the purpose of this project, both terms will be used differently, as energy efficiency is only focused in a very specific set of conditions that simplify the role of the building as an energy consumer/producer.

The importance of ensuring energy efficiency on buildings is driven by the massive impact that they have on energy consumption patterns around the globe, as building construction and use account for almost one-third of total final energy consumption according to the International Energy Agency (IEA), much of which associated to the use of fossil fuels, thus producing 15% of global CO2 emissions (Abergel & Delmastro, 2021); this makes building's energy efficient improvement one of the basis on the decarbonization efforts to limit Greenhouse gas emissions (GHG) and tackle climate change. Additionally, especially in developing countries, rapid urbanization is expected to increase building stock adding more pressure to energy systems.

The current goal is to reduce the energy consumed per building square meter by 45% in 2030 to align with the path for achieving Net Zero Emissions by 2050 and limit global temperature rise to 1.5 °C (Abergel & Delmastro, 2021). Most of the efforts are focused on reducing the use of fossil fuels on site and increasing the proportion of electricity (already the main energy carrier) in the building's energy consumption, as it is planned to progressively decarbonize electricity generation.

Figure 20:Global building energy use and floor area growth in the Net Zero Scenario 2010-2030 (Abergel & Delmastro, 2021)

2.1.2.1.1 Building energy use in the United States

Specifically in the United States, residential and commercial sectors (including building related and non-related consumption) account for a combined 28% of the total energy consumed, most of it sourced from electricity and natural gas. The electricity demand is particularly important as 74%

of all electricity powers residential and commercial activities; and is generated from a 41% of low CO_2 emissions sources (renewable and nuclear). (U.S. Energy Information Administration, 2022)

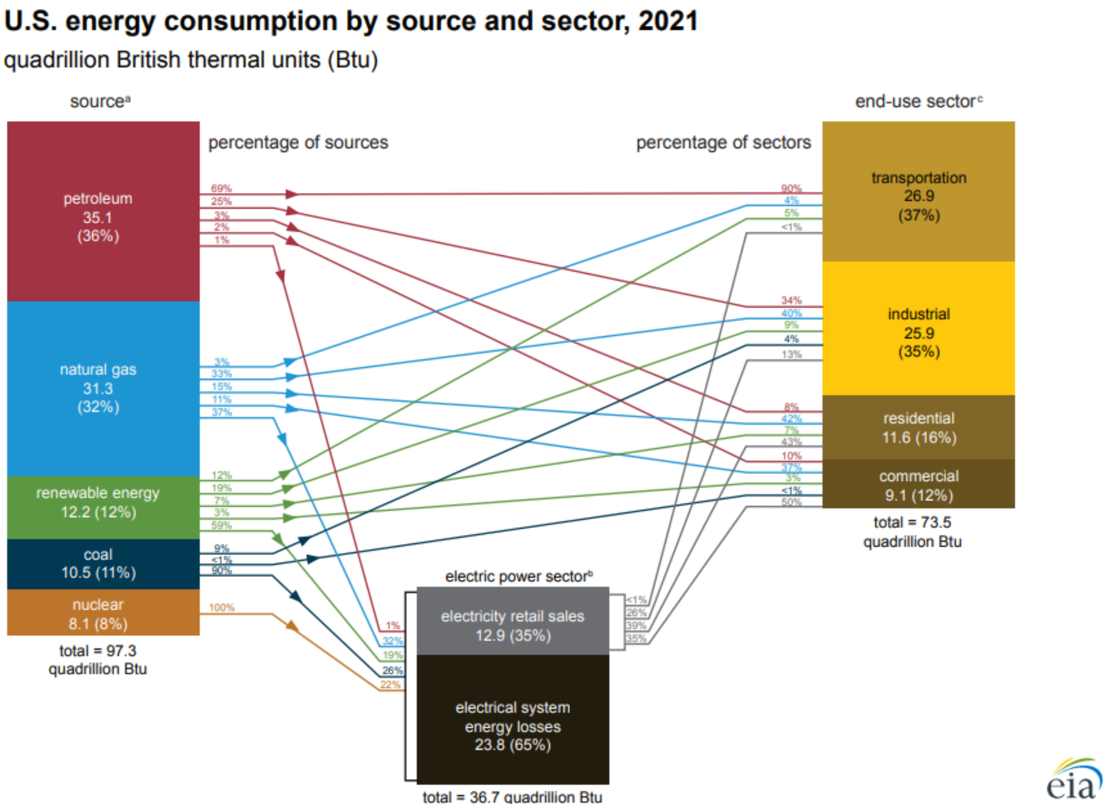


Figure 21: U.S. Energy consumption by source and sector, 2021 (U.S. Energy Information Administration, 2022)

Inside the commercial sector, buildings have an important influence in the demand, using up to 6963 trillion BTUs (2040 TWh) (U.S. Energy Information Administration, 2018), approximately two thirds of the total commercial sector consumption. From all commercial building types, the highest consumers are office ones, taking 14% of the consumption by 2012, this can be partly explained by the big amount of area dedicated to administrative services in cities covering several economic sectors under one category.

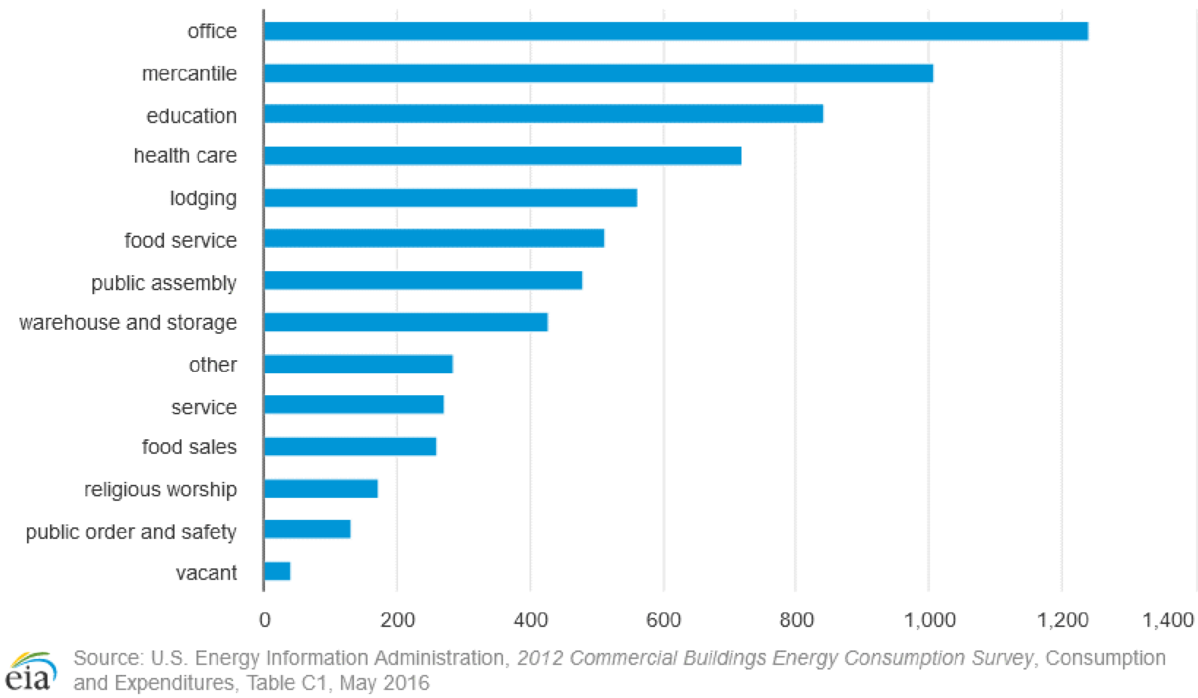


Figure 22: Energy use by type of U.S. commercial buildings in 2012 (U.S. Energy Information Administration, 2018)

Regarding energy sources, commercial buildings primarily rely on electricity (61%) to run their services, from which lighting is the biggest individual use consumer, closely followed by cooling, air conditioning and ventilation; equipment and appliances have a lower impact than previously mentioned uses, but still important as they are the ones that have experienced the highest increase in recent years. Heating and cooking have a relatively small impact on commercial buildings electricity demand but are mostly responsible for the use of natural gas as the second energy source for commercial buildings (32%).

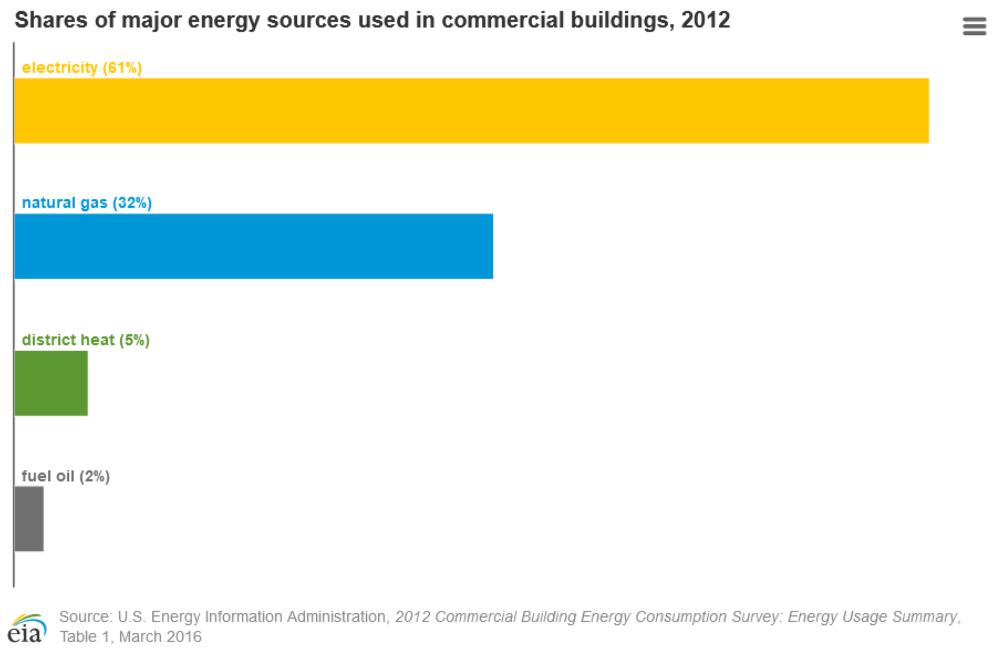


Figure 23:Shares of major energy sources used in commercial buildings, 2012 (U.S. Energy Information Administration, 2018)

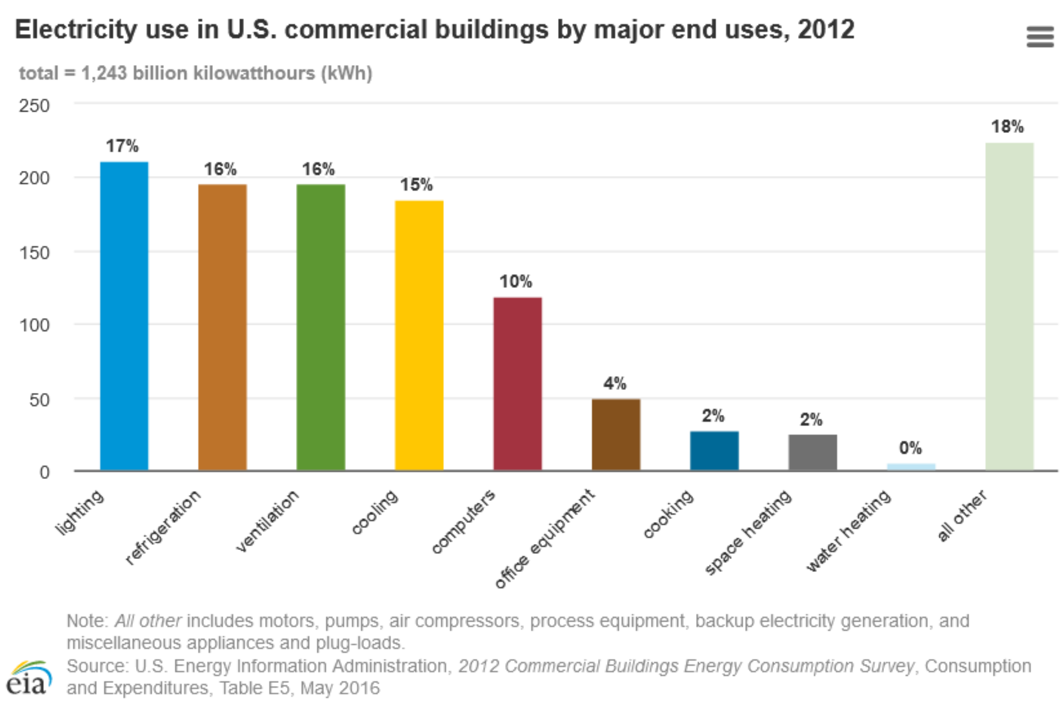


Figure 24: Electricity use in U.S. commercial buildings by major end uses, 2012 (U.S. Energy Information Administration, 2018)

2.1.2.1.2 Buildings energy use in Philadelphia

The city of Philadelphia has applied an Energy Benchmarking program since 2017, to assess energy and water use in residential multifamily and commercial buildings with more than 50000 ft2 (4645 m²), summing up more than 320 million square feet (around 30 million m²) and covering 20% of the city's total built space; then it uses Energy Star scoring system to compare results between individual buildings, by category and with the rest of the country. The results of the reported data for office buildings show an average Site EUI of 84.6 kBTU/ft2 (266.8 kWh/m²), 10% higher than the national median value (City of Philadelphia, 2019); this means there is still a lot of room for improvement in the city, given that office is the building use with the higher total energy consumption in the city, and also one of the most demanded for new development.

Energy efficiency can then be evaluated and compared at the city level, and for the purpose of this project, using the data of the city's benchmarking system.

	Number of Buildings Reported	Percent of Total Property GFA	Median ENERGY STAR Score	Average WN Site EUI (kBtu/ft²)	National Median Site EUI Score	Median Water Use Intensity (kgal/ft²)
College/University	366	11.89%	44	163.6	99.6	21.6
Data Center	2	0.60%	N/A	338.8	40.1	43.4
Hospital	72	4.63%	77	241.9	251.0	45.8
Industrial	26	0.98%	N/A	144.1	47.9	8.2
Laboratory	4	0.41%	N/A	274.9	159.1	56.5
Medical Office	17	0.93%	59	132.9	114.6	23.6
Multifamily	767	24.09%	58	66.5	66.9	35.2
Municipal	31	4.41%	25	140.3	176.1	20.1
Museum	6	0.03%	N/A	219.5	59.7	19.3
Office	182	20.86%	63	84.6	76.7	13.3
Other	75	7.00%	50	108.6	49.9	9.8
Parking	14	1.01%	N/A	23.2	N/A	0.9
Retail	47	1.90%	58	83.5	81.7	8.1
School (K-12)	295	9.96%	49	71.4	68.6	10.8
Supermarket	24	0.75%	39	243.5	223.4	18.6
Warehouse	109	5.81%	59	35.9	37.6	1.7
Worship	32	0.44%	90	63.7	48.6	6.0

Figure 25: Building Energy Performance by Building Sector, 2018 (City of Philadelphia, 2019)

2.1.2.2 *Sustainable material and resource use*

Besides the previously explained attribute of energy efficiency, high-performance buildings also aim to minimize their negative impact in the environment and society through efficiently and responsibly using resources other than energy.

Energy-efficiency is usually regarded as the most focused aspect of sustainability, as it has direct connection to the emission of greenhouse gases to the atmosphere and the highest impact on climate change at a global scale; however, during its life cycle buildings also influence at the local and regional level through their use of material resources and occupation of space. The following examples are indicative of their measured impact in the United States, extracted from an official statistical summary (U.S. Environmental Protection Agency, 2009):

A) Locally, hard building surfaces produce heat island effect, increasing the mean air temperature in big cities (more than 1 million inhabitants) by 1- 3°C, and temporarily rising it up to 12°C under specific conditions, this increases the pressure and consumption of conditioning systems and affect people well-being, especially during extreme weather events.

B) The construction of building and infrastructure takes up space and has increased the urban land area by 400% between 1945 and 2002, doubling population growth, occupying previously rural land.

C) Construction and demolition of buildings generate around 160 million tons of debris per year, covering 26% of all non-industrial waste generation; almost half of it is generated only during demolition. Just around 20-30% of debris is recycled, usually concrete, asphalt metals and wood. Adding the municipal solid waste due to use, buildings produce two thirds of all non-industrial solid waste.

D) Water use in buildings represents 13% of the total water consumption in the U.S., from that, 25.6% is consumed on commercial buildings. 30% of the total water consumption is used outdoors, mainly for landscaping, especially on suburban lawns. During the end of last century, total water use tripled while population doubled.

E) Stormwater is usually not recovered, in fact urbanization creates impervious surfaces that don't allow infiltration into the ground, increase run-off, pressure drainage systems, worsen flooding risk, and transport pollutants and sediments to water bodies (especially rivers) affecting natural processes. Total impervious surface covers 83.337 m^2 in the U.S., the majority is due to transportation surfaces, and 35% directly related to buildings.

Additionally, a global accelerated pace of urbanization increases the high demand for resources that the construction industry already has; and the widespread application of modern construction techniques and materials puts even more pressure on the most used resources, like water, and sand, which is being extracted at a higher rate than it can be naturally replenished (United Nations Environment Programme, 2022).

Among the measures that can help reduce the negative impact of building on their local environment, the ones at the design stage are the most effective, for example, optimizing site potential, favoring rehabilitation of existing buildings, or using previously developed sites, that have already artificially modified and thus have a smaller contribution to natural ecosystems; orientation and envelope design can also help reduce the disruption of natural patterns, like winds, and run-off. Water management is particularly important, due to its role on human activities and ecosystem processes, efficient fixtures, and correct landscaping (using proper local or adapted species) should reduce demand, while on-site rainwater capture and recycling can take advantage of the are the building occupies to harvest and contain water that otherwise would be directed to drainage systems.

Material use should consider the environmental impact of production and disposal, beyond the use phase, prefer local and responsibly sourced materials, recycled content, and lightweight construction. Life Cycle Assessment (LCA) of buildings can be very useful to identify their real direct and indirect impact of building materials, these are thorough analyses and require information from all phases of building life: material manufacturing, construction, use and maintenance, end of life.

2.1.2.3 Well-being and comfort

The quality of interior habitable spaces has a great impact on the health and well-being of humans living in cities, in fact, Americans spend indoors around 87% of their total time during a year, most of it inside their residences and the rest of it inside institutional, office or factory buildings (Klepeis, et al., 2001). Office and factory buildings are occupied, as it is expected, mainly during working hours, and their relative contribution to the total time is reduced due to their almost lack of use on weekends, vacations, and by not-employed people, like children and elderly.

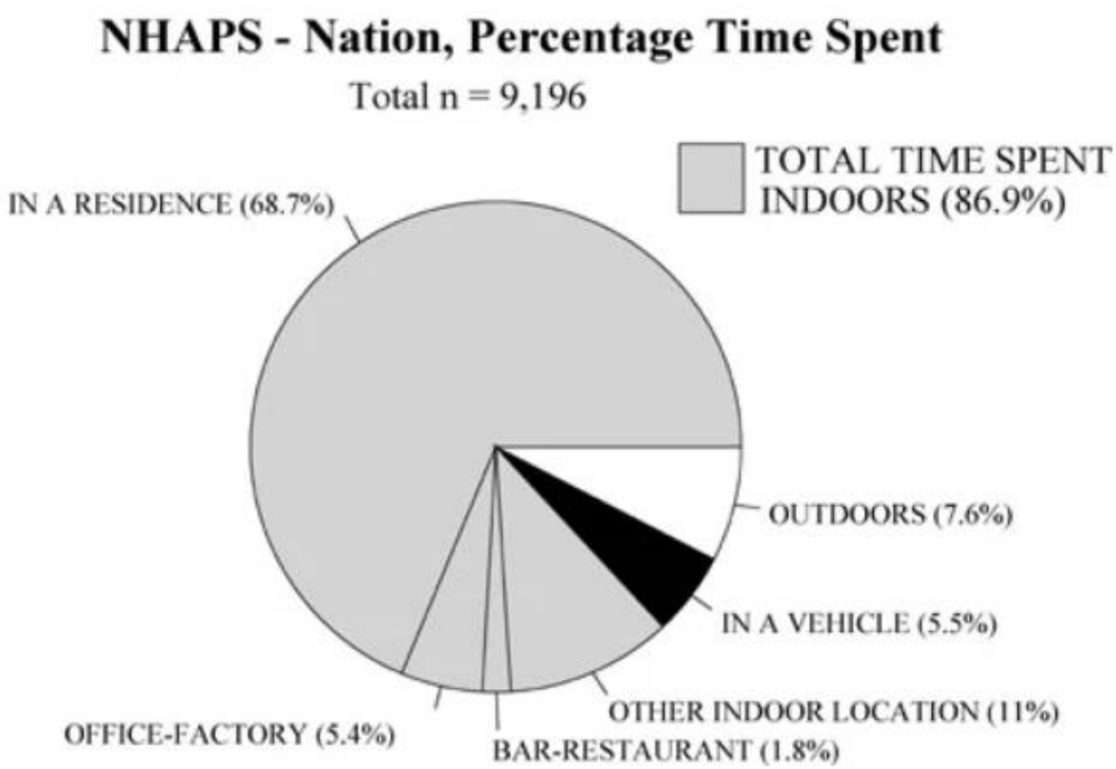


Figure 26: Average time spent by Americans in different common locations (Klepeis, et al., 2001)

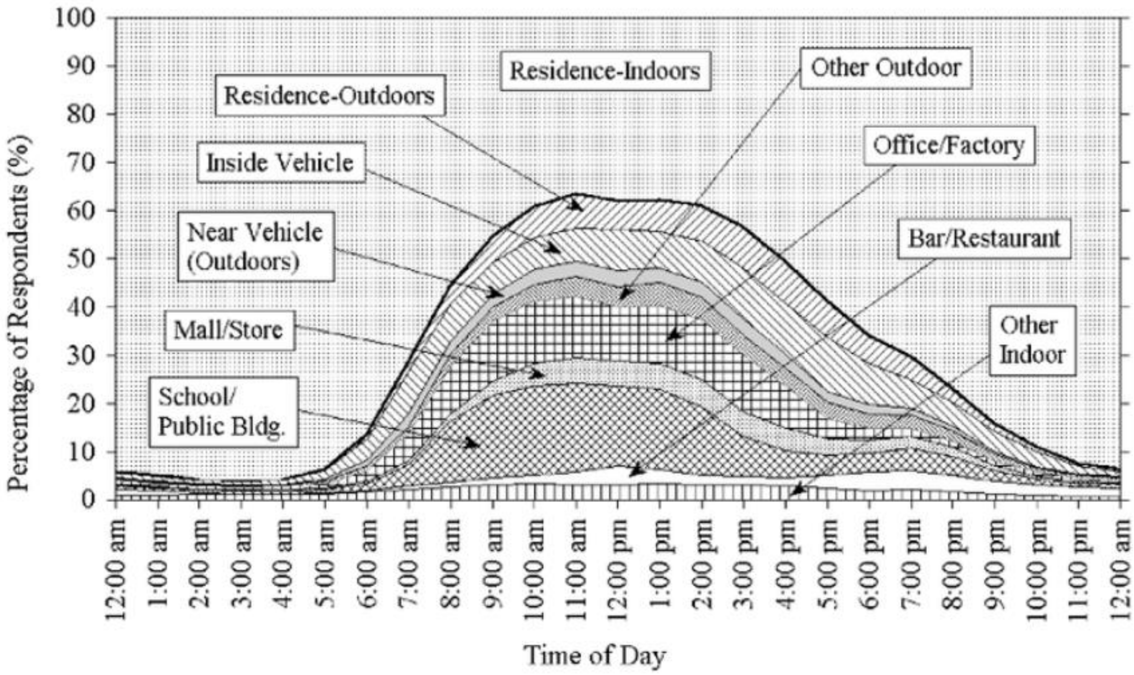


Figure 27: Time spent by Americans in different common locations, by time of the day (Klepeis, et al., 2001)

By hosting such an extended number of hours from human's *time budget*, internal building environment has become the primary human habitat, having a great influence on the health of its occupants; then, providing a healthy environment is one of the primary goals to be fulfilled by a properly performing building.

Health is defined as "…a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (World Health Organization, 2005), so every occupied space must tackle these three aspects:

2.1.2.3.1 Physical health

Physical health refers to a state of appropriate functioning of body organs, systems and processes, that allows to develop unrestricted daily activities and resist disease; it can be enhanced through certain building features like: ergonomic support, circadian effective light, comfort controls (temperature, light, sound), enhanced ventilation, access to indoor and outdoor activity spaces and alternative transportation, availability of healthy food and clean water, stair design to encourage regular use, cleaning chemical and air filter management plans, and integrated pest management (U.S. General Services Administration, n.d.)

Basically, the building aim is to provide an environment that despite being artificial is able to disrupt natural body processes as little as possible, encourage physical activity, reduce stressors and provide protection from potential hazards, like extreme weather and diseases.

2.1.2.3.2 Social Well-being

Social component of health or well-being is described as "…the extent to which a person feels a sense of belonging, acceptance, and social inclusion including participation in community activities. Positive social well-being includes having mutually beneficial friendships and social supports." (U.S. General Services Administration, n.d.)

A building must ensure fair and equitable distribution of amenities, space that supports a sense of connection to others, variety of spaces to support different social needs including private conversations, informal interaction, formal meetings, and visual connection to others. The aim is to avoid potential conflicts in the use of space, or environments that generate a hostile relationship between its users by obstructing community contact or forcing unwanted social interaction.

2.1.2.3.3 Psychological Well-being

Psychological well-being can be defined as "…a positive mental state that allows people to realize their full potential, cope with the stresses of life, work productively, and make meaningful contributions to their communities. It also includes resilience, happiness, high levels of satisfaction with life, and a feeling of belonging and sense of purpose." (U.S. General Services Administration, n.d.); it is supported by ensuring provision of a connection to nature, access to daylight from all regularly occupied spaces, occupant control of the physical environment, equitable access to workplace features and amenities, access to a variety of environments, including those for respite, focus, and social connection, and access to spaces with effective acoustic design.

These aspects are related to the perception of safety, controllability of the environment conditions and an innate need to have access to familiar sensorial stimuli, commonly found in nature, biophilia can then be used to improve psychological well-being, and will be discussed more in deep inside the next subchapter.

2.1.3 Relationship between high-performance attributes

In summary, the different attributes, and criteria for the definition of high-performance design are represented and organized in the following diagram, according to the classification previously used:

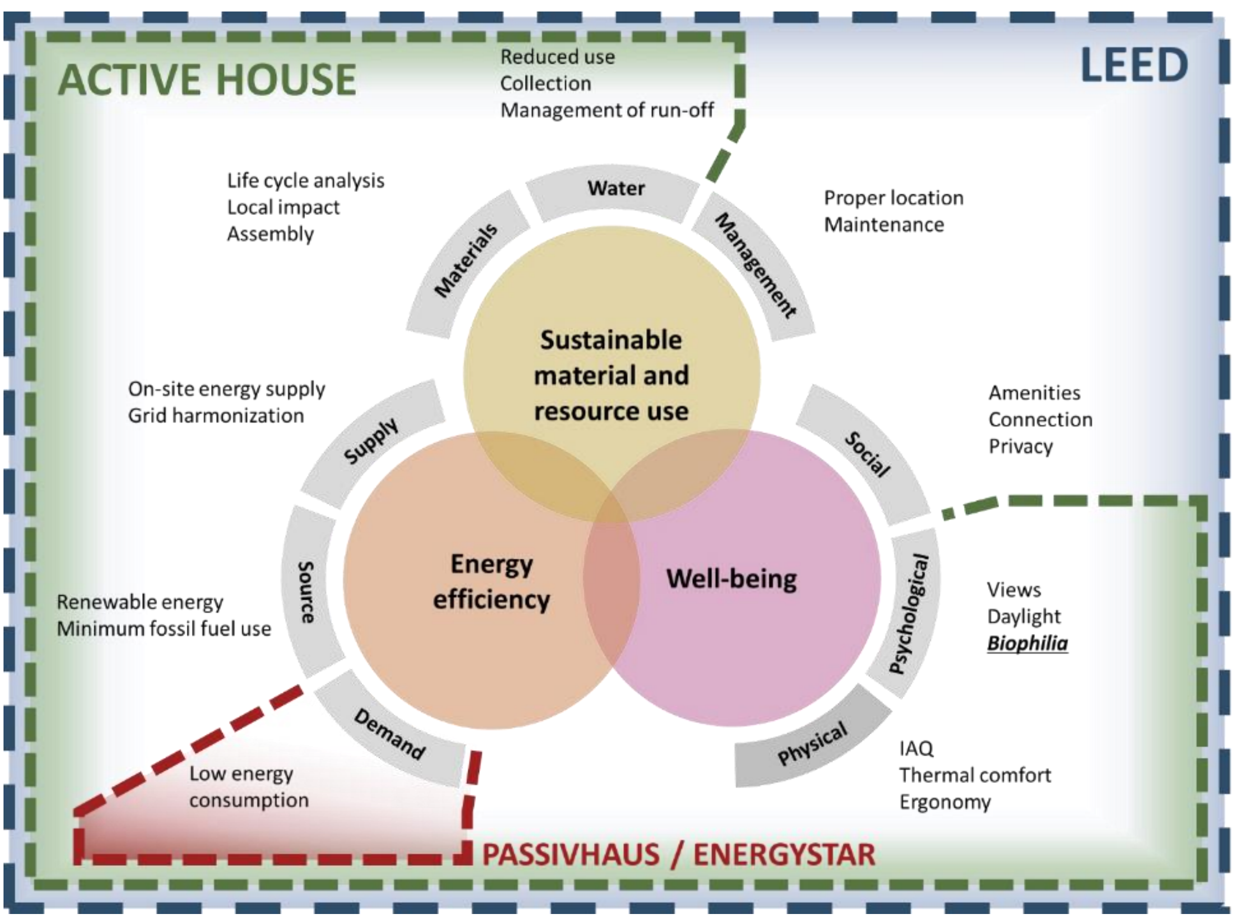


Figure 28: Relationship between high-performance design attributes and standards

2.2 Biophilia

For thousands of years humans lived with a very strong connection with the nature, and only in relatively recent time humans started to create an artificial environment where they can have a higher quality of life. To understand this improvement of quality, it is possible to think about how the life expectation of women and men has increased since people started to live in an urban environment; how humans are always in a place with an adequate climatic condition, that makes them feel in comfort, how peoples are always protected against atmospheric events etc…

Despite this improvement of the quality of the life, and despite the evolution, the memory of the thousands of years passed immersed in the nature by humans is still present in our DNAs, and so for humans the contact with the nature remains a fundamental point for the well-being.

The attachment to nature is innate, and everybody, when exposed to nature gets, generally in an unconscious way, some benefits that are usually related to recover, reduction of stress and fatigue, motivation, improving of self-esteem, concentration, productivity etc… These regenerative benefits are perceived in a stronger or weaker way depending by every person, but everybody feels them, because they are connected to the fact that people, when immersed in nature, perceive a "return to the origins", a return to be what they are (Barbiero, Ecologia Affettiva, 2017).

The innate attachment to the nature by humans is called Biophilia, and this concept can be applied in a lot of fields, including architecture. The use of biophilia into a design process is called Biophilic Design and is an applied science that takes advantage of the strong connections between humans and nature to create places where people can feel the positive benefits given by nature.

It's not sufficient to place some plants in a room to obtain a space with a perfect biophilic design. It is necessary that the designer has a good connection with the nature, a good knowledge of biophilia and a good naturalistic intelligence. These knowledges, mixed, give to the designer the ability to create a space where people feel a real connection with the nature.

Biophilia is “the inherent human inclination to affiliate with natural systems and processes, especially life and life-like features of the nonhuman environment” (Kellert, Heerwagen, & Mador, 2008). The term “biophilia” has been created by the social psychologist Eric Fromm, and then popularized by the biologist Edward Osborne Wilson. So, the concept starts from the fields of biology and psychology, and then has been used in the fields of neuroscience, endocrinology, architecture, and others (Terrapin Bright Green, 2014).

Humans have a strong attachment to nature since they passed a strong part of their existence totally immersed in it. They lived in the African savanna for about 125.000 years, and only about 75.000 years ago, the eruption of the super volcano Toba and the glaciation of the planet, at that time already in progress, forced the sapiens to find new places where they would be able to survive. The very long period spent in a natural environment, in particular in the savanna, affect also nowadays our preferences for some environments, especially the ones that have characteristics similar to the one present in the savanna. These characteristics have been listed by the American biologist Gordon Orians with the “Savanna Hypothesis”, and are the followings:

A) Presence of a panoramic view, wide and clear
B) Abundance of plants, animals, and edible fungi
C) Presence of elevated places useful for supervision
D) Presence of caverns and cliffs for refuge during the night
E) Presence of river of lake, sources of food and protection

So, humans still prefer to live in places with these proprieties, and it’s not a case that an apartment at the last floor of a tall building, with a panoramic view on a park with tree and a river is much more expensive than the same apartment without these characteristics (Barbiero, Ecologia Affettiva, 2017).

After the eruption of Toba, humans didn’t stop to live in nature, but they simply started to discover other environment different from the savanna. The first detachment from the nature by the humans happened at the invention of the agriculture, the end of the Palaeolithic, about 10.000 years ago. With the agriculture, people become able to control the amount and the availability of food during the year, and so there was no more the necessity to migrate according to the seasons to survive, and so refuges where people lived started to become permanent, and this point is when the first "houses" born (Barbiero, Ecologia Affettiva, 2017).

Over the course of the time, the detachment between humans and nature is increased, till the XX century when, with the study on the biophilia, we started to understand the real potential of the contact with nature. Then, from about the 2020, after some lockdowns due to Covid-19 pandemic, and in front of the first consequences of the climate change, people start to appreciate more the nature and understand its benefits. For example, people that during the pandemic have been exposed to nature and did physical activity showed lower stress levels and a greater facility to go through the lockdown period (Javelle, Laborde, Hosang, Metcalfe, & Zimmer, 2021). Also, the current will to save the nature from the climate change is an expression of biophilia, and it is an instinct that is more or less present in all the people. The sensibility for the nature is related to the experience that every single person had with the nature. More a person lived in contact with the nature, more is awareness of its importance, but due to the loss of biodiversity that is happening nowadays, these experiences can also become rarer. To explain the problem of the loss of biodiversity, we can say that nowadays the extinction rate due to human activities is 100 times higher than the natural one, and if unchanged our routine, this will increase till 1000 or 10.000 (Barbiero, Ecologia Affettiva, 2017). In only 200 years humans have started the 6th major extinction of the Pharenozoic, and 10 milions of years of natural evolutions are needed to recover this (Barbiero & Berto, Introduzione alla biofilia, 2019). By disrupting the nature, we are giving away all the benefits and the services that we can take form it, and the sensibility from some humans to the ruin of nature is due to the innate awareness of the presence of these benefits.

Maintaining a good relationship with nature is very important because the benefits given by a direct or non-direct contact with it are related to health, productivity, and wellbeing. For example, some studies have demonstrated that people exposed to natural stimuli have a quicker recovery from illness and surgical procedures, fewer health and social problems, higher performance at work, less stress and higher motivation, concentration, and memory (Kellert, Heerwagen, & Mador, 2008). Furthermore, spaces with vegetation can improve self-esteem and water can have a relaxing effect (Terrapin Bright Green, 2014). These stimuli are perceived by humans through three types of attention: direct, involuntary and open. The first one is the ability of humans to start an alert status to an interesting object or event, and in both cases, if it is spontaneous or not, it requests a big use of psychic energy. The second type of attention doesn't require any type of energy and it self-activate themself when the context permits it, thing that typically happens a natural context. The third and last type is involuntary but conscious, and doesn't require any type of energy too. This type of attention requires a direct attention to be activated, indeed it is present only during routine activities, activities than needed a direct attention when done the first times, but done in an "automatic" way the next times (Barbiero & Berto, Introduzione alla biofilia, 2019)

In the stressful lives that people live today it would be great to pass the time in an environment that is able to give the benefits just explained, and since it's not possible to force people to live in a forest, it's necessary to take the characteristics typical of natural environments and apply them on the artificial one, by the use of the biophilic design.

2.2.1 Biophilic design

The built environment is so a place where a person can have a higher quality of life, with a higher comfort, but can be at the same time more stressed, especially if this person is a worker. Other than that, the creation of the build environment, especially the modern one, caused an unsustainable energy and resources consumption, loss of biodiversity and pollution, things that were in balance before the modern human era, and now, that the balance is no more present, there is the problem of the climate change, a major problem for the life on the earth.

To solve the problem of climate change it's necessary to make buildings with the lower possible impact on the environment, but at the same time they must also guarantee very high comfort levels for people that live in them. In addition, it would be better to make buildings where people can be more in contact with the nature (biophilic design), and so can also have the benefits explained before. This combination of sustainability and biophilic design, is called "restorative environmental design" and guarantees a true and lasting sustainability and wellbeing for people (Kellert, Heerwagen, & Mador, 2008). It's important to highlight that the goals from the biophilic design are neutral or in some cases good for make a building with a low impact on the environment.

Biophilic design can be divided in two basic dimensions (Kellert, Heerwagen, & Mador, 2008): a) organic or naturalistic, and b) place-based or Vernacular.

The first one (organic or naturalistic dimension) represents characteristics of the build environment that can give to humans a sense of connection with nature. This sense of connection can be perceived through 3 types of experiences:

a) *Direct experience*: refer to the contact by people with the features of the natural environment, such as daylight, plants animals and ecosystems.
b) *Indirect experience*: refers to the contact by people with nature that needs a human input to survive, like potted plant, fountain, or aquarium.
c) *Symbolic or vicarious experience*: doesn't involve a real contact with the nature but a contact trough pictures, videos or metaphors.

The second dimension (place-based or vernacular) represents buildings and landscapes that connect people to the culture and ecology of an area. In this dimension it is included the spirit of place, that is the way in which some buildings and landscapes that are considered important in some way for people, become integral part to their individual and collective identities. This spirit of place is so the psychological need for calling some places "home", and this attachment to some territories is the major reason why people assume the responsibility to take care for buildings and landscapes.

These two basic dimensions can be related to six biophilic design elements (Kellert, Heerwagen, & Mador, 2008): ***environmental features, natural shapes and forms, natural patterns and processes, light and space, place-based relationship, and evolved human-nature relationships***.

These elements are then revealed in more than 70 biophilic design attributes. The classification of these attributes is not definitive and can grow at the increasing of the knowledge of the biophilic design (Kellert, Heerwagen, & Mador, 2008). All these attributes are characteristic that a build environment should have to be perceived "biophilic" by people.

2.2.1.1 Environmental features

Are the natural features that are well-recognizable in the build environment. Twelve attributes are defined:

a) ***Colour:*** this was an important element for the survival of humans, since it identifies resources, dangers, water etc. So, people for this reason are still attracted to colours and earth tones are always good for a successful biophilic design.

b) ***Water:*** it is fundamental for the life of humans, for this reason its presence is very appreciate by people and it would be better to give the perception of quality, quantity, and movement.

c) ***Air:*** it is important to always guarantee natural ventilation and not stagnant air.

d) ***Sunlight:*** the presence of daylight is the preferred feature in a build environment because can improve comfort, health, and productivity. This preference for daylight is since humans are diurnal animals.

e) ***Plants*:** are fundamental for human survival since they are source of food, fibres etc. Their presence in an anthropic space and give a sense og comfort, satisfaction, well-being, and performance.

f) ***Animals:*** are fundamental too for human existence since they are source of food, resources, protection, and companionship. Animals can be included in a build environment by using aquarium or aviaries. Their presence causes satisfaction, stimulation, and pleasure.

g) ***Natural materials:*** these are always preferred over artificial materials, also if these are a good ocpy of the natural ones.

h) ***Views and vistas:*** people prefer to see outside, especially on natural environments.

i) ***Façade greening:*** green walls and roof often provoke satisfaction. This because organig material was used in the past as insulation, protection and food.

j) ***Geology and landscape:*** it’s important to make buildings that have a good relationship with their natural context and topography

k) ***Habitats and ecosystems:*** buildings should have a relationship with the local habitats and ecosystems, like wetlands, forests, grasslands and watersheds.

l) ***Fire:*** it is associated to heating and cooking, gives a sense of comfort and civilization, providing warmth and movement, but it is difficult to be included in the build environment.

2.2.1.2 Natural shapes and forms

This element includes the simulations and representations of the natural word. These characteristics are usually founded in the facades and in the interiors. The attributes associated to this design element are 11:

a) ***Botanical motifs:*** shapes, forms and patterns of plants and other organisms are an important design element to be included in the build environment.

b) ***Tree and columnar supports:*** trees are for humans source of foods and building material. It is possible to make columns with a shape like the one of the trees.

c) ***Animal (mainly vertebrates) motifs:*** it is possible to place animal motifs in the interiors and in the facades.

d) ***Shells and spirals*** are elements of invertebrates that can be used in various way in the building. Other invertebrates can be bees (with their hives), butterflies, and others. It is possible to design a building that mimic the processes of the invertebrates (process called Biomimicry). Some examples can be the bioclimatic controls of the termite mounds, the structural strength of shells and the pattern of the webs.

e) ***Egg, oval, and tubular forms:*** these are organic shapes that can be used for some elements of the building and in the landscape

f) ***Arches, vaults and domes*** are elements with a shape similar to some elements in nature, like beehives, nests, shells and cliffs.

g) ***Shapes resisting straight lines and right angles:*** to have a design perceived as more natural it would be better to use natural sinuous forms and not rigid shapes.

h) ***Simulation of natural features:*** this is the tendency to simulate rather than replicate the nature. This is more effective if the simulations are present for a precise scope and not only for decoration.

i) ***Biomorphy:*** sometimes architectural shapes aren’t made to mimic natural shapes but are anyway perceived as organic.

j) ***Geomorphology:*** the building can be designed with a shape that mimic the topography of the context in its proximity. In this way buildings appears fully integrated in the context.

k) ***Biomimicry:*** it is the tendency to use for some purposes functionalities used by other species, like structural strength and bioclimatic proprieties of shells, crystals, webs, mounds and hives.

2.2.1.3 Natural patterns and processes

This element is related to the natural proprieties applied in the build environment, and not representations or simulations. There are 14 attributes:

a) ***Sensory variability:*** the build environment, like ne natural one, should be rich of stimuli like light variability, sounds, touch, smell, and other sensory environmental conditions.

b) ***Information richness:*** people prefer buildings and landscapes rich of information, variety, natural textures, and patterns.

c) ***Age, change and patina of time:*** the build environment, as the natural one, should be free of get old. This characteristic eques familiarity and satisfaction among people.

d) ***Growth and efflorescence*** are characteristics related to the aging of the building. As the point before provokes for people pleasure and satisfaction.

e) ***Central focal point:*** the navigation in a natural environment is enhanced by the presence of a central focal point. This point makes the chaotic context more organized around it.

f) ***Patterned wholes***: people responds well when they are in an environment with variabilities are united by patterned holes.

g) ***Bounded spaces:*** humans prefer to be in bounded spaces because is a territorial tendency developed over their evolution and gives a sense of security.

h) ***Transitional spaces:*** these areas in the middle between a natural and an artificial environment offer often comfort.

i) ***Linked series and chains:*** linked spaces give a sense of organization and sometimes mystery.

j) ***Integration of parts to wholes:*** people appreciate when in both build and natural environments, some discrete parts comprise a overall whole, especially if this whole have a value higher than the sum of the parts.

k) ***Complementary contrasts:*** contrasting elements are perceived as good for people, like, light and dark, hight and low and open and closed.

l) ***Dynamic balance and tension:*** a sense of strength and durability is given by the dynamic balancing of different and contrasting forms.

m) ***Fractals:*** in nature it is very rare that an element is the exact copy of another, and this should be done also in the patterns used in the building, that can be repeated but also varied.

Fractal geometries, that are the multiple repetition of a single simple geometries in different scales, obtaining as final shape one similar to the starting one, are a perfect example for this.

n) ***Hierarchically organized ratios and scales:*** forms organized in a hierarchically way, like arithmetically or geometrically, like Fibonacci ratio, are perceived well by people.

2.2.1.4 Light and space

This element put the focus on the light and the spatial relationships. There are 12 attributes:

a) ***Natural light:*** daylight gives positive effects to people.

b) ***Filtered and diffused light:*** the modulation of daylight and the mitigation of the glare enhance the benefits of daylight

c) ***Light and shadow:*** contrast of light and dark spaces gives a sense of satisfaction and can create curiosity, mystery, and stimulation.

d) ***Reflected light:*** it is possible to include reflecting elements like coloured walls, ceilings, and reflective bodies like water.

e) ***Light pools:*** are light places that emerge into a dark space. These elements assist movement and way-finding.

f) ***Warm light:*** areas with modulated sunlight immersed in a dark space enhance the feeling of nested, secure, and inviting interior.

g) ***Light as shape and form:*** manipulation of light can create dynamic and sculptural forms. These shapes improve curiosity, exploration and discovery.

h) ***Spaciousness:*** people like to feel the openness of a space, especially if in relation with protected refuges.

i) ***Spatial variability***: improves emotional and intellectual stimulation and it is better if spatial diversity is correlated with organization of the spaces.

j) ***Space as shape and form:*** space can be manipulated to convey shapes and forms. This stimulates interest, curiosity, exploration and discovery.

k) ***Spatial harmony:*** a successful design of the building is the one that combines light, mass, and scale.

l) ***Inside-outside spaces:*** interior spaces should have a connection with the exterior ones. There can also be transitional spaces like colonnades, porches, atrium, and interior gardens.

2.2.1.5 Place-Based Relationships

This element refers to the union between culture and geographical context. The connection of people with places is due to the inherit human need to have a territorial control. There are eleven attributes related to this element:

a) ***Geographic connection to place:*** by emphasizing geological features associated with the siting, orientation and view of buildings and landscapes it is possible to create a connection with the geography of the area that gives a sense of familiarity and predictability.

b) ***Historic connection to place:*** historical buildings and landscapes are symbols of the passage of the time, and this gives to people a sense of participation and awareness of an area's culture.

c) ***Ecological connection to place:*** it is important the t the impact of the build environment is minimal on the natural one, and shouldn't diminish the overall biological productivity, biodiversity, and ecological integrity of proximate ecological communities.

d) ***Cultural connection to place:*** this is the connection between places and history, geography, and ecology of that area. The culture is a universal human need.

e) ***Indigenous materials:*** a positive relation to place is enhanced using local and indigenous materials. Local sources can remind the local culture and require less energy for transportation.

f) ***Landscape orientation:*** buildings and landscapes should be connected to the local environment and emphasize its features, such as slope, aspect, sunlight, and wind direction.

g) ***Landscape ecology:*** some design can be able to improve and reinforce the local landscape ecology over the long term. Landscape structure, pattern and process should be considered.

h) ***Integration of culture and ecology:*** the mix between culture and ecology, so humans and nature, gives as result a long-term sustainability.

i) ***Spirit of place:*** it signifies the meaning that people give to a natural of built environment.

j) ***Avoiding placelessness:*** the "Placelessness" is the opposite of place-based design and should be always avoided. Buildings that are not connected with the biocultural context resulted in a decline of the relationship between humans and nature and sustainability.

2.2.1.6 Evolved Human-Nature Relationships:

The attributes related to this element are focused on the inherit human relationship with nature. The attributes are twelve:

a) ***Prospect and refuge***: the refuge is the ability of a space to provide a protected setting, while the prospect is the ability to see distant objects habitats and horizons.

b) ***Order and complexity:*** order can be reached by impose a structure and an organization to a space, but to avoid the missing of variability some complexity in the design can be added.

c) ***Curiosity and enticement:*** curiosity reflects the human need of exploration, discovery, and mystery.

d) ***Change and metamorphosis:*** change reflects the process of growth, maturation, and metamorphosis.

e) ***Security and protection:*** an environment should ensure protection from the forces of the nature.

f) ***Mastery and control:*** constructed landscape reflects the human desire to have a control over the nature.

g) ***Affection and attachment:*** Buildings and landscapes that elicit strong emotional affinities for nature are typically recipients of lasting loyalty and commitment. Furthermore, buildings must be perceived cool for people in order to have this effect and should not only have a low impact on the environment.

h) ***Attraction and beauty:*** the aesthetic attraction to the nature is very strong for humans and buildings and landscapes should be able to foster this aesthetical appreciation.

i) ***Exploration and discovery:*** buildings and landscapes should facilitate the opportunities for the exploration of the nature since it is the most information-rich and intellectually stimulation environment that humans ever encountered.

j) ***Information and cognition:*** Design that emphasize the shapes and forms of the nature, and gives to people direct and indirect stimuli, can improve intellectual satisfaction and cognitive prowess.

k) ***Fear and awe:*** the protection from risks present in the natural environment has always been a primary objective of the buildings. It is possible to include in the buildings elements that gives a sense of risk to people that live in them.

l) ***Reverence and spirituality:*** humans need to establish a relation to creation. Buildings should defy the feeling of being alone in the space and time.

Currently, all these attributes are applied in the design of the buildings with two different schools of thought. The first one uses the classical industrial design but incorporating in it natural features following the biophilic design guidelines. The second one, instead, uses innovative building materials, surfaces, and geometries to create a neurological connection with the users, and is more like traditional vernacular architecture. The two methods are different, but both are contributing to recreate the almost lost connection between humans and nature (Kellert, Heerwagen and Mador 2008).

Green outdoor areas should be placed as close as possible to buildings and should include water bodies and trees. The latter can also be fruit trees, like blueberries, raspberry bushes etc., so that people can take fruit from them and so can have a higher level of contact with nature. Also creating open lawns can be good for active play or sunbathing, and the presence of benches near the pathways, maybe shaded by trees, can be very good especially for elderly people. Furthermore, the pathways in the designed landscape should be pedestrian and cycle only, and connected to the main parks, natural areas and services near the site (Kellert, Heerwagen and Mador 2008). In case the access by car to the site can't be avoided it should be discouraged by proposing a layout of the street that consent the passage of the cars only at low speed and by giving the priority to pedestrians.

It should be also taken in account that the landscape preferences are influenced by human evolution. There are places where people have the innate sensation to feel more in comfort, and this is due to the presence of some characteristics that are unconsciously perceived as positive for the survival of the person. In general savannah-like landscapes are the preferred one, but this can vary by cultural influences and experiences, ethnic groups, genders, and ages. For example, different ethnic groups interact with nature in different ways; women perceive higher stress than man, and so the influence of the natural stimuli is perceived as different; and gains from nature are in general higher for young people than for older (Terrapin Bright Green 2014).

Another place where people feel in an innate way in comfort is the refuge. This place has always been essential for the human life, since it is a small, enclosed area where people are protected against weather and predators, and where can get food and water in safety. The refuge should have also a big view to outside, that is what it is called prospect, that is useful to see resources and dangers outside and to understand the time by the changing of the light. The refuge is so small and dark, while the prospect is expansive and bright, and these two elements can’t coexist in the same space. This characteristic can be implemented in the modern buildings especially in the interiors, by implementing spaces with low ceilings, with opaque walls on three sides and low levels of light (refuge), that have an open view on a larger space well illuminated and with a high ceiling (prospect). The preference to be in a refuge or in a prospect depends on the gender, women generally prefer to be in refuges, while men in prospects (Kellert, Heerwagen and Mador 2008).

Also, the streets can be useful to improve the biophilic design, since they are not only an infrastructure for the cars, but also places that harbour native plants and biodiversity, that can treat stormwater and where pedestrian are in contact with the nature. So streets should have green spaces where plants are free to grow, and so maintain the biodiversity of the area, and at the same time these permeable spaces are useful to collect and treat rainwater. Of course, the greenery along a street is not sufficient to have an experience in the nature, and for this reason every neighbourhood needs a park that is should be like a forest, with also animals (Kellert, Heerwagen and Mador 2008).

Biophilic design is based on biophilia, that is the love for the life, but a fundamental part of al the living beings is the death, and so to obtain a successful biophilic building it should be included in the design too. So, the design of the building should not include only the assembling of the parts, but also the dismantling of them, that is the representation of the death of the building.

2.2.2 Biomimicry

Humans are used to get inspired by the nature for techniques, geometries, strategies etc… This can be very good for innovations, since the techniques proposed by plants, animals, insects, and nature in general are the results of billion years of improvement and evolution. The tendency to copy and learn from nature is called “Biomimicry”, and the emulation of it is part of biophilia.

The biomimicry is not a style of building or a design, it is a process for finding solutions for a specified problem. In particular, the designer that is in front of that problem looks for an organism or ecosystem that had the same problem but developed a technique to solve it in the best way possible. Once found the solution proposed by the selected organism or ecosystem, the challenge is to apply it on the design of a building or an element in general, because with our technology, we should emulate a process that has been developed by nature through millions of years. Anyway, the final aesthetical results may or may not look organically or visually resemble to the organism from which the lesson came. An example could be the solar cells, that have a function inspired by the photosynthesis of the leaves but have a totally different appearance. The presence of decorations with natural shapes, like leaves, feathers, insects etc, that have only an aesthetical purpose are simply artistic mimesis of nature and not biomimetic one (Kellert, Heerwagen and Mador 2008). The goal of the biomimicry is to create an object that works in the same way an organism works, but without necessarily looks like it, so this object can for example provide by itself the energy that it needs, repair and clean itself etc… Furthermore, for the design of the same object or building, bio-inspired solutions coming from multiple organisms can be applied together to solve multiple problems.

To use biomimicry in a design, the designer should focus on three aspects of the organism that he wants to copy (Kellert, Heerwagen and Mador 2008):

Form: why an organism is using that shape?
Process: how does this solution works and how is it made?
Ecosystem: how does this solution fit with the whole?

The best way to apply this inquiry is to follow these five points (Kellert, Heerwagen and Mador 2008):

a) ***A functional survey at every site***: study the organism on its site and understand how it takes water and food, how it builds its home, how it communicates etc. Organisms can tell more about sotie conditions than any text.

b) ***Biologist at the design table:*** biologist can answer to question related to how an organism is able to do specific things, like track the sun, filter salt out of water etc.

c) ***A biological filter for all design decision:*** for every decision the designer should ask himself if what he have proposed is safe and usable for a long period of time, reflecting what natural selection do, that is eliminate what is not working properly.

d) ***A biomimetic innovation credit in building-rating systems (e.g., LEED):*** rewarding a good behaviour of a person with some advantages would be a great route to well-adapted buildings.

e) ***A thanksgiving loop:*** a percentage of proceeds or savings can be spent for the preservation of the habitat of the organism that inspired the innovation proposed by the designer.

By applying biomimicry in the buildings, people can feel more in contact with the nature, because it is not only a matter to see some plants or organic forms, but it is also a matter to be in contact with the elegance and the simplicity of the natural design, as well as the fact of having elements that work without human intervention, like the self-sufficient wild places (Kellert, Heerwagen and Mador 2008).

Despite biomimicry is not decorative and the aesthetic results can sometimes not be organic, it may happen that these two characteristics can be present together in the same product, and an example can be the objects that have been made by inspiring to the structures of the bones or the trees. These two elements can change their shape during the time by removing material in places where is no needed and adding it where there is more stress, following a process called biological optimisation. The final shape is the result of natural selection over millions of years, and it is also the visual representation of the stresses acting on the organisms.

The structures adapted to the loads by the error strategy, that creates a better design after failures, and by the self-repair and adaptive growth, that reinforces the points with the higher local stress and repair the failures, process that gives a more homogeneous stress distribution in all the structure (Kellert, Heerwagen and Mador 2008) (Mattheck e Tesari 2002).

The biologist Claus Mattheck studied this self-strengthening mechanism and proposed three structural engineering software for the design of objects that take advantage of this characteristic of bones and trees. The concept of these software is to design objects haven't a solid geometry, but can have some holes in their structure, and at the same time they can support the same stresses of the solid version but using much less material. This design process follows three steps that mimic the natural process (Mattheck e Tesari 2002):

A) ***Soft Kill Option (SKO method):*** is the topology optimisation by coping the adaptive bone mineralisation (the ability to adapt to different loading conditions), and it is useful to find an optimal design proposal.

B) ***Computer Aided Optimization method (CAO method):*** is the shape optimisation by simulating the adaptive biological growth. By inspiring to the trees, this methos avoids local stress concentrations on the surfaces, making the stress distribution homogeneous, and so preventing failures.

C) ***Computer Aided Internal Optimization (CAIO method):*** is the optimization of the composite material by optimizing the fibre arrangements, minimizing the shear stress in between the fibres, mimicking the structure of the trees. This, as CAO, minimise the failure risk.

This process has been applied by Mercedes-Benz to make a prototype of car 40% lighter than others car, and by the designer Joris Laarman designed a chair with an organic shape. The aesthetical result of objects made with this technique is absolutely organic and so there is a coexistence of biomimicry and biophilia (Kellert, Heerwagen and Mador 2008).

Other biomimicry solutions can be the ones for keeping daylight in the buildings, coping solution used by sponges that live in the deep sea to get light. Furthermore, windows can also be useful to gather the solar energy by using flexible films that use a process similar to the photosynthesis. The energy gained is less than the one obtained by using traditional PV panels, but this technology is less toxic and cheaper to produce (Kellert, Heerwagen and Mador 2008).

For the ventilation an important lesson can be learned by the mounds of the termites. They are able to make channels that move surface air into the deep of the mound, and at the same time hot air can be expelled through a chimney by the use of Venturi effect, present thanks to the sun that heat up the mound above. The pipes (bronchial tubes) used to take and exhaust air are able to regulate humidity and maintain a constant temperature at about 30°C, while outside temperatures can be from 3°C to 42°C. A solution similar to this has been applied by the architect Mick Pearce and the engineers of the Arup group in a building without air conditioning in the Zimbabwe, obtaining a use of energy 35% lower than six conventional buildings of the same city combined, and a ventilation system that costs 1/10 of the one of a comparable air-conditioned building. The atrium of the building, ductwork and hollow floors mimic the bronchial tubes, the floor slabs mimic the mud, and 48 chimneys let rising air escape (Kellert, Heerwagen and Mador 2008).

Some elements of the building, in particular the interiors, can be coloured without using pigments, but by using the structural colour, that is a strategy used by a large number of insects that consists in a certain amount of overlapping structure layers that reflect bend, bounce and diffract the light, to create brilliant and metallic colours. This works because some wavelengths can penetrate trough some layers and in others they are reflected. Structural colours are generally able to change colour at the variation of the angle for which people see this object and at the variation of the angle of the source of light. This variation of the colour can improve the biophilic effect of a space, since it reflects the tendency of the natural environments to change their colours hours per hours at the changing of the position of the sun in the sky (Kellert, Heerwagen and Mador 2008).

Plants in the build environment are not useful only for giving a visual connection to nature but can gives some beneficial effects such as filter wastes, absorb excess water, mask sounds and purify air (Kellert, Heerwagen and Mador 2008). Plants can also be used for phytodepuration, a process able to clean wastewater, by mimic the self-purification principle typical of the aquatic environments. The solution consists in a basin where the wastewater passes through and the aquatic plants transfer atmospheric oxygen into the aqueous basin, favouring the growth of an aerobic bacterial flora, the true protagonist of purification, which eliminates the pollutants present in the wastewater through biochemical agents. This process can substitute the traditional sewer, and the resulting water can be redistributed in the soil or in a water stream or can be used for irrigation.

This solution requires a big place of land, but this, by the passage of the time, and the growth of the plants, becomes totally integrated with the context, also attracting animals and insects, and so improving the biodiversity of the area. This process can be used also inside the building. An example is the Bertschi school in Seattle, where the soapy water coming from the bathrooms pass through a vertical green wall, where the plants totally clean it. This solution requires 3m² of surface for every habitant, that is less than the surface requested by a traditional horizontal phytodepuration system.

Biomimicry can be applied also in the landscape designs, because landscape can be designed in a way to connect some green areas in the city that are disconnected each other, and in a way to create green corridors for the animals, mimicking and restoring the uncontaminated natural environment (Kellert, Heerwagen and Mador 2008).

2.2.3 Principles of Biophilic design

It's not important the number of interventions to reach biophilic design and wellbeing of people, but the quality of the interventions. In addition, there is also a minimum exposure duration to the goals proposed by biophilic design (patterns) in order to take benefits from them, that generally it is from 5 to 20 minutes. This period can be long in some cases, and so, to reach it, it's possible to put the patterns along paths where people pass frequently. In addition, biophilic design is not appliable only on a single space but can be applied also on an entire district (Terrapin Bright Green, 2014).

Different biographies suggest a bit different goals to be reached to gain a successful biophilic building, but all of them are of course based on the fundamental concepts of biophilic design explained in the previous chapters. These goals are just suggestions, not mandatory characteristics to be applied on the buildings, and it is up to the designer to decide which of them are good or not for his projects.

Here the goals suggested by Stepheen Robert Kellert, Judith Heerwagen, and Martin Mador, in their book "Biophilic Design: The Theory, Science, and Practice of Bringing Buildings to Life":

a) The smallest perceivable scale is established with the microstructure of natural materials or by using very fine-grained texture or ornament, and the area containing these fine details must be accessible by human contact. This rule refers to the use of fractal geometries.

b) Design should respect a hierarchy for the scale for the elements. In particular every time that the scale changes, the nest one should be 2,7 times bigger than the previous one, or at least between 2 and 5 times.

c) Symmetry should be applied in the design, not in an overall scale, butt applied on smaller and intermediate scales.

d) For small buildings: natural materials that have been used for the construction of the building should not been hided by other materials like plasterboard, in a way that people can be in contact with them also by the touch. In general, it would be better to use as much natural material as possible, also by substituting concrete and steel with wood.

e) For big buildings: this typology of construction requires industrial techniques, that don't give to people any sensation of nature. Pattern used by Guimard, Sullivan and Wright on the modular panels produced in the nineteenth century were neurologically engaging and could be a good inspiration also for the present modular buildings.

f) Natural materials from older buildings can be reused. Also raw and natural non-modular materials can be included, in a way to don't show a human control over the nature.

g) Concrete, if indispensable in the building, should be manipulated in a way to give the sensation to be a natural material, maybe by allying a pattern on the surface.

h) When possible, the workers should be left free to express their personal taste during the construction of the building.

i) Computer can be used to generate alone some components of the building. Computers are able to create components with high variability of characteristics, that is what happen in nature, where standardized modules don't exist.

j) Standard materials and components that don't have a fractal geometry can be used anyway in a building, but should be reconsidered in an innovative way that is able to provide an high degree of neurological connectivity.

k) The shape of the building can be more meandering and can be surrounded gardens, verandas and patios. Also, an indoor garden can be present.

l) The natural geometry formed by the growing of the wild native plants and the signs of the passing of the time, like the weathering and the invasion of plants, should be maintained as sign of increasing life.

m) Green spaces must be physically accessible by people and sidewalks should not be exposed only over the asphalt, but also over natural elements like trees.

n) Biodiversity must be maintained, and the parks shouldn't have only a decorative purpose.

Shown below there are the goals proposed by Terrapin in "14 Pattern of Biophilic Design, improving health & well-being in the built environment". The following goals are the ones that have been followed for the realisation of this project, but anyway also some suggestions proposed by the previous authors have been followed. The 14 goals (patterns) in this book have been divided in 3 main categories (Nature in the space patterns, Natural analogues patterns and Nature of the space patterns) and the effectiveness and reliability of every pattern has been evaluated based on the available scientific research. Of course, the patterns with stronger scientific evidence of their effectiveness are the ones that must be implemented in the building.

2.2.3.1 Nature in the space:

This main topic addresses the direct, physical, and ephemeral presence of nature. It includes the presence of plants, water, animals, breezes, and sounds. The connections with the nature must be strong and can be reached through diversity, movement, and multi-sensory interactions.

a) ***Visual connection with Nature:*** A space with a visual connection with nature can be stimulating and calming, can give the sense of time, improve the mood and the self-esteem. Looking down a slope is the preferred view, and should include copses of trees, flowers, animals, humans, and water. Of course, this can't be reached in a dense developed urban area, but the psychological benefits can improve by increasing the biodiversity of the area and not the vegetative area: 5 minutes of exposure can improve of mood and self-esteem, 10 minutes stimulate heart rate variability and parasympathetic activity (regulation of internal organs and glands), 20 minutes help blood flow and brain activity to return at a relaxed level. The goal of this pattern is to relax eye muscles and reduce cognitive fatigue by prioritizing real nature over simulated nature, biodiversity over area or quantity, providing visual connection to nature that can be experienced of at least 5-20 min a day, and avoid blockings of the view when seated.

b) ***Non-visual Connection with Nature*** represents the sounds, aromas and textures that create the sensation to be immerse in the nature. This pattern can reduce blood pressure, fatigue, and stress hormones and can also improve mental health and motivation. Sounds coming from nature can guarantee a physiological and psychological restoration 37% faster than noises from the urban environment. Design considerations to apply this pattern in include prioritizing natural sounds over urban sounds, be easily reachable to spend 5/20 min a day there, prioritize interventions that can give a non-visual connection in multiple ways, and in simultaneity with visual connection to nature.

c) ***Non-Rhythmic Sensory Stimuli:*** This pattern focusses its attention on the looking behaviour, in particular the periphery vision movement reflexes. Staying a long time in front of the screen of the PC with a short visual focus, makes the eye’s lens round, contracting the muscles of the eyes. If this happens for a period longer that 20 minutes, will occur fatigue, eyes strain, headache, and physical discomfort. To avoid this, and let the muscles of the eyes relax, it’s necessary a visual or auditory distraction that let the people move the eyes from their pc for at least 20 seconds and see to a place distant at least 6 m. This element is continuously experienced when a person is surrounded by nature and receives non-rhythmic stimulus, but this effect is weaker when the natural environment where the person is, is extremely manicured and deliberately predictable, like in the urban environment. Design considerations to apply this pattern: stimuli should be present every 20 minutes and should let a person focus to a place 6 meters away for about 20 seconds, be experienced every time of the year (not only seasonally), use plants that attract bees or other insects, movements must be stochastic and not something repetitive. Movements are better perceived by peripheral view than by the direct one, and movements of mechanical elements are perceived as something neutral or negative, while the movement of a natural element is always positive.

d) ***Thermal and Airflow Variability:*** provides a refreshing, active, alive and comfortable feeling; natural ventilation in a working space improves comfort, concentration and productivity and a variability of temperature, ventilation and humidity is preferred compared with the mechanical ventilation system. The positive effects coming from natural ventilation can be improved by adding a variation of light and sounds, and by permitting to the users to control the indoor climatic conditions, also by operable windows. Design considerations to apply this pattern include incorporation of ventilation, different thermal conductivity of materials, daylight, mechanical ventilation and operable windows to increase variability in the space; organize the variability in a way to reach thermal comfort and so reduce energy demand; allowing users to modify the thermal condition of the room will increase the range of acceptable temperatures by two Celsius degrees above and belove the limits of thermal comfort; good schematic design is important to reach this goal.

e) ***Presence of Water:*** Fluidity, sounds, and light coming from water, and also the possibility to interact with it, makes the space more stimulating and with a sensation of calm. Water reduces stress by reducing blood pressure and can also improve concentration and memory restoration. These effects and the restoration from cognitive fatigue are given by the multisensory experience given by water. To enhance this effect, it is advised to prioritize water movement while avoiding high turbulence (it can affect acoustic quality and RH) and consider effect on energy use.

f) ***Dynamic and Diffuse Light:*** Different light conditions give different psychological responses. The sunlight has different colour by the period of the day, yellow at morning, blue at midday and red in the afternoon. In presence of blue light, the body produces serotonin, and when blue light is absent melatonin; the balance of these two elements improves sleep quality, mood, depression, and health in general. The movement of light due to shadows or reflections attract the attention of a person, and as explained in the previous pattern, this causes benefits for workers. In the design, it is advised to use dynamic light conditions help transition between indoor and outdoor spaces, avoid drastic changes, and consider circadian artificial lighting where people stay for long time.

g) ***Connection with Natural Systems:*** Good connection with natural systems gives a sense of linkage between user activities and the local natural environment. This can be complemented by capturing and using rainwater in an evident way, providing visual access to existing natural systems or create them if needed, include interactive opportunities, horticulture programs, community gardens.

2.2.3.2 Nature analogues

This main topic addresses to organic, non-living and indirect evocations of nature. All this can be reached by the use of objects, materials, colours, shapes and pattern that can be found in nature, and also by mimicking natural elements. The experience is stronger if the stimuli are perceived in an organized and evolving way.

a) ***Biomorphic Forms and Patterns:*** Organic and biomorphic forms are preferred by people and the view of them enhances concentration and reduces stress. The objective of the pattern is to design elements in the build environment that have characteristic connected to natural elements. This can be made by the application of Fibonacci series or Golden Section, both solutions found in nature. The pattern can be used as decoration and/or also applied on the structure or on the design in general, considering that they should be in 2 o 3 planes or dimensions, avoid overuse of repetitive patterns, and consider them from the beginning of the design.

b) ***Material Connection with Nature:*** Natural colours and materials have an impact on the cognitive performance, comfort, and relaxation of people. The more in a space there are natural elements and colours, more the effects are enhanced. Design considerations to apply this pattern include the definition of quantities of natural materials and colours based on the functions of the spaces, provide variability of material and colours even in the same space, real natural materials are preferred over synthetic materials, incorporation of colour green (the most effective one for this pattern) improves the creativity in the space.

c) ***Complexity and Order:*** The objective of the pattern is to provide symmetries and fractal geometries, combined with a hierarchical organization of the spaces. All of this gives a positive psychological and cognitive response. The design must prioritize artwork, materials, schemes with fractal geometries and hierarchies, this can be achieved using computerized tools, however, the overuse of fractals should be avoided as it can produce negative effects

2.2.3.3 Nature of the space

This main topic is related to the spatial configurations in nature and includes the innate desire of be able to see beyond the surroundings, and the fascination to dangerous and unknown elements.

a) ***Prospect:*** Space with a good prospect guarantees a sense of opening, safety, and control. Due to evolution, people prefer the view on a certain environment over another. For example, environments that look like savanna are preferred, especially if combined with copses of trees, water and flowers, the latter seen subconsciously by humans as symbol of healthy plants. The best view is on a prospect distant more than 30 m. The goal of this pattern is to give to people a sense of control and safety of the area, so it would be better if the view comes from an elevated position. It is advised to orient the building to maximize the views outside and inside, design landscape as a savanna like ecosystem (trees, water, and human activity), guarantee a view to a place 30 m far, removing visual obstacles, having glass walls for stairwells along the perimeter, elevate perimeter or interior spaces by 30/45cm.

b) ***Refuge:*** This pattern is important for restoration experience and stress and fatigue reduction; it also offers to people a sensation of safety. The objective is to provide to people a safe and protective environment that is a portion of a larger space. The access to the refuge must be visible and people should be protected on 3 sides, one side should have a contact with the rest of the environment for surveillance. Common attributes of Refuge conditions are weather/climate protection, speech or visual privacy, different and controllable light settings, lowered ceilings; and is required for areas of reading, reflection or meditation, complex or cognitive tasks.

c) ***Mystery:*** This pattern comes from the need of the people to understand and explore the space where they are. Mystery generates a very positive response in the brain because a mechanism of anticipation is created, where the person tries to imagine and guess what there could be hid behind a corner, for example. This pattern creates more curiosity for people in the space. The exploration reduces stress and improves restoration; curving edges are more effective than sharp edges for the exploration, dramatic shade and shadows can enhance mystery; natural environment changes characteristic over the time, it's necessary to verify if they maintain their mystery conditions.

d) ***Risk/Peril:*** Being in front of a situation with a controllable risk, is positive for people, because in these situations the body produces dopamine. Dopamine supports motivation, memory and problem solving, but an over-production of it causes depression and mood disorder. The objective of this pattern is to arouse attention and curiosity, and refresh memory and problem-solving skills. It is important to consider that Risk/Peril design interventions are not good for all the users, and elements of safety must protect users from harm while still permitting the experience of the risk.

The 14 patterns have been classified on the base of their effectiveness (that depends on the scientific research on them). The categories are 4: high effectiveness, medium effectiveness, low effectiveness, and N/D effectiveness (for the patterns that are not provided of scientific research about them); as reported in Figure 29.

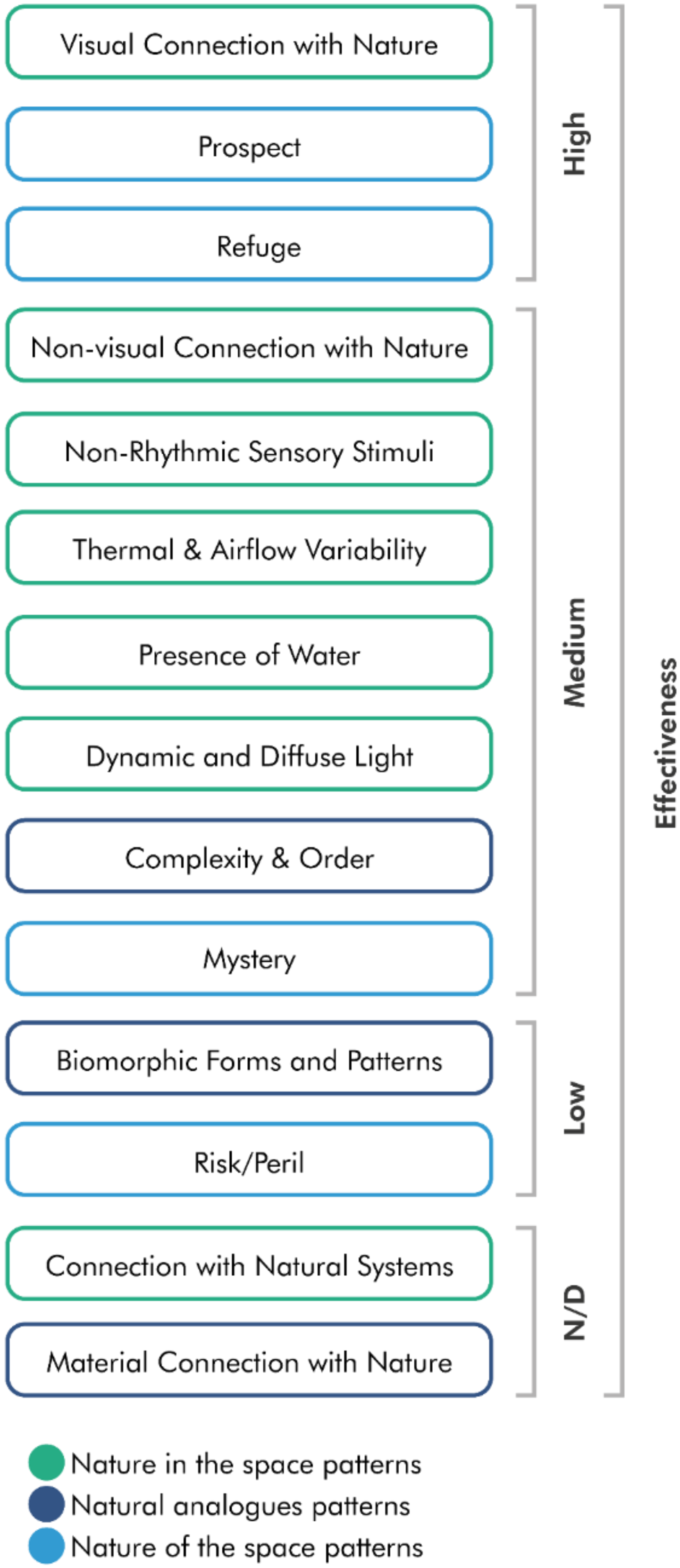


Figure 29: Summary of biophilic design patterns, classified by effectiveness

CHAPTER 3: METHODOLOGY

This chapter describes the nature, structure, and phasing of the research project, while explaining the processes and tools used during the process of investigation and design to obtain objective data for assessment and comparison of different scenarios and proposals.

3.1 Research structure and phases

3.1.1 Diagnostic phase

The research process started with an initial *diagnostic phase*, contained in Chapter 1 of this book, which focuses on the description and analysis of the current state of the physical, social and legal context of the project, identifying the factors that determine the site's problems and opportunities, and surveying previous research and plans for its development covering it at a broader scale; the aim is to understand the initial conditions and the broader implications the research has on its surrounding areas.

The diagnosis was made after a thorough process of bibliographical research aimed to identify the current state of the project site and the previous officially sponsored studies and proposals on the area. Official documentation obtained from City of Philadelphia website, Drexel University website, Brandywine Realty Trust was given priority, along with produced material by their appointed Consulting Team, given their involvement in the ownership and planning process of the area. Also, specific data related to other disciplines was obtained from dedicated institutions, like the Federal Emergency Management Agency and the National Weather Service.

Specific planimetric material of the project site was not available, so the resulting plans and models of the project context were created based on the publicly accessible information from the City of Philadelphia Open Maps platform, satellite imagery and previously generated volumetry by other development teams; Google Street View panoramas of the site and known reference distances were used together following optical and geometrical rules to interpolate information and obtain measurements not reported in other sources (SEE IMAGE).

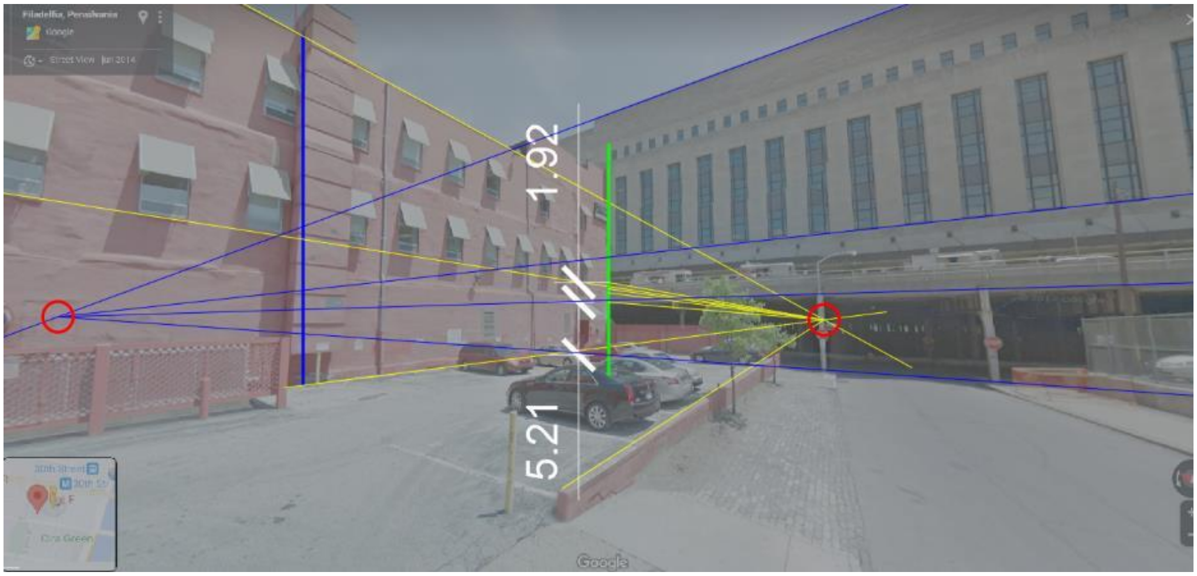


Figure 30: Example of site measurements interpolation using geometrical rules

3.1.2 Exploratory phase

A second *exploratory and comparative phase* was developed in Chapter 2, and comprises the investigation of concepts, principles and strategies already defined in existing literature from diverse disciplines. During this phase, an extensive bibliography about biophilic and high-performance design was analyzed, to draw its main conclusions, strategies, and potential contribution to the project.

3.1.3 Proposal phase

A third *proposal* phase is centered on the generation of a design scheme, based on the conclusions drawn from the previous phases; this proposal is developed at two scales with different aims:

a) An initial *building complex* scale covers the entirety of the project site and sets a preliminary line of strategies and characteristics to organize and guarantee a proper relationship between individual buildings inside the proposal and the surrounding urban context. This is presented as a site masterplan and is mainly focused on the conceptual and strategic framing for the proposal, and the definition of general massing, uses, and open space characteristics to comply to prescriptive requirements at an urban and district level, integrating the project to the broader context current reality and future perspectives.

b) Then, the project at *building unit* scale revolves around one selected building volume to be developed in a more detailed way, covering the architectural and technical development process of spaces, and building components, analyzing, and reporting their behavior and evolution.

   Given the complexity and level of detail at this scale, the building unit to be designed is limited to a maximum of 6000m² of internal area; and despite having a holistic approach towards the project, a set of priorities is stablished so the level of detail in the design is deepened on the building components that have a higher impact on the biophilic and performance aspects of the building.

The generation of the project documentation and visualization was performed using Building Information Modelling (BIM) and Computer-Aided Design (CAD) software; specifically, Trimble SketchUp was used at the first stages of massing of the building complex, while for the later stages Autodesk Revit 2021 was preferred for modelling and analysis of the proposal at both scales, finally, Autodesk AutoCAD 2021 was used for technical detailing.

3.2 Analytical methods and tools

Besides following the prescribed legal and technical requirements enforceable to the project, a Performance Based Design approach was taken during the development of the selected building unit's components, using specific analysis and indicators to predict and compare their behavior under expected scenarios, and determine their individual impact on the performance of the building as a whole; this allowed to make well-informed decisions that ultimately defined the path and outcome of the project proposal. Building performance analysis was carried out using a set of different tools and methods, explained in the following lines:

3.2.1 Lighting analysis

Daylight Analyses intend to quantitatively identify how effectively the building can take advantage of natural light to guarantee visual comfort in indoor spaces, they were based in two contemporary lighting performance assessments:

a) Spatial Daylight Autonomy (sDA) is a yearly study that indicates the percentage of usable space that is expected to receive more than 300 lux of daylight for more than half of the occupied hours (estimated to be between 8am and 6pm), as a standard procedure and following the indications of LEED v4, the study considers as “appropriate” an sDA higher than 55%, and “optimal” a value above 75%. Daylight levels are calculated on a reference working plane of 30 inches (76.2cm).

b) Annual Solar Exposure (ASE) analysis indicates the percentage of space that receives less than 1000 lux of daylight for less than 250 hours a year, a value below 10% is considered satisfactory, but even below 20% could be acceptable. Daylight levels are calculated on a reference working plane of 30 inches (76.2cm).

Both analyses were performed using *Daylight Autonomy (sDA Preview)* tool from Insight Lighting plug-in for Revit 2021, due to its integration with the modelling environment.

Complementary analyses used the *LEED v4 EQc7 opt2* tool of Insight Lighting, which is able to estimate illuminance levels at 9am and 3pm on a working plane assumed to be at 30 inches (76.2cm) above finished floor, during spring and autumn solstices: March 21 and September 21, respectively; threshold for acceptable levels is between 300 and 3000 lux. (Autodesk Insight, 2017)

The lighting analysis results were mainly used on the design optioneering process of shading elements (explained in page 144)

3.2.2 Solar analysis

Solar irradiation on building surfaces was calculated considering both conceptual masses and building elements through Insight Solar Analysis plugin for Revit. This tool uses the Perez Solar Model, a calculation method that takes into consideration the direct solar radiation, diffuse light from the sky and a reflective band along the horizon, including the effect of weather variations.

In the 3D model, glazed envelope systems were converted to opaque walls for the system to be able to calculate the total incident radiation over them, facades were later subdivided in surfaces that represented different conditions, and each surface got an ID number and a grid of points with different values of solar radiation; this data was later combined to obtain average or peak insolation for the entire surface.

The resulting sets of data would be combined to verify insolation levels at the end of the shading elements design process (page 154) and would be useful to estimate the influence of those elements on the reduction of cooling peak loads for HVAC sizing. (page 160)

3.2.3 Peak loads analysis

The Heating and Cooling Load Analysis tool, integrated into Revit 2021 was used to determine the peak loads that separate habitable spaces, and the building, are subjected to; the results obtained from this analysis allowed for an informed selection of the most appropriate HVAC system type and sizing.

The calculation tool uses an Analytical model simplified variant of the architectural model already generated on Revit, considers the location of the project and the thermal properties that have been manually assigned to construction elements; with those inputs it is able to calculate peak loads for spaces and groups of spaces, according to the procedure stated in the 2005 ASHRAE Handbook of Fundamentals, which is different for heating and cooling (Autodesk, 2020).

a) *Heating loads*: are calculated following a steady state analysis, it accounts for instantaneous heat losses due to conduction, ventilation, and infiltration, ignores the delaying effect of thermal mass, the contribution of internal heat gains and the effect of solar radiation. In this way, it considers the worst-case scenario, for example in a winter night with minimum occupation

b) *Cooling loads*: are estimated in a transient calculation, called Radiant Time Series (RTS) calculation method; it calculates the hourly heat gain profile of each component for 24h, separating its convective and radiant components, the radiant component is multiplied by a radiant time series that accounts for the effect of thermal mass on delaying the re-radiation of heat, and the sum of both convective and delayed radiant components is calculated for each hour; the highest value is represented as the peak load, at a specific month and hour.

   In opposition to heating load calculations (that only considers U-values and temperature differentials for estimating heat gains through the envelope), RTS method takes beam and diffuse solar radiation into account, using sol-air temperature in the conductive heat gains calculation; and considering the glazing area, temperature differences, irradiance values and solar heat gain coefficients (SHGC) to determine solar heat gains through windows and skylights.

It is important to highlight that on this procedure, solar heat gain estimations only consider material data from individual glazing elements (area and SHGC) and climate data (irradiance for incident angle); so, the RTS calculation method is unable to consider the shading effect of external elements on glazed surfaces, thus overestimating the amount of solar heat gains and their contribution to peak cooling loads. A workaround to this problem is applied on the post-processing of data (see page 159), using inputs from the previous solar analysis.

3.2.4 Energy performance analysis

The energy performance analysis of the building has been made by using the online tools Insight and Green Building Studio (GBS), both developed by Autodesk, and based on a BIM model created in Autodesk Revit. Insight is useful to optimize various parameter of the building, creating the desired combination, while in GBS is more complex and so has been used only for detailed calculations. For the analysis of the peak loads a specific function inside Revit that takes in account the typologies of use in the building has been used.

After that the BIM model is created in Revit, the first thing is to apply the thermal characteristics of all the rooms of the building. These thermal characteristics specify the occupied area per person, sensible and latent heat production, energy use, occupation, needs of air changes, and other characteristics of the room depending by the use. In the following picture, the values assumed for an enclosed office. All the proposed values have been taken by Revit from the ASHRAE standards.

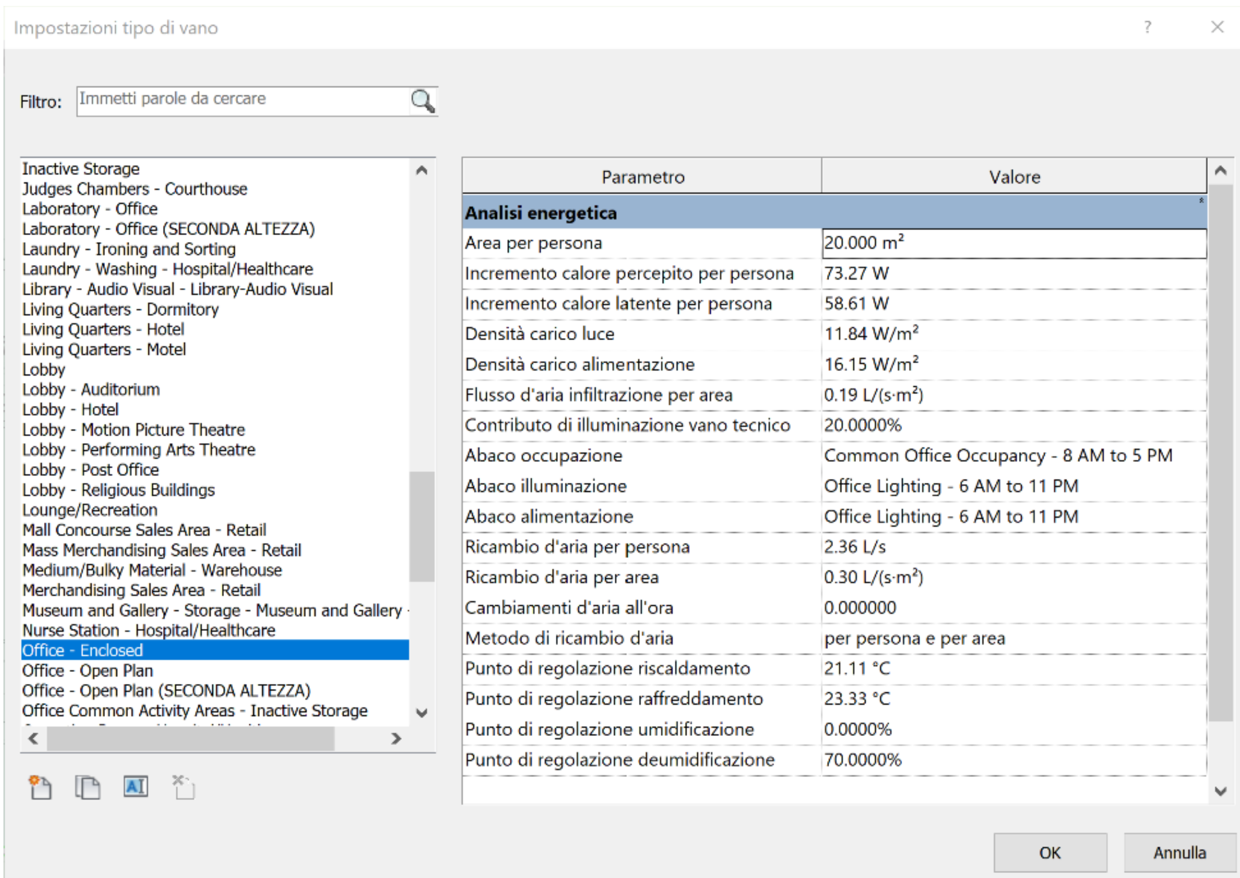


Figure 31: Example of the used data for an enclosed office for the energetic analysis

Only once to all the spaces of the building the thermal characteristics have been applied an energetic analysis can be performed. In the case of this building the first two analysis have been the peak loads analysis and the energy consumption analysis in Insight.

For the peak loads analysis type of building, location, level of the ground floor and design phase must be specified, with also the HVAC system used. By obtaining the peak loads for every room and also the flow rate of air, it is possible to do a duct sizing and also a dimensioning of the HVAC system.

Peak load analysis can't be performed in Insight, and this tool is useful only to optimize the building by changing the characteristics of some parameters, including:

- Orientation of the building
- Window to wall ratio
- Window shades
- Window glass type
- Wall construction
- Roof construction
- Infiltration
- Light efficiency
- Daylight and occupancy controls
- Plug load efficiency
- HVAC system
- Operating schedule
- PV panels

Every of these characteristics can be modified, but only choosing between some options given by default by Insight. For example, the assignable values for the plug load efficiency are 27.99W/m², 21.53W/m², 17.22W/m², 13.99W/m², 10.76W/m² and 6.46W/m², and so it is not possible to assign a value of 12W/m² for example, despite this value is specified in the BIM model. This concept is applied to all the editable characteristics listed before.

The strategy followed in all the three study case of the building analysed in Insight (building with an envelope with the minimum U-values by law; building with optimized envelope; and building with optimized envelope and double skin applied) has been to fix the properties that shouldn't change, like orientation, window to wall ratio, window shade, glass type and walls and roofs construction, and then change the others in a way to reach the lower possible amount of energy consumption.

This process is simplified by the presence of response curves that indicates the parameter with the higher or lower EUI.

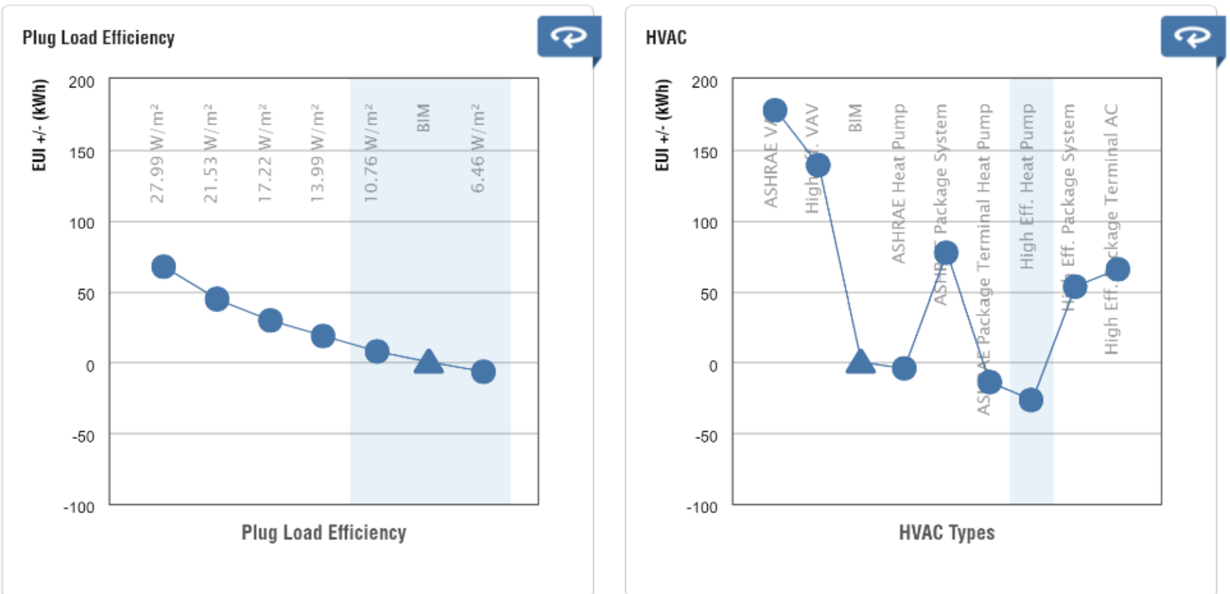


Figure 32: example of response curves for Plug Load Efficiency and HVAC system

After the final optimization in Insight a more detailed analysis has been made in Green Building Studio. This online tool, as for Insight, uses the gbxml file exported by the BIM model to calculated the EUI, but here it is possible to see the distribution of the EUI per element, and not only for the whole building, so it is possible to understand for example how much the HVAC system affects theo verall energy consumption of the building in percentage. This tool has been used also to analyse the natural ventilation potential and also the thermal comfort.

CHAPTER 4: SITE MASTERPLAN

Given the size of the site and the extensive scope of the project, the proposal was organized around two levels: a) a masterplan project covering the entire site area for the organization of the open spaces, massing definition of the complex and use distribution among the built areas, linked to the guidelines of the broader 30th Street District Plan, and b) an Architectural project for one building inside the complex, destined to Innovation and Research facilities for Drexel University, and limited to <6000m^2 to allow for detailed development and analysis. In this chapter, the first level of proposal is discussed, at *building complex scale*.

4.1 Conceptual and strategic guidelines

Based on the results of the context analysis and the selection of a set of main principles for biophilic design and high performance according to the parameters previously explained, a set of proposed solutions was established as a framework for the project design at all levels; the objectives stablished at 30th Street Station District Plan, and the main biophilic principles and patterns identified during the bibliographical research were overlayed, and from their intersection it was possible to generate several specific solutions able to be transformed into tangible design choices.

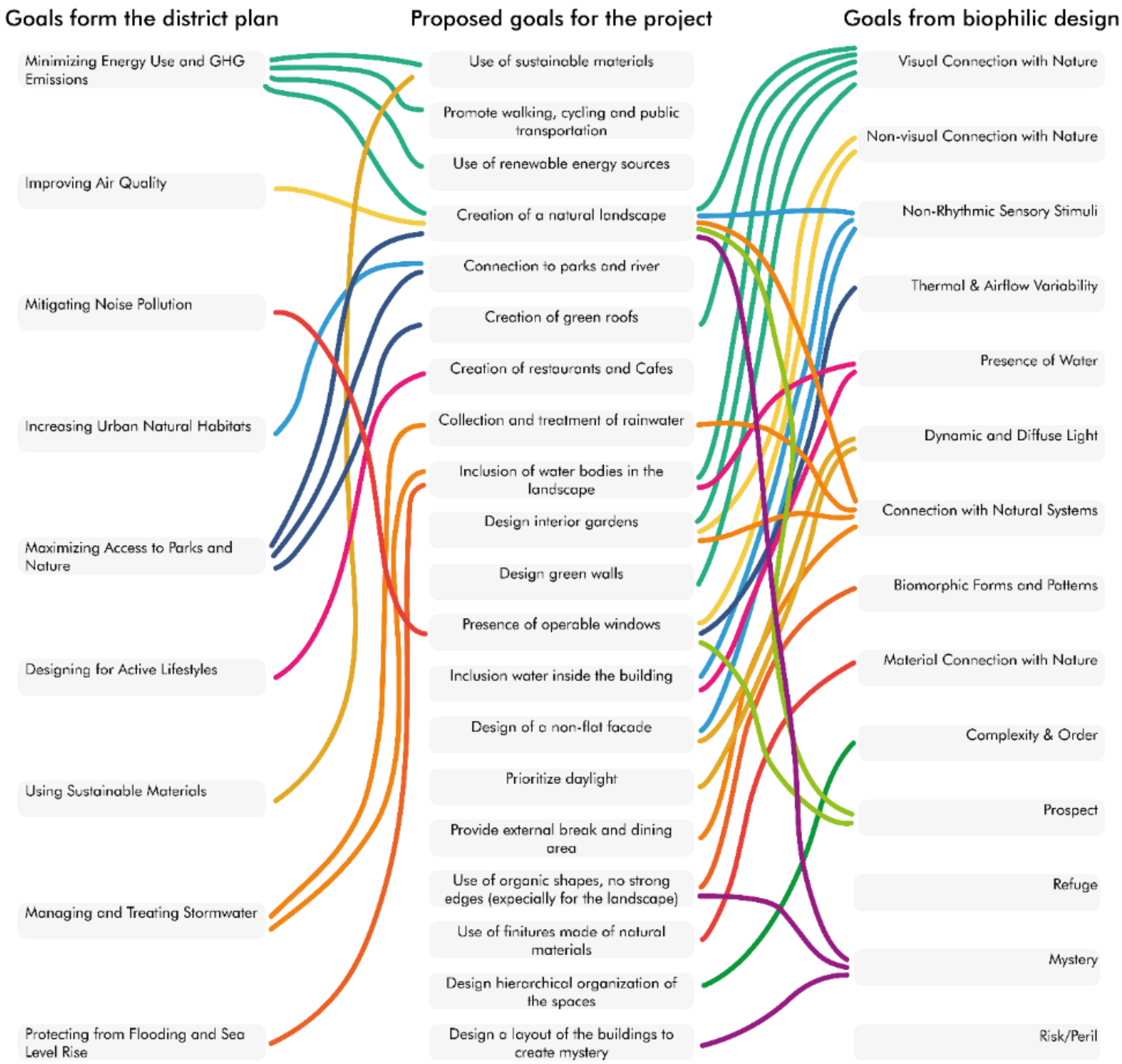


Figure 33: Diagram of proposed project strategies and solutions

The resulting solutions would be applied at different scales, and in coherence with other urban, architectural, economic, and technical aspects to be considered in any building project.

4.2 Masterplan massing

The definition of the masterplan in the site was done following a series of steps that started with the delimitation on the massing allowances given by the Philadelphia Building Code, from which a theoretical massing was drafted to visualize the maximum volumes that could possibly be obtained by applying the maximum allowed FAR, and the minimum required yards and setbacks. This generated group of volumes helped to have an initial idea of the massing possibilities and limitations inside the site.

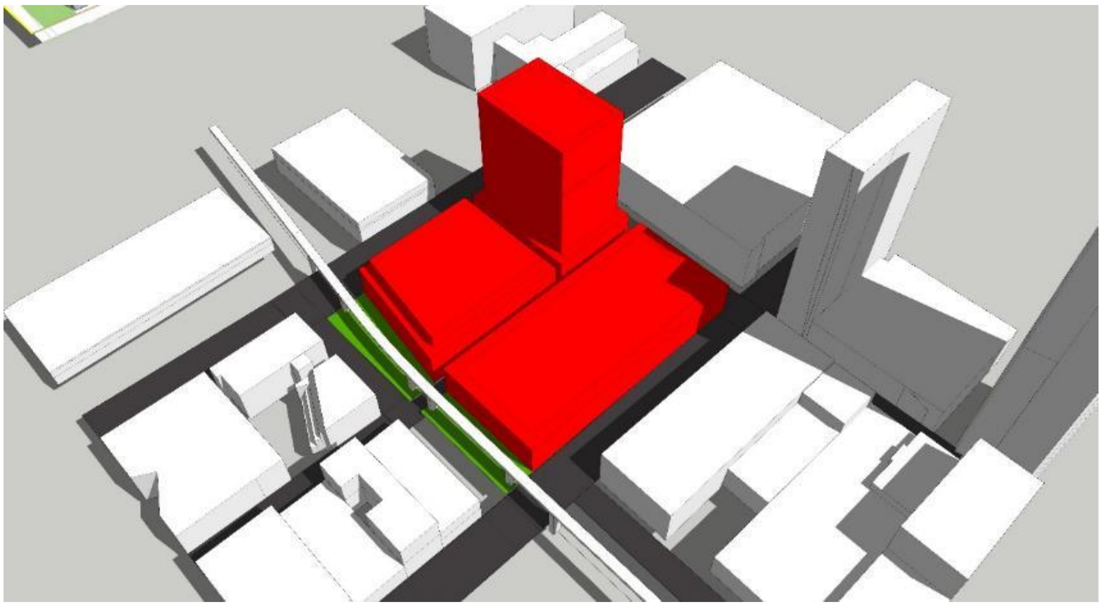


Figure 34: Theoretical site massing with maximized volume and occupation

The resulting model showed a block volumetry in alignment to the surrounding context, able to preserve the regularity of the urban pattern and provide a maximized usable area. However, a particular aspect considered during the design process, was the heavy reliance that biophilic design principles have on the interaction between users and natural elements or phenomena, much of it anchored on the exterior areas; due to this, creating quality open spaces inside the site and between buildings became an essential requirement, and the excessively compact and regular condition of surrounding blocks was to be avoided inside the project site.

From this point onwards, the weighing between positive and negative (or hostile) conditions in the context had a great influence in the location and shape of building volumes and open spaces. In order to provide exterior spaces, the buildings could connect to, while minimizing potential hostile conditions from the urban context (e.g. high noise levels, glare from surrounding surfaces), an enclosed and relatively controlled open area was created at the center of the site, bordered by a "ring" of built volumes that define the block and give continuity to the urban grid.

The exterior face of the built "ring" would define the interface with the public areas of the street and the surrounding context, so several volumetric modifications were applied in order to better adapt to the particular conditions and dynamics at each point of the border, improving the alignment with surrounding buildings through the use of setbacks, and providing openings to allow a natural flow of people from and towards the main attractors nearby, like the Drexel Campus, Drexel Plaza, 30st train Station and surrounding bus stops.

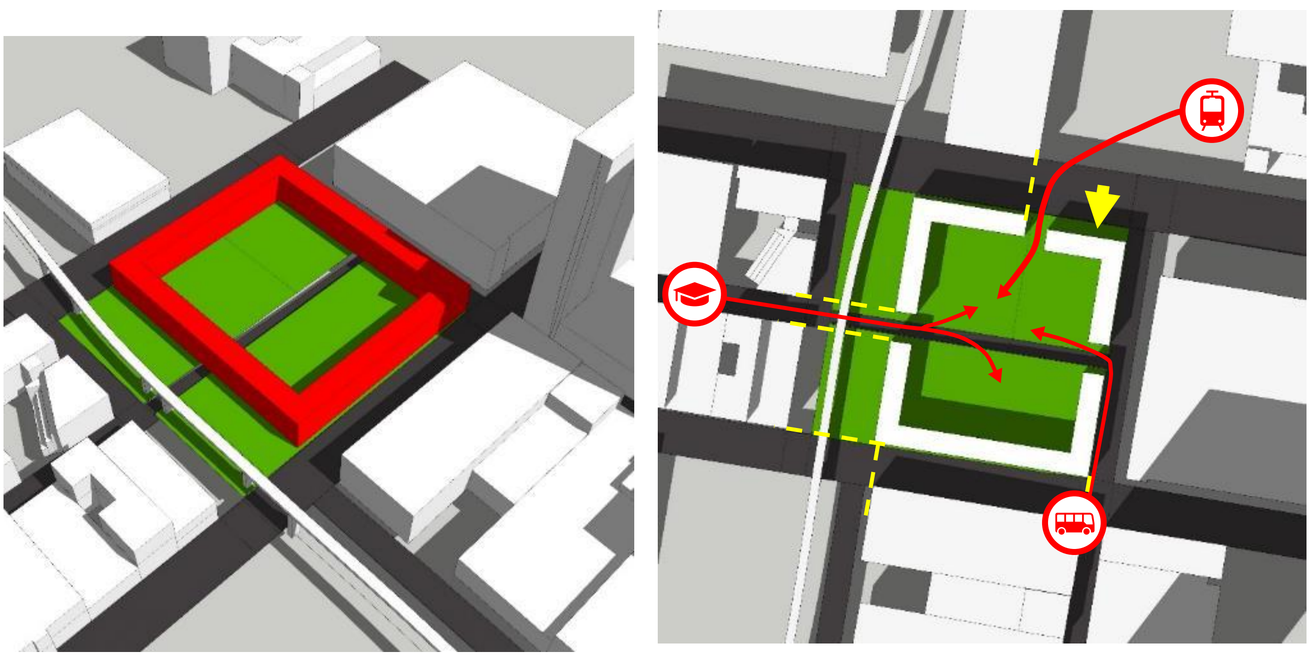


Figure 35: Massing, steps 1 and 2. Block enclosure and openings

The resulting inner space was subdivided in smaller areas that could be differentiated and provide a more human scale, allowing certain *refuge* while keeping *prospect* and long-distance visuals towards the rest of the complex. Then, a pair of high-rise buildings was included in the north block, to provide for more usable area, taking advantage of the increased FAR allowed by the Philadelphia Building Code for CMX-5 zones, and following the guidelines for the Schuylkill Yards development area stated in the 30th St. Station District Plan, which promotes the creation of high-rise buildings in the proximity of the station. Both towers were placed in a setback in relation to the street, to comply with the Bulking and Massing restrictions of the code, and avoid volumes of excessive scale along the pedestrian path of Market Street; in the other hand, buildings in the south portion of the site where kept lower, to better adapt to the heights of existing nearby buildings (outside Schuylkill Yards area) and allow for more sunlight to reach the open spaces in the core of the complex.

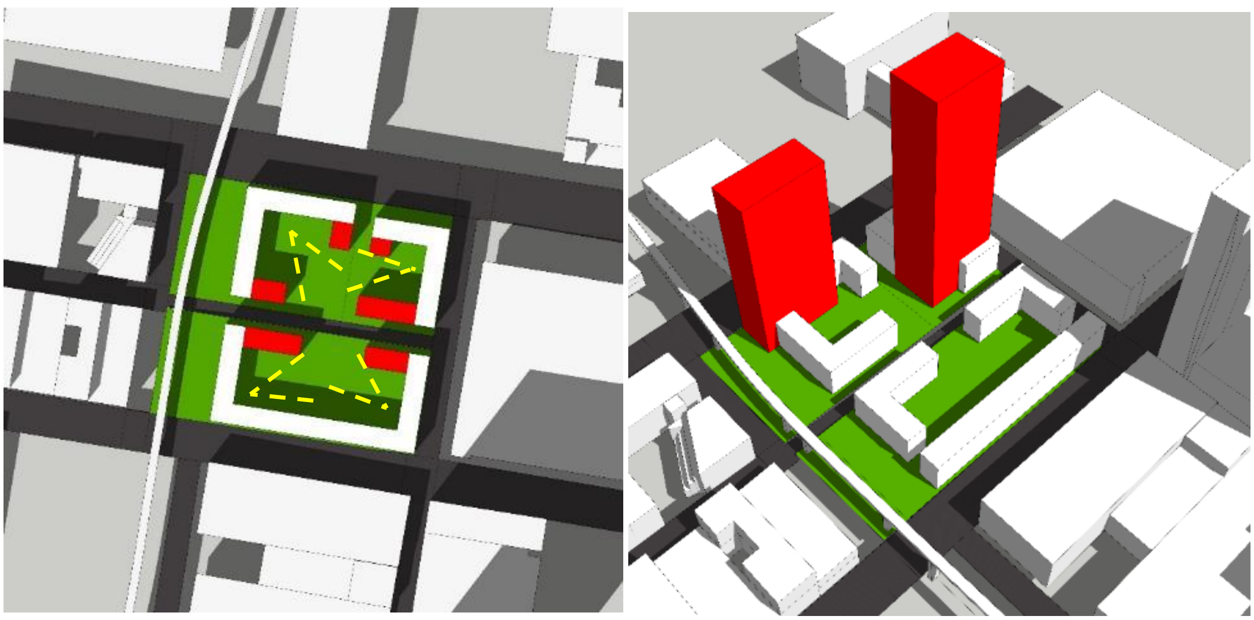


Figure 36: Massing, steps 3 and 4. Block subdivision and towers

Finally, several of the low-rise volumes were enlarged to use the available space more efficiently, get closer to the allowed FAR, and generate more compact buildings with a reduced demand of energy for indoor conditioning, in which the ratio between external surface area and internal volume plays a major role. The resulting massing generates six differentiated buildings, located inside the boundaries of the original lots, while connected by internal open spaces and subspaces that provide an accessible but relatively controlled environment.

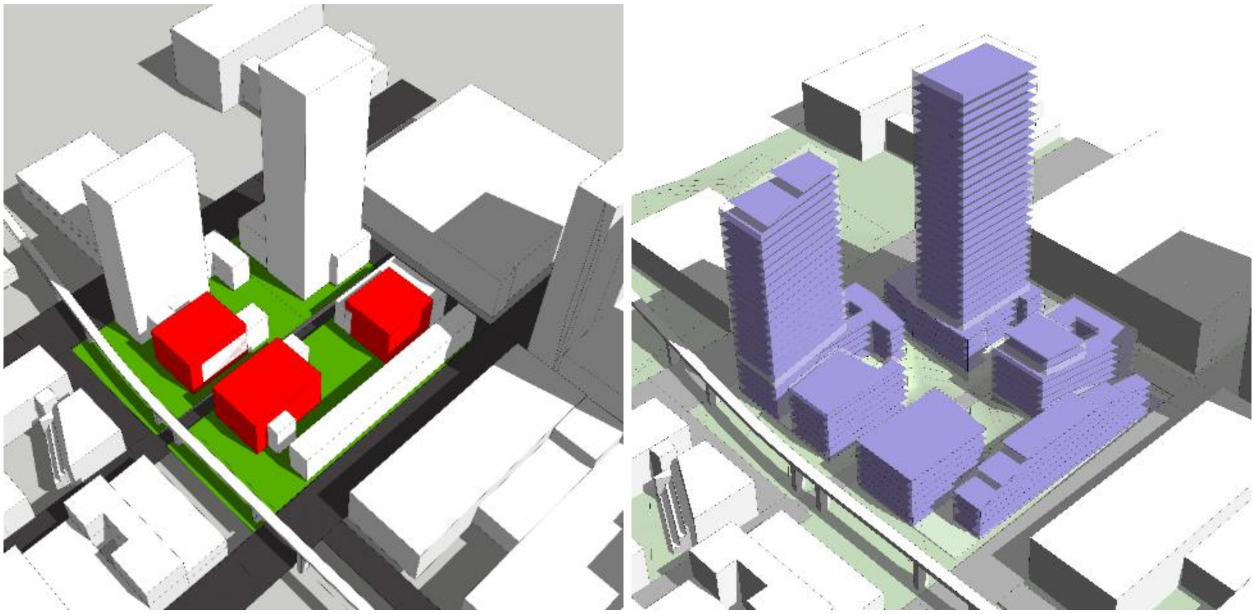
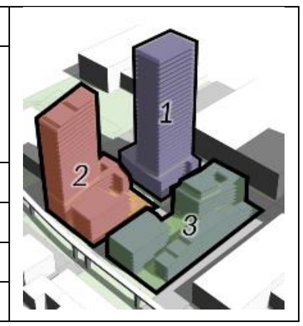


Figure 37: Massing, steps 3 and 4. Increased density and final version

Based on the proposed massing the complex has the following dimensions:

Table 5: Developed area due to massing, by urban plot

		By code*			By design	
Lot number	Location	Zoning	Max. FAR	Max. GFA (m2)	GFA (m2)	**GFA capacity used**
1	NE	CMX5	1600%	63,264.0	46,900.0	**74%**
2	NW	I-2	500%	36,935.0	35,900.0	**97%**
3	S	I-2	500%	45,130.0	29,900.0	**66%**
* Philadelphia Building code						



From the table it is possible to notice that the proposed massing allows for lots 1 and 2 (facing north) to take the most of their allowed gross floor area (GFA), providing maximized usable space in the valuable and active Market Street; meanwhile, the southern lot is less dense, given the lower level of the buildings, to better fit the surroundings and allow direct sunlight to access the center of the block.

4.3 Allocation of uses

The project intends to provide a mixed use and diverse environment that enriches the dynamics of the area, following the goal already set for the Schuylkill Yards neighborhood. The four buildings facing Market Street, 30th Street and Chestnut Street, are dedicated to Retail and Commerce in the lower levels, taking advantage of their extensive frontage toward the street and the green spaces in the center of the site, where significant pedestrian traffic is expected from and to the transit nodes and Drexel University; the upper levels are entirely dedicated to accommodating office space, which is in growing demand.

The remaining two western buildings are reserved for academic and research facilities of Drexel University, as they are very close to the rest of the campus and only directly connected to Ludlow Street, in the center of the site; due to its location and use, both buildings could work as an entrance gate for Drexel campus and an intersection point for the educational and research with the public and industry, enhancing cooperation and boosting innovation.

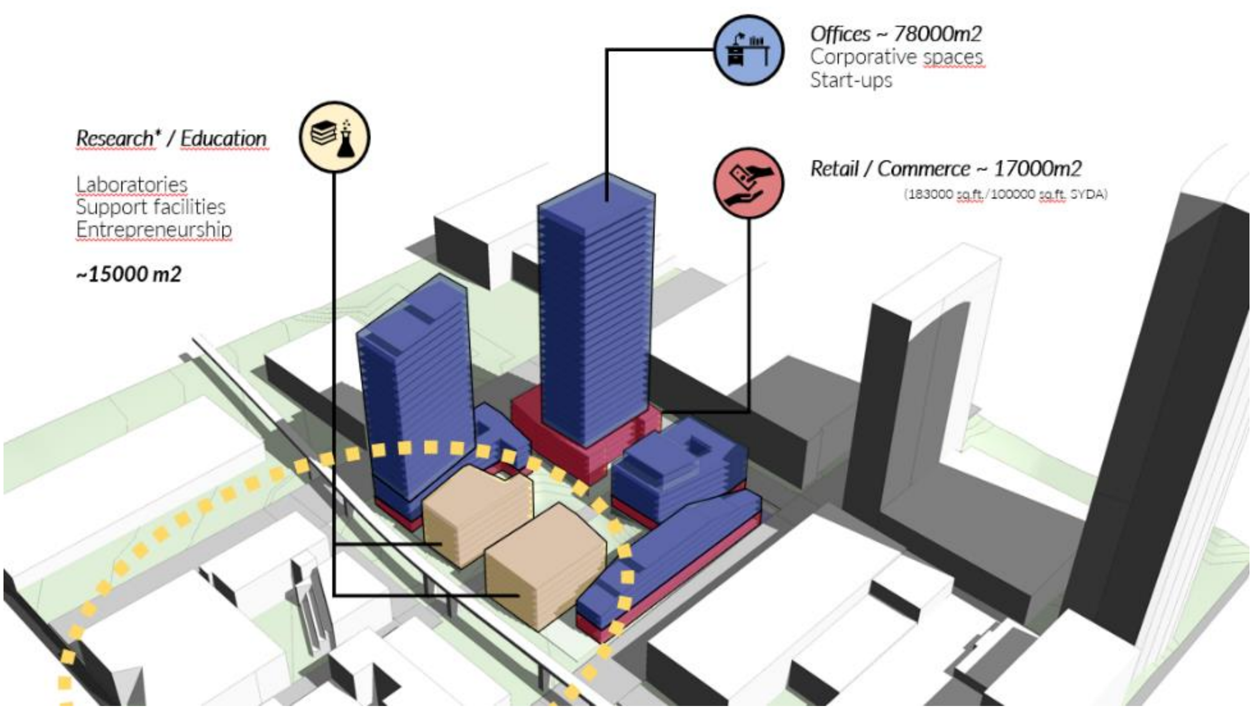


Figure 38: Uses distribution inside the building complex

Beneath all buildings, a podium accommodates parking lots and support facilities, to free up space above ground, while taking advantage of the slightly lower altitude of the terrain in relation to the surrounding streets; the parking facilities themselves are located at level 8m above sea level, roughly 600mm above the Base Flood Elevation (BFE) stablished by FEMA in the area, and the ground floor of the buildings are further elevated 4m, protected from the 500-years floodplain.

4.4 Open areas

In between the buildings, open green spaces look to provide a comfortable exterior environment for pedestrians with the ideal conditions to promote a close relationship between the building occupants and nature. The core of the complex are two central green areas in the center of both site blocks, connected by an elevated structure with greenery that spans above the central part of Ludlow Street to provide continuity in the park area while reducing the impact of street traffic on views, noise and pedestrian links inside the complex; both on-grade green spaces are slightly excavated to allow for water retention and partial infiltration during periods of heavy rain and reduce the pressure over urban drainage systems, one of the retention basins (south) is in fact designed to feature a small permanent water pond in part of the retention area, as a landscape feature, especially useful for cooling down the surrounding air during summer months and provide more comfortable exterior spaces.

Green spaces extend from the site core through the gaps between the buildings and connect with the linear parks along the rail highline already proposed by the development plan, inserting themselves as part of the green network of the district. Paved areas are also provided for pedestrians and cyclist, and one main plaza is in the north half of the complex, to provide space for events as an extension of commercial and business activities on the towers.

Figure 39: Project site view and landscape plan

Figure 40: North-south section of masterplan green areas

The resulting masterplan adds 7418 m² of green spaces to the city (without accounting for green roofs) and provides capacity for the retention and slow release of stormwater, reducing the strain on the drainage system of Philadelphia, which is one of the oldest in north America.

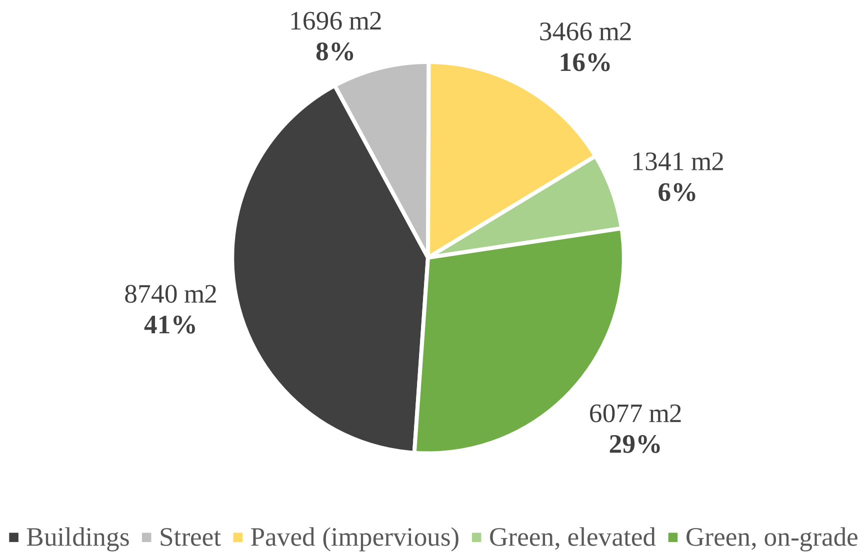


Figure 41: Project site surface occupation by type, from masterplan

Included buildings in the masterplan are set to be designed individually, following the massing indications of this masterplan, and complementing the selected strategies at the building scale. In the next chapter, an architectural design proposal for Drexel Research and Innovation Building will be presented, located in the southwest section of the complex.

CHAPTER 5: INNOVATION CENTER BUILDING

As previously explained, two of the buildings in the proposed complex are entirely dedicated to Drexel University research and innovation programs, in this chapter, the architectural design for one of them will be presented.

5.1 Program and aim.

The objective of this building is to provide spaces for hosting research activities, link both academic and industry innovation projects, entrepreneurships, and technical support to start-ups. Furthermore, inside the scope of this project, the proposed building needs to provide spaces that properly articulate the principles and guidelines of biophilic and high-performance building design (as defined in Chapter 2), and effectively generate many of the benefits associated to both.

A set of qualitative and quantitative indicators was applied to objectively indicate the steps of the design and evaluate its results. Regarding the Biophilic Design component of the project, qualitative requirements were selected from the main patterns stated and evaluated in Chapter 2, while the High-Performance component of the project was assessed using the qualitative and quantitative criteria of the Active House approach and LEED v4. It is important to notice that Active House standards and LEED criteria meet biophilic design principles in several points.

5.2 General layout

The Innovation and Research building location determined its layout configuration, an analysis of the specific building site highlighted the different phenomena each side of the building would be exposed to:

a) The west façade is the closer one to the university campus and directly faces the historic Philadelphia High Line (still serving train routes) and the linear park proposed to run along it according to the development plan, which separates the building and 31st Street; this creates conditions for a building entrance to provide access for the university community and connection with the green areas of the linear park, but also exposes it to high levels of noise produced by the trains, potentially amplified due to the metallic viaduct construction (Shiva, Purohit, Rana, & Koli, 2017), a situation that is not expected to be sufficiently mitigated by the greenery of the linear park (Skidmore, Owings & Merrill LLP, 2016, p. 144). Additionally, the façade is expected to be exposed to high amounts of low-angle direct sunlight during summer afternoons, when temperatures go beyond comfort levels. Due to these conditions, it was determined that the west portion of the building is the less suitable for spaces of permanent use, and was destined to a volume of service areas that act as a buffer for the rest of the building spaces, the envelope is mostly opaque due to reduced need for natural light and to minimize solar heat gains

b) The north façade faces the nearby second Drexel proposed building and Ludlow Street, which as an auxiliar street doesn't expect to have large amounts of traffic and noise. The façade orientation protects this portion of the building from overheating and glare, while allowing access of diffuse light to the upper levels, where the view of the sky is higher. These conditions allow the upper levels to host working areas while the lower levels are reserved for service areas and spaces with less strict natural lighting requirements. Also, the lower level of Ludlow Street in relation to the surroundings makes it ideal for accessing the parking spaces located in the basement.

c) The east façade directly faces the building complex's central green space, a much more controlled environment where extended views are possible and the connection of the building with the exterior can be enhanced due to the presence of natural elements, and the protected condition of the space from exterior negative phenomena, like noise. This portion of the building offers ideal conditions for the location of spaces hosting permanent use and public amenities that can extend their activities towards the public space however a façade treatment must be designed to limit the excessive radiation of internal spaces due to low-angle sun rays during mornings, specially in summer, while allowing maximized views of the green areas.

d) The south façade has a mixed condition, partly opened to Chestnut Street and partly shielded from it by another building from the complex, the position of the façade guarantees access to sunlight all year long and in consequence requires protection to avoid overheating and glare. Areas closer to the ground receive less solar radiation and light, so the shading devices must adapt to the changing conditions along the facade to allow an optimum indoor environment.

e) The roof of the building is completely exposed to direct solar radiation and subject to minimal shadows from nearby buildings, this provides a great potential for solar-photovoltaic electricity generation, and the possibility for natural light to access central areas of the building from the top, additionally it can be useful to harvest rainwater along the year due to the relatively regular yearly precipitation pattern on Philadelphia. However, solar heat gains in summer and losses in winter can increase in the last level through the roof, so increased insulation is to be tackled, an extensive flat green roof is proposed to increase the insulation and thermal mass of the roof, make it functional and comfortable for building users and contribute to the mitigation of urban heat island effect.

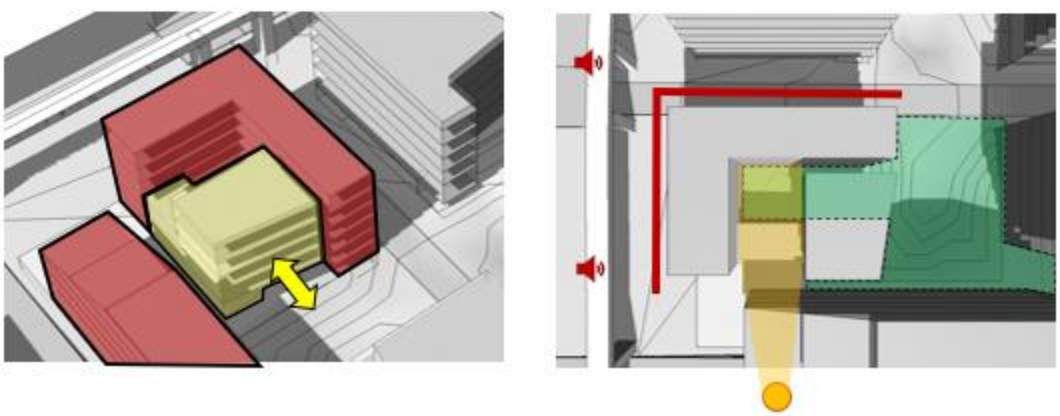


Figure 42: Initial 3D organization of building volumes

The resulting proposed building consist of a compact rectangular volume of ***6126 m2***, with working spaces located in relatively narrow blocks revolving around a central atrium that works as a transitional semi-public space connecting to the park in the center of the complex and extending upwards to the roof and sky. The volume blocks host semipublic amenities, offices, and laboratories in three sides, while the west block is reserved for services, circulation elements and supporting facilities that generate a barrier towards the rail highline; the relatively narrow shape of the working areas is intended to maximize natural light penetration, cross-ventilation, and views towards the exterior and the atrium. In summary, the building is designed to enhance user interactions with natural phenomena on the context and the use of sunlight and winds as resources that can be capitalized by the building for increased comfort and efficiency.

Vertically the building's seven levels are organized in four clusters, according to their use:

a) *Parking - Underground level:* Extend beyond the visible volume and accommodates parking spaces for the building, located about 800mm above the Base Flood Elevation (BFE), it is accessible from Ludlow Street and provides 49 parking lots.

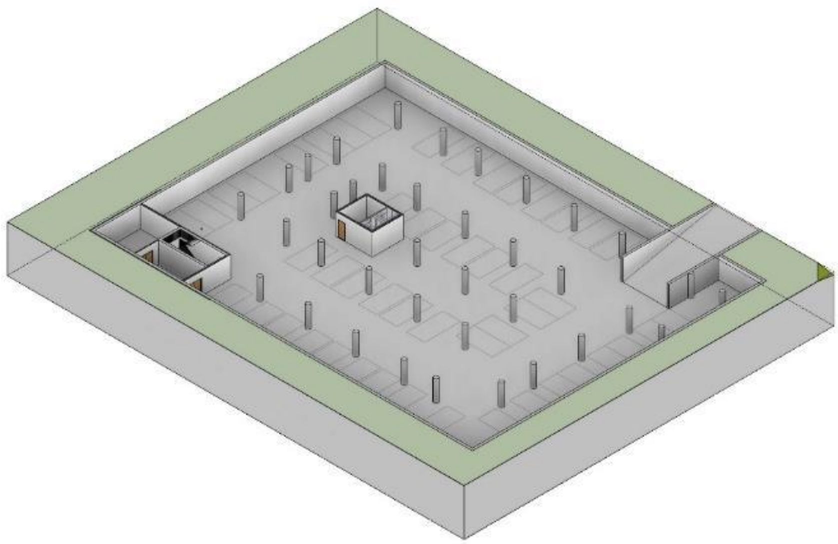


Figure 43: Building layout 3D view - Parking level

b) *Semi-public amenities - Ground Level and Mezzanine:* Hosts spaces that can be used by both building permanent workers and people not related to Drexel University activities, representing an intersection point for events relating research/education and the public. It contains the atrium, reception, exhibition spaces, a public café overlooking the park, an auditorium and study areas. It is specifically designed to extend the presence of natural elements, like water and greenery, inside the building; and organizes the space to take advantage of natural light and views in the main areas while placing the auditorium and café services towards the north, right next to Ludlow Street, as they require less natural light and connection to the exterior. The Mezzanine level extends the spaces for the uses on the ground floor, providing extra interior space for the café on the east, the auditorium extended height, and private study cabins over the common study room in the south.

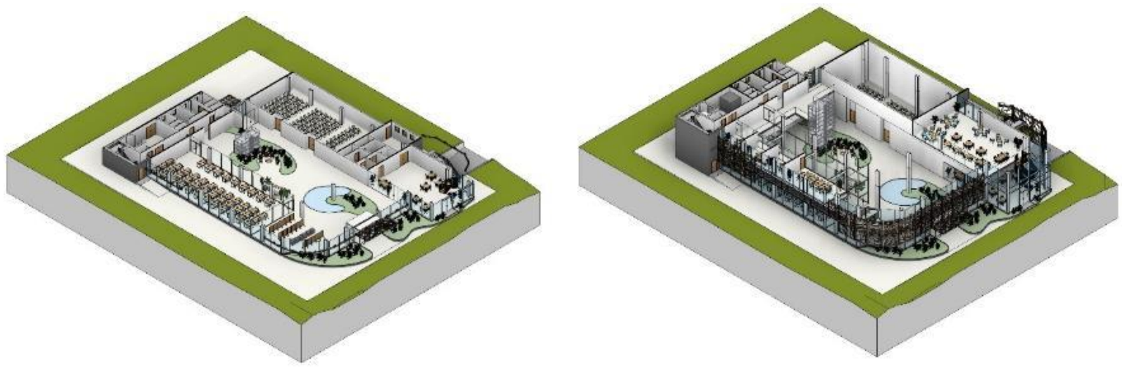


Figure 44: Building layout 3D view - Ground floor and Mezzanine

c) *Offices – 1st and 2nd floors:* Contain administrative areas destined for research project teams and university-backed start-ups, the aim is to provide appropriate and affordable spaces for innovative businesses that require technical and logistical support from the university when at their first stages of development before inserting themselves as competitive participants in the industry, especially directed to enterprises related to medicine and biology innovative products and services, which are growing in Philadelphia and clustered around the University City area. The first floor is organized as an open plan for coworking spaces, flexible enough to be physically subdivided according to the working teams' changing needs; the second floor is dedicated to private offices and meeting rooms facing the exterior, generating a setback and a double height towards the interior that spatially connects it to the lower level and allows for more natural light to penetrate the coworking spaces through the atrium.

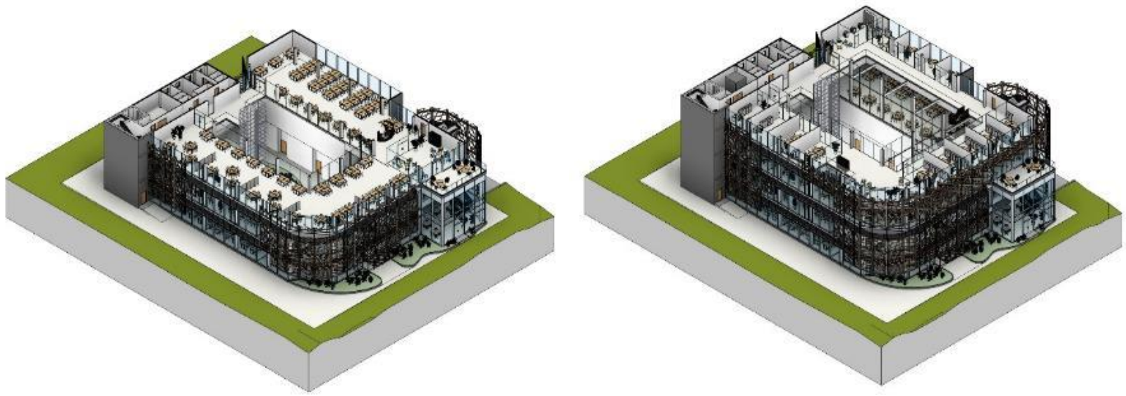


Figure 45: Building layout 3D view - Levels 1 and 2

d) *Laboratories – 3rd and 4th floors:* Accommodate experimental research facilities, that provide the necessary technical equipment and conditions for scientific investigation, both for educational purposes and to support industry innovation and development.

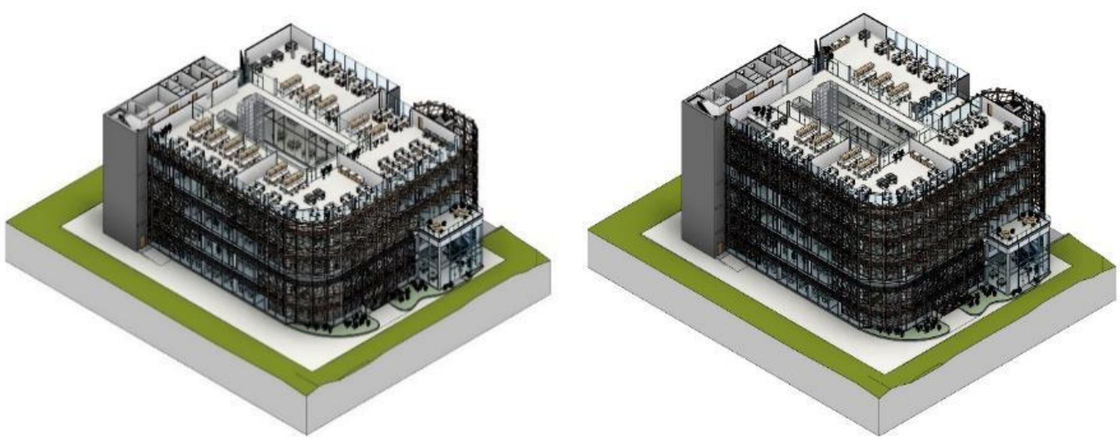


Figure 46: Building layout 3D view - Levels 3 and 4

The stratification of these clusters was made following the need for privacy and access control of different spaces, that increases in the uppermost levels; and the differentiation of uses is proposed to be highlighted in the finishes towards the atrium.

The last floor of the building consists in a green roof where people can spend their free time, for example during the lunch, and is equipped with benches and a microwave area where people can heat up their food.

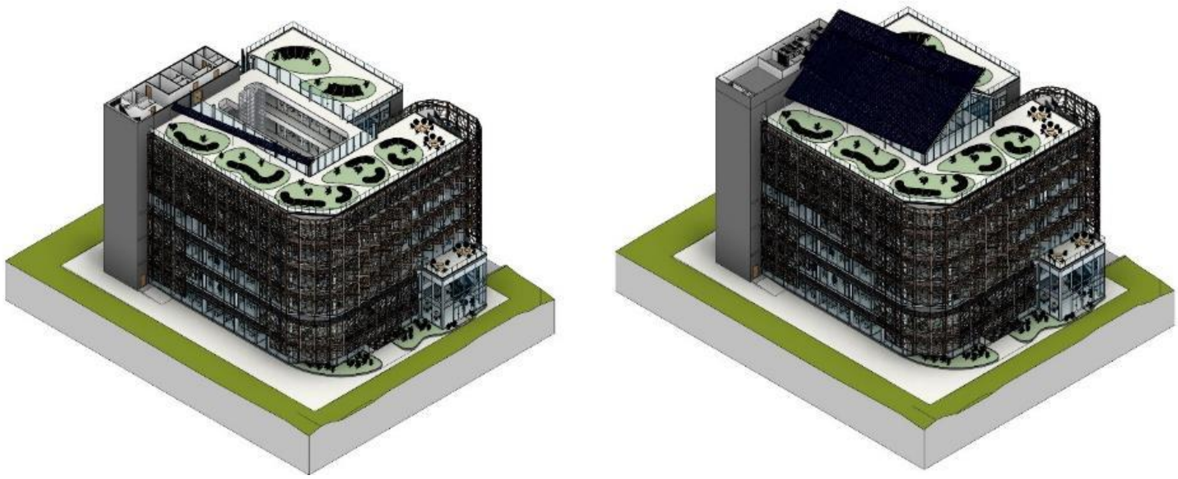


Figure 47: Building layout 3D view – Level 5 and the whole building

5.3 Building components characterization

Based on the defined program, layout and stratification of spaces that organizes the entirety of the building, a detailed review of its technical development is described in this subchapter; given the non-linear nature of the design process and the complex relationships between different elements of the project, its evolution and results won't be presented in a chronological way, nor separated by discipline, instead the building design will be subdivided in its components.

The different components of the building design and its development process will be organized following the concept of "shearing layers", created by Frank Duffy in 1992 and extended by Stewart Brand in 1994, which describes the buildings as systems made of different layers that have specific functions and different rates of evolution during the entire lifetime of the construction (Brand, 1994). Under this concept, the building was subdivided in six layers, rated from longer to shorter lifespan (and from smaller to greater flexibility) as: *site*, *structure*, *skin*, *services*, *space plan* and *stuff*.

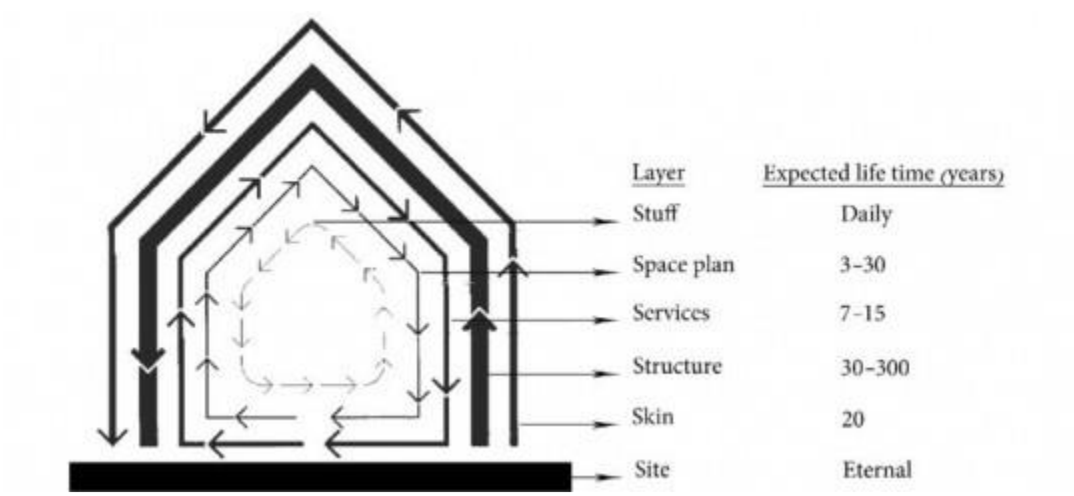


Figure 48: Diagram of building's shearing layers and expected lifetime (Brand, 1994)

The *site* layer is basically invariable, and its characteristics were explained in the previous chapter, so, the next section explains in detail the remaining layers:

5.3.1 Structure

The structure layer groups the load bearing elements of the building and determine several of its restrictions for organization and function. For the Drexel Innovation and Research Building a steel frame system was chosen for all levels above ground, due to its capacity to cover long spans and its lightweight characteristics, that allow to maintain open and flexible floorplans with a reduced impact on the height of horizontal bearing elements; on the contrary, the ground floor slab and parking underground structure were designed in reinforced concrete, due to its increased durability and protection against corrosion, given the humidity levels they will be exposed to at the interface with the ground. Given the goal and scope of this project, not centered in detailed structural design, only the dimensioning of some structural elements was performed, giving priority to main spaces and critical elements in order to give an idea of the feasibility of construction and influence of the structure on other aspects of the project. The calculation method used for structure dimensioning was based on the Eurocode 3 an NTC 2018, which despite not being applicable to construction projects in the United States, seemed appropriate for an academic project like this, developed for a European university; similarly, all calculations are displayed in the International System units.

First, an estimation of building loads for the elements that must be taken in account for the dimensioning of the chosen part of the structure. Here only the vertical elements, the horizontal elements have been calculated later after dimensioning the structural slab.

Table 6: Estimation of structural loads due to partitions and envelope

			PLASTERBOARD PARTITION			
			ELEMENT	SPECIFIC WEIGHT [kN/m³]	THICKNESS [m]	WEIGHT [kN/m²]
P1	G2	1	Plasterboard partition (with metallic structure)			0.49
					TOT	0.49

			GLASS PARTITIONS			
			ELEMENT	SPECIFIC WEIGHT [kN/m³]	THICKNESS [m]	WEIGHT [kN/m²]
P2	G2	1	Glass partition			0.4
					TOT	0.4

			CURTAIN WALL (load for every mullion)					
				Height (m)	Lenght (m)	Weight (kN/m)	Weight (kN/m²)	Load (kN)
P3	G2	1	Mullion	4.5		0.0455		0.20475
		2	Transom		2.2	0.0336		0.14784
		3	Glass (5+7+4+7+5mm)	4	2.2		0.35	3.08
		4	Opaque panel	0.5	2.2		0.07	0.077
		5	Windows					0.4
							TOT	3.90959

			SHADING ELEMENT (load every bracket)					
				Volume (m³)	Height (m)	Weight (kN/m³)	Weight (kN/m)	Load (kN)
Sh1		1	Wood	0.23		7.5		1.725
		2	Mullions		4.5		0.04	0.18
		3	Bracket					0.2
							TOT	2.105

Composite slabs of galvanized steel decking and reinforced concrete were designed to provide thermal mass to the working spaces, allowing for a better regulation of temperature changes during the day, selection of the appropriate decking was made using design tables from one selected manufacturer: Metecno.

The dimensioning of the slab have been made by using the tables given by the producer, that, given the loads on the slab (G2 (permanent, nonstructural load, like partitions and nonstructural elements of the slabs) plus Q (variable loads, like weight of people and furniture, or snow load)), give the maximum span of the slab, and so the maximum distance between two secondary beams, the thickness of the steel dock and the concrete over it.

By having a G2 load of 1.49kN/m² and a Q load of 4.2 kN/m², for a total of 5.69kN/m², the resulting structural slab must have a steel dock 0.8mm thick, covered by 10cm of concrete and there must be a support every maximum 2.82m. In the designed building the maximum distance between 2 supports of the slab is 2.8m.

Once knowing the load of the structural part of the slabs also the load analysis of these has been calculated.

Table 7: Estimation of structural loads due to slabs and roofs

FROM 1° TO 5° FLOOR SLAB					
	N.	ELEMENT	SPECIFIC WEIGHT [kN/m³]	THICKNESS [m]	WEIGHT [kN/m²]
G1	1	Steel dock		0.1	1.9
				TOT	1.9
G2	2	Light concrete	11.7	0.1	1.17
	3	Tiles	20	0.01	0.2
	4	Rockwool	0.6	0.05	0.03
	5	Plasterboard	6.8	0.0125	0.085
				TOT	1.485

	ROOF GREEN					
S2		N.	ELEMENT	SPECIFIC WEIGHT [kN/m³]	THICKNESS [m]	WEIGHT [kN/m²]
	G1	1	Steel dock		0.1	1.9
					TOT	1.9
	G2	2	Rockwool	0.6	0.05	0.03
		3	Plasterboard	6.8	0.0125	0.085
		4	XPS	0.6	0.05	0.03
		5	Light concrete	11.7	0.1	1.17
		6	Ground	7	0.15	1.05
					TOT	2.365

			ROOF			
		N.	ELEMENT	SPECIFIC WEIGHT [kN/m³]	THICKNESS [m]	WEIGHT [kN/m²]
S2	G1	1	Steel dock		0.1	1.9
					TOT	1.9
	G2	2	Rockwool	0.6	0.05	0.03
		3	Plasterboard	6.8	0.0125	0.085
		4	XPS	0.6	0.05	0.03
		5	Light concrete	11.7	0.1	1.17
		6	Tiles	20	0.015	0.3
					TOT	1.615

Steel secondary beams run perpendicular to the space length, and primary beams are placed on the edges, allowing the most loaded elements to have relatively shorter spans and keep their height as reduced as possible to increase the usable height of the spaces beneath. IPE profiles were selected for the beams, using S275 steel, following strength and deformability verifications at Ultimate Limit State (ULS) and Serviceability Limit State (SLS), respectively. Here an example of the calculation method used to dimension the main and secondary beams.

a) *Pre-dimensioning for secondary beam S1:*

The height of the beam can be assumed to be 1/25 of its length. For S1 the starting height was calculated to be 0.336m, so an IPE 360 has been chosen.

b) *Weight analysis of secondary beam S1:*

The area of influence of the beam must be calculated by considering half of the slab sustained by it, for every side of the beam, in this case 1.1m for each side, for a total of 1.1*2=2.2m.

By knowing the loads on the slabs:

	kN/m²
G1 (structural load)	1.9
G2 (nonstructural load)	2.69
Q (variable load)	3

Various combination of loads have been made, considering the fact that G1, G2 and Q loads could be both favorable or non-favorable for the structure. Here the applied coefficients during the calculation of favorable and non-favorable loads:

Table 8: Safety coefficients for permanent and variable structural loads

COEFFICENTS			
		ULS	SLS
Permanent Loads G1	Favorable	1	1
	Non-favorable	1.3	1
Non strucutral permanent Loads G2	Favorable	0.8	0
	Non-favorable	1.5	1
Variable Loads Q	Favorable	0	0
	Non-favorable	1.5	1

Here the results for the minimum and maximum combination of loads at both ULS and SLS.

SLS:

MAX	17.337	kN/m
MIN	4.830	kN/m

ULS:

MAX	25.040	kN/m
MIN	9.556	kN/m

c) *Dimensioning and verifications of secondary beam S1:*

It is necessary to verify that the beams can support the bending moment acting on them, and this must be made at both SLS and ULS. In the first case it must be verified that the maximum deflection δ is lower than 1/250 of the span of the beam in meters (δ_{max}), and the verification is done using the Young module E of the steel (210000 Mpa) and the moment of inertia I that depends by the profile of the beam. In the second case it must be verified that the acting moment M_{ed} is lower than the resisting one $M_{pl,rd}$. The first one is calculated by using the combination of loads evaluated before, and the second one by using the resisting module $W_{pl,min}$ of the profile.

Furthermore, the beam must be verified at shear resistance: acting shear V_{ed}, calculated using the loads combination, must be lower than the resisting one $V_{pl,Rd}$, calculated using the area of the section of the profile A_v and f_{yd} of S275 steel (261.9N/mm²). Here the result of the verification at SLS and ULS for secondary beam S1, using an IPE 400 profile.

Table 9: Secondary beam deflection check

1. SLS				
δ_{max} =	0.0336	m		
I =	23130	cm^4		
E =	210000	Mpa		
δ =	25.532	mm	OK	75.99%

Table 10: Secondary beam bending moment check

2. ULS				
M_{ed} =	220.850464	kNm		
V_{ed} =	105.166888	kN		
$W_{pl,min}$ =	1156	cm^3		
$M_{pl,rd}$ =	302.761905	kNm	OK	72.95%

Table 11: Secondary beam shear check

3. ULS								
b [mm]	r [mm]	tw [mm]	tf [mm]	A [cm²]	A_v [mm²]	$V_{pl,Rd}$ [kN]		
180	21	8.6	13.5	84.46	4269.1	645.53	OK	16.29%

Applying the same process, other secondary beams (with a name starting with S or C, in case of cantilever beams, and colored in green), and main beams (with a name starting with M, and colored in orange) have been dimensioned. Here a scheme with the chosen steel profile for these one and also the position in the building on a typical plan. In the scheme the pink rectangle highlight the most critical point for the dimensioning of the slab, and the yellow circle the column calculated later.

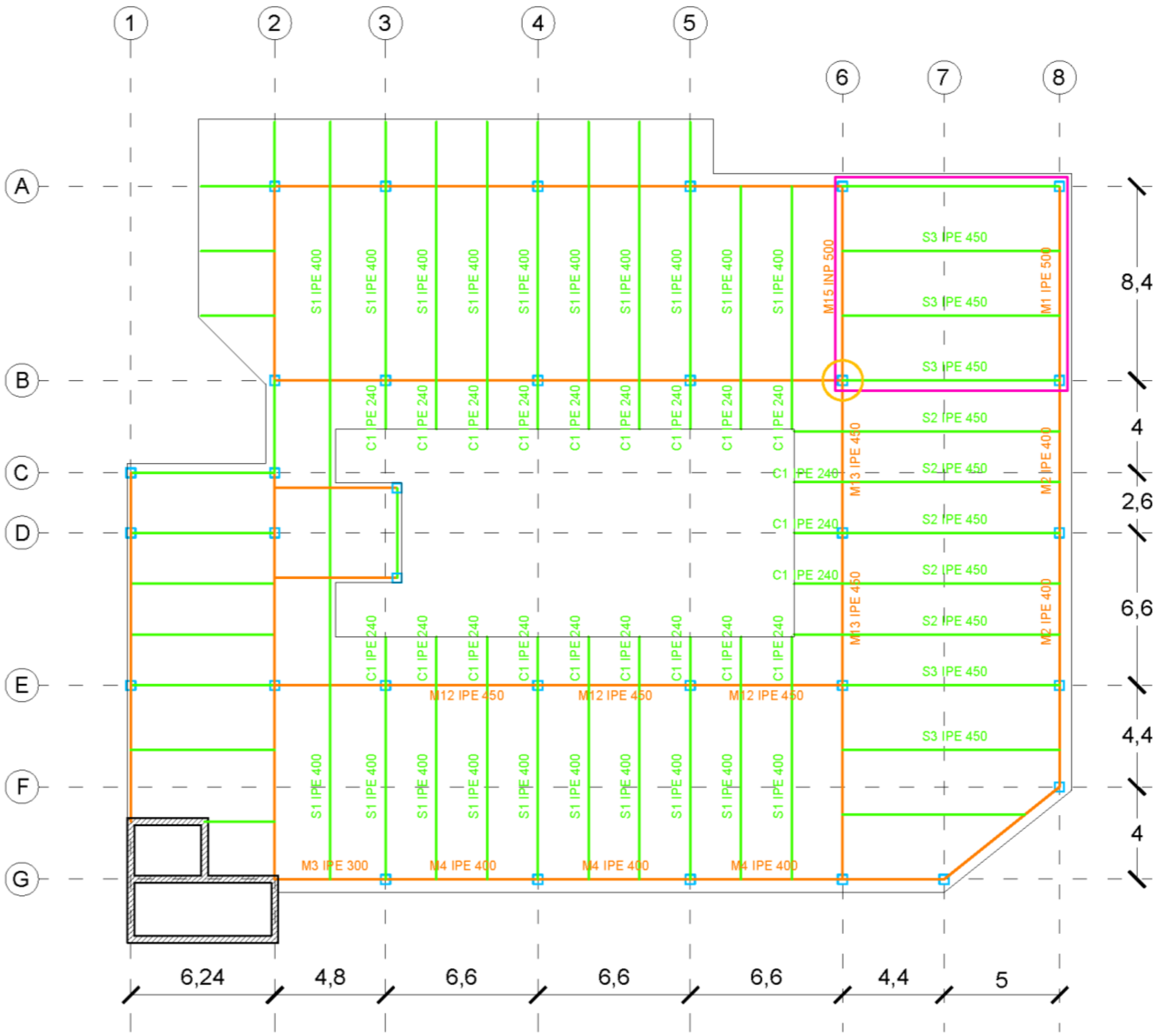


Figure 49: Reference structural layout, level 1

The steel column in the yellow circle were so dimensioned too, by using the Eurocode guidelines, performing a buckling resistance verification; calculation steps and results are displayed in the following paragraphs. As done for beams, S275 steel has been used, with, in this case, HE steel profiles.

d) Load analysis

As done for the beams, also for columns it is necessary to calculate the area of influence, by taking half of the slabs acting on it. In this building, where the plans have different configurations there are 3 influence areas for the calculated column:

Table 12: Calculated column influence areas

Influenced area (Roof)		
1/2 slab	3.3	m
1/2 slab	4.7	m
1/2 slab	4.2	m
1/2 slab	3.3	
A TOT	13.86	m²
A to use	16.632	m²
A TOT (green)	35.25	m²
A to use (green)	42.3	m²
A TOT	58.932	m²
Influenced area (1°floor)		
1/2 slab	3.3	m
1/2 slab	4.7	m
1/2 slab	4.2	m
1/2 slab	0	m
A TOT	33.6	m²
A to use	40.32	m²
Influenced area (0°/2°-5°floor)		
1/2 slab	3.3	m
1/2 slab	4.7	m
1/2 slab	4.2	m
1/2 slab	3.3	m
A TOT	49.11	m²
A to use	58.932	m²

Then the loads due to the weight of horizontal elements, dependent on the assembly:

Table 13: Structural distributed loads over calculated column's area of influence

Loads			
Roof green	G1	1.9	kN/m²
	G2	2.365	kN/m²
	Q	5.2	kN/m²
Roof	G1	1.9	kN/m²
	G2	1.615	kN/m²
	Q	5.2	kN/m²
1°-5° FLOOR	G1	1.9	kN/m²
	G2	1.485	kN/m²
	Q	3	kN/m²

e) Dimensioning and verification of column, Ground to Mezzanine:

The loads acting on the column at ULS are calculated by every floor using, as done for the beams, the same coefficients for favorable and non-favorable loads. Once calculated the load Q is converted in axial force $N_{ed,ULS}$ by multiplying it by the area of influence.

Table 14: Structural point loads over calculated column

ULS roof		
Q max =	12.6925	kN/m²
$N_{ed,ULS}$ =	211.10166	kN

ULS green roof		
Q max =	13.8175	kN/m²
$N_{ed,ULS}$ =	584.48025	kN

ULS 1° floor		
Q max =	9.1975	kN/m²
$N_{ed,ULS}$ =	370.8432	kN

ULS 2°-5° floor		
Q max =	36.79	kN/m²
$N_{ed,ULS}$ =	2168.10828	kN

$N_{ed,ULS}$ TOT =	3451.865658	kN

For the dimensioning of the beam a slenderness equal to $\lambda = 120$ has been hypothesized. Starting from this situation, the normalized onslenderness $\underline{\lambda}$ has been calculated and the instability curve chosen (coefficient α), depending by the steel profile of the column. By knowing these factors, the minimum area A_{min} can be calculated, and a profile with an higher one must be chosen:

Table 15: Calculation of characteristics for buckling resistance of steel column

Hypotesis:	λ =	120

$\bar{\lambda}$ =	1.37931	λ/87
α =	0.34	
φ =	1.651731	
χ =	0.390561	
A_{min} =	33745.98	mm²
Choosen A =	34430	mm²
Choosen HEM =	500	
Iz =	7.46	cm

For the verification the real slenderness λ of the column must be calculated, and then, as done before the normalized one. Then, the resistinf axial force $N_{b,rd}$ can be evaluated, and must be of course higher than the acting one $N_{ed,ULS}$ TOT. Here the results, again for the part of the column from the ground to the mezzanine floor:

Table 16: Buckling verification of calculated column

λ =	60.32172	OK	
$\bar{\lambda}$ =	0.693353	OK	
φ =	0.824239	OK	
χ =	0.787451	OK	
$N_{b,Rd}$ =	7100.744	OK	48.61%

By doing the same calculation at every floor, and so for all the length of the column, the different steel profiles to be used at every floor has been calculated and are:

From Ground to 1st floor: HEM 500

Form 1st to 3rd floor: HEM 300

From 3rd to 4th floor: HEM 220

From 4th floor to roof: HEB 220.

5.3.2 Skin

The skin layer comprises all exterior surfaces of the building that define its boundary and determine the degree of interaction between interior spaces and exterior conditions. It has a great influence in energy performance and user's comfort, so a particular emphasis was made in the development and detailing of its elements; as explained at the beginning of this chapter, the location façade elements was made in response to the context conditions at each side of the building, in particular, south and east facades required additional protection from solar radiation, so a shading second skin was created in conjunction with transparent glazed elements and will be considered an additional layer inside the *skin* group. Thus, the skin elements will be further subdivided according to their characteristics as: opaque (walls, slab and roofs), transparent (windows and skylight) and shadings.

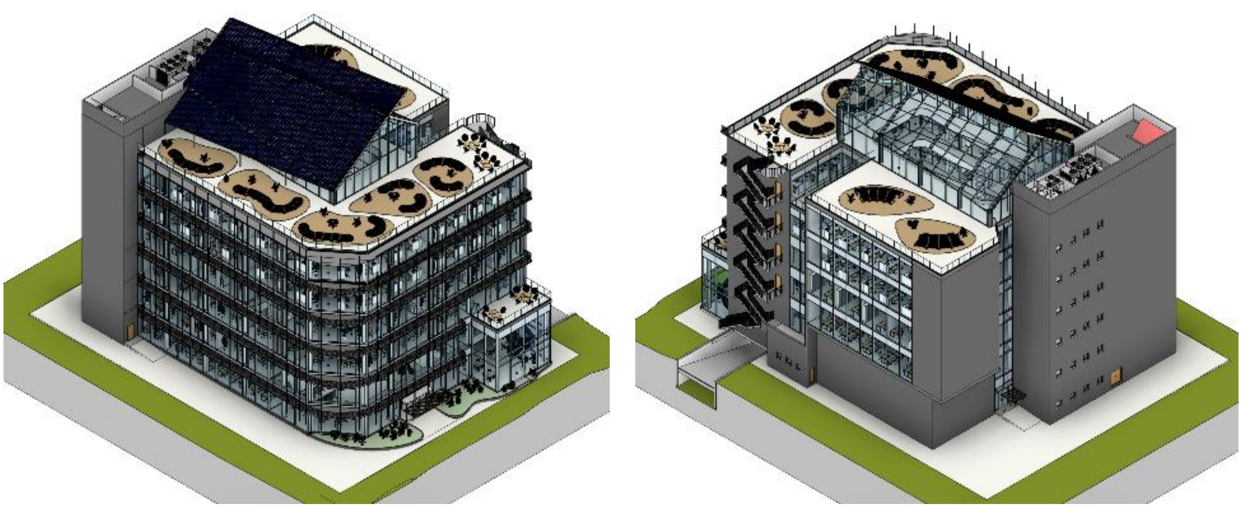


Figure 50: Suoth-East and Nort-West 3d view of the building without the double skin applied, to show better the opaque and transparent areas

5.3.2.1 Opaque envelope elements

Opaque elements comprise all non-glazed components of the envelope, including walls, slabs and roofs. Given the extensive area they occupy, their thermal properties and configuration can have a high influence on energy performance, due to their modulation heat gains and losses through conduction; in particular, roof surfaces design can be of great impact, as they have a relatively higher extension and exposure to both solar radiation as heat source on cooling season, and clear sky which acts as radiative heat sink during heating season.

As a starting point, all opaque envelope assemblies were set following the minimum prescriptions given by the International Energy Conservation Code (IECC), which is adopted as part of the Philadelphia Building Code (Philadelphia Building Code, pp. §EC-1.1).

IECC stablishes the acceptable maximum U-values for opaque envelope assemblies, depending on their nature and location; the applicable values for this project, situated on Climate Zone 4A, were taken from the Commercial Energy Efficiency sub-chapter, transformed to the International System of Units, and reported in Table XX

Table 17: Maximum U-values requirements for opaque envelope assembly on climate zone 4A (International Code Council, 2021)

Opaque element	Maximum required U-value	
	BTU/h*ft^2*F	**W/m²K**
Roof	0.035	**0.199**
Frame wall	0.064	**0.363**
Mass wall*	0.104	**0.590**
Floor	0.033	**0.187**

Envelope assemblies with similar characteristics to the required ones were added to the Revit virtual model of the building, where the designer can choose between some default options, and a preliminary energy analysis was performed using Insight tool to establish the baseline of energy consumption.

Then, the design was subjected to an optimization process through optioneering, using Insight cloud-based tool to obtain response curves that allowed to compare the variations on the energy performance of the whole building when subjected to different scenarios involving one parameter or component configuration. The tool can compare and visualize the performance of eight different generic wall assemblies with the one set on the model, having the following characteristics (converted to metric system):

Table 18: Generic wall assembly options and properties for optimization (Autodesk Insight, n.d.)

		Imperial system		Metric system		
Name	Assembly	R-Value (h*ft²*°F/ BTU)	Heat Capacity (BTU/ ft²*°F)	R-Value (m²K)/ W	**U-Value W/(m²K)**	**Heat Capacity (kJ/m²K)**
Uninsulated	R0 Wood Frame Wall	2.97	10.71	0.52	**1.91**	**69.16**
R13 Metal	R13 Metal Frame Wall	5.77	10.05	1.02	**0.98**	**64.89**
R13 Wood	R13 Wood Frame Wall, Wood Shingle	11.66	1.74	2.05	**0.49**	**11.24**
R13+R10 Metal	R13 + R10 Metal Frame Wall	17.13	11.35	3.02	**0.33**	**73.29**
14-inch ICF	Insulated Concrete Form Wall 14 inch (36 cm) U-0.034	28.91	14.11	5.09	**0.20**	**91.11**
R38 Wood	R38 Wood Frame Wall	36.75	1.8	6.48	**0.15**	**11.62**
R2 CMU	R2 CMU Wall	4.02	18.69	0.71	**1.41**	**120.68**
12.25-inch SIP	Structurally Insulated Panel (SIP) Wall 12.25 inch (311 mm)	37.27	4.21	6.57	**0.15**	**27.18**
BIM	Settings from model					

Also some typologies of roofs are present by default in the Insight tool and their values are reported in the following table (as before, converted to metric system):

Table 19: Generic roof assembly options and properties for optimization (Autodesk Insight, n.d.)

		Imperial system		Metric system		
Name	Assembly	R-Value (h*ft²*°F/ BTU)	Heat Capacity (BTU/ ft²*°F)	R-Value (m²K)/ W	**U-Value W/(m²K)**	**Heat Capacity (kJ/m²K)**
Uninsulated	R0 over Roof Deck	1.33	1.43	0.23	4.2695	9.23
R10	R10 over Roof Deck	11.75	2.06	2.07	0.4832	13.30

R15	R15 Wood Frame Roof	15.61	2.03	2.75	0.364	13.11
R19	R19 insulation Wood Frame Roof	16.39	1.18	2.89	0.3464	7.62
R38	R38 Wood Frame Roof	42.57	1.3	7.50	0.1334	8.39
R60	R60 Wood Frame Roof	66.23	1.37	11.67	0.0857	8.85
10.25-inch SIP	Structurally Insulated Panel (SIP) Roof 10.25 inch thick (260mm)	37.71	1.44	6.64	0.1505	9.30
BIM	Settings from model					

Here the response curve, where the values of the BIM typology are the U-values given by the IECC guidelines.

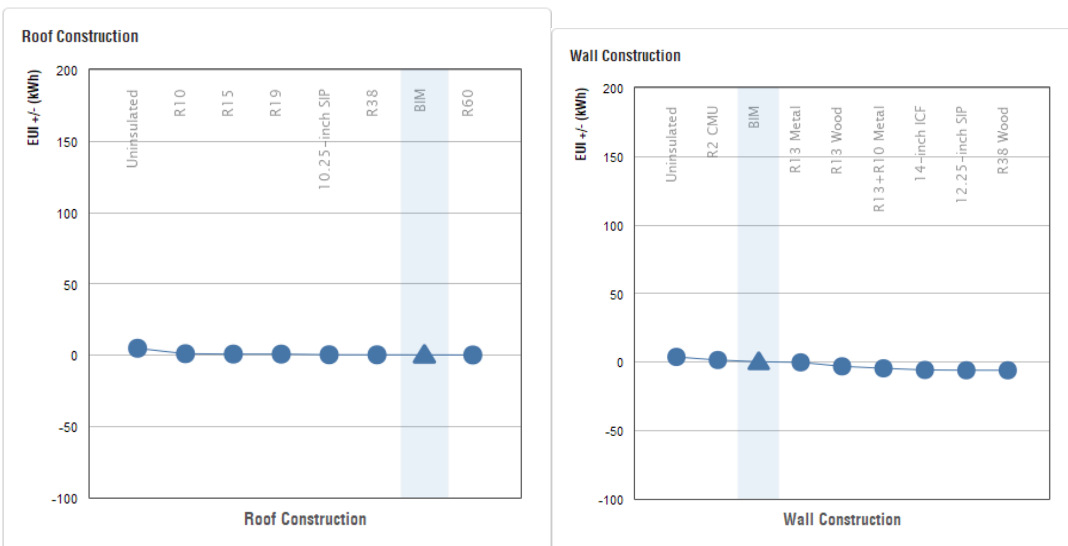


Figure 51: Response curves comparing generic options for roof and wall assemblies

The response curve data provided feedback about the optimal wall assembly among the previously specified options, it is visible a trend of Energy Use Intensity (EUI) reduction as the overall U-value decreases too, especially in the wall construction, generating, by improving it, a maximum savings of 6.23 KWh/m²*y (around 3% of EUI improvement of the whole building). As shown by the response curve, the U-value given by law is already a very good value for the thermal transmittance of the building, and so, by tying to improve it (roof contruction type R60), only 0.07 KWh/m²*y are saved, so there are no reasons to apply a lower U-value for roofs and so spend more money for a bigger insulation that doesn't give many benefits.

To choose the best construction type for walls, the response curve has been converted in numbers, and the improvement (expressed in percentage) of the EUI have been calculated compared to the EUI of the BIM case and the EUI of every precedent case (R13 Metal with BIM, R13 wood with R13 Metal etc…). Only the cases in which an improvement of the EUI is present have been taken into consideration:

Table 20: Comparison of optimization results for walls assemblies

Name	Assembly	EUI (kWh/m²yr)	Improvement compared to BIM case	Improvement compared to each previous case
BIM	Settings from model	173	-	-
R13 Metal	R13 Metal Frame Wall	172.55	0.26%	0.26%
R13 Wood	R13 Wood Frame Wall, Wood Shingle	169.66	1.93%	1.67%
R13+R10 Metal	R13 + R10 Metal Frame Wall	168.21	2.77%	0.85%
14-inch ICF	Insulated Concrete Form Wall 14 inch (36 cm) U-0.034	167.01	3.46%	0.71%
12.25-inch SIP	Structurally Insulated Panel (SIP) Wall 12.25 inch (311 mm)	166.8	3.58%	0.13%
R38 Wood	R38 Wood Frame Wall	166.77	3.60%	0.02%

As shown by the table, the biggest improvement are present till "14-inch ICF" type, after that improvements of only 0.13% and 0.02% are achieved, so there is no sense to have a wall with an higher performance compared to the "14-inch ICF" one.

So opaque elements were then detailed to match as closely as possible with the optimal U-values obtained before (0.199 W/m²K for roofs and 0.2 W/m²K for walls). Separate wall and roofs assemblies were so designed taking in account this and the following parameters (with the respective formulas) have been calculated for each element (walls, roofs, floors):

- Heat resistance:

$$R\ value = \sum R_i \ \ [\mathrm{m^2K/W}]$$

Where R_i stands for the heat resistance of every material that compose the element and is calculated with the formula: $R_i = \frac{s}{\lambda}\ [m^2K/W]$, where s is the thickness of the material's layer and λ the thermal conductivity

- U-value:

$$U\ value = \frac{1}{R\ value}\ [W/m^2K]$$

- Vapor resistance:

$$R_v = \sum R_{v,i}\ [m^2hPa/kg]$$

Where $R_{v,i}$ stands for the vapor resistance of every material that compose the element and can be calculated thanks to the water vapor resistance factor (μ) typical of every material. This is useful for the calculation of the Vapor Permeability (P) as: $P = \frac{670*10^{-9}}{\mu}\ [kg/mhPa]$, and then $R_{v,i} = \frac{s}{P}\ [m^2hPa/kg]$.

Convective internal and external heat transmittance h_i and h_e depends by the position of the element and have been chosen according to this scheme provided by www.htflux.com and based on ISO 6946.

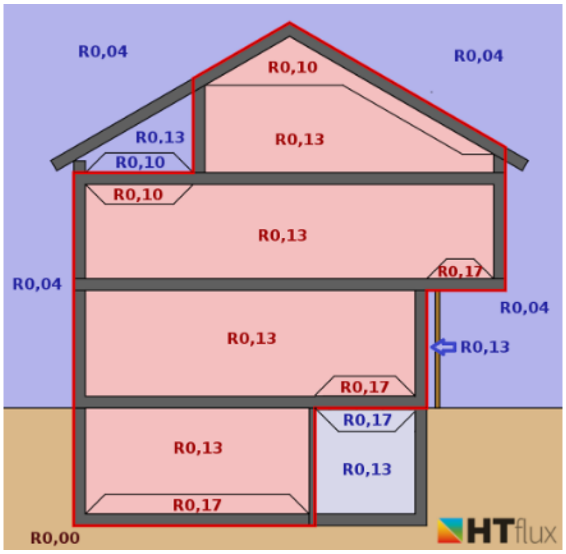


Table 21: Example of designed stratigraphy and characteristics for one wall type (W_E_28_P) inside the building

N°	Material	s (m)	λ (W/mK)	R (m^2K/W)	Specific heat (J/kgK)	Density (kg/m^3)	μ	P (kg/mhPa)	R_v (m^2hPa/kg)
	Int		7.69	0.13					0
1	Render	0.002	0.7	0.00	1000	1500	8	8.375E-08	23880.60
2	Plasterboard	0.025	0.2	0.13	1000	680	8	8.375E-08	298507.46
3	Rockwool	0.05	0.035	1.43	1030	70	1	0.00000067	74626.87
4	Air cavity	0.05		0.18	1030	1.225	1	0.00000067	74626.87
5	vapor barrier	0.001	0.17	0.01	840	750	28000	2.39286E-11	41791044.78
6	Rockwool	0.05	0.035	1.43	1030	70	1	0.00000067	74626.87
7	Fibro reinforced panel	0.025	0.35	0.07	830	1450	49	1.36735E-08	1828358.21
8	XPS	0.07	0.034	2.06	1030	70	70	9.57143E-09	7313432.84
9	Finishing	0.006	1	0.01	800	2350	1	0.00000067	8955.22
	Ext		25	0.04					0

TOT thickness = 0.279 m
R value= 5.48 m^2K/W
U value = 0.18 W/m^2K
R vapor = 51488059.7 m^2hPa/kg

The vapor resistance have been calculated to verify the absence of interstitial condensation in the elements placed between an internal and external area. A specific law on this aspect for Philadelphia couldn’t be found, so the temperature (T) and relative humidity (RH) used for this check are, respectively, 20°C and 50% for the internal side, and the following for the external side, one for every month:

Table 22: Outdoor temperature (T) and relative humidity (RH) per month, used for condensation verification (EnergyPlus)

Month	T (°C)	RH (%)
January	-11.7	50
February	-11.7	58
March	-5.6	40
April	-0.6	45
May	4.4	60
June	9.4	77
July	15	97
August	14.4	78

September	7.2	89
October	-3.9	68
November	-6.1	84
December	-9.4	74

Since the external temperatures for the calculation of the interstitial condensation weren't specified on any law, the minimal minimum temperature for every month have been assumed, since lower is the external temperature, higher is the risk of interstitial condensation. For the Relative Humidity, the one related to the same hour in which the lower temperature is recorded, has been the one used in the calculation and so present in the previous table.

The method used for the calculation of the interstitial condensation is the Glaser one and assumes that if the values of $P_{vs,i}$ (Saturated vapor pression) in the interface between each layer of an element are higher than the values of $P_{v,i}$ (Vapor pression), there will not be interstitial condensation. To know $P_{vs,i}$ and $P_{v,i}$, Thermal and Vapor flux (respectively q and g) must be calculated, and also $P_{vs,air}$ and $P_{v,air}$ of the internal or external air in every month. The following equations have been used:

$$P_{vs,air} = 6.11 * 10^{\frac{7,5*T}{237.7+T}} * 100\ [Pa]$$

$$P_{v,air} = P_{vs,air} * RH\ [Pa]$$

$$q = \frac{T_I - T_E}{R\ value}\ [W/m^2]$$

$$g = \frac{P_{v,I} - P_{v,E}}{R\ vapor}\ [kg/m^2h]$$

Here the results of $P_{vs,air}$ and $P_{v,air}$ (internal and external) for every month and also an example of the results for q and g for every month for the wall W_E_28_P as before:

Table 23: Calculation of resulting vapor pressure levels for one wall type (W_E_28_P) inside the building

Month	$P_{vs,air,I}$ (Pa)	$P_{vs,air,E}$ (Pa)	$P_{vs,air,I}$ (Pa)	$P_{vs,air,E}$ (Pa)
Jan	1167	125	2334.07	249.90
Feb	1167	144.9	2334.07	249.90
March	1167	161.1	2334.07	402.80

Apr	1167	263.2	2334.07	584.87
May	1167	501.8	2334.07	836.27
Jun	1167	907.5	2334.07	1178.56
Jul	1167	1652	2334.07	1703.07
Aug	1167	1278	2334.07	1638.49
Sept	1167	903.5	2334.07	1015.17
Oct	1167	311.5	2334.07	458.07
Nov	1167	325.7	2334.07	387.71
Dec	1167	222.1	2334.07	300.08

Table 24: Calculation of resulting heat and vapor flux for one wall type (W_E_28_P) inside the building

Month	q (W/m²)	g (kg/m²h)
Jan	5.79	2.02E-05
Feb	5.79	2.00E-05
March	4.67	1.95E-05
Apr	3.76	1.76E-05
May	2.85	1.29E-05
Jun	1.93	5.04E-06
Jul	0.91	-9.42E-06
Aug	1.02	-2.16E-06
Sept	2.34	5.12E-06
Oct	4.36	1.66E-05
Nov	4.77	1.63E-05
Dec	5.37	1.84E-05

The equations used for the calculation of $P_{v,i}$ and $P_{vs,i}$ in each layer are the following:

$$P_{v,x} = P_{v,x-1} - R_{v,i} * g \ [Pa]$$

$$P_{vs,x} = 6.11 * 10^{\frac{7,5*T_x}{237.7+T_x}} * 100 \ [Pa]$$

Where x indicates the number of the interface between two layers, and x-1 the number of the previous interface.

Here an example of the application of the Glaser verification for the wall W_E_28_P in January (this has been made for every month):

Table 25: Example of Glaser verification for one wall type (W_E_28_P) in January

JANUARY					
	X (m)	T_x (°C)	$P_{v,x}$ (Pa)	$P_{vs,x}$ (Pa)	
Int air		20	1167.03	2334.07	OK
Int surface	0	19.25	1167.03	2227.70	OK
S1-S2	0.002	19.23	1166.55	2225.41	OK
S2-S3	0.027	18.51	1160.51	2127.24	OK
S3-S4	0.077	10.24	1159.00	1246.75	OK
S4-S5	0.127	9.20	1157.49	1162.62	OK
S5-S6	0.177	9.16	311.67	1159.96	OK
S6-S7	0.178	0.90	310.16	651.91	OK
S7-S8	0.203	0.48	273.15	632.73	OK
S8-S9	0.273	-11.43	125.13	255.30	OK
Ext surface	0.279	-11.47	124.95	254.59	OK
Ext air		-11.70	124.95	249.90	OK

The same procedure was applied for every month for all external opaque wall assemblies, including walls, slabs, on-grade slabs and roofs, the resulting configurations and U-values are shown by category. For simplicity the whole procedure isn't shown for all the elements, but only the list of the material and the recap of R value, U value and R vapor.

It's important to notice that during the verifications at interstitial condensation, in the middle of the elements with the cold side covered by an impermeable material (for example impermeable membrane or steel dock), some condensation was created, also with the application of a traditional vapor barrier on the hot side of the insulation. To avoid the interstitial condensation for these elements aluminum vapor barrier has been used, since it is much more performant than the traditional one, having a much higher μ value.

The code used to give a name to every element has been created following this structure: "A_B_XXX_C description". Where: A stands for the typology of element (W = walls, S = slabs); B stands for where the element is placed (I = interior, E = exterior); XXX stand for the thickness of the element in cm; C stands for the main material of the element (only for the walls) (P = plasterboard, C = concrete, R = REI concrete blocks); and description is used for eventual annotations for the element.

5.3.2.1.1 Exterior wall assemblies

The exterior walls of the buildings are made with plasterboard, concrete on REI blocks, and two types of finishings have been used: a ceramic façade and a green façade.

In particular the chosen producer for the first one is Laminam, that makes ceramic tiles with a thickness of 5,5mm and dimensions of 3x1m. The chosen texture for the finishing panels is “Pietra di Cardosio nero naturale”, so a natural stone texture to give to the building a more natural style, combined with the double sink in wood.

Table 26: Sample texture of exterior cladding panels (Laminam S.P.A, 2022)

The green wall has been chosen, as for the stone texture, to give a more natural look to the building, and also because is suggested by the main biophilic design principles.
For both the cases the stratigraphies are present in the following tables.

Table 27: Exterior wall assembly W_E_28_P

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		7.69	0.13					0
1	Render	0.002	0.70	0.00	1000	1500	8	8.38E-8	23880.60
2	Plasterboard	0.025	0.20	0.125	1000	680	8	8.38E-8	298507.50
3	Rockwool	0.05	0.04	1.43	1030	70	1	6.70E-7	74626.87
4	Air cavity	0.05		0.18	1030	1.225	1	6.70E-7	74626.87
5	vapor barrier	0.001	0.17	0.01	840	750	28000	2.39E-11	41791045
6	Rockwool	0.05	0.04	1.43	1030	70	1	6.70E-7	74626.87
7	Fibro reinforced panel	0.025	0.35	0.07	830	1450	49.00	1.37E-8	1828358.00
8	XPS	0.07	0.03	2.06	1030	70	70	9.57E-9	7313433.00
9	Finishing	0.006	1	0.01	800	2350	1	6.70E-7	8955.224
	Ext		25.00	0.04					0

TOT thickness = 0.279 m
R value= 5.48 m²K/W
U value = 0.18 W/m²K
R vapor = 51488059.7 m²hPa/kg
Verified at interstitial condensation

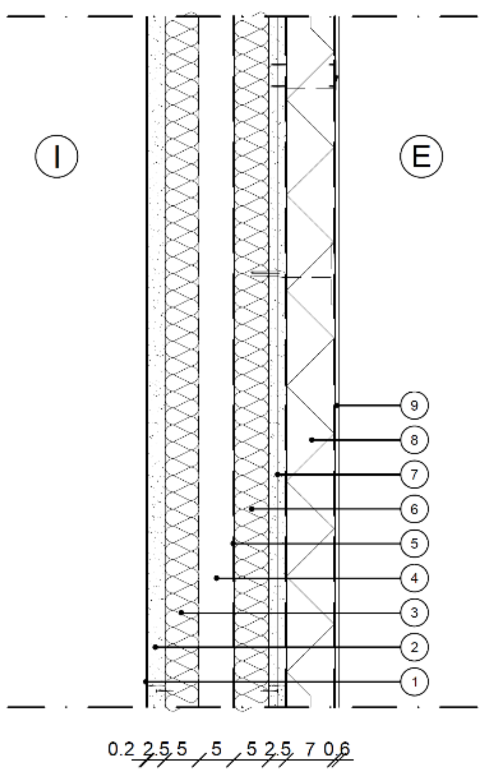


Figure 52: Exterior wall assembly W_E_28_P

Table 28: Exterior wall assembly W_E_49_C

N°	Material	s (m)	λ (W/mK)	R (m^2K/W)	Specific heat (J/kgK)	Density (kg/m^3)	μ	P (kg/mhPa)	Rv (m^2hPa/kg)
	Int		7.69	0.13					0
1	Plaster	0.01	0.78	0.01	1000	1600	15	4.47E-8	223880.60
2	Concrete	0.3	2.00	0.15	1000	2400	50	1.34E-8	22388060.00
3	Xps	0.17	0.03	5.00	1030	70	70	9.57E-9	17761194.00
4	Finishing	0.006	1.00	0.01	1000	1800	1	6.70E-7	8955.22
	Ext		25.00	0.04					0

TOT thickness = 0.486 m
R value= 5.34 m^2K/W
U value = 0.19 W/m^2K
R vapor = 40382089.55 m^2hPa/kg
Verified at interstitial condensation

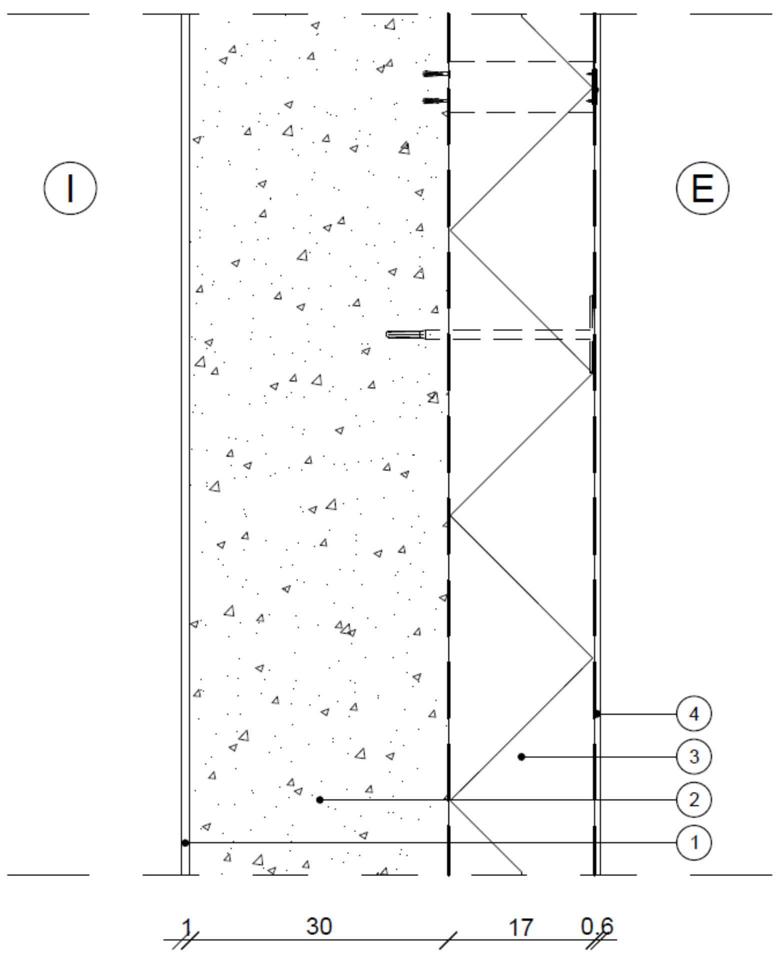


Figure 53: Exterior wall assembly W_E_49_C

Table 29: Exterior wall assembly W_E_48_C (no render)

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		7.69	0.13					0
1	Concrete	0.3	2.00	0.15	1000	2400	50	1.34E-8	22388060.00
2	Xps	0.17	0.03	5.00	1030	70	70	9.57E-9	17761194.00
3	Finishing	0.006	1.00	0.01	1000	1800	1	6.70E-7	8955.22
	Ext		25	0.04					0

TOT thickness = 0.476 m
R value= 5.33 m²K/W
U value = 0.19 W/m²K
R vapor = 40158208.96 m²hPa/kg
Verified at interstitial condensation

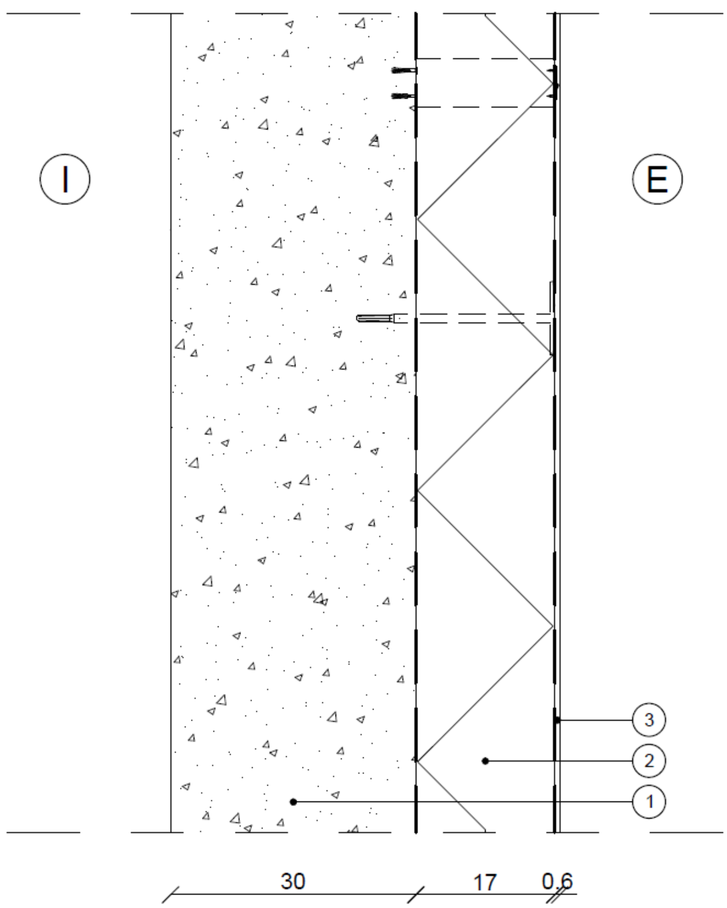


Figure 54: Exterior wall assembly W_E_48_C (no render)

Table 30: Exterior wall assembly W_E_39_R

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		7.69	0.13					0
1	Plaster	0.01	0.78	0.01	1000	1600	15	4.47E-8	223880.60
2	REI blocks	0.2	2.53	0.08	1110	1400	6	1.12E-7	1791045.00
3	Xps	0.17	0.03	5.00	1030	70	70	9.57E-9	17761194.00
4	Finishing	0.006	1.00	0.01	1000	1800	1	6.70E-7	8955.22
	Ext		25.00	0.04					0

TOT thickness = 0.386 m
R value= 5.27 m²K/W
U value = 0.19 W/m²K
R vapor = 19785074.63 m²hPa/kg
Verified at interstitial condensation

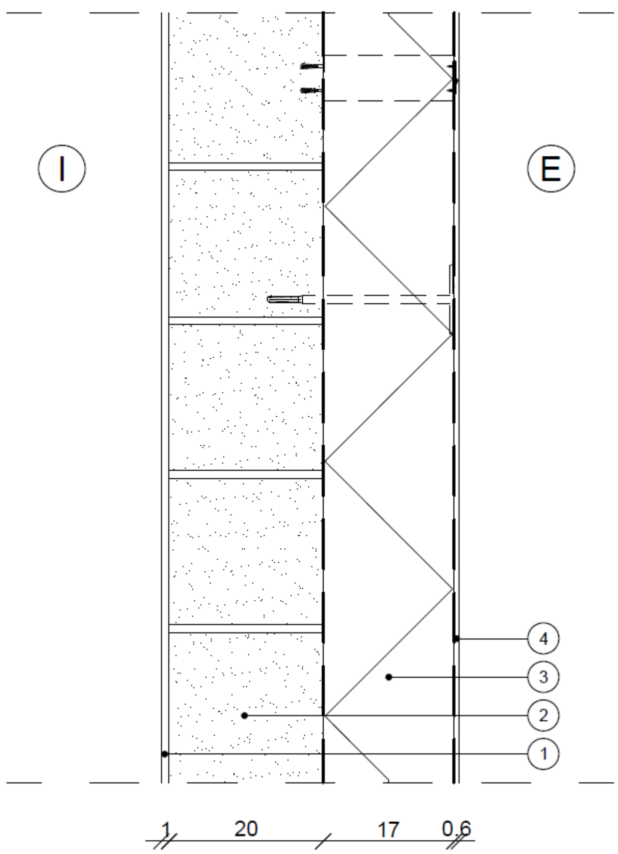


Figure 55: Exterior wall assembly W_E_39_R

Table 31: Exterior wall assembly W_E_41_C (insulated retention wall)

N°	Material	s (m)	λ (W/mK)	R (m^2K/W)	Specific heat (J/kgK)	Density (kg/m^3)	μ	P (kg/mhPa)	Rv (m^2hPa/kg)
	Int		7.69	0.13					0
1	Plaster	0.01	0.78	0.01	1000	1600	15	4.47E-8	223880.60
2	Concrete	0.3	2.00	0.15	1000	2400	50	1.34E-8	22388060.00
3	Vapor barrier aluminium	0.0001	220.00	4.55E-07	963	2700	3.5E+9	1.91E-16	5.22E+11
4	Xps	0.1	0.03	2.94	1030	70	70	9.57E-9	10447761.00
5	Waterproofing and mechanical protection	0.003	0.20	0.02	1350	1000	60000	1.12E-11	2.69E+08
	Ext			0					0

TOT thickness = 0.413 m
R value= 3.25 m^2K/W
U value = 0.31 W/m^2K

No need to verify presence of interstitial condensation since the element isn't between a heated and non-heated area.
Note: the insulation of this wall is minimal and is present in the walls that are between an external and an internal not heated space, just to reduce the thermal bridge in the building.

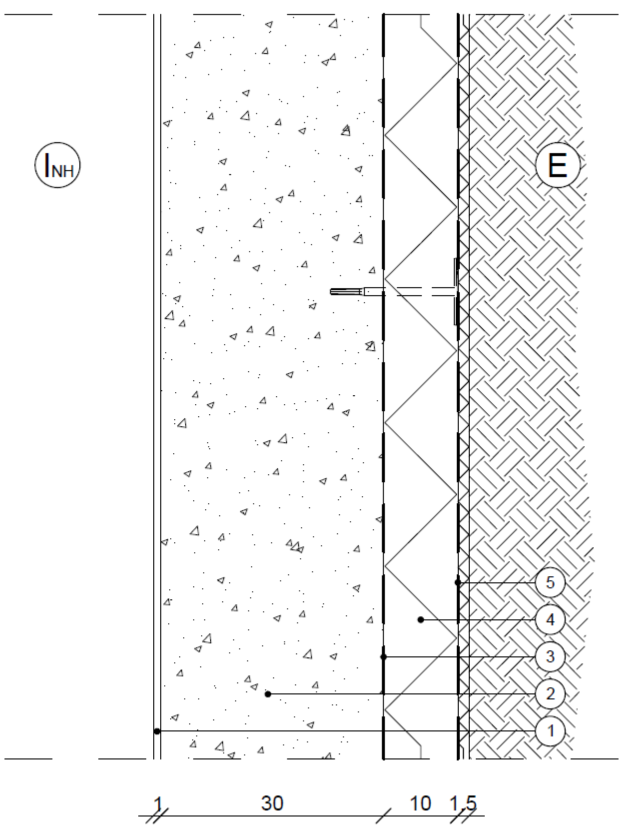


Figure 56: Exterior wall assembly W_E_41_C (insulated retention wall)

Table 32: Exterior wall assembly W_E_31_C (retention wall)

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		7.69	0.13					0
1	Plaster	0.01	0.78	0.01	1000	1600	15	4.47E-8	223880.60
2	Concrete	0.3	2.00	0.15	1000	2400	50	1.34E-8	22388060.00
3	Waterproofing and mechanical protection	0.003	0.20	0.02	1350	1000	60000	1.12E-11	2.69E+08
	Ext			0					0

TOT thickness = 0.313 m
R value= 0.31 m²K/W
U value = 3.25 W/m²K

No need to verify presence of interstitial condensation since the element isn't between a heated and non-heated area.

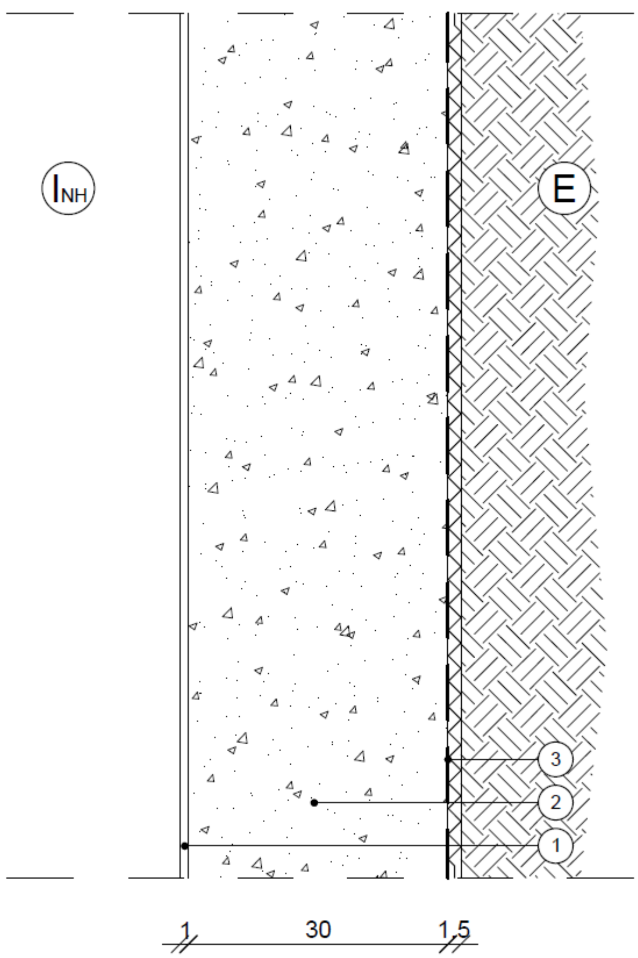


Figure 57: Exterior wall assembly W_E_31_C (retention wall)

Table 33: Exterior wall assembly W_E_45_R (green wall)

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		7.69	0.13					0
1	Plaster	0.01	0.78	0.01	1000	1600	15	4.47E-8	223880.60
2	REI blocks	0.2	2.53	0.08	1110	1400	6	1.12E-7	1791045.00
3	Xps	0.12	0.03	3.53	1030	70	70	9.57E-9	12537313.00
4	Air	0.05		0.18	1030	1.23	1	6.70E-7	74626.87
5	Impermeable board	0.0125	0.25	0.0500	1000	864	11	6.09E-8	205223.90
6	Polyprolilene fabric membrane	0.004	0.17	0.0235	1400	275	36	1.86E-8	214925.40
7	Rockwool	0.055	0.04	1.5714	1030	70	1	6.70E-7	82089.55
	Ext		25.00	0.04					0

TOT thickness = 0.451 m
R value= 5.62 m²K/W
U value = 0.18 W/m²K

R vapor = 15129104.48 m²hPa/kg

Verified at interstitial condensation

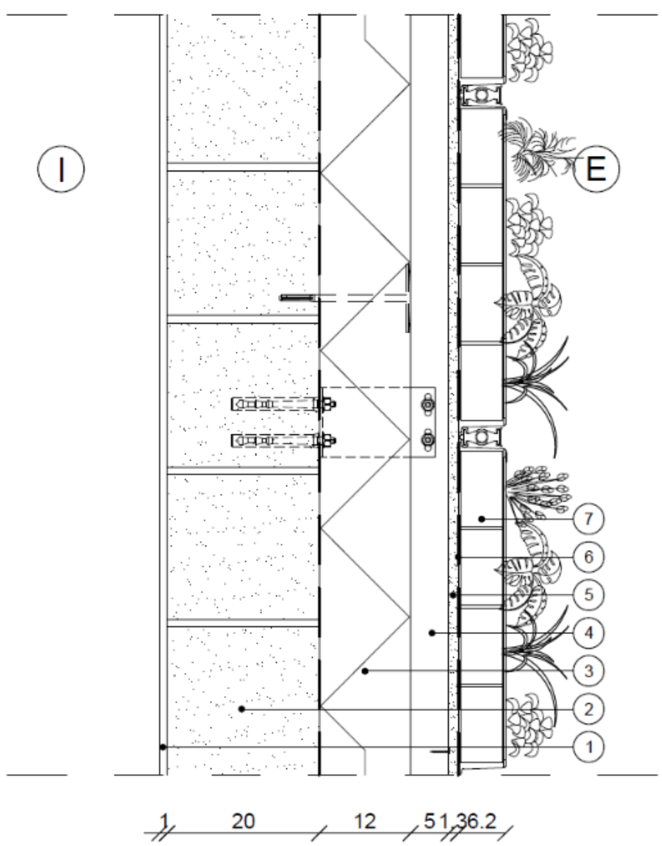


Figure 58: Exterior wall assembly W_E_45_R (green wall)

5.3.2.1.2 Exterior slabs assemblies

Table 34: Exterior slab assembly S_E_74 (ground floor)

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		5.88	0.17					0
1	Tiles	0.01	1.00	0.01	800	2000	40	1.68E-8	597014.90
2	Air	0.20		0			1	6.70E-7	298507.50
3	Light weight concrete	0.1	0.31	0.32	900	1170	10	6.70E-8	1492537.00
4	Vapor barrier aluminium	0.0001	220.00	4.55E-07	963	2700	3.50E+9	1.91E-16	5.22E+11
5	Xps	0.18	0.03	6.21	1450	35	70	9.57E-9	18805970.00
6	Concrete	0.05	2.00	0.03	1000	2400	50	1.34E-8	3731343.00
7	Concrete + polystyrene	0.15	1.91	0.08	835	1250	27	2.46E-8	6105834.00
8	Concrete	0.04	2.00	0.02	1000	2400	50	1.34E-8	2985075.00
9	Plaster	0.01	0.78	0.01	1000	1600	15	4.47E-8	223880.60
	Ext		5.88	0.17					0

TOT thickness = 0.740 m
R value= 7.02 m²K/W

U value = 0.14 W/m²K
R vapor = 5.22422E+11 m²hPa/kg
Verified at interstitial condensation

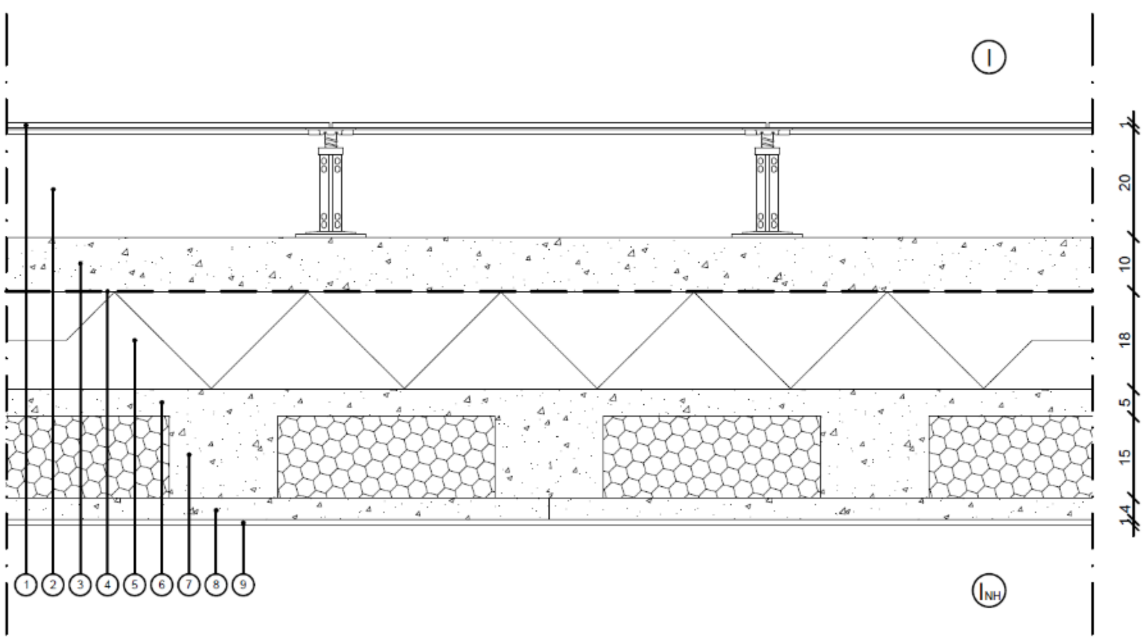


Figure 59: Exterior slab assembly S_E_74 (ground floor)

Table 35: Exterior slab assembly S_E_74 (ground floor + green)

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		5.88	0.17					0
1	Ground	0.15	0.42	0.36	1046	1600	22	3.05E-8	4925373.00
2	Polyprolilene fabric membrane	0.001	0.17	0.01	1400	275	36	1.86E-8	53731.34
3	Drainage layer	0.002	0.15	0.01	1256	22	10000	6.70E-11	29850746.00
4	Waterproofing (double)	0.006	0.20	0.03	1350	1000	120000	5.58E-12	1.07E+9
5	Light weight concrete	0.10	0.31	0.32	900	1170	10	6.70E-8	1492537.00
6	vapor barrier aluminium	0.0001	220	4.55E-07	963	2700	3.50E+9	1.91E-16	5.22E+11
7	Xps	0.18	0.03	6.21	1450	35	70	9.57E-9	18805970.00
8	Concrete	0.05	2.00	0.03	1000	2400	50	1.34E-8	3731343.00
9	Concrete + polystyrene	0.15		0.08					6105834.00
10	Concrete	0.04	2.00	0.02	1000	2400	50	1.34E-8	2985075.00
11	Plaster	0.01	0.78	0.01	1000	1600	15	4.47E-8	223880.60
	Ext		5.88	0.17					0

TOT thickness = 0.689 m
R value= 7.41 m²K/W
U value = 0.13 W/m²K

R vapor = 5.23531E+11 m²hPa/kg
Verified at interstitial condensation

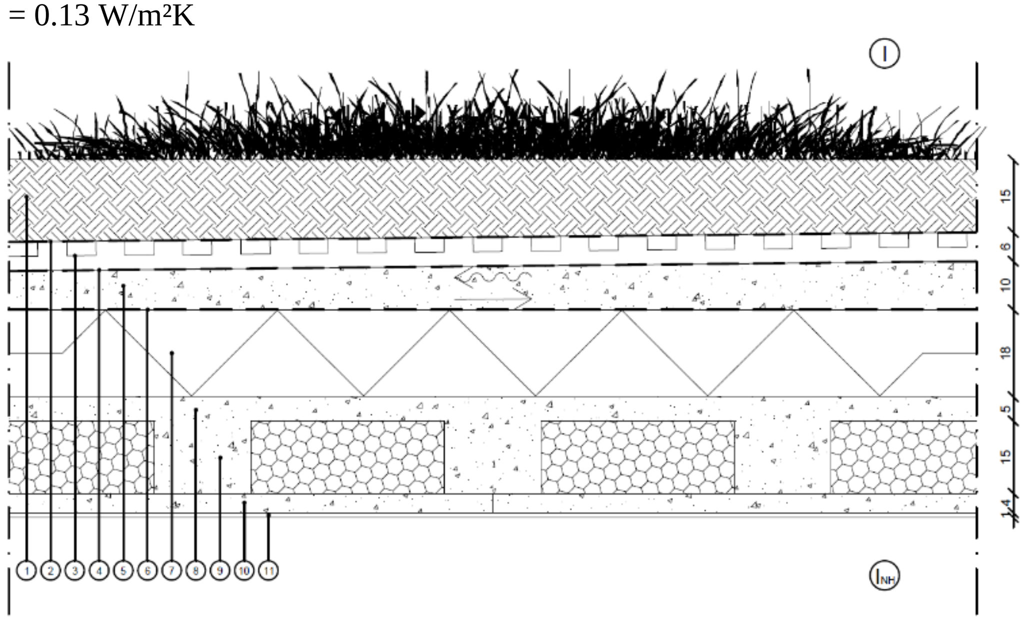


Figure 60: Exterior slab assembly S_E_74 (ground floor + green)

Table 36: Exterior slab assembly S_E_74 (ground floor + water)

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		5.88	0.17					0
1	Water	0.21	0.60	0.35	4200	997	1	6.7E-7	313432.80
2	Waterproofing (double)	0.006	0.20	0.03	1350	1000	120000	5.58E-12	1.79E+8
3	Light weight concrete	0.1	0.31	0.32	900	1170	10	6.7E-8	1492537.00
4	vapor barrier aluminium	0.0001	220.00	4.55E-7	963	2700	3.5E+9	1.91E-16	5.22E+11
5	Xps	0.18	0.03	6.21	1450	35	70	9.57E-9	18805970.00
6	Concrete	0.05	2.00	0.03	1000	2400	50	1.34E-8	3731343.00
7	Concrete + polystyrene	0.15		0.08					6105834.00
8	Concrete	0.04	2.00	0.02	1000	2400	50	1.34E-8	2985075.00
9	Plaster	0.01	0.78	0.01	1000	1600	15	4.47E-8	6105834.00
	Ext		5.88	0.17					0

TOT thickness = 0.746 m
R value= 7.39 m²K/W
U value = 0.14 W/m²K

R vapor = 5.22607E+11 m²hPa/kg
Verified at interstitial condensation

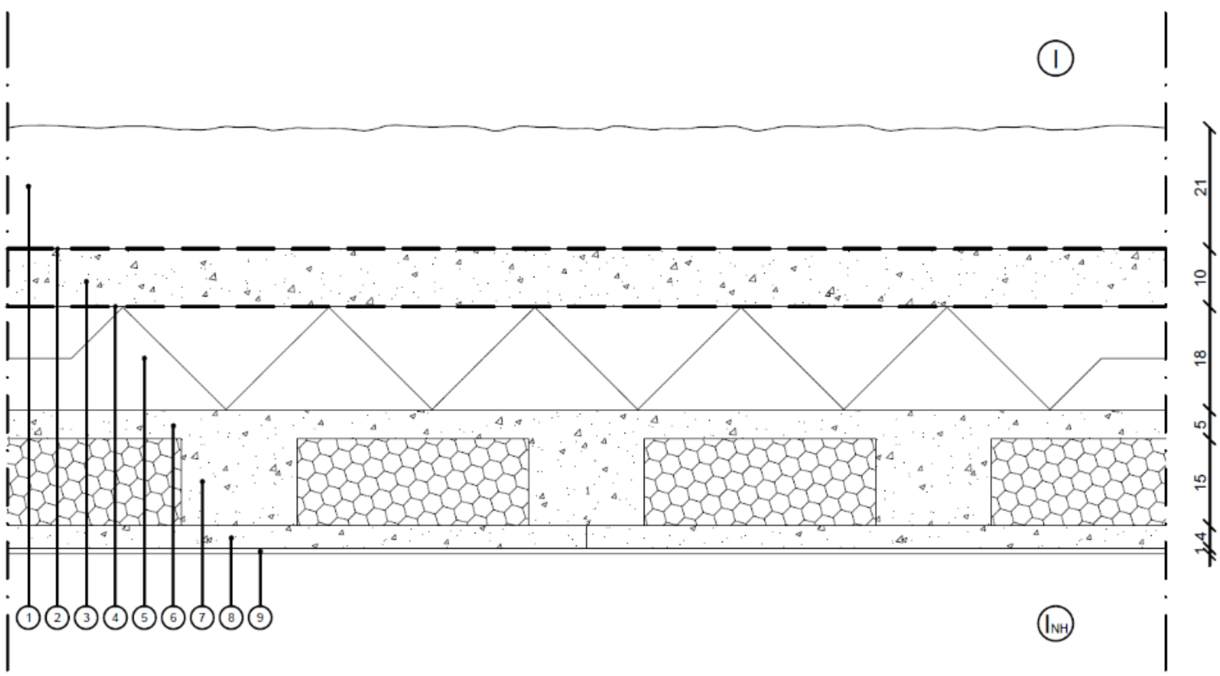


Figure 61: Exterior slab assembly S_E_74 (ground floor + water)

Table 37: Exterior slab assembly S_E_68 (cantilever)

N°	Material	s (m)	λ (W/mK)	R (m^2K/W)	Specific heat (J/kgK)	Density (kg/m^3)	μ	P (kg/mhPa)	Rv (m^2hPa/kg)
	Int		5.88	0.17					0
1	Tiles	0.01	1	0.01	800	2000	40	1.68E-8	597014.90
2	Light weight concrete	0.1	0.31	0.32	900	1170	10	6.7E-8	1492537.00
3	Polyethylene	0.003	0.03	0.09	1800	30	2000	3.35E-10	8955224.00
4	Concrete	0.1	2	0.05	1000	2400	50	1.34E-8	7462687.00
5	Steel dock	0.008	50	0.00	450	7800	2144444	3.12E-13	2.56E+10
6	Xps	0.18	0.03	6.21	1450	35	70	9.57E-9	18805970.00
7	Air cavity	0.22					1	6.7E-7	328358.20
8	Rockwool	0.05	0.03	1.47	1030	60	70	9.57E-9	5223881.00
9	Aquaboard	0.0125	0.25	0.05	1000	900	11	6.09E-8	205223.90
	Ext		25	0.04					0

TOT thickness = 0.683 m
R value = 8.57 m^2K/W
U value = 0.12 W/m^2K

R vapor = 25648372388 m^2hPa/kg
Verified at interstitial condensation

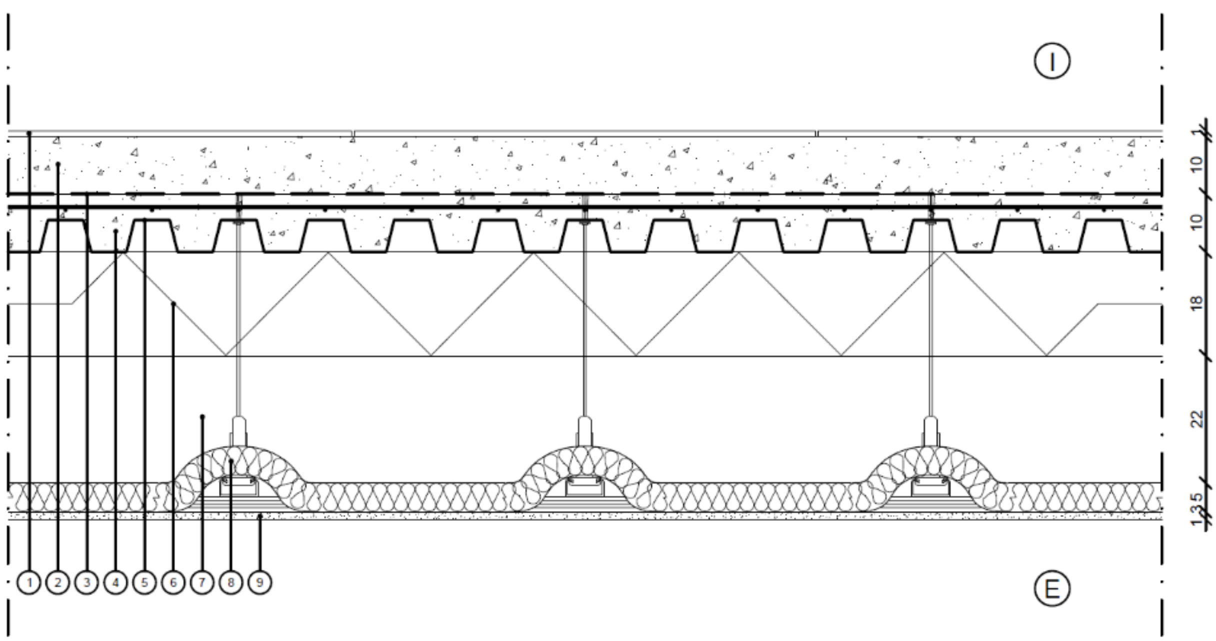


Figure 62: Exterior slab assembly S_E_68 (cantilever)

Table 38: Exterior slab assembly S_E_64 (underground)

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		5.88	0.17					0
1	Concrete	0.05	2.00	0.03	1000	2400	50	1.34E-8	3731343.00
2	Light weight concrete	0.08	0.31	0.26	900	1170	10	6.7E-8	1194030.00
3	Polyprolilene fabric membrane	0.001	0.17	0	1400	275	36	1.86E-8	53731.34
4	Waterproofing (double)	0.006	0.20	0.03	1350	1000	120000	5.58E-12	1.07E+9
5	Concrete	0.5	2	0.25	1000	2400	50	1.34E-8	37313433.00
	Ext			0					0

TOT thickness = 0.637 m
R value= 0.73 m²K/W
U value = 1.36 W/m²K

No need to verify presence of interstitial condensation since the element isn't between a heated and non-heated area.

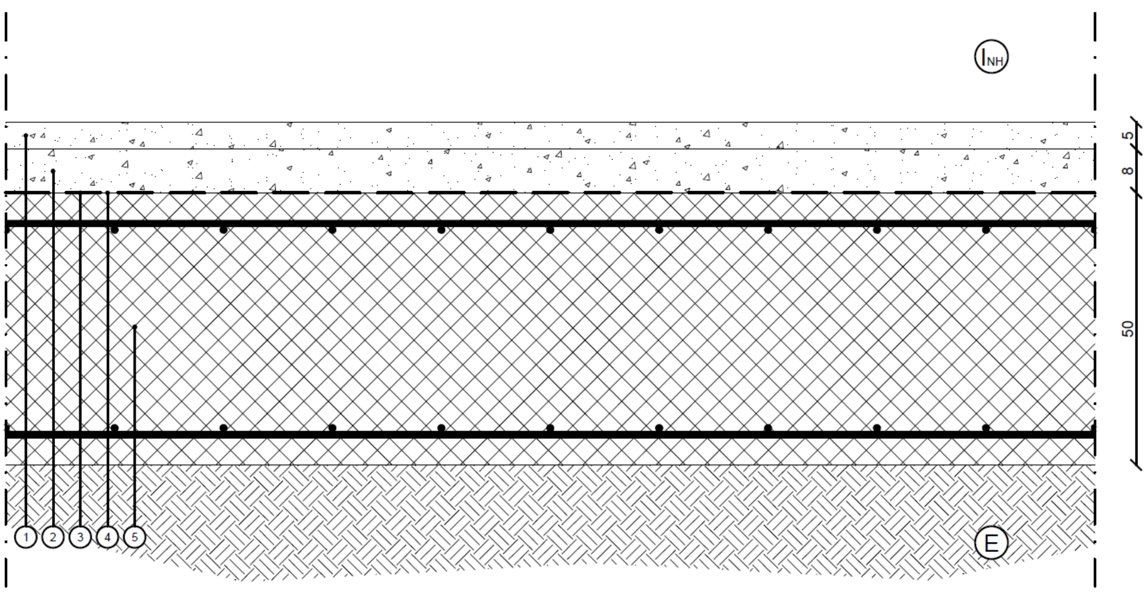


Figure 63: Exterior slab assembly S_E_64 (underground)

Table 39: Exterior slab assembly S_E_42 (outdoors)

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		5.88	0.17					0
1	Plaster	0.01	0.78	0.01	1000	1600	15	4.47E-8	223880.60
2	Concrete	0.04	2	0.02	1000	2400	50	1.34E-8	2985075.00
3	Concrete + polystyrene	0.15		0.08			6105834	1.10E-13	1.37E+12
4	Concrete	0.05	2	0	1000	2400	50		0.08
5	Waterproofing	0.003	0.2	0.08	1350	1000	120000		6105834.00
6	Light weight concrete	0.15	0.31	0.48	900	1170	10	6.70E-8	2238806.00
7	Tiles	0.015	1	0.02	800	2000	40	1.68E-8	895522.40
	Ext		25	0.04					0

TOT thickness = 0.418 m
R value= 0.90 m²K/W
U value = 1.11 W/m²K

No need to verify presence of interstitial condensation since the element isn't between a heated and non-heated area.

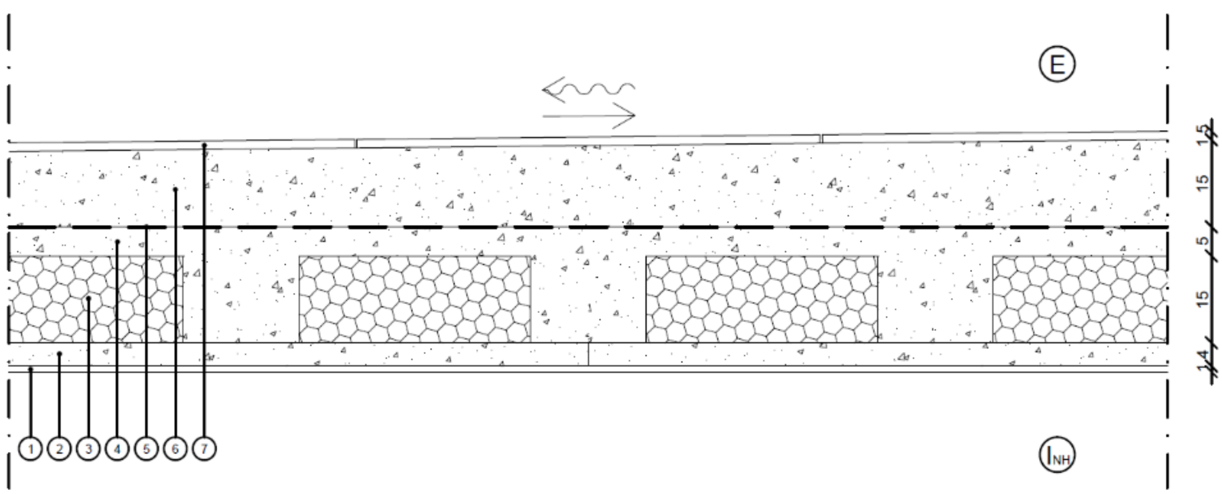


Figure 64: Exterior slab assembly S_E_42 (outdoors)

5.3.2.1.3 Roof assemblies

Table 40: Roof assembly S_E_37

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		10	0.1					0
1	Steel dock	0.008	50	0.00	450	7800	2144444	3.12E-13	2.56E+10
2	Concrete	0.1	2	0.05	1000	2400	50	1.34E-8	7462687.00
3	Xps	0.14	0.03	4.83	1450	35	70	9.57E-9	14626866.00
4	Waterproofing	0.003	0.20	0.02	1350	1000	120000	5.58E-12	5.37E+8
5	Light weight concrete	0.1	0.31	0.32	900	1170	10	6.70E-8	1492537.00
6	Tiles	0.015	1	0.02	800	2000	40	1.68E-8	895522.40
	Ext		25	0.04					0

TOT thickness = 0.366 m
R value = 5.37 m²K/W
U value = 0.19 W/m²K
R vapor = 26167092537 m²hPa/kg
Verified at interstitial condensation

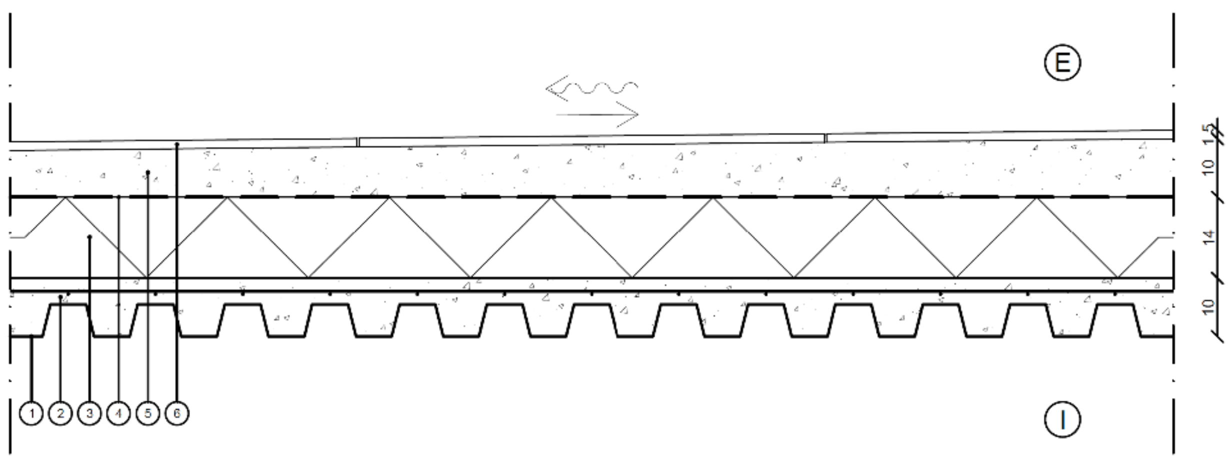


Figure 65: Roof assembly S_E_37

Table 41: Roof assembly S_E_36 (without tiles)

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		10	0.1					0
1	Steel dock	0.008	50	0.00	450	7800	2144444	3.12E-13	2.56E+10
2	Concrete	0.1	2	0.05	1000	2400	50	1.34E-8	7462687.00
3	Xps	0.14	0.03	4.83	1450	35	70	9.57E-9	14626866.00
4	Waterproofing	0.003	0.20	0.02	1350	1000	120000	5.58E-12	5.37E+8
5	Light weight concrete	0.1	0.31	0.32	900	1170	10	6.70E-8	1492537.00
6	Waterproofing	0.006	0.20	0.03	1350	1000	60000	1.12E-11	5.37E+8
	Ext		25	0.04					0

TOT thickness = 0.357 m
R value = 5.39 m²K/W
U value = 0.19 W/m²K
R vapor = 26703510448 m²hPa/kg
Verified at interstitial condensation

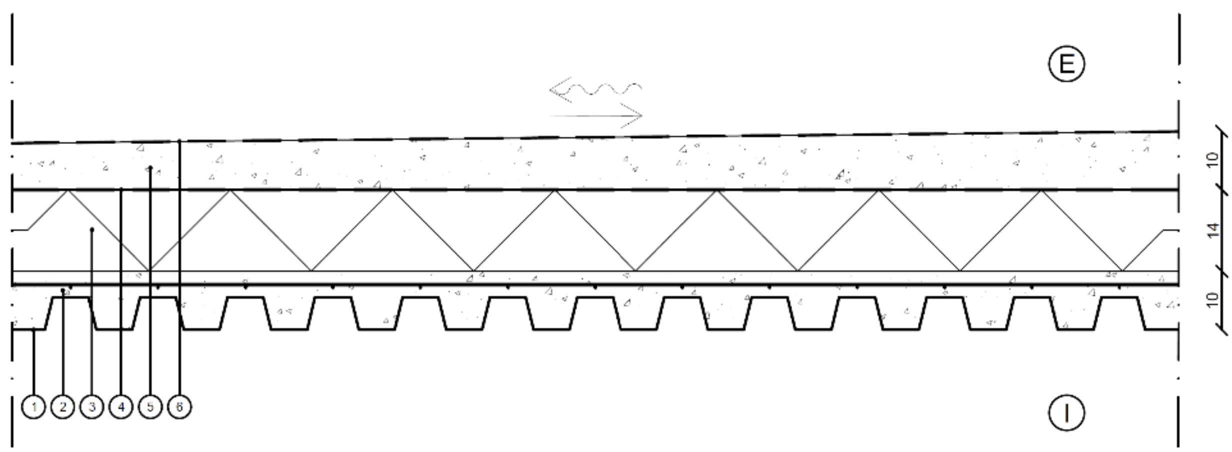


Figure 66: Roof assembly S_E_36 (without tiles)

Table 42: Roof assembly S_E_57 (with deck)

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		10	0.1					0
1	Steel dock	0.008	50	0.00	450	7800	2144444	3.12E-13	2.56E+10
2	Concrete	0.1	2	0.05	1000	2400	50	1.34E-8	7462687.00
3	Xps	0.14	0.03	4.83	1450	35	70	9.57E-9	14626866.00
4	Waterproofing	0.003	0.20	0.02	1350	1000	120000	5.58E-12	5.37E+8
5	Light weight concrete	0.1	0.31	0.32	900	1170	10	6.7E-8	1492537.00
6	Waterproofing	0.006	0.20	0.03	1350	1000	60000	1.12E-11	5.37E+8
7	Air	0.195		0			1	6.7E-7	291044.80
8	Tiles	0.015	1	0.02	800	2000	40	1.68E-8	895522.40
	Ext		25	0.04					0

TOT thickness = 0.567 m
R value = 5.40 m²K/W
U value = 0.19 W/m²K
R vapor = 26704697015 m²hPa/kg
Verified at interstitial condensation

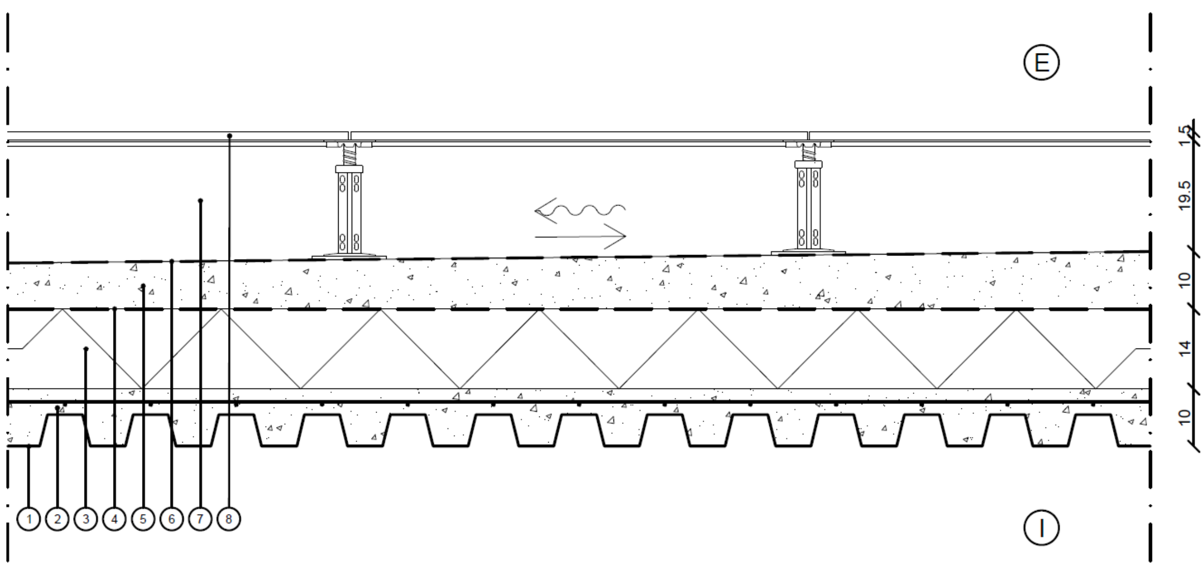


Figure 67: Roof assembly S_E_57 (with deck)

Table 43: Roof assembly S_E_146 (green roof)

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		10	0.1					0
1	Steel dock	0.008	50	0.00	450	7800	2144444	3.12E-13	2.56E+10
2	Concrete	0.1	2	0.05	1000	2400	50	1.34E-8	7462687.00
3	Xps	0.14	0.03	4.83	1450	35	70	9.57E-9	14626866.00
4	Waterproofing	0.003	0.20	0.02	1350	1000	120000	5.58E-12	5.37E+8
5	Light weight concrete	0.1	0.31	0.32	900	1170	10	6.70E-8	1492537.00
6	Waterproofing (double)	0.006	0.20	0.03	1350	1000	120000	5.58E-12	1.07E+9
7	Drainage layer	0.002	0.15	0.01	1256	22	10000	6.70E-11	29850746.00
8	Polyprolilene fabric membrane	0.001	0.17	0.01	1400	275	36	1.86E-8	53731.34
9	Ground	0.15	0.42	0.36	1046	1600	22	3.05E-8	4925373.00
	Ext		25	0.04					0

TOT thickness = 0.51 m
R value = 5.76 m²K/W
U value = 0.17 W/m²K
R vapor = 27275653731 m²hPa/kg
Verified at interstitial condensation

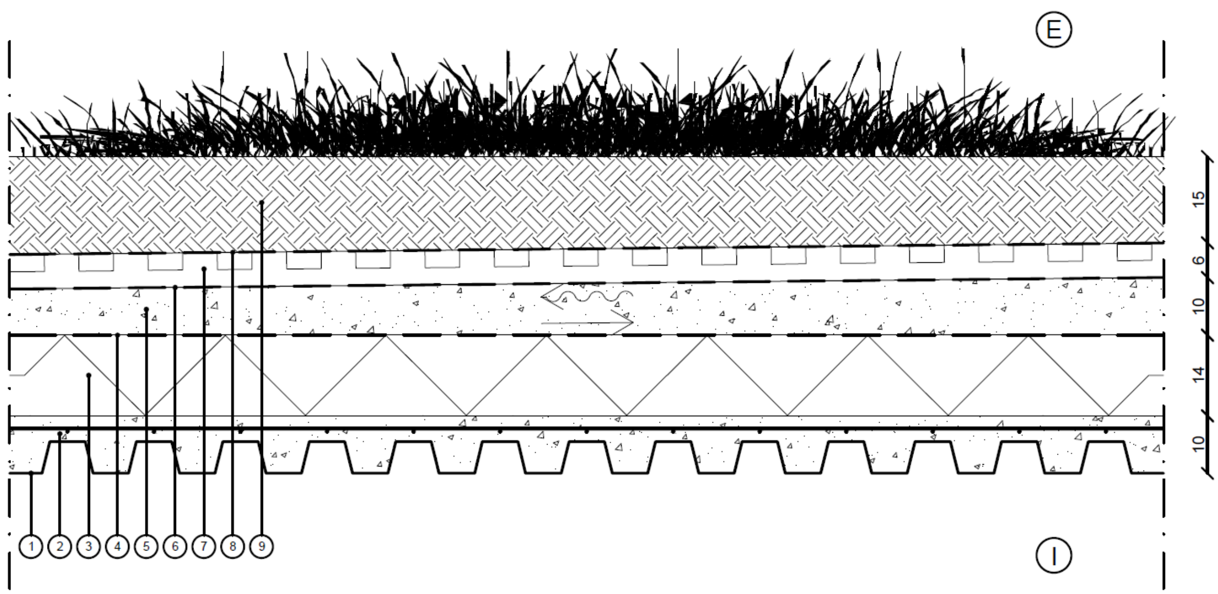


Figure 68: Roof assembly S_E_146 (green roof)

5.3.2.2 Transparent envelope elements

Transparent envelope elements include all components of the building skin, primarily made of glazed panels or glass blocks, this category includes external windows, glazed curtain wall systems, and skylights (glazed surfaces with less than 60° tilt); and excludes all internal partitions. Transparent envelope elements have a great level of influence on building energy performance and comfort, as they allow a considerable part of visible light and radiant heat to directly access to internal spaces, increasing heat gains and allowing the use of daylight.

Thus, the design process was driven by a balancing between positive and negative effects that glazed envelope would have on adjacent spaces, this was managed at two levels:

a) The transparent or glazing assembly was designed by selecting the extension, location and type of windows and curtain walls, the materials of framing members, the location of spandrel panels, and the initial reference properties of the glass panels

b) The glazed panel stratigraphy was designed by defining the detailed layering inside glazed areas: thickness of glass panels, characteristics of the cavities between them and eventual use of films or coatings; to determine their precise thermal properties: u-value, SHGC, and optical properties: Visible Light Transmittance (VLT)

Like the procedure followed for the design of opaque envelope elements, transparent assemblies were initially set to comply with the minimum standards set by the IECC for Commercial buildings under climate zone 4A. The minimum prescriptions for *fenestrations*, as transparent envelope elements are defined by the code, are reported in TABLE XX, containing U-values in both imperial and SI units, and Solar Heat Gain Coefficients for different directions:

Table 44: Maximum U-values requirements for fenestration assemblies on climate zone 4A (International Code Council, 2021)

Element	Max. U-value		Max. SHGC	
	BTU/h*ft²*F	**W/m²K**	**N**	**SEW**
Fenestration fixed	0.38	**2.156**	**0.48**	**0.36**
Fenestration operable	0.45	**2.554**		
Skylight	0.5	**2.837**	**0.4**	

As done for the opaque part, a preliminary analysis of the building with the U-values and SHGC very close to the one given by law applied has been made and using the response curve given by Insight the most convenient U-value has been chosen. In the following table the default typologies of glass proposed by Insight:

Table 45: Generic glazing assembly options and properties for optimization (Autodesk Insight, n.d.)

Window Glass Name	Glazing Type	U-Value (W/m^2K)	U-value (BTU/hr-ft2-F)	Solar Heat Gain Coefficient (SHGC)	Visible Light Transmittance (VLT)
No Change	No change	No change	No change	No change	No change
Sgl Clr	Single Clear 6mm	6.17	1.09	0.81	0.88
Dbl Clr	Double Clear 6/13 Air	2.74	0.48	0.7	0.78
Dbl LoE	Double Low-E (e3=0.2) Clear 3/13 Air	1.99	0.35	0.73	0.74
Trp LoE	Triple Low-E (e2=e5=0.1) Clear 3mm/6mm Air	1.55	0.27	0.47	0.66
Quad LoE	Quadruple LoE Films (88) 3mm/8mm Krypton	0.66	0.12	0.45	0.62
BIM	The setting in your model (Building Information Model)				

The response curves given by insight are four, one for each side of the building. In this way it is possible to choose the best glass type for every orientation of the building.

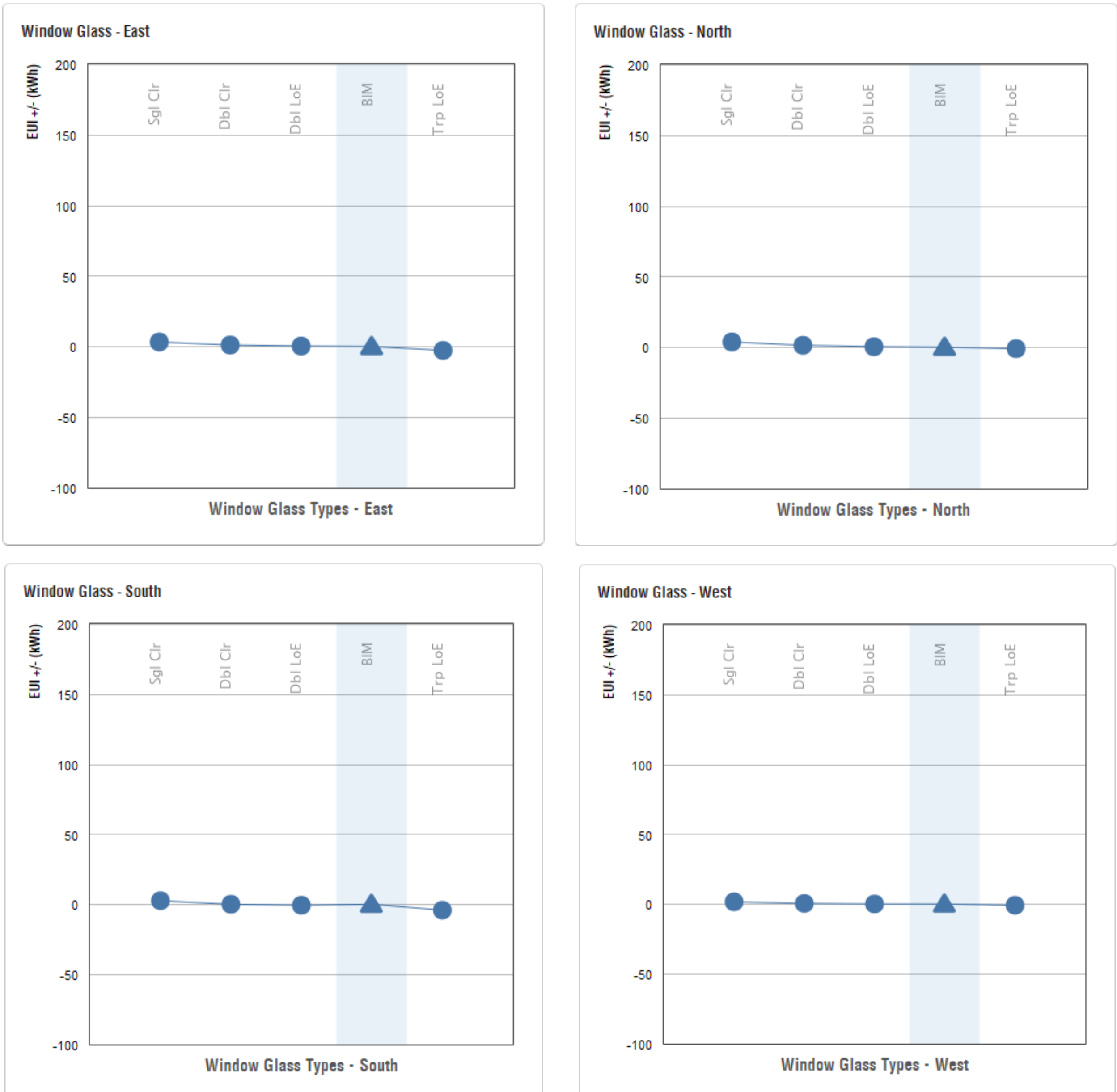


Figure 69: Response curves comparing generic options for glazing assemblies (Autodesk Insight, n.d.)

To choose the best typology of glass the curves have been translated in percentages of gain of EUI, only for the typologies of glass that are convenient. So, the comparison for all the sides have to be made simply between the glass with the characteristics given by law and the "Trp LoE" type by Insight.

North:

Name	Assembly	EUI (kWh/m²yr)	Improvement compared to BIM case
BIM	The setting in your model (Building Information Model)	173	-
Trp LoE	Triple Low-E (e2=e5=0.1) Clear 3mm/6mm Air	172.02	0.57%

South:

Name	Assembly	EUI (kWh/m²yr)	Improvement compared to BIM case
BIM	The setting in your model (Building Information Model)	173	-
Trp LoE	Triple Low-E (e2=e5=0.1) Clear 3mm/6mm Air	168.76	2.45%

East:

Name	Assembly	EUI (kWh/m²yr)	Improvement compared to BIM case
BIM	The setting in your model (Building Information Model)	173	-
Trp LoE	Triple Low-E (e2=e5=0.1) Clear 3mm/6mm Air	170.22	1.61%

West:

Name	Assembly	EUI (kWh/m²yr)	Improvement compared to BIM case
BIM	The setting in your model (Building Information Model)	173	-
Trp LoE	Triple Low-E (e2=e5=0.1) Clear 3mm/6mm Air	172.08	0.53%

As shown in the tables, the gain in term of percentage of EUI at north and west is very low, when using glass with higher performance, while at east and especially south the gain is good, so in these sides can be convenient to use a glass with characteristics close to “Trp LoE” type, while in the other ones a glass with the characteristics given by law. It is important to highlight that the “Trp LoE” has a SHGC of 47%, higher than the one given by law (36%), so in the glass that will be chosen the SHGC will be lower than 36%.

The results are for sure influenced by the fact that south and east are the sides of the building with the biggest amount of glass (79% and 82% of the whole façade area are covered by glass, respectively).

5.3.2.2.1 Vertical glazing assembly

The curtain wall has been designed using a stick system and in ha way to host panels of glass with the dimensions of 2.2 x 3m, on floors that are 4.5m high. The remaining 1,5m are covered by a spandrel panel with a finishing of opaque glass to have a continuity of the materials in all the façade.

In the south and east sides, in the position of the columns, operable windows have been placed to guarantee natural ventilation in mostly of the rooms of the building. These windows can be opened to the exterior side with turn and vasistas movement and have a dimension of 0.84x3m and permit the access on the catwalk, used mainly for the maintenance of the curtain wall, between the curtain wall and the double skin of the building.

The pre-dimensioning of the curtain wall has been made by following the indications given by Ponzio, a producer of curtain wall, that gives charts to evaluate the dimension of mullions and transoms depending by pressure of the wind and other characteristics. In particular, for the mullions the distance between two floors (and so between the two anchors of the curtain wall) and the space between two mullions are the characteristics to be taken in account, while, for the transom, the space between two mullions and the space between two transoms. To choose the correct chart for the pre-dimensioning a wind load analysis should be made, but in this thesis the chart related to the maximum wind load (1200Pa) has been choose for simplicity (of course, probably the structure of the whole curtain wall will be over-dimensioned).
Here the charts used for the pre-dimensioning of mullions and transoms:

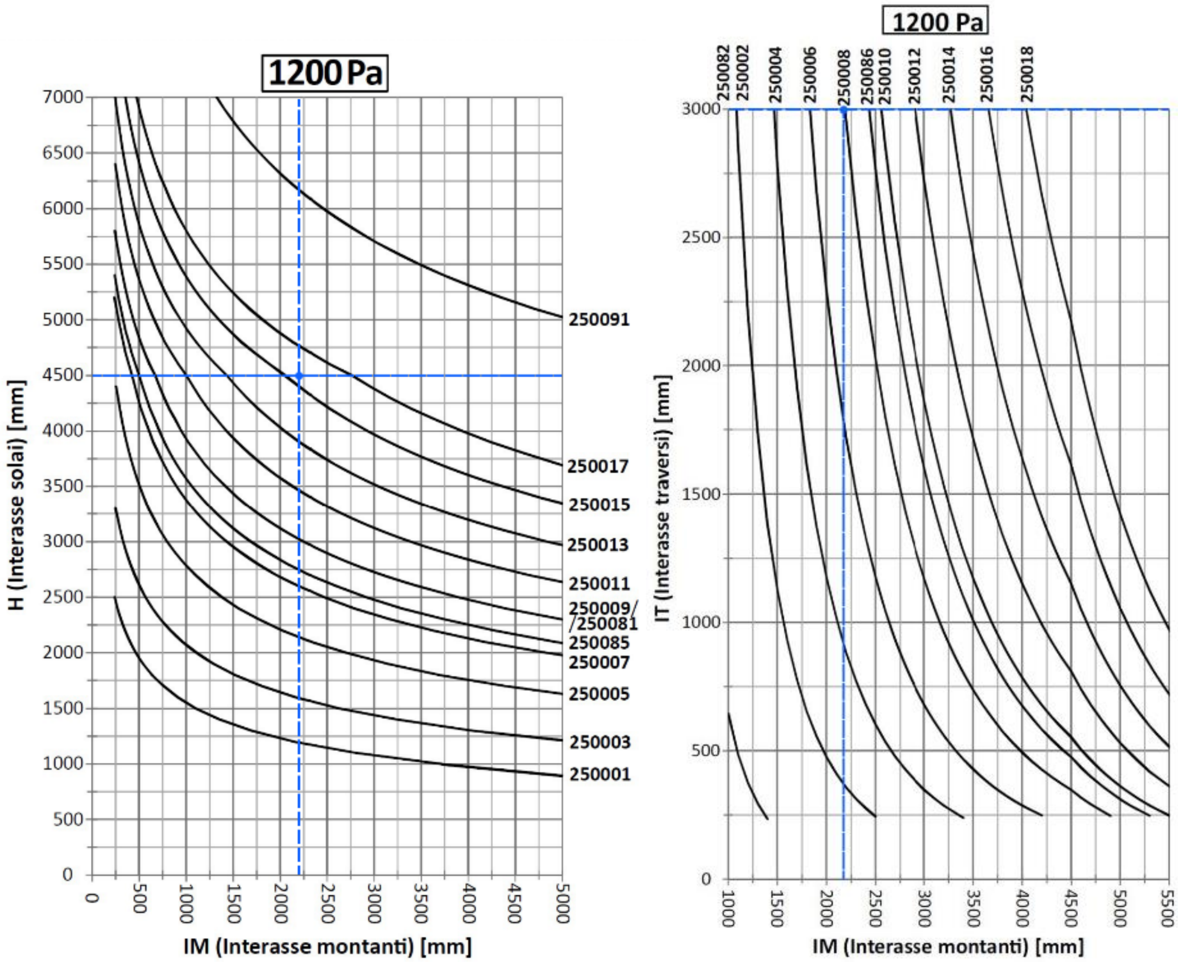


Figure 70: Pre-dimensioning chart for mullions (left) and for transoms (right) (Ponzio S.R.L., 2021)

The chosen profile for the mullions is the 250017, an aluminium mullion with the dimensions of the cross section of 50x250mm, while for transoms the 250008, an aluminium transom with the dimension of the cross section of 50x129.5mm.

The spandrel panels used in the building are composed by a layer of 0.6cm of opaque glass and 15 cm of rockwool, with an U-value of 0.23W/m²K.

The chosen frame for the curtain wall is the FWS 50.SI produced by Schuco with an U-value of the frame of 0.7 W/m²K. This model of system is designed to host also operable windows.

5.3.2.2.2 Skylight glazing assembly

For the curtain wall on the top of the building, the same dimensions of mullions and transoms have been used, but in this case the structure is supported by a steel structure that is the continuation of the main steel structure of the building.

The structure consists in five arches made with HEB 220 steel profiles (the same profile of the column of the last floor), on which some mullions are placed in a way to be more resistant to the wint loads that are high on the roof.

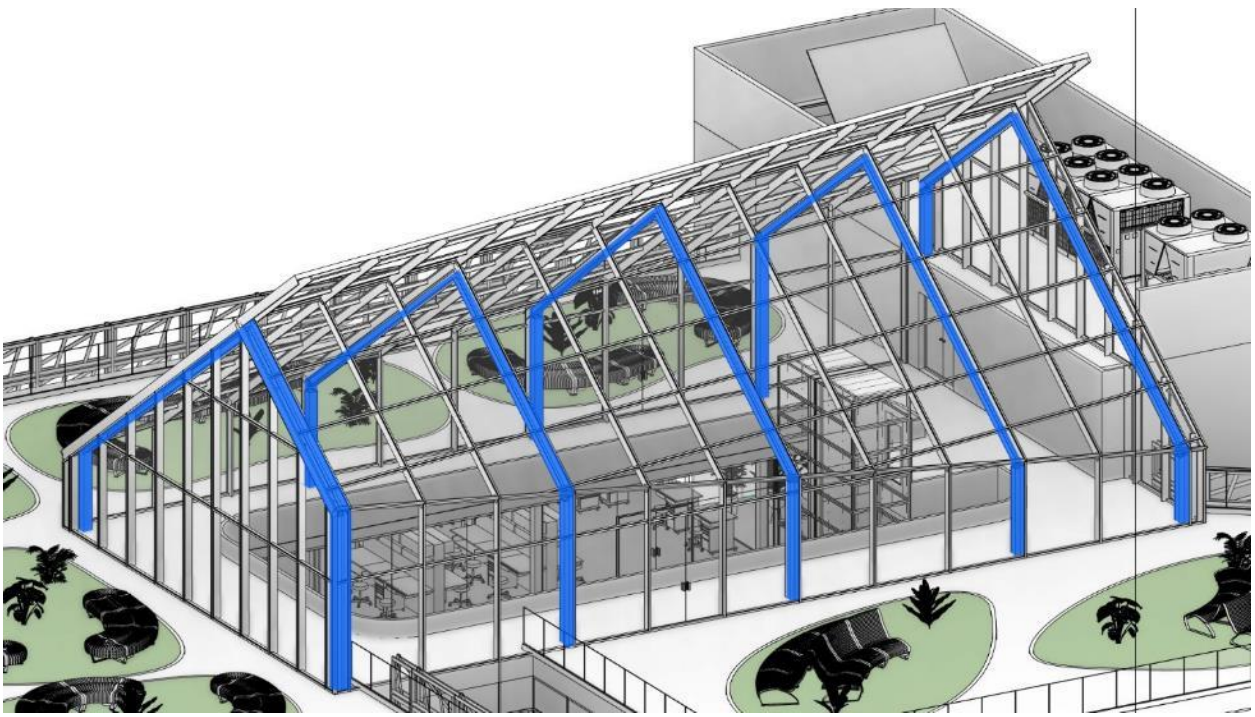


Figure 71: 3d View of glazed roof, with highlighted structural gables

Since Insight doesn't give options for the optimization of the glass roof, and since this part of the building receives the higher amount of solar radiation, the glass proposed is the triple one used for the vertical curtain wall on the south and east side. Here is used on each side of the glass roof.

Furthermore, the southern face of the glazed roof, photovoltaic cells were integrated in the glass panels, to avoid excessive solar radiation to access the atrium and use it for on-site electricity generation; in fact, the roof has been rotated to 9 degrees counterclockwise to directly face the south, and was tilted 36 degrees to maximize electricity generation throughout the year, as suggested by the preliminar analysis done using the Photovoltaic Geographical Information System (European Comission, 2022), more information about electricity generation on the roof is explained in page 170.

Even when protecting the southern face, it was observed a high amount of radiation reaching the northern face during summer months (as the sun is higher in the sky), to reduce this effect it was decided to add an extended surface on the top of the roof, made of single layered glass panels also covered in PV cells, that increase the shaded area in the north slope and electricity generation, while allowing diffuse light to access from the northern sky; this extension effectively acts as an awning, was made with the same inclination of the south slope and with a stick system of mullions and transoms to maintain the continuity of the material of the roof. This part of the roof will be for sure subjected to high wind loads, so some structural reinforcement that connects this element to the main glass roof have been added.

In the entire southern slope and extensions, the PV cells cover approximately 64% of the glazed area, having an important role in controlling the amount of sunlight entering the building, for improved lighting and thermal comfort

5.3.2.2.3 Glass configuration

Then the stratigraphy of the of a glass panel with the characteristic proposed by insight has been defined using AGC Glass Configurator. This website proposes some pre-assembled types of glass that can be in case edited.

The glass with the characteristics most similar to the ones given by law (and so the one that will be used on the north and west side) have the following stratigraphy (where the light blue elements represent the glass, the grey one the infill and the red one the coating:

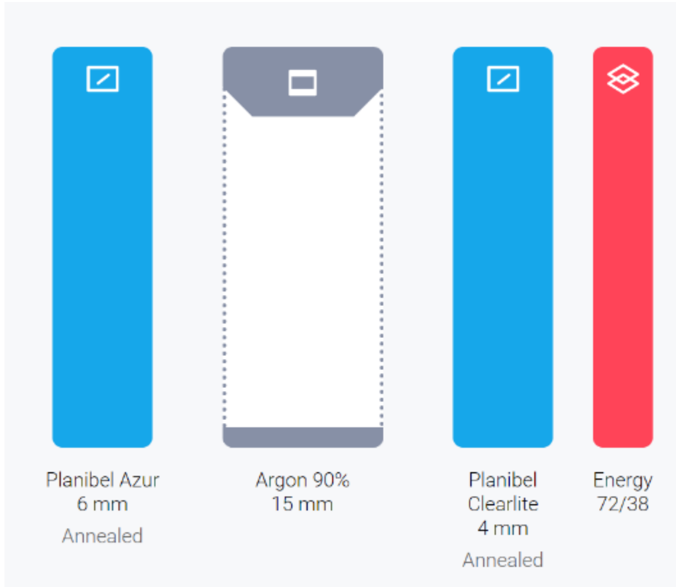


Figure 72: Stratigraphy of the glazing unit required to comply with IECC (AGC Glass Europe, 2022)

And have the following proprieties:

Table 46: Properties of the glazing unit required to comply with IECC

VLT	59%
SHGC	36%
U-value (W/m²K)	1.9
Weight (kg/m²)	25

For south and east side, the following stratigraphy of the class has been chosen:

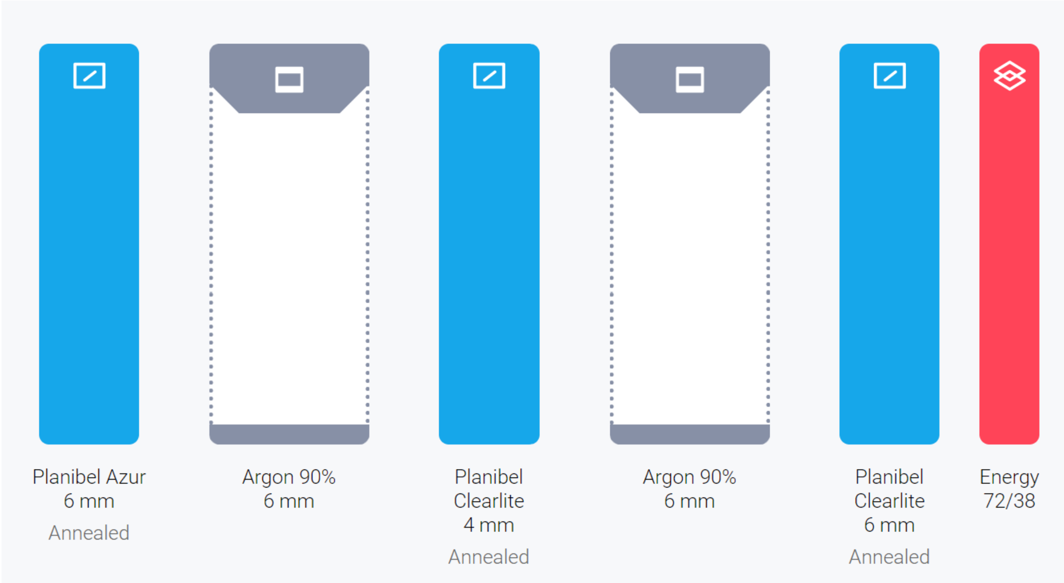


Figure 73:Stratigraphy of the glazing unit by design (AGC Glass Europe, 2022)

Table 47: Properties of the glazing unit by design

VLT	53%
SHGC	34%
U-value (W/m²K)	1.6
Weight (kg/m²)	40

By having the U-value of the frame and the U-value of the two types of glass, it is possible to evaluate the U-value of the whole curtain wall system (frame and glass) with this formula:

$$U\ value_{cw} = \frac{A_g * U_g + A_f * U_f + l_g * \Psi_g}{A_g + A_f}$$

Where:

- A_g and A_f are the areas of the glass and of the frame, respectively
- U_g and U_f are the U-values of the glass and of the frame, respectively
- l_g is the perimeter of the glass
- Ψ_g is the linear thermal transmittance

The linear thermal transmittance can be taken from the table E.1 of the UNI EN ISO 10077-1, depending by the combination of the type of glass and frame. In this case, for a double or triple glazing with a low-E coating and a thermal frame with thermal break, Ψ_g is equal to 0.11W/mK.

So, the U-value for the whole curtain wall system with double glazing is equal to 2.02 W/m²K, and for the curtain wall with the triple glazing mounted the U-value is 1.73 W/m²K.

5.3.2.3 Shading elements

Given the high levels of direct solar radiation incident on mostly glazed south and east facades, a second skin of shading elements was designed to keep control on the solar heat gains and illumination levels of the spaces facing the exterior. Lighting levels were considered critical and became the main driver of the shading envelope design.

In addition to offering protection from excessive solar incidence, the shading elements would determine the appearance of the building from the exterior and the quality of the views from the interior, so in accordance with biophilic design principles it should provide for complex patterns, non-rhythmic sensory stimuli and allow for visual connection with nature from the inside; this implied the avoidance of merely horizontal or vertical elements repeated along the façade, while providing certain level of rationalization to satisfy technical and economic criteria for manufacturing and installation.

The initial concept was inspired on the way some groups of plants, like pines and palms, are able to provide partial shading by overlaying layers of non-parallel linear elements, like fine leaves and branches, resulting in a filtered and dynamic light conditions that change as the sunlight arrives at different angles.

Figure 74: Examples of natural shading effect of leaves used in the conceptual design of shading modules

After a gradual rationalization process, a modular shading system was designed, based on rectangular elements of consistent dimension and alignment with the modulation of the glazed curtain wall system of the envelope; each shading module is made of two slightly separated wooden frames containing rectangular wooden profiles at different angles in the plane of the frame and with variable separation between them that would determine the "density" or shading degree it provides to the adjacent space.

5.3.2.3.1 Optimization for lighting

To determine the appropriate level of shading required for each space, two particular lighting analysis were carried out on all habitable building levels: sDA300/50 and ASE1000/250, following the methodology and tools explained in the methodology (page Lighting analysis71); these studies were applied for identical versions of the building with a shading envelope under four different conditions: a) no shading modules, b) external profiles at 80cm separation, c) 60cm separation, and d) 40cm separation.

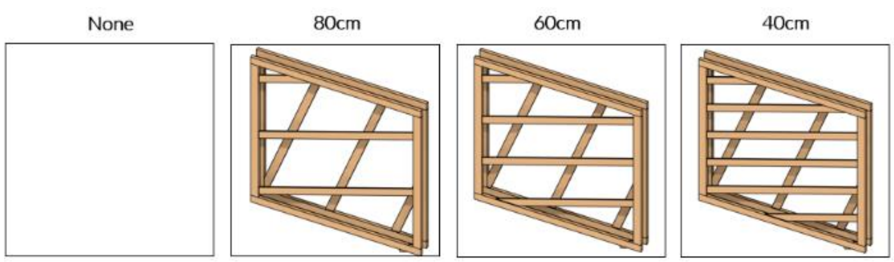


Figure 75: Types of façade shading modules

The graphical results of the analysis are compiled in false colour maps (appendix), and the comparison of the quantitative results for each serviced space is reported in Table 48, highlighting the cases with satisfactory and optimal results; service areas and spaces non dependant on natural light (e.g. auditorium) were excluded.

Table 48: sDA and ASE results by space during 1st stage optimization process of shading modules

	Name	No.	Area	No shading		Ext 80		Ext 40	
				sDA	ASE	sDA	ASE	sDA	ASE
				%	%	%	%	%	%
30st Street	Study room	20	199 m²	63	11	47	7	42	5
	Auditorium	22	187 m²	0	0	0	0	0	0
	Cafe	23	119 m²	47	20	44	15	44	15
	Atrium	24	528 m²	92	26	84	10	78	7
Mezzanine	Cafe	43	141 m²	16	2	13	2	15	2
	Study cabin	44	14 m²	100	71	69	29	57	14
	Study cabin	45	14 m²	97	40	69	3	66	0
	Study cabin	46	14 m²	80	17	51	3	26	0
	Meeting room	47	39 m²	48	13	14	3	4	1
Level 1	Chill area	64	134 m²	45	23	17	7	11	4
	Coworking spaces	65	385 m²	75	20	34	5	23	2
	Coworking spaces	66	305 m²	37	3	33	3	33	3
Level 2	Double office	81	27 m²	0	0	0	0	0	0
	Meeting room	83	29 m²	52	22	27	0	25	0
	Meeting room	84	29 m²	62	27	35	4	22	0
	Office	85	24 m²	57	40	21	11	19	5
	Double office	86	29 m²	70	36	52	6	47	0
	Meeting room	87	24 m²	54	35	21	6	17	3
	Office	88	24 m²	48	41	19	10	13	3
	Office	89	24 m²	41	35	19	10	10	2
	Office	90	24 m²	60	37	17	8	11	3
	Double office	94	18 m²	81	0	80	0	78	0
	Office	95	14 m²	97	0	94	0	94	0
	Office	96	14 m²	89	0	86	0	86	0
	Office	97	14 m²	89	0	86	0	86	0
	Double office	99	29 m²	65	30	34	10	28	5
Level 3	Laboratory	112	213 m²	60	17	27	8	20	5
	Laboratory	113	246 m²	83	2	83	2	82	2
	Laboratory	114	159 m²	99	33	85	13	78	5
	Laboratory	115	200 m²	99	29	64	11	52	6
Level 4	Laboratory	130	200 m²	100	31	98	9	95	4
	Laboratory	131	119 m²	100	29	100	5	99	2
	Laboratory	132	155 m²	100	28	57	11	48	8
	Laboratory	134	253 m²	92	13	94	11	94	11
	Laboratory	137	40 m²						

sDA: **<55% (insufficient)** **>55% (good)** **>70% (optimal)**
ASE: **>20% (excessive)** **<20% (acceptable)** **<10% (optimal)**

From the result it was possible to identify the best shading module configuration for each space, however it was noticeable the relatively negative results for several spaces at the east façade, the problem seemed to suggest an impossibility to provide enough protection from morning direct sunlight without negatively affecting diffuse light penetration during the rest of the day. To improve the situation, a variation of the shading device was created: a typical module rotated 45 degrees around the vertical axis, disposed in a way that provides partial protection from the southeast direct sunlight, while allowing diffuse light to access from the northeast, the change resulted in an improved situation, but still not quite optimal, that required the modification of the building layout in some specific points.

Later a further modification was applied to all modules, the internal parallel wooden profiles were rotated 45 degrees towards the ground to better protect from incident radiation from the top while allowing for improved visibility towards the ground. Finally, some rotated modules, like the ones applied to the east, proved to be useful for some sections of the south façade, where an asymmetry in the amount of incident solar radiation between mornings and afternoons was caused by the projected shade of proposed and existing neighbouring building at the southeast, the numerical results of the optimized envelope are reported in Table 49: sDA and ASE results by space during 2nd stage optimization process of shading modulesTable 49, and graphical results of the final version are reported in Table 51.

The resulting data demonstrated that for some spaces the variable nature of light during different periods made impossible obtaining optimal lighting conditions by only using fixed shading elements, so a complementary set of internal roller blinds was added to critical spaces to guarantee lighting levels below the acceptable threshold of 1000 lux in the working areas, thus preventing glare. The effect of these roller blinds can’t be assessed in the yearly sDA-ASE study, so an additional verification analysis was performed, measuring illuminance levels at 9am and 3pm during the spring and autumn equinoxes, as stated in LEED v4 (Autodesk Insight, 2017). The numerical results are reported in Table 50 and the graphical ones are compiled in false colour maps in Table 52.

Table 49: sDA and ASE results by space during 2nd stage optimization process of shading modules

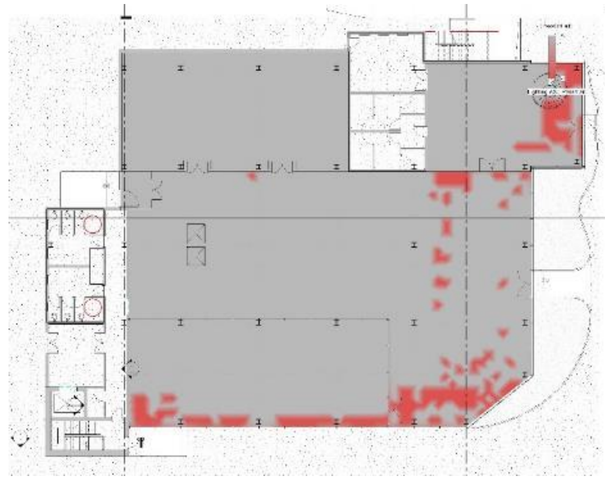
Level	Name	Number	Rotated modules east 45		Tilted louvers		Rotated modules south 45	
			sDA %	ASE %	sDA %	ASE %	sDA %	ASE %
30st Street	Study room	14	62	8	61	7	56	7
	Cafe	17	47	15	43	14	43	14
	Atrium	18	72	8	71	6	71	6
Mezzanine	Cafe	32	11	0	10	1	9	1
	Study cabin	33	86	20	74	14	91	20
	Study cabin	34	97	9	97	6	97	14
	Study cabin	35	71	17	71	17	71	6
	Meeting room	36	72	17	61	15	56	11
Level 1	Coworking spaces	55	40	9	40	8	39	8
	Chill area	57	47	30	44	29	43	27
	Coworking spaces	148	32	0	32	0	32	0
	Coworking spaces	149	61	10	61	11	62	9
Level 2	Double office	72	0	0	0	0	0	0
	Meeting room	74	44	1	55	10	56	10
	Meeting room	75	48	22	47	22	47	3
	Office	76	46	41	40	40	44	40
	Double office	77	64	36	60	18	53	12
	Meeting room	78	49	33	54	33	49	33
	Office	79	41	33	35	32	40	30
	Office	80	35	18	39	17	34	17
	Office	81	49	14	48	13	51	11
	Double office	83	80	0	82	0	80	0
	Office	84	97	0	100	0	100	0
	Office	85	91	0	91	0	91	0
	Office	86	94	0	94	0	91	0
	Double office	88	60	32	61	31	49	8
Level 3	Laboratory	104	51	13	50	13	49	13
	Laboratory	105	58	1	59	1	59	1
	Laboratory	106	75	7	71	7	77	7
	Laboratory	107	80	10	85	10	86	10
Level 4	Laboratory	123	98	16	96	5	96	5
	Laboratory	124	97	12	94	3	97	3
	Laboratory	125	84	11	74	5	76	5
	Laboratory	126	91	6	91	5	90	5

sDA: **<55% (insufficient)** **>55% (good)** **>70% (optimal)**
ASE: **>20% (excessive)** **<20% (acceptable)** **<10% (optimal)**

Table 50: Calculation of areas complying with 1000>luxes>300 at 9am and 3pm during equinoxes

Location	Level	Name	Number	% of area within threshold
S	30st Street	Study room	14	21
E		Cafe	17	56
E		Atrium	18	87
E	Mezzanine	Cafe	32	26
S		Study cabin	33	40
S		Study cabin	34	50
S		Study cabin	35	8
S		Meeting room	36	13
E	Level 1	Coworking spaces	55	59
E		Chill area	57	94
N		Coworking spaces	148	69
S		Coworking spaces	149	33
N	Level 2	Double office	72	1
S		Meeting room	74	31
S		Meeting room	75	19
E		Office	76	100
S		Double office	77	48
E		Meeting room	78	98
E		Office	79	100
E		Office	80	85
E		Office	81	87
N		Double office	83	99
N		Office	84	97
N		Office	85	91
N		Office	86	99
S		Double office	88	45
E	Level 3	Laboratory	104	99
N		Laboratory	105	85
S		Laboratory	106	74
E		Laboratory	107	71
E	Level 4	Laboratory	123	86
S		Laboratory	124	88
E		Laboratory	125	100
N		Laboratory	126	82

Table 51: False colour maps of areas complying with sDA300/50 and ASE1000/250. Final version

sDA – Ground floor 	ASE – Ground floor 
sDA – Mezzanine 	ASE – Mezzanine 
sDA – 1st floor 	ASE – 1st floor 

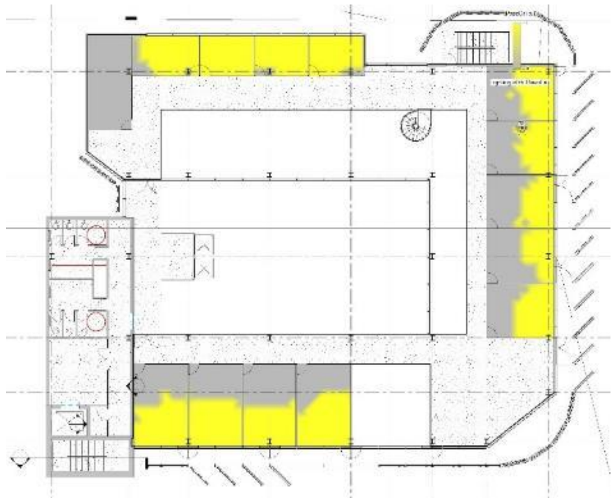
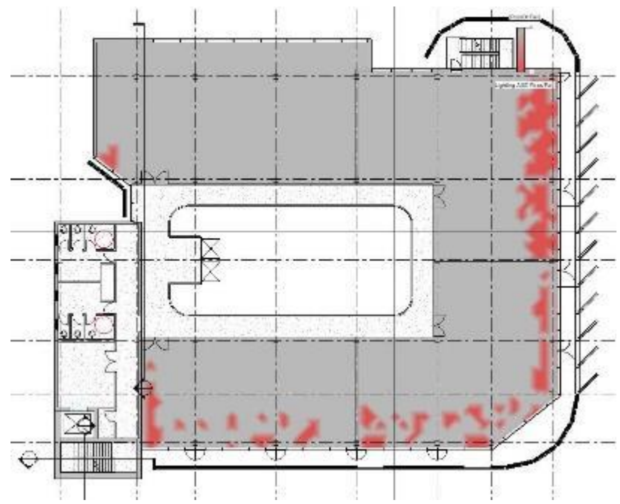
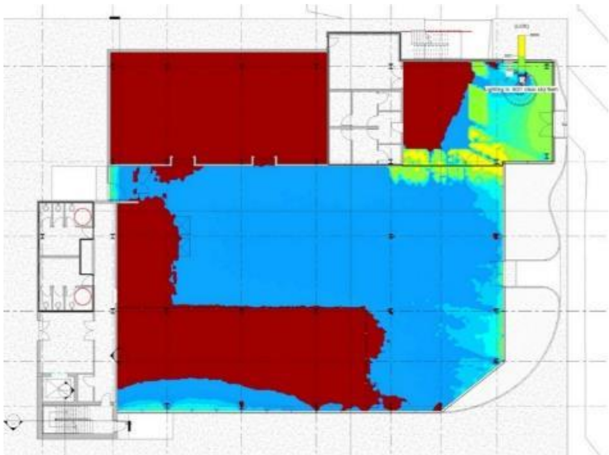
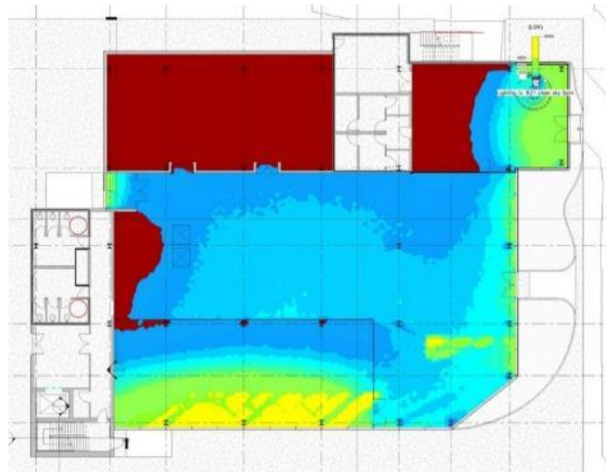
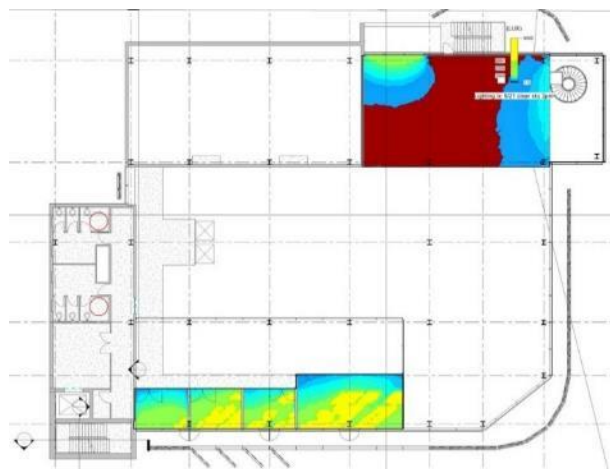
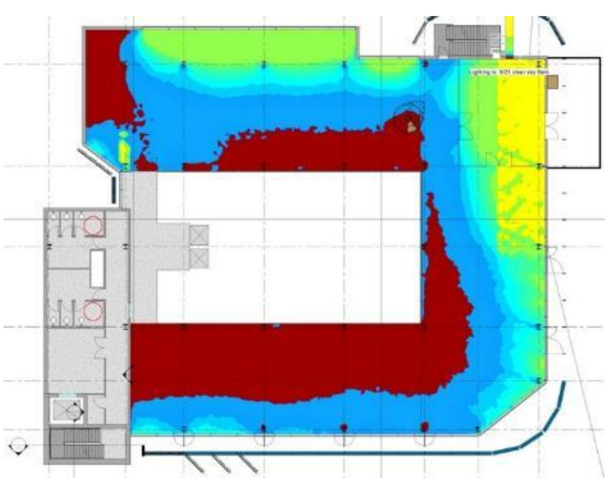
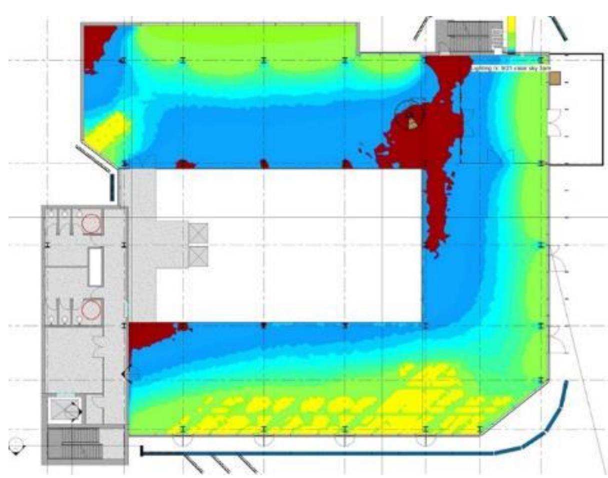
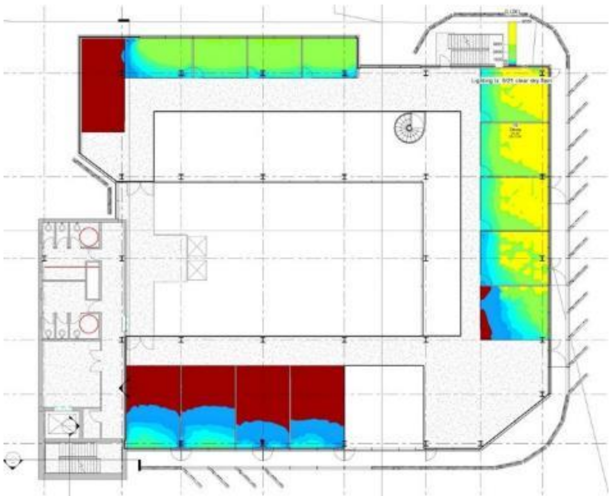
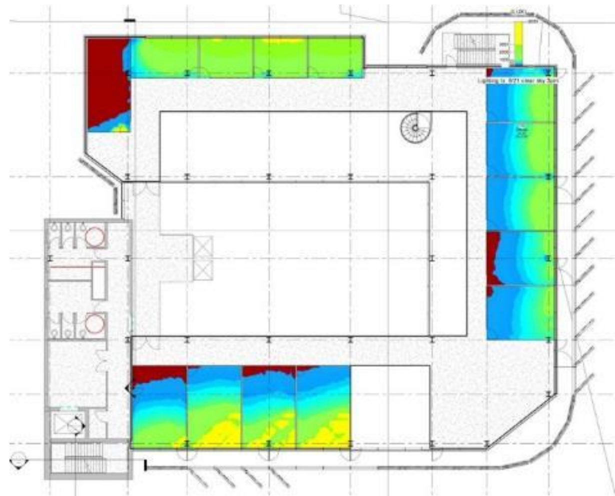
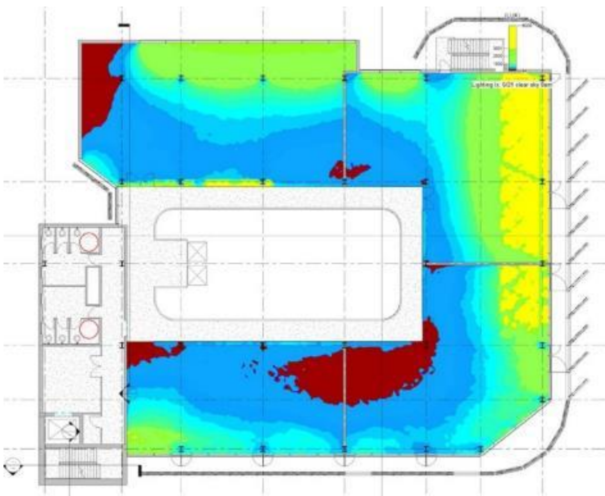
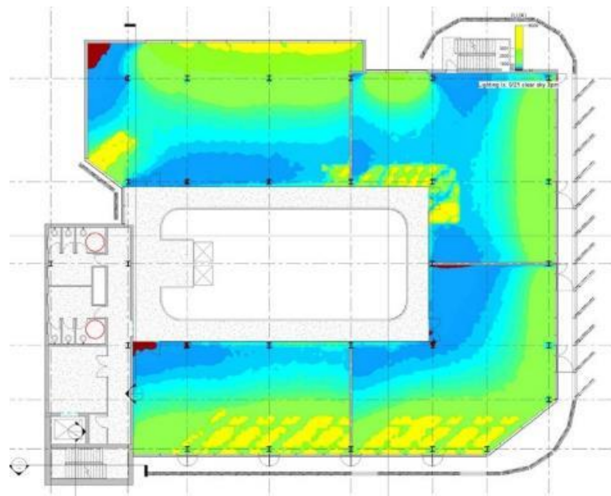
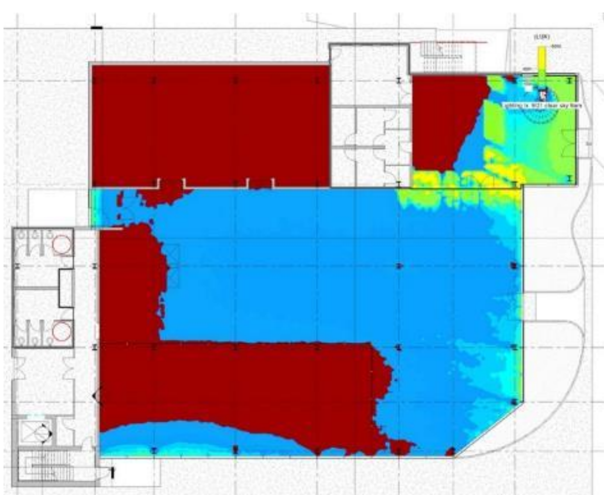
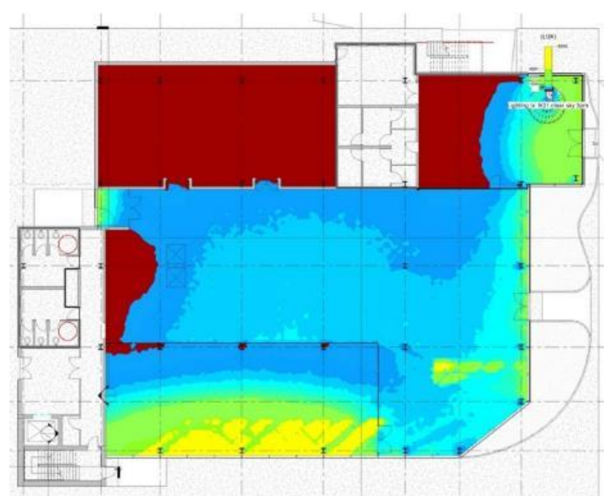
sDA – 2nd floor	ASE – 2nd floor
	
sDA – 3rd floor	ASE – 3rd floor
	
sDA – 4th floor	ASE – 4th floor
	

Table 52: False colour maps of resulting illumination levels during equinoxes at 9am and 3pm

9am – Ground floor	3pm – Ground floor
	
9am – Mezzanine	3pm – Mezzanine
	
9am – 1st floor	3pm – 1st floor
	

9am – 2nd floor	3pm – 2nd floor
	
9am – 3rd floor	3pm – 3rd floor
	
9am – 4th floor	3pm – 4th floor
	

5.3.2.3.2 Solar irradiation results

Apart from controlling daylight to generate a visually comfortable indoor environment, shading elements have the objective of reducing the amount of direct solar radiation reaching the glazed elements of the envelope, thus reducing the solar heat gains inside the building; this is particularly important to decrease the possibility of overheating and control the energy consumption of HVAC systems during cooling season.

To evaluate the direct impact of shading elements on the irradiation levels of glazed surfaces, three models of identical building geometry were created: a) Without context nor shading devices, b) Building in its context, without shading devices and c) Building with shading devices in its context; and were analysed at four scenarios: summer / winter solstices, and spring / autumn equinoxes.

The resulting twelve sets of data were compared for each façade sub-surface, and ratios between the insolation values (represented in kWh/m²) were calculated, each ratio indicates the reduction on solar radiation reaching the glazing at each location when context and shading elements are added. In this way the separate shading contribution of context buildings and proposed shading modules could be accounted for, as reported on tables Table 53 to Table 56; results indicate that the percentage of solar radiation arriving to the glazing envelope is greatly reduced from the original standalone/unshaded case: 63% in summer solstice, 48-49% during equinoxes and 33% in winter solstice. In most cases the reduction is mainly driven by the designed **shading modules in the façade**, that allow between **65-69% of the solar radiation** to pass through (blocking 31-35%), while neighbouring buildings have a smaller and more variable contribution allowing 91% of insolation in summer as the sun beam has a higher angle, 74-75% during equinoxes, and 50% in winter solstice. These values would be useful for a more detailed estimation of the peak loads in further steps of development.

Table 53: Glazing average insolation and shading values during spring equinox, by surface

SPRING EQUINOX							
		Surface Insolation			**Insolation ratio / Shading correction factor (SCF)**		
Parent object ID	Surface Area	No shadings	Only context	Context + Shadings	Only Context	**Only shadings**	**Context + shadings**
447029.00	76.94	180.77	86.56	86.56	0.48	1.00	0.48
448557.00	62.64	87.90	81.25	56.09	0.92	0.69	0.64
451447.00	87.41	58.86	38.37	37.90	0.65	0.99	0.64
459217.00	27.85	56.29	40.73	25.62	0.72	0.63	0.46
464810.00	34.69	23.03	22.25	17.18	0.97	0.77	0.75
581990.00	37.57	28.55	17.58	16.98	0.62	0.97	0.59
611590.00	38.07	79.70	57.01	48.21	0.72	0.85	0.60
636427.00	112.18	317.22	294.66	139.03	0.93	0.47	0.44
641641.00	34.69	31.94	30.19	28.87	0.95	0.96	0.90
659103.00	22.32	11.76	9.90	9.82	0.84	0.99	0.83
706146.00	306.03	236.91	155.52	155.22	0.66	1.00	0.66
1046793.00	87.28	62.91	53.73	45.82	0.85	0.85	0.73
1180291.00	71.32	165.90	148.28	148.28	0.89	1.00	0.89
1180355.00	238.74	429.92	403.39	270.55	0.94	0.67	0.63
1180355.00	238.73	1297.60	1271.45	584.67	0.98	0.46	0.45
1180364.00	87.98	269.80	262.45	262.45	0.97	1.00	0.97
1180391.00	90.80	63.35	51.72	51.71	0.82	1.00	0.82
1334328.00	42.11	73.29	73.28	72.75	1.00	0.99	0.99
1647860.00	118.48	196.30	155.35	100.02	0.79	0.64	0.51
1647903.00	31.80	110.46	19.82	17.67	0.18	0.89	0.16
1647904.00	98.91	374.74	160.64	115.19	0.43	0.72	0.31
1647945.00	78.65	173.06	83.15	50.00	0.48	0.60	0.29
1648006.00	31.80	110.44	44.04	30.29	0.40	0.69	0.27
1648007.00	128.05	489.99	329.14	228.86	0.67	0.70	0.47
1648048.00	78.87	185.05	110.03	69.51	0.59	0.63	0.38
1648105.00	31.80	110.38	71.67	44.89	0.65	0.63	0.41
1648106.00	59.39	216.94	191.19	112.24	0.88	0.59	0.52
1648147.00	59.07	138.73	91.76	56.32	0.66	0.61	0.41
1648204.00	31.80	109.45	76.84	41.73	0.70	0.54	0.38
1648205.00	128.05	489.43	437.67	217.13	0.89	0.50	0.44
1648246.00	49.59	115.70	82.78	51.78	0.72	0.63	0.45
1648368.00	31.80	110.45	22.63	20.00	0.20	0.88	0.18
1648369.00	39.59	138.53	99.93	56.48	0.72	0.57	0.41
1648370.00	78.65	182.37	97.95	67.96	0.54	0.69	0.37
1648476.00	29.13	115.70	18.35	17.70	0.16	0.96	0.15
1648602.00	29.13	115.70	19.35	18.78	0.17	0.97	0.16
1648658.00	59.32	235.31	84.00	61.13	0.36	0.73	0.26
1648770.00	39.56	91.39	59.57	44.73	0.65	0.75	0.49
1648810.00	59.41	139.29	103.18	72.64	0.74	0.70	0.52
1648844.00	68.66	272.48	223.92	139.23	0.82	0.62	0.51
1648866.00	68.88	160.13	133.32	90.27	0.83	0.68	0.56
TOTAL	3127.71	7857.72	5814.64	3782.27	**0.74**	**0.65**	**0.48**
					Radiation weighted Insolation Ratio		

Table 54: Glazing average insolation and shading values during summer solstice, by surface

SUMMER SOLSTICE							
		Surface Insolation			**Insolation ratio / Shading correction factor (SCF)**		
Parent object ID	Surface Area	No shadings	Only context	Context + Shadings	Only Context	**Only shadings**	**Context + shadings**
447029.00	76.94	205.76	171.50	171.50	0.83	1.00	0.83
448557.00	62.64	163.46	159.96	86.76	0.98	0.54	0.53
451447.00	87.41	86.64	63.37	62.57	0.73	0.99	0.72
459217.00	27.85	33.47	28.10	23.56	0.84	0.84	0.70
464810.00	34.69	61.76	60.86	46.50	0.99	0.76	0.75
581990.00	37.57	43.58	30.56	29.61	0.70	0.97	0.68
611590.00	38.07	55.06	47.36	43.26	0.86	0.91	0.79
636427.00	112.18	122.60	114.23	95.64	0.93	0.84	0.78
641641.00	34.69	68.52	66.45	62.27	0.97	0.94	0.91
659103.00	22.32	18.31	16.25	16.16	0.89	0.99	0.88
706146.00	306.03	367.69	271.59	269.28	0.74	0.99	0.73
1046793.00	87.28	177.74	168.17	120.78	0.95	0.72	0.68
1180291.00	71.32	188.50	173.35	173.35	0.92	1.00	0.92
1180355.00	238.74	1258.81	1228.37	921.07	0.98	0.75	0.73
1180355.00	238.73	1575.21	1557.78	708.52	0.99	0.45	0.45
1180364.00	87.98	155.49	150.96	150.96	0.97	1.00	0.97
1180391.00	90.80	96.47	83.50	83.49	0.87	1.00	0.87
1334328.00	42.11	121.32	121.31	118.30	1.00	0.98	0.98
1647860.00	118.48	208.27	179.82	131.58	0.86	0.73	0.63
1647903.00	31.80	82.91	68.59	47.08	0.83	0.69	0.57
1647904.00	98.91	224.35	194.08	136.76	0.87	0.70	0.61
1647945.00	78.65	201.67	168.09	102.83	0.83	0.61	0.51
1648006.00	31.80	82.36	70.06	42.68	0.85	0.61	0.52
1648007.00	128.05	294.92	258.28	163.45	0.88	0.63	0.55
1648048.00	78.87	210.66	182.52	126.59	0.87	0.69	0.60
1648105.00	31.80	80.00	68.76	40.77	0.86	0.59	0.51
1648106.00	59.39	126.19	117.26	57.16	0.93	0.49	0.45
1648147.00	59.07	157.36	137.67	92.36	0.87	0.67	0.59
1648204.00	31.80	66.24	56.76	35.47	0.86	0.62	0.54
1648205.00	128.05	272.73	255.04	129.50	0.94	0.51	0.47
1648246.00	49.59	128.79	113.72	77.30	0.88	0.68	0.60
1648368.00	31.80	82.89	69.77	47.48	0.84	0.68	0.57
1648369.00	39.59	80.50	72.96	46.07	0.91	0.63	0.57
1648370.00	78.65	207.38	179.62	127.86	0.87	0.71	0.62
1648476.00	29.13	71.70	58.68	43.73	0.82	0.75	0.61
1648602.00	29.13	71.70	59.30	50.28	0.83	0.85	0.70
1648658.00	59.32	143.35	122.59	87.91	0.86	0.72	0.61
1648770.00	39.56	104.33	91.81	74.30	0.88	0.81	0.71
1648810.00	59.41	158.10	138.35	106.83	0.88	0.77	0.68
1648844.00	68.66	166.06	145.31	75.45	0.88	0.52	0.45
1648866.00	68.88	178.71	157.71	116.83	0.88	0.74	0.65
TOTAL	3127.71	8201.54	7480.44	5143.84	**0.91**	**0.69**	**0.63**
					Radiation weighted Insolation Ratio		

Table 55: Glazing average insolation and shading values during autumn equinox, by surface

AUTUMN EQUINOX							
		Surface Insolation			**Insolation ratio / Shading correction factor (SCF)**		
Parent object ID	Surface Area	No shadings	Only context	Context + Shadings	Only Context	**Only shadings**	**Context + shadings**
447029.00	76.94	174.15	91.89	91.89	0.53	1.00	0.53
448557.00	62.64	69.84	63.56	44.01	0.91	0.69	0.63
451447.00	87.41	52.27	34.52	34.12	0.66	0.99	0.65
459217.00	27.85	51.37	36.81	23.44	0.72	0.64	0.46
464810.00	34.69	19.25	18.57	15.17	0.96	0.82	0.79
581990.00	37.57	25.28	15.76	15.26	0.62	0.97	0.60
611590.00	38.07	83.78	64.05	52.72	0.76	0.82	0.63
636427.00	112.18	273.78	253.90	123.41	0.93	0.49	0.45
641641.00	34.69	31.41	29.89	28.83	0.95	0.96	0.92
659103.00	22.32	10.51	8.90	8.83	0.85	0.99	0.84
706146.00	306.03	209.54	138.88	138.62	0.66	1.00	0.66
1046793.00	87.28	56.54	47.69	41.01	0.84	0.86	0.73
1180291.00	71.32	159.16	144.65	144.65	0.91	1.00	0.91
1180355.00	238.74	399.49	376.62	244.96	0.94	0.65	0.61
1180355.00	238.73	1161.00	1139.59	525.70	0.98	0.46	0.45
1180364.00	87.98	232.06	226.12	226.12	0.97	1.00	0.97
1180391.00	90.80	56.18	46.12	46.11	0.82	1.00	0.82
1334328.00	42.11	56.82	56.82	56.37	1.00	0.99	0.99
1647860.00	118.48	182.35	148.18	93.62	0.81	0.63	0.51
1647903.00	31.80	105.02	17.01	15.04	0.16	0.88	0.14
1647904.00	98.91	324.38	120.99	87.77	0.37	0.73	0.27
1647945.00	78.65	167.98	85.93	48.41	0.51	0.56	0.29
1648006.00	31.80	105.00	48.03	31.50	0.46	0.66	0.30
1648007.00	128.05	423.36	290.51	207.53	0.69	0.71	0.49
1648048.00	78.87	178.33	116.86	70.51	0.66	0.60	0.40
1648105.00	31.80	104.95	70.98	44.17	0.68	0.62	0.42
1648106.00	59.39	189.25	168.40	98.99	0.89	0.59	0.52
1648147.00	59.07	133.41	94.77	55.53	0.71	0.59	0.42
1648204.00	31.80	104.22	74.76	39.87	0.72	0.53	0.38
1648205.00	128.05	422.88	379.46	190.54	0.90	0.50	0.45
1648246.00	49.59	110.73	82.45	49.93	0.74	0.61	0.45
1648368.00	31.80	105.01	20.23	18.12	0.19	0.90	0.17
1648369.00	39.59	122.03	86.11	48.87	0.71	0.57	0.40
1648370.00	78.65	175.99	103.98	69.77	0.59	0.67	0.40
1648476.00	29.13	99.25	16.31	15.79	0.16	0.97	0.16
1648602.00	29.13	99.25	17.32	16.84	0.17	0.97	0.17
1648658.00	59.32	201.81	67.44	49.55	0.33	0.73	0.25
1648770.00	39.56	88.19	64.02	47.62	0.73	0.74	0.54
1648810.00	59.41	133.63	109.42	76.80	0.82	0.70	0.57
1648844.00	68.66	233.73	192.37	121.08	0.82	0.63	0.52
1648866.00	68.88	153.09	130.87	87.04	0.85	0.67	0.57
TOTAL	3127.71	7086.29	5300.75	3446.12	**0.75**	**0.65**	**0.49**
					Radiation weighted Insolation Ratio		

Table 56: Glazing average insolation and shading values during winter solstice, by surface

WINTER SOLSTICE							
		Surface Insolation			**Insolation ratio / Shading correction factor (SCF)**		
Parent object ID	Surface Area	No shadings	Only context	Context + Shadings	Only Context	**Only shadings**	**Context + shadings**
447029.00	76.94	113.48	22.35	22.35	0.20	1.00	0.20
448557.00	62.64	24.41	21.88	17.38	0.90	0.79	0.71
451447.00	87.41	36.04	18.86	18.46	0.52	0.98	0.51
459217.00	27.85	77.01	53.73	29.05	0.70	0.54	0.38
464810.00	34.69	9.41	8.77	7.88	0.93	0.90	0.84
581990.00	37.57	17.96	9.03	8.55	0.50	0.95	0.48
611590.00	38.07	92.43	9.54	8.88	0.10	0.93	0.10
636427.00	112.18	413.99	351.03	214.62	0.85	0.61	0.52
641641.00	34.69	10.16	8.55	8.35	0.84	0.98	0.82
659103.00	22.32	6.54	4.92	4.85	0.75	0.99	0.74
706146.00	306.03	148.95	81.83	81.61	0.55	1.00	0.55
1046793.00	87.28	30.92	26.98	22.36	0.87	0.83	0.72
1180291.00	71.32	103.60	58.51	58.51	0.56	1.00	0.56
1180355.00	238.74	122.64	100.03	88.82	0.82	0.89	0.72
1180355.00	238.73	867.92	730.43	333.44	0.84	0.46	0.38
1180364.00	87.98	273.10	234.34	234.34	0.86	1.00	0.86
1180391.00	90.80	38.78	28.97	28.96	0.75	1.00	0.75
1334328.00	42.11	31.91	31.91	31.57	1.00	0.99	0.99
1647860.00	118.48	131.95	59.36	37.00	0.45	0.62	0.28
1647903.00	31.80	107.27	7.57	6.95	0.07	0.92	0.06
1647904.00	98.91	369.69	105.56	79.56	0.29	0.75	0.22
1647945.00	78.65	106.23	19.41	17.10	0.18	0.88	0.16
1648006.00	31.80	107.25	8.51	7.40	0.08	0.87	0.07
1648007.00	128.05	480.45	128.34	86.98	0.27	0.68	0.18
1648048.00	78.87	116.14	24.37	19.67	0.21	0.81	0.17
1648105.00	31.80	107.22	9.77	8.02	0.09	0.82	0.07
1648106.00	59.39	218.69	158.86	87.53	0.73	0.55	0.40
1648147.00	59.07	87.15	24.67	16.88	0.28	0.68	0.19
1648204.00	31.80	107.02	39.35	24.25	0.37	0.62	0.23
1648205.00	128.05	480.11	365.89	190.50	0.76	0.52	0.40
1648246.00	49.59	72.93	31.16	19.29	0.43	0.62	0.26
1648368.00	31.80	107.26	7.91	7.27	0.07	0.92	0.07
1648369.00	39.59	143.35	75.04	45.16	0.52	0.60	0.32
1648370.00	78.65	113.99	20.61	18.23	0.18	0.88	0.16
1648476.00	29.13	111.01	6.86	6.59	0.06	0.96	0.06
1648602.00	29.13	111.01	7.20	6.96	0.06	0.97	0.06
1648658.00	59.32	225.91	33.06	23.25	0.15	0.70	0.10
1648770.00	39.56	56.41	20.80	14.43	0.37	0.69	0.26
1648810.00	59.41	87.41	35.76	24.65	0.41	0.69	0.28
1648844.00	68.66	261.50	51.12	36.00	0.20	0.70	0.14
1648866.00	68.88	100.45	43.19	28.47	0.43	0.66	0.28
TOTAL	3127.71	6229.65	3085.99	2032.12	**0.50**	**0.66**	**0.33**
					Radiation weighted Insolation Ratio		

5.3.3 Services

Services layer contains all equipment and systems that allow the building to actively function, they provide resource inputs and outputs and regulate the processes happening inside. Inside this category are included: ventilation and air conditioning systems, electricity production and distribution network, and water distribution/ storage systems.

5.3.3.1 HVAC System

The HVAC system includes all elements for mechanical ventilation, heating and cooling, and in conditioned buildings (the case for this project), it is a vital component to guarantee thermal comfort and Indoor Air Quality (IAQ) in inner spaces. Given the characteristics of this project: medium size, office use, expected low energy consumption; a ***Primary Air System*** was chosen, as it can limit external air flowrate (reducing unwanted heat gains and losses) and reduce duct dimension, while ensuring thermal comfort using cooling/heating terminal.

For dimensioning the HVAC system an analysis of the heating and cooling loads of the building model was performed using Insight tool (calculation method explained in page 72), where peak loads were obtained for each space and for the building as a whole; as explained in the calculation method reference, the used tool only takes into consideration the climatic data and thermal properties of the envelope to calculate peak loads, so it is unable to take into account the effect of shading over the façade due to surrounding context or building external shading modules, so a special procedure was created as a workaround to obtain more refined cooling peak load results.

Using the same geometrical model, two analyses were performed: one with the SHGC value for glazing according to the design, representing the real envelope characteristics; and one with a SHGC equal to zero, equivalent to a hypothetical condition in which the glazing is able to transfer heat by conduction but doesn't transfer the incident solar radiation towards the interior (as in a completely shaded condition), as it was an opaque element.

The resulting data was then post-processed, the difference in peak load for both scenarios would represent the power input into the system due to solar incident radiation entering through transparent elements, or the *peak Solar Heat Gain (SHG) load*; so, that value was multiplied by a correction factor that represents the reduction of incident solar radiation due to shadings, called in this project as *Shading Correction Factor (SC*F); the result of that product is a *corrected peak SHG load*, and when added to the peak load in the hypothetical SHGC=0 case, it would report the corrected total peak cooling load, that takes into consideration the influence of shading elements.

$$Peak\ load\ \begin{bmatrix} design \\ SHGC \end{bmatrix} - Peak\ load\ \begin{bmatrix} SHGC \\ = 0 \end{bmatrix} = Peak\ load_{SHG}$$

$$(\ Peak\ load_{SHG} * SCF) +\ Peak\ cooling\ load\ [SHGC = 0] \\ = Corrected\ total\ peak\ load$$

The *shading correction factor* (SCF) must be representative of the insolated proportion of façade when cooling loads reach their peak values (in which 1 = 100% insolation and 0 = 0% insolation), these results were already obtained from the solar analyses for solstices and equinoxes, so a similar procedure was followed for the period of the year with peak cooling load (September at 13:00, for the building as a whole).

5.3.3.1.1 Heating/cooling generation

Peak cooling and heating loads of the entire building were calculated to dimension the water-side part of the HVAC system, the following the previously explained procedure it was possible to obtain total peak loads for cooling and heating (sum of all zones peak loads), and the maximum required cooling capacity (which considers the non-contemporary surge on loads at all spaces in the building). According to the analysis, peak cooling load at the building level happens during September at 13:00, so a solar analysis was performed at that time, using Insight Solar (as explained in page 72), the results were postprocessed to separately obtain the shading contribution of the context and the shading modules, in addition to the combined shading effect weighted by area and by insolation levels. Findings are reported in the next table.

Table 57: Glazing average insolation and SCF during cooling peak load (September at 13:00), by surface

Surface ID	Surface Area	Total Surface Insolation Value (KWh)			SHADING CORRECTION FACTOR (SCF)			
		No shade	Only context	Context + shadings	Only Context	Only shadings	**Context + shadings**	
447029.00	76.94	76.17	53.31	53.31	0.70	1.00	**0.70**	
448557.00	62.64	56.17	53.54	43.27	0.95	0.81	**0.77**	
451447.00	87.41	73.18	52.69	52.25	0.72	0.99	**0.71**	
459217.00	27.85	38.76	33.98	24.91	0.88	0.73	**0.64**	
464810.00	34.69	32.81	32.08	23.71	0.98	0.74	**0.72**	
581990.00	37.57	34.33	23.64	23.06	0.69	0.98	**0.67**	
611590.00	38.07	73.48	65.39	34.55	0.89	0.53	**0.47**	
636427.00	112.18	410.91	403.87	202.12	0.98	0.50	**0.49**	
641641.00	34.69	23.70	22.10	21.82	0.93	0.99	**0.92**	
659103.00	22.32	15.45	13.55	13.47	0.88	0.99	**0.87**	
706146.00	306.03	282.95	202.22	202.00	0.71	1.00	**0.71**	
1046793.00	87.28	67.29	62.63	56.90	0.93	0.91	**0.85**	
1180291.00	71.32	68.50	56.69	56.69	0.83	1.00	**0.83**	
1180355.00	238.74	649.95	624.20	373.94	0.96	0.60	**0.58**	
1180355.00	238.73	1755.49	1742.05	818.67	0.99	0.47	**0.47**	
1180364.00	87.98	364.20	360.54	360.54	0.99	1.00	**0.99**	
1180391.00	90.80	77.23	65.59	65.57	0.85	1.00	**0.85**	
1334328.00	42.11	65.94	65.93	65.54	1.00	0.99	**0.99**	
1647860.00	118.48	103.26	80.77	74.18	0.78	0.92	**0.72**	
1647903.00	31.80	111.80	20.35	19.48	0.18	0.96	**0.17**	
1647904.00	98.91	494.93	249.16	158.62	0.50	0.64	**0.32**	
1647945.00	78.65	73.87	52.93	47.93	0.72	0.91	**0.65**	
1648006.00	31.80	111.77	74.87	42.14	0.67	0.56	**0.38**	
1648007.00	128.05	644.73	540.32	386.63	0.84	0.72	**0.60**	
1648048.00	78.87	77.70	55.83	49.93	0.72	0.89	**0.64**	
1648105.00	31.80	111.69	99.67	56.34	0.89	0.57	**0.50**	
1648106.00	59.39	290.02	281.16	163.04	0.97	0.58	**0.56**	
1648147.00	59.07	57.58	42.06	37.74	0.73	0.90	**0.66**	
1648204.00	31.80	104.74	95.36	47.53	0.91	0.50	**0.45**	
1648205.00	128.05	644.11	626.44	338.47	0.97	0.54	**0.53**	
1648246.00	49.59	47.27	35.33	31.93	0.75	0.90	**0.68**	
1648368.00	31.80	111.79	33.23	26.49	0.30	0.80	**0.24**	
1648369.00	39.59	187.98	177.27	98.80	0.94	0.56	**0.53**	
1648370.00	78.65	75.91	54.49	49.08	0.72	0.90	**0.65**	
1648476.00	29.13	150.35	18.76	18.29	0.12	0.97	**0.12**	
1648602.00	29.13	150.34	26.04	25.51	0.17	0.98	**0.17**	
1648658.00	59.32	305.98	146.64	109.49	0.48	0.75	**0.36**	
1648770.00	39.56	37.30	27.84	25.50	0.75	0.92	**0.68**	
1648810.00	59.41	56.46	41.19	38.56	0.73	0.94	**0.68**	
1648844.00	68.66	354.15	328.54	213.89	0.93	0.65	**0.60**	
1648866.00	68.88	64.84	48.58	45.18	0.75	0.93	**0.70**	
					0.81	0.79	**0.62**	**Total Area weighted SCF**
					0.83	0.68	**0.54**	**Tot. Insolation weighted SCF**

From the results it is possible to identify that the combined effect of context surrounding volumes, and façade shading modules affect insolation values of the façade; in terms of area, 62% of glazed surface receives solar beam and diffuse radiation (38% of shading effect), but more importantly, in terms of total insolation levels, the building receives 54% of the radiation it would receive if shading effect during peak cooling hours was unaccounted, this means that ***projected shades on glazing surfaces effectively block 46% of the Solar Heat Gains during peak cooling hours***.

The obtained *total insolation weighted SCF* for September at 13:00 (54%) was then applied to the calculation procedure to correct cooling peak load values and account for the effect of shadings on the reduction of required cooling power for the HVAC system, the results are reported in TABLE XX

Table 58: Total building cooling and heating peak loads, as obtained and corrected with SCF

	Insight analyses		**Solar component of peak load**		
	SHGC by design	**SHGC = 0**	**Peak SHG load (W)**	**Corrected peak SHG load (SCF=0.54)**	**Corrected total peak cooling load (W)**
Peak cooling load (W)	646,502	372,682	273,820	147,482	520,164.5
Maximum required cooling capacity (W)	**510,596**	**330,966**	179,630	96,750.72	**427,716.7**
Peak heating load (W)	**145,968**				

Based on these results, the corrected total peak heating load and the corrected maximum required cooling capacity, were used to size the heating and cooling generation components of the HVAC system.

High efficiency heat pumps and chillers were selected for heating and cooling generation respectively, as they provide increased energy efficiency and, unlike boilers, avoid the use of fossil fuels. Both were selected to be air cooled (air-to-water) and roof mounted, due to the lack of information about possible underground water sources able to be used as heat sinks for more efficient water-to-water heat pumps and the relatively small size of the project which would make other additional heat-rejection systems, like cooling towers, more expensive to operate.

A separate 4-pipe water network was used to be able to provide contemporarily cooled and hot water to different terminals at separate areas of the building, which could have opposing demands during mid-season. In this way, one chiller and one heat pump were selected and sized according to the calculated needs; model Carrier, *AquaSnap® - Air-to-water scroll heat pump 30RQ / 30RQP* was used as a reference of the installed system, its characteristics are reported in TABLE XX

Table 59: Requirements and characteristics of selected heat pumps for cooling and heating

SPECS.	REQUIRED	PROVIDED	
		Cooling	Heating
		30RBP-450R **	30RQ-165R **
Cooling capacity (kW)	427.7	**451.0**	
Heating capacity (kW)	146.0		**178.0**
SEER (kWh/kWh)		6.0	
SEER (BTU/Wh)	>14.3 *	21.6	
COP (kWh/kWh)			3.2
HSPF (BTU/Wh)	>8.2 *		10.8
Length (mm)		4798.0	2410.0
Width (mm)		2253.0	2253.0
Height (mm)		2324.0	2324.0

* minimum efficiency requirements C403.3.2.(2) (International Code Council, 2021)
**Product data from manufacturer (Carrier Global)

The selected equipment was then located on the rooftop, over the west services volume, respecting the required distances and surrounded by a parapet that covers it from external views from levels below, the location was chosen to free up other roof areas for users' leisure and have direct access to service shafts on the west side of the building.

Figure 76: Image of the selected heat pump for reference, AquaSnap® - Air-to-water (Carrier Global)

5.3.3.1.2 Air Handling

The building was separated in three main air-zones, according to the different uses: a) Semi-public areas, where a high amount of non-permanent users can access (atrium, café, auditorium, study room); b) Office areas in floor 1 and 2, hosting a relatively stable group of users (coworking spaces and meeting rooms); and c) Laboratories, with higher air quality and filtration requirements.

In this way, the handled air of the three areas is not mixed, and special measures for IAQ control can be applied to specifically fit the need of each air-zone, e.g., installing extra-filters on laboratories or increasing ventilation rates on semi-public areas during times with higher number of visitors. Each air-zone has its own Air Handling Unit (AHU), placed on levels Mezzanine, 2^{nd} and 4^{th} in a separate room inside the western service volume (where noise levels are not critical) from which ducts transfer the air to, and from, conditioned spaces. In this way the amount of vertical ducting to move ventilation air is reduced as they only must cross a maximum of 4.5m as all levels either contain or are neighboring one AHU.

Given that thermal comfort is controlled by a separate hydronics system with terminal units, the AHUs were sized according to the ventilation requirements for IAQ; laboratories, the most restrictive case, were used as reference for design, and its required airflow was calculated following the procedure indicated in ASHRAE 62_1 Ventilation for Acceptable Indoor Air Quality (ASHRAE Standards Committee, 2003):

$$Vbz = (Rp * Pz) + (Ra * Az)$$

Where: *Vbz is* Breathing Zone Outdoor Air Ventilation Rate

Rp is the minimum ventilation rate per person

Pz is the number of people

Ra is the minimum ventilation rate per area

Az is the floor area

In the analyzed case (the levels of laboratories), it is required to have a minimum ventilation rate of 5.0 l/(s*person), and 0.9 l/(s*m²); the total laboratory area, including both floors, is 1545m², and following an assumed occupant density of 0.25 people/m² (387 people), the resulting ventilation rate is

$$Vbz = \left(5\frac{l}{s * person} * 387people\right) + \left(0.9\frac{l}{s * m^2} * 1545m^2\right) = 3325\ {}^{l}/_{s} = 11970\ {}^{m^3}/_{h}$$

Then, the outdoor air intake flow (Vot) was calculated considering a zone air distribution effectiveness (Ez) of 1.0, for ceiling supply of cool air; which keeps the Vot=3325 l/s

The AHU was then selected from a reference manufacturer; model 39HXE, size 150, of Carrier was chosen, an unit that incorporates high performance fan, and a rotatory heat exchanger (efficiency >80%); it can handle a nominal flow rate of 15000 m3/h, providing an adaptable range that goes from a minimum flow rate of 3000 m3/h to a maximum of 18000m3/h. Its dimensions (2.3m x 2.2m x 2.3m) suitable to be installed inside the dedicated space (Carrier, 2022).

Figure 77: Image of the selected AHU for reference, model 39HXE (Carrier, 2022)

5.3.3.1.3 Main ducts

Starting from the same assumption used to size the HVAC system, the size of the main duct crossing conditioned spaces was calculated to identify its impact on the ceiling height. Given the ring shape of the building, it is assumed for the duct system to start from the west service volume and create two branches, each running along the north and south volumes, connecting in the east portion to form a ring that allows to accommodate the airflow according to changes in the ventilation needs by space.

Given the 3325 l/s flow rate going out of the AHU, divided among both laboratory levels and further subdivided in two branches (one in the north and one in the south), the main ducts going over conditioned spaces would have to deliver an approximated maximum of 831.3 l/s of ventilation air. Based on the required airflow and considering a maximum air velocity of 10.2 m/s to avoid excessive noise, but a recommended one of 6.1m/s for minimal sound generation, the ducts were sized according to Wright friction chart for round ducts:

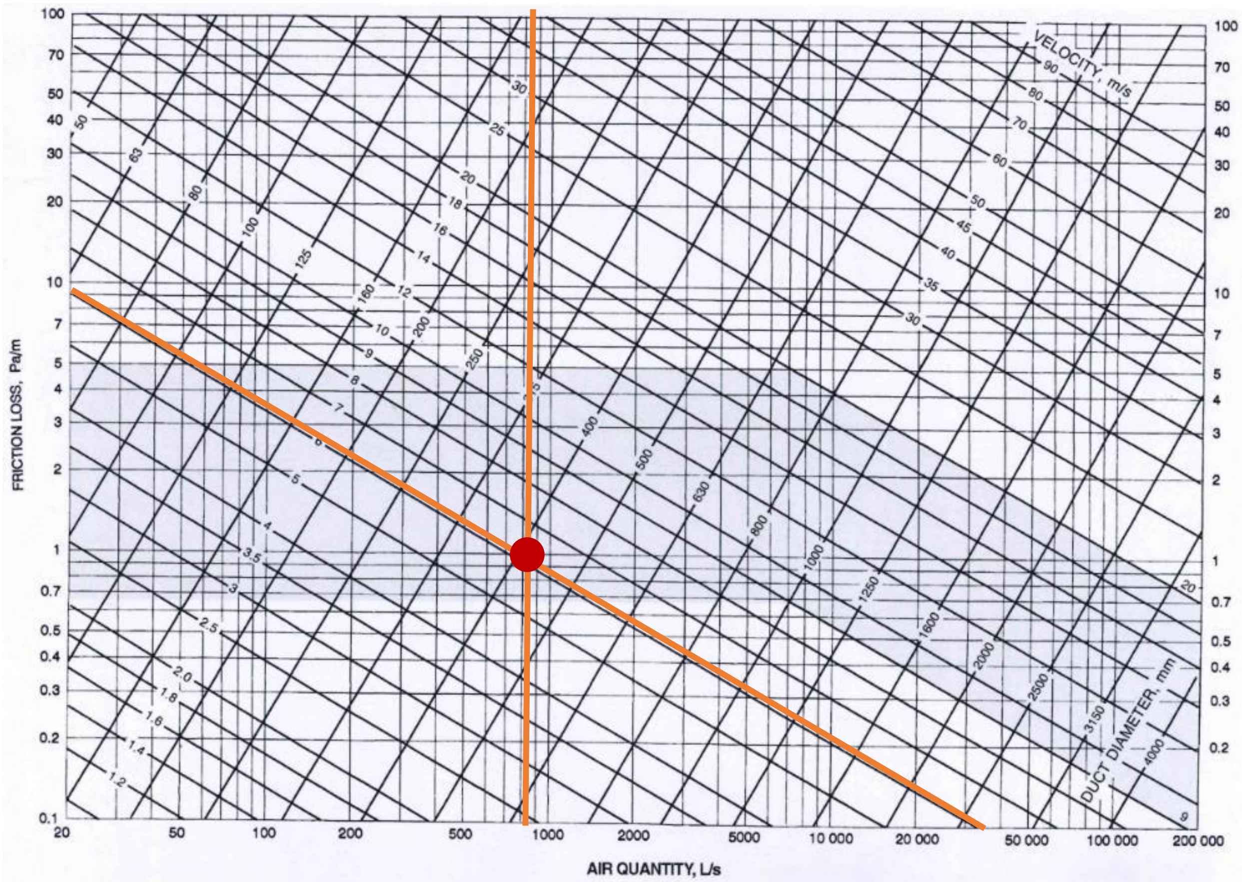


Figure 78: Wright friction chart for round ducts (Pedranzini, 2020)

The charts suggests that a round duct of 400mm could handle the required ventilation airflow with reasonably low velocity and, consequently, low noise levels. Alternatively, a rectangular main duct of 500mm x 300mm can be used, as it is equivalent to the required diameter (De), according to the equation:

$$De = \frac{1.30(a * b)^{0.625}}{(a + b)^{0.25}} \rightarrow \frac{1.30(500 * 300)^{0.625}}{(500 + 300)^{0.25}} = 419.98mm$$

So, the rectangular 500x300mm ducts would set the most strict requirement for ceiling height in the conditioned spaces of the project (excluding service volume, where the AHU is placed).

5.3.3.1.4 Terminals

Terminals are devices directly located inside occupied areas that use water coming from cooling/heating generation units, exchanging heat with the treated air coming from the AHU and the recirculated are from indoors, to provide thermal comfort; they allow to separately control setpoints in different areas of the building to meet specific requirements, however, in general they are not able to guarantee Indoor Air Quality, a task mainly covered by the AHUs.

	Active chilled beams	Fan coil units (FCU)	VAV	Radiant
Max cooling capacity	120 W/m²	140 W/m²	140 W/m²	80 W/m²
Energy efficiency	●●	●●	●●	●●●
Reliability	●●●	●●	●●	●●●
Load maintenance	●●	●●	●●	●●●
Future flexibility	●●	●●●	●●	●●
Temperature control	●●	●●●	●●	●●
Noise	●●●	●●	●●	●●●
Useful life	●●●	●●	●●	●●●
Installation cost	●	●●	●●	●●
Operating cost	●●	●●	●●	●
Riser area (% of total)	0,5%	0,5%	2%	0,5%
Plant room area (% of total)	1-2%	1-2%	4%	1-2%
False ceiling depth	> 550 mm	> 650 mm	> 800 mm	> 200 mm

Good ●●● **Medium** ●● **Bad** ●

Figure 79: Comparative table of HVAC terminal systems (Mirabella, 2021)

Ideally a low-noise and low-energy system, like radiant panels or active chilled beams was envisioned as optimal terminal unit type, however they have a lower cooling capacity than other systems; the main driver in the selection of terminal types was its capacity to handle local heating and cooling demands, so peak cooling and heating loads were calculated inside individual spaces of the building. In a similar way to the total building peak loads calculation (used for sizing cooling and heating generation devices), the heating and cooling load calculation tool from Revit was used, and specific critical spaces (where the loads are higher) had the procedure for correction of cooling loads due to shadings on glazed envelope elements, using the shading correction factor associated to the room’s portion of glazed envelope, the results are reported in Table 60.

Table 60: Peak heating and cooling load results, by space

Level	Space	Area (m²)	HEATING: Peak heating load (W)	HEATING: Peak heating load (W/m²)	COOLING UNCORRECTED: Peak cooling load (W)	COOLING UNCORRECTED: Peak cooling load (W/m²)	COOLING CORRECTED: SCF	COOLING CORRECTED: Peak cooling load (W/m²)
Ground floor	014 Study room	200	-803	-4.0	28,777	143.9		
	016 Auditorium	187	-17,738	-94.9	20,140	107.7		
	017 Cafe	119	-4,468	-37.5	25,998	218.5	0.53	166.6
	018 Atrium	529	-9,713	-18.4	60,939	115.2		
Mezzanine	032 Cafe	141	-11,766	-83.4	14,383	102.0		
	033 Study cabin	14	408	29.1	5,118	365.6	0.32	149.9
	034 Study cabin	14	420	30.0	5,115	365.4	0.32	149.4
	035 Study cabin	14	418	29.9	5,102	364.4	0.1	79.3
	036 Meeting room	39	-1,368	-35.1	12,474	319.8	0.1	118.0
First floor	055 Coworking spaces	762	-1,979	-2.6	72,308	94.9		
	057 Chill area	62	881	14.2	2,539	41.0		
Second floor	072 Double office	27	-391	-14.5	710	26.3		
	074 Meeting room	30	-1,434	-47.8	5,419	180.6	0.52	138.8
	075 Meeting room	29	-1,343	-46.3	5,151	177.6	0.52	136.3
	076 Office	24	196	8.2	3,548	147.8	0.57	102.1
	077 Double office	29	76	2.6	3,743	129.1	0.52	86.6
	078 Meeting room	24	-874	-36.4	4,685	195.2	0.57	151.8
	079 Office	24	196	8.2	3,548	147.8	0.57	102.1
	080 Office	24	195	8.1	3,539	147.5	0.57	101.9
	081 Office	24	188	7.8	3,556	148.2	0.57	102.5
	083 Double office	18	366	20.3	727	40.4		
	084 Office	14	424	30.3	631	45.1		
	085 Office	14	424	30.3	631	45.1		
	086 Office	14	425	30.4	634	45.3		
	088 Double office	29	75	2.6	3,780	130.3	0.52	87.5
Third floor	104 Laboratory	213	-1,631	-7.7	9,674	45.4		
	105 Laboratory	246	-2,142	-8.7	11,692	47.5		
	106 Laboratory	159	-5	0.0	27,971	175.9	0.45	102.2
	107 Laboratory	200	-106	-0.5	24,396	122.0	0.57	87.4
Fourth floor	123 Laboratory	200	-285	-1.4	23,341	116.7		
	124 Laboratory	119	-824	-6.9	16,242	136.5	0.45	83.4
	125 Laboratory	155	400	2.6	8,636	55.7		
	126 Laboratory	253	-1,232	-4.9	12,979	51.3		

Highlighted in yellow: spaces with a very high uncorrected cooling peak load
Highlighted in red: spaces with a very high corrected peak load

It is possible to observe that radiant ceilings are immediately excluded from the options, as many of the spaces have higher cooling loads than it is able to handle; also several spaces had higher uncorrected cooling loads than the capacity of chilled beams (120W/m²), however, when applying the correction factor to account for shading effect on external glazing, only few spaces remained outside the capacity range of chilled beams: the café in ground floor, and 5 south-facing small offices on Mezzanine and 2nd floor.

Given these conditions it was decided to install Active Chilled Beams in all open plan spaces (coworking areas, laboratories, study area) and north/east facing meeting rooms and offices; these terminals were preferred as they have an increased energy efficiency and reduced noise generation due to the lack of fans or motors in the unit.

Spaces with higher cooling requirements, where chilled beams are not appropriate, like the south facing offices, auditorium, and cafe would have higher capacity systems, like fan-coils or hybrid chilled beam units with integrated fans.

5.3.3.2 Electricity production

As explained in page 139, the atrium glazed roof (skylight) has Photovoltaic cells integrated into the glass panes, so, besides providing partial shade and reducing likelihood of overheating in the atrium below, it is able to generate part of the electricity to be consumed by the building.

The roof was made in direct alignment with the south and its tilt was purposedly established at 36 degrees, as it maximizes the total yearly electricity generation from the PV cells, according to the results of a preliminar analysis performed in the Photovoltaic Geographical Information System (PVGIS) of the European Comission, done considering the conditions of the site.

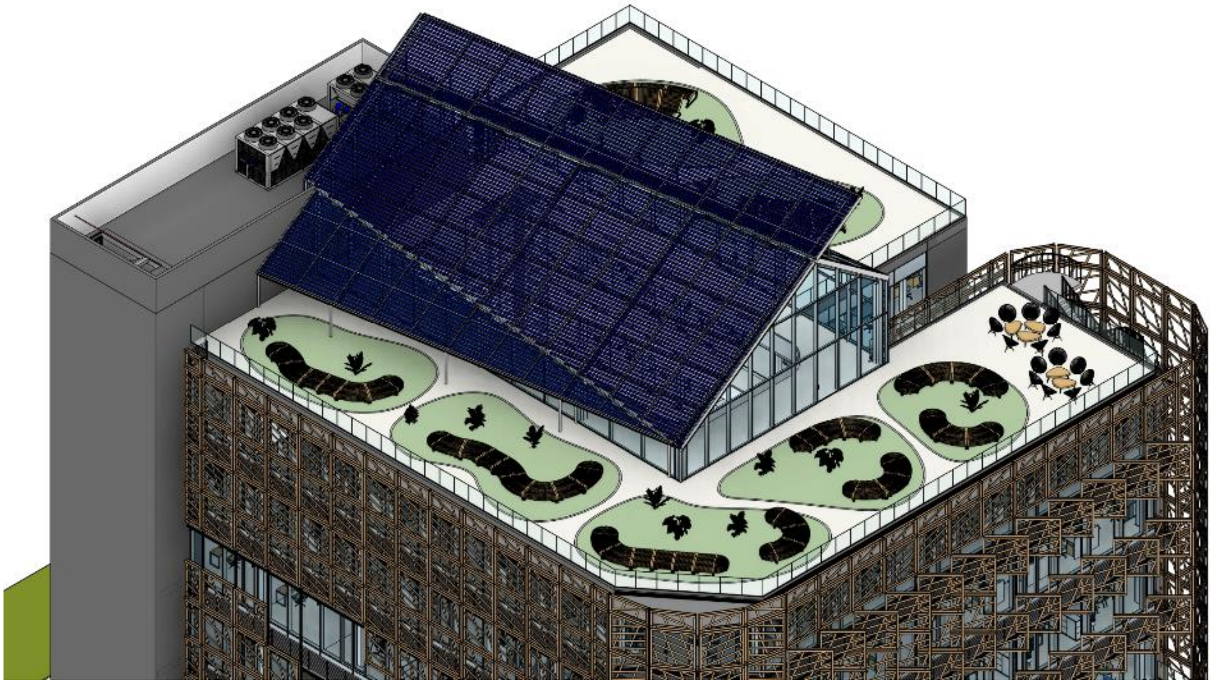


Figure 80: 3D view of the PV cells on the roof

The south facing side of the roof and its upper/lower extensions sum up an area of 390.2 m², from which 249.7 m² (64%) is occupied by integrated PV cells. To maximize energy production, high-performance cells were chosen, taking as reference Maxeon™ GEN III solar cells, from SunPower; they are made of monocrystalline silicon and have an efficiency of around 23% under Standard Test Conditions (STC), with dimensions of 125mm x 125mm (SunPower Corporation, 2017)

Under these circumstances the installed peak power on the roof is 57.4 Kw; then a new analysis was performed in the PVGIS tool to calculate energy production throughout the year, system losses were estimated at 14%. The resulting yearly electricity production is estimated to be 75,281.7 kWh/year, able to cover 7.8 % of the total electricity demand of the building (see page 186)

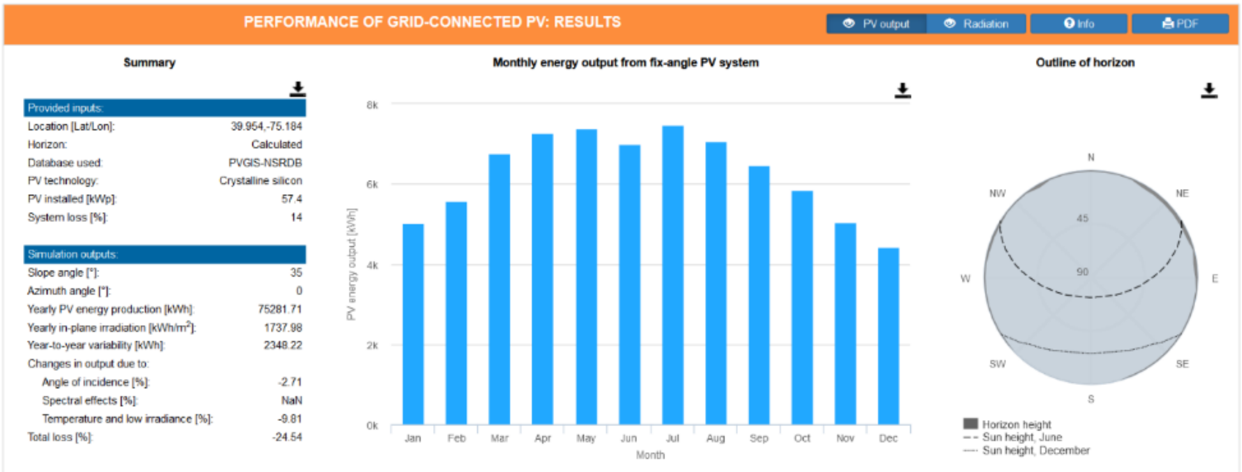


Figure 81: Average monthly and yearly renewable energy generation from roof PV cells, calculated using PVGIS system

5.3.3.3 Water systems

On the building site, reduction of stormwater run-off is a priority to help mitigate flooding risk, the pressure over drainage systems and pollution of the Schuylkill River; so the building was provided with a system for rainwater collection and use, taking advantage of the frequency of rain in Philadelphia (see climatic data), and also reducing overall treated water demand for non-potable uses, like WC flushing, and landscaping.

The available rainwater was calculated, considering the dimension (1272.8 m²) and surface type of the catchment area (partly green and partly impervious roof), and the average precipitation in Philadelphia, which is between 44 and 48 inches per year (1.1-1.2 m/year), the results are reported in Table 61

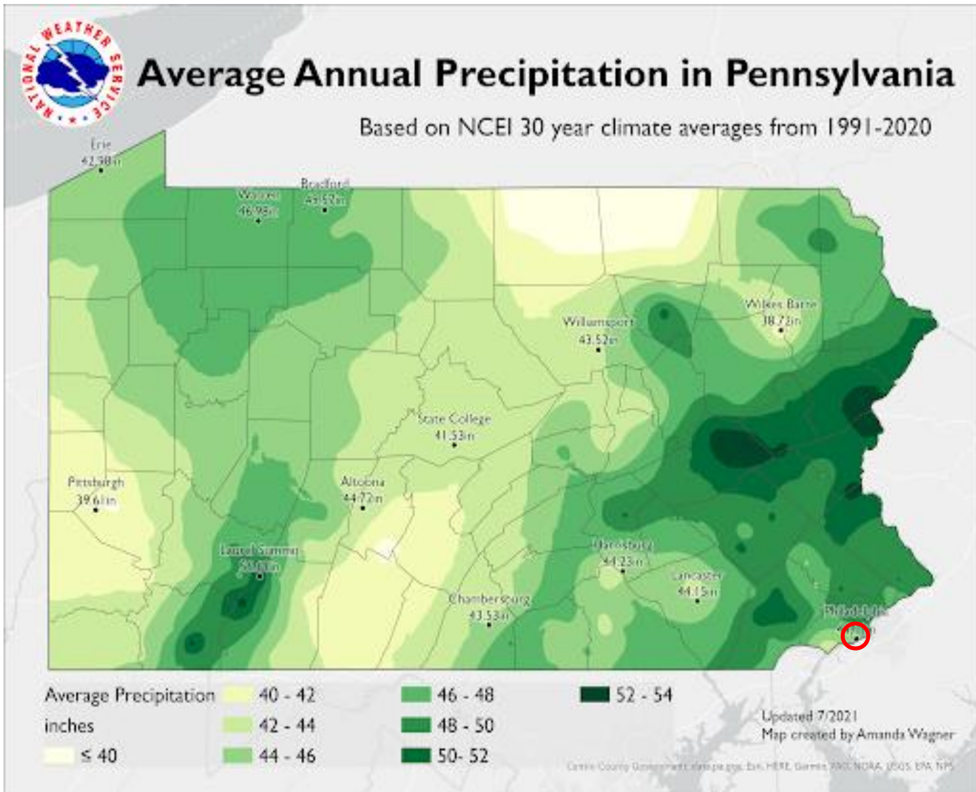


Figure 82: Map of average annual precipitation in Pennsylvania (National Weather Service, n.d.)

Table 61: Available rainwater collection on-site, calculation results

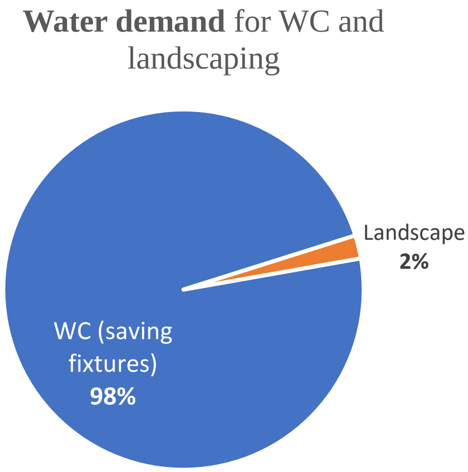
AVAILABLE RAINWATER (Q)	*RUNOFF COEFFICIENTS*	
	Building roof (impervious)	0.90
	Building green roof	0.75
	Green areas on soil	0.15
	CATCHMENT AREA (A) (m2)	
	Impervious roof	830.80
	Green roof	442.00
	Average annual rainfall (h) in meters	1.15
	*AVERAGE ANNUAL RUNOFF (Q=A*runoff coefficient*h)*	
	Impervious roof (m3)	859.88
	Green roof (m3)	381.23
	TOTAL Q (m3)	**1241.10**

The annual collected rainwater is then compared to the annual water demand of the building for WC flushing and landscape maintenance, the consumptions values were taken from the reference values stated in the Italian code ENI 11445:2012 (Fabbisogno giornaliero procapite negli uffici) due to the lack of access to a similar calculation method for Philadelphia. The efficiency of water fixtures has a high impact on demand, so very efficient water fixtures were assumed in this calculation

Table 62: Building water demand for WC flushing and landscaping, calculation results

WATER DEMAND (WC + LANDSCAPE)	**WC**	Number of People	949.00	people
		Water demand for WC per person per day	30.00	liters
		IF water saving fixtures (20% less)	24.00	liters
		IF water saving fixtures (40% less)	18.00	liters
		D toilet (l) = 30l * N people * 365 days	6234930.00	liters
		D toilet per year (m3)	**6234.93**	**m3**
	LANDSCAPE	Landscaping (m2)	442.00	m2
		Water demand for 1m2 of green area	300.00	liters/m2
		D landscaping per year	132600.00	liters
		D landscaping per year (m3)	**132.60**	m3
	TOTAL	Total D in liters	6367530.00	liters
		Total D in m3	**6367.53**	m3

The resulting demand, as expected, is higher to the available rainwater (not considering potable water to be used in sinks and kitchen), still the last one can cover up to 19% of all WC and landscaping water demand.



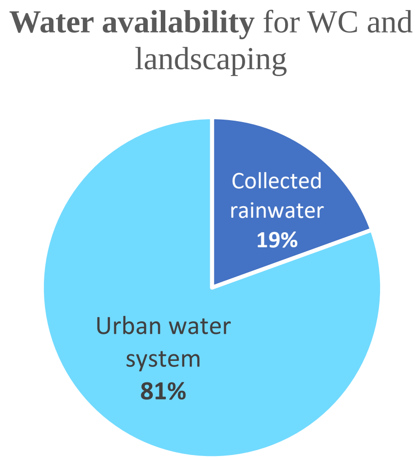


Figure 83: Proportion of water demand (left) and availability (right), by use and source

Finally, the water storage tank was sized to be able to hold collected water from heavy rainfall during dry periods, following the procedures from UNI-EN 11445:2012; considering a storage capacity 6% of the total yearly rainfall, the resulting tank must be able to hold 111.7 m3 of rainwater (equivalent to a volume of 3m x 6.1m x 6.1m)

Table 63: Rainwater collection tank capacity, calculation results

WATER TANK CAPACITY	
Max storage volume in m3 [Ws] (min{Q,D} * 0.06)	74.47
Tank volume in m3 [Wt] (=Ws*1.5)	**111.70**
Tank volume in liters	111,699.27

5.3.4 Space plan

Space plan comprises all semipermanent elements located inside the spaces of the building, that give form to the layout and enclose the different internal occupied areas, including the non-structural part of internal slabs, partitions and ceilings

5.3.4.1 Internal slabs

Table 64: Stratigraphy of internal slabs

N°	Material	s (m)	λ (W/mK)	R (m^2K/W)	Specific heat (J/kgK)	Density (kg/m^3)	μ	P (kg/mhPa)	Rv (m^2hPa/kg)
	Int		5,88	0,17					0
1	Tiles	0,01	1	0,01	800	2000	40	1,68E-8	597014,93
2	Air	0,145		0			1	0,00	216417,91
3	Light weight concrete	0,1	0,31	0,323	900	1170	10	0,00	1492537,31
4	Polyethylene	0,003	0,03	0,09	1800	30	2000	3,35E-10	8955223,88
5	Concrete	0,1	2	0,05	1000	2400	50	1,34E-8	7462686,57
6	Steel dock	0,008	50	0,00	450	7800	2144444	3,12E-13	25605301493
	Ext		25	0,04					0

TOT thickness = 0.23 m
R value = 0.66 m^2K/W
U value = 1.53 W/m^2K

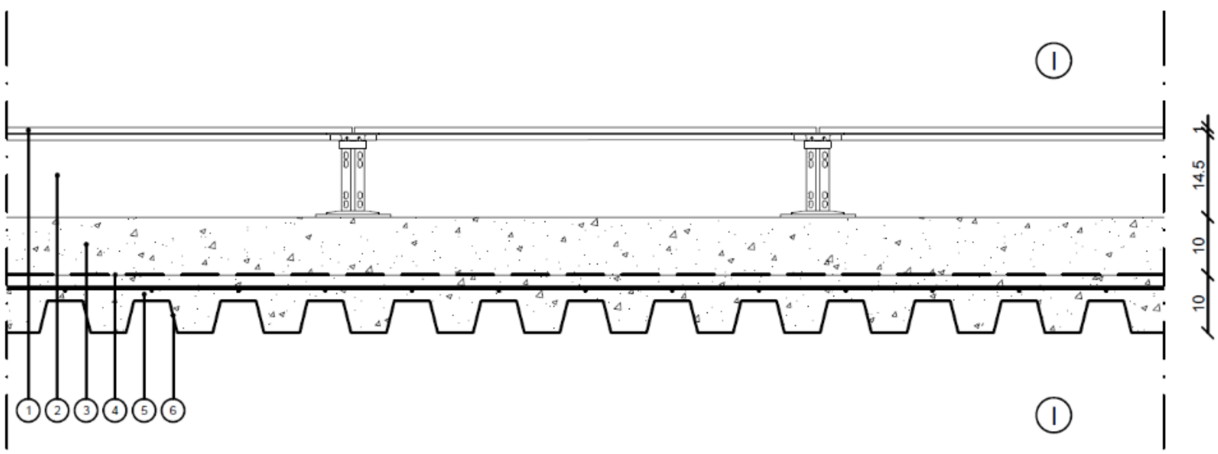


Figure 84: Stratigraphy of internal slabs

5.3.4.2 Internal ceilings

Under the internal slabs, and also under some roofs, a false ceiling is attached in order to cover the systems that pass under the slabs, and create a plenum for the return of air from the rooms to the HVAC units. The false ceiling has the following composition:

Table 65: Stratigraphy of internal ceilings

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		5,88	0,17					0
1	Rockwool	0,05	0,034	1,47	1030	60	70	9,57E-9	5223880,6
2	Plasterboard	0,0125	0,2	0,06	1000	680	8	8,38E-8	149253,7
	Ext		5,88	0,17					0

TOT thickness = 0.0625 m
R value = 1.74 m²K/W
U value = 0.57 W/m²K

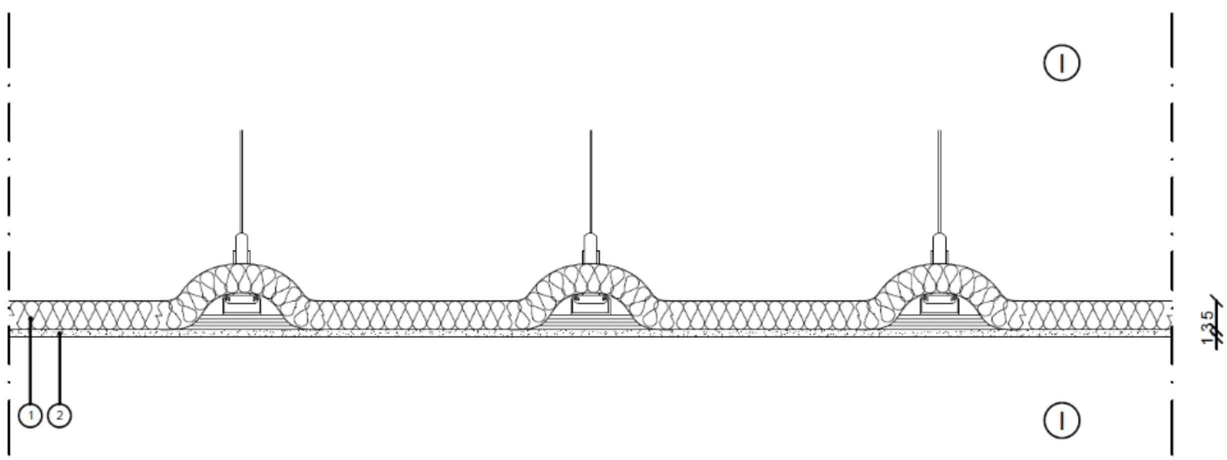


Figure 85: Stratigraphy of internal ceilings

The air gap between the slab and the false ceiling is smaller in near the curtain walls, and bigger in the center of the room. This solution had been made in a way to guaranty the entering of the higher possible amount of light where there are the windows (where the ceiling gets closer to the beams) and at the same time guarantee a space for the passage of the systems in the center of the room; in between the areas with different height an inclined ceiling is used. Regarding the finishings, elements must have a reflectance of 80% by design, in order to maximize the amount of diffuse light redirected towards the center of the spaces.

Figure 86: Perspective view of ceiling and indoor spaces

5.3.4.3 Internal partitions

There are two types of internal partitions in the project: glazed and opaque ones. Glazed internal partitions are made of very clear glass (90% VT) and a 5cm wooden frame, to guarantee light penetration in the rooms not only from the external curtain wall, but also from the atrium. Glazed internal partitions with a double height were made with aluminum frame covered by a wrap with the same wood color of the frame of the single-story glass partitions. The dimensioning of these curtain wall has been made following the same process used for the external curtain wall, explained in the previous chapter, but applying the minimum possible wind load.

Opaque internal partitions are made mostly in plasterboard, apart some solutions made in REI concrete blocks for the fire resistance, or others in concrete where there are the stairs of the elevator. Different opaque stratigraphy types are shown in the following pages:

Table 66: Internal partition assembly W_I_42_C (underground insulated)

N °	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		7,69	0,13					0
1	Plaster	0,01	0,78	0,01	1000	1600	15	4,47E-8	223880,60
2	Concrete	0,3	2,00	0,15	1000	2400	50	1,34E-8	22388059,70
3	Xps	0,1	0,03	2,94	1030	70	70	9,57E-9	10447761,19
4	Plaster	0,01	0,78	0,01	1000	1600	15	4,47E-8	223880,60
	Ext		7,69	0,13					0

TOT thickness = 0.42 m
R value = 3.38 m²K/W
U value = 0.30 W/m²K

Note: the insulation of this wall is minimal and is present in the walls that are between an external and an internal not heated space, just to reduce the thermal bridge in the building.

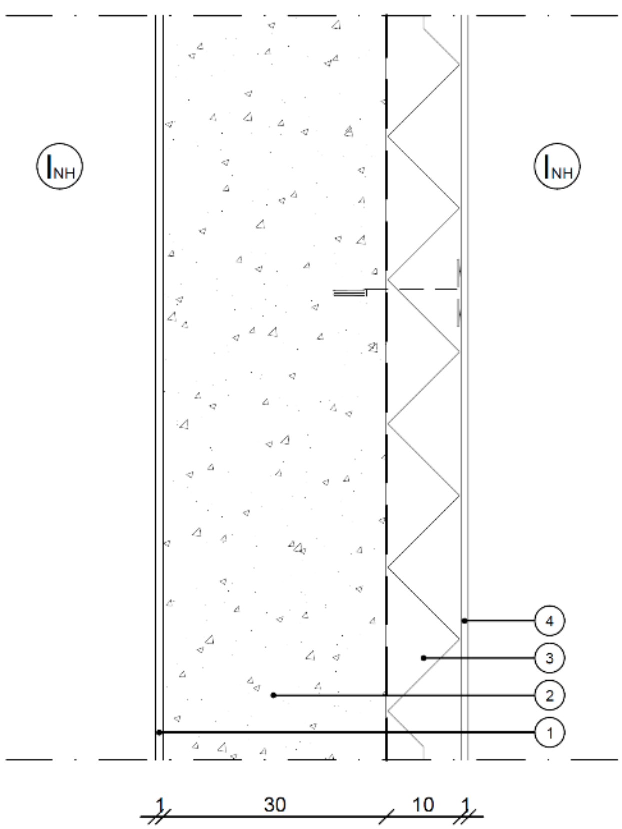


Figure 87: Internal partition assembly W_I_42_C (underground insulated)

Table 67: Internal partition assembly W_I_32_C

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		7,69	0,13					0
1	Plaster	0,01	0,78	0,01	1000	1600	15	4,47E-8	223880,60
2	Concrete	0,3	2	0,15	1000	2400	50	1,34E-8	22388059,7
3	Plaster	0,01	0,78	0,01	1000	1600	15	4,47E-8	223880,60
	Ext		7,69	0,13					0

TOT thickness = 0.32 m

R value = 0.44 m²K/W

U value = 2.30 W/m²K

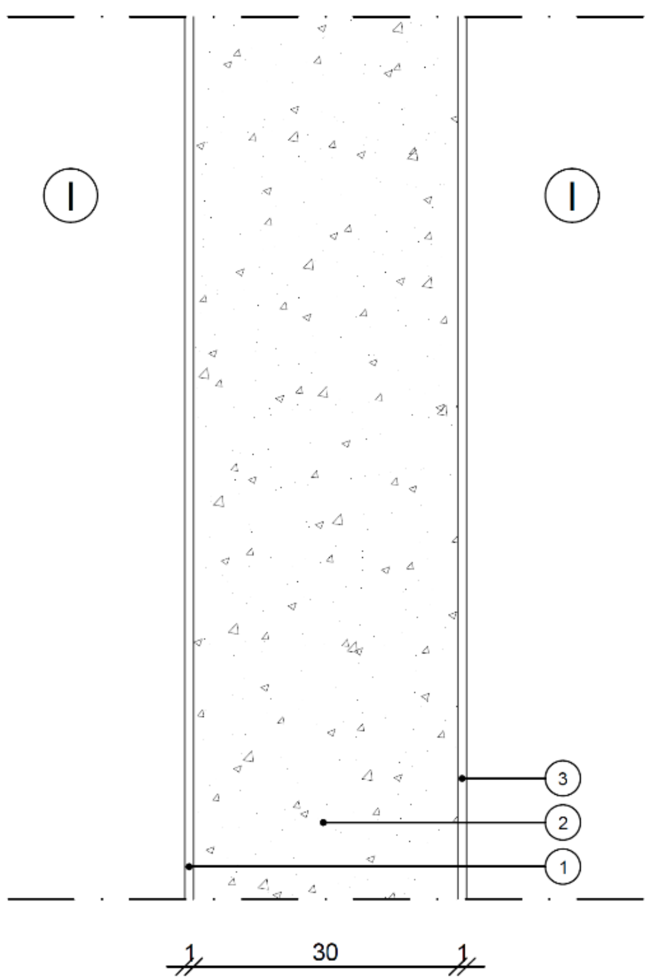


Figure 88: Internal partition assembly W_I_32_C

Table 68: Internal partition assembly W_I_31_C (no render)

N°	Material	s (m)	λ (W/mK)	R (m^2K/W)	Specific heat (J/kgK)	Density (kg/m^3)	μ	P (kg/mhPa)	Rv (m^2hPa/kg)
	Int		7,69	0,13					0
1	Plaster	0,01	0,78	0,01	1000	1600	15	4,47E-8	223880,60
2	Concrete	0,3	2	0,15	1000	2400	50	1,34E-8	22388059,70
	Ext		7,69	0,13					0

TOT thickness = 0.31 m

R value = 0.42m^2K/W

U value = 2.37 W/m^2K

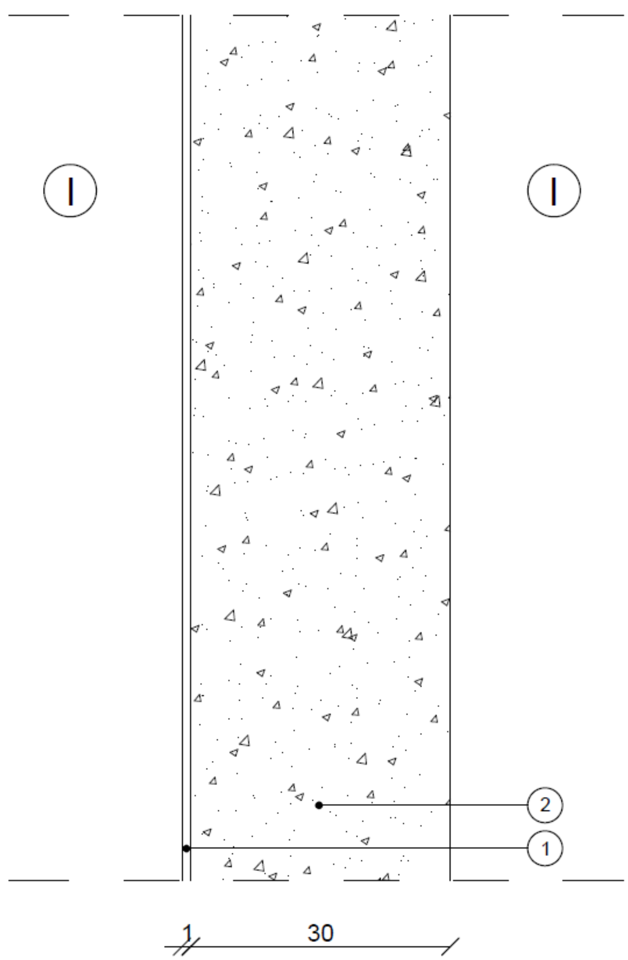


Figure 89: Internal partition assembly W_I_31_C (no render)

Table 69: Internal partition assembly W_I_24_R (insulated)

N°	Material	s (m)	λ (W/mK)	R (m^2K/W)	Specific heat (J/kgK)	Density (kg/m^3)	μ	P (kg/mhPa)	Rv (m^2hPa/kg)
	Int		7,69	0,13					0
1	Plaster	0,01	0,78	0,01	1000	1600	15	4,47E-8	223880,60
2	REI blocks	0,12	2,53	0,05	1110	1400	6	1,12E-7	1074626,87
3	Xps	0,1	0,034	2,94	1030	70	70	9,57E-9	10447761,19
4	Plaster	0,01	0,78	0,01	1000	1600	15	4,47E-8	223880,60
	Ext		7,69	0,13					0

TOT thickness = 0.24 m
R value = 3.27m²K/W
U value = 0.31 W/m²K
Note: the insulation of this wall is minimal and is present in the walls that are between an external and an internal not heated space, just to reduce the thermal bridge in the building.

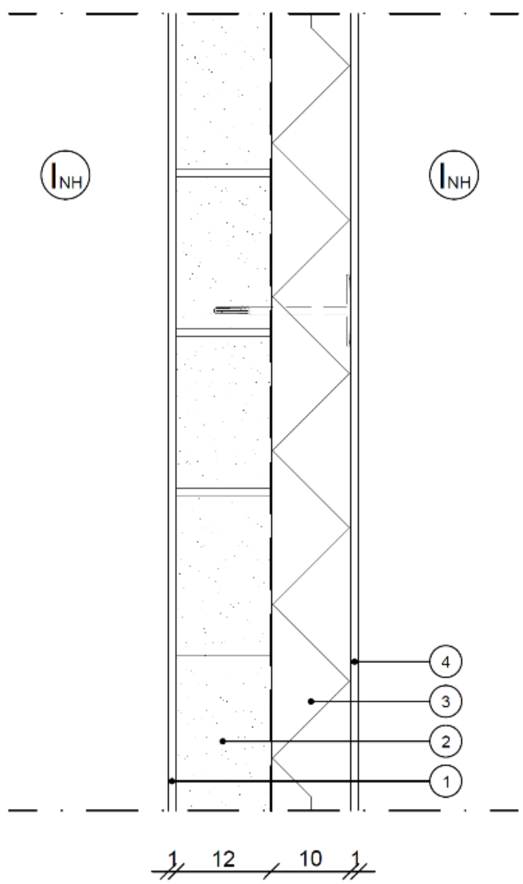


Figure 90: Internal partition assembly W_I_24_R (insulated)

Table 70: Internal partition assembly W_I_14_R

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		7,69	0,13					0
1	Plaster	0,01	0,78	0,01	1000	1600	15	4,47E-8	223880,60
2	REI blocks	0,12	2,53	0,05	1110	1400	6	1,12E-7	1074626,87
3	Plaster	0,01	0,78	0,01	1000	1600	15	4,47E-8	223880,60
	Ext		7,69	0,13					0

TOT thickness = 0.14 m
R value = 0.33m²K/W
U value = 3.00 W/m²K

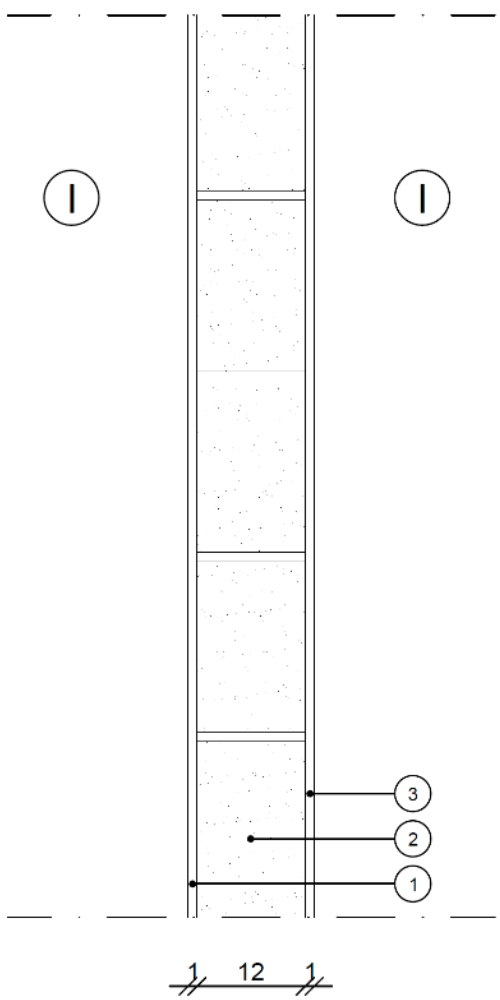


Figure 91: Internal partition assembly W_I_14_R

Table 71: Internal partition assembly W_I_20_P

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		7,69	0,13					0
1	Render	0,002	0,7	0	1000	1500	8	8,38E-8	23880,60
2	Plasterboard	0,025	0,2	0,13	1000	680	8	8,38E-8	298507,46
3	Rockwool	0,05	0,035	1,43	1030	70	1	0,00000067	74626,87
4	Air cavity	0,05		0,18			1	0,00000067	74626,87
5	Rockwool	0,05	0,035	1,43	1030	70	1	0,00000067	74626,87
6	Plasterboard	0,025	0,2	0,13	1000	680	8	8,38E-8	298507,46
7	Render	0,002	0,7	0	1000	1500	8	8,38E-8	23880,60
	Ext		7,69	0,13					0

TOT thickness = 0.20 m
R value = 3.46 m²K/W
U value = 0.29 W/m²K

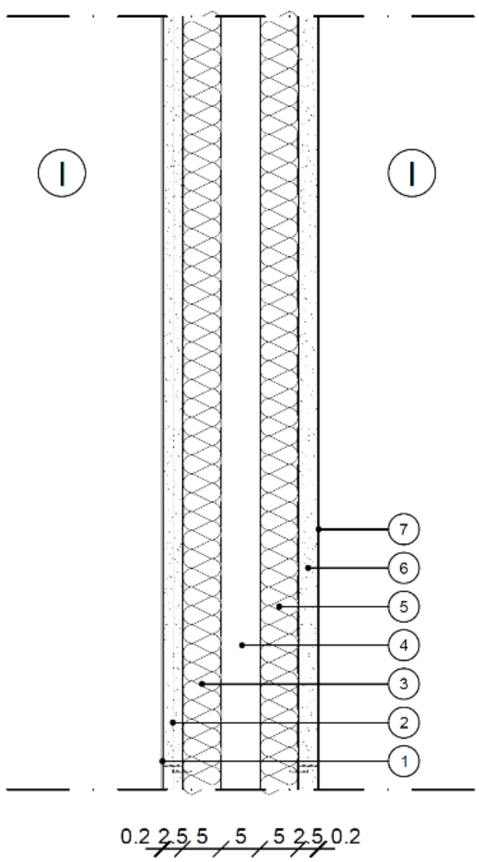


Figure 92: Internal partition assembly W_I_20_P

Table 72: Internal partition assembly W_I_10_P

N°	Material	s (m)	λ (W/mK)	R (m²K/W)	Specific heat (J/kgK)	Density (kg/m³)	μ	P (kg/mhPa)	Rv (m²hPa/kg)
	Int		7,69	0,13					0
1	Render	0,002	0,70	0	1000	1500	8	8,38E-8	23880,60
2	Plasterboard	0,025	0,20	0,13	1000	680	8	8,38E-8	298507,46
3	Rockwool	0,05	0,04	1,43	1030	70	1	0,00000067	74626,87
4	Plasterboard	0,025	0,20	0,13	1000	680	8	8,38E-8	298507,46
5	Render	0,002	0,70	0	1000	1500	8	8,38E-8	23880,60
	Ext		25	0,04					0

TOT thickness = 0.10 m

R value = 1.85 m²K/W

U value = 0.54 W/m²K

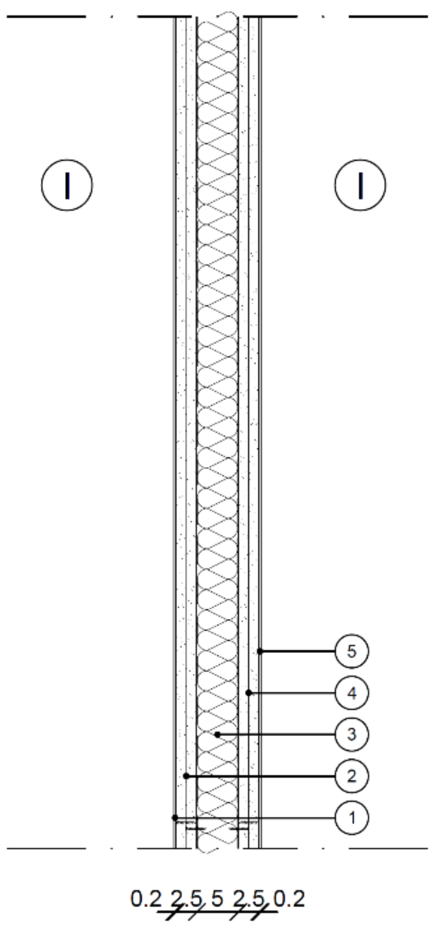


Figure 93: Internal partition assembly W_I_10_P

5.3.5 Stuff

Stuff layer comprises all mobile elements used by occupants, mainly furniture and appliances, that have a very high rate of change throughout the entire building life. The layout of this building is designed to provide flexibility in the subdivision of the space in order to allow fitting the evolving needs of use and occupation inside, so the appliances and furniture would be very dependant on the requirements of the moment.

For this reason, the selection and design of these elements is outside the scope of this project, and it only includes a reference set of furniture and appliances to give an idea of the possible spaces and present the building layout in a way that the uses and proportions can be identified. This can be explored inside architectural plans.

5.4 Energy performance results

When combining all layers that compose the building, and after the optimization process, the final geometry and set of characteristics of the building was subject to final assessments to verify their behaviour as a building unit, the analysis focused on comfort and energy.

During the development of the building an important reduction in terms of energy consumption (EUI) has been noticed. The improvement has been analysed along three main steps: the base case (with the minimum requirements by law applied on the building); the optimized case (with the optimized opaque and transparent envelopes as explained in the chapters 5.3.2.1 and 5.3.2.2) and the optimized case with the double skin applied.

At the base case, meeting the minimum prescriptions defined in the IECC, the EUI of the building was 173 kWh/m²/year; after optimizing the envelope assemblies an EUI of 164 kWh/m²/year was reached, the application of the double skin on the building gave an improvement of another 4.88% of EUI respect to the previous version, reaching an energy use of 156 kWh/m²/yr; which translates to around 970000 kWh/m2 year

In all the values expressed here, the characteristics for light efficiency, daylight, and occupancy controls, plug load efficiency, HVAC system and operating schedule were applied following the recommendations of IECC, as required by the Philadelphia Building Code. Additionally, two common practice examples were assessed to provide comparison with the performance of other buildings that sit outside IECC regulations, in particular a lower efficiency artificial lighting fixtures and HVAC system (ASHRAE Packaged Unit) were represented, showing the average EUI of Building in Philadelphia for comparison.

Natural ventilation can be used during periods when outdoor temperatures are inside the comfort range, for the climate of Philadelphia that totalize 853 hours of potential natural ventilation hours, reducing the time when mechanical cooling is required from 2469h to 1616h (34.5%), saving up to 60451 kWh/year.

As explained in page 170 (electricity production subchapter), the PV system in the roof has an installed power of 57.4 Kw, able to produce up to 75281.7 kWh/year, equivalent to 7.8% of building energy demand.

The resulting building demand after applying all strategies is of about 834 MWh/year, with an EUI of 134 kWh/m2 year, being 50% lower than the Philadelphia average for offices (266 kWh/m2 year), 45% lower than the U.S. median average (242.9 kWh/m2 year), and 22.5% lower than the base case compliant with the IECC requirements (City of Philadelphia, 2019). Results are reported in Figure 94.

In the final version of the optimization, HVAC systems alone consume 58.7% of the total energy used by the building, while 41.3% is used by appliances and lighting fixtures (see Figure 95)

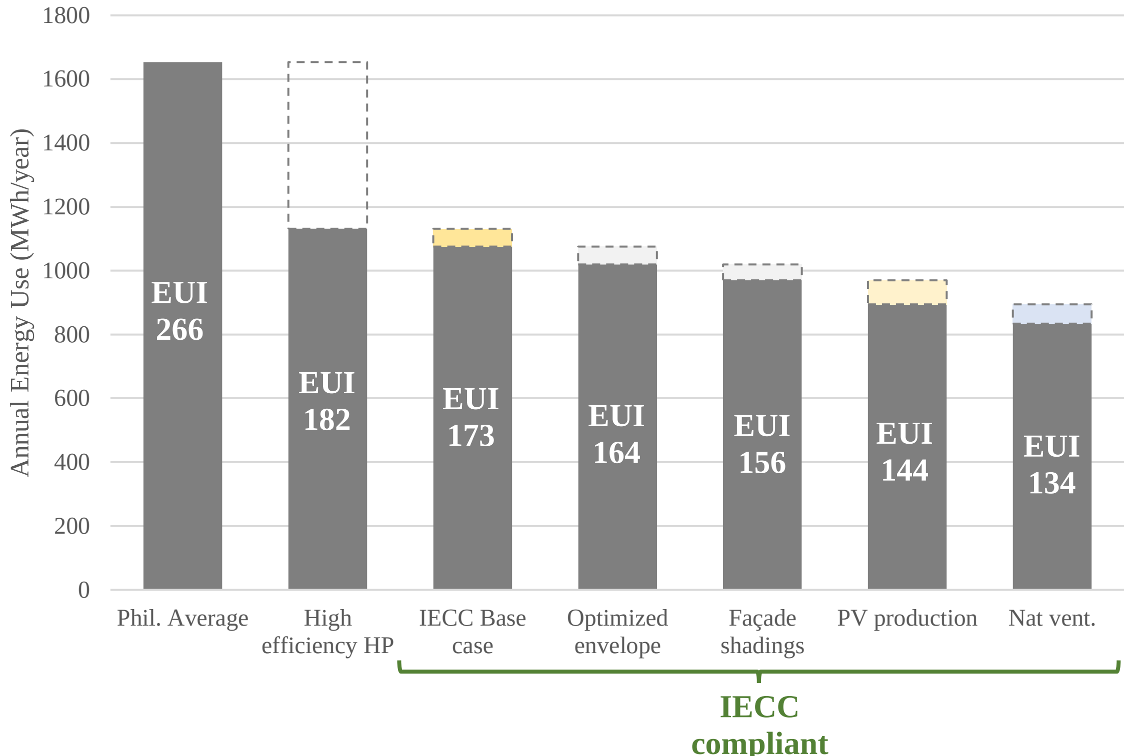


Figure 94: Energy optimization evolution of the building

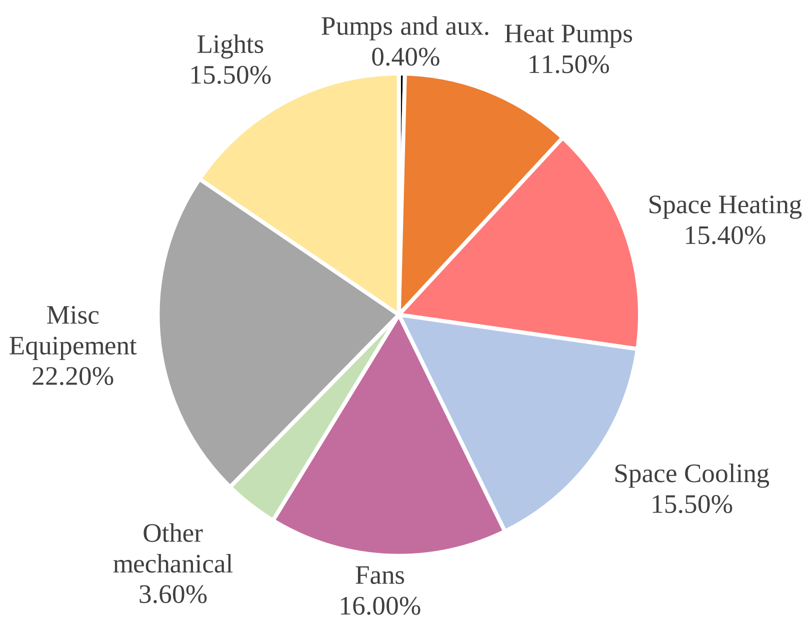


Figure 95: Distribution of energy consumption among building uses

CONCLUSIONS

The project for Drexel University's Innovation Center, allowed to approach the complex reality of a building design from a holistic perspective, spanning through different scales, approaches and analysis methodology; the project site presented a set of physical, social and legal conditions that defined the requirements the proposal had to comply, the opportunities for improvement of the area, and highlighted the attachment to the place that any building project has to use to define its form and character.

At a bigger scale, the definition of the site masterplan was essential to give continuation to the Schuylkill Yards and 30th Street Station Development Plan and connect to the existing/projected morphology and dynamics of the surrounding area. At the same time, a correct massing organization of the complex proved vital to guarantee a relatively controlled outdoor environment, that allows buildings to increase their relationship with exterior positive phenomena: breezes, nature sounds, and diffuse daylight; while protecting occupied areas from hostile stressors that could result from being overexposed to the exterior: pollution, glare noise and excessive heat.

In an analogous way, at the individual Building Scale much of the process of optimization revolved around the control and filtration of stimuli at the boundaries, protecting from overexposure while avoiding entire isolation; essentially the building works as an organism that adapts to the conditions of the surrounding environment and takes its shape and organization following internal requirements and external factors. This aspect was a key takeaway, as the first approach to biophilic design could naturally mislead to the generation of an organic shape made to resemble other natural elements, like trees or mountains; that happened in the first steps of this building design and proved infructuous as a building is still an artificial structure, subjected to different targets and cycles than any living being. The figurative nature analogies proved more useful at a lower level, where components are subjected to less constraints in their design (as the case of shading modules in this project); while the building volume worked more efficiently using a regular shape that favoured a simple and flexible layout within a rational structure and services distribution.

Thus, it was understood that following biophilic design principles required focusing on the human perception of phenomena instead of the real shape of the volumes; in this way spatial hierarchies were created to produce a sense of refuge and prospect (towards the exterior and the internal atrium) with stimulating dynamic conditions, like variations in the sunlight entering the building, and changing views.

There are not predefined solutions for all buildings, as the optimization process requires a balancing of positive and negative effects at each design decision; in the project for example, the increased density of shading elements could reduce peak loads to improve thermal comfort and decrease energy needed for cooling, however, this effect was counteracted by the reduction of available daylight for visual comfort, increasing energy use for artificial lighting. Trade-offs must then be evaluated for each specific project, climate and use; but as a general remark biophilic design principles can be aligned to energy efficiency, as many of the natural phenomena it aims to provide contact with (e.g. daylight, breezes), potentially reduces the need for artificial appliances already used to achieve these environmental conditions (e.g. artificial lighting and mechanical ventilation).

Finally, this proposal provides a base that can be further optimized to expand comfort and energy efficiency conditions, by studying internal operative temperatures for individual spaces, consider free-cooling, and assess the behaviour of breezes going through the building to improve the design of openings for enhanced natural cross-ventilation; or to cover other aspects of high-performance not focused in this research, like life-cycle analysis of materials and management of operations, or detailed landscape design to integrate green areas to the local biodiversity. Beyond the scope of this project, the great extent of criteria comprising the classification of high-performance building design allows for the development of much more than energy efficiency and well-being.

REFERENCES

Abergel, T., & Delmastro, C. (2021). *Tracking Buildings 2021*. Retrieved 2022, from International Energy Agency: https://www.iea.org/reports/tracking-buildings-2021

Active House Alliance. (2020). *The Active House specifications. 3rd Edition.* Retrieved 2022, from https://www.activehouse.info/wp-content/uploads/2020/01/Guidelines_ActiveHouse_III_2020_Spreads.pdf

AGC Glass Europe. (2022). *AGC Glass Configurator*. Retrieved 2022, from https://configurator.agc-yourglass.com/configurator/en

American Lung Association. (2022). *Pennsylvania: Philadelphia*. Retrieved 2022, from State of the Air: https://www.lung.org/research/sota/city-rankings/states/pennsylvania/philadelphia

ASHRAE Standards Committee. (2003). *Ventilation for Acceptable Indoor Air Quality.* Standard Addendum. Retrieved from https://www.ashrae.org/File%20Library/Technical%20Resources/Standards%20and%20Guidelines/Standards%20Addenda/62-2001/62-2001_Addendum-n.pdf

Autodesk. (2020, September). *Revit Support and Learning. Calculation Reference for Heating and Cooling Loads*. Retrieved from Autodesk Knowledge Network: https://knowledge.autodesk.com/support/revit/learn-explore/caas/CloudHelp/cloudhelp/2020/ENU/Revit-Analyze/files/GUID-B3E90100-0CC9-4874-AEFC-079727ECDA12-htm.html

Autodesk Insight. (2017). *About Insight Lighting Analysis*. Retrieved 2022, from GitBook: https://adskinsight.gitbooks.io/insight-lighting-analysis-help/content/about-insight-lighting-analysis.html

Autodesk Insight. (2017). *About Insight Solar Analysis*. Retrieved 2022, from GitBook: https://adskinsight.gitbooks.io/insight-solar-analysis-help/content/about-insight-solar-analysis.html

Autodesk Insight. (n.d.). *Insight Widget Settings*. Retrieved 2022, from Gitbook: https://adskinsight.gitbooks.io/insight-widget-settings/content/insight_widget_settings/

Barbiero, G. (2017). *Ecologia Affettiva.* Milano: Mondadori.

Barbiero, G., & Berto, R. (2019). *Introduzione alla biofilia. La relazione con la Natura tra genetica e psicologia* (2nd ed.). Rome: Carocci editore.

Brand, S. (1994). *How Buildings Learn: What Happens After They're Built.* Viking Press.

Brandywine Realty Trust. (n.d.). Life Sciences Brochure. Retrieved 2021, from https://hs.brandywinerealty.com/hubfs/Life%20Sciences%20-%20B-Labs/Brandywine%20Life%20Sciences%20-%20March2021%20-%20Digital%20ver%202.pdf

Brandywine Realty Trust. (n.d.). Schuylkill Yards Brochure. Philadelphia. Retrieved 2022, from https://hs.brandywinerealty.com/hubfs/Schuylkill%20Yards/Schuylkill%20Yards%20Brand%20Elevation%20Book%20-%202021.pdf

Browning, W., Ryan, C., & Clancy, J. (2014). *14 Patterns of Biophilic Design.* New York: Terrapin Bright Green LLC. Retrieved June 2021, from https://www.terrapinbrightgreen.com/reports/14-patterns

Cambridge Dictionary. (2022). Cambridge University Press. Retrieved from https://dictionary.cambridge.org/dictionary/english/

Carrier. (2022). *Installation Operation and Maintenance Instructions 39HXC - 39HXE - 39HXEZ - 39 HXV.* Product manual. Retrieved 2022, from https://eto.carrier.com/litterature/iom/EN7565707-02_IOM_01_2022_39HXC_39HXE_39HXEZ_39HXV.pdf

Carrier Global. (n.d.). *Product selection data.* Scroll Chillers and Heat Pumps with air cooled condenser and Greenspeed® Intelligence. Retrieved 2022, from https://eto.carrier.com/litterature/psd_short/10578_PSD_03_2022_30RB_RBP_30RQ_RQP_R32_165R_950R_Short%20version.pdf

City of Philadelphia. (2019). *Philadelphia Building Energy Benchmarking. 2019 Report.* City of Philadelphia, Office of Sustainability. Retrieved from https://www.phila.gov/media/20191210092812/2019-Citywide-Energy-Benchmarking-Report.pdf

City of Philadelphia. (n.d.). *Atlas*. Retrieved May 2022, from https://atlas.phila.gov/3001%20CHESTNUT%20ST/property

City of Philadelphia. (n.d.). *OpenMaps*. Retrieved 2022, from https://openmaps.phila.gov/#/

EnergyPlus. (n.d.). *Weather Data by Location.* Retrieved 2021, from EnergyPlus: https://energyplus.net/weather-location/north_and_central_america_wmo_region_4/USA/PA/USA_PA_Philadelphia.Intl.AP.724080_TMY3

European Comission. (2022). *Photovoltaic Geographical Information System PVGIS*. Retrieved 2022, from https://re.jrc.ec.europa.eu/pvg_tools/en/

Federal Emergency Management Agency. (2021). *FEMA Flood Map Service Center: Search By Address*. Retrieved 2022, from FEMA: https://msc.fema.gov/portal/search?AddressQuery=philadelphia#searchresultsanchor

International Code Council. (2021). International Energy Conservation Code. Retrieved from https://codes.iccsafe.org/content/IECC2021P2

Javelle, F., Laborde, S., Hosang, T. J., Metcalfe, A. J., & Zimmer, P. (2021). The Importance of Nature Exposure and Physical Activity for Psychological Health and Stress Perception: Evidence From the First Lockdown Period During the Coronavirus Pandemic 2020 in France and Germany. 11.

Kabisch, N., Korn, H., Stadler, J., & Bonn, A. (Eds.). (2017). *Nature-based Solutions to Climate Change Adaptation in Urban Areas.* Cham, Switzerland: Springer Nature. Retrieved June 2021, from https://link.springer.com/book/10.1007/978-3-319-56091-5

Kellert, S. R., Heerwagen, J., & Mador, M. (2008). *Biophilic Design: The Theory, Science, and Practice of Bringing Buildings to Life.* Hoboken: John Wiley & Sons.

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., . . . Engelmann, W. H. (2001, July 26). The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal of Exposure Science & Environmental Epidemiology, 11*, 231-252. Retrieved from https://doi.org/10.1038/sj.jea.7500165

Laminam S.P.A. (2022). *Laminam website*. Retrieved from Pietra di Cardoso Nero Naturale: https://www.laminam.com/it/product/pietra-di-cardoso-nero/

Merriam-Webster Dictionary. (2022). Merrian-Webster Inc. Retrieved from https://www.merriam-webster.com/dictionary/

Mirabella, A. C. (2021). *Building Services - HVAC Systems.* Lecture presentation, Politecnico di Milano.

National Weather Service. (n.d.). *JetStream Max: Addition Köppen-Geiger Climate Subdivisions*. Retrieved 2022, from National Weather Service: https://www.weather.gov/jetstream/climate_max

Office of Energy Efficiency & Renewable Energy. (n.d.). *Energy Efficiency*. Retrieved 2022, from U.S. Department of Energy: https://www.energy.gov/eere/energy-efficiency

Passive House Institute. (2015). *Passive House requirements*. Retrieved 2022, from Passive House Institute website: https://passiv.de/en/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm

Pedranzini, F. (2020). *HVAC Air Handling Systems – Understanding the basis.* Lecture presentation, Politecnico di Milano.

Philadelphia Building Code. Retrieved 2022, from https://codelibrary.amlegal.com/codes/philadelphia/latest/philadelphia_pa/0-0-0-186840

Ponzio S.R.L. (2021). *Ponzio WS 50. Profili per facciata continua.* Product brochure.

Reed, B. (2007, September 13). Shifting from 'sustainability' to regeneration. *Building Research & Information, 35*(6), 674-680. doi:10.1080/09613210701475753

Sandak, A., Sandak, J., Brzezicki, M., & Kutnar, A. (2019). *Bio-based Building Skin.* Singapore: Springer Nature. Retrieved 2021, from https://link.springer.com/book/10.1007/978-981-13-3747-5

Shiva, A., Purohit, R., Rana, R., & Koli, D. K. (2017). Noise and Vibration Emissions of Railway Bridges. *Materials Today: Proceedings, 4*, 1-5. Retrieved 2022, from https://doi.org/10.1016/j.matpr.2017.02.270

Skidmore, Owings & Merrill LLP. (2016). *Philadelphia 30th Street Station District Plan.* Amtrak, Brandywine Realty Trust, Drexel University, Pennsylvania Department of Transportation, SEPTA. Retrieved 2021, from https://static1.squarespace.com/static/539b050fe4b077b40b221f4f/t/57694caaff7c5085d0a3de31/1466518722881/District+Plan+Final+Report_June2016_8.5x11_web.pdf

SunPower Corporation. (2017). *Maxeon™ Gen III Solar Cells.* Product brochure. Retrieved from https://us.sunpower.com/solar-resources/sunpower-maxeon-gen-iii-solar-cells

Terrapin Bright Green. (2014). 14 Patterns of Biophilic Design. 64.

U.S. Code, Chapter 149- National Energy Policy and Programs. Retrieved 2021, from https://uscode.house.gov/view.xhtml?req=granuleid:USC-prelim-title42-section16194&num=0&edition=prelim

U.S. Energy Information Administration. (2018). *Use of energy explained. Energy use in commercial buildings*. Retrieved 2022, from EIA Independent Statistics and Analysis: https://www.eia.gov/energyexplained/use-of-energy/commercial-buildings.php

U.S. Energy Information Administration. (2022). *U.S. Energy facts explained*. Retrieved 2022, from https://www.eia.gov/energyexplained/us-energy-facts/

U.S. Environmental Protection Agency. (2009). *Buildings and their Impact on the Environment: A Statistical Summary.* EPA Archive document. Retrieved 2022, from https://archive.epa.gov/greenbuilding/web/pdf/gbstats.pdf#:~:text=Buildings%20in%20the%20United%20States%20contribute%2038.9%20percent,can%20be%201.8%E2%80%935.4%C2%B0F%20%281%E2%80%933%C2%B0C%29%20warmer%20than%20its%20surroundings.

U.S. General Services Administration. (n.d.). *Buildings and Health*. Retrieved 2022, from Sustainable Facilities Tool: https://sftool.gov/learn/about/576/buildings-health#source4

U.S. Green Building Council. (2019). *LEED v4 for Building Design and Construction.* Rating system. Retrieved from https://www.usgbc.org/sites/default/files/LEED%20v4%20BDC_07.25.19_current.pdf

U.S. Green Building Council. (2021). *LEED v4.1 Building Design and Construction. Getting started guide for beta participants.* Retrieved 2022, from https://www.usgbc.org/leed/v41#bdc

United Nations Environment Programme. (2022, April 26). *Our use of sand brings us "up against the wall", says UNEP report*. (A. Laguna, & P. Peduzzi, Eds.) Geneva. Retrieved 2022, from https://www.unep.org/news-and-stories/press-release/our-use-sand-brings-us-against-wall-says-unep-report

West 8 Urban Design & Landscape Architecture P.C. (2016). *Drexel University Public Realm Plan.* Retrieved 2021, from Drexel Public Realm Plan: https://drexel.edu/facilities/design/masterPlan/publicrealm/

Wijesooriya, N., & Brambilla, A. (2021, February 10). Bridging biophilic design and environmentally sustainable design: A critical review. (J. J. Klemes, Ed.) *Journal of*

Cleaner Production, 283. Retrieved 2022, from https://doi.org/10.1016/j.jclepro.2020.124591

World Health Organization. (2005). *Constitution.* Retrieved 2022, from https://apps.who.int/gb/bd/PDF/bd47/EN/constitution-en.pdf?ua=1

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