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BIM APPROACHED SUSTAINABLE DESIGN METHODS

From Bioclimatic to Regenerative Design

BIM A+ European Master in Building Information Modelling

Master thesis No.:

Supervisor:
Tomo Cerovšek

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Izvleček:

Različne metode trajnostnega načrtovanja, okviri in sistemi ocenjevanja trajnostne gradnje so bili razviti že od prve opredelitve poročila o trajnostnem razvoju - *Brundtland*. Bioklimatski pristop k arhitekturnemu načrtovanju lahko najdemo v vernakularni arhitekturi in je bil formalno predlagan v vrsti raziskovalnih in strokovnih publikacij od petdesetih let prejšnjega stoletja dalje. Bioklimatski pristop označuje skupek načrtovalskih strategij, ki temeljijo na lokalni klimi, uporabi naravnih virov in energetskih tokov s ciljem, da se zagotovijo fiziološke in psihološke potrebe po zdravju in udobju ljudi. Podnebne spremembe, linearna ekonomija in velik vpliv grajenega okolja na planet zahtevajo takojšnjo preobrazbo, da bi dosegli podnebne cilje OZN in IPCC SR1.5°C.

Ta študija podaja pregled metod trajnostnega oblikovanja v povezavi s krožnim gospodarstvom in novo paradigmo projektiranja in gradnje grajenega okolja s pomočjo informacijskega modeliranja zgradb. Regenerativno načrtovanje nudi odmik od sedanje prakse in se osredotoča na zmanjšanje vplivov na okolje in povečanje učinkovitosti, s ciljem zasnovati stavbe in mesta, ki so regenerativni, brez škodljivih vplivov na okolje, vendar obnavljajo ekosisteme, kar omogoča človeku in naravnim sistemom, da se razvijajo hkrati. Predlagan je okvir regenerativnega načrtovanja, ki temelji na celostnem pristopu z orodji za digitalno načrtovanje. Pristop je prikazan na študiji primera večjega objekta v Ljubljani. Na testni študiji se uporabljajo in navzkrižno preverijo najsodobnejši integrirani delotoki projektiranja, orodja in metrike BIM. Raziskava prispeva k lažji izbiri metod, orodij in informacijskih zahtev za naročnika in projektno skupino, in temelji na skupini standardov za BIM - ISO 19650, regenerativnem razvoju in načrtovanju.

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BIBLIOGRAPHIC– DOCUMENTALISTIC INFORMATION AND ABSTRACT

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Abstract:

Different Sustainable Design methods, frameworks and green building rating systems have been developed since the first definition of Sustainable Development of the *Brundtland* report. Bioclimatic approach to architectural design can be found in vernacular architecture and was proposed formally in a series of research and professional publications since the 1950s. The bioclimatic approach is about making design strategies based on the local climate, utilizing natural resources and energy flows to provide for physiological and psychological needs for human health and comfort. Climate Change, a Linear Economy and the high impact of the built environment on the planet require an immediate transformation to achieve the UN SDGs and IPCC SR1.5°C climate goals.

This study makes a review of Sustainable Design Methods, with links to a Circular Economy, and the new paradigm for the design and construction of the built environment with Building Information Modelling. Regenerative Design holds the promise for shifting from the current practice focused on reducing environmental impacts and increasing efficiency towards designing buildings and cities that are regenerative, climate neutral, restore ecosystems, allowing human and natural systems to co-evolve. A Regenerative Design framework is proposed based on a holistic approach with digital design tools. State of the art BIM integrated workflows, tools and metrics are used and cross-checked on a case study for Ljubljana. The research is a contribution to the selection of methods, KPIs and Information Requirements from the Client-side and for the project team based on ISO 19650 series for Regenerative Design and Development.

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Finally, to my family, thank you for encouraging and supporting me in all of my pursuits and inspiring me to follow my dreams.

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This dissertation contributes to the following Sustainable Development Goals:

UN SDG#3: Good Health and Well-being: Ensure healthy lives and promote well-being for all at all ages.

UN SDG#7: Affordable and Clean Energy: Ensure access to affordable, reliable, sustainable and modern energy for all.

UN SDG#9: Industry, Innovation and Infrastructure: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

UN SDG#11: Sustainable Cities and Communities: Make cities inclusive, safe, resilient and sustainable.

UN SDG #12: Responsible Production and Consumption: Ensure sustainable consumption and production patterns.

UN SDG #13: Climate Action: Take urgent action to combat climate change and its impacts.

UN SDG #15: Life on Land: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.

1 INTRODUCTION

Architecture in the past centuries has been a product of human collaboration, climate, context, building traditions, styles and academic canons. In the 20th century, architecture was shaped by the new emerging theories in different fields and global challenges such as the oil crisis, natural and man-made disasters, rapid urbanization, and need to make healthier cities. In our times, it is again undergoing fast changes. How we design, collaborate, and define "what is architecture" and "how should good architecture look like" is being transformed by the fourth industrial revolution, climate change, and the need for more sustainable design practice for the built environment.

The knowledge and requirements for designing buildings have grown exponentially in our times. From studying the sun to orient buildings and shadings to the simulation of wind, earthquake, energy, and generative design options combining a variety of project inputs and measurable desirable outputs. Until now, the design, construction and operation of assets have made use of sustainable design methods in few cases compared to the whole design and building practice. The problems have been approached separately. Sustainability frameworks are mostly applied when the design is complete, such as verification of daylighting levels, acoustic performance, life cycle assessment, energy modelling or green building certification. The design team has not changed over the years, but other specialists are joining and contributing to the development of projects. The evolving tools and knowledge for design and analysis with Building Information Modelling (BIM) allow the use of building simulations early on the concept stage of the project, thus not only when the design is complete for building regulations application. Design goals and desired outcomes can be explored and inform design decisions with specialized tools that make use of parametric objects, algorithms, databases, templates, and automation.

1.1 Key research questions

The main goal of the thesis is to explore how the designers, clients and everyone involved in the process can benefit from the new paradigm shift from Computer-Aided Design (CAD) to BIM and holistic design thinking required to achieve goals for Regenerative Development and Design.

The main objectives and research questions of this academic work:

- What are the Sustainable Design principles, methods, and frameworks to respond to the societal challenges within meeting planetary boundaries and achieving the Sustainable Development Goals for all?

- How is Climate Change, the Circular Economy and development trends in the construction industry related and how can Digital Design support the transformation towards the positive nature of regenerative developments, climate-neutrality and achieve the climate goals of the Paris Agreemnt and European Green Deal?

- How can Sustainable Design be integrated in the current Digital Design and Construction practice?

- What are the workflows, tools, and standards that can support and be combined for Regenerative Design?

- Modelling and different types of building performance analysis for achieving Sustainable Outcomes.

- Key Performance Indicators for Regenerative Design applicable to the urban and building level.

- How can Regenerative Design be integrated with Building Information Modelling and Integrated Project Delivery?

- Information Requirements based on ISO 19650 series for Regenerative Development and Design.

A Regenerative Design framework will be proposed and an applied methodology through BIM integrated workflows and Key Performance Indicators. The promotion of human health and well-being, environmental performance and restoration of natural systems to a healthy state requires new ways of thinking and a holistic approach to architectural design.

Climate, the uniqueness of the place, big data, computational design approaches, and exchange information requirements are explored for achieving Regenerative Design goals. Workflows for Design and Analysis are tested and examined with the most advanced Digital Design tools available. Computational and BIM integrated approaches, from bioclimatic design strategies to the building and single-unit level simulations based on International and European standards, and when there are synergies with green building rating systems are exposed throughout the work and applied to a case study in Ljubljana.

The results of the applied methodology will provide valuable insights into the framework for selecting high-level and detailed BIM Information Requirements based on ISO 19650 series for Regenerative Design in an Integrated Project Delivery.

2 DEVELOPMENT OF METHODS FOR SUSTAINABLE DESIGN

This chapter introduces some key milestones that shaped the design methods and frameworks in Contemporary Architecture. A short overview of the transitions of architectural design from the vernacular, classical, stylistic thinking in the past to the Modern Movement rejection of styles and Beaux-Arts of the XIX century is given. Different concepts and principles of Sustainable Design and relevant frameworks for climatic, environmental, energy-efficient, inspired by nature and holistic design approach are reviewed. The similarities, differences or inclusion of the exposed concepts into one another are explained. The Design Methods are presented chronologically, and the relevance and link to Climate Change, Circular Economy and current societal challenges are put forward.

2.1 Design Methods in History

In every place where humans lived, architecture and building in history have been designed according to similar principles, e.g. adapting to the local climate and landscape, making use of the sun exposure for the home or settlements, and employing materials close to the site of construction. Over the years and centuries, the accumulated knowledge of building has transformed in recognisable patterns of the vernacular (traditional) architecture of the locations, cities and countries. The evolution of how we build has been shaped by traditions passed from people to people, written documents, and later with formal university education.

One notable example of written documents from western culture in architecture has been “De Architectura” or “Ten Books on Architecture” written around 29 BC – 23 BC by Roman architect Vitruvius. Vitruvius books were rediscovered during the Renaissance and brought into light lost knowledge on the Orders of Greek and Roman Architecture and the design for different buildings of the Romans. Since ancient times, to the Italian Renaissance and arriving in the 19th century, architecture had evolved into recognisable styles with prescribed rules that offered infinite possibilities, e.g. Byzantine Architecture, Gothic, Renaissance, Mannerism, Baroque, Neoclassicism, Neo-Greek, Neo-Roman and Eclecticism styles.

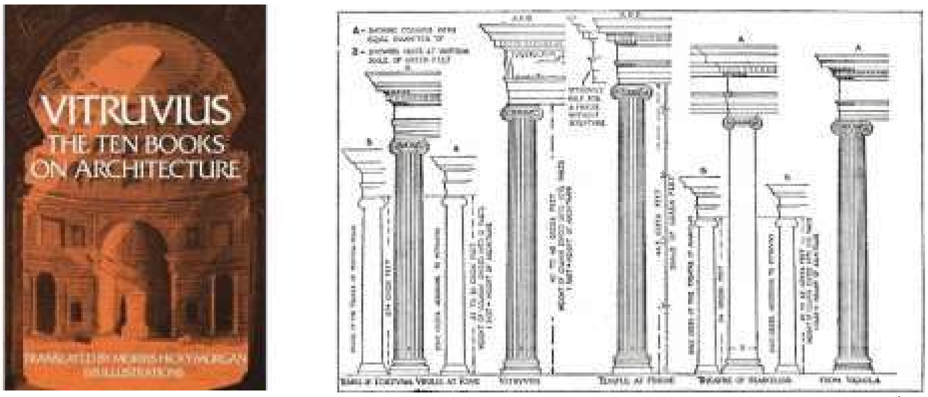


Figure 2. 1: Vitruvius, P. (1960). The ten books on architecture [Book Cover, drawings].[1] Amazon. https://www.amazon.com/Vitruvius-Ten-Books-Architecture-Bks/dp/0486206459

[1] Vitruvius, P., & Morgan, M. H. (1960). Vitruvius: The ten books on architecture. Dover Publications.

Even though there are differences in the same style between regions, the way people build in that time followed the rules laid in books and formal education. The European colonization age, first and the second industrial revolution, new modes of transport, and the world becoming a smaller place in the 19th and 20th made architecture and building less dependent on traditions, local climate and materials. The Eiffel Tower in Paris, Crystal Palace in London, industrial age bridges and civil constructions were not considered objects of architecture like in previous historical times and were not designed anymore by architects.

Moreover, the 19th and 20th centuries are a moment with many developing changes in the world as we know it. Cities are growing exponentially. Skyscrapers, new routes of land, water and aerial transport are shaping the world. Architects and urban planners shifted from academic canons of design to new proposals for the cities of the future with new architectural design theories.

The "Modern Architecture: International Exhibition" in 1932 at MoMA in New York, organized by Philip Johnson brought attention to the novel work of architects like Frank Lloyd Wright, Le Corbusier and mostly Europeans drifting apart from the ornamental and academic styles that architects designed before[2]. These pioneers influenced the following generations of architects to come. The Masters of the 20th century have developed new theories, methods, and knowledge for the design and construction of the built environment.

From the second half of the 20th century to today, from the oil crisis to climate change adaptation, architects and experts in other fields have developed new approaches to mitigate natural disasters, and a design culture that is aware of the location, e.g. bioclimatic architecture, responsible use of resources, sustainability, life cycle assessment, circular economy, systems thinking, regenerative design, performance-based rating systems such as nearly Zero Energy Building, Passive House, LEED.

2.2 Transitions in Architecture

During the 19th century and ongoing industrialization, cities in Europe like London, Paris, Barcelona expanded, and the population increased at a rapid rate. Factories were built around cities and needed the labour force. Many people moved to cities for work. The living and housing conditions were very far from the standards that we think of today.

[2] Museum of Modern Art. (1932 February 10 – 1932 March 23). Modern Architecture: International Exhibition. New York. https://www.moma.org/calendar/exhibitions/2044

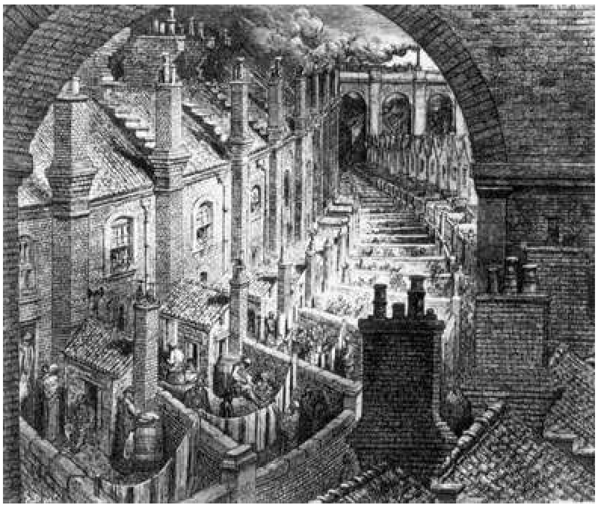


Figure 2. 2: Dore, G. (1872). Over London by rail [Engraving]. Wikipedia.
https://commons.wikimedia.org/wiki/File:Dore_London.jpg

The approach to solving the problems was focused on health risk reduction through designing healthier cities. Urban Planner Ildefonso Cerda drew the plan in 1859 for the expansion of the city of Barcelona. Ebenezer Howard started the Garden City movement in the UK in the late 19th century. In the work of Le Corbusier, we find his influential Ville Radieuse (Radiant City). His proposal tried to solve the spatial design of cities. The principles of his planning proposal are the need for direct sunlight, minimum daylight hours to reach building facades and courtyards, provide ventilation for buildings, public green spaces, waste disposal, water supply, sewerage systems. The growing metabolism of cities in terms of people, goods and energy required new solutions.

Figure 2. 3: Cerda, I. (1859). Barcelona Plan of Expansion [Drawing]. Wikipedia.
https://commons.wikimedia.org/wiki/File:Ensanche_-_eixample_-_Barcelona.jpg

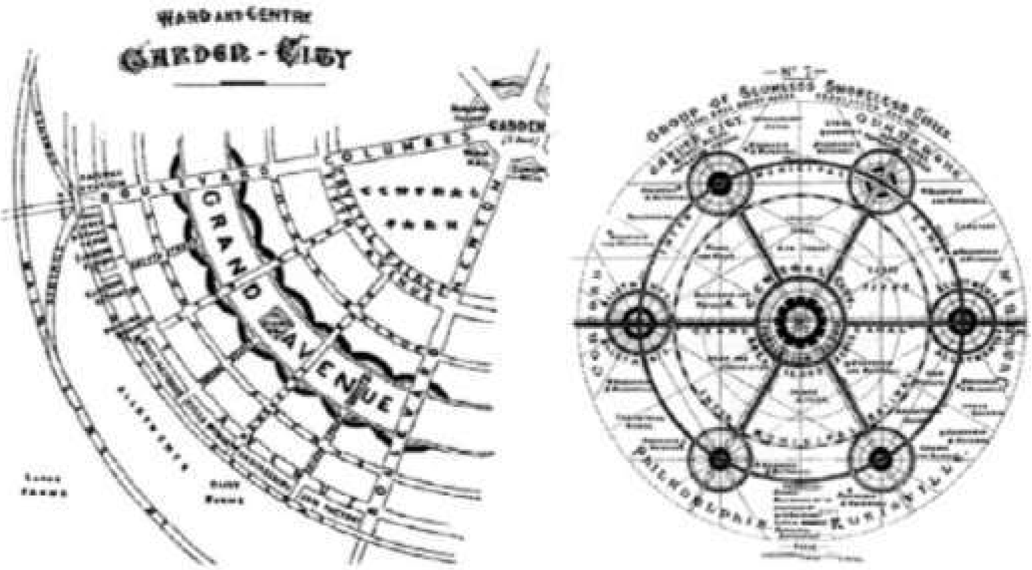


Figure 2. 4: Howard, E. (1902). Garden City Diagram No. 3 and No. 7 [Diagram]. In Garden Cities of To-morrow. Wikipedia. https://en.wikipedia.org/wiki/Garden_city_movement

Figure 2. 5: Merin, G. (2013). Ville Radieuse 1933 (left), Cité Radieuse, Marseille, 1952 (right) [Photograph]. In AD Classics: Ville Radieuse / Le Corbusier. https://www.archdaily.com/411878/ad-classics-ville-radieuse-le-corbusier

Later in his work, Le Corbusier started implementing a new architectural element in the design, which he called the "brise-soleil". The term comes from the French and means "sun breaker".

"Brise-soleil" are **modern sun-shading structures** used to control the amount of sunlight entering a building, allowing exposure in winter and protection in summer by blocking the direct sun rays. These elements have been present in vernacular architecture with the function of reducing the effects of overheating, glare and reducing solar gains, e.g. **lattices (*mashrabiya*), pierced screens (*qamarīyah*), or split bamboo blinds as used in Japan (*sudare*).**

Figure 2. 6: Good, F. (1856). Mashrabiya in Cairo [Photograph]. Wikipedia. https://en.wikipedia.org/wiki/Mashrabiya; Fund, R. (1993). 16th century Indian Pierced Window screen [Photograph]. https://www.metmuseum.org/art/collection/search/453343; [Photograph of Sudare]. (n.d.). Wikipedia. https://en.wikipedia.org/wiki/Sudare#/media/File:Gion_kyoto_japan.JPG

Le Corbusier made use extensively of the "brise-soleil" in his projects of the 1930s and most notably in the design of public buildings when he worked on the ex-Novo urban planning of Chandigarh, capital city of Punjab region in India.

"To introduce the sun is the new and most imperative duty of the architect."

- Le Corbusier in The Athens Charter

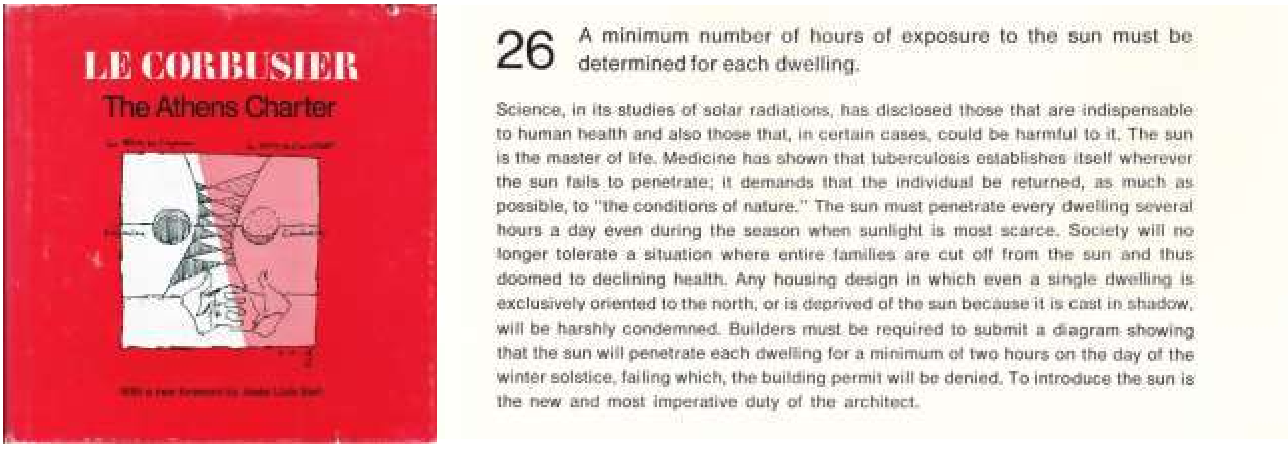
"Space and light and order. Those are the things that men need just as much as they need bread or a place to sleep." - Attributed to Le Corbusier

"Architecture is the masterly, correct and magnificent play of masses brought together in light."

- Le Corbusier in "Vers une Architecture" (1923)

Figure 2. 7: Le Corbusier. (n.d.). Chalkboard drawings of Unité d'habitation de Marseille with the sun [Photograph]; Le Corbusier. (1955). Unité d'habitation with Sun Path in Summer and Winter [Painting]. In Le Poeme de l'Angle Droit. FLC-ADAGP. http://www.fondationlecorbusier.fr

These famous quotes of Le Corbusier remind us of the importance of a design approach following principles that are still relevant today and not prescriptive to an architectural language of his.



26 A minimum number of hours of exposure to the sun must be determined for each dwelling.

Science, in its studies of solar radiations, has disclosed those that are indispensable to human health and also those that, in certain cases, could be harmful to it. The sun is the master of life. Medicine has shown that tuberculosis establishes itself wherever the sun fails to penetrate; it demands that the individual be returned, as much as possible, to "the conditions of nature." The sun must penetrate every dwelling several hours a day even during the season when sunlight is most scarce. Society will no longer tolerate a situation where entire families are cut off from the sun and thus doomed to declining health. Any housing design in which even a single dwelling is exclusively oriented to the north, or is deprived of the sun because it is cast in shadow, will be harshly condemned. Builders must be required to submit a diagram showing that the sun will penetrate each dwelling for a minimum of two hours on the day of the winter solstice, failing which, the building permit will be denied. To introduce the sun is the new and most imperative duty of the architect.

Figure 2. 8: Denzer, A. (2013, October 28). The Athens Charter: Article 26 Sun requirements. In: Le Corbusier and the sun [Cover, Article]. Retrieved April 5, 2020, from http://solarhousehistory.com/blog/2013/10/28/le-corbusier-and-the-sun

Heliotherapy and fresh air were one of the effective treatments for Tuberculosis. It was a widely implemented treatment in Sanatorium designs of the time until the first implementation of antibiotics for treatment of Tuberculosis in the 1940s. The positive benefits of sun-oriented architecture that bring the right amount of light through openings, fresh air circulation through ventilation and balconies were of paramount importance for designers in the first half of the 20th century. The Athens Charter demonstrates an approach towards promoting a healthier built environment.[3]

"Penicillin started as a chance observation. My only merit is that I did not neglect the observation…"

Alexander Fleming in his Noble speech talk in 1945

"One sometimes finds what one is not looking for." - Alexander Fleming

2.3 Bioclimatic Design

The following provides a recent and complete definition of Bioclimatic Design:

Bioclimatic design refers to an architectural design approach that utilizes solar energy and other related environmental resources to provide indoor and outdoor human thermal comfort.[4]

[3] Le Corbusier. (1933). The Athens Charter. Congrès internationaux d'architecture moderne (CIAM). http://www.getty.edu/conservation/publications_resources/research_resources/charters/charter04.html
[4] Daemei, A. B., Eghbali, S. R., & Khotbehsara, E. M. (2019). Bioclimatic design strategies: A guideline to enhance human thermal comfort in Cfa climate zones. Journal of Building Engineering.

"Bioclimatic design – combining "biology" and "climate" – is an approach to the design of buildings and landscape that is based on local Climate. The approach was promoted in a series of professional and popular publications in the 1950s. In using the term "bioclimatic," architectural design is linked to the physiological and psychological need for health and comfort. In adopting bioclimatic approaches, the designer endeavors to create comfort conditions in buildings by understanding the microclimate and resulting design strategies that include natural ventilation, daylighting, and passive heating and cooling. The premise of bioclimatic design is that buildings utilize natural heating, cooling, and daylighting in accordance with local climatic conditions"[5].

Bioclimatic Design makes use of passive systems for indoor air control, ventilation, noise protection, the lighting of spaces through optimizing the use of heat gains, air, and sun that the local climate conditions provide. Every passive system, from the simplest (the window) to the more complex (Trombe wall, curtain wall façade systems with dynamic shading devices) has to be studied concerning the climatic characteristics of the place.

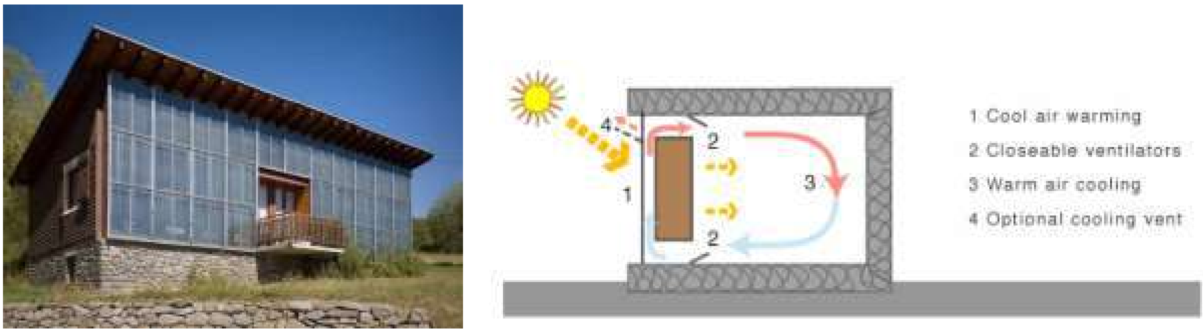


Figure 2. 9: Michel, J., Trombe, F. (1967). Solar house with Trombe wall in Odeillo, France [Photograph, Diagram]. Wikipedia. https://en.wikipedia.org/wiki/Trombe_wall

Numerous examples of passive systems can be found in vernacular architecture:

- **Light plasters** to increase reflection of solar radiation in summer
- **Massive constructions** (thick and heavy walls, also made from earth-based materials) to insulate and stabilize the internal temperature
- **Lighting and solar gains control** of the building envelope (**windows, brise-soleil**)
- **Water, vegetation and landscape** are used to create a favourable **microclimate** around the building.
- **Wind** analysis and **natural ventilation** for outdoor and indoor comfort. It can be used cooling, heating or even humidifying the air.

[5] Watson D. (2013). Bioclimatic Design. In: Loftness V., Haase D. (eds) Sustainable Built Environments. Springer.


Figure 2. 10: Windcatcher tower of Ganjali Khan Complex in Iran used for natural ventilation (left); Sassi di Matera in Italy are cave and stone dwellings (right). Wikipedia.
https://en.wikipedia.org/wiki/Windcatcher https://en.wikipedia.org/wiki/Sassi_di_Matera


Figure 2. 11: Shibam Hadramawt or known as “Manhattan of the Desert” is a mud-brick town in Yemen (left); Santorini white houses, commonly found in Greece’s Aegean islands (right). Wikipedia.
https://en.wikipedia.org/wiki/Shibam_Hadramawt https://en.wikipedia.org/wiki/Santorini

The Bioclimatic Design of vernacular architecture that we find still today makes use of local materials, e.g. stone, wood or earth with little or no need for professional design and technologies. The principles of Bioclimatic design that one can draw inspiration for contemporary design practice are unlimited. The strategies at disposal are as broad as the diversity of climates, cultures, and locations.

2.3.1 *The Psychrometric Chart*

Victor Olgyay is the first architect-pioneer to introduce the Bioclimatic Chart as a tool to understand the climate and determine comfort based on context. Bioclimatic approach to architectural design utilizes Passive Design Strategies based on architectural regionalism. Baruch Givoni is one of the most prominent experts in Bioclimatic Architecture. In his research, the Psychrometric Chart revises the Bioclimatic diagrams of Olgyay and the applicability of passive design strategies in buildings in different climates[6]. These strategies try to achieve an expected indoor temperature utilizing approaches such as ventilation, structural mass for thermal storage coupled with night-time ventilation, solar gains and evaporative cooling. The adapted chart from Givoni can be applied to fourteen climate zones and devise specific strategies based on the climatic zone to achieve comfort and reduced energy consumption. The review of these bioclimatic architecture strategies employed in particular countries can be used in other contexts with similar climate conditions.[7]

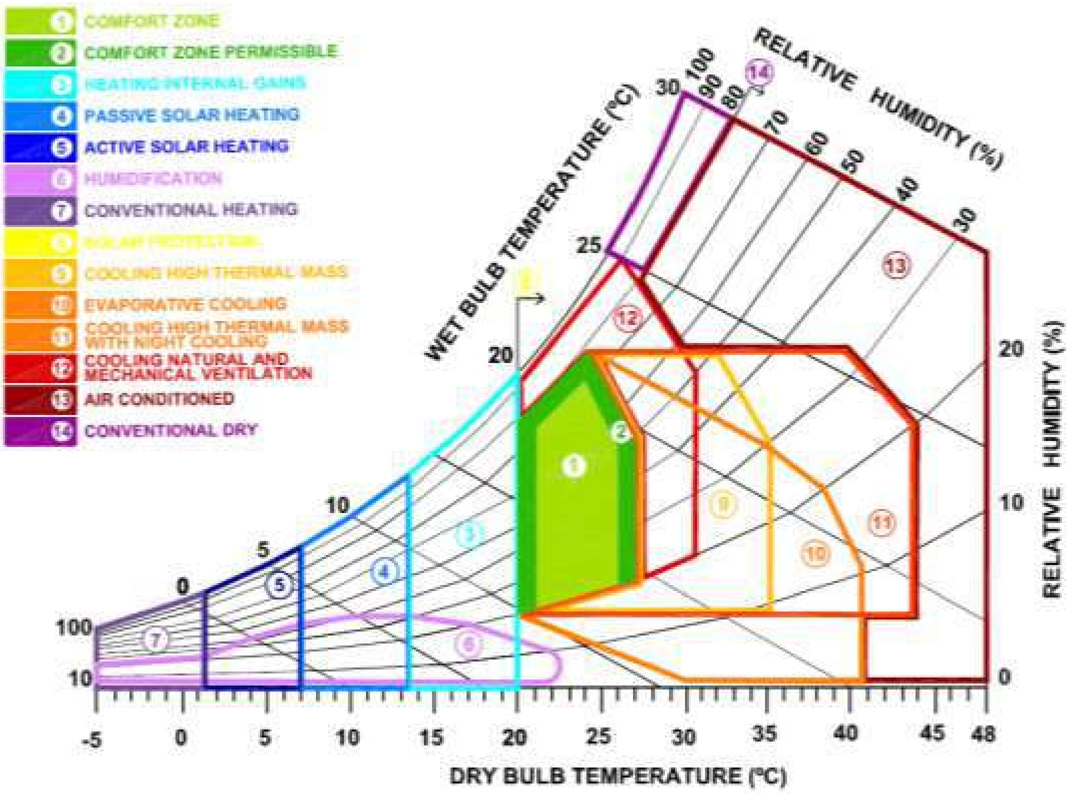


Figure 2. 12: Psychrometric chart adapted from Givoni (Manzano-Agugliaro, 2015).

[6] Givoni, B. (1992). Comfort, Climate Analysis and Building Design Guidelines. Energy and Buildings 18(1):11–23.
[7] Manzano-Agugliaro, F. et al. (2015). Review of bioclimatic architecture strategies for achieving thermal comfort. Renewable and Sustainable Energy Reviews, 49, 736–755.

Bioclimatic design can guide the design process in providing thermal comfort and reducing energy loads. It is essential to take advantage of these opportunities to meet the Sustainable Developments Goals[8] of the United Nations and to achieve the Paris Agreement and IPCC SR1.5° climate goals[9].

Figure 2. 13: United Nations. (2015). Sustainable Development Goals [Diagram]. https://sustainabledevelopment.un.org/?menu=1300

2.3.2 *Thermal Comfort*

***Thermal comfort** is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation.* (ASHRAE Standard 55, 2017). In other words, it is a state of **thermal neutrality** of a person for whom thermal accumulation is zero, and the organism leaves inactive the behavioural mechanisms of thermal adaptation.

What parameters influence thermal neutrality? The **human body** can be seen as a **thermodynamic system** that exchanges heat and work with the surrounding environment. **Six parameters** influence thermal comfort and are divided into **two categories: personal factors and environmental factors**.

Energy balance in the human body: $S = M - W - E_{sk} - R_{res} - C - R - C_k$

Where:

S [W] = variation of internal energy of the human body

M [W] = metabolic rate expressed in met units, 1 met = 58.2 W/m² (18.4 Btu/h·ft²)

W [W] = power exchanged from the body with the environment (activity/work done)

E_{sk} [W] = thermal power exchange from skin evaporation

R_{res} [W] = thermal power exchange from respiration

C [W] = thermal power exchange from convection

R [W] = thermal power exchange from radiation

C_k [W] = thermal power exchange from conduction

[8] United Nations. (2015). Transforming our world: The 2030 agenda for sustainable development, A/RES/70/1

[9] Intergovernmental Panel on Climate Change. (2018). Special Report on Global Warming of 1.5 °C.

2 Personal parameters of thermal comfort (related to the occupant):

- **Metabolic rate** is dependent on activity/work done. The average surface of the human body is **1,8 m^2.**
- **Clothing Insulation** as thermal resistance [m^{2}K/W] or in the inconsistent unit of measurement in clo (1clo = 0.155 m^2°K/W)
  Typically the clothing insulation is 0.5 clo (summer) and 1.0 clo (winter).

4 Environmental Parameters of thermal comfort (related to the microclimate):

- **Air Temperature** t_a [°C] ambient temperature near the occupant
- **Mean Radiant Temperature** t_{mr} [°C] amount of radiant heat transferred from a surface
- **Air Velocity** v_a [m/s]
- **Relative Humidity of Air** φ [-] or partial vapour pressure pv [Pa]

Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) is a widespread method for determining thermal comfort developed by Povl Ole Fanger that uses heat-balance equations and the parameters mentioned above to define comfort. ISO 7730:2005 provides the methodology for measuring thermal comfort using PMV and PPD. The parameters of human comfort are provided in the tables of the standard. An environment with high comfort can still result in some dissatisfied users up to 10% for the PPD.

-0.5 < PMV < +0.5 corresponds a PPD < 10%

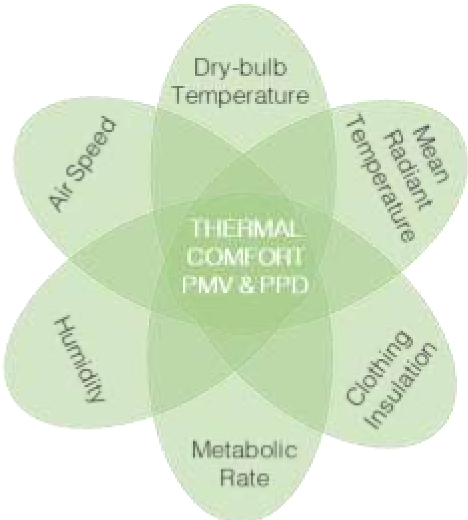


Figure 2. 14: Thermal Comfort Parameters based on PMV and PPD method.

The Center for the Built Environment of the University of California Berkeley has developed a simple online tool allowing to input the six comfort parameters to determine whether a combination complies with ASHRAE Standard 55-2017 or EN 16798-2019[10]. The CBE tool can calculate comfort, including input information of solar gains on occupants and local discomfort, which is also introduced in the ASHRAE Standard 55-2017.

[10] Tyler, H., Schiavon, S.,Tartarini, F., Cheung, T., Steinfeld, K., Piccioli, A., & Moon, D. (2019). CBE Thermal Comfort Tool. Center for the Built Environment, University of California Berkeley. https://comfort.cbe.berkeley.edu/

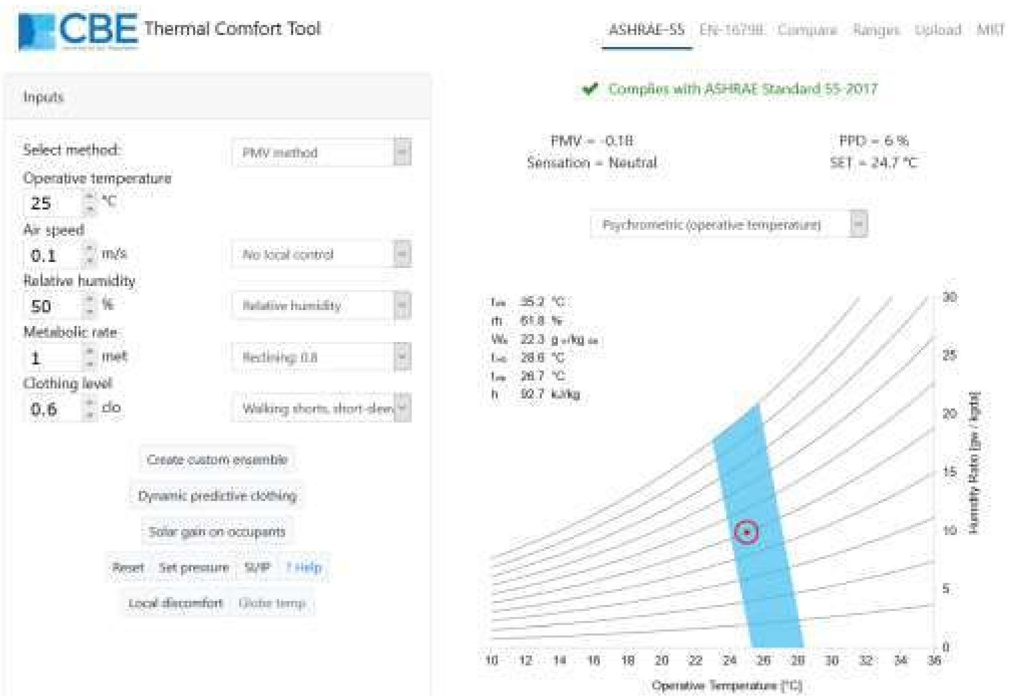


Figure 2. 15: CBE Thermal Comfort Tool PMV and PPD method.

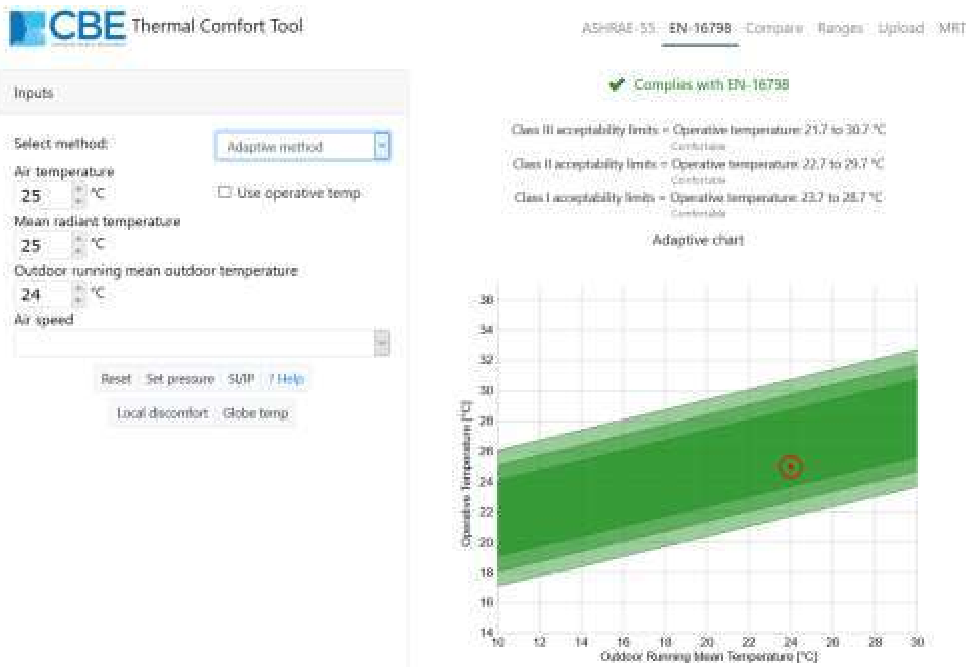


Figure 2. 16: CBE Thermal Comfort Tool Adaptive model.

The **Adaptive method** is implemented in the CBE tool. It is based on the influence of the outdoor Climate on indoor comfort. The main principle of Adaptive Comfort is that if a change occurs, such as to produce discomfort, people react in ways which tend to restore their comfort[11]. The Adaptive comfort principles can be applied in non-air-conditioned buildings with natural ventilation in ASHRAE 55 and EN 16798-1 when the

[11] Nicol, J. F., & Humphreys, M. (2002). Adaptive Thermal Comfort and Sustainable Thermal Standards for Buildings. Energy and Buildings. 34. 563-572. https://doi.org/10.1016/S0378-7788(02)00006-3

mechanical ventilation system is not used, and the occupants regulate thermal conditions through natural ventilation by opening windows. The Adaptive model takes into account physiological, psychological and behavioural factors. The operative temperature of perceived comfort thus depends on the mean outdoor temperature when within limits set of the model. Comfort can be achieved with temperatures higher than the conventional PMV method. Thermal comfort is the primary driver of energy consumption.

Table 2. 1: Adaptive Comfort Model influencing factors

Physiological	Psychological	Behavioural
- Acclimatization (short period of time for thermal adjustment), e.g. Vasoconstriction, vasodilation, sweating, shivering. - Genetic adaptation	- Expectations and Thermal Memory of previous experiences - Adaptive opportunity (sense of control, perceived type of environment)	- Changing clothing - Work or Activity done - Consuming food and beverages - Occupant control of windows, fans, shading devices

Definition of Adaptive Comfort from EN 16798-1: *Physiological, psychological or behavioural adjustment of building occupants to the interior thermal environment in order to avoid or to limit thermal discomfort*.

2.4 Regenerative Design

Regenerative Design is still an emerging field with few proponents and built examples. Regenerative Development constitutes an important step for the transformation and application of sustainability, requiring holistic thinking and whole-systems integrated approach in the design and management of human and natural systems. The widely recognized definition of sustainability is human-centric, passive, and relying on doing nothing now to allow future generations to meet their needs.

***Sustainable development** is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs*[12]. - Brundtland Report

The Anthropocentric view has been criticised early on, and attempts are being made to expand it and gradually shift towards an ecological perspective. Sustainable or green design practice is focused primarily on reducing impacts on natural systems and human health and increased efficiency in the use of resources and processes. Regenerative Design aims to go beyond the current slow degeneration of the planetary resources and ecosystems. The goal is to reverse the damages of earth’s systems, restoring them to a healthy state, and shaping built environments that give back more than they take from the place, supporting co-evolution of human and natural systems.

[12] Brundtland, G. H. et al. (1987). Our Common Future. World Commission on Environment and Development.

"The implication, and all too often the reality, has been that fully sustainable simply meant '100% less bad'."

- William McDonough, architect, and cradle-to-cradle thinker.[13]

The approaches to sustainable design and green architecture have not been sufficient in reversing the damages to ecosystems until now. The concept of sustainability stands on three pillars of social, financial and environmental dimensions. Usually, the design approach focuses more on the environmental side and misses the other parts. A whole-systems thinking approach is required to deal with built and natural systems. The construction and operation of buildings are responsible for nearly **40% of energy-related and CO_2 emissions globally**[14]. Therefore, energy performance remains a critical aspect to improve and reverse its damages.

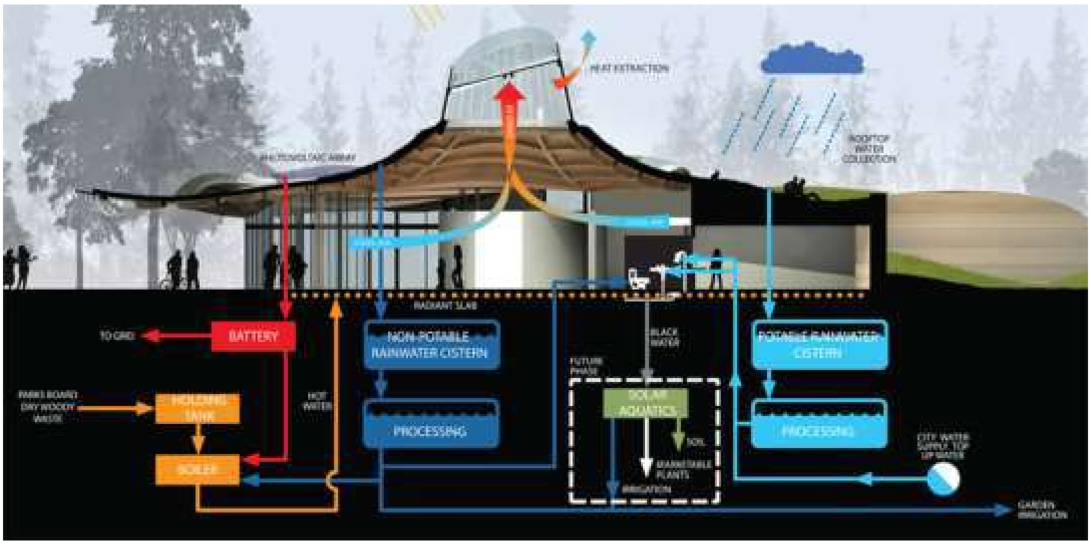


Figure 2. 17: Perkins+Will. (2011). Vancouver's VanDusen Botanical Garden Visitor Centre [Diagram]. https://inhabitat.com/vandusen-botanical-centre-to-be-canadas-first-living-building/

Figure 2.18: Vinnitskaya, I. (2012). VanDusen Botanical Garden Visitor Centre [Photograph]. Archdaily. https://www.archdaily.com/215855/vandusen-botanical-garden-visitor-centre-perkinswill

[13] Pawlyn, M. (2019, September 13). What is regenerative architecture. The RIBA Journal. https://www.ribaj.com/intelligence/climate-change-emergency-regenerative-design-michael-pawlyn

[14] International Energy Agency and the United Nations Environment Programme. (2018). 2018 Global Status Report: Towards a zero-emission, efficient and resilient buildings and construction sector.

Regenerative Design challenges "business as usual" towards holistic and new models of development. Regenerative thinking integrates the concepts of biomimicry, biophilia, nature-based solutions, and whole-systems-thinking to create environments where the role of humans is not merely to reduce environmental impacts, but to **participate in the restoration of ecosystems**, to allow for **natural and human-made systems to co-evolve**. This new way of thinking creates opportunities for architects and engineers that go beyond the current design practice, for developing products, projects and re-designing human activities.

Principles of Regenerative Design:

- Net carbon positive (buildings sequester carbon and produce renewable energy)
- Net positive energy (buildings produce more energy than they consume)
- Reverse causes of climate change and ecosystem degradation
- Human and natural systems evolve together
- Circularity thinking applied to all life cycle stages and resources (air, water, soil, waste, materials)

Figure 2. 19: Stefano Boeri Architetti. (n.d.). Vertical forest in Milan (left) [Photograph]; Tirana in 2018 (centre) [Render]; Liuzhou in 2016 (right) [Render]. https://www.stefanoboeriarchitetti.net

The first Vertical Forest was built in 2014 in Milan. It can be described as an example of **Green Architecture** and Regenerative Design. The high-rise's vegetation absorbs around 30 tons of CO_2 yearly[15]. The Vertical Forest has 900 trees, 5,000 shrubs and 11,000 perennial plants that mitigate pollution and produce oxygen. More than 20 species of birds are nesting. New designs of the concept are being built in Tirana in Albania, Liuzhou in China and other places.

Based on the Regenerative concept, new green building rating systems such as the **Living Building Challenge** haven been developed[16].

[15] Stefano Boeri Architetti. (2020). Vertical Foresting. https://www.stefanoboeriarchitetti.net/en/vertical-foresting
[16] International Living Future Institute. (2020). The Living Building Challenge. https://living-future.org

Basic principles of the Living Building Challenge:

- Buildings that connect occupants to light, air, food, nature, and community.
- Self-sufficient and remain within the resource limits of their site.
- Create a positive impact on human and natural systems.

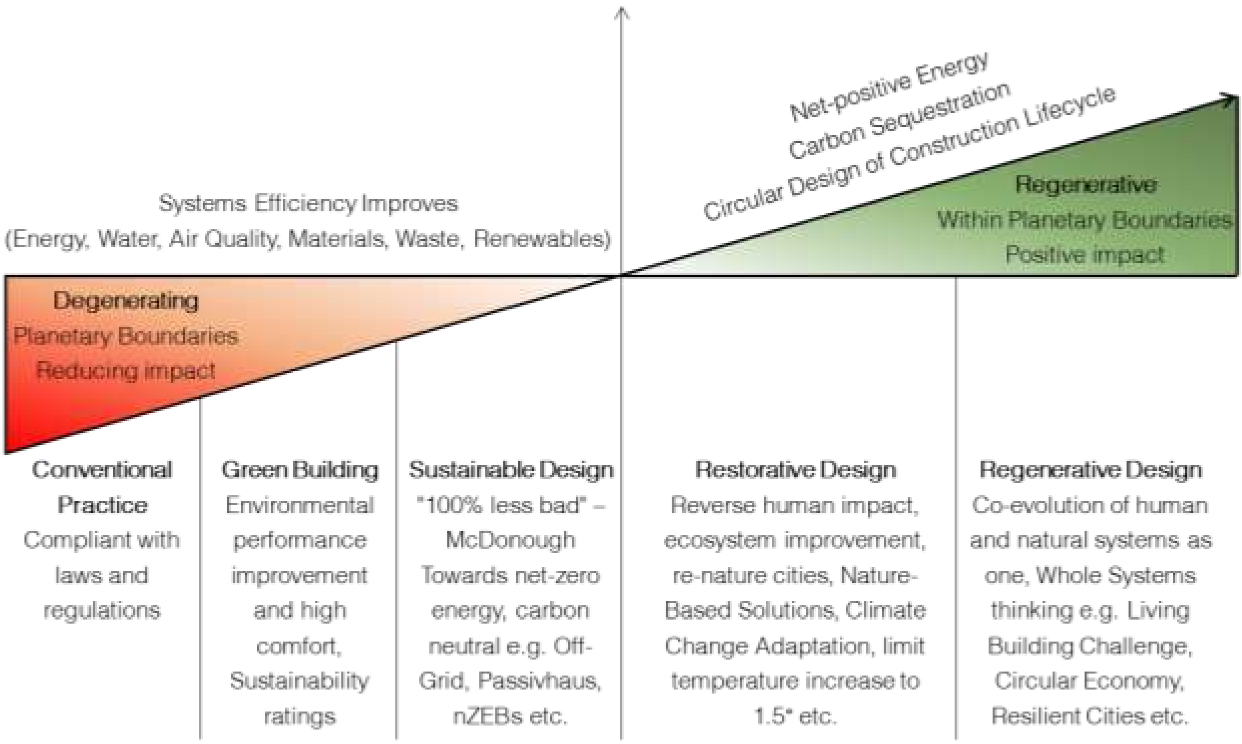


Figure 2. 20: Trajectory towards Regenerative Development and Design. (Adapted from Reed, 2007)

Reed is the first to propose a trajectory for environmentally responsible design[17]. Sustainable Design needs to shift from the conventional practice that focuses on improving systems efficiency and reducing the environmental impact of degenerating natural system that humans rely on as much as possible and aiming for neutrality. Restorative Design seeks to bring back social and natural systems to a healthy state while the regenerative principles strive to make developments where social and ecological systems can reach a healthy state and co-evolve over time.

Regenerative development – *"working to reverse the degeneration of ecosystems through harmonizing human activities with the continuing evolution of life on our planet."* - Regenesis Group

The Green Building concept needs to shift from minimizing impact and carbon footprint or zero-energy towards how we can make cities and buildings that have a positive contribution to the improvement of natural systems and biodiversity. The concept looks at the potentials that the project can draw from the context-specific conditions by looking at the whole picture and finding opportunities instead of solving problems separately.

[17] Reed, B. (2007). Shifting from 'sustainability' to regeneration. Building Research & Information, vol. 35, no. 6, pp. 674–680. https://doi.org/10.1080/09613210701475753

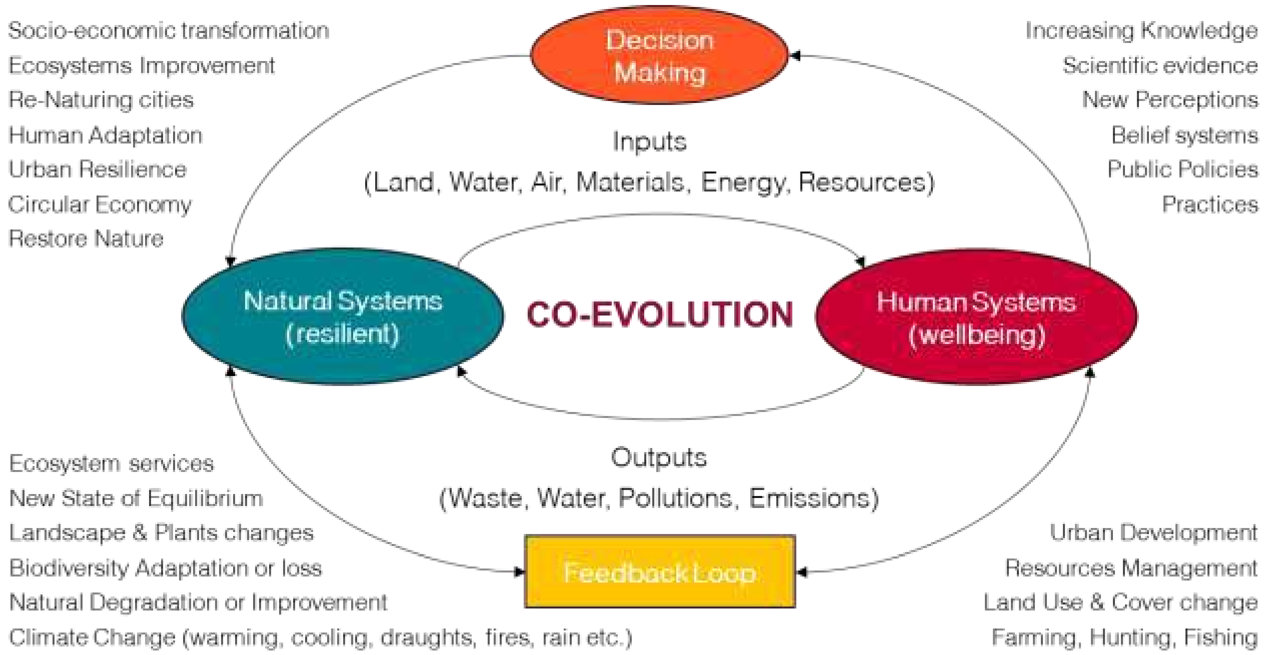


Figure 2. 21: Feedback loop in Regenerative Design.

Regenerative Design requires holistic thinking and converging approaches to **Design with Climate, Design with Nature, and to Design with People**. The foundations of such key concepts were laid a long time ago. Written more than 50 years ago, “Design” with Climate” by Olgyay is the first book that deals with Bioclimatic design and remains today an essential reference for sustainable design[18]. He demonstrates how design and climate management can be combined by drawing principles from physics, biology, engineering, and meteorology.

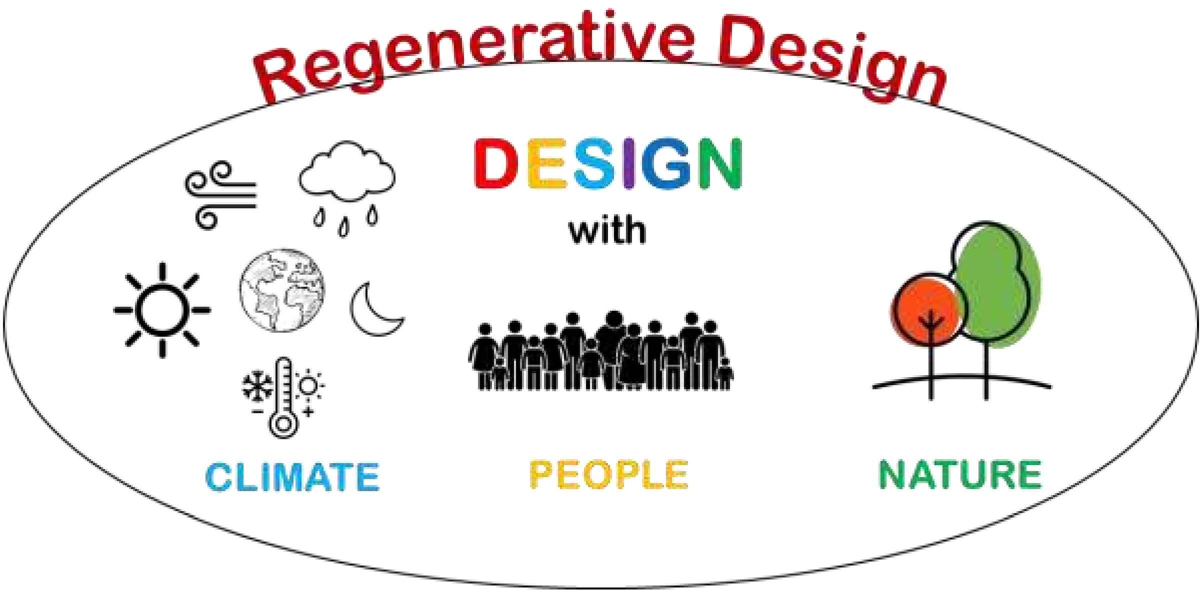


Figure 2. 22: Holistic Regenerative Design framework diagram based on Climate, People and Nature.

[18] Olgyay, V. (1963). Design with climate: Bioclimatic Approach to Architectural Regionalism. Princeton University Press.

"Design with Nature" is the title of the book of Landscape Architect Ian McHarg written in 1971[19]. He put forward many of the concepts of environmental conservation, ecological planning, thinking holistically and integrating all the processes of nature in the design. The methods he theorized, not only as academic understanding, have yet to come to fruition to its full potential in the contemporary design process.

In addition to the above, we need to "design with people" to achieve restorative and regenerative whole-systems. People need connection with nature in cities and buildings, for indoor and outdoor comfort, to be safe in case of earthquakes, floods, extreme weather events, and ultimately improve citizens well-being. To achieve co-evolution of the systems, we need to design better urban environments in light of Climate Change, with clean air and water.

Innovation is about doing, learning, and improving. We need to think of design, building and cities as **living**, **extend their life** as much as possible, and when decommissioned to give them a **second life**, or be seen as a **resource in circular and regenerative processes.**

2.5 Biomimicry

Biomimicry is a practice that learns and mimics the strategies found in nature to solve human design challenges. Biomimicry is about valuing nature for what we can learn, not what we can extract, harvest, or domesticate. In the process, we learn about ourselves, our purpose, and our connection to each other and our home on earth[20]. - Janine Benyus, The Biomimicry Institute

Biology and nature have inspired human art and architecture in the past as in the mosaics of Greek and Roman houses, classical column capitals, motifs of medieval art, Art Nouveau and many other examples. We can find natural and organic forms in the work of Antoni Gaudi's Sagrada Familia, where the upper-level inclined columns resemble tree branches and the inner roof geometry the leaves of a tree. Biomimicry has seen growing interest from architects and engineers in recent years. Learning from nature and imitating it, we can achieve higher efficiency in terms of resources and energy used for the built environment.

Figure 2. 23: Animalogic. (2019). Kingfisher [Video]. Youtube. https://www.youtube.com/watch?v=5dnouQtSIL0 (left); Nakatsu, E. (n.d.). The engineer of the Bullet

[19] McHarg, I. L. (1995). Design with Nature (25th anniversary edition). Wiley.
[20] Benyus, J. M. (1998). Biomimicry: Innovations inspired by nature. Harper Perennial Press.

train in Japan draws inspiration from the Kingfisher for the design of the next generation of trains [Photograph]. https://asknature.org/idea/shinkansen-train (right).

Figure 2. 24: Hislop, J. (2018). Wind turbines inspired by tubercles of Humpback Whales that reduce the water drag [Photograph]. https://energi.media/innovation/canadian-inventors-turbine-humpback-whales-increasing-wind-efficiency/

In the 20th century, architects and engineers learned and designed by copying natural forms, such as Pier Luigi Nervi with his Ferro-cement structures, Frei Otto tensile membranes in Munich Olympic Stadium (1972), Frank Lloyd Wright mushroom-shaped columns for Johnson Wax headquarters (1939), Heinz Isler and Felix Candela thin shells, and many others, creating impressive designs.

Natural systems work differently. The waste of one organism is food for another. Designers are exploring new ways to make products, use recyclable and biodegradable materials or upcycled materials for construction. Even though there have been numerous of cradle to cradle examples and circular design applied in the construction industry, they are only a small percentage of the whole picture, being more as manifestos of such approaches compared to the mainstream practice.

Nature has done for 3.8 billion years of Research and Development before humans**. Nature is the best designer, but it can offer more than just good design**. Biomimicry can be applied to design **form, processes or whole systems**. New patterns and relationships could be defined. Some principles of **closed-loop** applied to architectural design:

- Transform biodegradable waste with anaerobic digestion to natural gas for heating and electricity.
- Treat wastewater through plants and microorganisms and turn it into freshwater.
- Adapt buildings to the local Climate as animals and vegetation adapt.
- Capture rainwater and reuse in building services and landscape irrigation.
- Achieve thermal comfort by passive strategies of relying on natural flows of solar energy, wind, the thermal mass of constructions.
- Ventilation system inspired by nature, e.g. airflow of termite mounds.
- Interconnected natural systems inspiration, e.g. The Edge in Amsterdam connects Smart Buildings systems with the occupants for automated entrance in the parking, having no fixed workspace (less than half of the

desks compared to a regular building), dimmable LED light panels connected with ethernet cables to data and occupants.

- Carbon sequestration by employing wood as a construction material and vegetation in indoor and outdoor spaces.

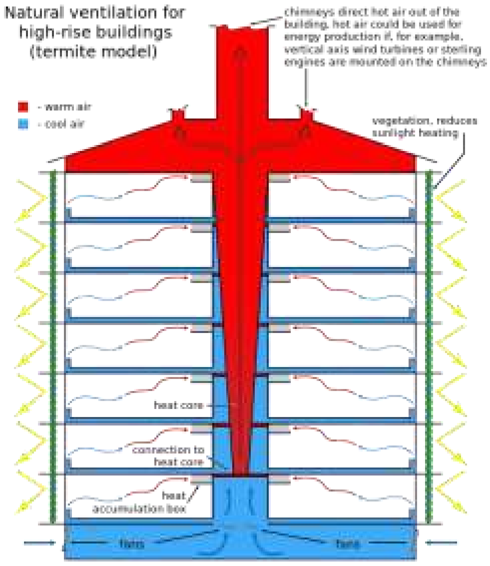


Figure 2. 25: Pearce, M. (1996). Eastgate Centre in Harare, Zimbabwe [Diagram, Photograph]. Wikipedia. https://en.wikipedia.org/wiki/Eastgate_Centre,_Harare

The architect of the Eastgate Centre draws inspiration from local termite mounds. Termites farm fungus inside the mound, where air passes through freely as temperatures change during the day. Materials with high thermal mass like concrete and bricks are employed. Low power fans to bring the air in the building and chimneys work together to keep the building cool during the day.

2.6 High Energy Performance concepts and methods

The Passive House concept and nearly Zero Energy Buildings are two of the most well-known concepts and solutions in the European context towards making highly energy-efficient buildings, provide for human comfort and minimized energy and related CO_2 emissions.

2.6.1 *The Passive House*

The Passive House is one of the major leading standards in energy-efficient construction. The concept was first introduced by Wolfang Feist (founder of Passivhaus-Institut Darmstadt in Germany) and Bo Adamson in 1988.

The first project to apply the passive house concept is the Kranichstein Passive House in Darmstadt in 1991. The multi-family residential building achieved a documented heating energy consumption of below 10 kWh/m²/annually. The simplicity of the principles and maximum energy consumption target make the standard applicable to all building types and different geographical regions.

Definition: *A Passive House is a building, for which* ***thermal comfort*** *(ISO 7730) can be achieved solely* ***by post-heating*** *or* ***post-cooling*** *of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air*[21].

Passive Houses are buildings that require minima**l energy demand** even in the Cold Climates like Central Europe. This is achieved by a series of design and construction strategies that are well codified in German literature, such as **superinsulation**, **orientation**, **distribution, low ratio of building shape S/V** (surface to volume), use of **passive systems**. Such houses can be kept warm "passively", solely by utilizing free heat gains of passive solar systems (windows, Trombe wall, greenhouse) and existing internal heat sources (cooking, equipment, human activity), as well as by the minimal heating of incoming fresh air.

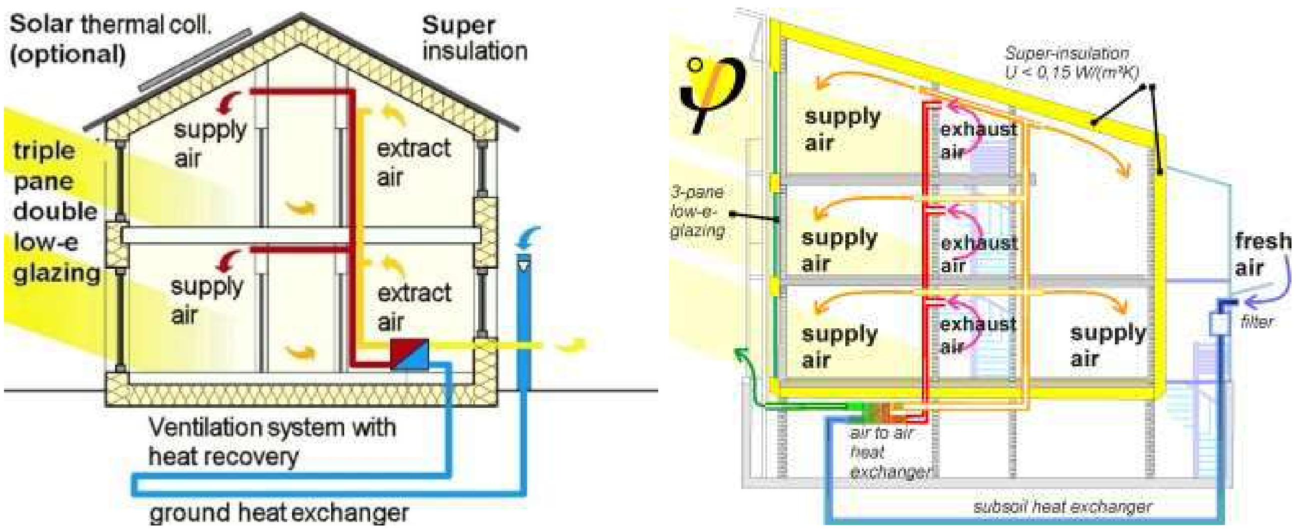


Figure 2. 26: Section of Passivhaus concept; section of the first Passivhaus in Darmstadt. Source: Passive House Institute.

The Passivhaus is **different from "solar house"** because of the emphasis given to the **reduction of the thermal load** rather than to **solar gains**.

[21] Passive House Institute. (2015). https://passivehouse.com/

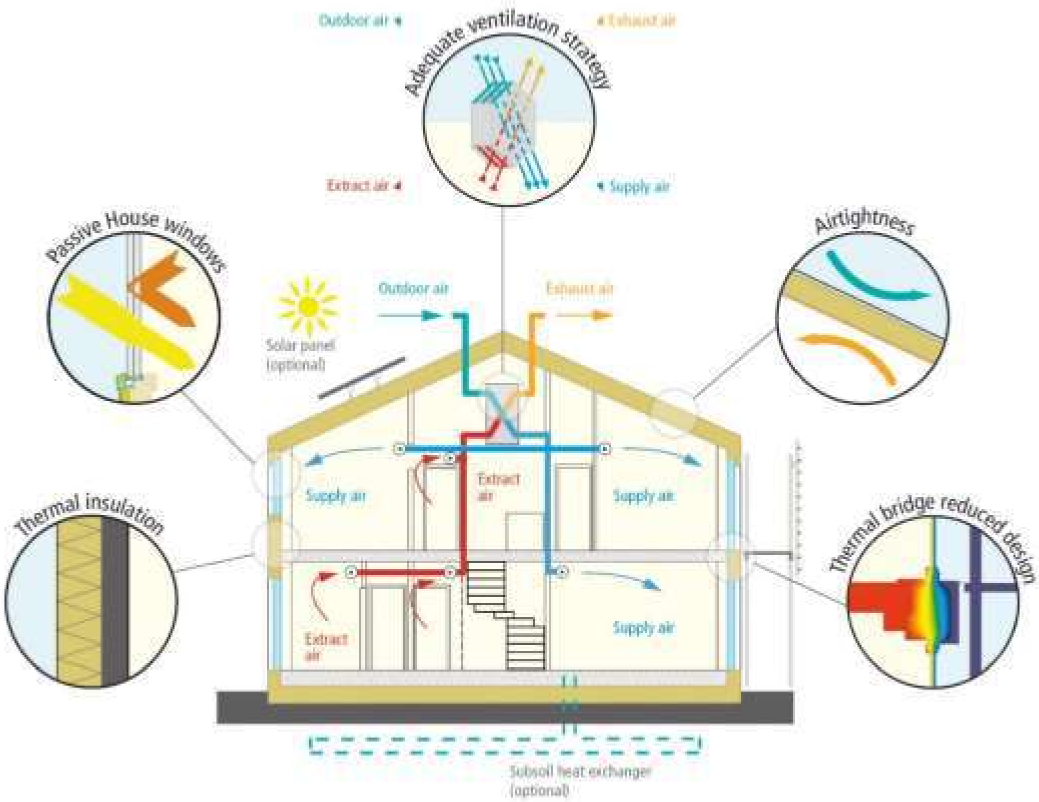


Figure 2. 27: Section with the five basic principles of Passivhaus. Source: Passive House Institute

Passivhaus Standard requirements:

- Requires less than **15 kWh/(m²yr)** for heating or cooling
- The heating/cooling load is limited to a maximum of **10 W/m2**
- Airtightness, a maximum **of 0.6 air changes per hour at 50 Pascals** pressure (ACH50), as verified with an onsite pressure test (in both pressurized and depressurized states)

Passivhaus Standard principles:

Criteria related to building design

- The shape of the building performance verified with the Form Factor (FF=S/V), is the ratio between the **dispersant surfaces and heated volume**.
- Building **Orientation**, priority is given to the south, also for transparent surfaces.
- **Window dimensions** are to maximize solar gains concerning losses.
- **Distribution** of heated spaces east-west or south and service spaces north.
- **Buffer zones** (not regularly occupied, not air controlled spaces with a temperature between interior and exterior). The function is to protect thermally and acoustically the interior.

Criteria related to the building envelope

- **Superinsulation** of walls and roof
- **Triple glass** low emission windows and high-performance frame.
- **Thermal bridge reduced designs** (by form or by the reduced U-value)
- **Airtightness** has to be guaranteed

Criteria related to building systems design

- **Controlled mechanical ventilation**
- Geothermal **heat exchanger** to pre-heat (in winter), pre-cool (in summer) the air
- **Heat Recovery Unit** (reduce further heat losses of air ventilation)
- **Heat Pump**
- **Sun shading devices**

The building compactness reduces heat loss from the transmission. Low S/V ratio is preferred. A balance between the form factor, south orientation and distribution has to be determined case by case.
Another useful criterion is the Het Loss Form Factor (HLFF). It is different from the Form Factor as it describes the relationship between **external dispersant surfaces (S)** and the **internal Treated Floor Area (TFA)** or the **Net Floor Area**. An **HLFF < 3** is a good benchmark for small Passivhaus buildings. Compact and multi-storey buildings like skyscrapers can achieve lower FF and HLFF numbers. An improved Form Factor can result in **a lower energy load, reduce the insulation thickness,** and represent a lower **carbon footprint and saving costs**.

Form Factor (FF) =Surface (S)/Volume(V) m^{-1} **$0{,}2\ m^{-1} < FF < 1\ m^{-1}$**

Heat Loss FF (HLFF) = Surface (S)/Treated Floor Area (TFA) **$0.5 < HLFF < 5$**

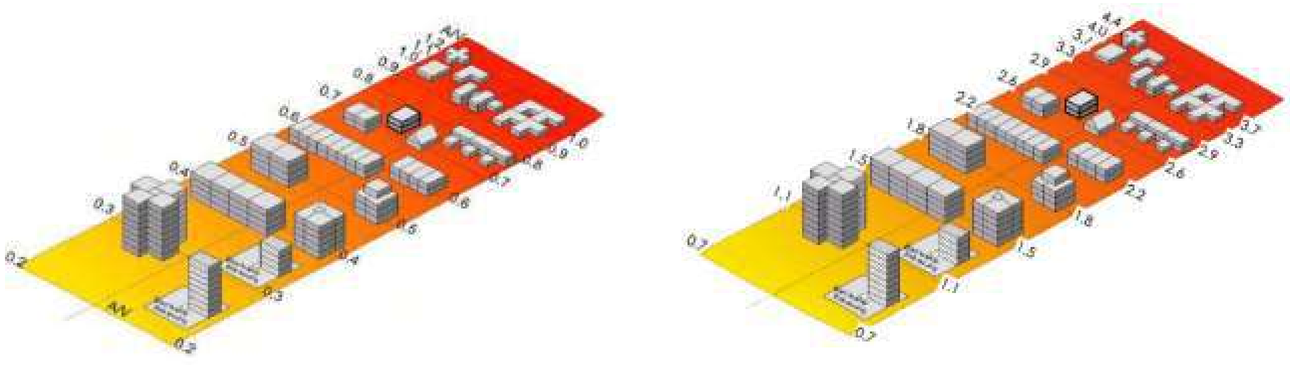


Figure 2. 28: Form Factor and Heat Loss Form Factor of different building typologies. Source: Passive House Institute.

Figure 2. 29: Relation of Form Factors to building performance and costs.

2.6.2 *Nearly Zero Energy Buildings*

Nearly Zero Energy Buildings (nZEBs) are buildings with very ***high energy performance***[22]**.** The low energy demand of ZEBs is such that it can be satisfied by energy production on-site from Renewable Sources. The objective is to design and operate buildings where the total amount of energy needed on an annual basis is nearly zero. The algebraic sum of renewable energy produced from sources on-site, nearby or far and non-renewable energy supply when required is almost zero (net-zero energy).

In the 1960s-1970s, the first houses producing their energy, unconnected from the electrical grid (Off Grid Homes), were built in the US. Later, it was better to make use of the connection to the electrical network as the production from renewables needs storage and is not available at night when there is demand for electricity. Incentives related to renewable energy integration and net metering (trading of electric energy with the grid) support this transition of the built environment.

The Energy Performance of Buildings Directive of the European Union (EPBD, Directive 2010/31/EU) defines the nearly zero, or very low amount of energy required should be covered to a very significant extent from renewable sources, including energy from renewable sources produced on-site or nearby. The EPBD requires all new buildings from 2021 (public buildings from 2019) to be nearly zero-energy buildings (nZEB).

nZEB principles:

- Reduce as much as possible energy demand, to make it possible to cover the remaining demand from renewable sources integrated into the building envelope or nearby sources.
- Passive solar design and thermal mass
- Highly insulated envelope
- Photovoltaic and solar thermal integrated systems
- Connected Photovoltaic system to the grid in net metering
- Heat recovery from refrigerators, freezers, showers
- Guaranteed indoor occupant comfort

In comparison to the Passivhaus standard, NZEBs are characterized by a **broader design choice**, especially in technological solutions and building systems.

[22] Nearly Zero Energy Buildings. (2020, March 12). Retrieved April 15, 2020, from https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/nearly-zero-energy-buildings_en

2.7 Climate Change

The Earth experiences natural fluctuations of the Climate. The average temperature of the Earth is around 15°C. In the past, it has been much higher or lower. The current rising temperatures are higher to what the Earth has experienced before. This higher temperature increase is attributed to carbon emissions in the atmosphere from human activities and classified by some researchers as the Anthropocene.

Researchers of three Swedish Universities interpret the Rök runestone as a warning of ancient Vikings of climate crisis ahead, and that the "Sun would disappear again". We know today that they experienced some extreme weather events in the 530s due to volcanic eruptions that lowered temperatures and "killed the Summer" for three years, ruined the crops, and decimated their populations[23]. They were concerned that this would happen again. They were not only warriors and raiders, but people fearing a climate catastrophe that they could not avoid in the future.

Figure 2. 30: [Rök runestone in Ödeshög Municipality, Östergötland, Sweden at the. Circa 800 a.d.]. (n.d.). Ancient Origins. https://www.ancient-origins.net/news-history-archaeology/new-interpretation-rok-runestone-inscription-changes-view-viking-age-005813

Today it is what we describe as Climate Change or Extreme Weather Events affecting the Climate for a particular time, reverberating effects in the economy, and putting at risk vulnerable communities.

Research communities and intergovernmental organizations are working on raising awareness, providing solutions and policies to prevent the irreversible damages that are being caused to our planet by global warming from human activity. There are two **approaches to Climate Change: mitigation and adaptation**.

[23] Savage, M., & Derrier, B. (2020, March 10). The ancient Viking runestone revealing a modern fear. BBC Reel. https://www.bbc.com/reel/video/p08676tt/the-ancient-viking-runestone-revealing-a-modern-fear

The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the scientific evidence for Climate Change and providing policy-makers of member countries with options to mitigation and adaptation.

In 2015, the Paris Agreement of the UN Convention on Climate Change brought together all nations into the common purpose to make ambitious efforts to tackle climate change and adapt to its effects.

"*The **Paris Agreement** central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise in this century **below 2 degrees Celsius above pre-industrial levels** and to pursue efforts to limit the temperature increase **even further to 1.5 degrees Celsius***"[24].

Definition: ***Adaptation** means **anticipating the adverse effects of climate change** and taking appropriate **action to prevent or minimise** the damage they can cause, or taking advantage of opportunities that may arise. It has been shown that well planned, and early adaptation action saves money and lives later*[25].

Growing levels of urbanization in the following decades are predicted. Human health risks are higher in cities due to pollution, loss of natural land and degradation of ecosystems. A response in the European context to Adaptation are Nature-Based Solutions, which draws some similarities with Regenerative Development principles.

The EU Research and Innovation policy agenda defines **nature-based solutions to societal challenges:** "*as solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions."*

Architecture and Engineering can play a role in Climate Change mitigation and adaptation through combined strategies of Nature-Based Solutions, Regenerative Design, Green Infrastructure, Sustainable Urban Development by addressing energy, transportation, resources, water, waste, land use, biodiversity and ecosystem improvement.

[24] United Nations. (2015). Adoption of the Paris Agreement. Conference of the Parties on Its Twenty-First Session. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement
[25] Adaptation to Climate Change. (n.d.). Retrieved May 5, 2020, from https://ec.europa.eu/clima/policies/adaptation_en

Figure 2. 31: European Commission. (n.d.). Urban Challenges [Infographic].
https://ec.europa.eu/research/environment/index.cfm?pg=nbs

Figure 2. 32: European Commission. (n.d.). Nature Based Solutions [Infographic].[26]

[26] Nature-Based Solutions. (n.d.). Retrieved March 25, 2020, from
https://ec.europa.eu/research/environment/index.cfm?pg=nbs

2.8 Circular Economy

During the Industrial Revolution, people switched from manual and animal labour to tools ad machines powered initially by steam to do work. Since then, advancements and capitalist societies made possible mass production of goods. Abundance and raise in the quality of life allowed the population to grow and communities to flourish. This is the success of the industrial revolution. GDP growth, poverty reduction, access to fresh water, better healthcare, products and services are available to many due to the increased use of natural resources. Natural capital is transformed into other forms and capital. Humanity relied more on the intense exploitation of natural resources. Linear economy and consuming without limits create pollution and waste. In turn, it impacts nature, biodiversity and our quality of life in a closed-loop, e.g. the air, the water, and ecosystems. A new way to design, make, and use things is needed.

A circular economy is based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems[27]. - Ellen MacArthur Foundation

The concept of Circular Economy was developed in parallel to Regenerative Design. One of the first definitions of Regenerative Design comes from Lyle: *"A regenerative system provides for continuous replacement, through its own functional processes, of the energy and materials used in its operation"*[28]. We can see from their definitions, how similar and interdependent are the two concepts in real-world and for design thinking.

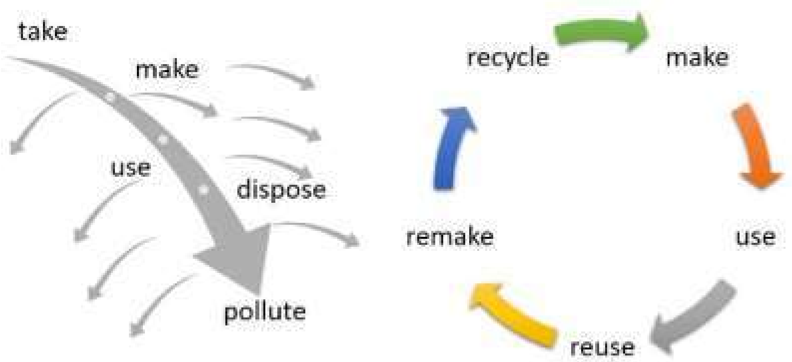


Figure 2. 33: Weetman, C. (2016). Linear versus circular economy model [Diagram]. Wikipedia. https://en.wikipedia.org/wiki/Circular_economy#/media/File:Linear_versus_circular.jpg

The economy that we know pursues the goal of GDP growth. Interestingly, this has pushed societies in broader income inequalities and into social and ecological crisis. The goal is changing towards meeting the needs of all, within the means of the planet[29]. "Doughnut Economics", is the title of the book by Kate Raworth proposing

[27] What is the Circular Economy. (n.d.). Ellen MacArthur Foundation. Retrieved April 20, 2020, from https://www.ellenmacarthurfoundation.org/circular-economy/what-is-the-circular-economy
[28] Lyle, J. T. (1996). Regenerative Design for Sustainable Development. New York: John Wiley & Sons.
[29] Raworth, K. (2017). Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist. Penguin Random House.

a new economy to replace the goal of **"endless growth"**, **"laissez-faire"** with a new economic story for the 21st century.

There is a need to change from the human-centred economic model, not being dominant over nature but profoundly dependent upon nature. From humans controlling the economy, we need to think as gardeners of the planet's economy. It can be viewed as a design problem, from divisive to a distributive design of the economy for the people. Economy models have used the planet's resources to create wealth, by depleting and degrading its resources. Thus it can be called "degenerative design of the economy". A "regenerative by design" model pursues to restore nature, put in place renewable energy and turn waste of the process to a resource in new operations. It is by working with, not against the cycles of nature, not relying only on GDP, but on managing the resources wisely, from the state economy to a global economy, with attention to the needs of people within the planetary boundaries that a circular economy operates.

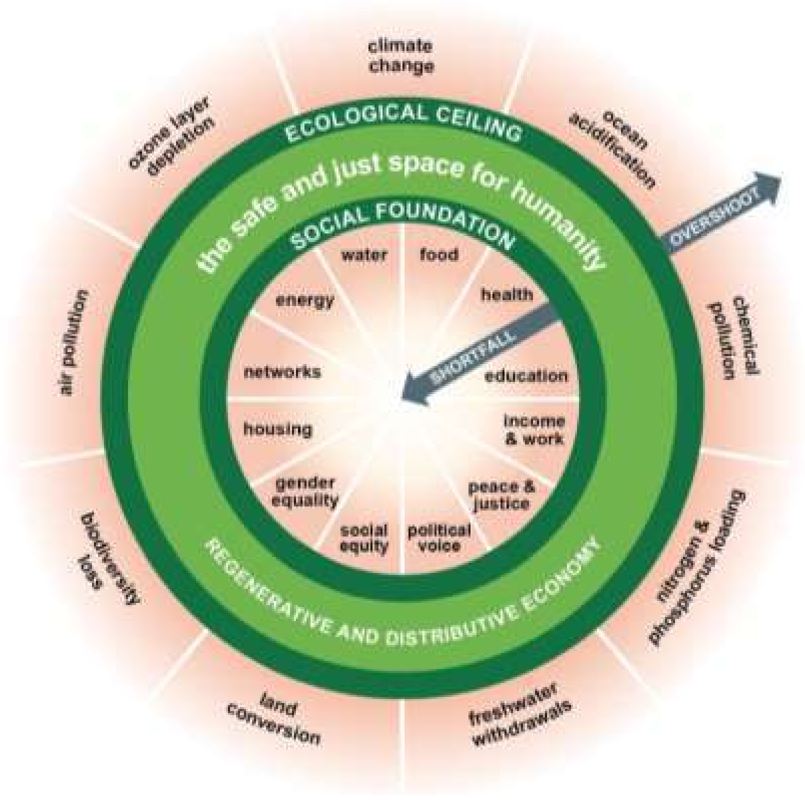


Figure 2. 34: Raworth, K. (2017). Doughnut Economics: Measuring performance based on meeting people's basic needs within planetary boundaries [Diagram]. Wikipedia. https://en.wikipedia.org/wiki/Doughnut_(economic_model)

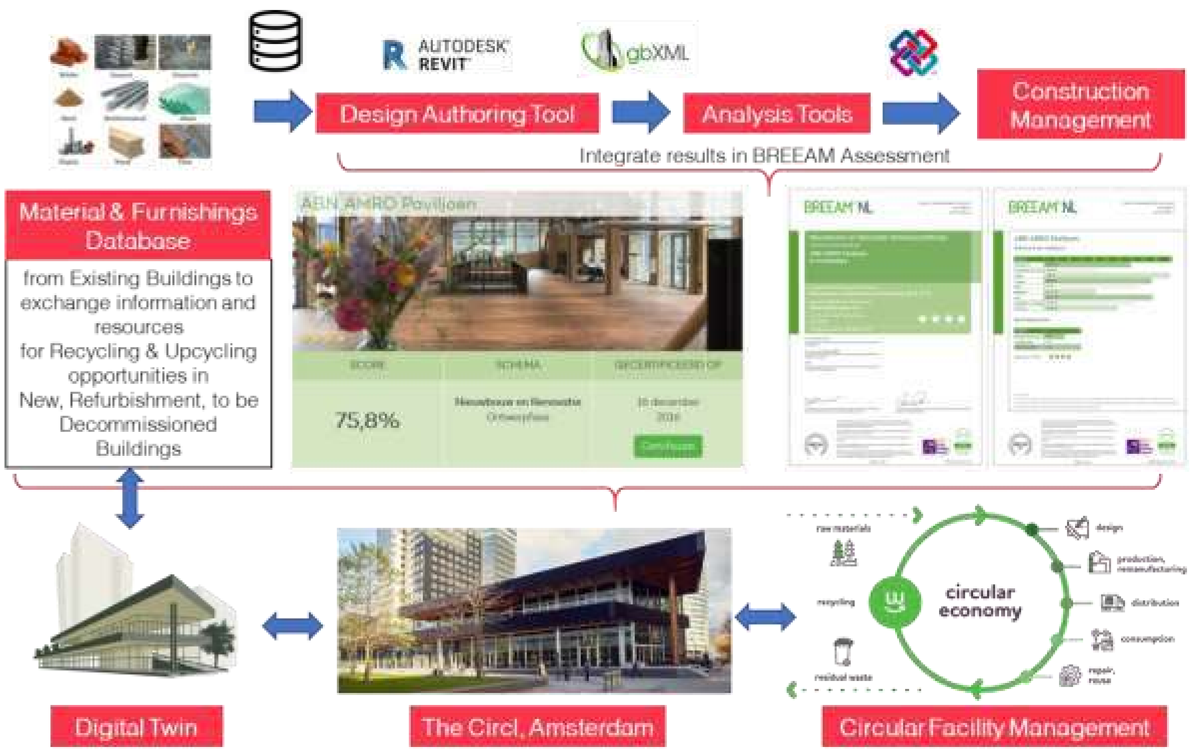


Figure 2. 35: Example of Circular Economy applied at The Circl Pavilion, Amsterdam.

The Circl in Amsterdam is designed with the most sustainable strategies for daylighting, energy efficiency, outside views for all spaces, and use of wood as a construction material to sequester carbon[30]. Innovative models or reuse, recycling, design for disassembly are used for building elements such as windows, furniture, insulation, and carpets that are reused or upcycled from buildings that were decommissioned. The concept of **Urban Mining** is applied. A **material bank**, the first database of its kind, to exchange materials and furniture between buildings to be demolished, built or refurbished has been created for this purpose. The project is BREEAM certified[31]. The **Database model** applied for the Circl will grow with new projects. Building materials will have an extended life (reuse, repair), or recycled to be introduced back in the construction loop. The BIM Model for Facility Management can be used to extract information from **component tags** about the need for maintenance, repair or exchange within the platform. In decommissioned buildings, a 3D scanning survey can be used to create a BIM Model. Selective deconstruction can be planned, integrating the Model with information gathered from the pre-deconstruction audit conducted on-site. The deconstruction project is enriched with data and options. The recovery of materials for construction processes **designs out waste** and **reduces the extraction of raw materials** for construction purposes. The reused materials may require repair, cleaning and assessment of quality for reuse in the market. In addition to this, the **economic** (cost of reuse compared to new materials), **technical** (compliance with standards) and **environmental** (safety and pollutant emissions) aspects need to be taken into consideration by the architects when evaluating alternatives.

[30] Circl: practical circular philosophy. (n.d.) Retrieved March 29, 2020, from https://cie.nl/projects/circl?lang=en
[31] ABN AMRO Paviljoen. (2016, December 16). BREEAM Netherlands. Retrieved May 10, 2020, from https://www.breeam.nl/projecten/abn-amro-paviljoen-0

2.9 Climate, People, Nature correlation in times of crisis

As the planet is facing a never seen before global pandemic of COVID-19, concentrations of nitrogen dioxide (NO2) have decreased in many European cities, which is a pollutant coming mainly from road transport. When it comes to particulate matter PM2.5 and PM10, the story is different. A smaller decrease has been monitored and is expected because of more varied sources, ranging from the remaining road traffic, combustion of fuel for heating of buildings, and industrial activities. Particulate matter can be formed as a result of Agricultural activities when employing fertilizer which in turn releases ammonia and pollutants that react in the air[32].

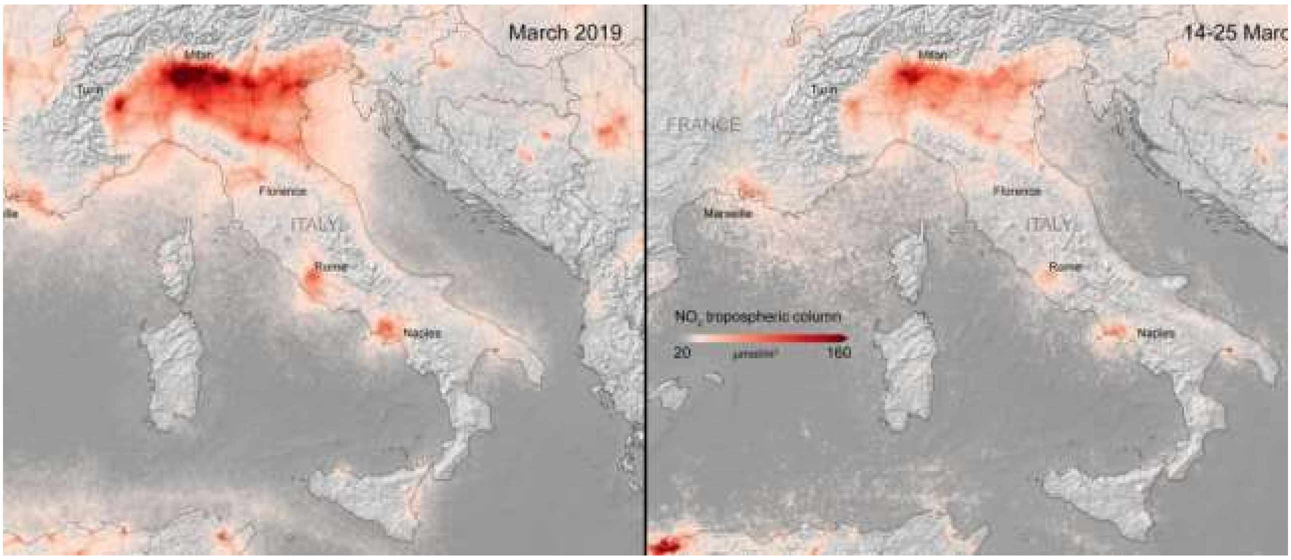


Figure 2. 36: Average nitrogen dioxide concentrations dropped after the Italian government placed the country under lockdown. Source: European Space Agency.

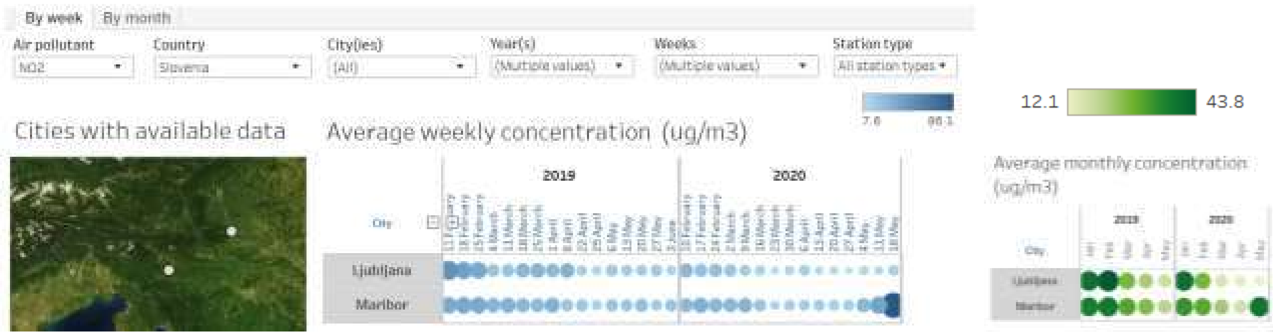


Figure 2. 37: The air quality measurement of NO_2 for Ljubljana and Maribor.

32 Air quality and COVID-19. (2020, April 4). European Environment Agency. Retrieved April 16, 2020, from https://www.eea.europa.eu/themes/air/air-quality-and-covid19/air-quality-and-covid19

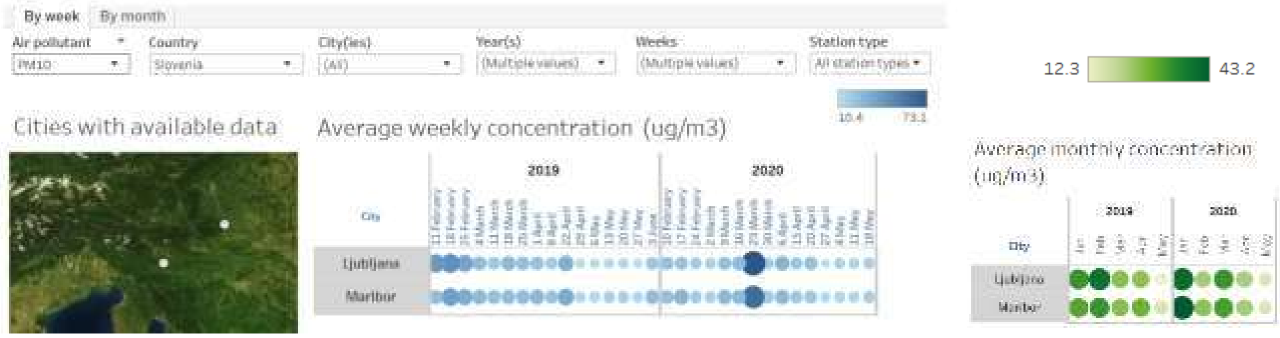


Figure 2. 38: The air quality measurement of PM10 for Ljubljana and Maribor.

For the year 2019 in Slovenia, there is a decrease in NO_2 and PM10 Jan-Apr period, given the reduction of building heat demand from Winter to Spring. For the year 2020, pollutant levels are slightly lower compared to the previous year due to lockdowns.

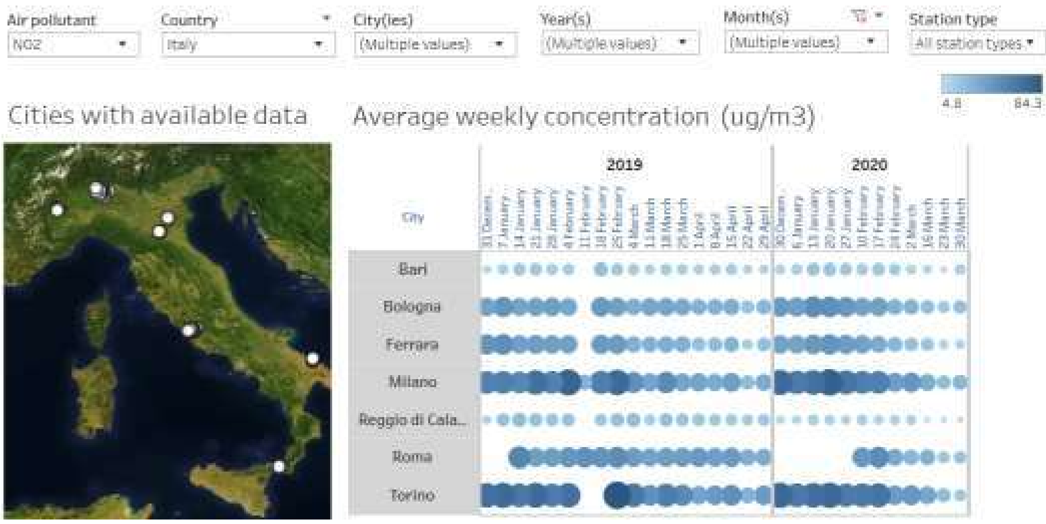


Figure 2. 39: The air quality measurement of NO_2 for some Italian cities.

Figure 2. 40: The air quality measurement of PM2.5 for some Italian cities.

In Italy, almost constant levels are observed throughout the year in Reggio di Calabria and Bari where energy demands are lower due to climate. Turin and Milan, due to their location in the Pianura Padana, pollution from industry and transportation have higher levels of NO_2, PM2.5 and PM10. The imposed lockdown shows a noticeable reduction for $N0_2$ emissions and a slight reduction of PM2.5 and PM10 levels in 2020 compared to 2019.

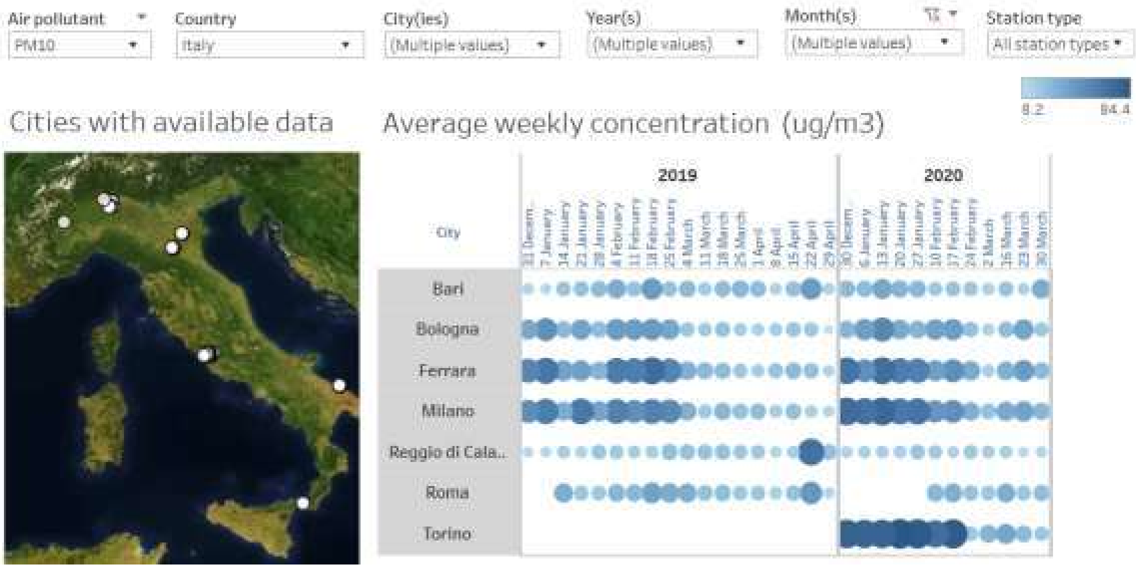


Figure 2. 41: The air quality measurement of PM10 for some Italian cities.

Reports from Italy correlate the high death rates of COVID-19 in the north of the country with higher levels of air pollution. These areas are at higher health risk[33]. The study of researchers at the Harvard School of Public Health finds that most pre-existing conditions that increase the risk of death for COVID-19 are the same diseases that are affected by long-term exposure to air pollution. An increase of only 1 $\mu g/m^3$ in PM2.5 is associated with a 15% increase in the COVID-19 death rate[34].

Urban environments and buildings can be thought of as "living organisms" exchanging at all time with the climate flows of energy, air, water, pollutants, and waste. The longer hours spent for social distancing can improve our understanding of the importance of the sun, air, water and landscape for human health and well-being. The connection of the built environment on human health and nature can be seen clearly in this time-period where the impacts of buildings are isolated from other activities and are evidenced by data. The need to reverse negative impacts is more significant than ever.

"We shape our buildings; thereafter they shape us". - Winston Churchill

[33] Carrington, D. (2020, April 7). Air pollution linked to far higher Covid-19 death rates, study finds. The Guardian. Retrieved April 20, 2020, from https://www.theguardian.com/environment/2020/apr/07/air-pollution-linked-to-far-higher-covid-19-death-rates-study-finds

[34] Xiao W., & Nethery, R. (2020, April 24). COVID-19 PM2.5. Retrieved April 28, 2020, from https://projects.iq.harvard.edu/covid-pm

3 A PARADIGM SHIFT FROM CAD TO BIM FOR DESIGN METHODS

Humans have created tools to help them in tasks throughout history, e.g. hunting, farming, and protection. The industrialization period brought an increasing set of new tools. Human and animal labour began to be substituted by machine labour, e.g. in agriculture, construction, and production of goods. Humans operated machines that used the power of steam and coal.

Society's ability to transform and reinvent itself sometimes can be found envisioned in the work of artists and writers. Jean-Marc Côté, a French artist, produced some 87 image series in 1899 depicting the distant future in the year 2000. En L'An 2000 was a series of prints for cigar boxes and postcards for the 1900 World Exhibition in Paris.

Figure 3. 1: Jean-Marc Côté. (1899). En L'An 2000. An architect building his design with controlled machines (left)[Postcard];Flying public and private operated transportation machines (right)[Postcard]. Wikipedia. https://commons.wikimedia.org/wiki/Category:France_in_XXI_Century_(fiction)

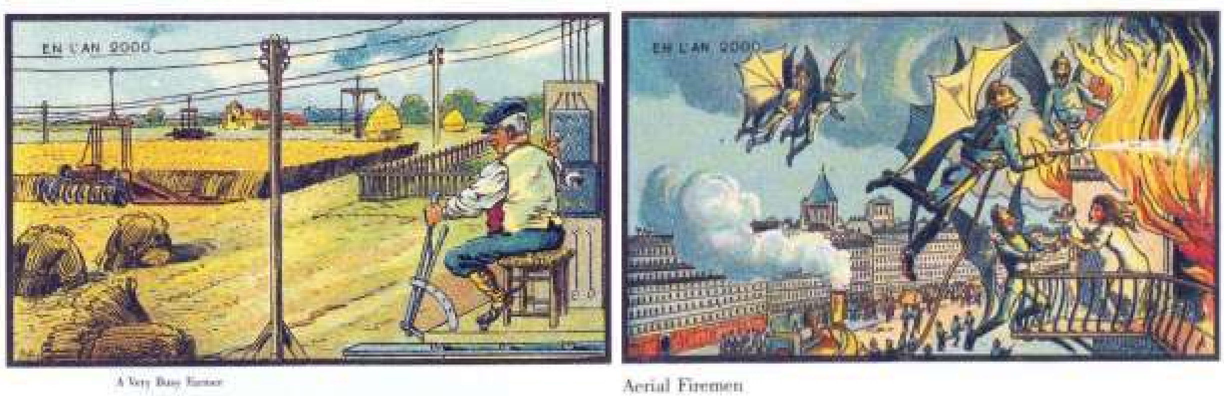


Figure 3. 2: Jean-Marc Côté. (1899). En L'An 2000. Automation in Agriculture (left)[Postcard]; Aerial Firemen (right) [Postcard]. Wikipedia. https://commons.wikimedia.org/wiki/Category:France_in_XXI_Century_(fiction)

Even though these predictions are far from today's innovations, some of them are getting closer to reality. Some ideas are present but different from what was imagined more than a century ago. One thing remains in common. Technology is changing the way we work. Computers and machines are part of the work process, assisting people in most of their activities as it has been predicted in the past.

Figure 3.3: Gäbler, M. (2013). Harvesting wheat with a combine harvester accompanied by a tractor and trailer [Photograph]. Wikipedia. https://en.wikipedia.org/wiki/Agriculture

Figure 3.4: Marin, I. (2019). Franky Zapata on his flyboard at Bastille day in Paris [Photograph]. France 24. https://www.france24.com/en/20190714-french-inventor-soars-above-champs-elysees-flyboard-paris-parade

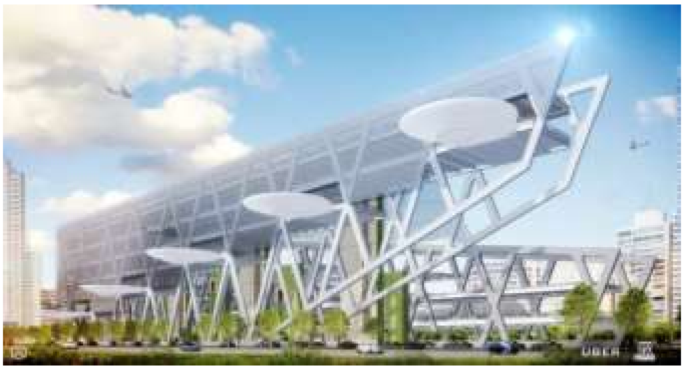


Figure 3.5: Boka Powell. (2019). Uber Skyport Concept [Render]. Archdaily. https://www.archdaily.com/894249/could-these-uber-flying-taxi-skyports-be-coming-to-a-city-near-you

Figure 3.6: ICD/ITKE. (2015). Research Pavilion 2014-2015 [Photograph]. https://www.icd.uni-stuttgart.de/projects/icditke-research-pavilion-2014-15/

Machinery has substituted human and animal labour in agriculture. Franky Zapata, the inventor of the Flyboard, gives a demonstration of his new Flyboard Air during the celebrations of the French National Day in 2019. Uber is working with international architecture offices to create and build the first Skyports in the world and bring affordable shared flights within 2023. ICD/ITKE Pavilion is constructed with the help of Digital Tools and controlled robots.

3.1 Digital Design from CAD to BIM

CAD (Computer-Aided Design) has been around for more than 50 years now. Architects and Engineers have made use of these tools to design and collaborate in projects and products with increased complexity.

When working with CAD, we continue to draw lines, just like we did with paper. The meaning associated with those lines is given from the "old language of communication" of architects that is the **drawing**. However, we are still drawing lines that have information attached to it, providing meaning only for us and not for the computers. In this workflow, we are confronted with issues such as **fragmentation of information**, repetitive task of entering data, interpretation of drawings, errors, loss in productivity and time. This process is being gradually substituted with Building Information Modelling tools for projects and expanding BIM libraries.

Figure 3.7: Bernstein, P. (2015). Diagram of CAD vs BIM from "The Future of Making Buildings" [Video]. TEDxYale. https://www.youtube.com/watch?v=Kg0gbG1DAkk

In the chart of CAD vs BIM, the red colour represents the knowledge flow of information in a traditional CAD process. The smooth blue curve can be made possible from a BIM approach that retains, reuses and values information for the whole project life cycle.

Computer-Aided Design has not ben able to evolve and achieve what the name itself promised in its meaning. Autodesk, one of the biggest software companies for the AEC industry and owner of one of the most commonly used software for technical design AutoCAD, describes CAD as an acronym that stands in reality only for computer-aided documentation[35].

[35] Kowalski, J. (2016, January 5). CAD Is a Lie: Generative Design to the Rescue. Redshift by Autodesk. Retrieved May 12, 2020, from https://www.autodesk.com/redshift/generative-design

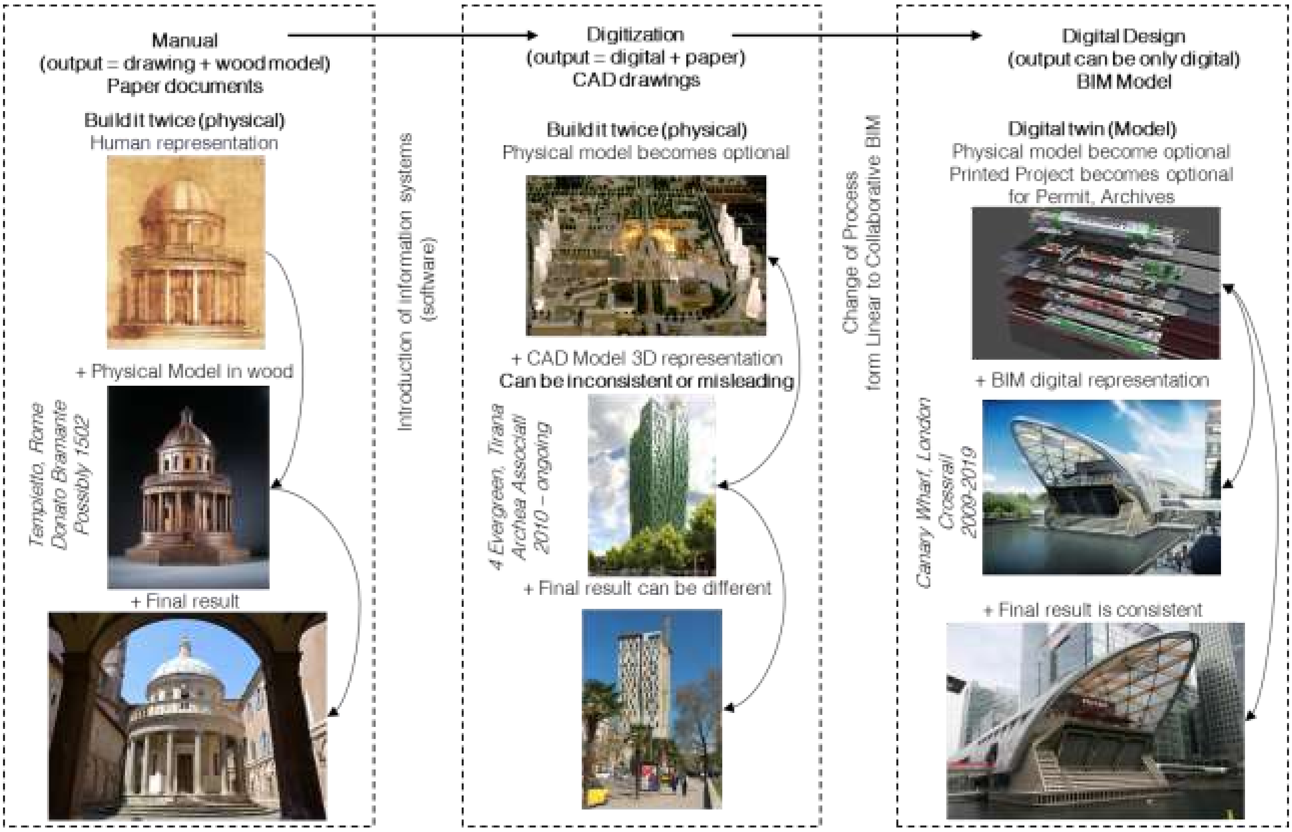


Figure 3.8: A paradigm shift from paper-CAD-BIM in design and construction.

Building Information Modelling has been around for almost 30 years, and since the mid-1970s as a concept. Only recently in this decade, it is gaining momentum from the industry, academia and professional communities. Architects and Engineers that saw an opportunity to design better with the aid of computers, to manage complex designs, using new tools, have realized ambitious projects ahead of their peers. Some examples of such approaches are the realizations of renowned architects like Frank Gehry and Zaha Hadid.

Björk introduced the formalized model of the construction process, making a distinction between information and material processes[36]. The **extended IDEF0 proposed diagram of construction processes** expands the current model with the "**Operation Process**" added to include the **whole life cycle of the asset**, **whole-systems thinking** and **contemporary design methods** described in the previous chapter.

[36] Björk, B.-C. (2002). A formalised model of the information and materials handling activities in the construction process. Construction Innovation, 2(3), 133–149. https://doi.org/10.1191/1471417502ci033oa

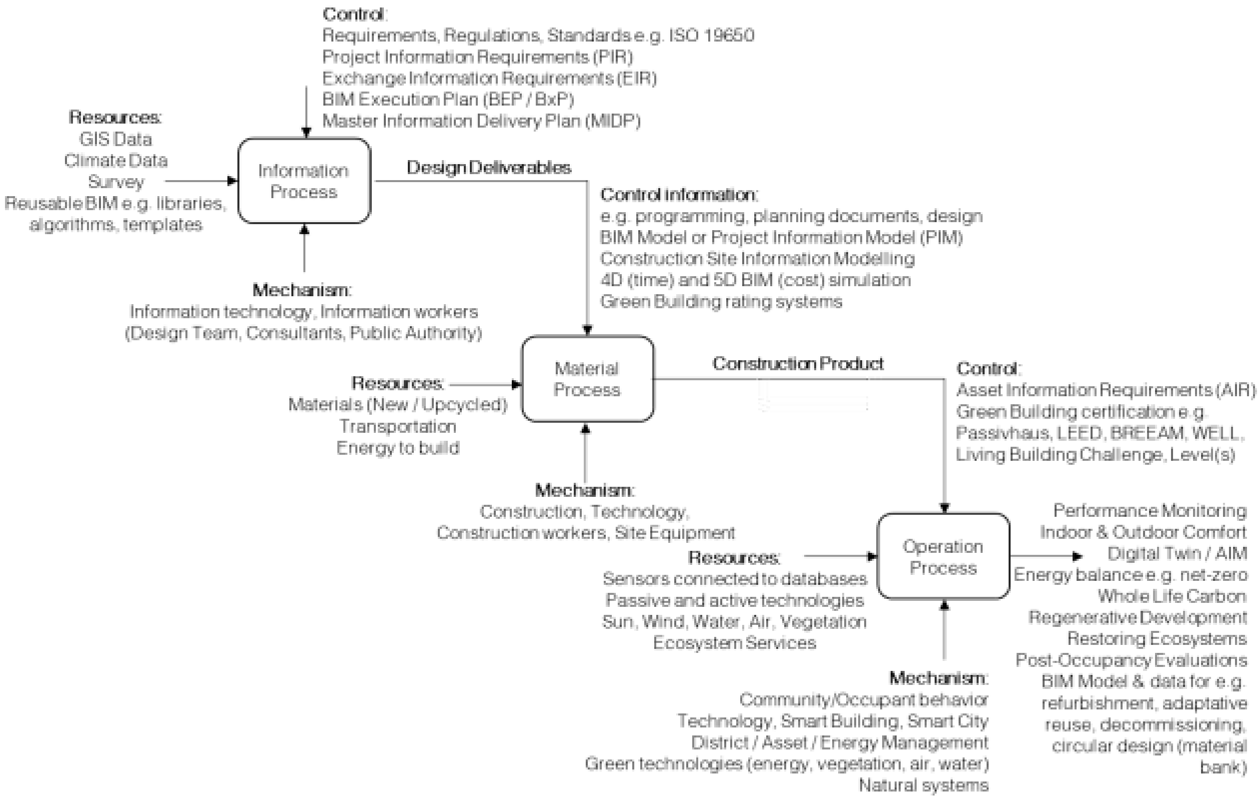


Figure 3.9: Extended IDEF0 model for the whole life cycle of assets. (Adapted from Björk, 2002)

Upstream BIM technologies are Design Authoring tools based on object-oriented modelling with integrated functionalities to support conceptual, technical, computational and generative design[37].

On the other side, Analysis software for Structural, Lighting, Energy simulations and other applications has always been about "**building information modelling**" where the geometry of the building model has information (data) attached to it to perform the specialized analysis.

Many new Downstream BIM functionalities have been developed to view and edit models, perform clash detection, extract Bill of Quantities, or to perform building simulations, e.g. Daylighting, Energy, Life Cycle Assessment. These tools and features support decision making for the design process and **automate** many repetitive calculations that used to be performed through excel spreadsheets and time-consuming tasks of entering the required data manually.

Some Downstream functionalities are integrated within Design Authoring tools. Most tools work on improving interoperability within their software solution ecosystems (**Closed BIM**). New tools for analysis, solve the interoperability problem with plug-ins where the BIM Model is connected through **cloud-computing services** with databases, cloud simulations and post-processing of results.

[37] Cerovšek, T. (2020). BIM Cube: Information management for digital construction [Manuscript in preparation]. Chair of Construction IT. University of Ljubljana.

Visualization tools such as Enscape, Twinmotion, and Lumion have developed a direct connection to work in real-time with Design Authoring tools to visualize projects, explore and modify in the Authoring Environment.

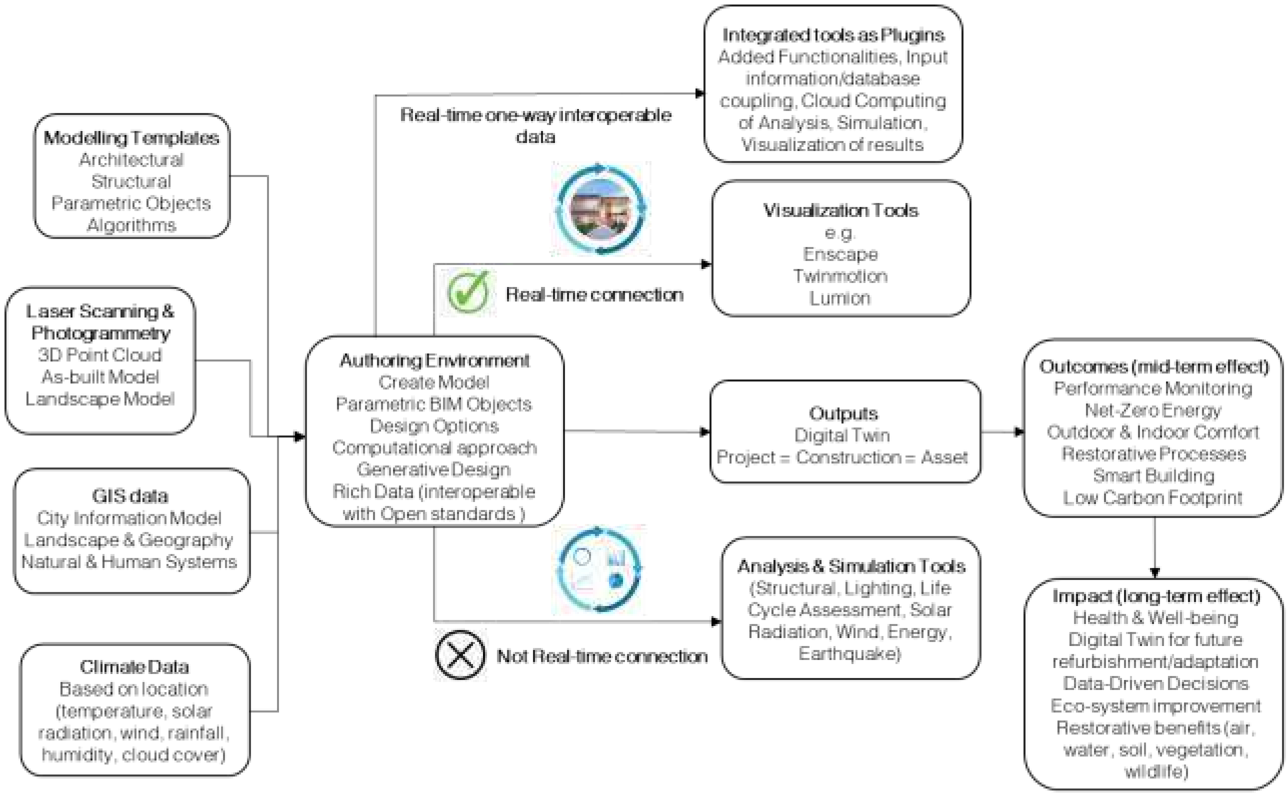


Figure 3.10: Conceptual Process Diagram of current available BIM workflows.

The current landscape of tools offers a wide range of solutions available. However, the **lack of real-time** connection between **Authoring and Analysis tools** and not having a **two-directional flow of information**, makes it necessary for the manual rework to update the Model in the Authoring tool after the analysis results.

The shift from CAD to BIM offers new opportunities for the project team. New tools and workflows for performance simulations at urban and building level can be used for all project stages. Clients can benefit from informed design decisions. Bioclimatic Design can be approached with computational tools. Non-digital methods of analysis, e.g. daylighting and wind, are being substituted or intergrated by computer simulations.

3.2 Interoperability test between Authoring and Analysis tool

In this example, a BIM model is exported from an Authoring Design tool to a Specialized Software for Lighting Design and Analysis. DIALux Evo 7 was the first Lighting Design tool able to import IFC files.

DIALux can import Manufacturers' luminaires directly in the software. Information such as 3D geometry, photometric data, mounting type and documentation for the luminaire, is needed in the BIM design process. DIALux can read IFC files and is working to export project data to IFC for manufacturers and architects[38].

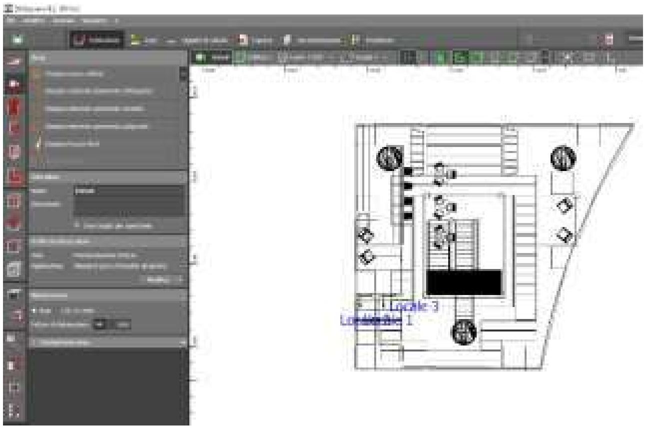


Figure 3.11: Model view in DIALux workspace

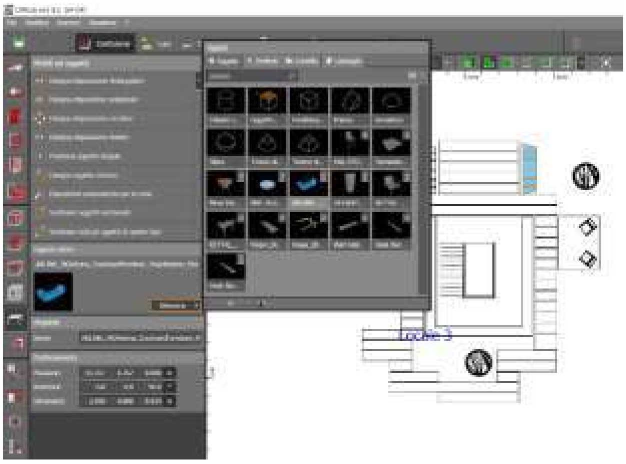


Figure 3. 12: Object-Oriented Modelling in DIALux. Select, input metadata, move, rotate IFC objects.

Figure 3.13: DIALux connection with Manufacturer's Products

Figure 3.14: LUMsearch database.

[38] Release DIALux evo 7: IFC import and more efficient workflows. (2017, April 5). https://www.dial.de/en/blog/article/release-dialux-evo-7-ifc-import-and-more-efficient-workflows

It is possible to Add a Catalogue to the Library, download a PDF, or view online catalogues to search and download luminaire objects. LUMsearch is a database that can filter the search of luminaires based on Project Requirements such as Application (indoor or outdoor), Mounting Type, Lamp Type, Lighting Parameters and Type of Protection. Product, Technical Data (PDF), DIALux (3D+IES data) of the luminaire is available for use in projects.

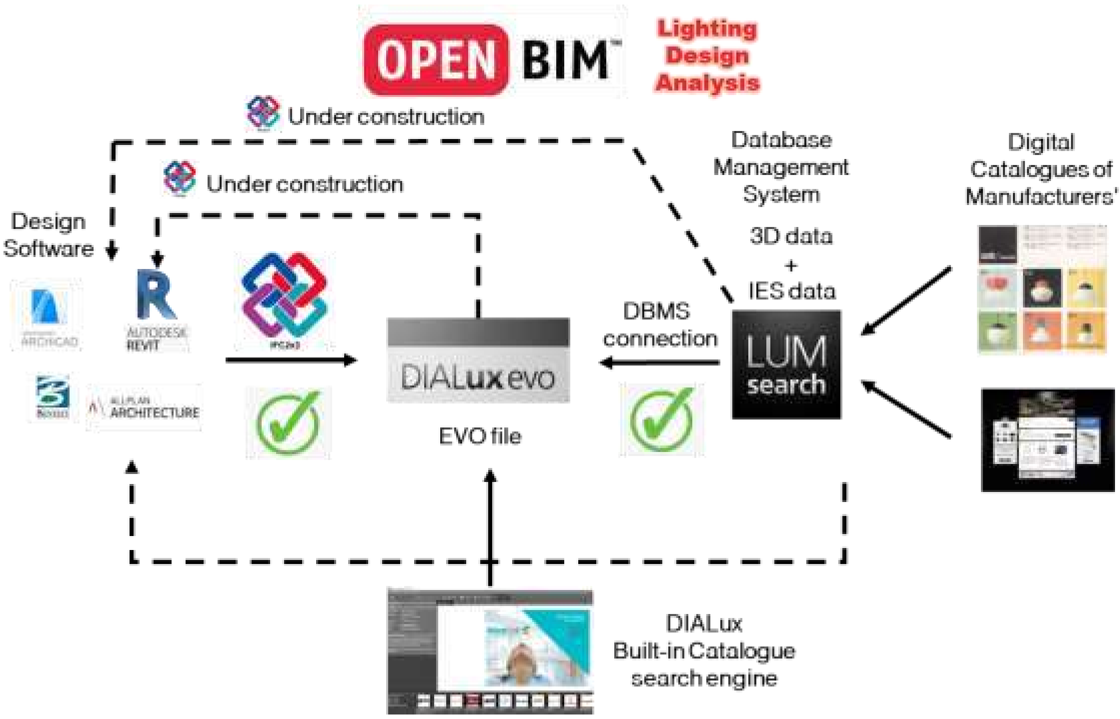


Figure 3. 15: Process diagram of Tested Interoperability and future development

DIALux is not yet able to export to IFC. Design decisions for lighting luminaires, geometry and location would benefit significantly from interoperable data with other software for the spatial coordination (Architecture, Structure, MEP) and consistency with simulation results.

3.3 Open BIM workflows

Tim Berners-Lee, in his 2009 TED talk "The Next Web", points out that the reason he created the world wide web was out of "frustration"[39]. He was working as a software engineer at CERN where people from all over the world came with their computers, software, new data formats, in different languages and different standards. He would have to connect to new machines, learn new programs to get the data and make use of it. That is how he thought of creating the first hypertext protocol.

Testing usability and interoperability of new tools can significantly benefit designers and stakeholders after the first efforts are made to "reduce frustration", what works and what does not, validating the accuracy of

[39] Berners-Lee, T. (2009). The Next Web. TED Conferences LLC.
https://www.ted.com/talks/tim_berners_lee_the_next_web

results and functional workflows. Design issues and tool limits are identified early on the process and improved for future projects.

Figure 3. 16: Berners-Lee, T. (2012). 5 star Open Data. https://5stardata.info/en/

Table 3. 1: 5-star Open Data example

Stars	Description	Acronym	Example
★	Available on the web under an open license	OL: Online and Open License	PDF
★★	Available as structured data	RE: Machine Readable	XLS
★★★	Non-proprietary open format	OF: Open Format	CSV
★★★★	use URIs to denote things, can be pointed at	URI: Universal Resource Identifier	RDF
★★★★★	link your data to other data to provide context	LD: Linked Data	RDF

An **open and exploring culture of BIM** creates a fertile ground for development and innovation in the industry. Contributions to functionalities and productivity are not coming anymore solely from new features of software companies. New **open-source tools, algorithms, plugins, open formats, libraries** developed by passionate people are expanding the Digital Design possibilities and improving productivity.

3.4 Data, Analysis and simulation for Sustainable Design

Architects and Engineers have made use of simulation in their work before the Digital Revolution. When we think of **Brunelleschi**, who first developed a system to draw in linear perspective, it was the intention of the architect to simulate through drawing **how the design would appear** before making a **scale model** or actual construction. Other notable examples are Gaudi's three-dimensional hanging chain models to establish the geometry of arches and vaults, Heinz Isler wet cloth hanging models to study shapes to scale up for thin concrete shells.

In recent years, there has been an increase in tools for building simulations. Computer simulations can inform the design process from an early stage. Analysis tools have been good at dealing with **one problem at a time**, which is sufficient with the requirements found in Building Regulations and Green Building rating systems.

How to connect different simulations and conflicting design goals of environmental performance and human comfort remains a challenge.

The sustainable design process would benefit if data and **performance of designs** were to be explored, visualized and become available **concurrently for a holistic approach** to take place.

A Holistic framework and integrated BIM workflows are needed to evaluate concurrently design parameters like daylighting, visual comfort, thermal comfort, energy loads, overheating, glare control, upfront and operational carbon.

The use of **Visual Programming Languages** (VPL) like Dynamo and Grasshopper can allow for Parametric modelling of design geometry and computational relations of input data and desired outputs of environmental performance and human comfort. The **parametric and relational approach** to the design creates opportunities to search for solutions that strive to optimize and balance requirements and inform decisions in a Regenerative and Sustainable Design process.

The process outlined above becomes increasingly complex. Interdisciplinary approach and collaboration of skilled professionals with different competencies are needed to achieve goals. However, such tools and workflows that provide feedback are not yet employed by the majority of architecture and engineering practice.

Skills and time are required to develop algorithms, interoperability and reusable BIM for the next projects. The moment when these workflows will become a regular practice to model and compare designs based on energy performance, comfort, lighting, glare, and embodied carbon is not that far.

"Building performance simulation is no longer just a good idea for some architectural practices; it is an essential part of building design and delivery[40]. - American Institute of Architects

[40] American Institute of Architects. (2019). Architect's Guide to Building Performance. https://www.aia.org/resources/6157114-architects-guide-to-building-performance

4 METHODOLOGY FOR REGENERATIVE DIGITAL DESIGN

A Regenerative Design approach **mitigates environmental impacts** and intends to **achieve higher goals** by **positively impacting** people's activities, human health, and restoring the natural system to a healthy state. The Holistic approach to make the desired changes requires tools and workflows that support the design process and provide feedback with measurable metrics of performance.

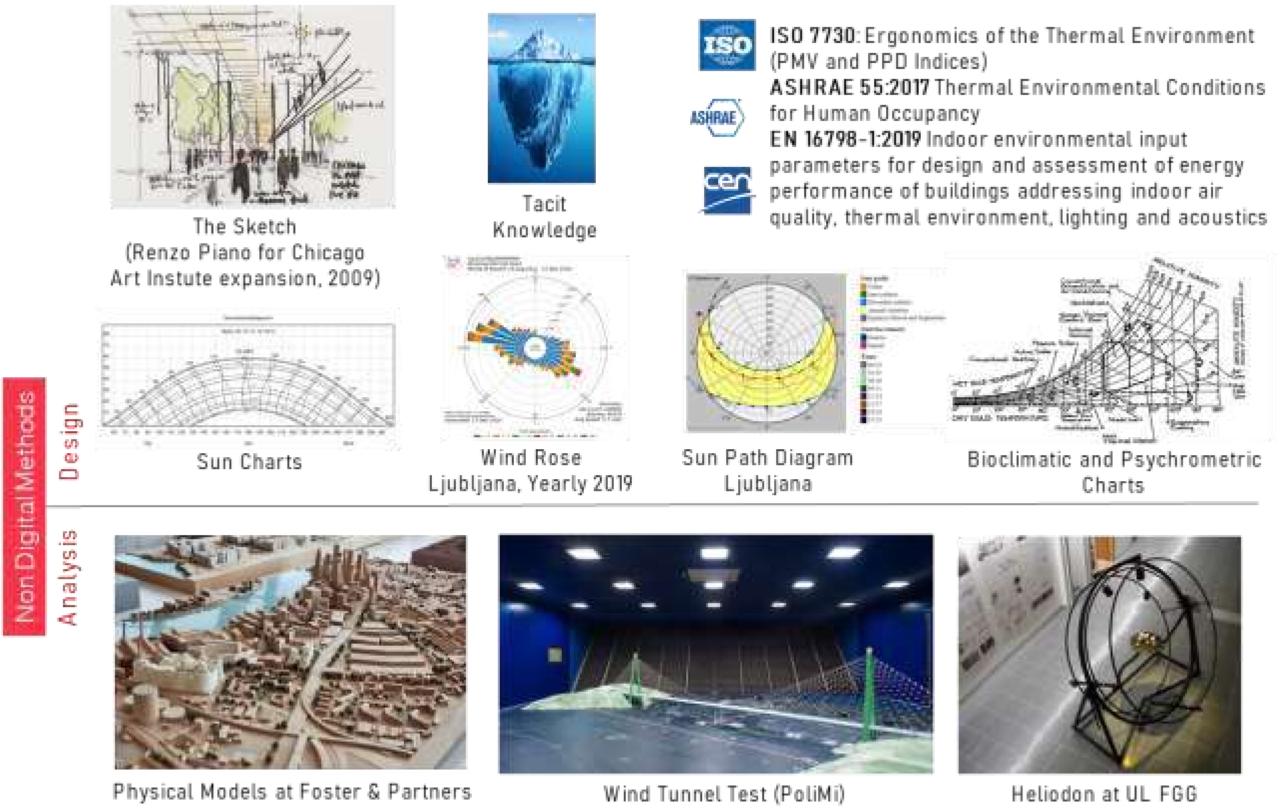


Figure 4. 1: Example of Bioclimatic Design approach and tools.

When designing new developments, the first thing an architect does is to study the context and design concept through sketches, as can be seen in the work of masters of architecture such as Le Corbusier, Frank Lloyd Wright and contemporary architect Renzo Piano. The architecture of Renzo Piano can be categorized by the use of advanced sustainable design strategies, technologies for natural light and a perceived lightness of construction connected with outdoor views. Tacit knowledge is the kind of knowledge that is not acquired through formal education that architects gain through experiencing, drawing, models, doing projects and building. Standards and regulations sometimes include requirements of bioclimatic design origin, e.g. the Daylight Factor, the right to light in the British context, minimum hours of insolation in the Athens Charter, the Thermal Comfort in ISO 7730, ASHRAE 55:2017, and EN 16798-1:2019. The Bioclimatic Chart guides into choosing passive and active strategies for achieving thermal comfort. Sun Charts guide the design through optimizing solar gains and designing shading devices according to latitude. Sun Path Diagrams are useful for shadow studies, building orientation and optimizing shape. The Wind Rose helps in understanding the prevailing wind patterns and choosing the best ways to use the wind for natural ventilation or provide some cover through landscape design. Non-digital analysis of design solutions is evaluated through scale models, which continues to be an essential practice in Universities and architecture offices. Heliodons and Wind tunnels are used to simulate real-world effects on scale models.

Figure 4. 2: Example of Bioclimatic-Regenerative integrated tools hierarchy.

There is a need to use bioclimatic design tools discussed above integrated with Digital workflows. Analysis and results from simulations instead of manual calculations of **static metrics** can be substituted with **climate-based**, **spatial and temporal alphanumerical data** that can be **visualized colour-coded** onto project **geometry**. Some digital tools have emerged in recent years that are capable of modelling urban energy flows, microclimate, daylighting and other metrics. Tools like City Energy Analyst, the Urban Modelling Interface, and CitySim Pro can be used for analysis at the Urban level. Tools like Hypar, Giraffe, TestFit and Modelur can be connected with GIS interfaces for fast modelling of plots and buildings. The computational approach is being applied when creating masterplans and buildings with real-time input data, algorithms and rules. Advanced simulations like CFD and Energy require specialised software which has specific geometry requirements and needs specialist knowledge to set up correctly for simulations. There are no Model View Definitions able to respond to exchange information requirements of analysis software. It is up to the designer to choose how to translate the BIM Model into a model for simulation. The best analysis tools use validated simulation engines like Energy Plus, Radiance and Open Foam. Simulations within Design Authoring tools do not require the designer to make changes to the BIM models. However, simulation results could have substantial margin errors from automation, e.g. Automated Building Energy Model. The proposed hierarchy requires designers to develop horizontal knowledge across domains for Sustainable Design practice and develop digital skills that are needed to take advantage of these new workflows.

4.1 Microclimate modelling for Cities

Green and blue infrastructure can have a positive impact in urban environments in many ways such as reducing the Urban Heat Island effect (UHI), increase the rainwater capacity of an area during heavy rain or extreme weather effects, and capture pollutants. However, the practice of landscape architecture and urban design has made little use of computational tools and data in the design practice. The field has been guided more from the creativity part of practitioners and positive human psychological and physiological health benefits from nature connection.

ENVI-met is a microclimate modelling tool with powerful functionalities. It can model urban environments such as buildings, vegetation and simulate climatic and microclimate conditions for the concerned design area. The type of systems, interactions of energy flows that happen in real environments is simulated, e.g. air, wind, sun, pollutants, water.

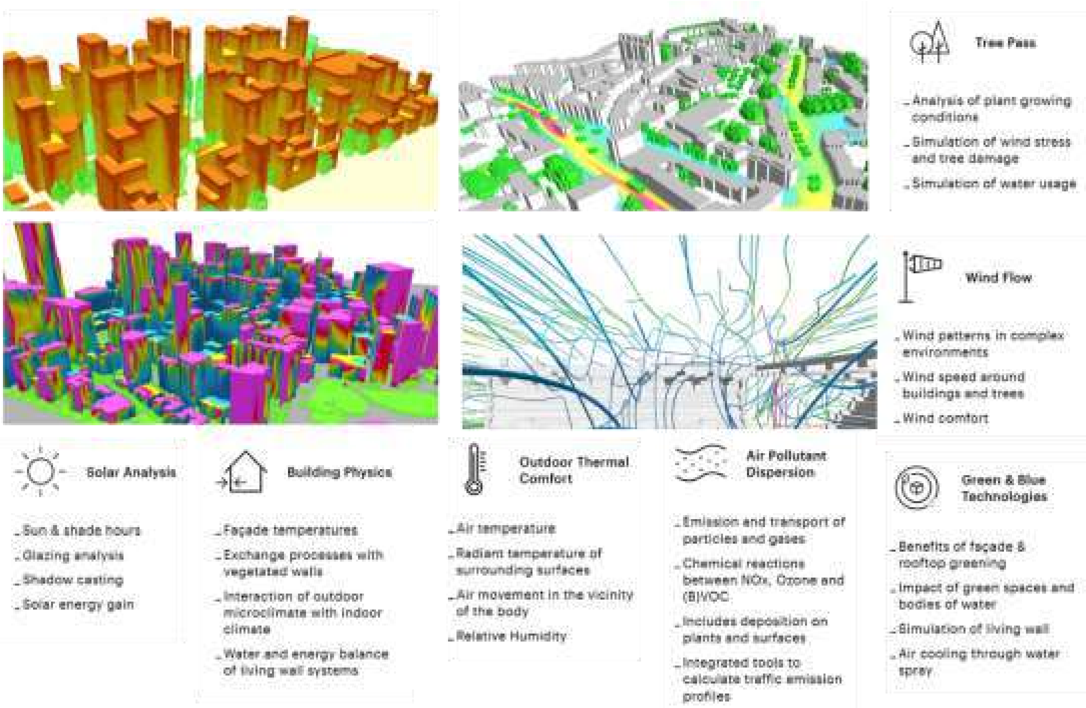


Figure 4. 3: ENVI-met simulation of urban microclimate and software features. Source: ENVI-met

The outdoor comfort is more difficult to predict compared to indoor comfort, because it is ever-changing due to weather conditions, with broad spatial and temporal variability. Methods and tools that can improve the understanding of the human physical needs (e.g. distances, walkability, accessibility), psychological effects (orientation, well-being) and physiological (comfort) adaptation to the environment are needed.

The microclimate of cities is shaped by the interaction between the local climate and the built environment. Every urban development process should start by understanding the climate and weather patterns. A problematic condition of cities today is the Urban Heat Island (UHI). It is a severe problem and hard to solve because of interdependencies of systems such as emissions from transportation and buildings, urban density, façade radiation of absorbed heat, hot air emitted from HVAC cooling systems and low green cover in urban contexts. The phenomenon represents the increase in temperature within cities compared to the rural areas. Higher temperatures result from the combination of heat absorbed and released in urban contexts, and lower green areas compared to rural locations, and reduced wind effect on urban setting (stagnant air).

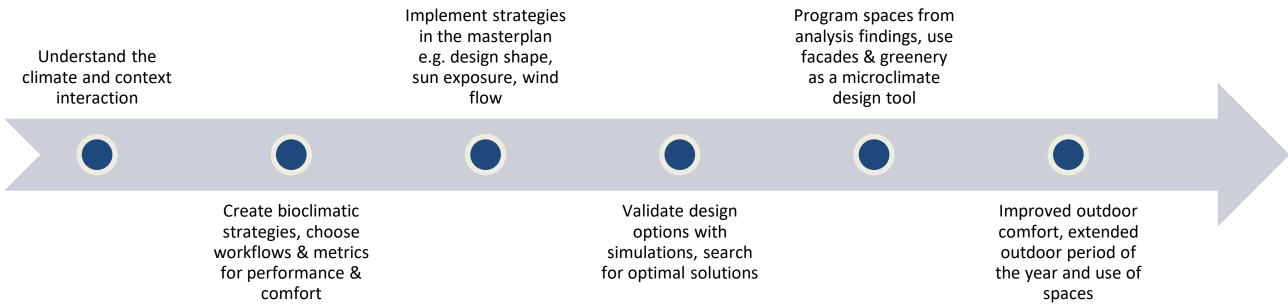


Figure 4. 4: Trajectory of Bioclimatic Design Strategies at the urban level.

An example of applied Bioclimatic Design strategy that is compliant with the proposed trajectory are the Porticos of the city of Turin that run for 18 km, which 12.5 km are interconnected. The Porticos were ordered to be built since the XVI century by the king Carlo Emanuele I of Savoia to allow the nobility to take long walks sheltered from the rain in winter and provide shade in the summer months. The portico architecture continued to be built in palaces during city expansions centuries ago, for the construction of Via Roma in the XX century, Casa Aurora designed by Aldo Rossi in the 1980s and even for contemporary buildings. The portico architecture has become part of architectural heritage and building tradition of Turin. In addition to the above, activities can be oriented towards sun exposure based on program, e.g. placing cafes and restaurants in the sun and sheltered from rain, using vegetation to cover from wind, locating garages or storage areas facing the wind or on the north side.

Figure 4. 5: Dervishaj, A. (2019). Turin's porticos as Bioclimatic Design strategy at city level. [Photograph]

Bioclimatic Strategies improve microclimatic conditions and can reduce the heat island effect. Circular positive results are created for outdoor comfort and human well-being.

4.2 Green City Concept

Cities are faced with many environmental concerns such as air quality, mobility, limited land for development, thus putting pressure on natural resources of water bodies, natural land and biodiversity. There is a rising need to respond with design strategies to adapt to climate change. According to the International Energy Agency (IEA), approximately two-thirds of energy consumption happens within urban systems. Globally, cities produce around 70% of CO_2 emissions, and the need to respond is increasing and becoming a 'must' if we are to meet the Paris Agreement goals.

On this matter, frameworks have been developed to measure the Green City Performance of cities and respond with Green City Action Plans (GCAP) to improve the environmental performance of cities and quality of life of citizens. The Economist Global Liveability Index, Siemens Green City Index and the IHS Green City Performance Index measure the social and environmental performance of global cities.

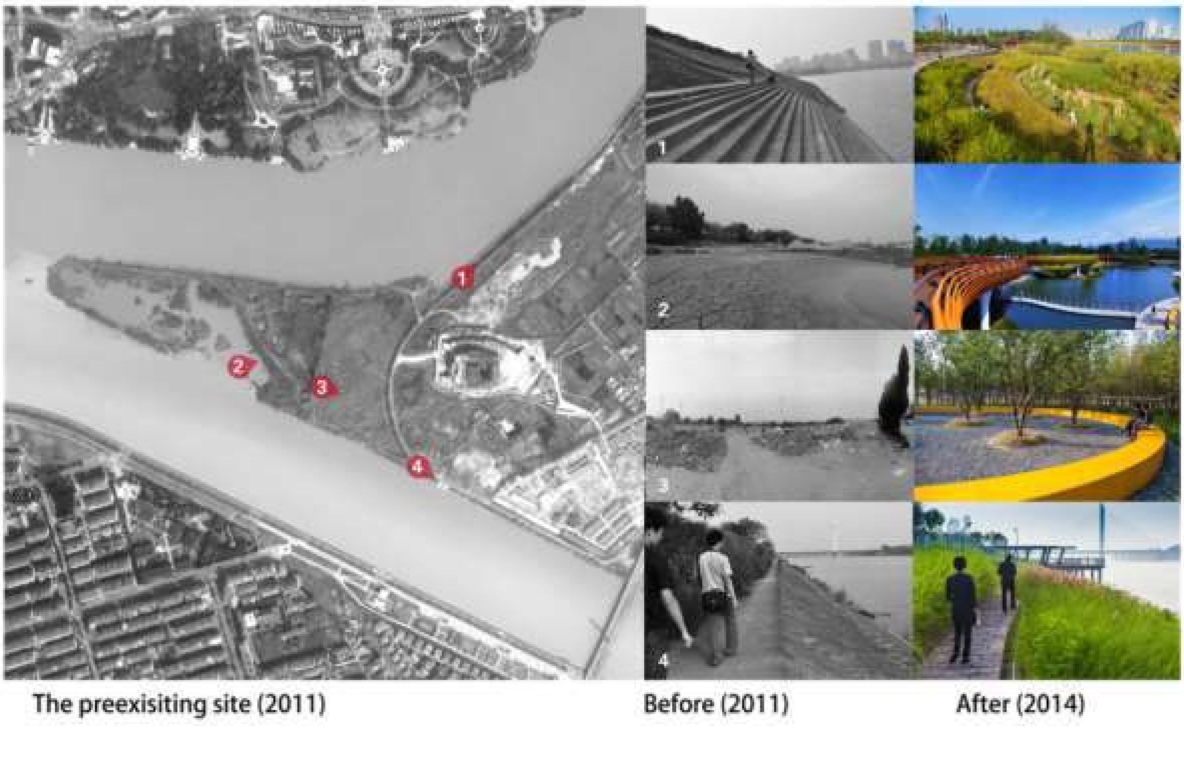
Green Infrastructure is the best solution against the Urban Heat Island effect. It can improve outdoor comfort, mitigate pollution and shorten the food supply chains.

4.2.1 ***Resilient and restorative landscape design***

Population growth in urban areas brings pressure for construction and increased density in cities, which in turn can reduce green spaces, air quality and create an urban heat island effects. Green and compact policies are in place in many global cities as a reaction to decreasing the urban sprawl and consumption of land, increase urban resilience and mitigate the increasingly extreme weather effects in cities.

Figure 4. 6: AFP. (2012). Wuhan residents passing in a flooded street [Photograph]. The Guardian. https://www.theguardian.com/cities/2019/jan/23/inside-chinas-leading-sponge-city-wuhans-war-with-water#img-3

An example in such direction comes from China leading the way with "Sponge Cities. Wuhan was once known " as the city of a hundred lakes" with 127 lakes but thanks to urbanisation that number decreased to 30.[41] Since then, the city has been more vulnerable to floods. Sponge spaces are being designed in Chinese towns with permeable pavements, rain gardens, and parks with grass swales, artificial ponds, wetlands and elevated passages above flood levels.



[41] Jing, L. (2019, January 23). Inside China's leading 'sponge city': Wuhan's war with water. The Guardian. https://www.theguardian.com/cities/2019/jan/23/inside-chinas-leading-sponge-city-wuhans-war-with-water

Figure 4. 7: Turenscape. (2014). Yanweizhou Park in Jinhua [Photograph].
https://www.turenscape.com/en/project/detail/4629.html

Yanweizhou Park is a 26-hectare wetland public park between three rivers. It is a resilient landscape that does not fight with nature but restores the ecosystems where human and natural systems can co-evolve. Green areas function for people (connecting with nature), infrastructure (increased the accessibility to the city and functions as a water basin) and nature (ecosystem improvement) at the same time.

Computational tools allow simulation of multiple metrics such as ENVI-met, Ladybug tools for Rhino, or CitySim Pro that simulates Solar shortwave and longwave radiation on surfaces, radiant temperatures of buildings, photovoltaic potential, and Sky View factor.

4.3 Data-driven Parametric Urban Design

One crucial feature of BIM tools for Design Authoring is the ability to create **parametric model elements**. Most CAD tools can create geometry, group geometry and modify it, but this can result in distortion of 2D/3D geometric features outside of the desired scope, e.g. scaling and non-preserving the desired proportions and technical requirements, composition, or structural criteria.

When working in a BIM environment, the parameters control the geometry. We can set desired parameters that are relevant to our criteria, good design practice or product regulations. The inputs of parameters create the geometrical property of the model. Information can label parameters to be easily remembered by the user, to allow for better design collaboration between people, and automate drawing generation. Passive properties can be calculated automatically, e.g. surface and volume that in turn can be used for Quantity Take-off in Cost Estimation and 4D-5D simulation. Parametric Models can output Model Instances compliant with their parametric constraints for the exploration of several design options or by creating when needed new instances.

Masterplanning, Urban Design or Mixed-use buildings projects can benefit from using Parametric Models.

Benefits of parametric modelling for urban design:

- Quickly model and explore design alternatives
- Increase productivity
- Input Parameters from Planning guides, e.g. minimum building distances, required standards for green and parking space per inhabitant, Floor Area Ratio (FAR = Gross Floor Area/Plot Area), Site Coverage (Built area/Plot area), Building Height.
- Turn inputs and parameters into computational relations for Bioclimatic Design such as Orientation degree, Form Factor, Heat Loss Form Factor into automatically calculated design outputs.
- Informed Design decisions

Software like Rhino and Grasshopper gives the possibility to designers to translate these user-defined requirements into computational parameters. Only in recent years, Revit has integrated Dynamo that allows designers to extend Revit beyond the provided set of functionalities. This novel design approach does not rely simply on the designer's intuition, but improves the process, feeding data for design exploration, improved productivity and informed design options. In turn, this process requires more knowledge from the designer's side into Computer Science concepts and time to develop algorithms.

VPLs allows for total freedom in the design process. On the other side, specialised tools promise to reduce the time and be easier to use with templates.

Modelur is an Urban Design Parametric tool that provides the benefits described above of Parametric Models with Data-driven informed designs, automatic reports and insights on conceptual energy efficiency predisposition of building shape.

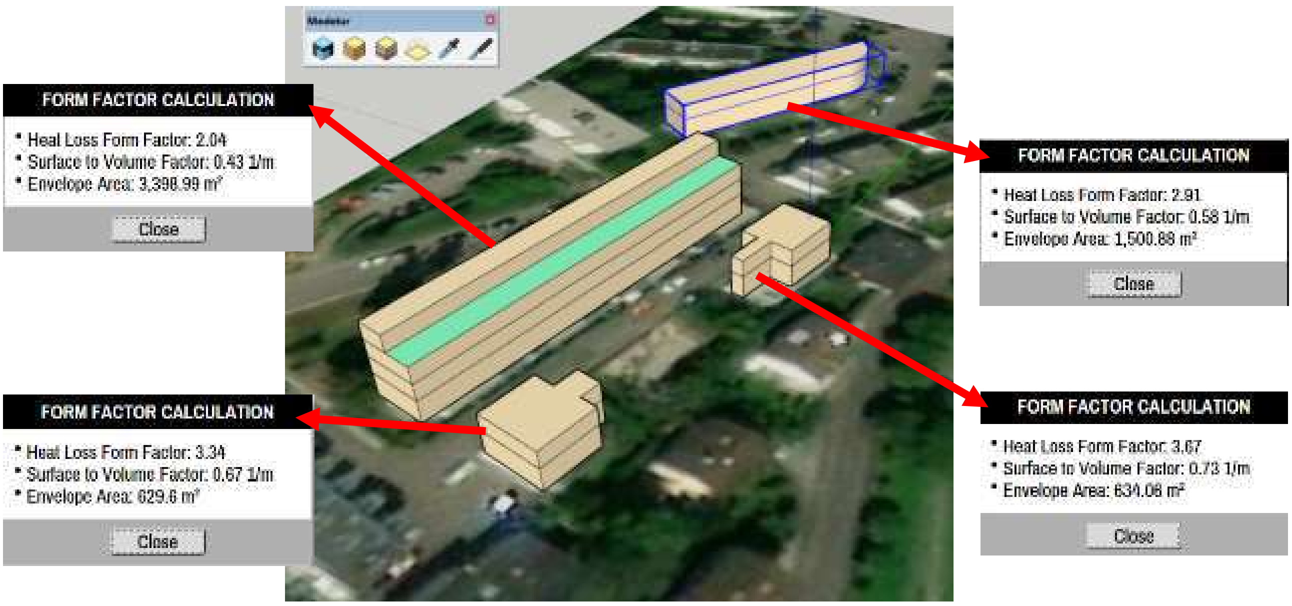


Figure 4. 8: Modelur. Comparison of some of Weissenhof Estate buildings Form Factor and Heat Transfer Form Factor, Stuttgart 1927.

SIMPLE BUILDINGS DATA															
Building name	Building ID	Gross Floor Area (m²)	Built-up Area (m²)	Building Height (m)	Number of Storeys	Building Volume (m³)	Required Green Area (m²)	Required Parking Spaces	Required Parking Area (m²)	Primary Unit	Primary Unit type	Secondary Unit	Secondary Unit type	Land Use	Net Floor Area (m²)
Building	1000001	737.14	368.57	7.0	2	2,580.01	147.43	14.74	368.57	9.83	Apartments	29.49	Residents	Residential	516.0
Building	1000002	247.11	123.55	7.0	2	864.88	49.42	4.94	123.55	3.29	Apartments	9.88	Residents	Residential	172.98
Building	1000003	2,724.1	681.02	13.0	4	7,824.4	544.82	54.48	1,362.05	36.32	Apartments	108.96	Residents	Residential	1,752.53
Building	1000004	269.52	134.76	7.0	2	943.31	53.9	5.39	134.76	3.59	Apartments	10.78	Residents	Residential	188.66

Figure 4. 9: Modelur automatic table with building data.

The Form Factor can inform the concept design to choose solutions that are more efficient and reduce heating and cooling demand without any cost before the next phase where the bioclimatic chart and analysis tools come into play. Buildings with better Form Factor may have less thermal bridges because of envelope shape and require less insulation to achieve performance goals.

Some additional benefits of Modelur: Interactive 3D zoning, GIS Data Import (buildings, trees), Real-time Data update, Real-time warnings (FAR, Site coverage, building distance, Development Timeline).

Table 4. 1: Exchange Requirements based Level of Information Need (ISO 19650) with Modelur.

Level of Definition (UK, in former PAS 1192-2), **Level of Development** (US, AIA, BIM Forum 2019)	
Geometrical Information	**Alphanumerical Information**
- Import GIS Data and convert to 3D CAD Model (buildings, trees) - LOD 100 – LOD 200 - Development Timeline - Simple / Complex Buildings type - Object colour - Exportable to GeoJSON	- Plot Area - Min. Distances (% of height and min. dist. of buildings) - Max. Permitted FAR = Gross Floor Area/Plot Area per Plot/City Block - Max. Permitted Site Coverage % (Built area/Plot area) per Plot/City Block - Max. Permitted Building Height per Plot/City Block - Number of stories - Land Use Type - Built-up Area - Gross Floor Area - Net Floor Area (Internal/terrace/loggia) - Primary Unit, e.g. Apartment, Office, Classroom with parameters rules - Secondary Unit, e.g. Residents, Employee, Student. automatic rules - Green Areas automatic rules - Parking Space automatic rules - Investment Value - Form Factor and Heat Loss Form Factor - Automatic building data tables

4.4 Computational Fluid Dynamics (CFD) for Urban Design and Ventilation

Computational Fluid Dynamics has been applied to a wide range of engineering problems such as aerodynamics, industrial design, heat transfer, combustion engine analysis. Wind Analysis and Design have been performed for large-scale infrastructure projects or Hight-Rise in Wind tunnels to test scale models behaviour under wind action. The availability of Climate data, computational methods, developing software tools, and new Software as a Service (SaaS) solutions open the way for the use of CFD analysis, not only for specialists in the fields like the automotive or industrial design but to the broader design community of Architecture, Engineering and Landscape Designers. The public and private stakeholders can now benefit from these tools from the early stages of design of an Urban Masterplan, public space design, or to the single building scale. CFD analysis can be used for a variety of simulations such as Pedestrian Wind Comfort, Pressure and Loads on Building Facades, Skyscraper Aerodynamics, Indoor Thermal Comfort and Energy Efficiency, Natural Ventilation, or Age of Fluid for mechanical ventilation in offices.

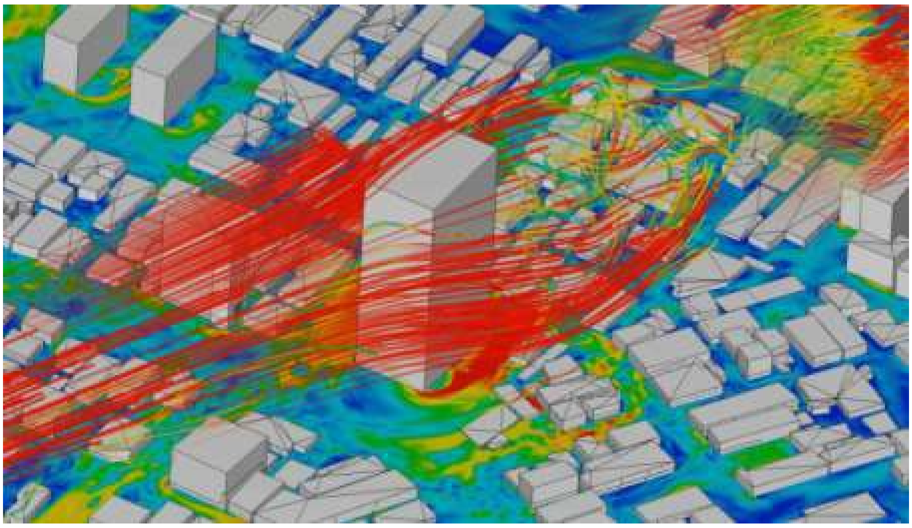


Figure 4. 10: CFD wind simulation in an urban context. Source: Simscale

CFD simulation can help reduce time and costs in the design workflow. Simulations are faster, and most iterations are made between design and simulation tools to achieve an optimized design solution. A physical prototype is prepared to validate results for important large-scale projects such as skyscrapers or bridges. Building location and orientation can be optimized to minimize local discomfort from the wind.

Wind Tunnel testing is costly, needs time and may require going back to the drawing board. Design iterations are done through a BIM Model prepared as CAD solid geometry for CFD simulation. Physical testing is done less often to reassure the correlation with simulation results.

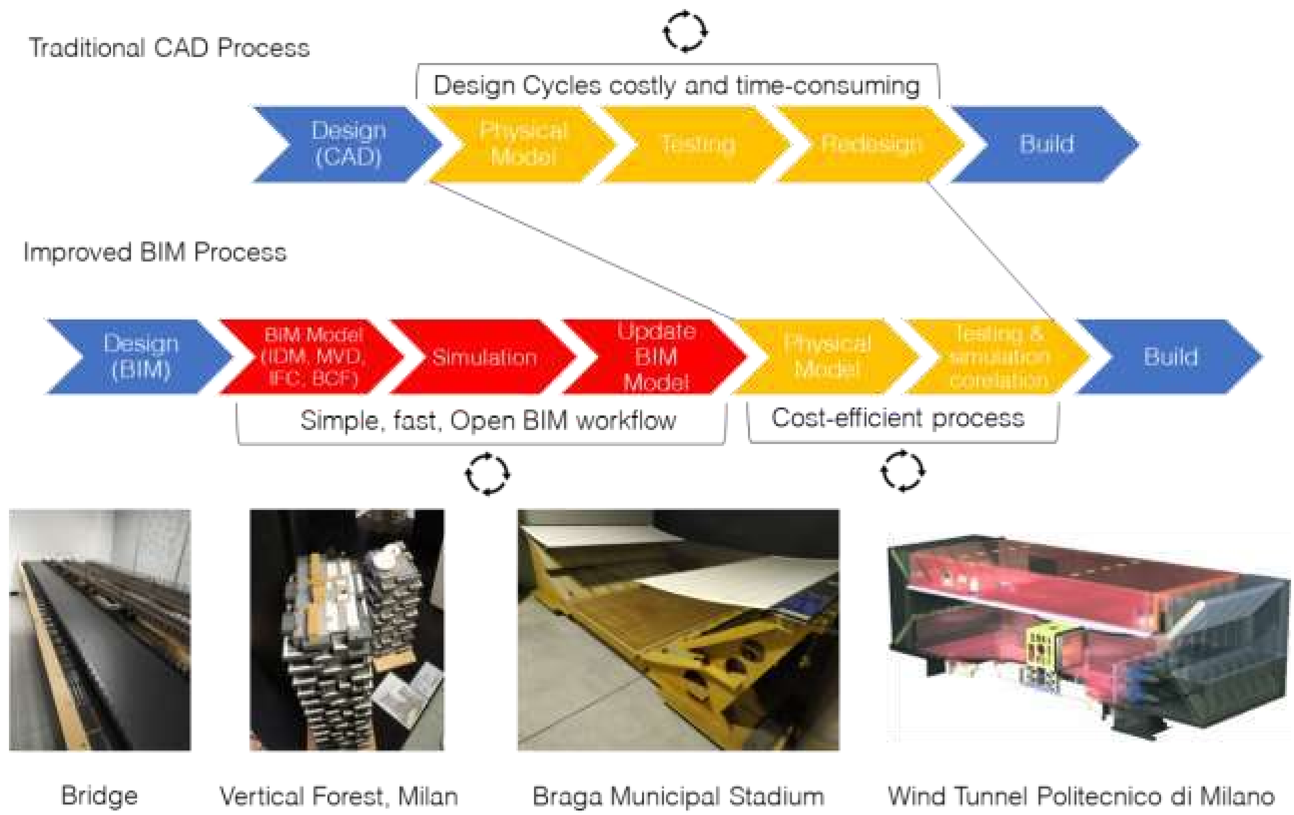


Figure 4. 11: Design Process in a traditional way versus current improving practices.

What negative impacts can wind have at the urban level?

- No shops/tenants of ground floor spaces
- Parks become underutilized because of discomfort
- People can get injured by being pulled from wind or objects driven by the wind
- Pollution - little wind or wind-blocking can reduce air quality. The wind is something we want to design with, not against it. Solutions aimed at blocking wind can often create the opposite effect by making windless areas with higher concentrations of pollutants.

What benefits can Wind simulation have in the design?

- Optimize Building Orientation to resolve Wake/Vortex effect situations and reduce turbulences.
- Optimize Building Distribution, e.g. location of the entrance, exits, shops, outdoor services for cafes and restaurants.
- Wind-blocking - Increase the safety of spaces and prevent injury from strong winds
- Informed Urban Design (trees, urban furniture, hardscape to reduce wind speed discomfort, e.g. contain Venturi effect (fluid accelerates because of the reduction in pressure created when going through a constricted section of space).
- Wind level evaluation to reduce high temperatures and summer heat.
- Identify suitable spaces for outdoor seating, public transportation (standing up), walking, biking, and running concerning wind speed.
- Improve building shape to reduce wind downwash effect (accelerating at ground).
- Optimize building shape, e.g. 1. Horizontal Plan form (squared, chamfered, recessed), 2 Vertical Section Form (pyramid/tapered, terraced/receding levels), 3 Twisting 4 Introduce floor openings.

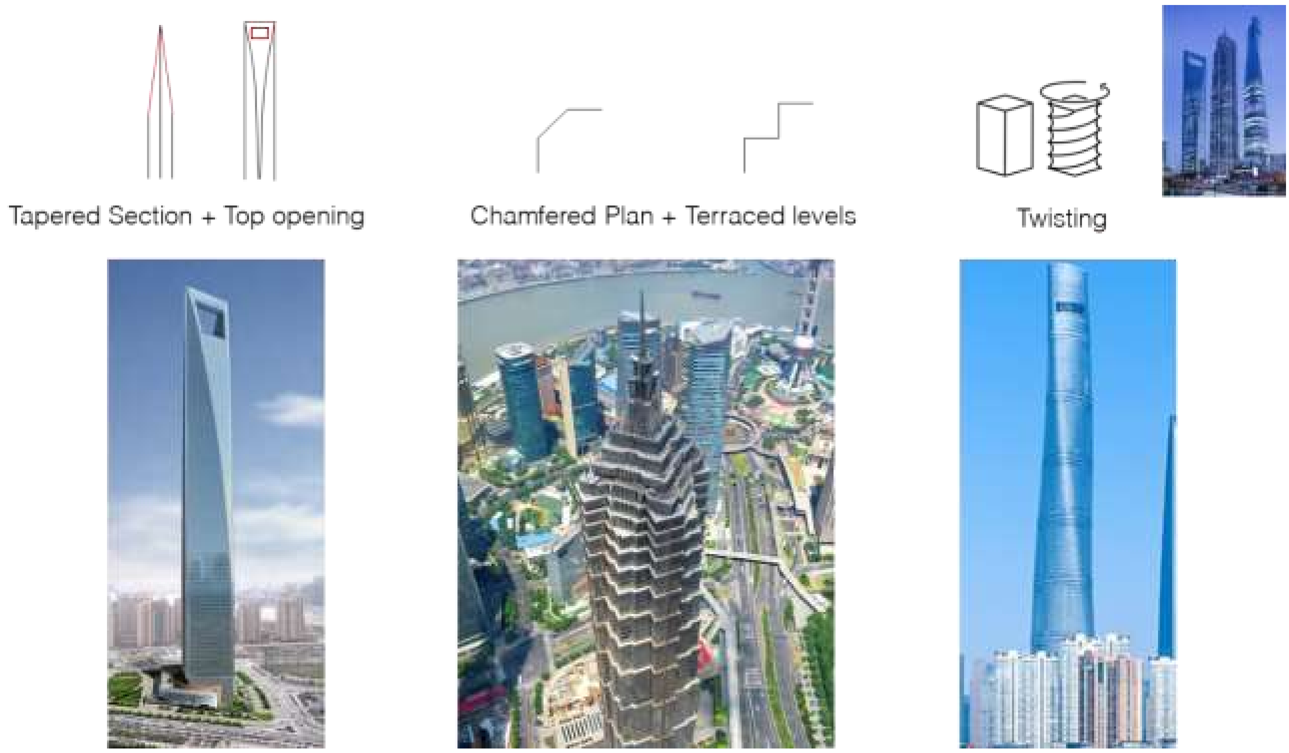


Figure 4. 12: Wind design strategy for the high-rise in Pudong district, Shanghai.

Jin Mao Tower (1999) in the centre is 420m high at the top, has a chamfered building plan and a recessed terraced shape going upwards. Shanghai World Financial Center (2008) on the left is 492m high, partially tapered and features an opening at the top. Shanghai Tower (2014) on the right is the highest at 632 m and has a twisting shape.

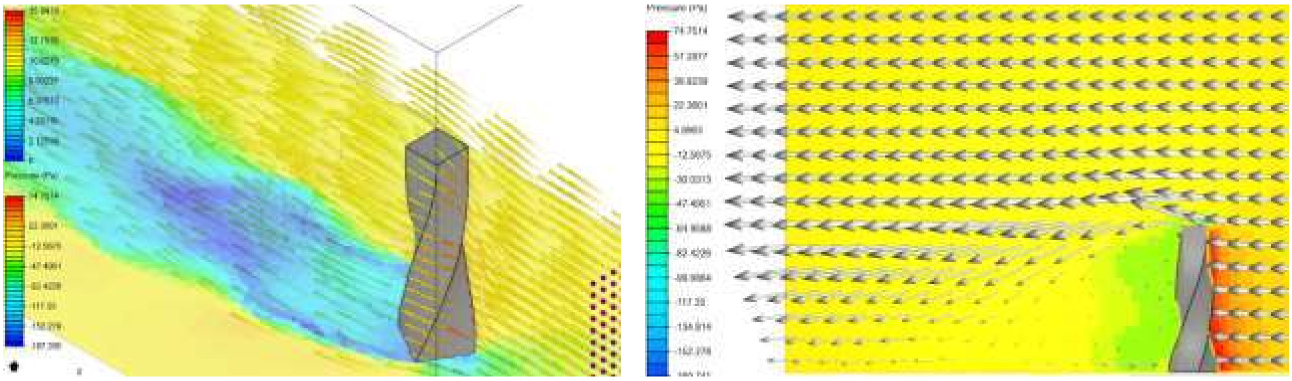


Figure 4. 13: Incompressible fluid test of a twisting shaped tower in Simscale.

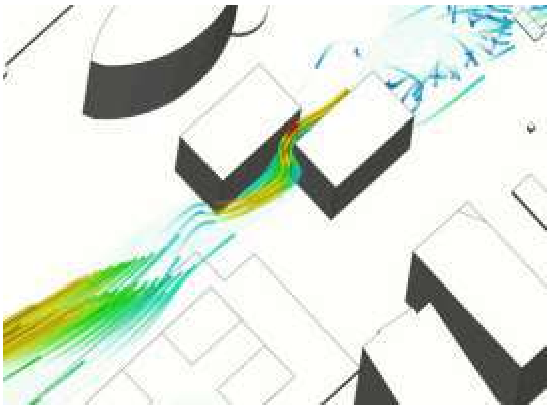


Figure 4. 14: Venturi effect in Urban spaces. Source: Simscale.

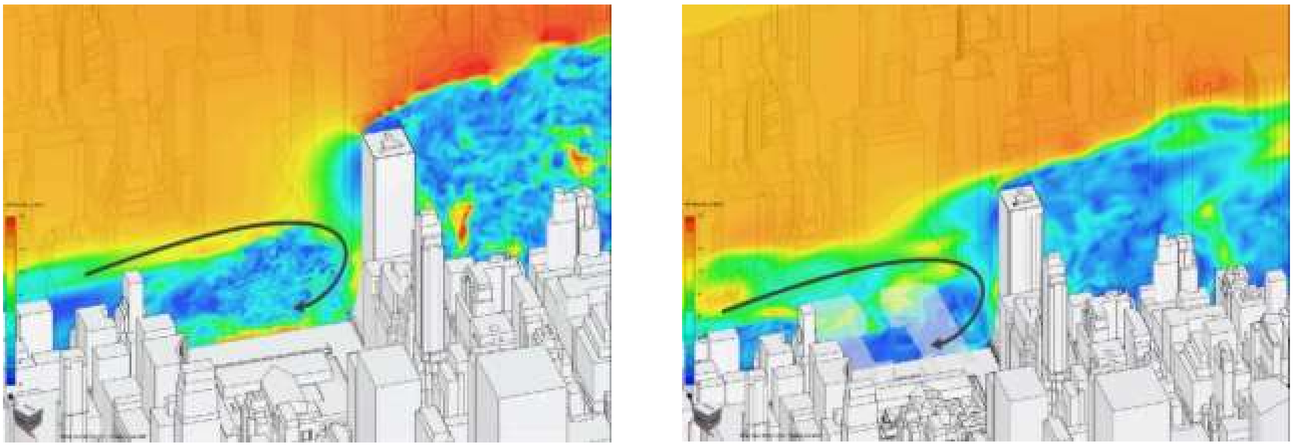


Figure 4. 15: Downwash effect on Bryant Park, NY. Reduced effect with porous region for trees.
Source: Simscale

Table 4. 2: Exchange Requirements based on Level of Information Need (ISO 19650) with Simscale.

Level of Definition (UK, in former PAS 1192-2), **Level of Development** (US, AIA, BIM Forum)	
Geometrical Information	**Alphanumerical Information**
- **CAD Geometry** – solid geometry **Parasolid** (*.x_t), SolidWorks (*.SLDPRT, *.SLDASM), Autodesk Inventor (*.3ds, *.iam), **Rhino** (*.3DM), CATIA (*.CATPart, *.CATProduct), ACIS (*.SAT), **STEP** (*.STEP / *.step / *.stp / *.STP), **IGES** (*.IGES / *.iges / *.IGS / *.igs), BREP (*.BREP / *.brep), **STL** (*.stl) - **IFC (STEP Physical file or IFC Extensible Markup Language) not supported!** - Scale (Units are correct / scale model) - Fluid/Flow Volume Extraction - Domain and Boundaries (create mesh - a discrete number of elements) - A simple version of the problem/model (clear problem understanding – what can be neglected, faster simulation times) - Use of Symmetry (symmetric boundary condition, faster computation) - **CAD model needs to be prepared** - **Trees need to be modelled as solids**	- **No IDM, MVD specified for BIM Model (user custom exchange & experience)** - Validated Simulation Engine - Weather data/wind rose - **Type of Simulation,** e.g. Wind Pedestrian Comfort, Thermal Comfort, Incompressible. - **Materials** (types of fluid) - **Boundary Conditions** (how fluid interacts with the environment, e.g. pressure, velocity, loads, flow rate, turbulence intensity. - **Equation solvers of simulation** - Simulation set-up (maximum run time, number of iterations, time) - **Porous region** (area covered by trees; numerical simulation takes into account the porosity of the trees) - **Results** (solutions fields, metrics, spatial 2D/3D colour maps)

4.4.1 *Effects of Trees and Urban Forestry in Cities*

Trees play a significant role in preventing natural disasters such as landslides, provide stability for river banks, preventing desertification, increase biodiversity, reduce UHI effect, mitigate heat waves during summer, filter pollution and capture water during heavy rains. The positive impact in urban settings is being recognized and quantified with tools and in Green Infrastructure projects. The effect of trees on outdoor comfort has not been quantified until recently. CFD tools can allow the modelling of tree objects as "porous regions" to take into account the impact of trees in the urban wind, and thus the effect it has on pedestrian wind comfort.

Definition: ***"A porous medium is a solid object with interconnected voids distributed more or less uniformly through the bulk of the body"***. Source: Simscale

Porosity of trees = void space/space occupied by tree branches, twigs and leaves

Full tree models are available in 3D cad libraries. However, they would not be necessary or even possible to make use of the geometric complexity of tree objects (branches, leaves) for high demanding CFD simulations. Trees are considered as "porous material" for CFD.

Parameters for porous media are:

- Value of porosity
- Inertial Resistance

Trees affect the wind in the following ways:

- The trajectory of the flow
- Wind speed
- The drop of pressure windward/leeward

Two parameters define the porosity of trees:

- **Leaf Area Index (LAI)** for woody plants depending on the type of tree[42].
- **Drag Coefficient** is the ratio of the pressure difference of windward and leeward and the dynamic force.
  Where **Leaf Area Index = Total Leaf Area / Total Ground Area**

[42] Iio, A., & Ito, A. (2014). A Global Database of Field-observed Leaf Area Index in Woody Plant Species, 1932-2011. ORNL DAAC. https://doi.org/10.3334/ORNLDAAC/1231

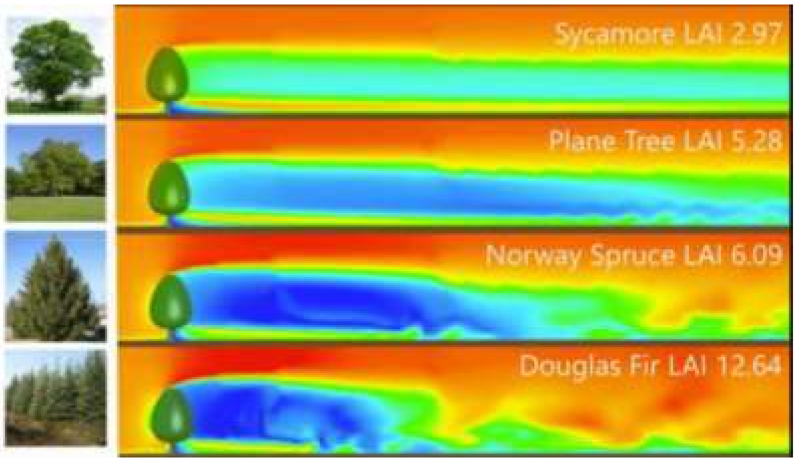


Figure 4. 16: Simulation of wind effect for different types of trees. Source: Simscale

The effect of trees is captured in the urban setting simulation by comparing the left side (no trees) and right side (with trees). The patterns have changed in the central area where trees were introduced, and speed has been reduced to allow long and short term use of the spaces based on Pedestrian Wind Comfort results.

Figure 4. 17: Simulation of Urban context with trees. Source: Simscale

Effects of trees in the urban environment:

- Wind-blocking
- reducing air pollution, e.g. evergreens such as the Common ivy (Hedera helix) can capture formaldehyde, benzene, finer particulates PM2.5.
- Trees such as Platanus (Platanus x hispanica), Maple (Acer Pseudoplatan), common beech (Fagus sylvatica), common hornbeam (Carpinus betulus) can absorb CO_2 and NO_2 pollutants.
- Trees coupled with bioswales can filter pollutants, convey stormwater, and clean it from contaminants.

4.4.2 *Wind comfort metrics*

Cities around the world are growing, in population size, becoming more dense and compact due to contemporary urban policies and with taller buildings. Wind Effect on tall buildings and at urban ground level is becoming more relevant. CFD tools with integrated weather data (wind rose for global locations) can simulate multi-direction wind flow analysis with transient simulations (time-based). Wind patterns can then be evaluated for every wind rose direction. The simulations can output Wind Comfort metrics.

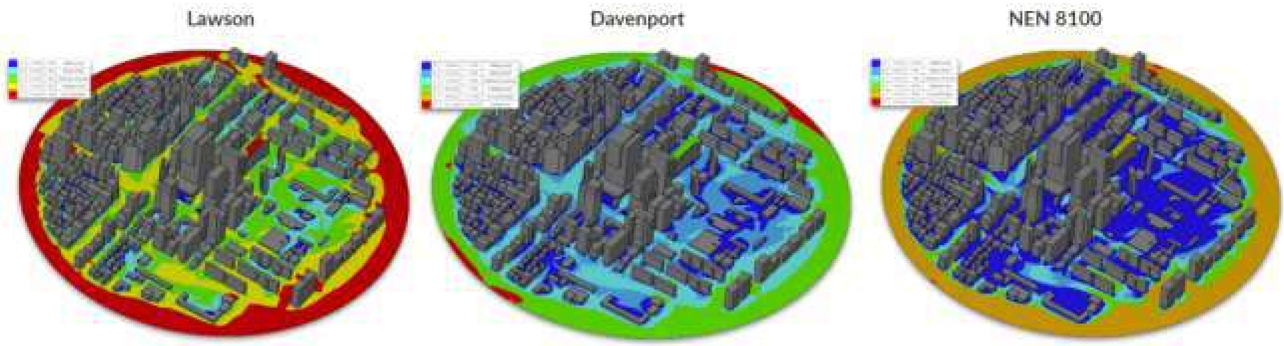


Figure 4. 18: Pedestrian wind comfort simulation with metrics. Source: Simscale.

Davenport is the first wind comfort criteria to be developed in 1975. It is divided for each type of activity. It assesses for each activity how often does the wind exceed the comfort speed in space. The longer the time it exceeds the limits, the more uncomfortable the activity becomes.

Table 4. 3: Davenport criteria for Wind Comfort. Source: Ingrid Cloud

	Preferable	Acceptable	Uncomfortable	Dangerous
Sitting	0.0 - 0.1 %	0.1 - 3.0 %	3.0 - 53 %	> 53 %
Occasional sitting	6.0 - 8.0 m/s	6.0 - 15 %	15 - 53 %	> 53 %
Strolling	0.0 - 23 %	23 - 34 %	34 - 53 %	> 53 %
Jogging or Cycling	0.0 - 43 %	43 - 50 %	50 - 53 %	> 53 %

Lawson criteria quantify the level of wind speed that is considered acceptable for typical human activities. The assumption is that the speed does not exceed the threshold values by more than 5% of the time studied.

Table 4. 4: Lawson 2001 comfort criteria. Source: Simscale.

A	4 m/s	< 5%	Sitting
B	6 m/s	< 5%	Standing
C	8 m/s	< 5%	Strolling
D	10 m/s	< 5%	Business Walking
E	10 m/s	> 5%	Uncomfortable
S	15 m/s	> 0.023%	Unsafe frail
S	20 m/s	> 0.023%	Unsafe all

The Dutch standard **NEN 8100** is the most recent one. The **discomfort threshold** is the hourly mean wind speed of **5 m/s for all activities**. The probability of exceeding the threshold wind speed is categorized in five levels. Also, **danger levels** are defined when wind speed reaches **15 m/s**.

Table 4. 5: NEN 8100 comfort table. Source: Simscale

A	5 m/s	< 2.5%	Sitting Long
B	5 m/s	< 5%	Sitting Short
C	5 m/s	< 10%	Walking Leisurely
D	5 m/s	< 20%	Walking Fast
E	5 m/s	>= 20%	Uncomfortable

Table 4. 6: NEN 8100 safety criteria. Source: Simscale

A	15 m/s	< 0.05%	No Risk
B	15 m/s	< 0.30%	Limited Risk
C	15 m/s	>= 0.30%	Dangerous

4.4.3 *Indoor Thermal Comfort with CFD*

Natural ventilation and mechanical ventilation can be simulated with CFD. An early design stage exploration of airflow strategies can guide the architectural design. Local discomfort caused by airflow can be predicted at any given point in space through horizontal or vertical sections with colour coded maps of air velocity or temperature and other comfort parameters. This data can be used by the software to calculate the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) spatially.

This type of analysis can a) confirm the design intent, b) reconsider a bold design decision due to not achieved comfort target, c) inform the decision making process towards the best solutions.

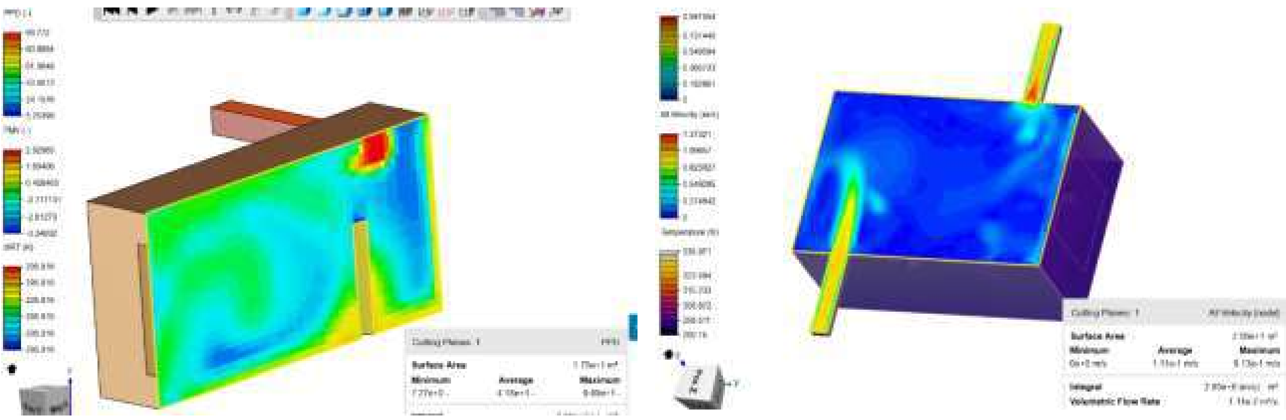


Figure 4. 19: Student room with mechanical ventilation. Simulation of Velocity, temperature, Mean Radiant Temperature (MRT), PMV and PPD in Simscale.

4.4.4 *Outdoor Comfort based on the Universal Thermal Climate Index (UTCI)*

Humans adapt the body heat balance to the thermal environment to optimise comfort and health. Outdoor comfort is usually measured by the air temperature and through weather forecasts through a **"feels like"** temperature which is different from the **Dry-bulb temperature** and is influenced from the **relative humidity** and **wind speed** of the day. To estimate the heat exchange on the human body in an outdoor environment, all the mechanisms of it need to be taken into account. Input variables include **air temperature**, **water vapour pressure**, **wind velocity**, **mean radiant temperature**, including the **short-wave and long-wave radiation** fluxes of the atmosphere, in addition to **metabolic rate** and **clothing insulation**.

The Universal Thermal Climate Index was developed under the COST Action 730 of the European Union[43]. An effort that started since 2000 from the International Society on Biometeorology (ISB) to develop a global index. The previous indexes, more than 100, had many shortcomings and did not produce comparable results for scientific research and application. UTCI objective is to create a **physiologically** based climate index that is **valid in all climates**, **seasons and scales**. It has not been adopted as an international standard to date. The model parameters include adaptive clothing, behavioural adaptation, wind effect and boundary conditions of humans walking at 4 km/h at the pedestrian level. UTCI follows the concept of equivalent temperature.

The UTCI equivalent temperature is calculated through predictive polynomial regression equations. The executable calculation is available on the project's website (www.utci.org). Applications of UTCI have been identified in the fields of public weather services, public health systems, urban planning and climate change adaptation. UTCI was introduced in 2009.

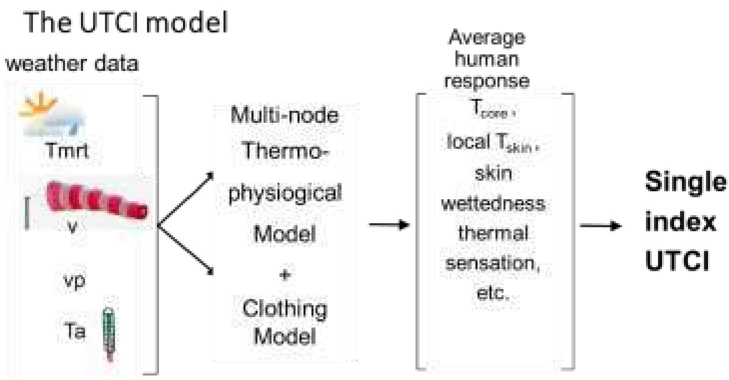


Figure 4. 20: Schematic presentation of UTCI model combining weather data with the physiological model of human thermoregulation (Fiala et al., 2001) to retrieve UTCI.

Climate data and computational methods that were developed in the following years have integrated the calculation of Thermal Comfort and UTCI, e.g. Ladybug for Grasshopper in Rhino. These new computational methods can visualize weather data, make Radiation Maps, CFD simulations, simulate and create false-colour maps for Wind Comfort, Indoor Thermal Comfort (PMV & PPD) and Outdoor Thermal Comfort (UTCI)[44]. The assessment scale of UTCI is drawn from the physiological responses simulated and has ten **"thermal stress"**[45] categories from extreme cold stress to extreme heat stress.

[43] COST Action 730. (2009). Towards a Universal Thermal Climate Index UTCI for Assessing the Thermal Environment of the Human Being. https://www.cost.eu/actions/730
[44] Naboni, E., & Havinga, L. (2019). Regenerative Design in Digital Practice. A Handbook for the Built Environment. Eurac Research. https://www.eurestore.eu/publications-and-articles
[45] Glossary of Terms for Thermal Physiology. (2003). Journal of Thermal Biology 28, 75-106

Table 4. 7: UTCI Assessment Scale categorized in terms of thermal stress.

UTCI (°C) range	Stress Category
above +46	extreme heat stress
+38 to +46	very strong heat stress
+32 to +38	strong heat stress
+26 to +32	moderate heat stress
+9 to +26	no thermal stress
+9 to 0	slight cold stress
0 to -13	moderate cold stress
-13 to -27	strong cold stress
-27 to -40	very strong cold stress
below -40	extreme cold stress

The goal of UCI is to create an international standard of outdoor temperature based on these principles:

a) Thermo-physiological significance in the whole range of heat exchange conditions of existing thermal environments.

b) Valid for all climates, seasons, and scales.

c) Useful for critical applications in human biometeorology.

4.5 Daylighting Design

UK Prescription Act (1832) – **Claim to the use of light enjoyed for 20 years**
When the access and use of light to and for any dwelling house, workshop, or other building shall have been actually enjoyed therewith for the full period of twenty years without interruption, the right thereto shall be deemed absolute and indefeasible, any local usage or custom to the contrary notwithstanding, unless it shall appear that the same was enjoyed by some consent or agreement expressly made or given for that purpose by deed or writing. (Daylight access for 20 years from other properties grants “rights to light”.)

Daylighting is the process of using natural daylight for lighting the interior and the exterior of the building.

Building design strategies should aim at optimizing solar gains throughout the year (energy performance), daylight availability, achieving healthy and productive human spaces with visual comfort (aesthetically pleasing to the eye, illuminance, glare, circadian rhythms, and other metrics).


Figure 4. 21: Office space with Venetian blinds (left); Solar-Shading made of Overhangs and Vertical Fins of the Harvard Science centre building in Cambridge, Massachusetts. Source: Wikipedia

Table 4. 8: Benefits and limitations of shading devices.

Shading Pros	Shading Cons
- Controlled solar gains (thermal comfort) - Avoid glare or very high levels of Luminance (visual discomfort) - Reduced cooling load (lower energy demand)	- May block connection to the outside/nature views (visual comfort) - Solar gains are needed in winter months to reduce heating loads

Strategies for indoor daylighting can range from external sun-shading devices to interior blinds. Daylight analysis and control need to be done at the level of the building envelope. There is a risk that the uncontrolled high luminance received, and overheating can cause discomfort and turn to the use of indoor solutions for protection from the sun like the blinds in the picture. While the integration of external or internal blinds fixed or automated can be a valid design solution, it can block occupants from having visual contact with the outside views and nature.

Definition of well-daylit space: *A space that is primarily lit with natural light and that combines a high occupant satisfaction with the visual and thermal environment with low overall energy use for lighting, heating and cooling*[46].

Benefits of Passive design strategies with shading devices:

- Reduce energy consumption with a low-tech solution
- Adapt to the changing needs of the day, provide a connection to the outdoor during the day and privacy during the night.
- Wind protection of openings
- Control views to the outside
- Heat gain control of the interior, block the sun in summer, allow in winter
- Increase the openings R-value of thermal resistance

[46] Reinhart, C., & Wienold, J. (2011). The daylighting dashboard – A simulation-based design analysis for daylit spaces. Building and Environment. 46. 386-396. https://doi.org/10.1016/j.buildenv.2010.08.001

- Desirable views often compete with unwanted solar gains, slide up/down open/close, rotate devices to achieve thermal comfort
- Sliding shutters can provide wind control for natural ventilation
- Noise control is not a primary function but can add to the noise reduction
- Horizontal overhangs can reflect sunlight into the spaces
- Transform indoor and outdoor space
- Protect the building from the outside at night or not used periods of the year
- Adjustable blades for light and wind control

4.5.1 *Lighting metrics*

Luminous intensity: Power emitted by a light source in a particular direction. It is measured in candela.

1 candela = 1 lumen / steradian

Luminous flux: the measure of the total amount of light emitted by a source. It is measured in Lumen.

Lumen = Candela* Steradiant

Luminance: the measure of the **density of luminous intensity**. It indicates how much luminous power reaches the eye of an observer looking at the surface from a particular viewpoint**. L [candela/m^2]** Luminance is the measure of the amount of light reflected or emitted from a surface. It is used to evaluate visual comfort and glare in the interior.

Glare is a subjective human sensation that describes "light within the field of vision that is brighter than the brightness to which the eyes are adapted" (HarperCollins, 2002). Existing metrics include **Unified Glare Rating (UGR)** and the **Daylight Glare Index (DGI)**.

Daylight Glare Probability (DGP) is a recent index which improves correlation with user assessment. It was developed by Wienold and Christoffersen. The Radiance module Evalglare was created to generate these metrics from a hemispherical fish-eye Radiance luminance image.

Table 4. 9: DGP Visual Comfort Ranges. Complete source: Table E.1 in EN 17037:2018

DGP < 35%	imperceptible
35% < DPP < 40%	perceptible
40% <DGP < 45%	disturbing
DGP > 45%	intolerable

Illuminance is the most widely used photometric quantity to describe the light in spaces. It is defined as the total **luminance flux** incident on a surface and measured in lumen per unit **area** or lux. E **[lux = lumen/m2]**.

Interior Illuminance should lie between 100 lux and 3000 lux.

Daylight factor (DF) is a **static** daylight availability metric that is expressed as a percentage the amount of daylight available inside a room (on a work plane) compared to the amount of unobstructed daylight available outside under overcast sky conditions (Hopkins, 1963). DF should lie between **2% - 5%.**

DF > 2% (electric light may still be needed), **5%** (strongly daylight).

Building parameters that determine the magnitude and distribution of the daylight factor in space are:

- size, placement, location and transmission properties of the facade and roof openings.
- The size and organization of the space.
- The reflective properties of internal and external building surfaces.
- The degree to which external structures obstruct the outside views.

Limitations of DF: a) not related to climate, b) fixed lighting requirements, c) no occupancy patterns, d) not taking into account shading devices.

Daylight factor levels are measured at work plane height usually **0.85 m** above the floor, with a **0.5 m border from the walls** around the perimeter of the work plane.

Daylight autonomy (DA) is a **dynamic climate-based** daylight availability metric that corresponds to the percentage of the occupied time when the target illuminance at a point in space is met by daylight. It is dependent on climate and geographic location. **DA > 50%** is a recommended value (for 50% of the time daylight levels are above the target illuminance) (IESNA, 2013).
Daylight Autonomy should vary around **20% to 90%** across the whole space.

Useful daylight illuminance (UDI) is a modification of the Daylight Autonomy. Mardaljevic and Nabil conceived it in 2005. It represents the annual occurrence of illuminances that is within a "useful" range for occupants. Daylight illuminances in the range of 100 to 300 lux are considered effective or to be integrated with electric lighting.

Green Building rating systems such as LEED, BREEAM and WELL make use of Daylighting as an important feature and with performance-based threshholds to meet for achieving credits and certification.

LEED v4.1[47] incorporates daylight credits in the Indoor Environmental Quality area, as shown below:
Quality Views (1 credit)
Achieve a direct line of sight to the outdoors via vision glazing for 75% of all regularly occupied floor area.
Daylight (1-3 credits) Option 1
Perform annual computer simulations for spatial daylight autonomy$_{300/50\%}$ (sDA$_{300/50\%}$)

However, Simulation tools are not the only source for Daylight prediction. Architects and Engineers have relied and continue to do so based on **Experience, Rules of Thumb, Design Guidelines**, and to some minor extent to **Manufacturer information** and **Scale models**[48].

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[47] U.S. Green Building Council. (2020, January 10). LEED v4.1 Building Design and Construction rating system.
[48] Galasiu, A., & Reinhart, C. (2008). Current daylighting design practice: A survey. Building Research and Information. 36. 159-174. https://doi.org/10.1080/09613210701549748

BIM Design Authoring or CAD Modelling tools that can simulate sun path diagrams can be used for shadow studies for exterior or interior design. However, they are not able to produce validated lighting analysis and metrics. Downstream applications such as Velux Daylight Visualizer or DIALux can calculate the most widely used metrics like luminance, daylight factor, illuminance and glare.

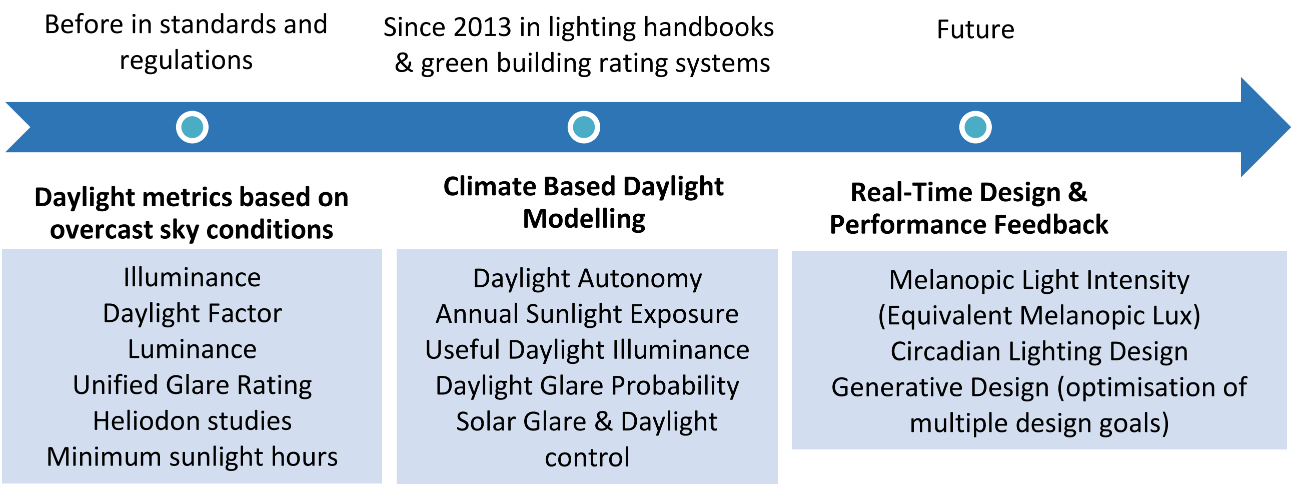

Figure 4. 22: Trajectory of evolution of Daylighting design requirements and metrics.

DIVA Plug-in for Rhino is a tool capable of handling environmental performance evaluations of buildings and urban settings such as Radiation Maps, Luminance, Illuminance maps, Climate-Based Daylighting Metrics (spatial and temporal), Annual and Time Step Glare Analysis, and Thermal Zone Energy Calculations.

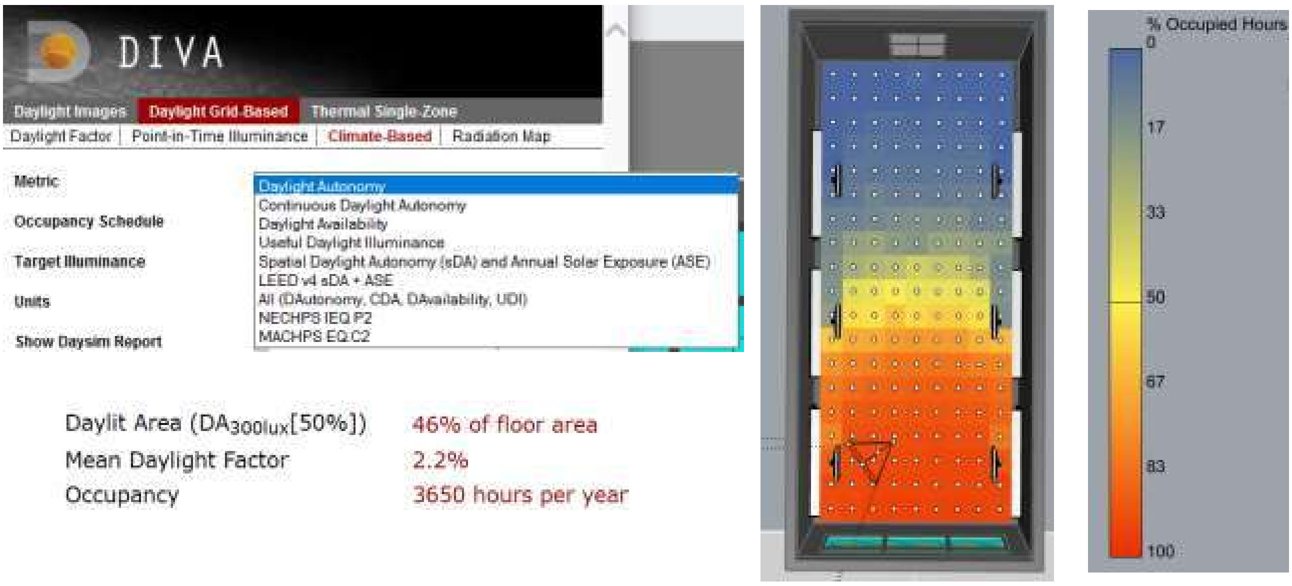

Figure 4. 23: DIVA's climate-based metrics, results of Daylight Autonomy for sample office space.

Figure 4. 24: Annual Glare based on DGP of sample office simulation.

First, the model has to be set correctly for the analysis. Results of analysis can inform the design decisions. Design changes and simulation iterations can be repeated to achieve the desired performance and comfort.

Table 4. 10: Exchange Information Requirements based on Level of Information Need (ISO 19650) for Daylighting Analysis with DIVA.

Level of Definition (UK, in former PAS 1192-2), Level of Development (US, AIA, BIMForum 2019)	
Geometrical Information	Alphanumerical Information
- Model Geometry (LOD 200 and higher) - Model Units in meters - A ground plane needs to be modelled - Obstructions (adjacent buildings, trees) - Window frames and Mullions (if not modelled, reduce visual transmittance for windows and skylights) - What you see (model) is what you get - Simplified one-single surface for double or triple glazing windows. Daylight tools assign optical properties of multiple glazing layers to a single surface. - Shading devices (LOD 300 and higher) - Control that sensors have the correct orientation, e.g. work plane nodes are facing up, and ceiling sensors are facing down.	- No IDM, MVD specified for BIM Model (user custom exchange & experience) - Daylighting performance metrics and ranges - Validated Simulation Engine (Radiance, Evalglare, Energy Plus) - Sky conditions for the type of simulation - Climate Data (solar radiation, direct and diffused radiation W/m^2) - Material Properties: Light Reflectance Value, Color RGB values, and Finish (specularity, roughness) - Visual transmittance of the glazing - Work Plane grid nodes of, e.g. 0.5m x 0.5m and around 0.85m above the floor. (based on the standard followed) - Sky angle, obstruction angle

4.6 Generative Design

Architects are experts in finding the right balance of **design tradeoffs** between aesthetics, client requirements, insights from experience, and scientific evidence they can get. When all these elements are combined in a holistic process, architecture and human experience are elevated to a higher level. Every decision and stage can result in inter-connected effects that have impact during construction, operation or a specific time of the year. The best architects try fo find a **balance** between the **tacit knowledge and design evidence**. Their design thinking process is always about competing project requirements, goals and client satisfaction.

The computational design process allows to translate in rules the design input parameters with boundary conditions and create outputs related to performance and optimization goals for lighting, low energy consumption, the layout of urban/building spaces and other goals. This process tries to extrapolate measurable design parameters and create relations that can influence the design solutions related to geometry/spatial quality, performance and comfort of occupants. While tacit knowledge may be difficult or impossible to transfer in computational terms, the computational approach can **guide design choices**, or it may only **discourage certain bold/bad decisions**. What is decisive is that the computational process extends the design space with solutions generated by the computer that the designer has no time to explore, has not thought of, does not explore consciously or unconsciously. It increases the possibilities and understanding of design choices. Usually, analysis tools or the designer focuses on handling fewer criteria of one domain. The synthesis process handles multiple criteria. The synthesis is now extended to all relevant project stages, with cascading effects passed on the next step, done by the design team in collaboration with the client.

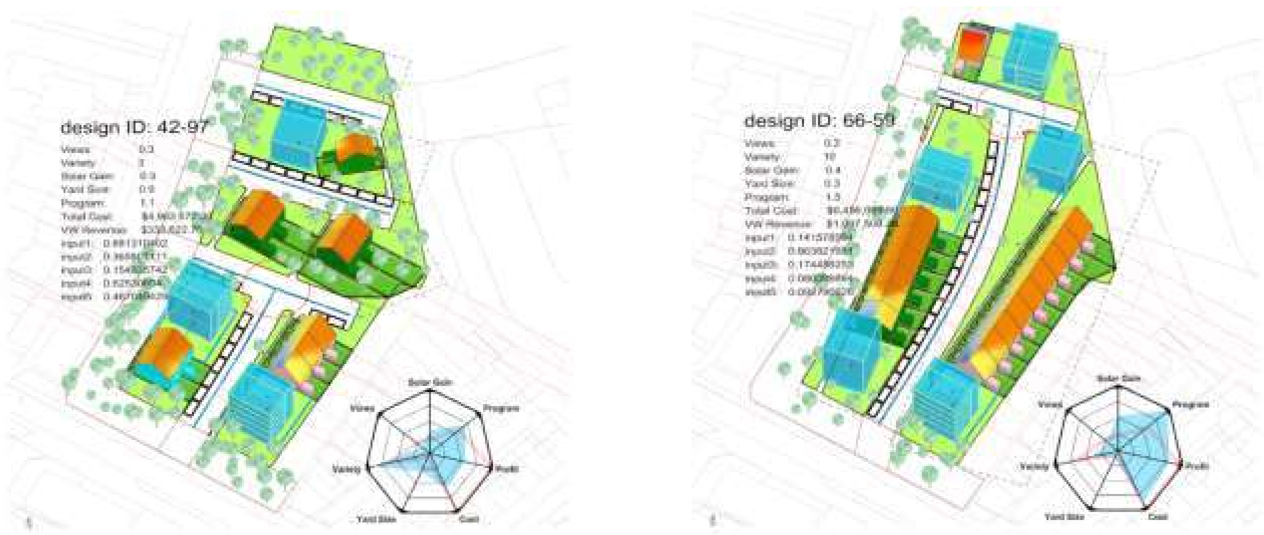

Figure 4. 25: The Living by Autodesk. (2018). Advanced Design Exploration with Computational tools and Generative Design optimization for Alkmaar Housing Masterplan in the Netherlands.

With Computational-aided Design, it is possible to create multi-criteria, use data and understand performance. Understanding microclimate, energy flows, and human comfort can not rely only on generative design computer solutions. Data-driven decision-making is considered a smart approach, but it can turn costly or dangerous when something that appears to be true is not right. At the same time, generative design solutions are based on genetic algorithms working to create solutions based on the survival of the fittest. While this may be a valid design goal to pursue, it can take away the designer from the **whole solutions space** which was set up with relative effort. Nature has demonstrated that life on earth and plants are not only a result of evolution but can be a result of "**exploration**" or "**adaptation**". The possibility to optimize specific design criteria, e.g. performance, net-zero energy, should **not exclude the exploration of the design space itself**. At the same time buildings have a conception, a life and an end. Urban environments and buildings are **adapting to changes** with interventions of refurbishments, energy retrofits, and green strategies. Thus, the design goal should strive to be **flexible for evolution** (e.g. retrofit, changing operational requirements), **restore** and **regenerate** nature processes and promote human health. **The design space should not be limited or look only at performance but strive for resilience and adaptation.**

"Ladybug tools" are a set of open-source plugins for Grasshopper that started in 2013 that support environmental design. Dynamo and Grasshopper, which are both VPLs, can be used by designers to take advantage of their computational approach and drive the design process.

The computational design comes with the **technological dilemma**, much like 2D and 3D CAD modelling that can have **drawing errors**, **modelling can be based on wrong data**, incorrect modelled objects or relations, and as a result, misused. The designer may not adequately understand the model they have built, make assumptions, limitations by the tool, or get results that may look acceptable but are wrong. This can lead to the wrong decisions during the design process, and in the end, detracting value rather than adding it. A critical view of the process and the results, and the integration of tacit knowledge and other non-digital methods of design and analysis remains relevant still today.

4.7 Building Energy Modelling

A Building Information Model can be used to create a Building Energy Model (BEM) from a coordination model or automatically in the Design Authoring tool. An accurate BEM can be prepared using the semi-automated process of BIM integration with Building Simulation software through open standards such as IFC or gbXML. A manually created BEM requires rework of the geometrical information, but in turn provides greater benefits in having full control over geometry, assigning thermal zones and inputs for the whole range of parameters required for energy simulation. An essential part of BEM is to understand energy loads since the early stage, inform design decisions and support the selection of natural/mechanical ventilation strategies and HVAC systems.

The installation of indoor air conditioning systems for summer cooling of buildings can result in increased outdoor urban temperature because heat is extracted from indoor spaces and emitted in the outside. The Urban Heat Island effect (UHI) rises from the heat and greenhouse gas emissions released from HVAC. Energy demands and UHI grows in a circular loop of negative environmental performance, health risks and nature stress.

4.7.1 *Energy metrics*

From the first law of thermodynamics, the total energy of a closed system remains constant.

Building Heat Balance: $E_{received} = E_{released} + E_{thermal\ mass}$

Volumetric Heat Capacity is the ability of a volume of a substance to store internal energy under temperature change. It may be derived by multiplying the density of a material by its specific heat. [kJ/m^3K]

Thermal Mass is the ability to store heat while experiencing a temperature change. The thermal mass of an element depends on its volume as well as its volumetric heat capacity.

Thermal Mass = Volume x Volumetric Heat Capacity

Solar Heat Gain Coefficient (SGHC): Fraction of incident total solar radiation that reaches the interior.

Visual Transmittance (T_{vis}): Fraction of incident visible radiation that reaches the interior.

Internal Heat Gains is heat generated in buildings from the program of use and is organized in three groups:

- Heat from occupants
- Heat from electrical equipment and appliances
- Heat from electric lighting

Heat from occupants:

100 W/person (sensible heat) x no. of persons (max occupancy) / m^2 (space area) = W/m^2 or persons/m^2

Internal gains are easy to model but hard to guess the patterns of behaviour and use schedules.

Ventilation is used to provide for indoor air quality. It can be composed of forced or natural ventilation, infiltration, suitably treated re-circulated air, or a combination. The introduction of air inside the building is desired and is divided into natural ventilation and forced ventilation.

Natural ventilation is the flow of air through open windows, doors, and passive design strategies with other building envelope solutions.

Forced ventilation is the intentional movement of air in and out of a building using fans, intake and exhaust vents.

Infiltration is the flow of outdoor air into a building through cracks and other unintentional openings. Infiltration is also known as **“air leakage”** into a building.

The Thermal Load is introduced in the Heat Balance equation to determine the energy needed to keep the heat balance equation within the **comfort range of 20 to 26° in the interior during the year**.

Energy Use Intensity is the annual energy use of a building divided by its floor area. It can be a measure of how efficient a building is, in terms of climate, program, heating, cooling and daylighting.

Operative Temperature is a simplified measure of human thermal comfort derived from air temperature, mean radiant temperature and air speed.

When Air Speed < 0.1 m/s then T_O =(Tair + MRT)/2

MRT = globe temperature + 2.42 x air velocity

4.8 Life Cycle Assessment and carbon-positive design

Life Cycle Assessment (LCA) is defined as *"the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle"*. (ISO 14044).

The first application of LCA has been the comparison between plastic and glass bottles done by Coca Cola in 1969. Research on the topic started mainly in the 1970s. Bruce Hannon coined the term **Embodied Energy**. The first standard for LCA application was created with the **ISO 14040 Environmental management** — Life cycle assessment — Principles and framework in 1997.

Greenhouse gases (GHGs) are grouped within the **Global Warming Potential Indicator** and defined as **"CO_2 equivalent"** in the unit **kgCO_2eq**. Material, construction processes and building energy demands are converted into primary energy and kgCO_2eq through coefficients.

Buildings are challenging for LCA application because the construction of even a small single-family building requires the production of hundreds of components. Standardization is a relatively small application usually for prefabricated buildings compared to the whole range of building design. The lifetime of a building can be determined according to the **service life**, but it is usually **50 years or more** and is highly **variable with performance, adaptative reuse, and retrofit**. The end of life brings other challenges. *Where do the materials flow?* Demolition or deconstruction can be thought of as the **inverse process of construction**. It becomes a process to output up-cyclable materials, as new inputs for construction and the rest ending up in landfills.

New approaches are being developed to attach a **Unique Object Identifier** for every model element of the Digital Twin of the real-world asset. This information can be used to analyze, measure performance or structural integrity of the component, perform maintenance, replace it in the future, or decommissioned at the end of life of the asset. This whole new approach with Digital Twins brings opportunities to connect BIM Models with databases and networks of construction activities aiming to create a closed-loop cycle of sustainable building industry. At the same time, more layers of complexity are added which need new methodologies to assess LCA in new models of the construction life cycle. The use phase of assets has the highest impact since it relates to the use of the building for years and decades to come.

The Climate Emergency Design Guide defines the Whole Life Carbon as composed of embodied carbon from upfront construction processes and operational carbon from the in-use phase of the asset[49].

Embodied carbon *is defined as the carbon emissions associated with the extraction and processing of materials and the energy and water consumption used by the factory in producing products and constructing the building. It includes 'in use' stage (maintenance, replacement) and 'end of life' stage (demolition, deconstruction) and any relating to the above.*

Operational Carbon *as the carbon dioxide and equivalent global warming potential (GWP) of other gases associated with the in-use operation of the building. Usually includes carbon emissions related to heating, hot water, cooling, ventilation, and lighting systems, as well as those associated with cooking, equipment, and lifts (e.g. both regulated and unregulated energy uses).*

Net zero operational carbon refers to: *"A new building that achieves a level of energy performance in-use in line with our national climate change targets that does not burn fossil fuels and that is 100% powered by renewable energy".*

Whole life carbon (WLC) *is composed of embodied carbon and operational carbon. The purpose of using WLC is to move towards a building or a product that generates the lowest carbon emissions over its whole life or sometimes referred to as 'cradle-to-grave'.*

4.8.1 *Global Carbon footprint and construction correlation*

The IPCC report estimates that human activities are responsible for approximately **1.0°C of global warming above preindustrial levels**, with a likely range of **0.8°C to 1.2°C**. Warming from anthropogenic emissions has been observed on land and ocean ecosystems across the globe. Limiting global warming means reducing global anthropogenic emissions. The **Carbon Budget** represents the additional CO_2 entering the atmosphere that would result in a **1.5°C global warming**. Two estimates are predicted, the first of 420 $GtCO_2$ with a two-thirds chance (66%), and 580 $GtCO_2$ with a 50% probability. The remaining carbon budget is estimated to being reduced each year by current emissions of **42 ± 3 $GtCO_2$ per year**. Given this rate, the first scenario of 1.5°C global warming is coming within ten years from the date of the report, and 14 years for the 50% probability.

[49] London Energy Transformation Initiative. (2020). Climate Emergency Design Guide. https://www.leti.london/cedg

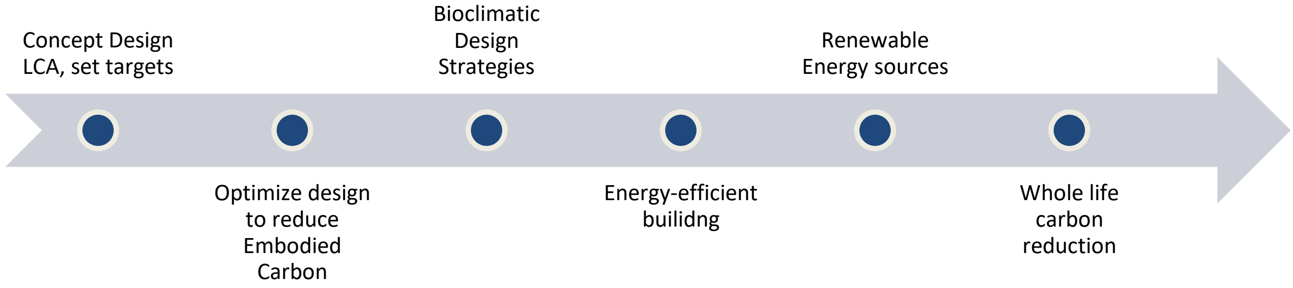

Figure 4. 26: Roadmap for Carbon Positive Design.

The European Union aims to become the first **climate-neutral continent by 2050**. The European Green Deal sets the roadmap towards a sustainable EU economy with **net-zero greenhouse gas emissions**. The built environment is responsible for approximately **40% of energy consumption and 36% of CO_2 emissions** in the EU[50]. Given the findings of the IPCC SR1.5°, the construction sector has to play a significant role in achieving the European Union's climate and energy goals. The sector would need to decrease carbon emissions drastically and strive to create Carbon Positive Designs within the following years to limit global warming.

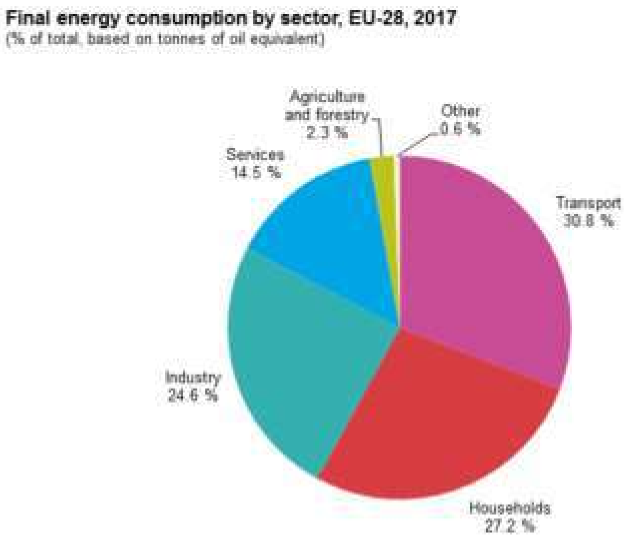

Figure 4. 27: Final energy consumption by sector in the EU. Source: Eurostat, Energy statistics.

Households and Services account for the energy from buildings in the EU reports. In the presented chart for EU countries in 2017, the cumulative consumption by buildings is 41.7%.

The effects of global warming are being felt in major European capitals. The analysis of 100 million meteorological data points, of more than a century of weather data from European Centre for Medium-Range

[50] Eurostat. (2020, April 15). Energy statistics - an overview. Retrieved May 27, 2020, from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview

Weather Forecasts (ECMWF), gives insights on the temperature increase in European cities in the 21st century (2000-2018) compared to the past century since 1900.

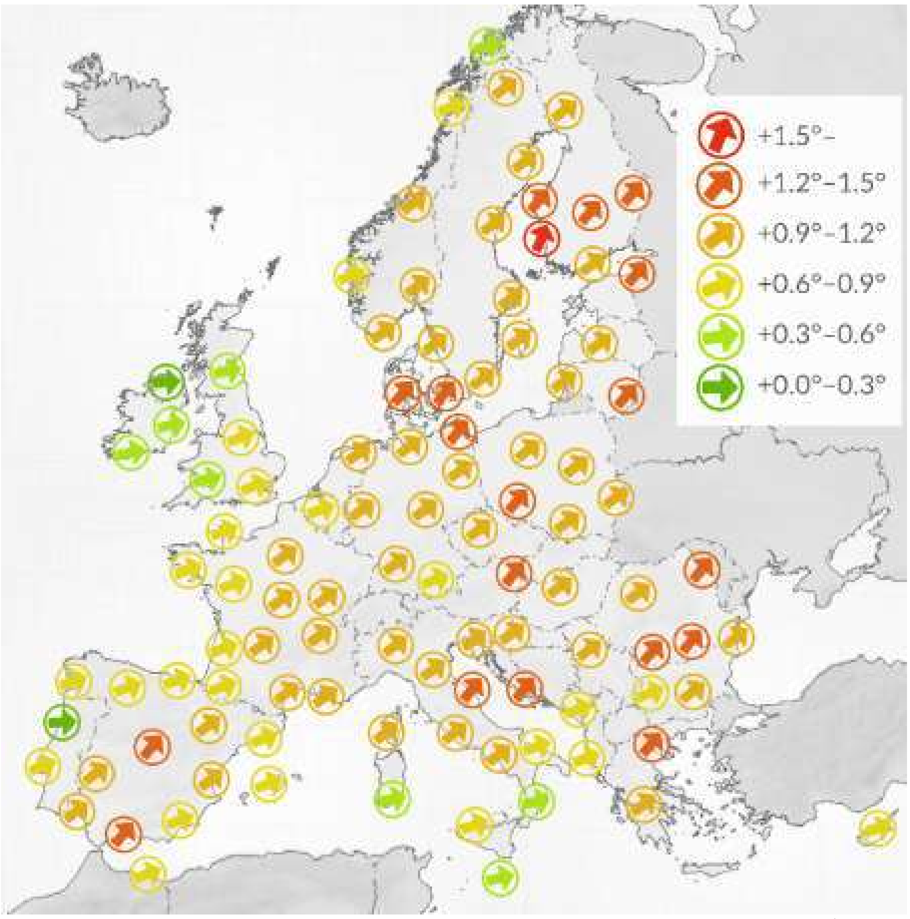

Figure 4. 28: Temperature increase in European. Source: EDJnet[51].

The effects of rising temperatures cause more prolonged droughts and heatwaves. Heat Island Effects and "too hot for school" temperatures are some of the consequences. Action is needed to mitigate adverse effects and adapt to climate change.

The population growth and global urbanization are related to the need for new construction, which is set to **double the size of the global building stock in the next 40 years**, **within 2060**[52]. As population and global floor area grow, so are energy demands and carbon emissions. Renewable Energy, Biogenic carbon materials, Energy-efficient buildings, nature protection and restoration, are needed to stay within planetary boundaries.

[51] Every major city in Europe is getting warmer. (2018, September 24). European Data Journalism Network. https://euobserver.com/environment/142894

[52] International Energy Agency and the United Nations Environment Programme. (2018). 2018 Global Status Report: Towards a zero-emission, efficient and resilient buildings and construction sector. https://www.worldgbc.org/news-media/2018-global-status-report-towards-zero-emission-efficient-and-resilient-buildings-and

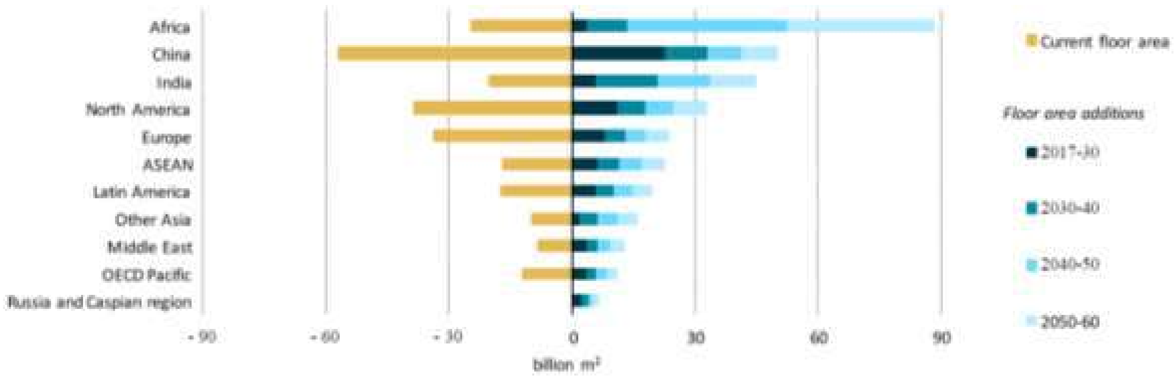

Figure 4. 29: IEA & UNDP. (2017). Global Status Report. Floor area increase to 2060 by key regions.

Carbon Positive Design means buildings and outdoor spaces that are made to **reduce carbon footprints** and **increase carbon sequestration** through design, materials and measured trade-offs. The Climate Positive Design initiative is offering landscape designers a novel tool similar to an LCA assessment to understand the impact of hardscape/landscape ratios, materials, types of vegetation used and outputting the number of years needed for the design to turn carbon positive[53].

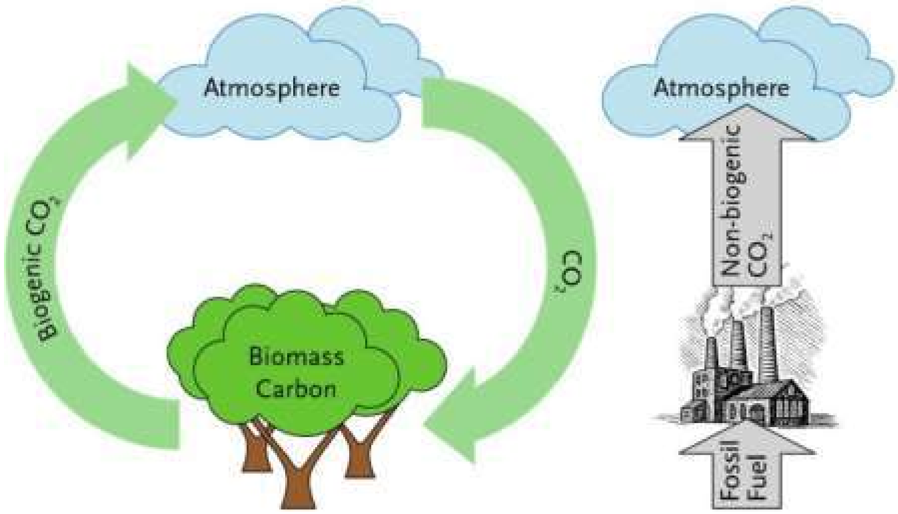

Figure 4. 30: IEA Bioenergy. (n.d.). Fossil versus biogenic CO_2 emissions [Diagram].
https://www.ieabioenergy.com/iea-publications/faq/woodybiomass/biogenic-co2/

The carbon released in the atmosphere by fossil fuels contributes to global warming. Fossil fuel use increases the total amount of carbon in the atmosphere, thus reducing the carbon budget. The Biogenic carbon cycle is the emissions related to the natural carbon cycle. Employing wood as a construction material is a strategy to sequester carbon from going into the atmosphere. Burning biomass for energy production would result in carbon that is part of the biogenic carbon cycle, thus not reducing the carbon budget.

[53] Climate Positive Design. (2020). https://climatepositivedesign.com

Table 4. 11:Life-Cycle Stages as defined by EN 15978, Tally report screenshot.

PRODUCT	CONSTRUCTION	USE	END-OF-LIFE	MODULE D
A1. Extraction **A2. Transport (to factory)** **A3. Manufacturing**	**A4. Transport (to site)** ***A5. Construction Installation***	B1. Use **B2. Maintenance** **B3. Repair** **B4. Replacement** **B5. Refurbishment** ***B6. Operational energy*** B7. Operational water	C1. Demolition **C2. Transport (to disposal)** **C3. Waste processing** **C4. Disposal**	**D. Benefits and loads beyond the system boundary from:** **1. Reuse** **2. Recycling** **3. Energy recovery**

4.9 Key Performance Indicators (KPIs) for Regenerative Design

A BIM integrated Regenerative Design approach makes use of geometrical information with data-information (materials, properties, costs) that can be extendable and connected to databases for analysis (climate data, LCA databases of building materials, Wind Rose for CFD simulation). Computational tools put in relation data from BIM models with quantifiable outputs for achieving optimization targets. In the case of LCA, benchmarks are not yet available. Voluntary reporting and optimization from baselines set by the designer's side exist in some Sustainable green building frameworks and rating systems[54].

The following table organizes KPIs in the form of measurable metrics that can be used for quantifiable alphanumerical information in BIM models through design, simulation, or algorithmic tools arranged according to the three macro-areas or sustainable Design Methods of a Regenerative Design framework. The Regenerative benefits of the Nature pillar are harder to quantify with measurable metrics during the delivery phase of assets and require longer times to evaluate outcomes and long-term impact during the whole life cycle of the development. While Green practice, rating systems and environmental policy measure the performance through metrics and evaluation, Regenerative Development would require a different qualitative approach and longer timeframes for "extremely patient science" to understand and notice the benefits of natural and cultural phenomena taking place[55].

Research and new metrics are under development such as the Biodiversity Net Gain[56], trying to quantify the outcomes with a metric based on the natural systems state before and after the development. The biological non-visual effects of light on humans, can be measured with an alternate metric based on the Melanopic Light Intensity weighted to the intrinsically photosensitive retinal ganglion cells (ipRGCs) instead of the cones[57].

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[54] Bionova. (2018). The Embodied Carbon Review. https://www.oneclicklca.com/embodied-carbon-review
[55] Cole, R. J. (2012). Regenerative design and development: current theory and practice. Building Research & Information, 40:1, 1-6. https://doi.org/10.1080/09613218.2012.617516
[56] Baker, J., Hoskin, R., Butterworth, T., Kerry, K., & White, N. (2019). Biodiversity Net Gain: Good Practice Principles for Development, A Practical Guide. CIRIA, CIEEM and IEMA. https://cieem.net/resource/biodiversity-net-gain-good-practice-principles-for-development-a-practical-guide/
[57] International WELL Building Institute. (2020). The WELL Building Standard v2 Pilot™.

As new research improves our understanding of human health, well-being, and on the functioning of ecosystems, new requirements and methodologies will be developed to evaluate qualitatively and quantitatively the sustainable outcomes for the planet.

Table 4. 12: Metrics and alphanumerical information for a Regenerative Design framework organized within the three dimensions of Climate, People and Nature.

Climate (performance)	**People (comfort and well-being)**	**Nature (circular and resilient)**
Illuminance lux	Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD)	Nature-Based Solutions (urban forestry, bioswales, wetlands, permeable surfaces, green infrastructure)
Luminance cd/m^2	Adaptive Model of Thermal Comfort	Wastewater treatment through plants and microorganisms, wetlands to turn it back into freshwater
Daylight Factor (DF) %	Outdoor Comfort based on the Universal Thermal Climate Index (UTCI)	Passive Design Strategies (solar heating, internal heat gains, natural ventilation, ground temperature vectors)
Daylight Autonomy (DA) %	Pedestrian Wind Comfort (Lawson Criteria, Davenport Criteria, NEN 8100, wind speed)	Transform waste into a resource for energy production (heating) or electricity (back to the grid).
Useful Daylight Illuminance (UDI) %	Air Quality (Pollutant levels of VOCs, POPs, PM2.5, PM10, CO_2, NO_2, SO_2, Ozone, Radon)	Circular Design - extend life of products / objects / materials, recycle, upcycle
Minimum Sunlight hours	Water Quality (turbidity, coliforms, organic and inorganic contaminants)	Designing out waste
Renewable Energy Potential	Daylight Glare Probability (DGP)	Rainwater collection, reuse in building, landscape irrigation
Annual Energy Loads kWh	Views to the outside	Capture Carbon - Building materials of organic origin (structure, insulation, interior etc.)
Energy Use Intensity (EUI) $kWh/m^2/year$	Melanopic Light Intensity (Equivalent Melanopic Lux)	Biophilia (introduction of vegetation inside and outside of building envelope
Embodied Carbon Benchmark $kgCO_2eq/m^2$	Smart Building – Sense-able Occupancy and Control	Air, Water and Light pollution as a threat for Ecosystems and Biodiversity
Operational Carbon $kgCO_2eq/m^2/year$	Overheating hours	Biodiversity Net Gain
Life Cycle Global Warming Potential or Whole Life Carbon (GWP) $kgCO_2eq/m^2/year$	Annual Sunlight Exposure (ASE)	

5 BIM INTEGRATED REGENERATIVE DESIGN

"When people talk, listen completely. Most people never listen." - Ernest Hemingway

"Most people do not listen with the intent to understand; they listen with the intent to reply."
- Stephen R. Covey

The way people communicate says a lot about them, even when they are not speaking. Architectural design can be thought in the same way. The advice for being a better listener should be followed from a designer's perspective. The process should start by understanding the local climate, context, sun, energy flows, people, and nature. Only after that, start answering and exploring ideas.

Design concepts can be the first, or the last thing drew when the project has been completed. Architects should not tend to put the sun, nature and arrows of energy flow to embellish drawings but test and validate designs solutions towards performance. There is a tendency of designing to impress, have an impact, and create complex shapes. Computational tools can handle very easily complex geometry, and there is capital that can build without limitations whatever is possible. Architecture practice needs to be more critical towards the freedom of computational tools. The societal challenge of our time is the environmental concerns of climate change and meeting human needs within planetary boundaries by reshaping the economy and human activities and the urban fabric by design.
Every climate and site requirements are different. The Genius Loci or the spirit of the place is the first source to listen and understand the site and all that it can tell us for a Sustainable Design Practice.

5.1 Gerbiceva Youth Housing Community

Figure 5. 1: Protim Ržišnik Perc. (2019). Gerbičeva Youth Housing Community project [Rendering].

Address: Gerbičeva Ulica 51, 1000, Ljubljana

Design: Protim Ržišnik Perc arhitekti in inženirji d.o.o.

Client: The Housing Fund of the Republic of Slovenia

Project type: Residential building for special social groups

Type of construction: New construction of multi-dwelling apartment building

Gross Floor Area: 4,436.20 m^2

Associated Services: Common areas & kitchen, laundry, study areas

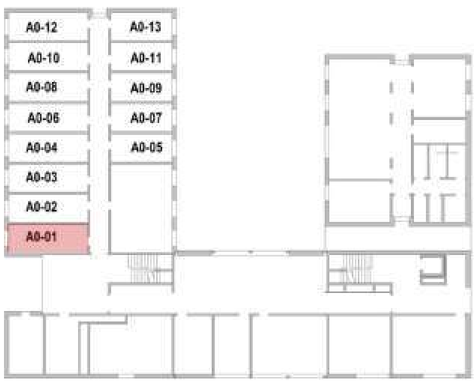
Number of units: 111

Presentation of the project:

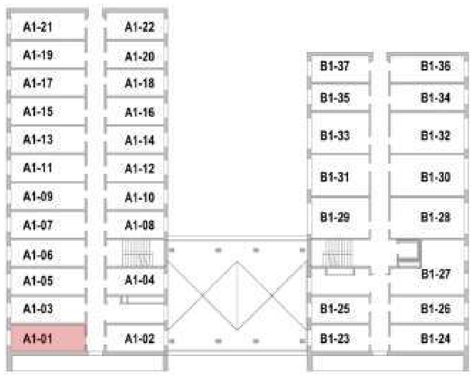
The facility represents a residential development of temporary residences for young people. The objective is to support young people between 18 and 28 years of age, especially those that have completed university studies towards the first years of economic independence. The ground floor has common areas such as social spaces, laundry, study rooms, dining room with kitchen, IT space, technical rooms. Entrances to the facility are placed in the west and one from the east side.

The development is made of two buildings. The project orientation is West-East with corridor distribution of apartments along the North-South axis. The two buildings are connected on the southern part on the ground floor where the entrances and distribution spaces are located. The West building has four stories above ground, and the East wing has three stories above ground. The facility features 111 accommodation units organized into five different typologies depending on the size or number of beds. A tenth of these units is adapted for occupants with disabilities. The upper floors feature loggias along the south facades as shared spaces. The northern side of the buildings has bicycle stands with a protective canopy. On three sides of the building, Western, eastern and south, parking spaces are located.

Ground Floor



First Floor



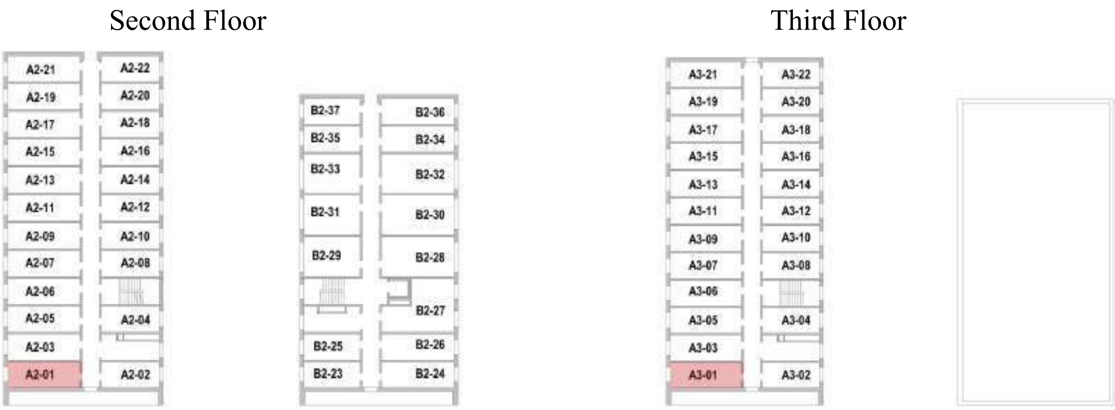
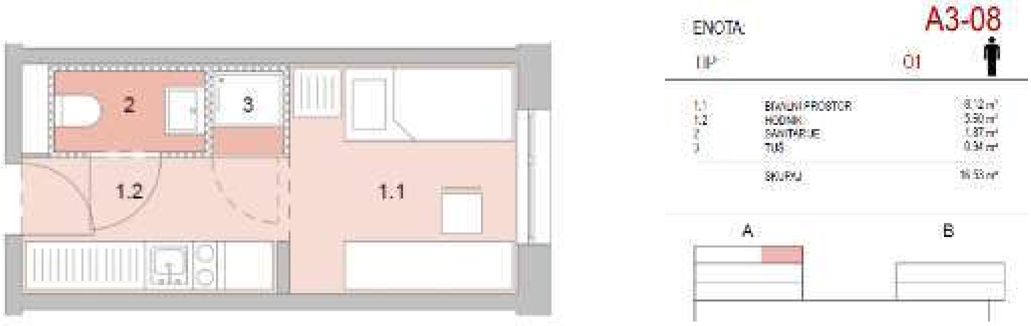
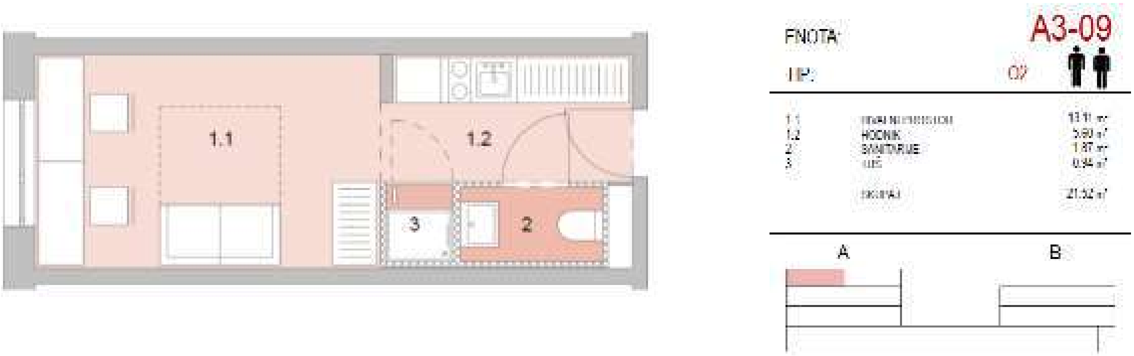


Figure 5. 2: Gerbiceva Youth Housing Community. Key Plans with accommodation unit tags.

1 Person accommodation Unit 01 (16.53 m^2)



2 Person accommodation Unit 02 (21.52 m^2)



3 Person accommodation Unit 02+1 (34.56 m^2)

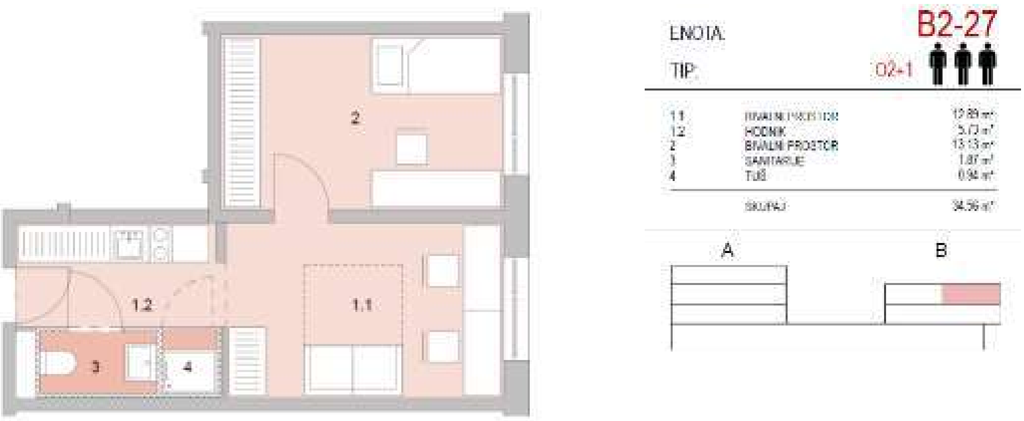
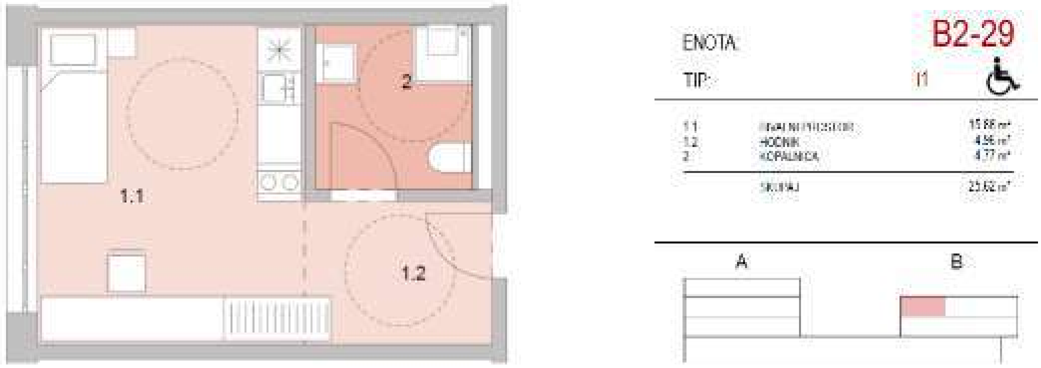


Figure 5. 3: Typology of accommodation units

1 Person-Flexible Accommodation unit L1 (25.63 m^2)



2 Person-Flexible Accommodation unit L2 (33.24 m^2)

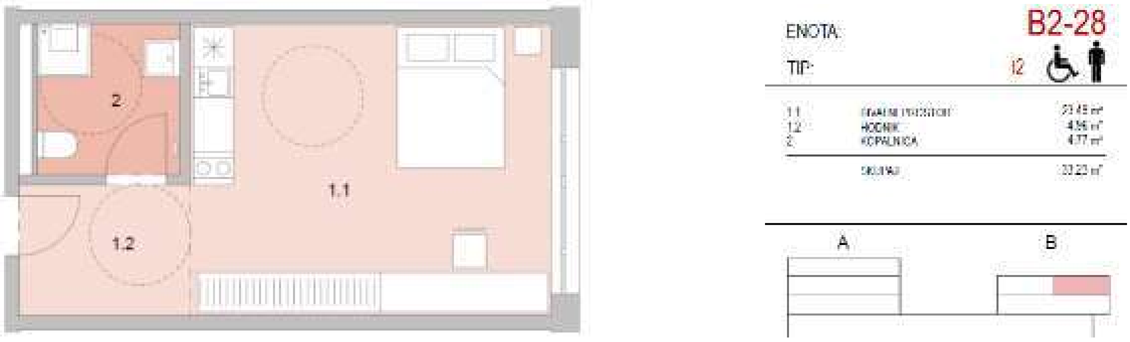


Figure 5. 4: Typology of accommodation units with disability compliance.

Heating and Cooling:

Mechanical ventilation will provide heating and cooling in winter and summer. The heating of common areas on the ground floor is done via floor heating and additional convectors which will be most used for cooling in summertime. The ventilation of accommodation units is intended to be controlled, energy-efficient with humidity regulation. Air inlets are placed in living areas. The air outlets are located in the kitchen and the bathroom. Heat recovery units are installed to exchange heat. The facility will be connected to the distribution network of natural gas of Ljubljana d.o.o. with the existing public infrastructure. Gas will be used for heating and hot water production. The use of gas for kitchen appliances is not included.

Landscape Design:

The public space is subdivided into roads, parking, green areas of the facility and inner private courtyard. The plot area is approximately 3,872 m^2. The open areas comprise a total of 1,249 m^2, of which 762 m^2 (61%) Green areas, and 487 m^2 (39%) open outdoor spaces.

a. Outdoor areas, comprising paved and green spaces are intended to be be used by the residents;

b. The entry areas form the north have bicycle stands;

c. Road-side parking types are placed on west, south and east areas, comprising the planting of ornamental trees and shrubs.

Urban Parameters according to regulation from the Municipality of Ljubljana:

Green spaces = 762 m^2

Outdoor areas = 487 m^2

Plot Area (PT) = 3,872 m^2

Standards:

Open Space Ratio (OSR) = (Green + Outdoor)/PT = 1,249 m^2/3,872 m^2 = 0.32 → 32% > 30% (regulation)

Provide a minimum of 5 m^2/inhabitant of green and outdoor spaces

111 x 5.00 m^2 = 555 m^2 minimum required → OSR = 1,249 m^2 > 555 m^2

Selected plants are adapted for the local climate and tolerant to given growing conditions. They have a flexible root system, are well-distributed and do not require maintenance. The selected deciduous species do not require special care. Shrubs must be trimmed regularly to preserve the form and avoiding excessive spread. The landscape presents a comprehensive arrangement, which is designed according to the specific programme of residences for young people. Outdoor space is designed to allow for the possibility of transformation by introducing various additional elements (urban equipment, community garden).

5.2 Big Data, Comfort, and the Psychrometric chart with computational tools

In the following sub-sections Ladybug Tools for Grasshopper in Rhino with Big Data is used to create visualizations for the location of Ljubljana.

5.2.1 *Visualization of Outdoor Comfort with a computational process*

Climate Data is essential to understand the conditions for the design of buildings, infrastructures and built environments. Outdoor spaces, buildings and vegetation are influenced and interact in the formation of the microclimate conditions. Ladybug Tools can visualize Climate data with a computational approach. Understanding this information can guide designers into choosing strategies that aim at mitigating outdoor discomfort, e.g. UTCI, urban hardscape that is permeable during heavy rain, wind comfort, maximize the outdoor season with design strategies.

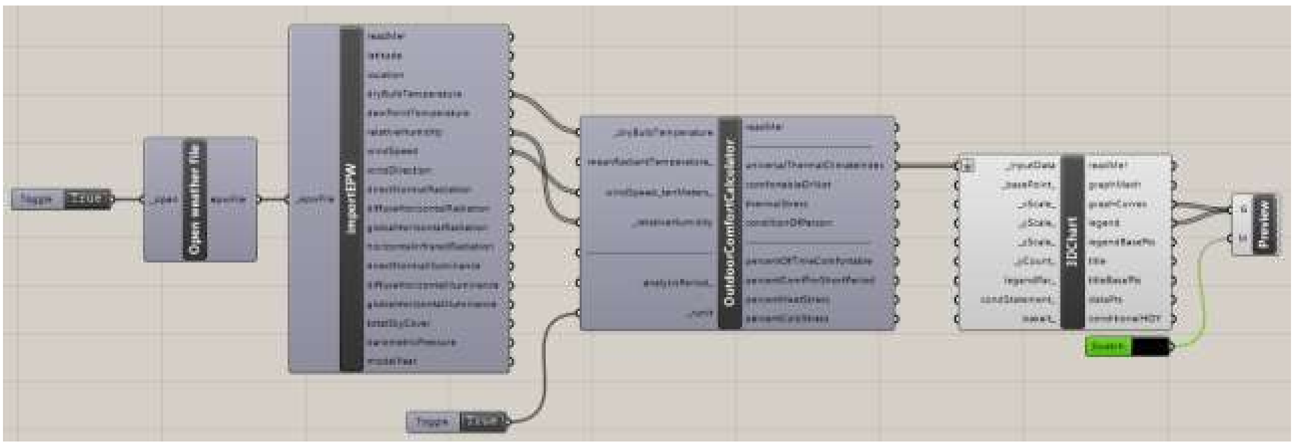


Figure 5. 5: Ladybug Tools code for UTCI calculation.

The Ljubljana .epw weather file is used. Climate data is connected to the UTCI calculator and a chart visualizer. The result is an hourly colour map of the entire year outdoor "feels like" temperatures.

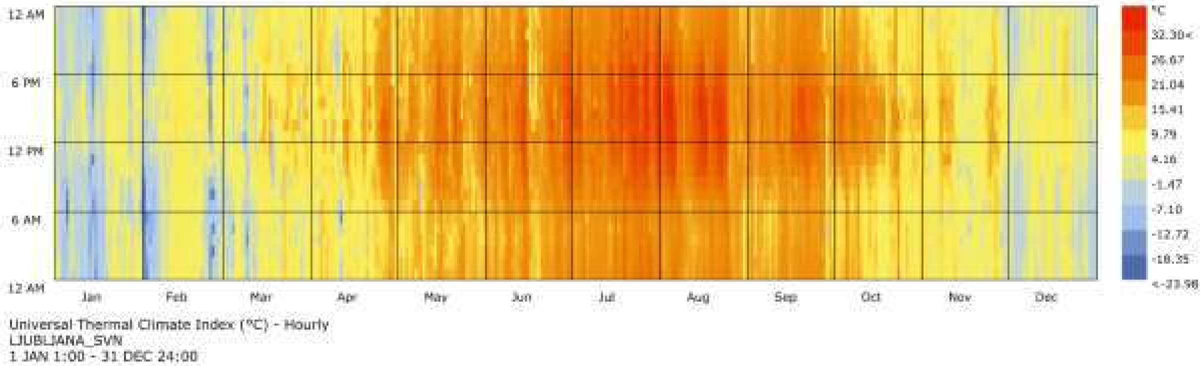


Figure 5. 6: UTCI temperature colour map for Ljubljana.

It can be useful to understand the period during the year with heatwaves (small probability in June, growing in July, most probable in August, and a slight chance also for September). January is the month with the highest outdoor discomfort, followed by February, December and March. A UTCI between 9 and 26 degrees Celsius indicates no thermal stress or comfortable conditions outdoors.

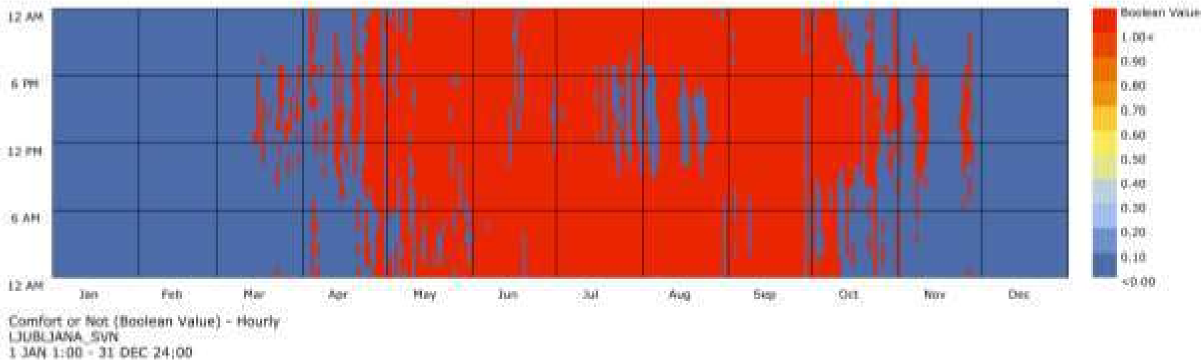


Figure 5. 7: UTCI colour map of comfortable or not hours.

The chart uses the Boolean condition of True or False. True conditions are based on the range of no thermal stress 9°C<UTCI<26°C. All other values have false condition, thus coloured blue.

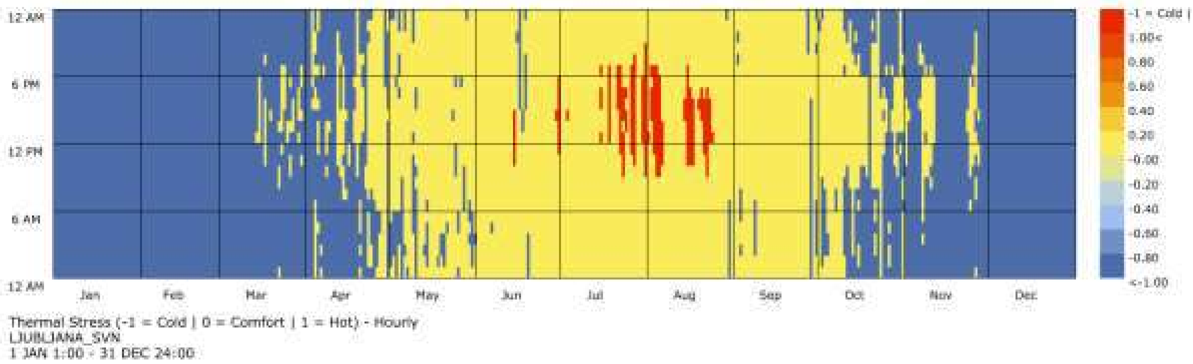


Figure 5. 8: UTCI colour map of thermal stress.

Values explanation: -1 = Cold Stress (all cold conditions) (UTCI < 9°C). 0 = No Thermal Stress (comfortable conditions) (9°C < UTCI < 26°C). +1 = Heat Stress (all hot conditions) (UTCI > 26°C).

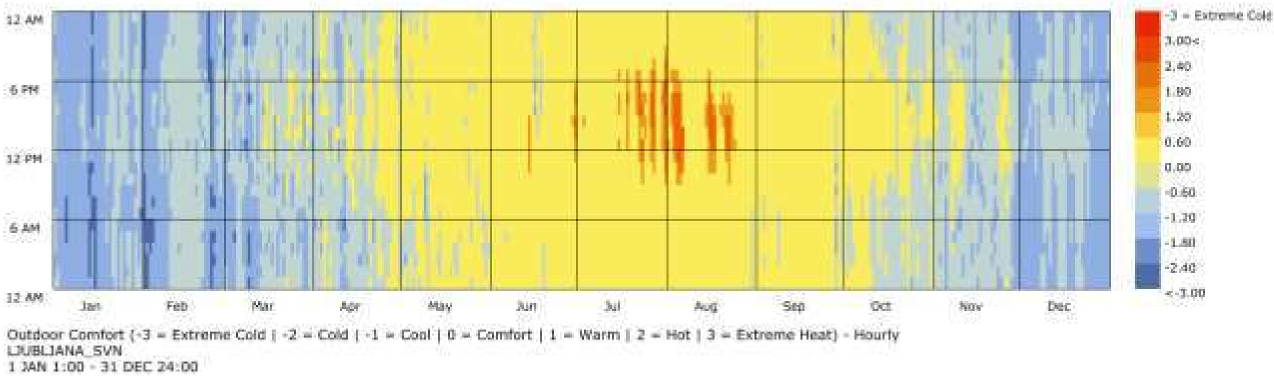


Figure 5. 9: UTCI colour map based on UTCI stress categories.

We can see that the best year period for the outdoor season from May to mid-October with the risk of heatwaves in July and August.

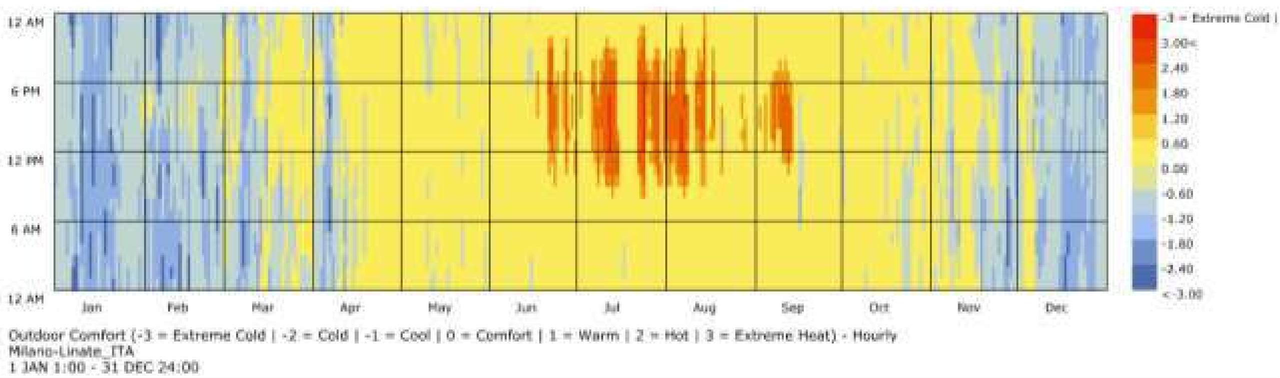


Figure 5. 10: UTCI colour map of Milan for comparison with Ljubljana.

Heatwaves are probable during summer months and September for Milan. The outdoor comfort period starts in March (partially) to early November and is more extended than Ljubljana.

Table 5. 1: Ladybug tools UTCI temperature scale

	Thermal Stress Category	Description	UTCI (°C) range
+3	Strong Heat Stress	potential public health hazard with higher-than-normal mortality rates	UTCI> 32°C
+2	Moderate Heat Stress	hot but no public health hazard	28°C<UTCI< 32°C
+1	Slight Heat Stress	warm but comfortable for short periods of time	26°C<UTCI<28°C
0	No Thermal Stress	comfortable conditions	9°C<UTCI<26°C
-1	Slight Cold Stress	cool but comfortable for short periods of time	0°C<UTCI<9°C
-2	Moderate Cold Stress	cold but no public health hazard	-13°C<UTCI<0°C
-3	Strong Cold Stress	potential public health hazard with higher-than-normal mortality rates	UTCI<-13°C

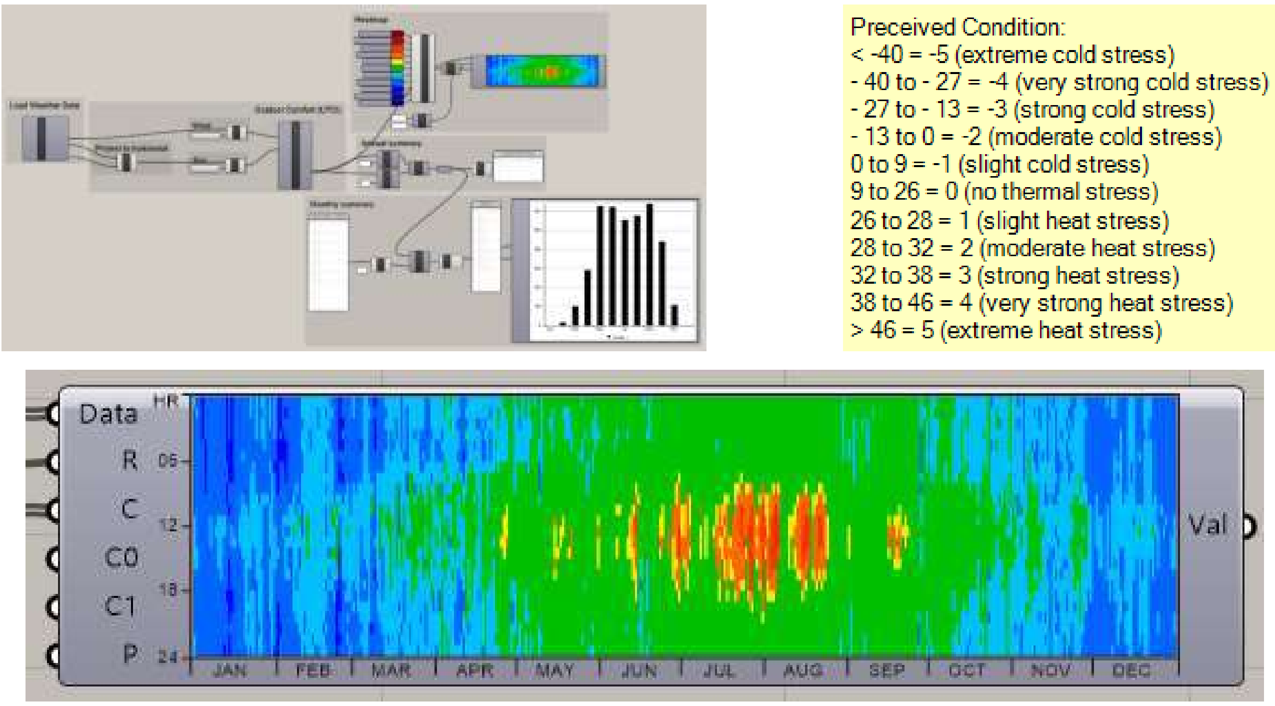


Figure 5. 11: UTCI colour map and algorithm with Climate Studio components in Grasshopper.

One year has 8760 hours. The colours with Climate Studio are plotted following the temperature scale of the UTCI published documentation. The annual comfort hours are 3991, for 45% of the year, which is a 2.5% difference from the 47.5% results with Ladybug Tools computation of the UTCI for the year with the same weather data.

Table 5. 2: UTCI comfortable time of the year comparison of Ljubljana and Milan with Ladybug.

UTCI range	Description	Ljubljana	Milan
9°C < UTCI < 26°C	Percentage of time comfortable	47.5	57.5
0°C < UTCI < 9°C 26°C < UTCI < 28°C	Percent of time comfortable for a short period	31.5	27.5
28°C < UTCI	Percentage of time experiencing Heat Stress	0.8	3.2
UTCI < 0°C	Percentage of time experiencing Cold Stress	20.2	11.8

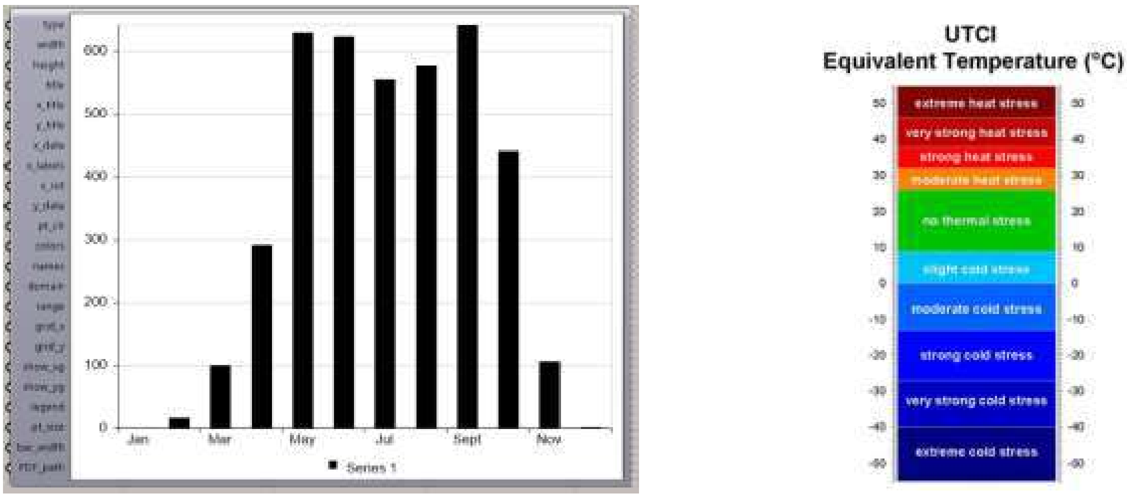


Figure 5. 12: Chart of Monthly comfort hours with Climate Studio and UTCI Temperature scale.

5.2.2 *Wind Data visualization and reliability of big data*

In the following images, the Wind Rose for Ljubljana is visualized with Ladybug. It offers greater flexibility as the graph can be adapted for a different analysis period, and the vectors can be extracted to analyse the wind patterns. In the other image is Wind Rose from the Ljubljana Airport visualized through the online tool of the Iowa State University. We can see that the two charts have similarities. However, they do not visualize in the same way the data.

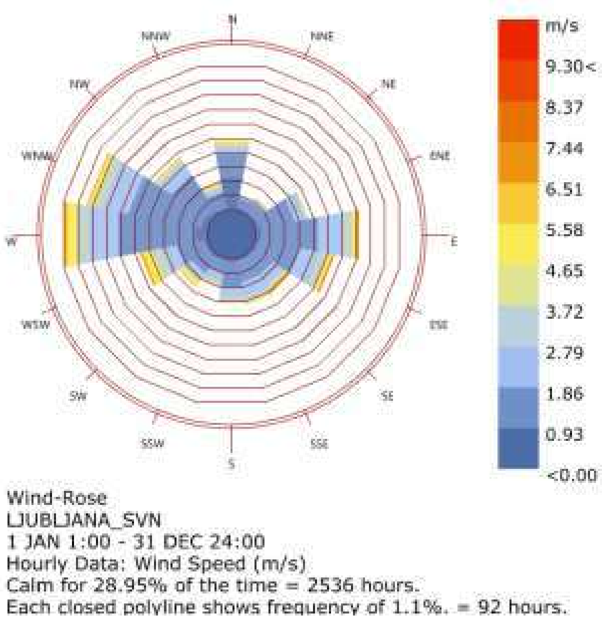


Figure 5. 13: Wind data from Energy Plus .epw file, visualized with Ladybug.

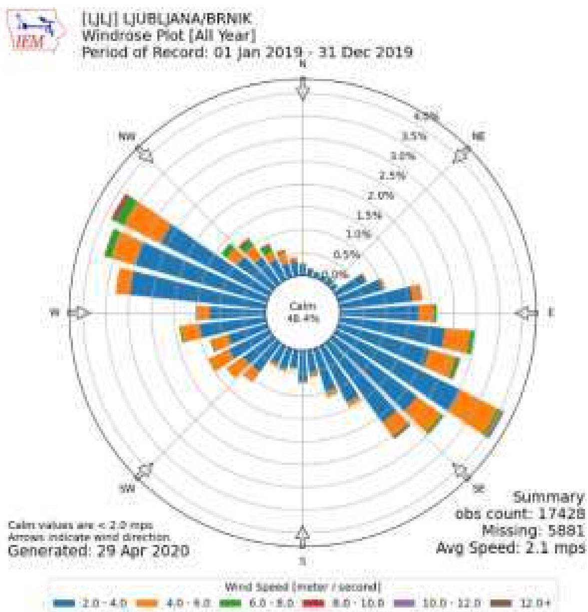


Figure 5. 14: Iowa Environmental Mesonet (IEM) global wind rose tool: Ljubljana in 2019[58].

[58] Iowa Environmental Mesonet. (n.d.). Ljubljana Wind Rose Plot 2019. www.climate.gov/maps-data/dataset/worldwide-wind-roses-graphics-and-tabular-data

5.2.3 *Sun Charts, Radiation Rose and the Psychrometric Chart with Computational Methods*

Understanding, visualizing and using climate data for the whole year, season or an analysis period is an essential step in the process towards bioclimatic design. The sun path, the wind rose, and other climate data can be visualized with a colour mapping of the weather scalars that we are most interested in using as guidance in the design process.

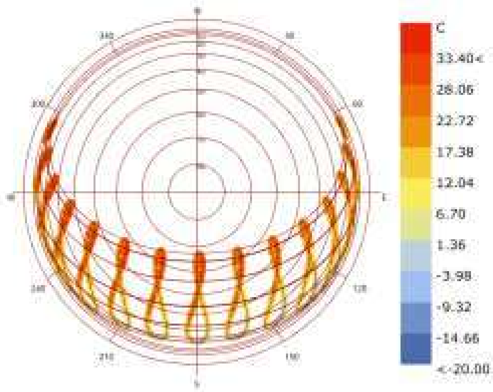


Figure 5. 15: Sun chart in Rhino with Ladybug. Orthographic projection of the sun with yearly dry bulb temperature.

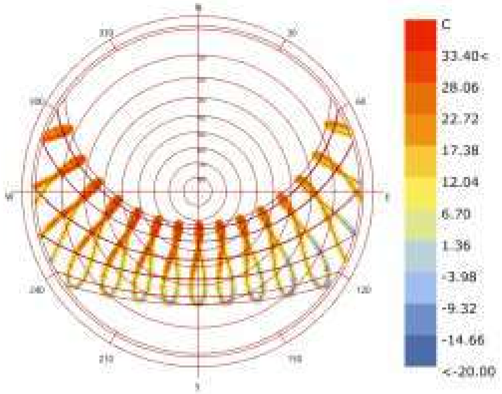


Figure 5. 16: Stereographic projection of sun path with yearly dry bulb temperature.

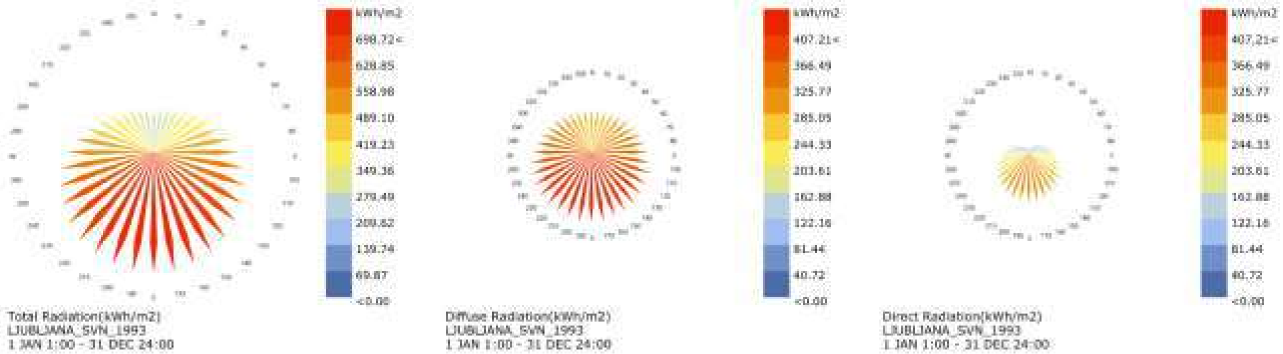


Figure 5. 17: Radiation Rose for Ljubljana: total, diffused and direct radiation.

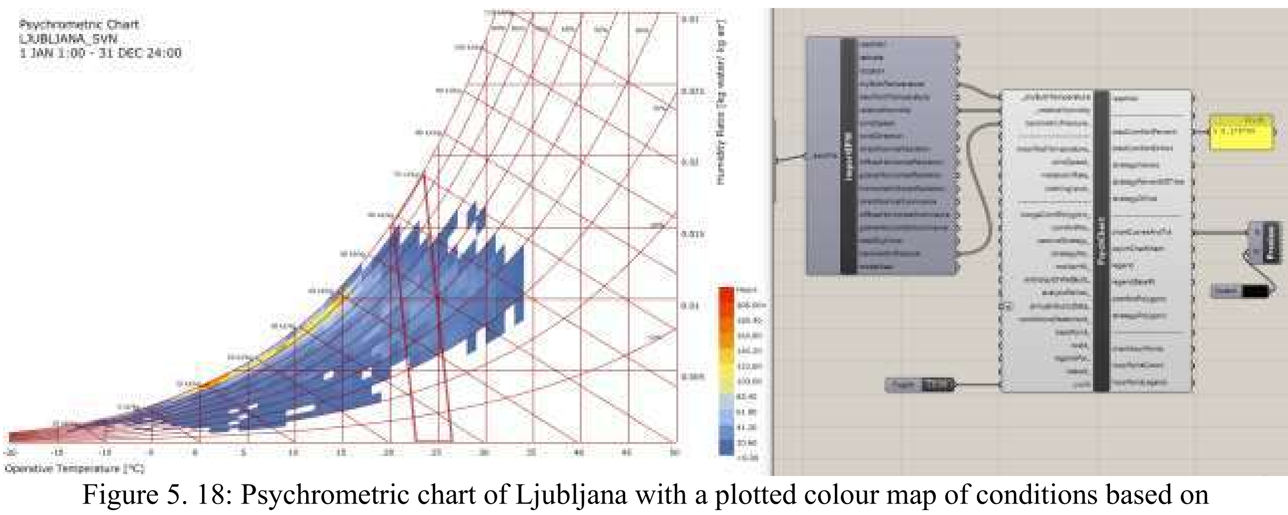


Figure 5. 18: Psychrometric chart of Ljubljana with a plotted colour map of conditions based on hourly data for the entire year. Thermal Comfort for 6.1% of the time in one year.

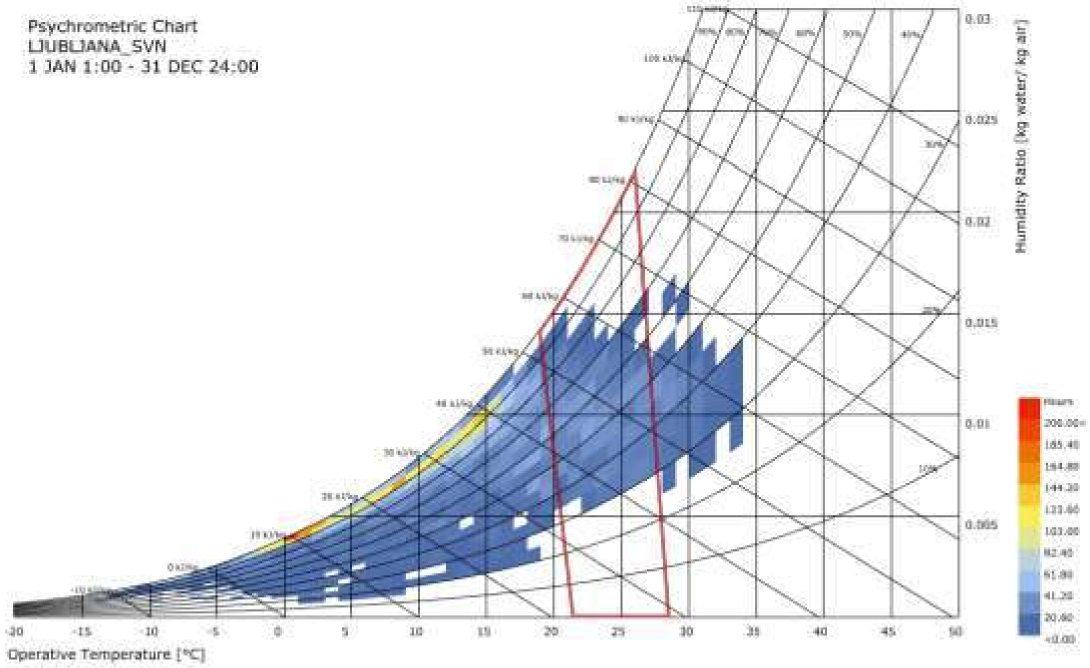


Figure 5. 19: Psychrometric chart based on Winter and Summer clothing range 0.5<x<1.2. Thermal Comfort reaches up to 11%.

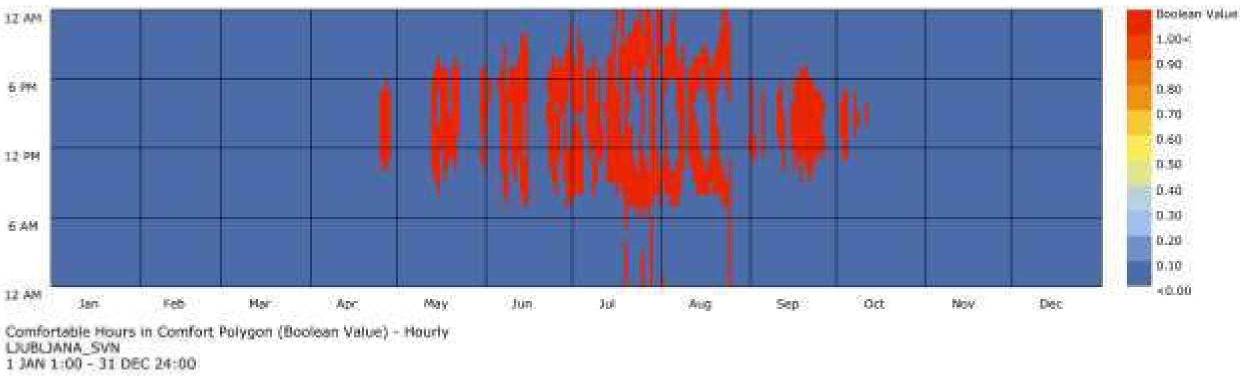


Figure 5. 20: Thermal Comfort based on adaptive clothing on the annual hourly data chart.

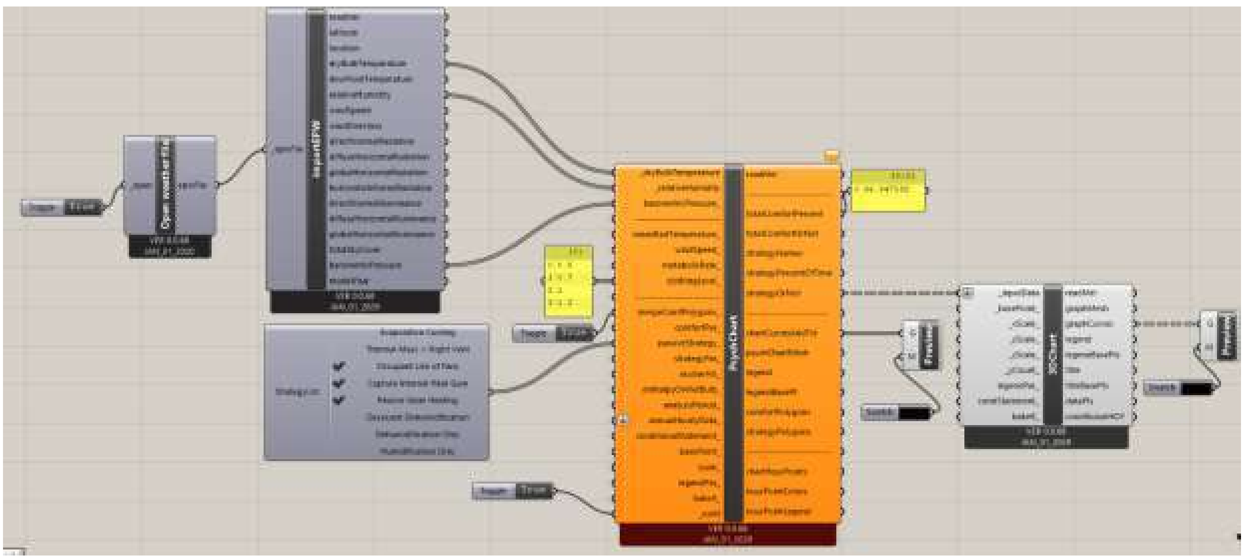


Figure 5. 21 Ladybug code with Adaptive Clothing and Passive Design Strategies to raise comfort.

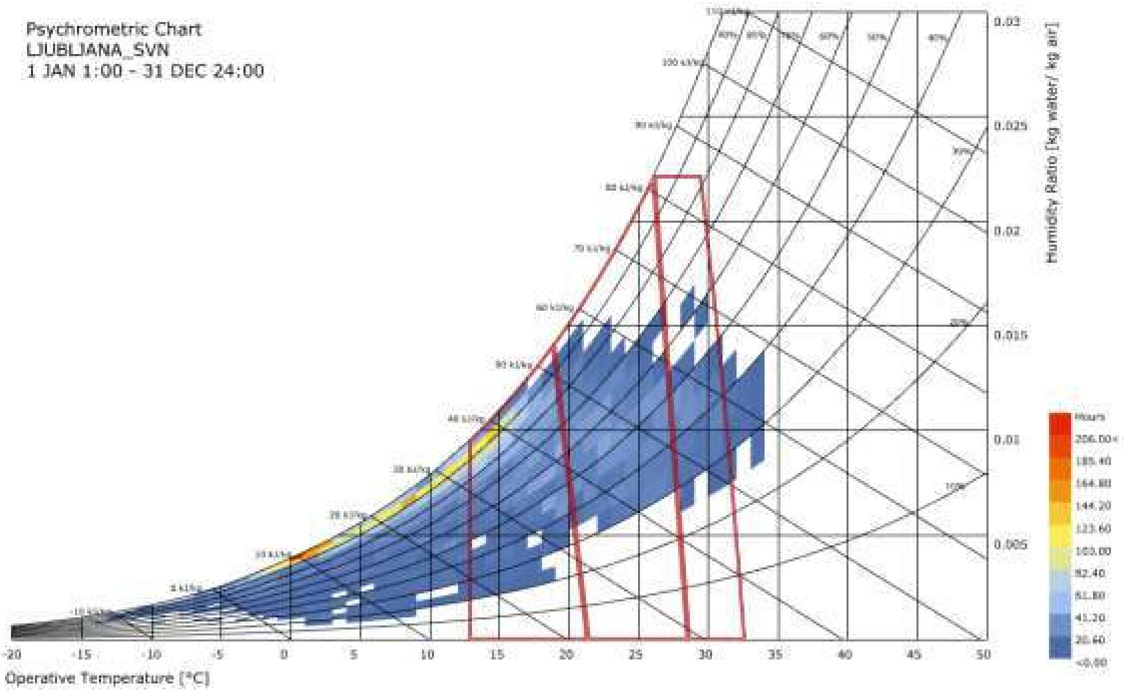


Figure 5. 22: Psychrometric chart with Thermal Comfort zones, including Passive Design Strategies.

Comfort increases by 25% to a total of 36% of the time in one year. The three simple strategies selected to increase thermal comfort are Internal Heat Gains, Passive Solar Heating and Occupant use of fans.

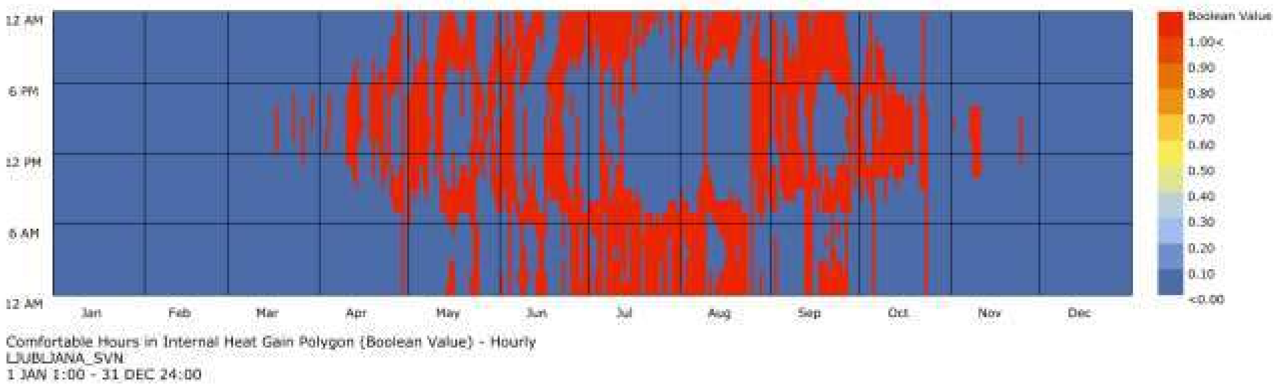


Figure 5. 23: Plotting the Thermal Comfort with the contribution of Internal Heat Gains.

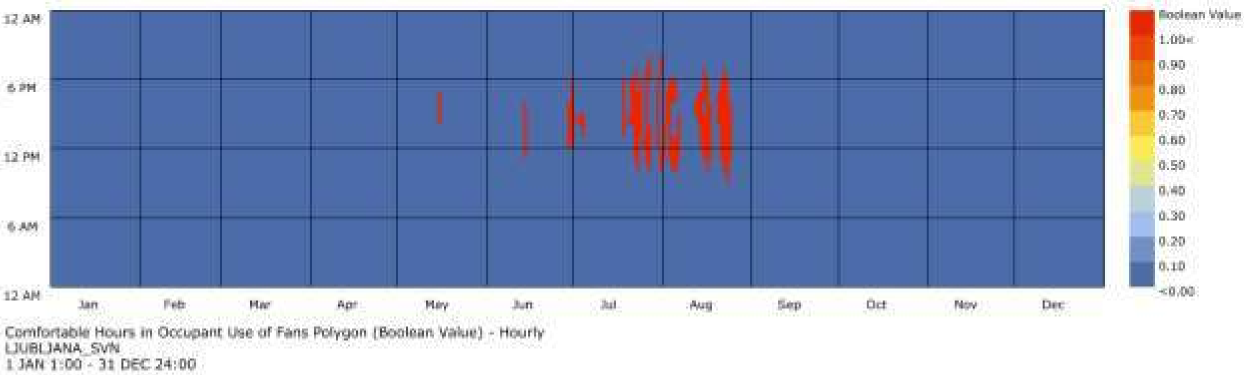
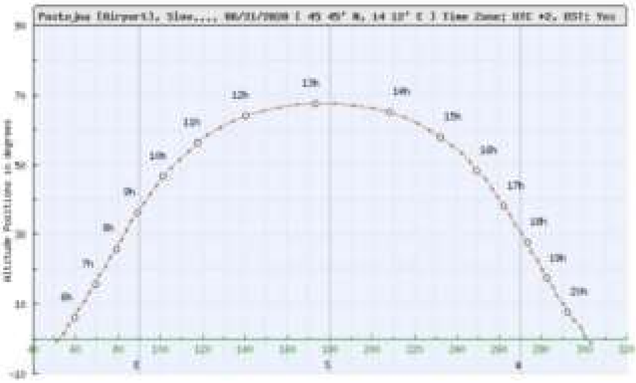


Figure 5. 24: Thermal Comfort based on Occupant use of fans.

5.3 Shadings Design for Ljubljana region

Overhangs can block the direct radiation of the sun that causes overheating in the summer and allow the solar gains when needed in the other periods of the year when the sun position is lower. The first step is to get the solar altitude during the days of the Summer solstice 21st of June (highest point) and Winter solstice 21st of December.



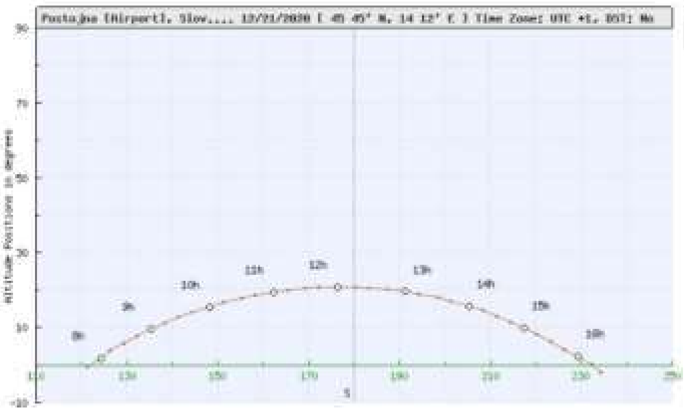
» Sunday, 21st June 2020 « Selected

Sunrise: 05:13 (Az 51.3°), Sunset: 20:56 (Az 302.3°)

« Sunday, 21st June 2020 »

Time (24 hr)	Azim.	Alt.
12:00	140°	64°
12:15	148°	65°
12:30	156°	67°
12:45	164°	67°
13:00	173°	68°
13:15	182°	68°
13:30	191°	67°
13:45	200°	66°
14:00	208°	65°

Figure 5. 25: Sun Chart and hourly table of sun Altitude and Azimuth on 21 June to determine the peak level of the day. Source: sunposition.info



» Monday, 21st December 2020 « Selected

Sunrise: 07:40 (Az 120.3°), Sunset: 16:21 (Az 233.3°)

« Monday, 21st December 2020 »

Time (24 hr)	Azim.	Alt.
11:00	162°	19°
11:15	165°	20°
11:30	169°	20°
11:45	172°	21°
12:00	176°	21°
12:15	180°	21°
12:30	183°	21°
12:45	187°	20°
13:00	191°	20°
13:15	194°	19°

Figure 5. 26: Sun Chart and hourly table of sun Altitude and Azimuth for Winter Solstice on 21 December to determine the peak level of the day: Source: sunposition.info[59].

Location: Ljubljana
Time: 21.Jun.2020, 13:03 UTC+2

Solar data for the Location		Geo data for the Location		
Dawn:	04:32:20	Height:		303m
Sunrise:	05:10:35	Latitude:	N 46°3'2.23''	46.05062°
Sun peak level:	13:03:53	Longitude:	E 14°30'10.15''	14.50282°
Sunset:	20:57:10	Timezone:	Europe/Ljubljana CEST	
Dusk:	21:35:25			
Duration:	15h46m35s			
Altitude:	67.39°			
Azimut:	179.47°			
Shadow length:	0.42	at an object level: 1m		

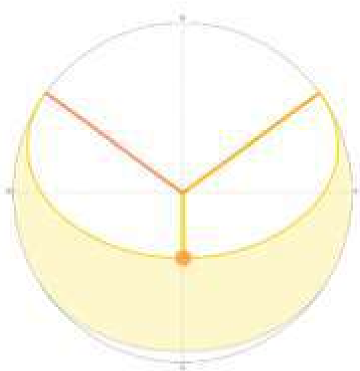


Figure 5. 27: Sun Path with position at peak level on the Summer solstice. Source: suncalc.org[60]

[59] Brackenridge, M. (2020). Sun Position. www.sunposition.info
[60] Hoffmann, T. (2020). Sun Calculator. www.suncalc.org

Location: Ljubljana
Time: 21.Dec.2020, 12:00 UTC+1

Solar data for the Location		**Geo data for the Location**		
Dawn:	07:06:32	Height:		303m
Sunrise:	07:40:50	Latitude:	N 46°3'2.23''	46.05062°
Sun peak level:	12:00:16	Longitude:	E 14°30'10.15''	14.50282°
Sunset:	16:19:42	Timezone:	Europe/Ljubljana CET	
Dusk:	16:54:00			
Duration:	8h38m52s			
Altitude:	20.55°			
Azimut:	179.93°			
Shadow length:	2.67	at an object level: 1m		

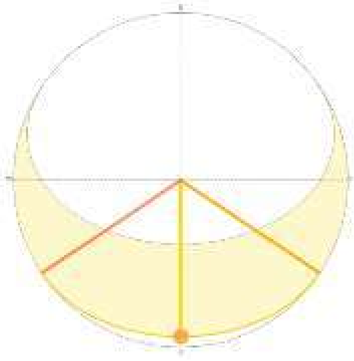


Figure 5. 28: Sun Path with position at peak level on Winter solstice. Source: suncalc.org.

The azimuth positions of the sun at sunrise and sunset are indicated in the Sun Path diagrams.

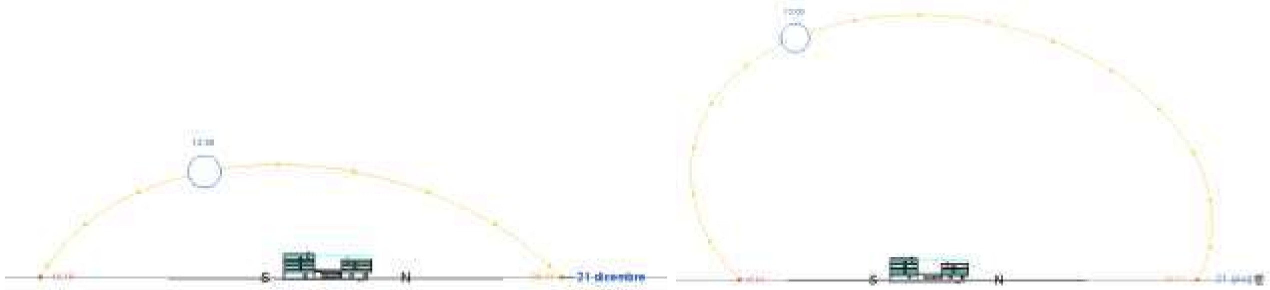
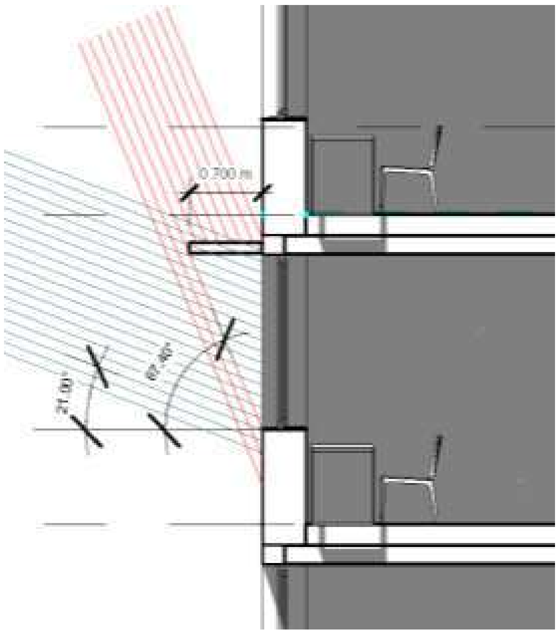


Figure 5. 29: Sun path displayed in Revit for the project in the Ljubljana location.

The Sun location in the model is shown at a lower position for the hour that should be at the peak. Using the sun path of the model would result in a longer overhang that covers sun when gains are needed in another period of the year and reducing natural light. A higher erroneous sun would produce a shorter overhang, overheating and having glare in summer, discomfort glare and gains in spring and autumn.



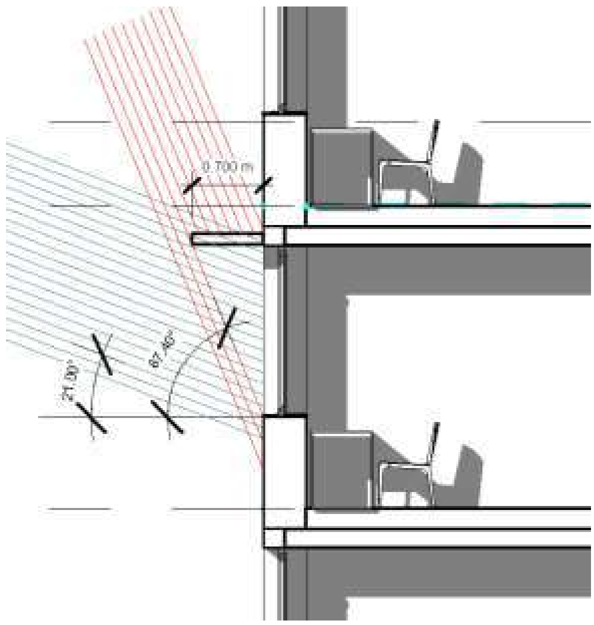


Figure 5. 30: Sections in Revit with overhangs using the altitude of the Summer solstice.

The angle of 67.40 from the window sill creates an overhang of 0.7 m. The solar study in Revit shows that the space in summer is protected from direct sun and in winter the sun reaches the interior of the space where occupants can benefit of the available natural daylight and free solar heating of areas.

5.4 Understanding Climate Data for Bioclimatic Design Strategies

Climate data and location are essential to understand and design with from the early project stage. Design Authoring tools can make sun path and shadow analysis with a considerable degree of error, as shown in the example of summer and winter solstices with Revit. Climate Consultant is a tool developed at the University of California in Los Angeles that reads Energy Plus climate data and transforms it into a meaningful graphic representation[61]. It also gives designers control over the data to create custom graphs and provides design guidelines based on data plotted on the Psychrometric chart according to ASHRAE Standard 55 PMV method and Adaptive Comfort.

Table 5. 3: Summary of Weather Data for Ljubljana from the. epw weather file.

WEATHER DATA SUMMARY

LOCATION: LJUBLJANA, -, SVN
Latitude/Longitude: 46.22° North, 14.48° East, **Time Zone from Greenwich** 1
Data Source: IWEC Data 130140 WMO Station Number, **Elevation** 385 m

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	108	158	217	274	296	316	358	345	252	213	104	72	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	94	120	129	146	137	145	211	248	160	183	58	31	Wh/sq.m
Diffuse Radiation (Avg Hourly)	77	108	150	178	199	214	204	174	157	121	82	62	Wh/sq.m
Global Horiz Radiation (Max Hourly)	405	540	713	838	906	889	900	858	684	620	412	266	Wh/sq.m
Direct Normal Radiation (Max Hourly)	725	805	938	821	802	758	828	807	736	768	588	454	Wh/sq.m
Diffuse Radiation (Max Hourly)	176	301	404	442	483	607	468	436	383	298	228	175	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	962	1588	2552	3682	4397	4914	5425	4829	3108	2293	903	615	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	836	1204	1509	1979	2045	2252	3190	3479	1967	1990	543	267	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	686	1091	1769	2386	2951	3323	3093	2429	1938	1293	762	533	Wh/sq.m
Global Horiz Illumination (Avg Hourly)	11944	17420	24040	30350	33067	35340	39804	38208	28033	23399	11610	8175	lux
Direct Normal Illumination (Avg Hourly)	8352	11183	12392	14316	13306	13633	20107	23482	15046	17245	5181	2672	lux
Dry Bulb Temperature (Avg Monthly)	-1	0	3	9	14	16	20	18	14	9	4	0	degrees C
Dew Point Temperature (Avg Monthly)	-4	-3	-1	3	8	11	13	12	11	6	2	-1	degrees C
Relative Humidity (Avg Monthly)	78	82	69	71	72	74	69	70	80	82	87	92	percent
Wind Direction (Monthly Mode)	0	310	300	300	240	120	300	0	90	300	280	0	degrees
Wind Speed (Avg Monthly)	1	0	1	1	1	1	1	1	0	0	0	1	m/s
Ground Temperature (Avg Monthly of 3 Depths)	5	3	2	1	4	7	11	14	15	15	13	9	degrees C

[61] University of California, Los Angeles. (2020). Climate Consultant. www.energy-design-tools.aud.ucla.edu/

Table 5. 4: Graph of Temperature ranges for Ljubljana.

Temperatures values start getting within the comfort zone from April to September. The majority of yearly hours are below the comfort zone. The climate of the city is heating dominant.

Table 5. 5: Setting the comfort criteria

ASHRAE Standard 55, current Handbook of Fundamentals Comfort Model (select Help for definitions)

1. COMFORT: (using ASHRAE Standard 55)

1.0	Winter Clothing Indoors (1.0 Clo=long pants,sweater)
0.5	Summer Clothing Indoors (.5 Clo=shorts,light top)
1.1	Activity Level Daytime (1.1 Met=sitting,reading)
90.0	Predicted Percent of People Satisfied (100 - PPD)
20.3	Comfort Lowest Winter Temp calculated by PMV model(ET* C)
24.3	Comfort Highest Winter Temp calculated by PMV model(ET* C)
26.7	Comfort Highest Summer Temp calculated by PMV model(ET* C)
84.6	Maximum Humidity calculated by PMV model (%)

2. SUN SHADING ZONE: (Defaults to Comfort Low)

23.8	Min. Dry Bulb Temperature when Need for Shading Begins (°C)
315.5	Min. Global Horiz. Radiation when Need for Shading Begins (Wh/sq.m)

3. HIGH THERMAL MASS ZONE:

8.3	Max. Outdoor Temperature Difference above Comfort High (°C)
1.7	Min. Nighttime Temperature Difference below Comfort High (°C)

4. HIGH THERMAL MASS WITH NIGHT FLUSHING ZONE:

16.7	Max. Outdoor Temperature Difference above Comfort High (°C)
1.7	Min. Nighttime Temperature Difference below Comfort High (°C)

5. DIRECT EVAPORATIVE COOLING ZONE: (Defined by Comfort Zone)

20.0	Max. Wet Bulb set by Max. Comfort Zone Wet Bulb (°C)
6.6	Min. Wet Bulb set by Min. Comfort Zone Wet Bulb (°C)

6. TWO-STAGE EVAPORATIVE COOLING ZONE:

50.0	% Efficiency of Indirect Stage

7. NATURAL VENTILATION COOLING ZONE:

2.0	Terrain Category to modify Wind Speed (2=suburban)
0.2	Min. Indoor Velocity to Effect Indoor Comfort (m/s)
1.5	Max. Comfortable Velocity (per ASHRAE Std. 55) (m/s)

8. FAN-FORCED VENTILATION COOLING ZONE:

0.8	Max. Mechanical Ventilation Velocity (m/s)
3.0	Max. Perceived Temperature Reduction (°C)
	(Min Vel, Max RH, Max WB match Natural Ventilation)

9. INTERNAL HEAT GAIN ZONE (lights, people, equipment):

12.8	Balance Point Temperature below which Heating is Needed (°C)

10. PASSIVE SOLAR DIRECT GAIN LOW MASS ZONE:

157.7	Min. South Window Radiation for 5.56°C Temperature Rise (Wh/sq.m)
3.0	Thermal Time Lag for Low Mass Buildings (hours)

11. PASSIVE SOLAR DIRECT GAIN HIGH MASS ZONE:

157.7	Min. South Window Radiation for 5.56°C Temperature Rise (Wh/sq.m)
12.0	Thermal Time Lag for High Mass Buildings (hours)

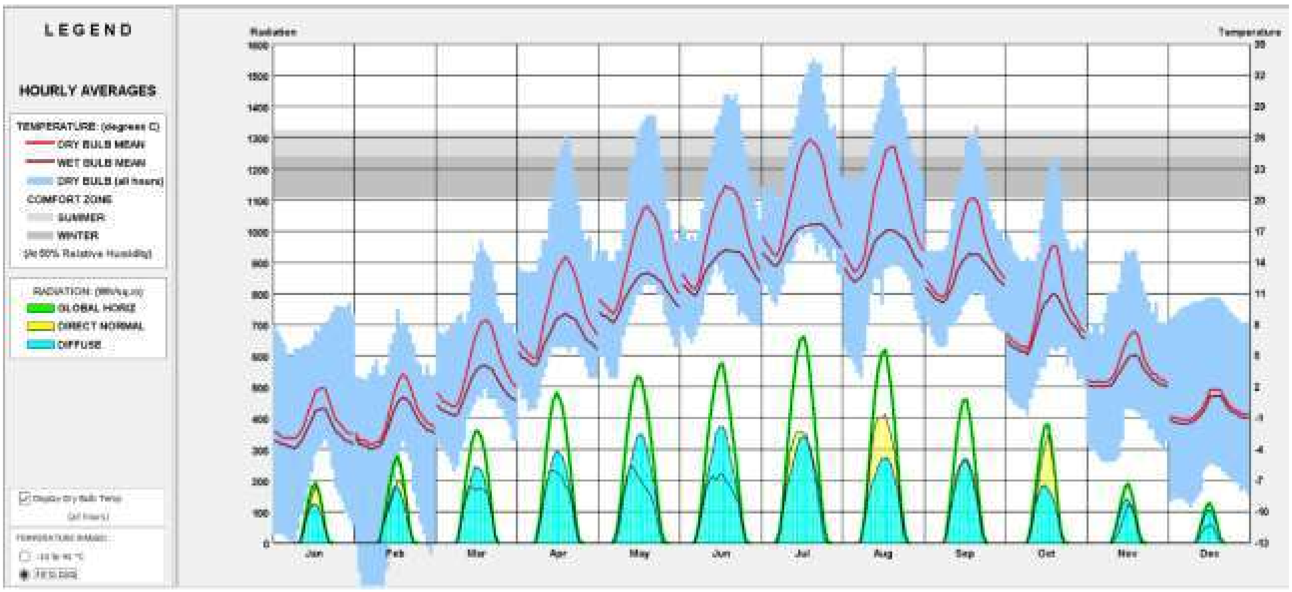
12. WIND PROTECTION OF OUTDOOR SPACES:

8.5	Velocity above which Wind Protection is Desirable (m/s)
11.1	Dry Bulb Temperature Above or Below Comfort Zone (°C)

13. HUMIDIFICATION ZONE: (defined by and below Comfort Zone)

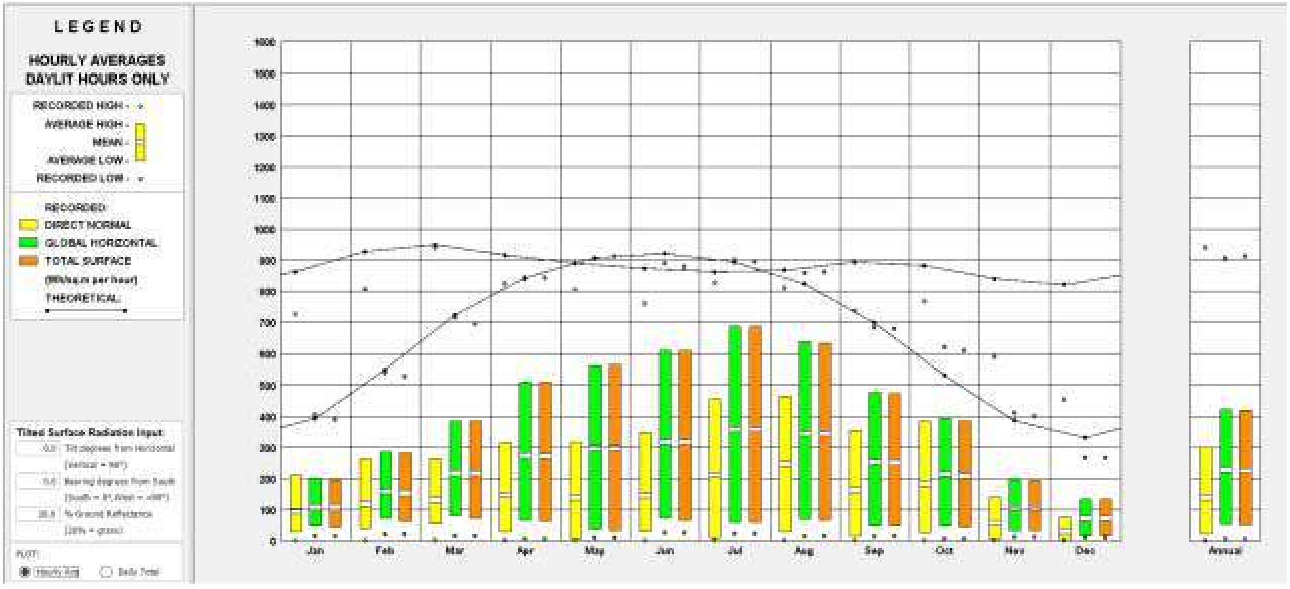
14. DEHUMIDIFICATION ZONE: (defined by and above Comfort Zone)

Table 5. 6: Monthly Diurnal Averages of Temperature and Radiation



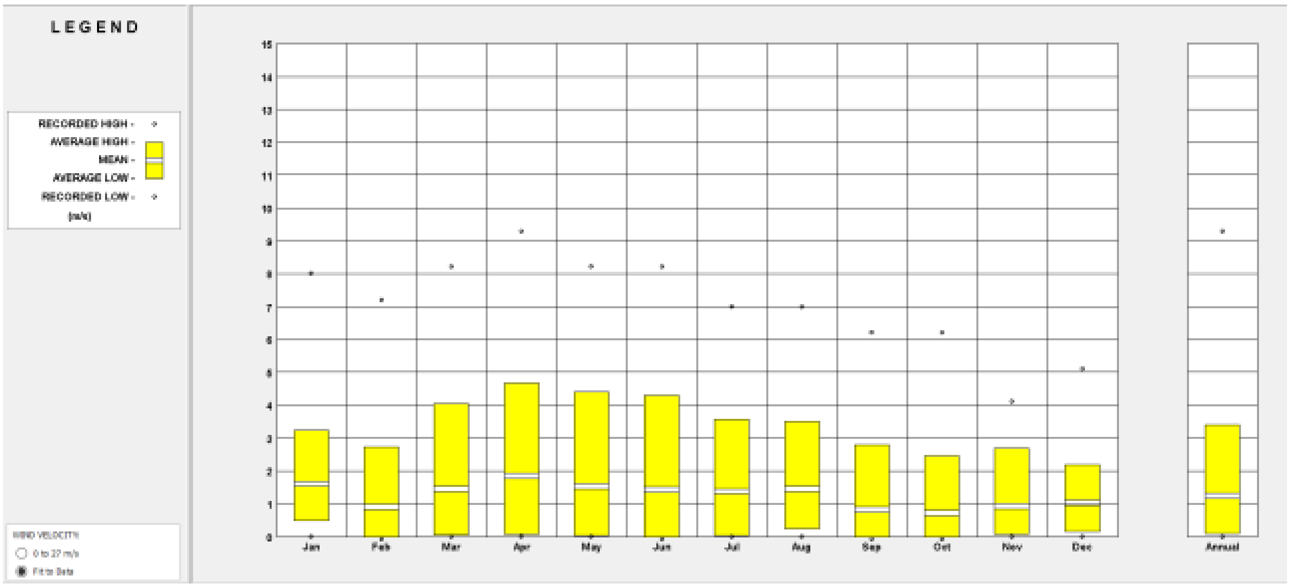
The graph compiles several variables. Wet-bulb temperature takes into account humidity. We can notice the thermal lag effect by looking at the peaks of Direct Normal Radiation and the temperature or hottest time of day, which corresponds several hours later. The higher the difference of the dry bulb and wet bulb temperature, the lower the humidity is. As the two curves get closer, relative humidity increases.

Table 5. 7: Solar Radiation ranges in Ljubljana.



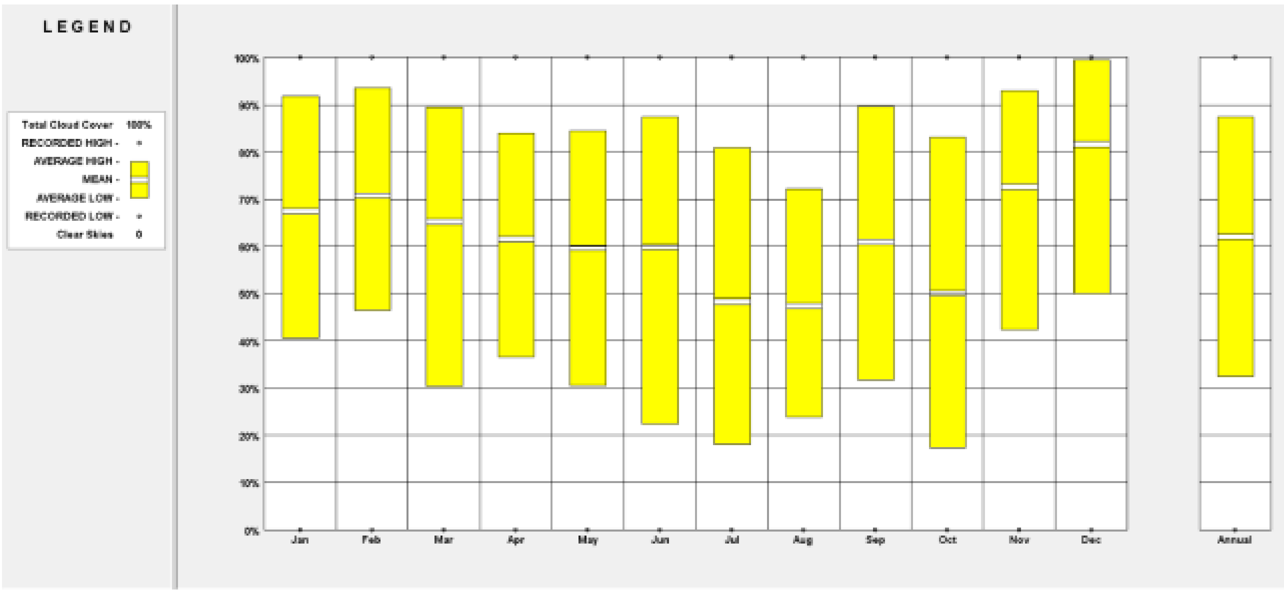
The graph displays monthly, yearly radiation ranges, high and low recorded values in Ljubljana. The direct normal, global horizontal and total radiation is given. The angle of the horizontal plane and bearing south angle can be changed for a project exposition. Can be used to evaluate the solar radiation on building surfaces.

Table 5. 8: Wind velocity



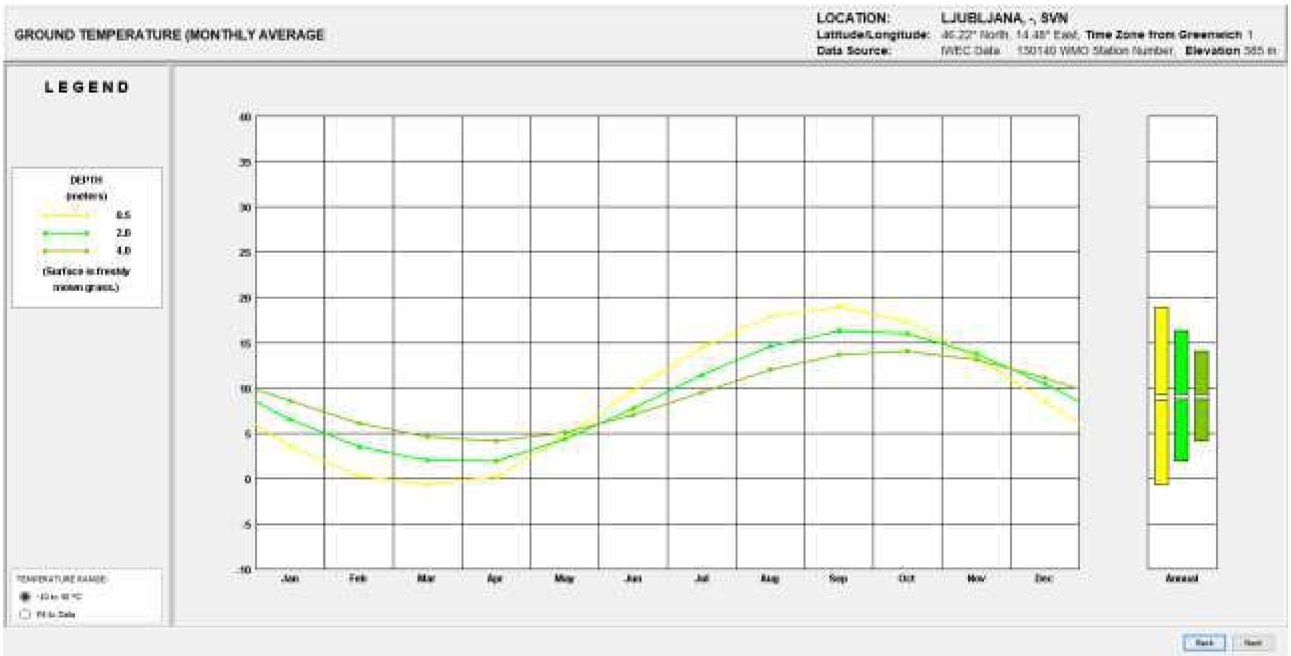
Monthly and Yearly high and mean average is below 5 m/s (limit of Dutch standard NEN 8100). Wind velocity changes in urban context due to downward, venturi effect, pressure and temperature differences. The recorded high value of wind speed does not exceed 10 m/s.

Table 5. 9: Sky Cover Range



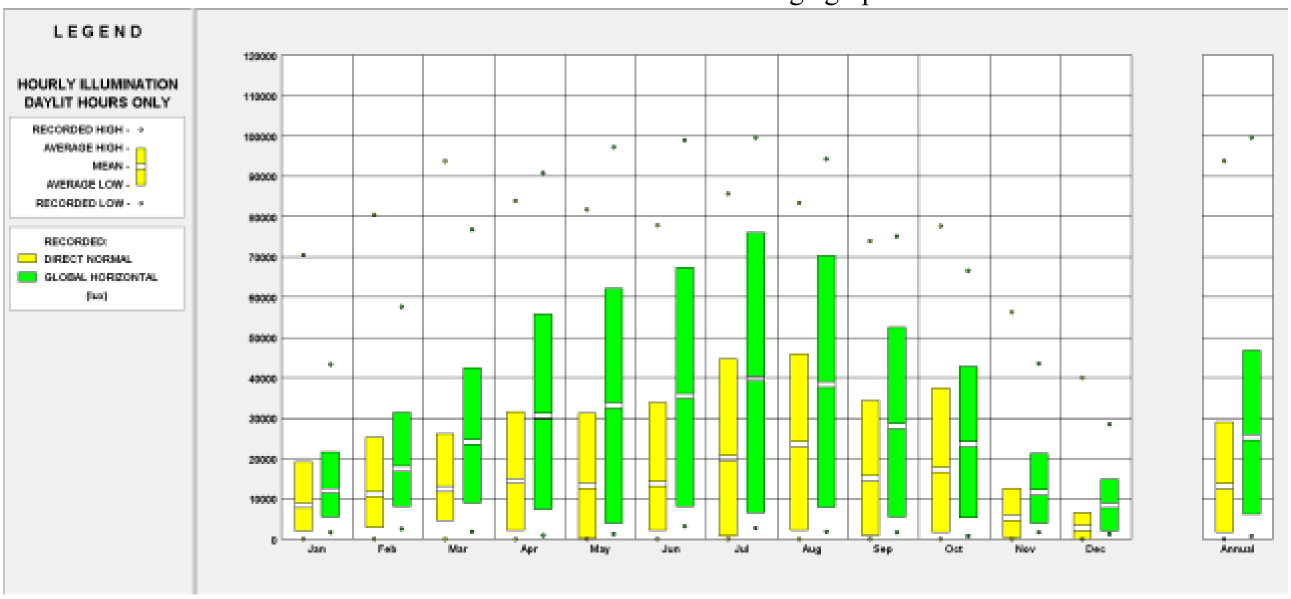
The sky cover provides information about the sky cover of the sun. It is expressed as a percentage of coverage of the time of the months and in a year.

Table 5. 10: Ground temperature



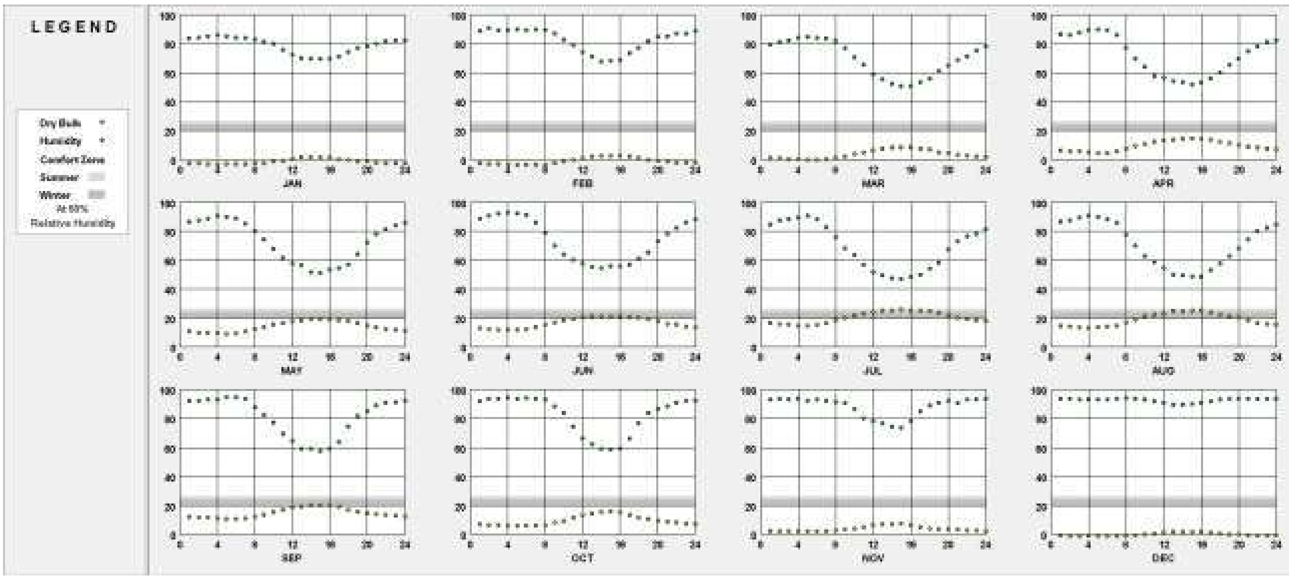
The Ground Temperature graph provides relevant information for the design of ground foundations and underground floors. It is also a good source for Passive House and naturally ventilated fan aided buildings utilizing underground tubes used to pre-heat and pre-cool the fresh air. The higher the depth of measurement, more constant and beneficial is the ground temperature vector throughout the year.

Table 5. 11: The Illumination range graph



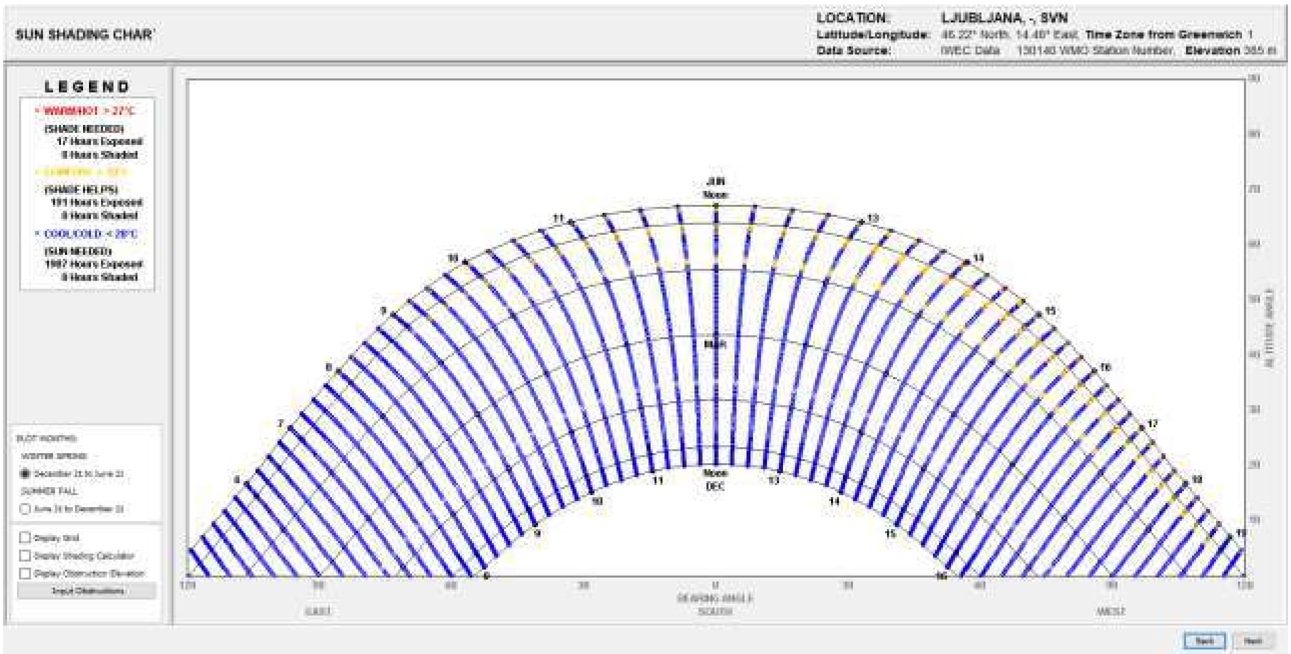
The data gives information about available solar radiation in lighting units. The sun provides sufficient light for the interior throughout the year with the need for electric lights support mostly in Winter. The radiation from April to September could result in some hours of the year above the needed threshold and risk of glare.

Table 5. 12: Dry Bulb Temperature and Relative Humidity shows the inverse relationship of the two. As one increases, the other decreases respectively.



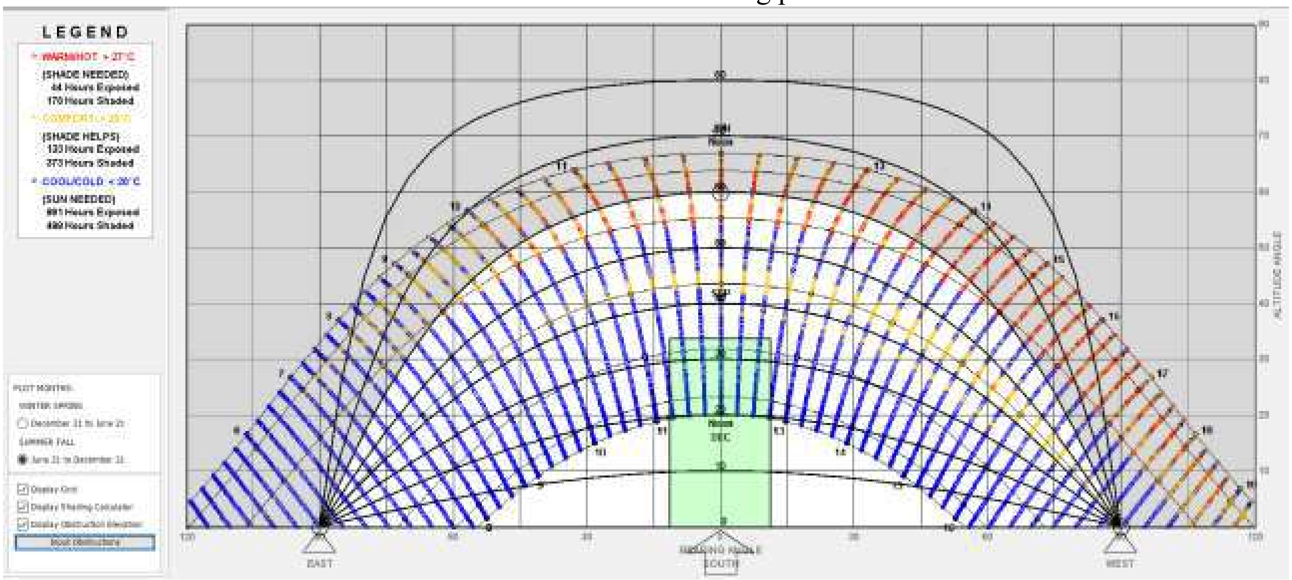
The Sun Shading chart is another useful tool. It plots the hours of the year by colour based on those that are above the comfort zone, comfortable, and below the comfort zone. On the period from December to June, most hours are below comfort zone with no need of shading devices. Comfort conditions are plotted on the chart and are calculated in total hours.

Table 5. 13: Sun Shading chart with December-June comfort plotting for Ljubljana.



The grey area displayed will be shaded by a horizontal device at the given angle (latitude of the sun) measured from the bottom of the window sill. A horizontal line means 0° and 90° would mean the vertical wall. We can tilt the face from the South to adjust to the project façade orientation. Vertical fins can be added if needed by moving the two West and East sliders. The total comfort hours are put in relation when the shade is required in summer and sun is needed in winter. Trying to cover the full range of summer discomfort would reduce the hours required during winter. A balance is needed. The graph can be used as a computational tool to select the best shading for optimal hours of comfort in summer and winter.

Table 5. 14: Sun chart with shading placed at 60°.



The obstruction is shown with a green shade for the neighbouring building at 4 m height and distance of 6 m (closest point with project south façade) at the ground floor. It would not create any shade at the first-floor level. The obstruction tool helps in defining when we need to provide shading or if not needed if provided by context trees and adjacent buildings.

Table 5. 15: Timetable plot of Dry Bulb Temperature daily data with colour-coding of year probability in percentage.

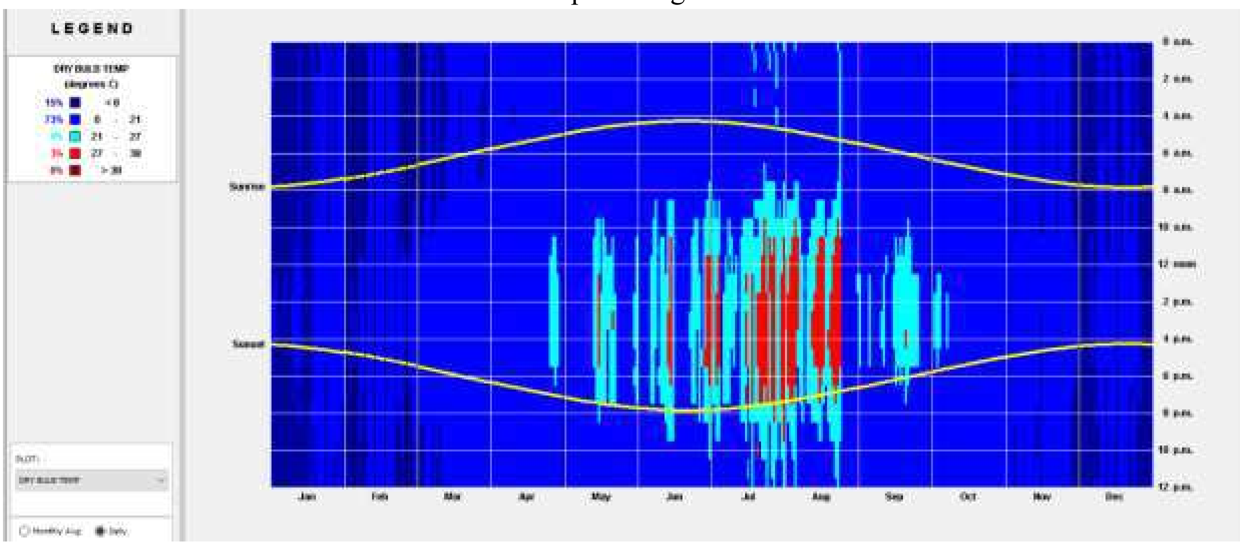
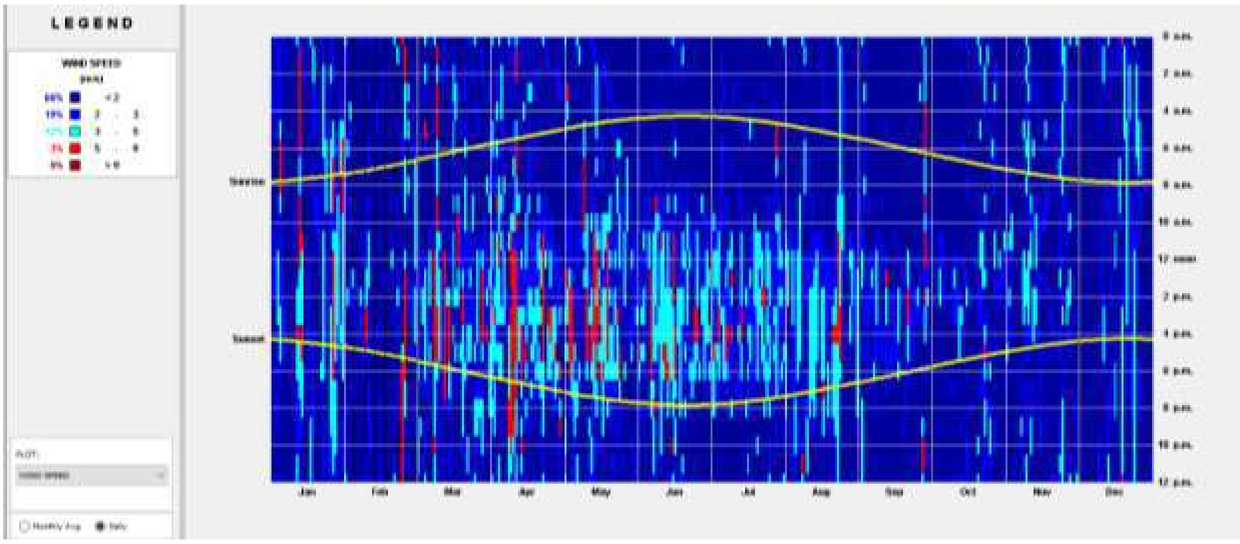


Table 5. 16: Timetable plot of Wind speed daily data with colour-coding of year probability.



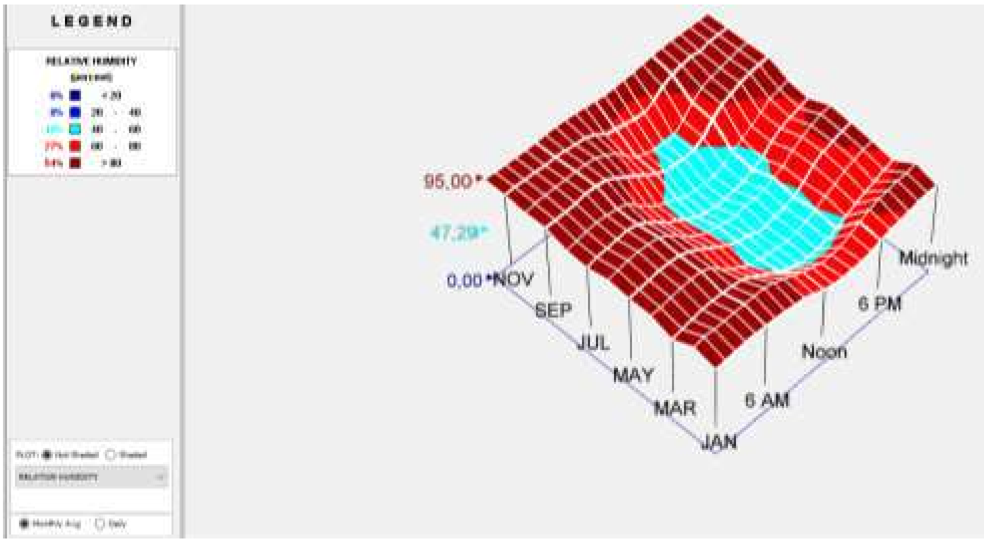


Figure 5. 31: 3D graph visualization of Relative Humidity for the year.

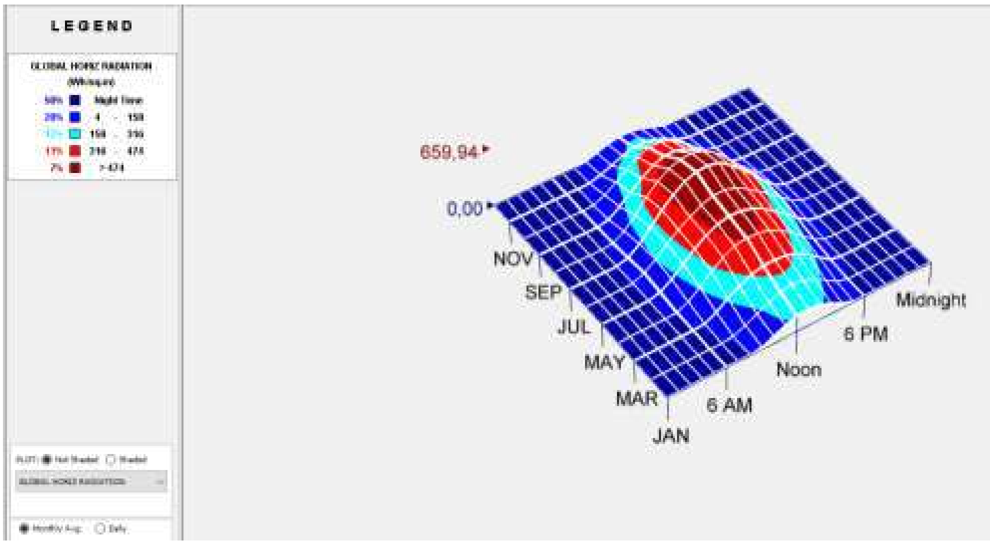


Figure 5. 32: 3D graph visualization of Global Horizontal Radiation.

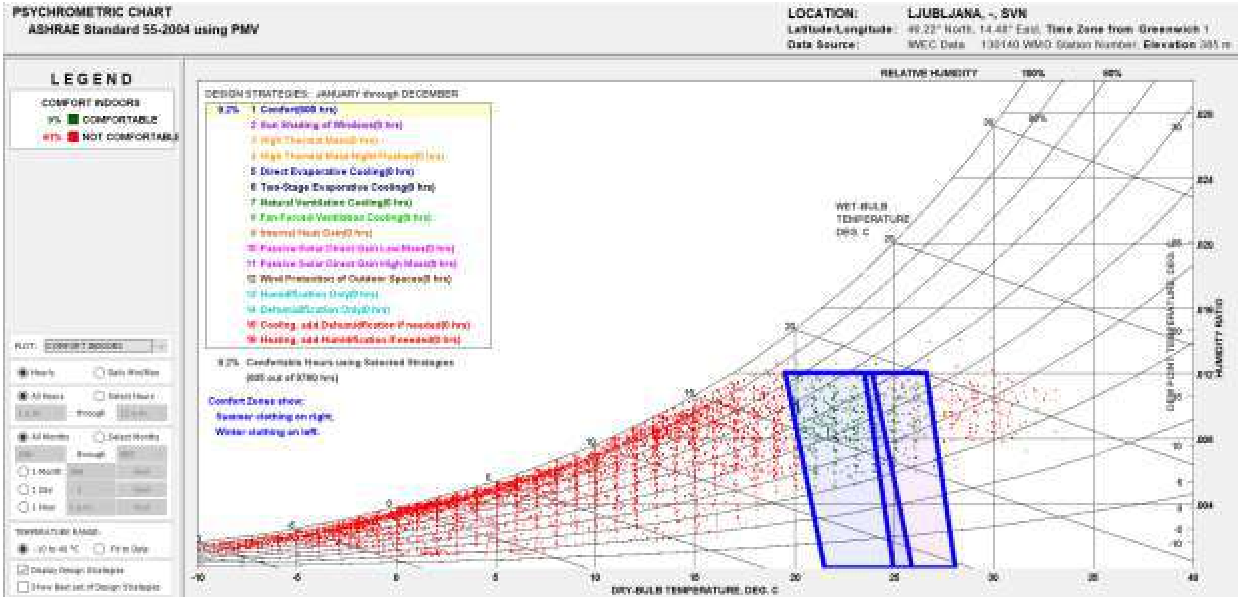


Figure 5. 33: Psychrometric chart with hourly plotted interior comfort.

Only 9.2% of the year people are comfortable with no design strategies. There is a 1.8% difference from the thermal comfort result of 11% obtained in the Psychrometric chart with Ladybug.

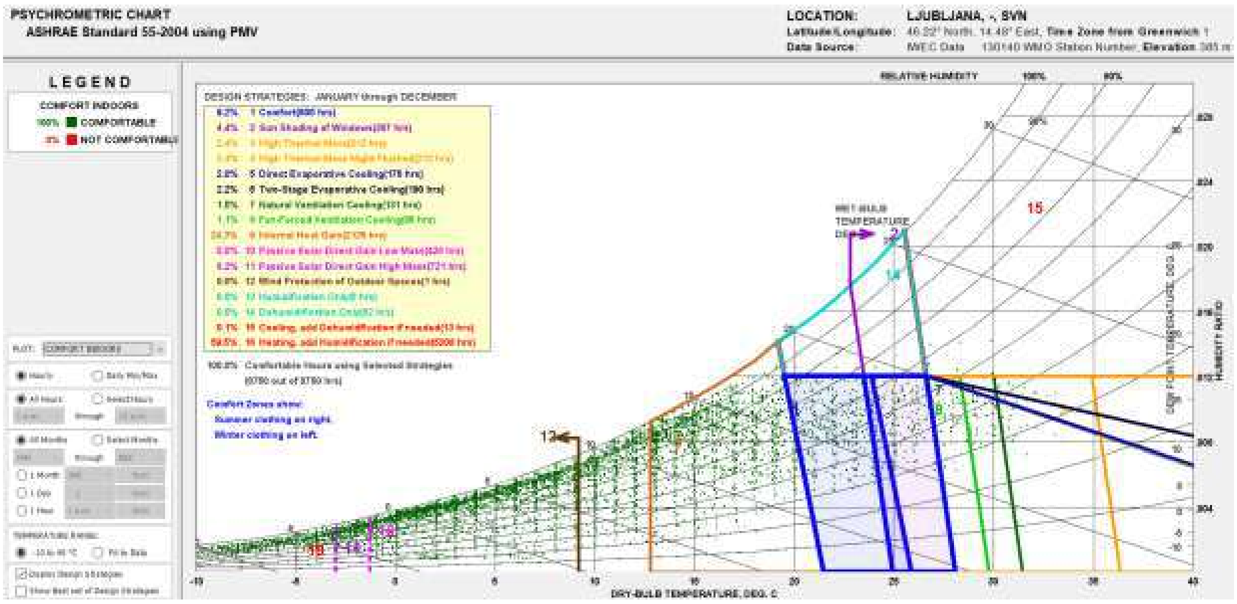


Figure 5. 34: Psychrometric chart with all design strategies selected to achieve comfort.

Sun Shading of Windows can provide more than 4-5% of yearly comfort, which can be achieved with simple and low-cost passive strategies. Natural ventilation and fan-forced ventilation for cooling provide little benefit in this climate. The Gerbiceva project predicts the use of controlled mechanical ventilation in winter and summer. Internal Heat Gains can add 24.3% of additional hours to the comfort zone if we insulate the building to capture the heat generated by people, lighting, and equipment. Heating is required for 60.4% of the time in one year. Passive Solar Direct Heat Gains and High Thermal Mass of the design could provide an additional 10% to the comfort zone compared to just 5% of a low thermal mass solution. By adding or removing strategies, the graph adapts the data plots and contribution to the comfort zone.

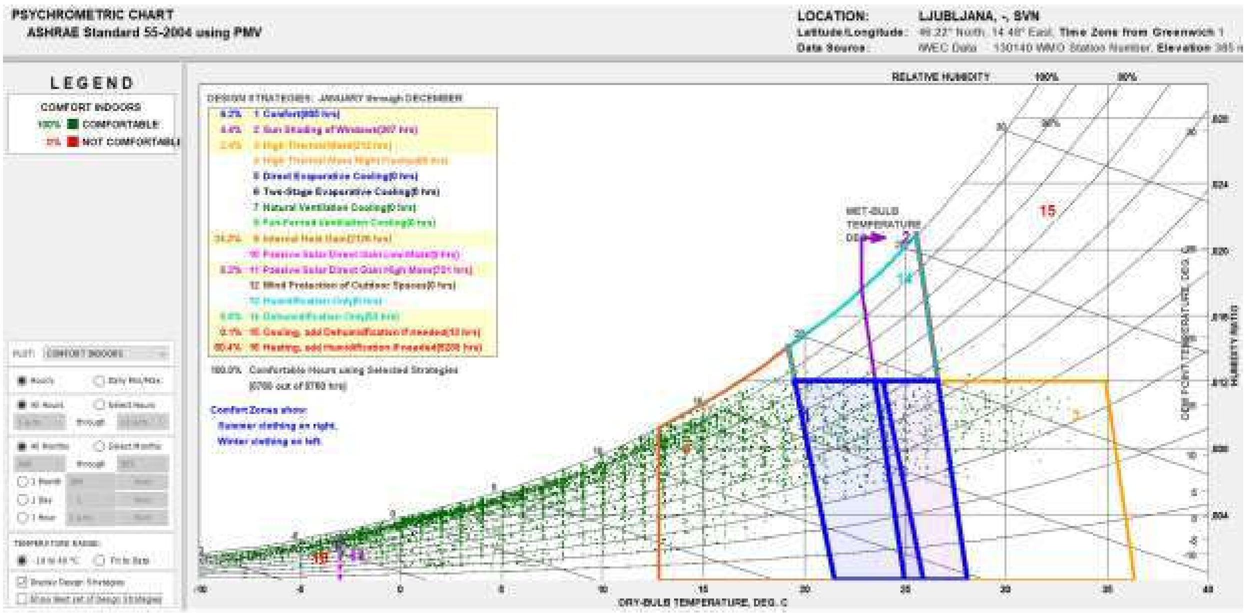


Figure 5. 35: Psychrometric chart with selection of best strategies to achieve comfort.

The Internal Heat Gain value of 24.3% is close to the 25% increase given by the Ladybug computation of the Weather data. The project accommodation units are oriented West or East. The total removal of Passive Solar Gains of 8%, increases the Heating design strategy from 60% to 63.5%. We can expect in the case study a Heating need within this range.

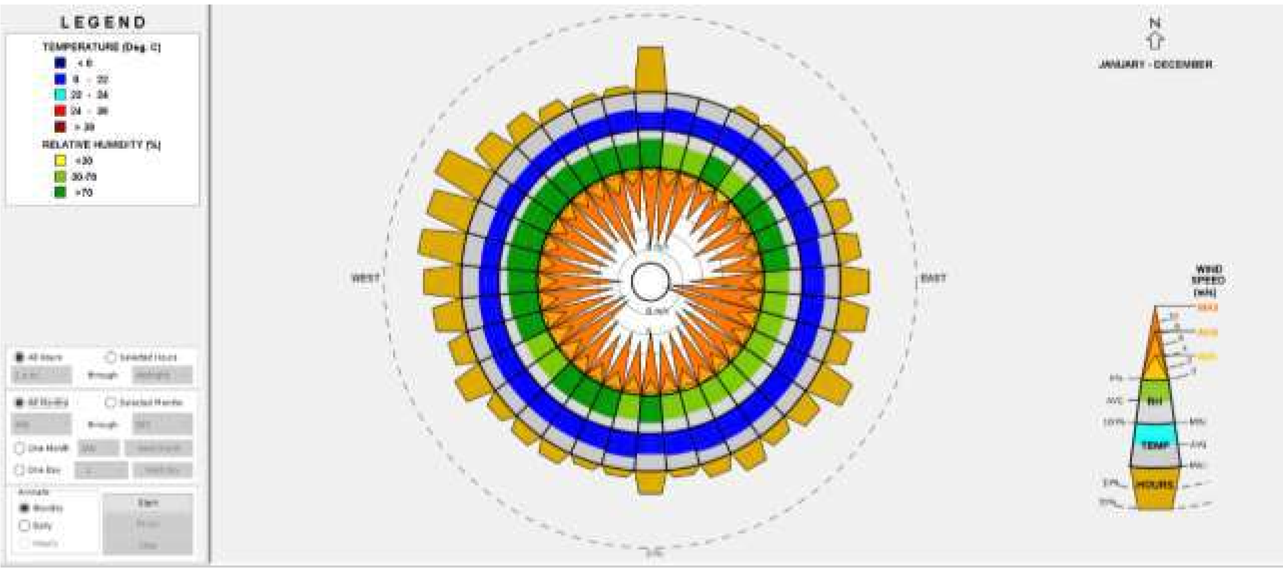


Figure 5. 36: Wind Wheel in relation to time occurrence, temperature, relative humidity and speed. Yearly and monthly graphs are available.

The two following strategies are for facing the architecture, and glazing towards south to maximize solar gains and using the mas of the interior surfaces for winter passive heating and summer night-time cooling. These are not possible to apply to the case study and typology of the Gerbiceva project.

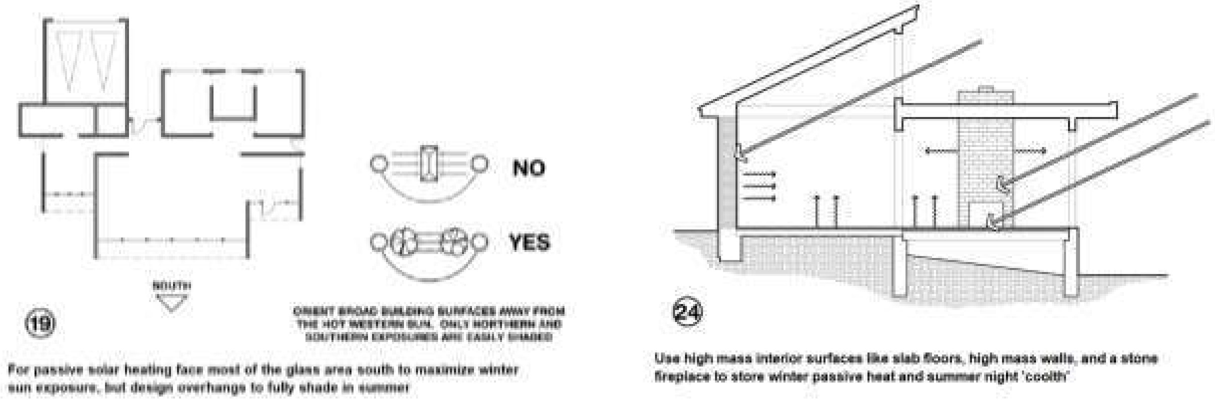


Figure 5. 37: Suggested Design Strategies by Climate Consultant for Ljubljana.

Double and triple glazing is applied to the design. Internal heating management system is predicted. Internal Heat Gains is possible due to the good insulation of external walls and compact shape. The U-Shaped interior courtyard with green spaces guarantees a comfortable outdoor space for most of the year.

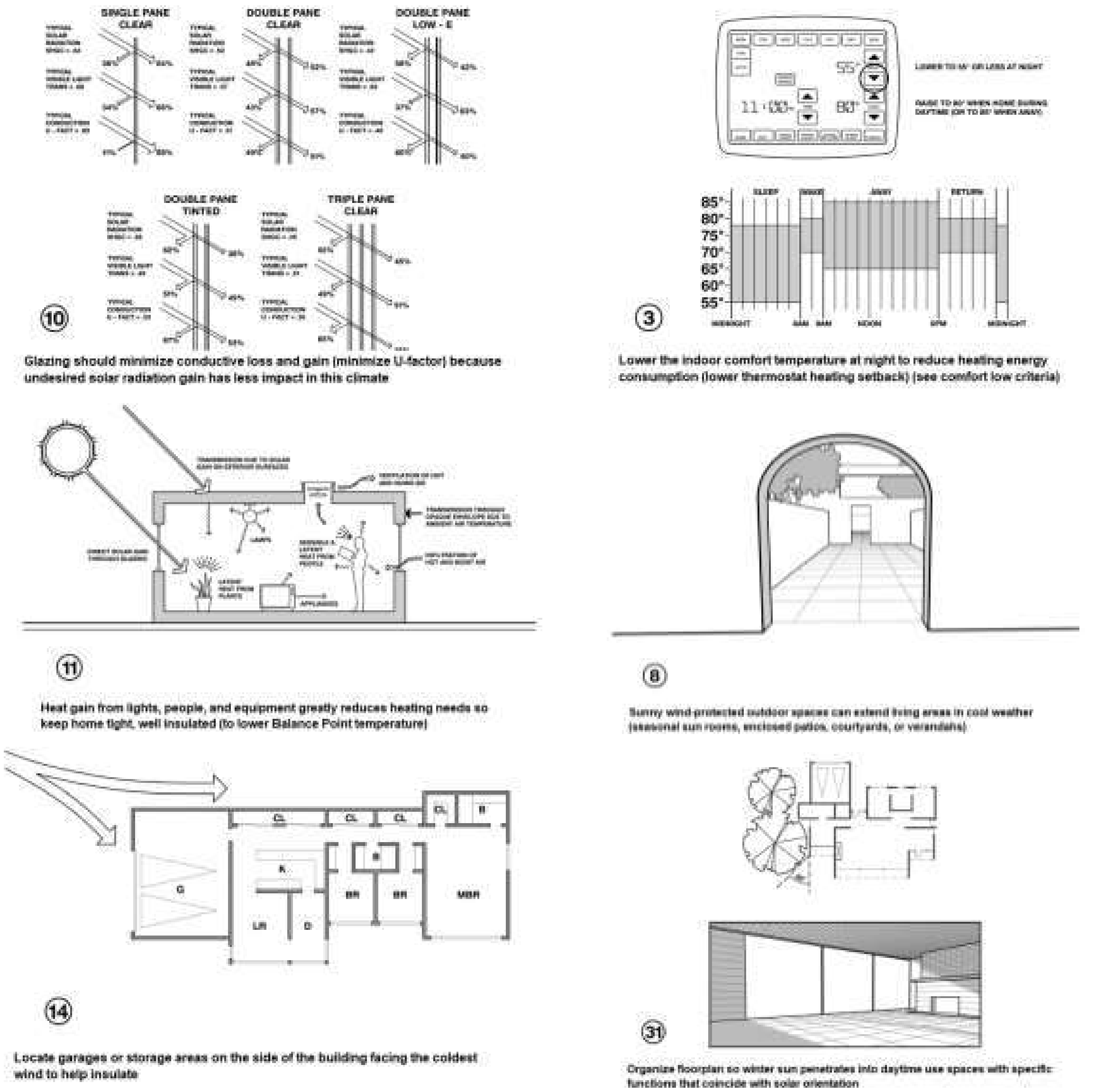


Figure 5. 38: Most relevant design strategies suggested by Climate Consultant for Ljubljana. Filtered based on applicability for the design of Gerbiceva Youth Housing Community.

5.5 Parametric Urban Design and form review of the project

Urban Design Parameters represent a requirement to be met by Building Regulations of Local Authorities and Laws issued at the national level by Governments. Design solutions need to comply with Zoning Plans, maximum permitted Height, Distances from Plot or Neighbouring buildings, Floor Area Ratio, Site Coverage, Parking and Green space requirements for obtaining a building permit. The role of the design team is to combine and optimize the different interests from the Client requirements, regulations, relate the design to the built environment context, evaluate alternatives based on bioclimatic and sustainable design potential to improve environmental performance, to guarantee human comfort, and include nature in the design parameters and feedback loop to achieve Regenerative Design goals.

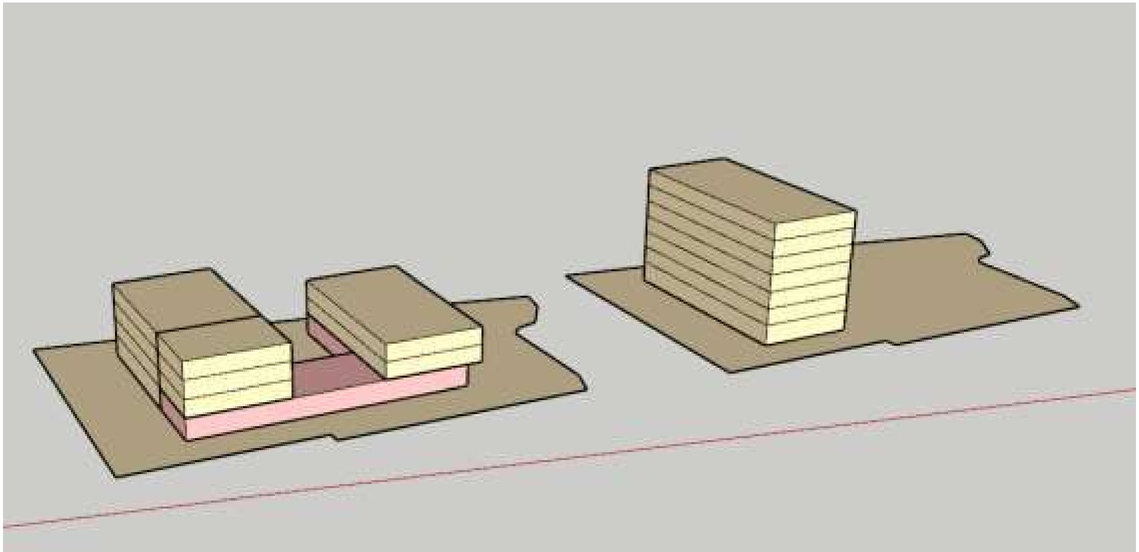


Figure 5. 39: Comparing the Gerbiceva project with a design option with the same Gross Floor Area, same Width, Length that permits to have a similar floor layout and distribution of a building of seven levels above ground.

Table 5. 17: Urban Design parameters comparison of Gerbiceva project and Design Option.

Urban Parameters	Gerbiceva project	Seven levels building
Gross Floor Area	4,436.20 m^2	4,340.56 m^2
Site Coverage	35.29	16.16
Floor Area Ratio	1.1	1.13
Form Factor (surface/volume)	0.37 m^{-1}	0.27 m^{-1}
Heat Loss Form Factor (Surface/GFA)	1.65	1.17
Envelope Area	5’025.59 m^2	3’568.67 m^2

The design option performs better in terms of building shape FF and HLFF metrics. However, the design solution adopted is in the range of buildings with a low and performing value of these metrics. The form selected makes better use of the building plot in terms of organization of space, preserving existing trees, sunny protected inner courtyard thus improving the outdoor comfort and extending the period of year people can stay outside with no thermal stress based on UTCI.

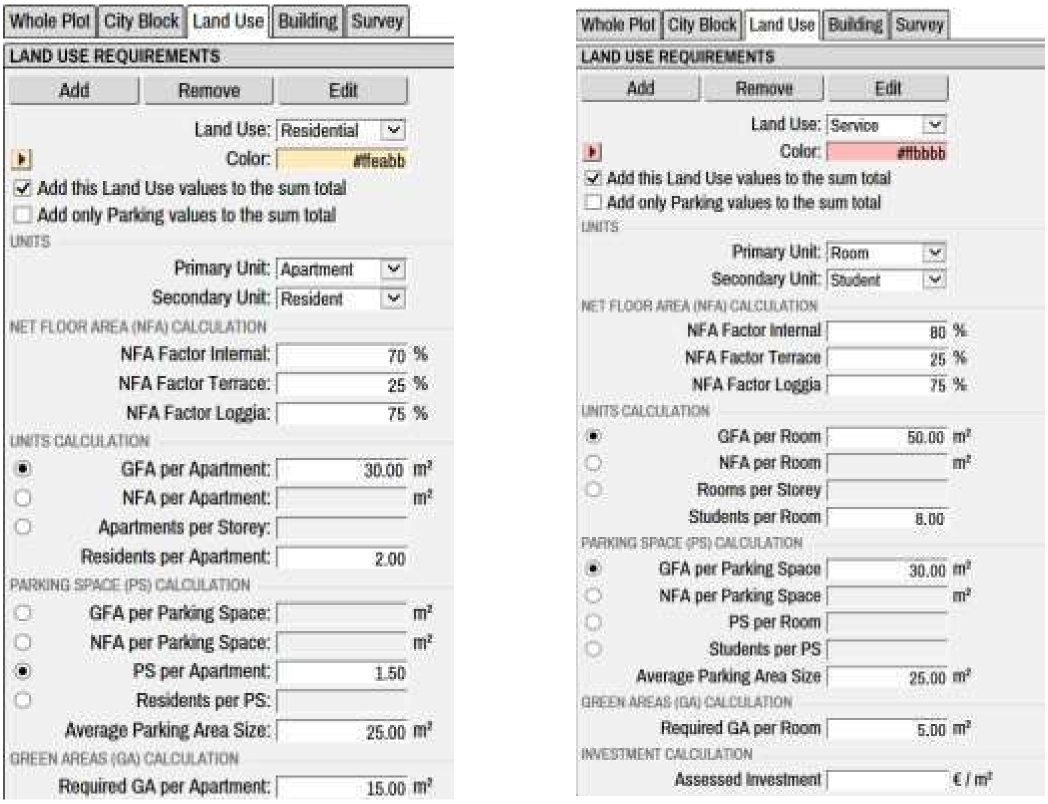


Figure 5. 40: Land Use parameters to match with Municipality requirements for the residential (accommodation units) and service (ground floor service estimation)

LAND USE DATA - RESIDENTIAL		
Gross Floor Area	3,357.16	m²
Number of Apartments	111.91	
Number of Residents	223.81	
Required Green Area	1,678.58	m²
Required Parking Spaces	167.86	
Required Parking Area	4,196.46	m²
Volume	10,359.29	m³
Net Floor Area	2,350.01	m²
Assessed Investment	/	€
Number of (Simple) Buildings	3	
LAND USE DATA - SERVICE		
Gross Floor Area	860.36	m²
Number of Rooms	17.21	
Number of Students	137.66	
Required Green Area	86.04	m²
Required Parking Spaces	28.68	
Required Parking Area	716.97	m²
Volume	3,183.33	m³
Net Floor Area	688.29	m²
Assessed Investment	/	€
Number of (Simple) Buildings	1	

Figure 5. 41**:** Automatic table with building data.

Table 5. 18: Automatic tables for urban and building data.

Urban Planning parameters comparison

CITY BLOCKS DATA											
City Block Name	City Block ID	City Block Area (m²)	Gross Floor Area (m²)	Built-up Area (m²)	Floor Area Ratio	Site Coverage	Green Area Deficit (m²)	Parking Spaces Deficit	Parking Area Deficit (m²)	Mean Number of Storeys	Net Floor Area (m²)
City Block	1000050	3,836.17	4,217.52	1,353.93	1.1	35.29	-645.56	-84.63	-2,115.79	3.12	3,038.3
City Block	1000051	3,836.17	4,340.56	620.08	1.13	16.16	-723.43	-72.34	-1,808.57	7.0	3,038.39

Gerbiceva project building parameters

COMPLEX BUILDINGS DATA															
Building name	Building ID	Gross Floor Area (m²)	Built-up Area (m²)	Building Height (m)	Number of Storeys	Building Volume (m³)	Required Green Area (m²)	Required Parking Spaces	Required Parking Area (m²)	Primary Unit	Primary Unit type	Secondary Unit	Secondary Unit type	Land Use	Net Floor Area (m²)
Complex Building	1000032	4,217.52	1,353.93	12.7	4	13,542.62	645.56	84.63	2,115.79	129.11	/	361.47	/	/	3,038.3

Alternative 7 floors building

SIMPLE BUILDINGS DATA															
Building name	Building ID	Gross Floor Area (m²)	Built-up Area (m²)	Building Height (m)	Number of Storeys	Building Volume (m³)	Required Green Area (m²)	Required Parking Spaces	Required Parking Area (m²)	Primary Unit	Primary Unit type	Secondary Unit	Secondary Unit type	Land Use	Net Floor Area (m²)
Building	1000036	4,340.56	620.08	21.7	7	13,455.74	723.43	72.34	1,808.57	144.69	Apartments	289.37	Residents	Residential	3,038.39

Parametric Urban Design tool Modelur is used to create the conceptual buildings, set up the design parameters and quickly review urban design alternatives. Automatic calculation of building data reduces drastically the time to validate Urban Design with regulations, compare options and give more space to creativity and exploring the design solution space.

5.6 Urban Modelling of Energy Flows

In cities, the urban environment is made from streets, walkways, greenery and buildings. These urban elements interact and create a microclimatic local condition. The organization of these elements shapes daylighting, energy use, outdoor comfort, carbon footprint, pollution and urban heat island effect. The combination of urban parameters and metrics to measure the performance is used to quantify the Green City Performance or Liveability Index of cities. The microclimatic effects of urban settings such as shading (buildings, tree canopies), urban heat island, heat waves, local wind patterns affecting outdoor comfort require tools that can be used in a design process.

The Urban Modeling Interface (UMI) is a tool developed by the Sustainable Design Lab at MIT to be used as urban modelling platform to evaluate the environmental performance at the urban level of buildings and cities concerning daylighting potential, energy, operational energy use, and walkability[62].

Figure 5-5: UMI modelling functionalities inside the Rhino environment.

[62] Reinhart, C. et al. (2020). Urban Modelling Interface. MIT Sustainable Design Lab. Retrieved May 05, 2020, from http://web.mit.edu/sustainabledesignlab/projects/umi/index.html

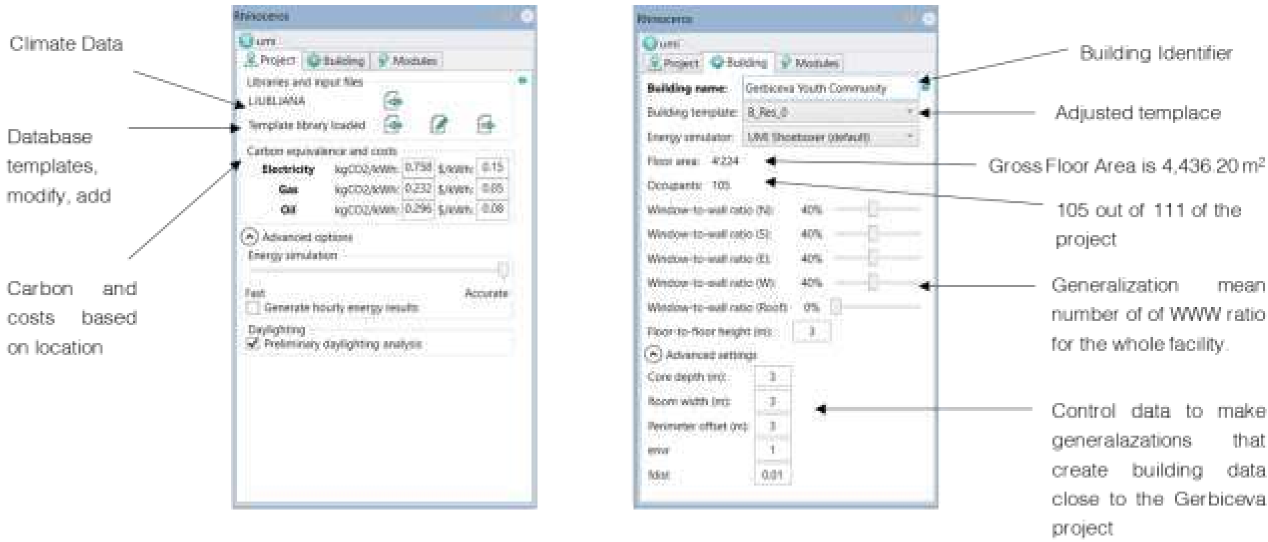


Figure 5. 42: Urban Energy Modelling Information Requirements

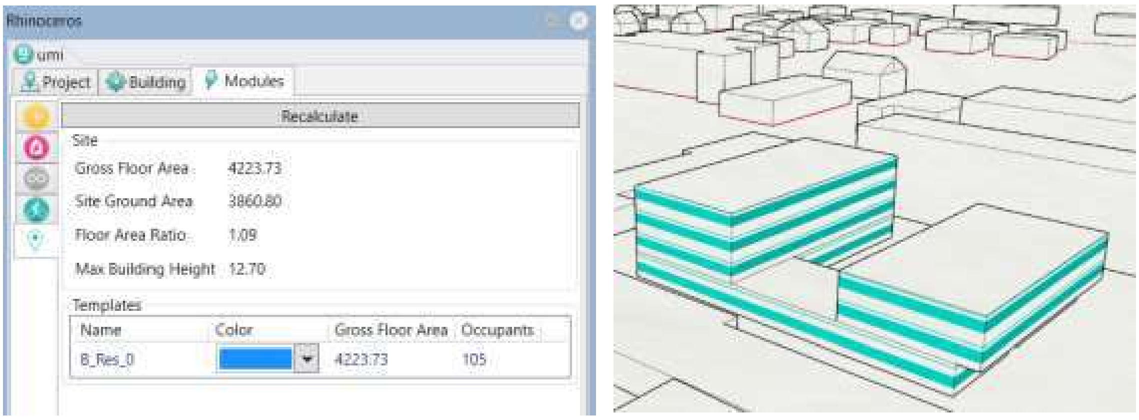


Figure 5. 43: Check of 3D Rhino Geometry to UMI building model

Benefits for Urban Design:

- Rules for automatic creation of levels
- Reliable automatic facade openings based on Window to Wall Ratio (WWR)
- Automatic areas calculation Gross Floor Area and Plot Area
- Floor Area Ratio (FAR)
- Building Height

Table 5. 19: Urban Parameters at comparison Gerbiceva project data-UMI-Modelur.

Urban Parameters	UMI	Gerbiceva Project Data	Modelur
Gross Floor Area (GFA)	4,223.73	4,436.20 m^2	4,217.52 m^2
Plot Area (PT)	3,860.80	3,872 m^2	3,836.17 m^2
Floor Area Ratio (FAR)	1.09	1.15	1.1

Conceptual modelling cannot replicate the exact values of project data because of details that cannot be included in conceptual geometry modelling. The approximation and reliability of conceptual data, in this case, has an acceptable margin to use these tools with confidence for project stages.

5.6.1 *Urban Modelling of Daylight*

In Regenerative Design, we could think of Daylight as the most valuable form of energy. The second most valuable is electricity. The width of 16 m of the residential blocks shows that daylight cannot penetrate more than 1.5-2 times the height of the window head. The Daylight credit of LEED v4 of achieving 55% sDA or 75% sDA can be explored since the concept phase. It is possible to try to achieve the credit in the next design phase by organizing regularly occupied spaces along the >55% isolines and spaces that do not require daylight such as technical areas and distribution corridors in the <55% daylit zones.

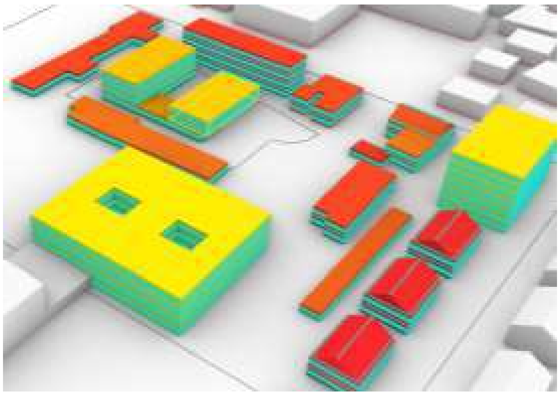


Figure 5. 44: Whole building cDA

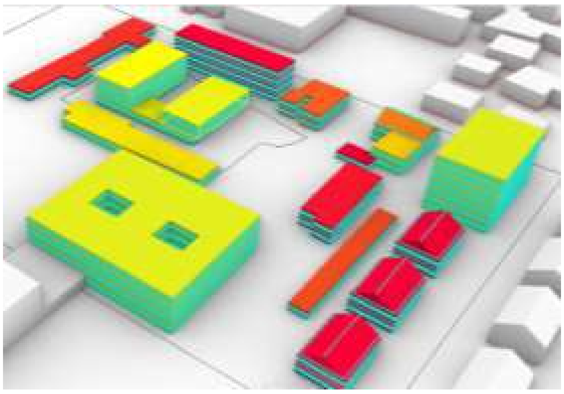


Figure 5. 45: Whole Building sDA

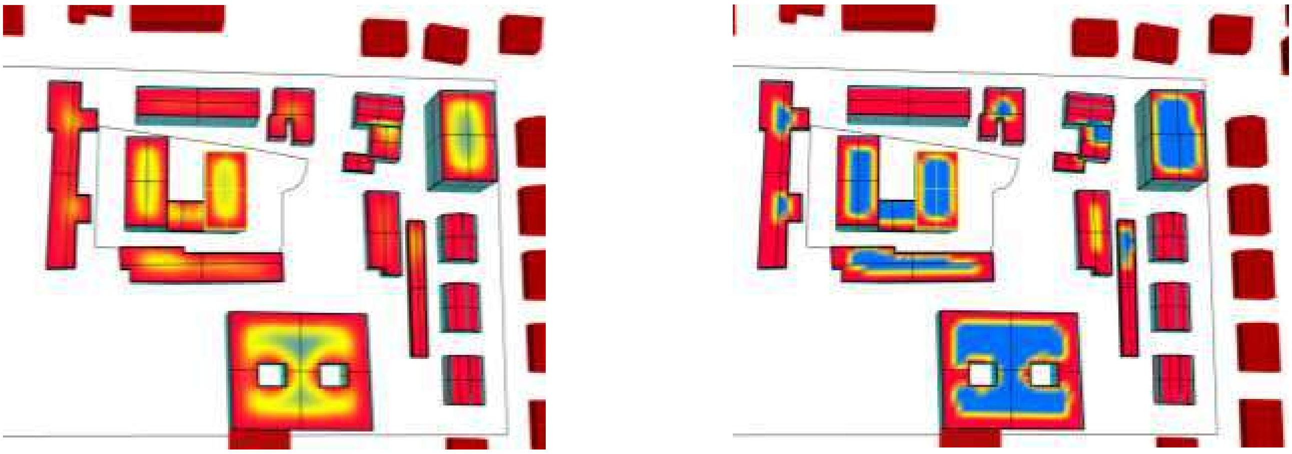


Figure 5. 46: Sensors for cDA (top floor plan view); Sensors sDA (top floor plan view).

Figure 5. 47: continuous Daylight Autonomy bar

Figure 5. 48: spatial Daylight Autonomy bar

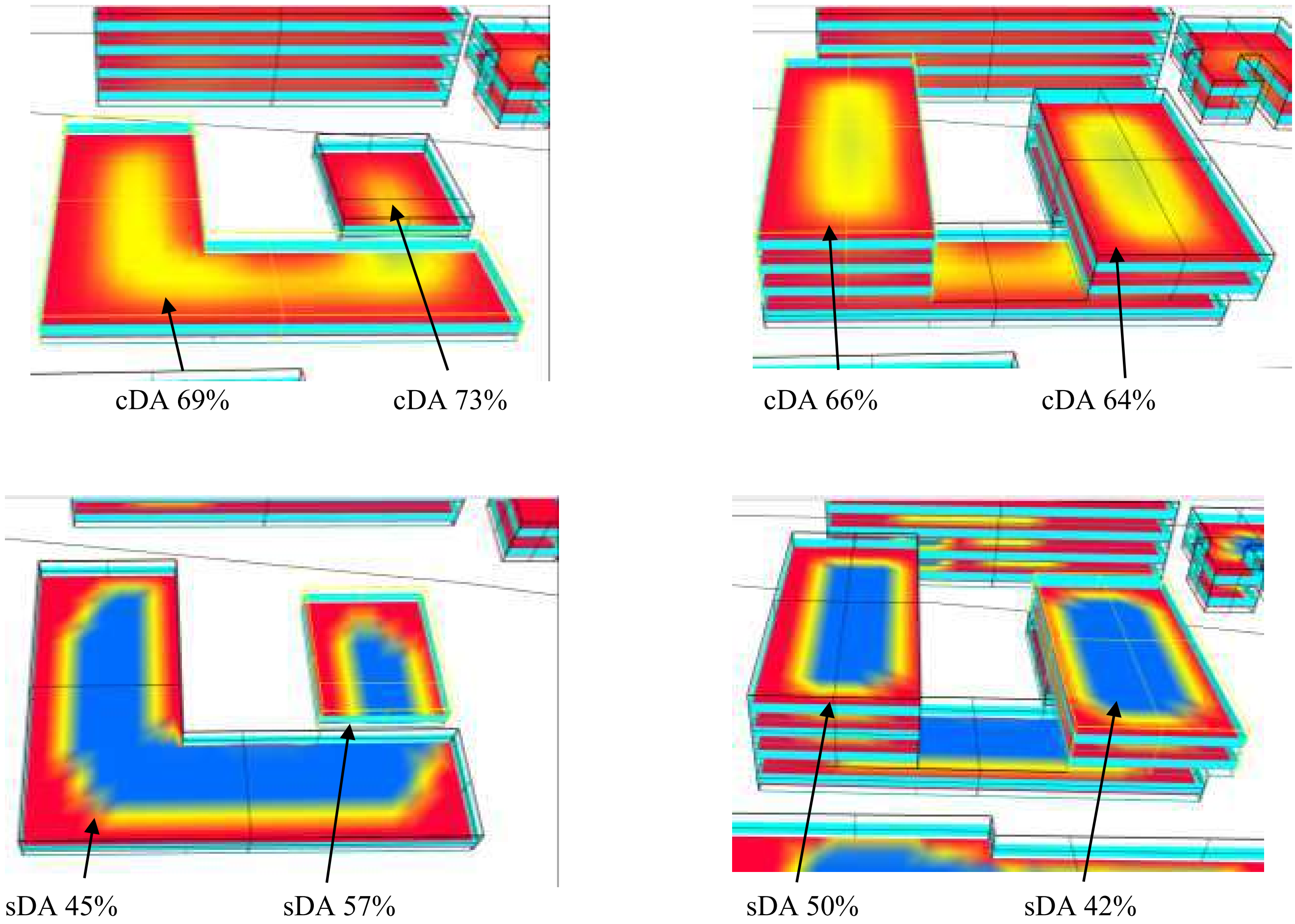


Figure 5. 49: cDA and sDA for every building level of Gerbiceva project.

Benefits of Urban Modelling of Daylight:

- Green Building Certifications credit exploration and setting design targets since urban design or building concept phase.
- Feedback of performance in the conceptual design stage.
- Design guidelines for distribution of building, location and sizing of spaces.
- Optimize form or floor plan for daylighting.

5.6.2 *Urban Modelling of Energy*

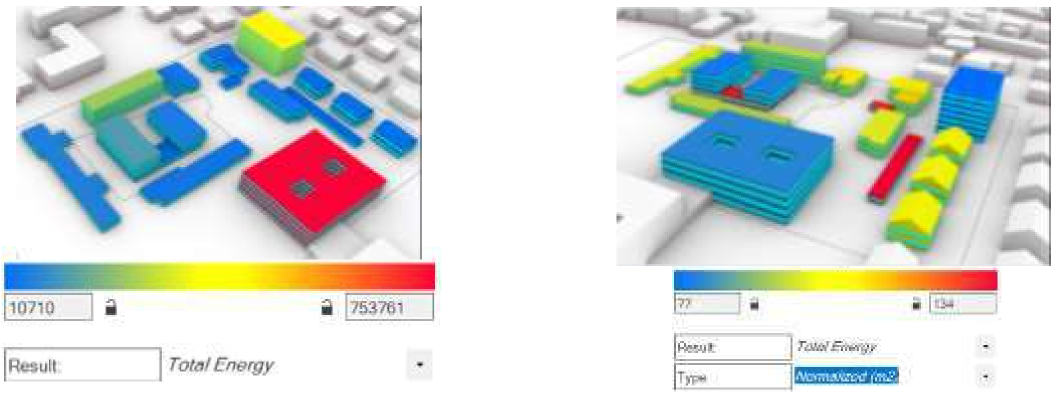


Figure 5. 50: Buildings Total Energy consumption/year. Values in kWh and normalized in kWh/m^2.

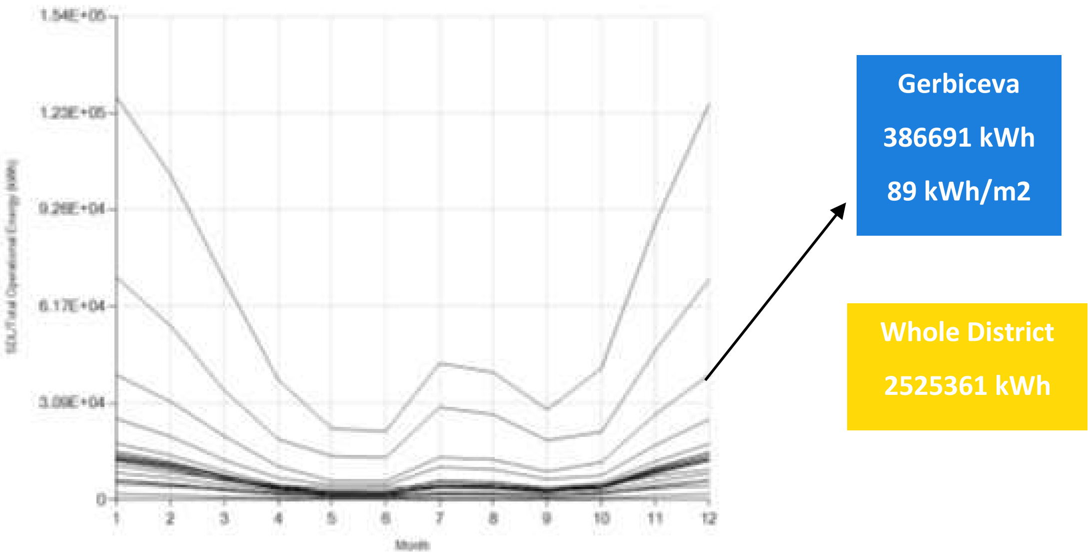


Figure 5. 51: Chart of Total operational energy monthly of district buildings (kWh).

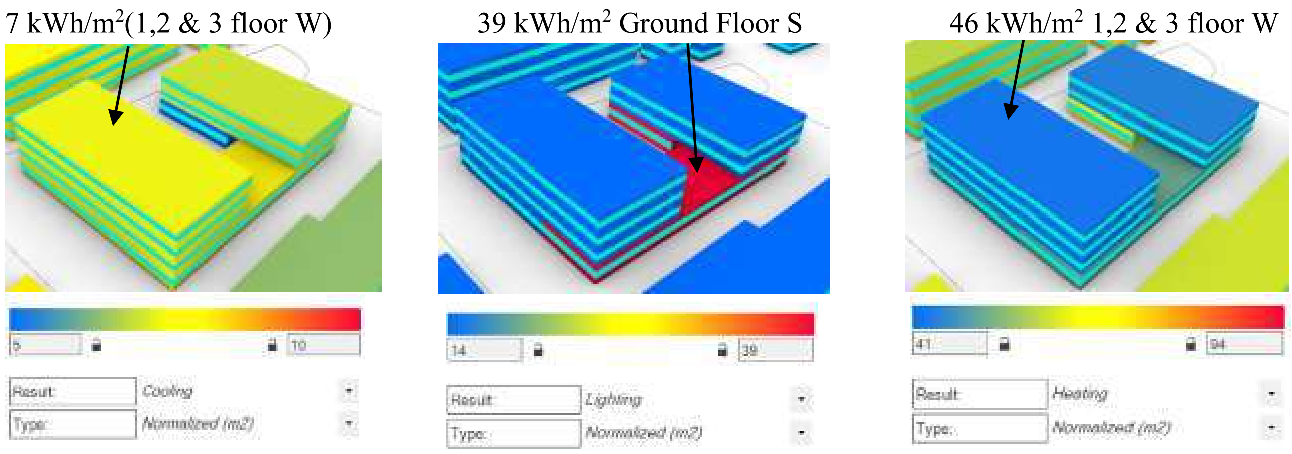


Figure 5. 52: UMI energy Loads of Cooling, Lighting, Heating.

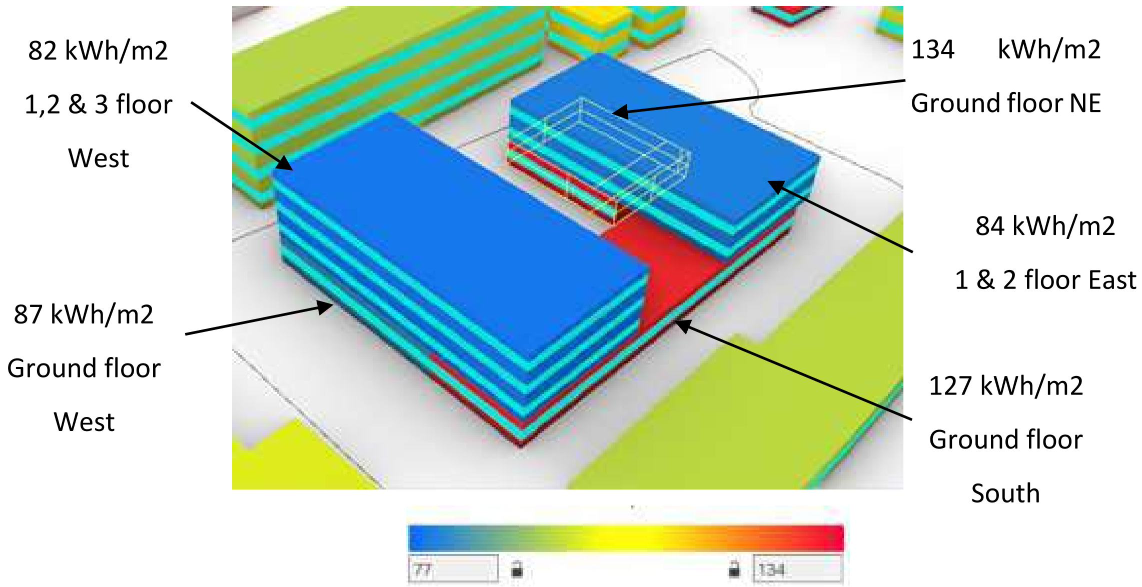


Figure 5. 53: Total Energy normalized kWh/m² for Gerbiceva project.

5.6.3 *Urban Modelling of Life Cycle Carbon*

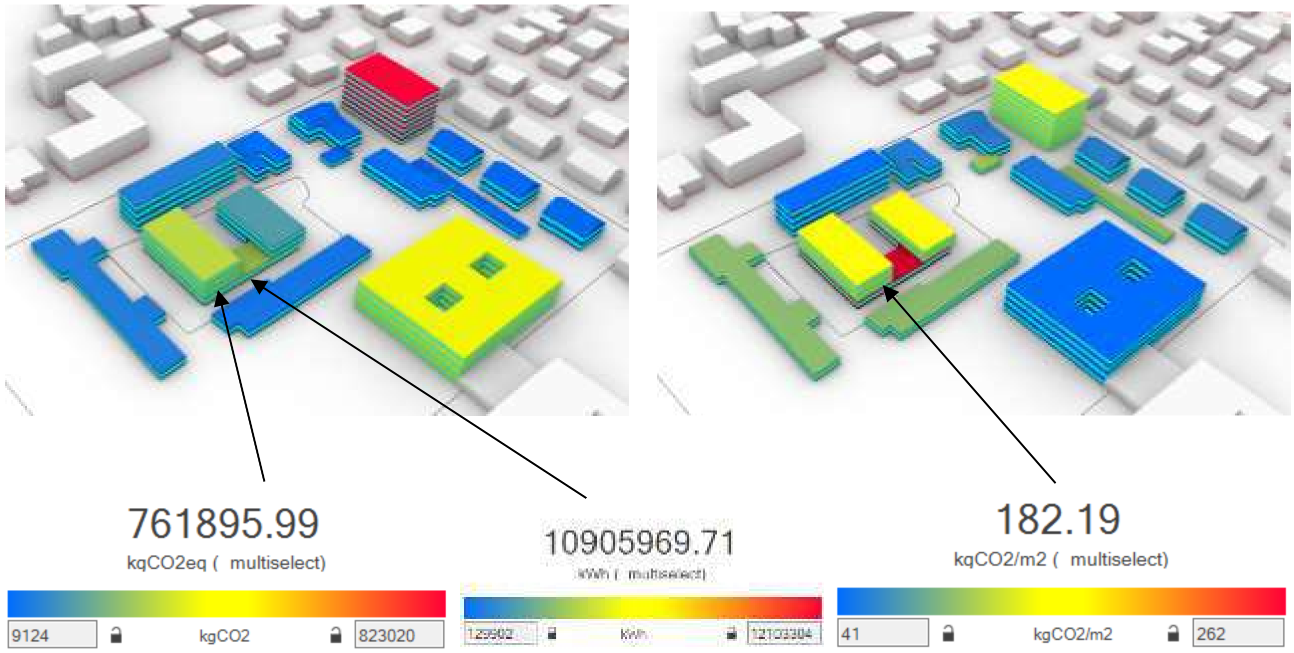


Figure 5. 54: Embodied and Operational Carbon for Gerbiceva project (50 years period).

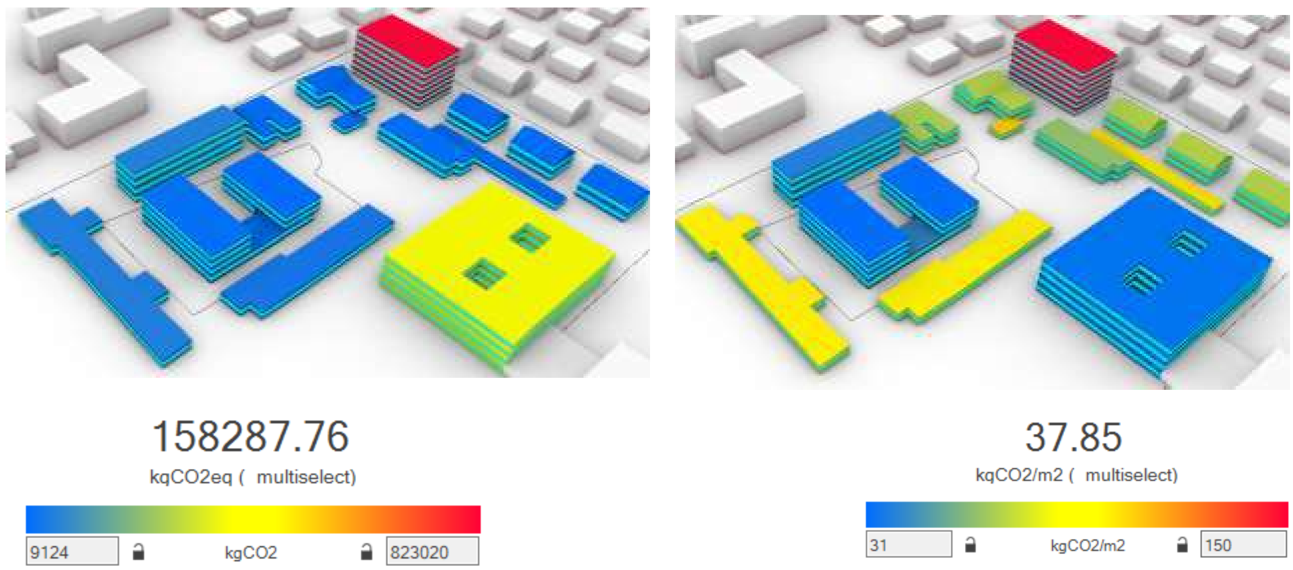


Figure 5. 55: Embodied and Operational Carbon normalized of Wood Design alternative.

The alternative was created with a Wooden based materials template in UMI. The reduction of embodied carbon is 78% from the baseline. UMI templates can be edited for materials, constructions, schedules and zone information properties. Building templates can be saved and different design solutions can be explored quickly.

5.6.4 *UMI for Grasshopper energy demands with costs calculation*

The interface of Grasshopper will be used to connect UMI databases of results of Heating and Domestic How Water to calculate the Natural Gas bill. The cost of Gas is set at 0.05€/kWh.

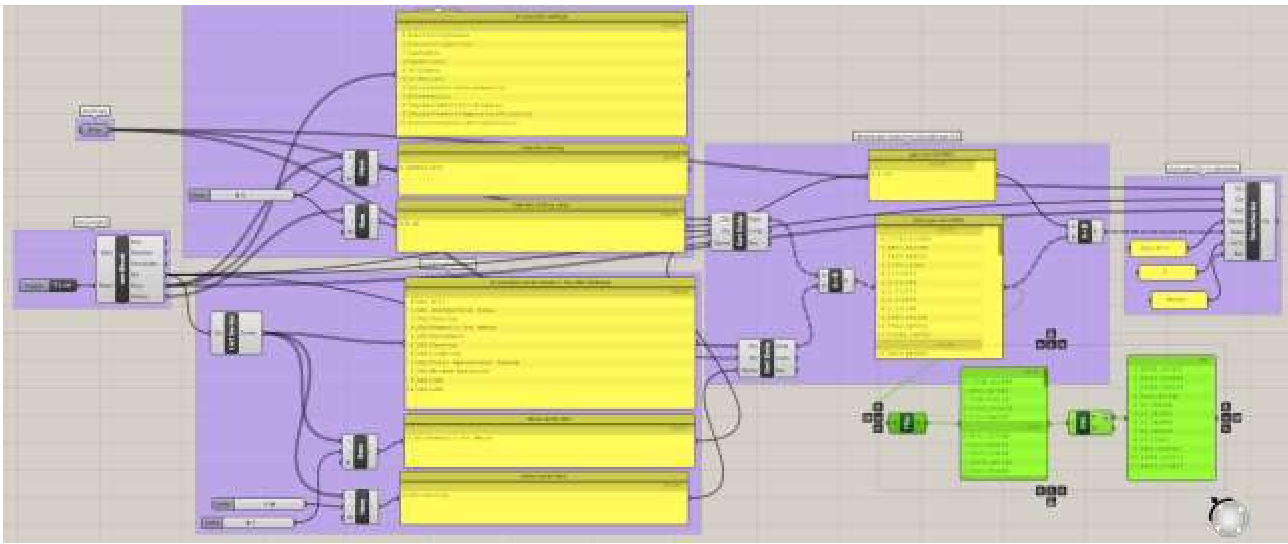


Figure 5. 56: UMI and Grasshopper code for retrieving monthly loads and Natural Gas bill.

Table 5. 20: Heating and DHW Monthly Loads and Gas Bill.

Months	**Heating and DHW Loads in kWh**	**Gas Bill €**
January	50787.94741	2539.397
February	38372.82949	1918.641
March	20480.54819	1024.027
April	6783.071082	339.1536
May	26.298544	1.314927
June	25.383425	1.269171
July	25.780996	1.28905
August	26.298544	1.314927
September	25.12465	1.256233
October	7861.460628	393.073
November	30487.91421	1524.396
December	48419.25387	2420.963
Total Loads	**203321.911**	**10166.1**

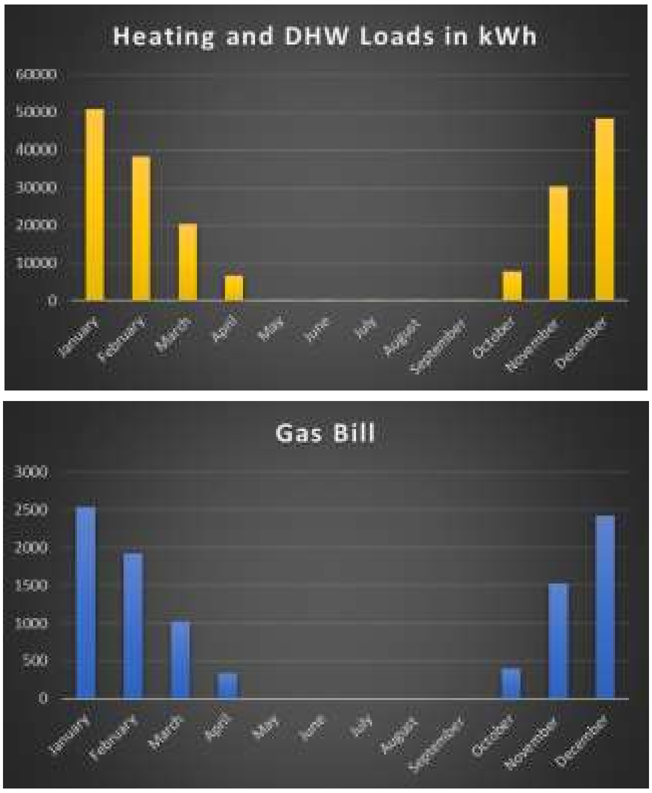


Figure 5. 57: Charts of Monthly Loads for Heating and DHW, and Natural Gas Bill.

5.7 Design validation according to EN 17037:2018 Daylight in Buildings

The new European Standard EN 17037:2018 Daylight in Buildings provides the calculation methods and recommended values of Daylight metrics for European capitals of CEN member states.

Table 5. 21: From EN 17037:2018 Table A.3: Target Daylight Factor corresponding to recommended target Illuminance level for the CEN capital cities.

Nation	Capital	Geographical latitude φ [°]	Median External Diffuse Illuminance Ev,d,med	DF to exceed 100 lux	DF to exceed 300 lux	DF to exceed 500 lux	DF to exceed 750 lux
Slovenia	Ljubljana	46,22	17 000	0,6 %	1,8%	2,9%	4,4%

Velux Daylight Visualizer is a validated lighting simulation tool for the analysis of daylight conditions in buildings[63]. It is distributed by Velux and is available free of charge. The software enables users to:

- create simple geometry of the project for simulation
- import models from Sketchup and 3D CAD files with layers
- make renderings
- make luminance false-colour images with isolines of values
- make illuminance images
- calculate the Daylight Factor for plan views, sections and camera views.

The target Illuminance of 300 lux for a fraction of space for target level ($F_{plane,\%}$) of 50% according to EN 17037 will be verified through the corresponding Daylight Factor that is to exceed 300 lux.

Figure 5. 58 Process Diagram of Interoperability with Exchange Information Requirements for Daylighting Analysis with Velux Daylight Visualizer.

[63] Velux. (2016). VELUX Daylight Visualizer (Version 3.0.22) [Software]. https://velcdn.azureedge.net/~/media/com/corp/visualizers/viz/daylightvisualizercievalidationreportpdf.pdf.

EN 17037:2018 recommended reflectances for surfaces:

Floor: 0.2 - 0-4

Ceiling: 0.7 - 0.9

Interior Walls: 0.5 - 0.8

Exterior Walls: 0.2 - 0.4

Exterior Ground: 0.2

Figure 5. 59: Workspace view of imported Model into Daylight Visualizer.

True north is set to 11° with the design’s South Facade to correspond with the location.

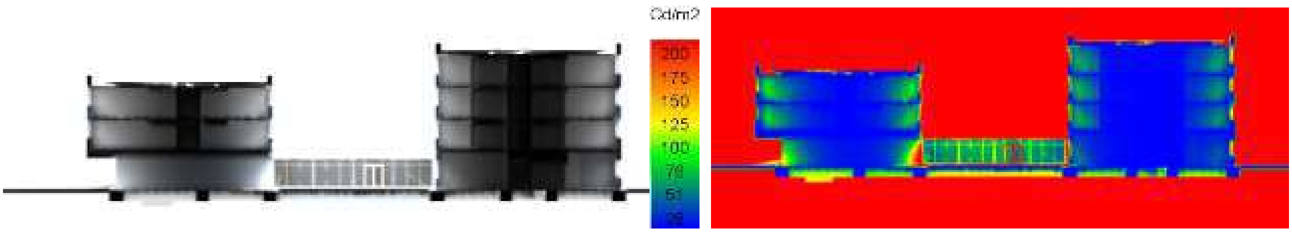


Figure 5. 60: Luminance and False-colour Section Renderings with Overcast Sky at 21 March 12:00.

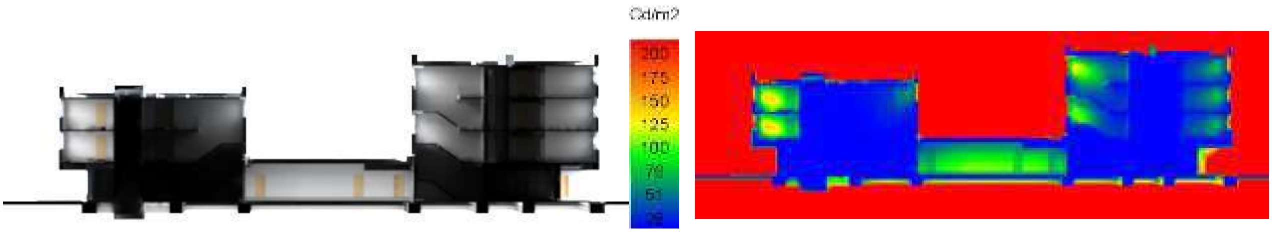


Figure 5. 61: Luminance and False-colour Section Renderings with Sunny Sky at 21 March 12:00.

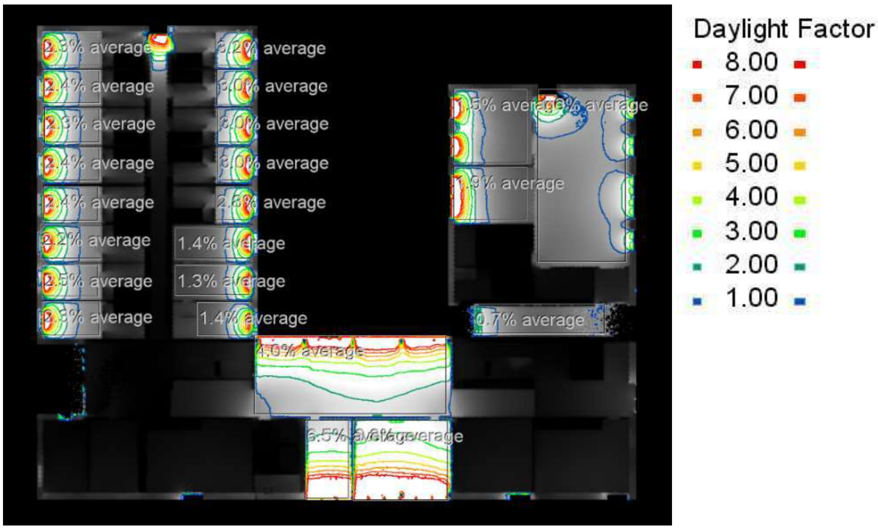


Figure 5. 62: Daylight Factor for the ground floor level

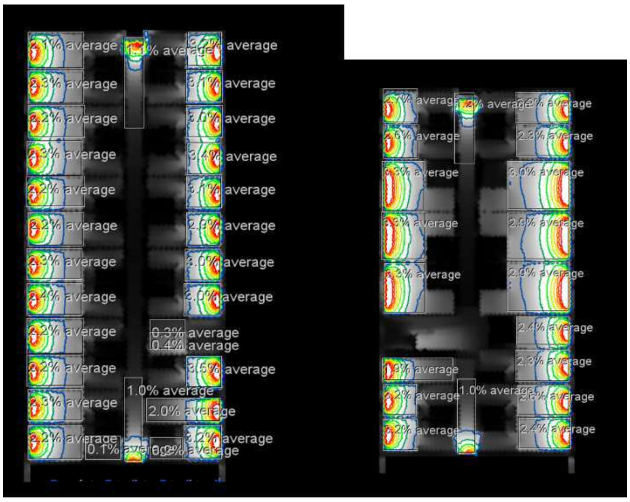


Figure 5. 63: Daylight Factor for the first level.

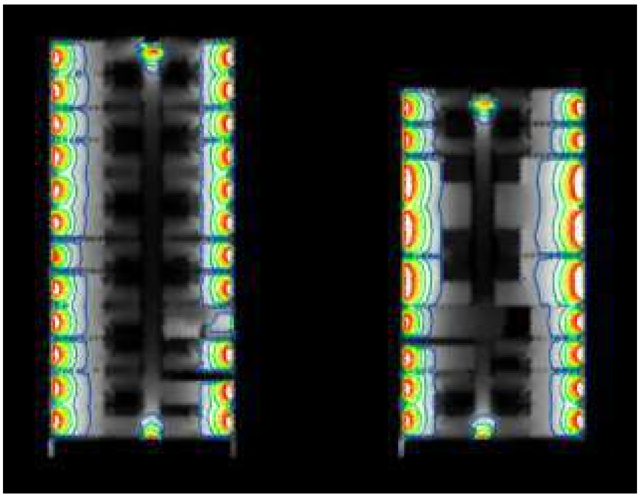


Figure 5. 64: Daylight Factor for the second level.

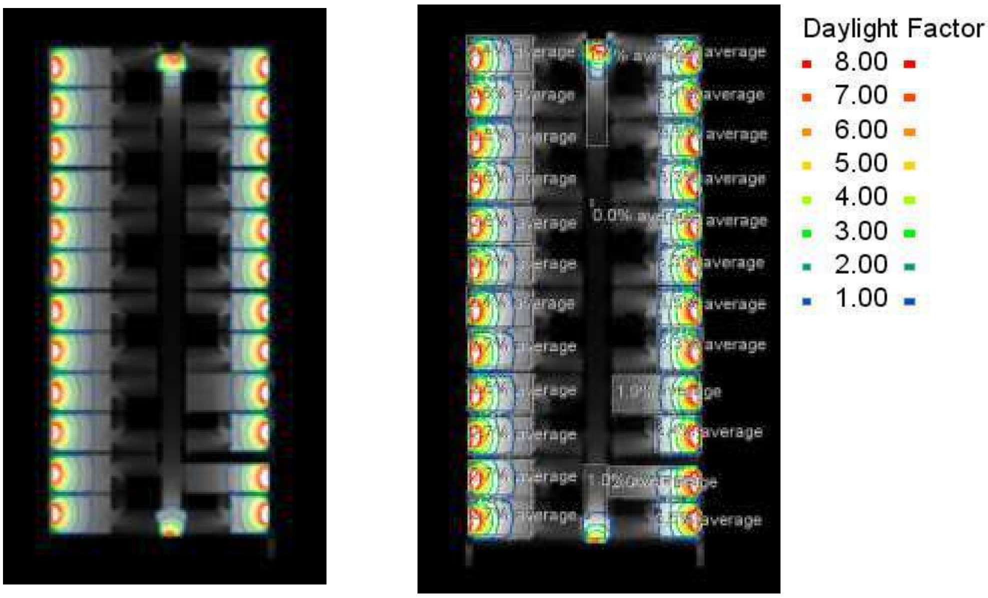


Figure 5. 65: Daylight Factor for the West Wing third level. Visualization of isolines and DF values for zones.

The building design is within EN 17037 recommended values for Ljubljana. The three spaces on the ground floor level that are below DF<1.8% are not assigned to accommodation units. The function assigned as not regularly occupied living spaces can be integrated with electrical lighting to achieve 300-500 lux on the workplane.

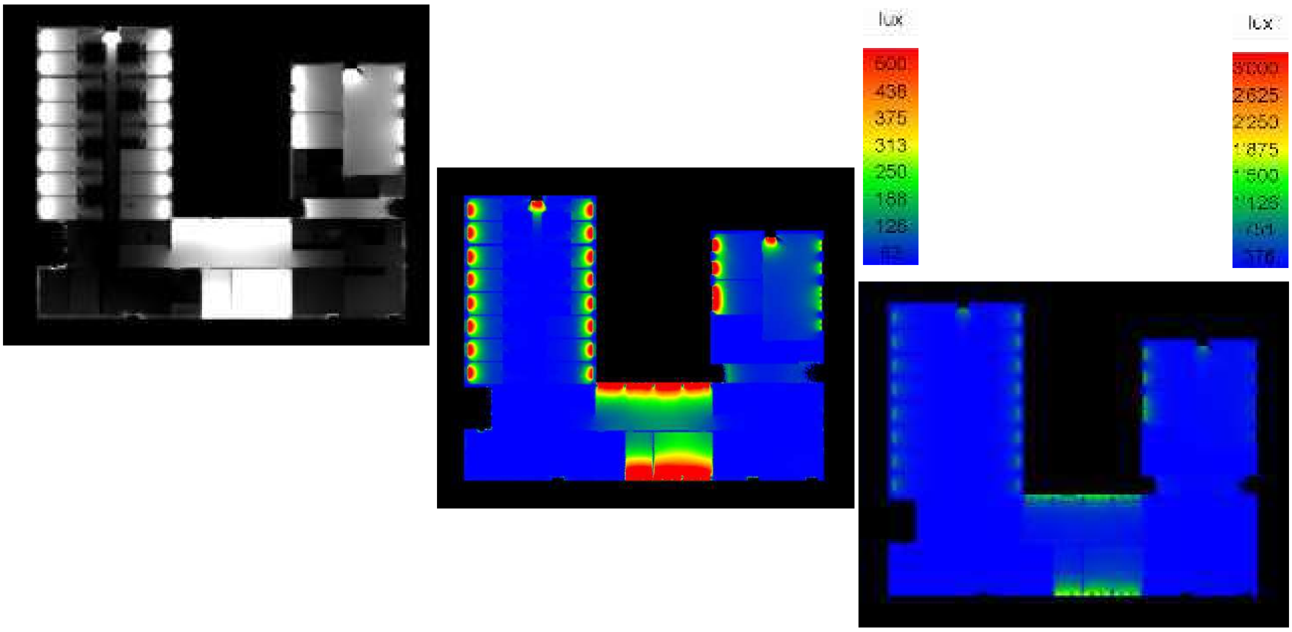


Figure 5. 66: Illuminance renderings at ground floor level.

The values of illuminance above 3000 lux are an indication of possible glare condition. The ground floor spaces receive sufficient daylight for the required activities with overcast sky conditions on 21 March at 12:00. The East spaces receive less than sufficient daylight at this time of the year due to the overhang condition created from the first floor above.

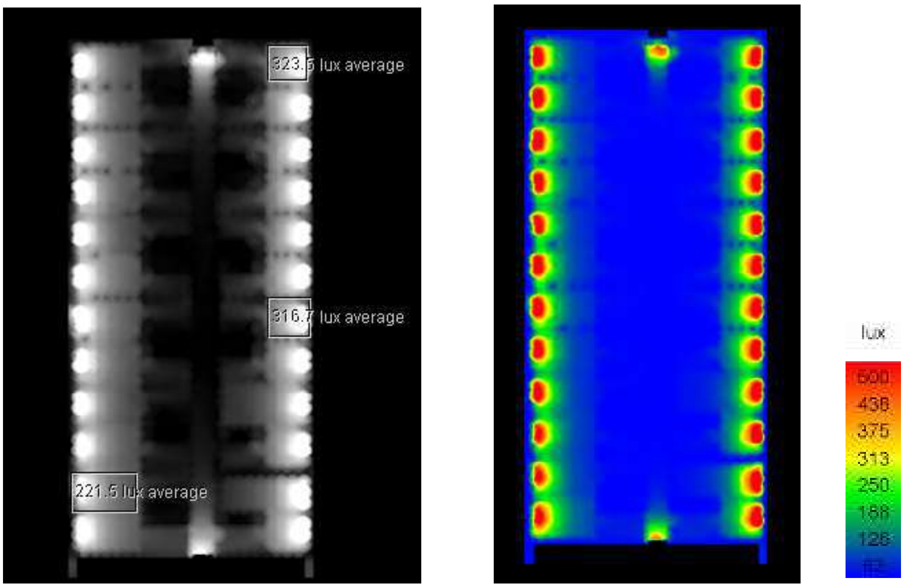


Figure 5. 67: Illuminance validation for the third level.

Illuminance target of more than 300 lux for 50 % of zones is reached as shown in the illuminance renderings.

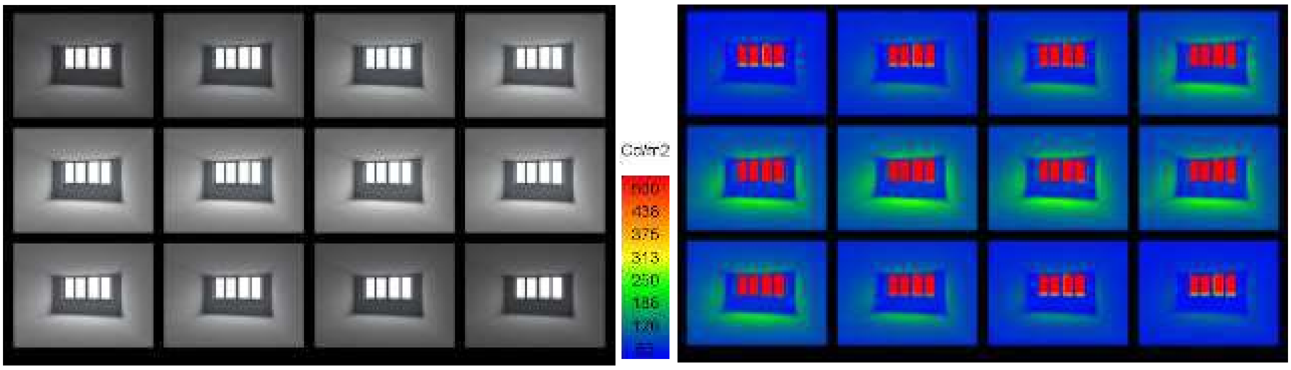


Figure 5. 68: Daylight Annual Overview of 3rd floor east unit with overcast sky conditions.

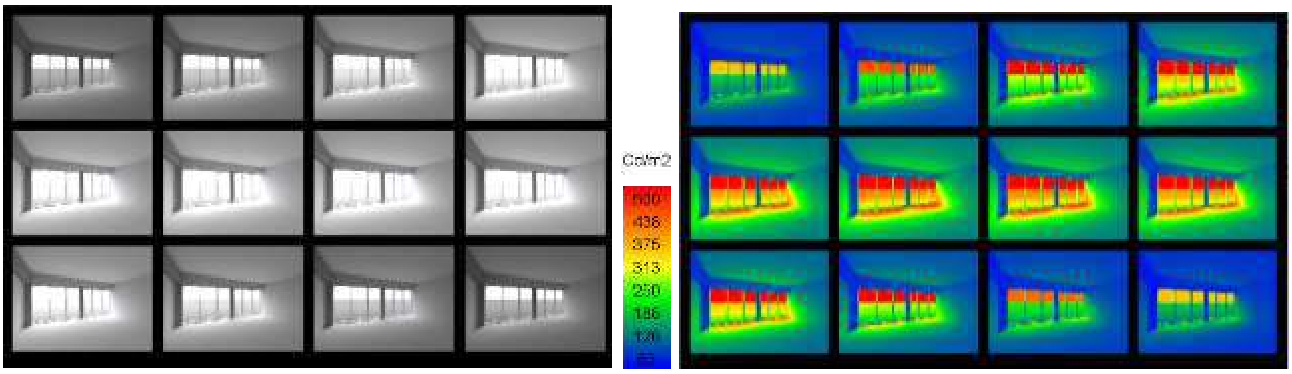


Figure 5. 69: Daylight Annual Overview of Ground floor south facade with overcast sky conditions.

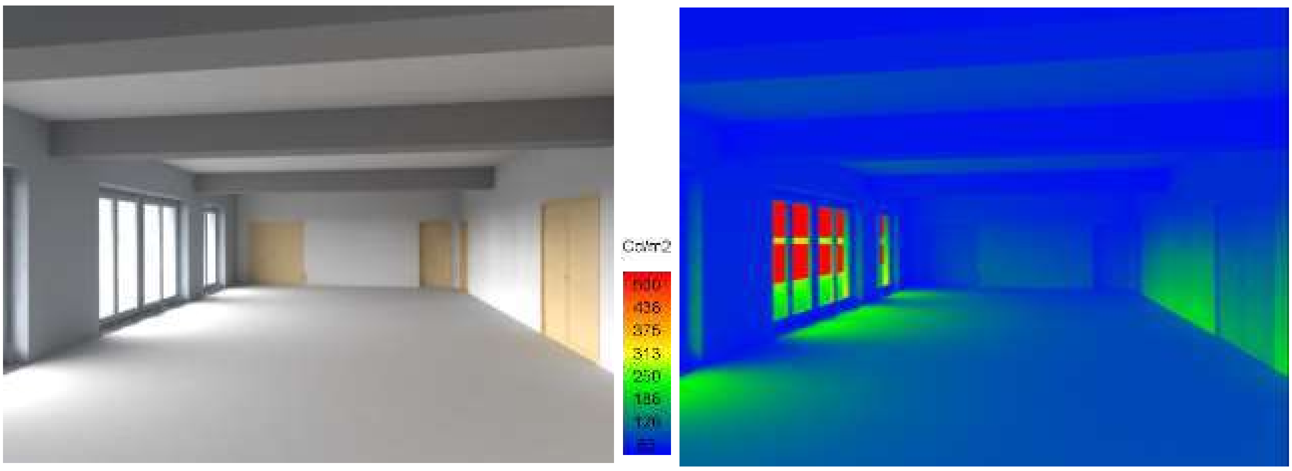


Figure 5. 70: East wing, west space, sunny sky, 21 March at 12.00.

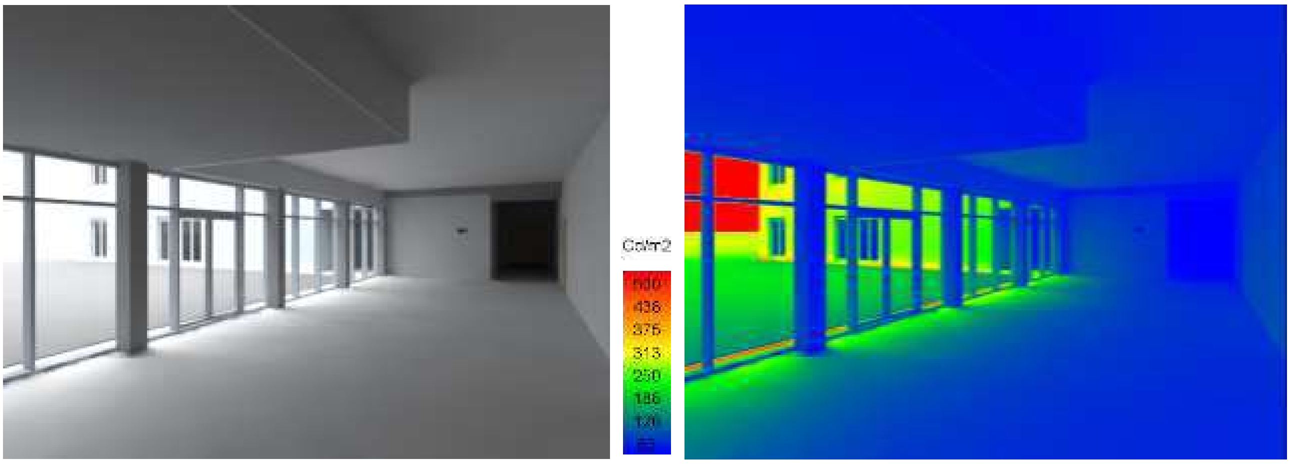


Figure 5. 71: South wing, north space, overcast sky, 21 March at 12.00.

Daylight Analysis requires geometric information, diffuse reflectances of surfaces and visible transmittance of glazings. Such information can be available since the concept phase and does not require detailed Manufacturer's product specifications. Recommended values of reflectances can be found in the EN 17037:2018 standard and values for glazings through lighting handbooks. The required level of information for this type of simulation is aligned with the requirements of Public Authorities such as the Housing Fund of the Republic of Slovenia to inform decisions in project stages with the feedback of design performance from the design team using **Generic Material Information**.

Benefits of Daylighting Analysis Model Use:

- Compliant with Generic materials requirement during design for Public Authorities
- Design validation following regulations and EN 17037:2018 standard
- Feedback of performance, visual comfort, shadings, electrical lighting requirements
- Whole Building Analysis

Exchange Information Requirements:

- Design Stage: RIBA 3 Spatial Coordination, 4 Technical Design, 7 In Use
- Geometry Requirements: LOD 200-LOD300 (BIM Forum, 2019)
- Alphanumerical Information Requirements: One surface modelling for transparent surfaces of glazing (no thickness), materials reflectance, visible transmittance of the glazing

5.8 Sunlight hours with Computational Design

Sunlight Hours is an essential factor in determining the quality of a unit based on direct sunlight accessibility during the day. Building Regulations across different countries may require a minimum of sunlight hours for the winter solstice. Le Corbusier introduced the concept through Article 26 of the Athens Charter in 1933. The Sunlight study can be used to assess also open space's access to sunlight. Computational Tools allow visualizing the Sun Path and Shadows on Buildings and urban spaces.

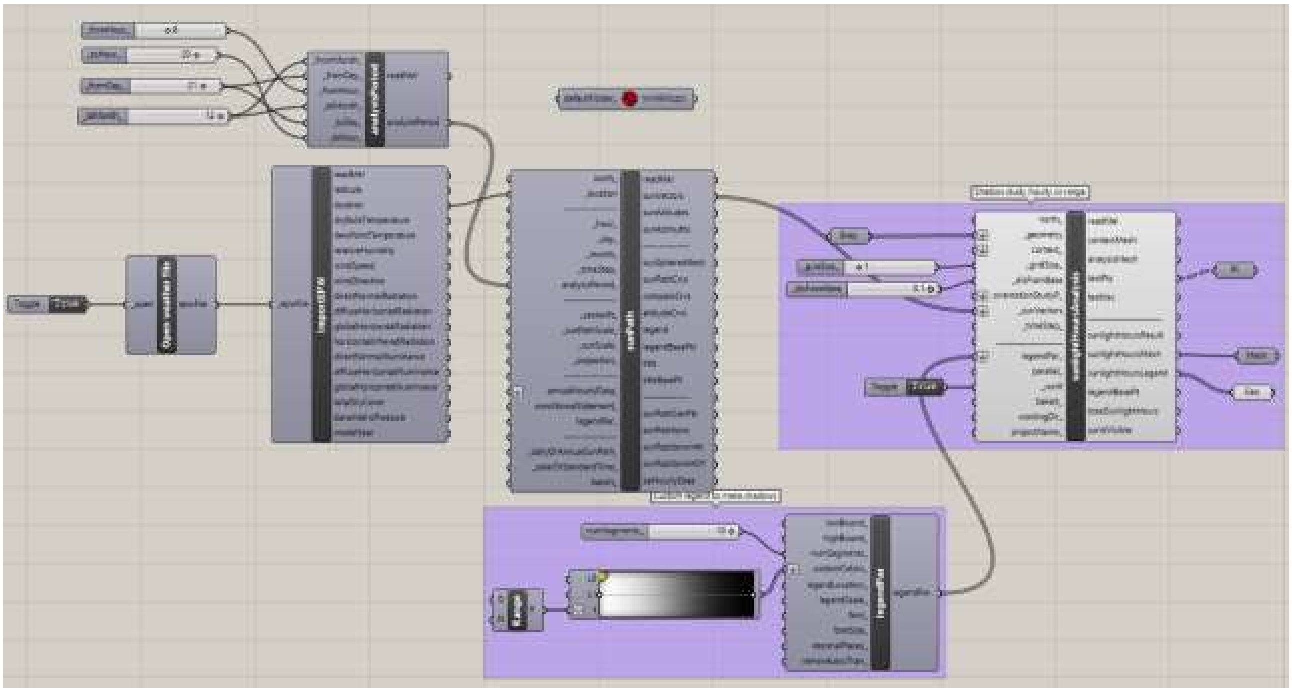


Figure 5. 72: Ladybug Tools Sunlight Hours Analysis algorithm in Grasshopper.

In contrast with traditional CAD shadow analysis, computational tools can visualize the sun for a given hour of the year, for a given range of the day, or user-defined analysis period of the year. It becomes useful since static single hourly data is transformed into complex data that can inform the design in new ways that are easier to handle than manually controlling for each hour. The results can be visualized through a colour map of sunlight hours on the surfaces. Thus, validating the design to regulations or working towards higher design goals.

In the appendix, larger images of the simulation are given with black and white colour mapping.

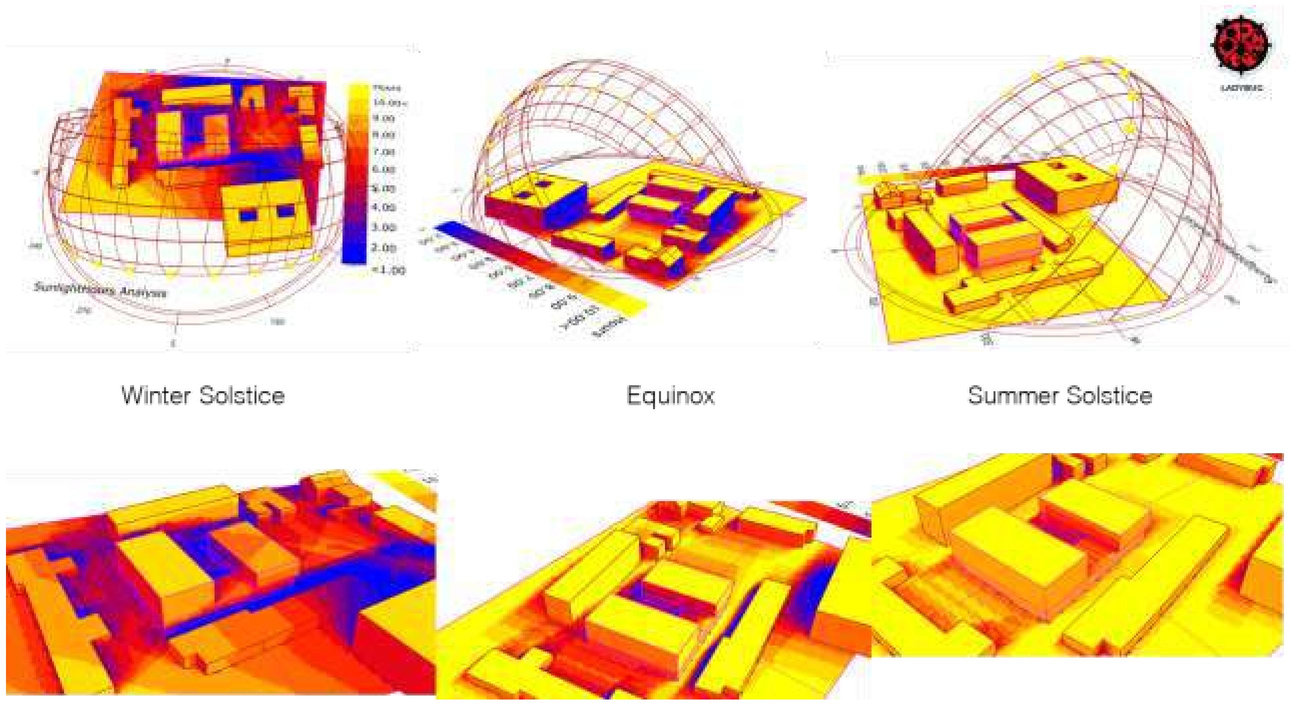


Figure 5. 73: Sunlight Hours with Ladybug tools, sun path and perspective view, coloured map.

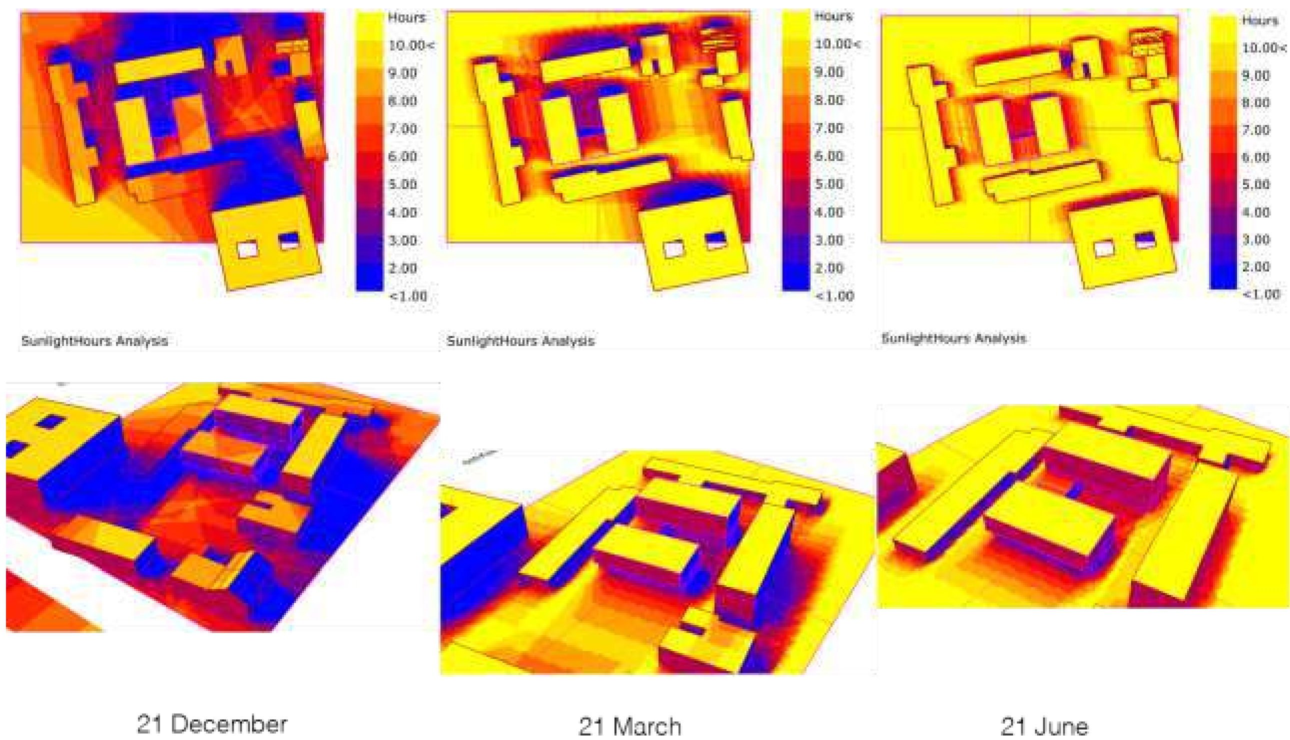


Figure 5. 74: Sunlight hours with Ladybug tools, plan and perspective view, coloured map.

The legend and colour-mapping of the building surfaces can be used to validate the design with regulations or explore qualitatively the sun exposure of facades, units or exterior open spaces.

5.9 Algorithmic process for Shadow studies

DIVA has extended functionalities for Grasshopper. Sun and Shadow analysis can be run through a computational process in Grasshopper based on customized design inputs and objectives.

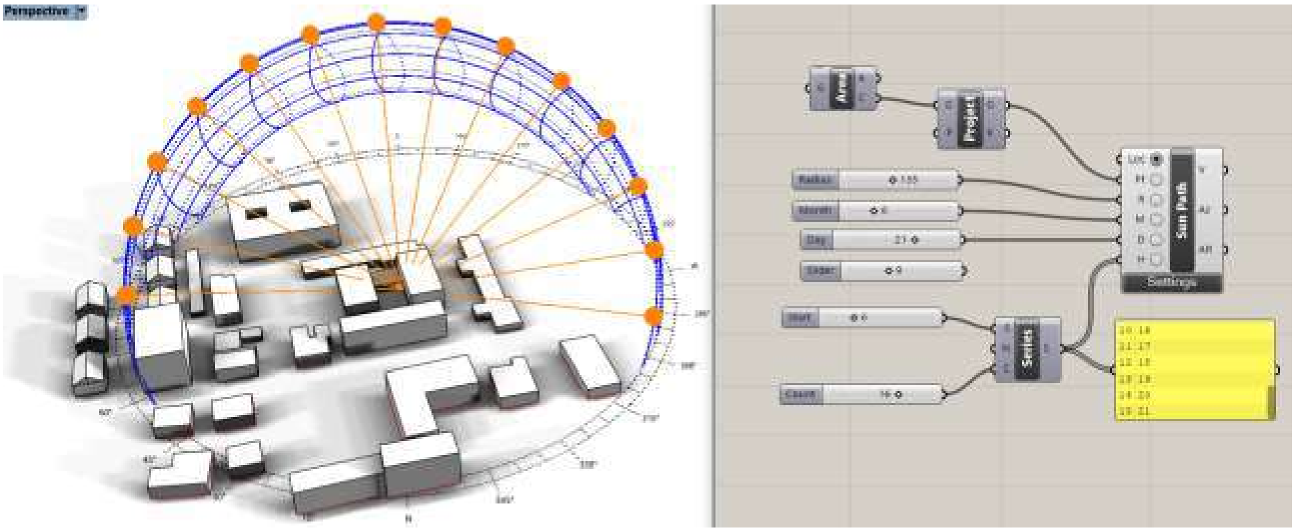


Figure 5. 75: Sun Path vectors on 21 June, shadows, and DIVA algorithm in Grasshopper.

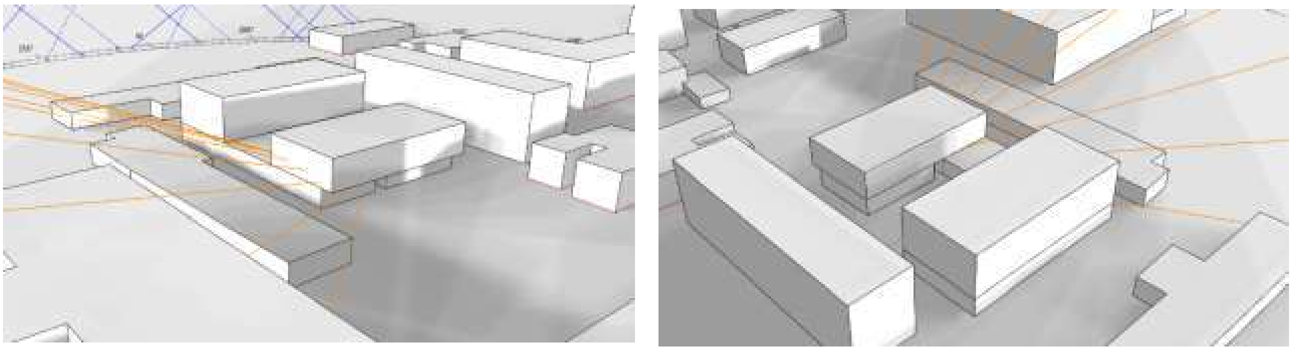


Figure 5. 76: Visualization of Shadow range on Winter Solstice

Shadows are visualized hourly or for a series of hours of the day. The impact of shadows on the entire day of winter solstice can be studied. Ladybug Sunlight Hours study is a colour map of values of sunlight hours. In contrast, DIVA analysis is a projection of shadows of surfaces from the input time that is overlaid from treating the sun each hour as multiple sources of light.

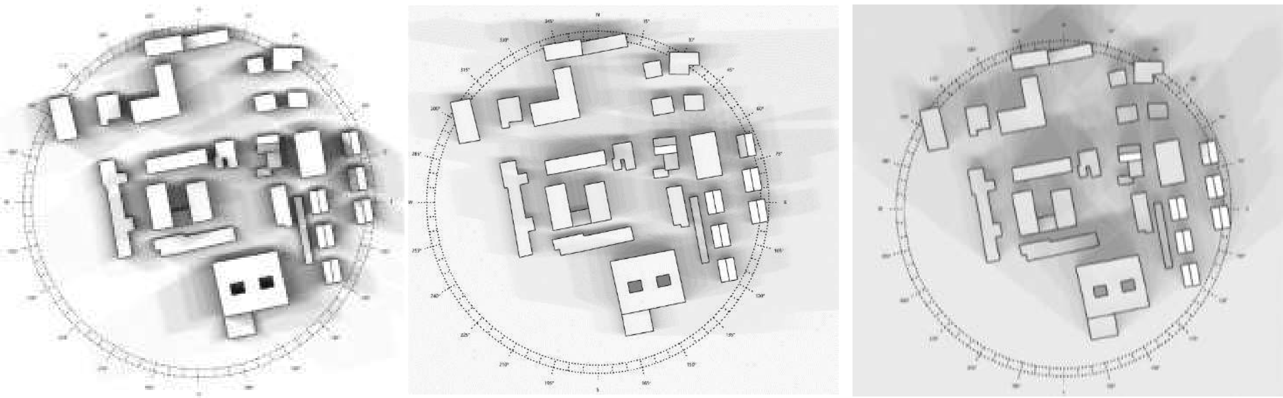


Figure 5. 77: Comparison of Shadows for Summer Solstice, Equinox and Winter Solstice (left to right)

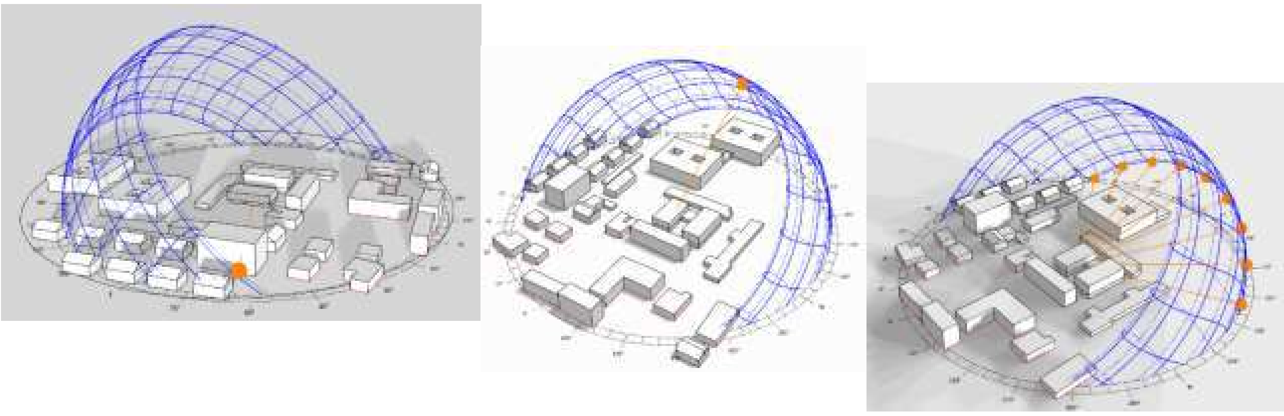


Figure 5. 78: Sun Path with Vectors on 5 am 21 June, 1 pm 21 June, 24 h on 21 December.

Different design tools can have the same, similar or different functionalities. It is the right design approach to test at least one alternative to understand if analysis and results are reliable and useful to inform decisions. The results given by DIVA, Ladybug Tools are similar visually. The sun positions displayed are correct as verified with SunCalc and SunPosition online tools.

Benefits of Sun and Shadow Analysis Model Use:

- Minimum Sunlight Hours
- Validate the design with the regulations
- Real-time urban massing of design with feedback
- Considering the impact of shadows for an hour of the year, day or analysis period
- Solar Fan (ensure solar access to public space or given window)
- Solar Envelope (buildable volume that does not cast shadows over public spaces or buildings)

Exchange Information Requirements:

- Design Stage: RIBA 2 Concept Design, 3 Spatial Coordination, 4 Technical Design
- Geometry Requirements: LOD200 (BIM Forum, 2019)
- Information Requirements: Design Target (surfaces to validate & value of sunlight hours)

5.10 PV system design in a computational process

A Radiation map simulation with DIVA 4 will be performed to find the best location of Photovoltaic panels on the roof of buildings. The Radiation map is used to optimize the placement and rotation angle of panels. Archsim will be used to simulate the annual and monthly electric output of the PV system.

The radiation map component in DIVA can simulate the total radiation received on a surface for a given analysis period. We need to know the radiation for the whole year from 1 January to 31 December.

Ljubljana latitude is 46.22° N. Three types of PV panels of 1 m x 1.5 m will be tested. The first group of PV panels is horizontal. The second group is rotated at 23° and the third at 46°. The latitude of the location is a rule of thumb for optimizing the angle of PV panels. All panels should be facing the true south of the location.

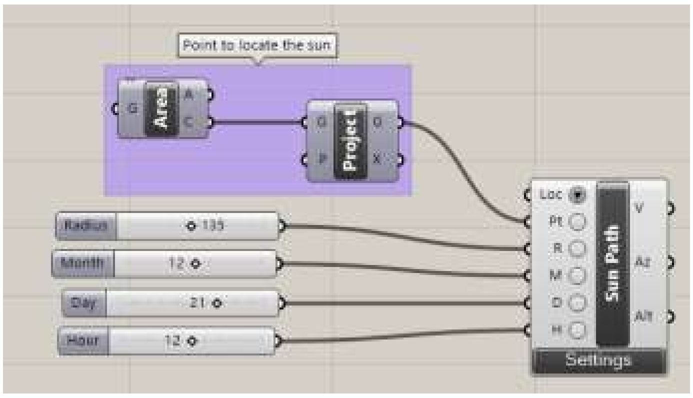


Figure 5. 79: DIVA for Grasshopper code to analyze worst-case shadows conditions.

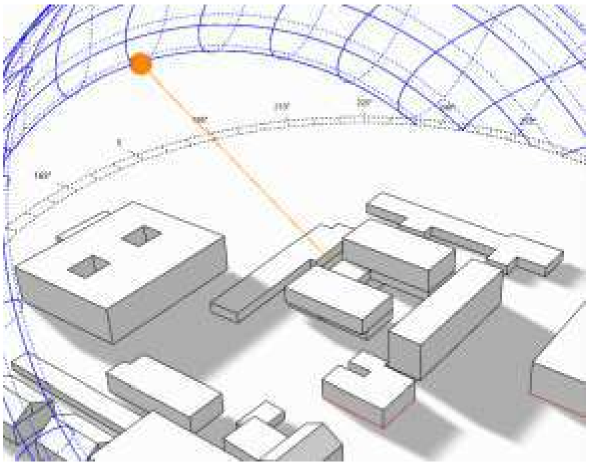


Figure 5. 80: Shadow verification for Winter Solstice.

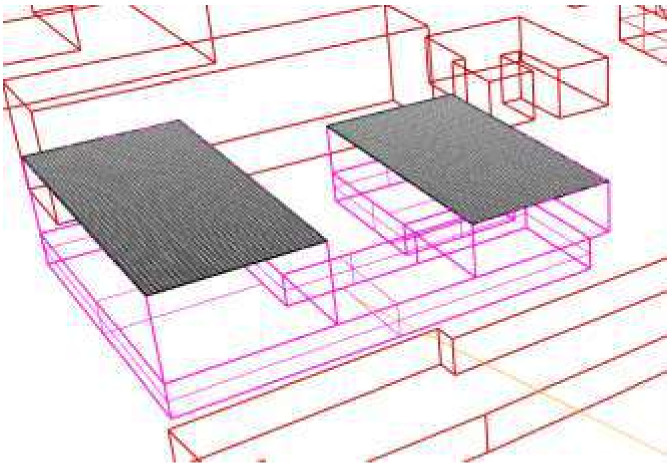


Figure 5. 81: Grid surfaces for Radiation study.

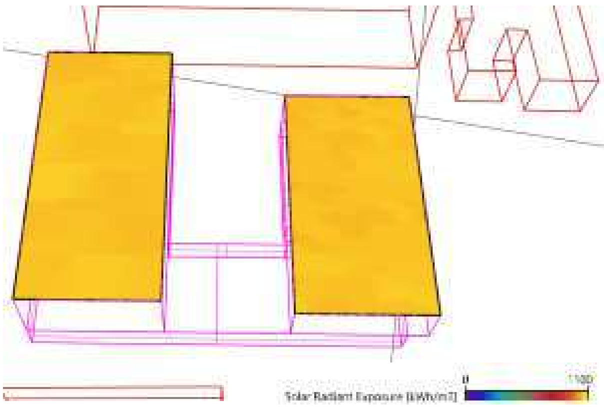


Figure 5. 82: Radiation Map for roofs.

A grid of 1m x 1m of spacing is set to perform the analysis only on the selected surfaces.

The two roof surfaces receive the highest possible radiation for the given location. Shadows have little impact on the overall cumulative insolation of the surfaces.

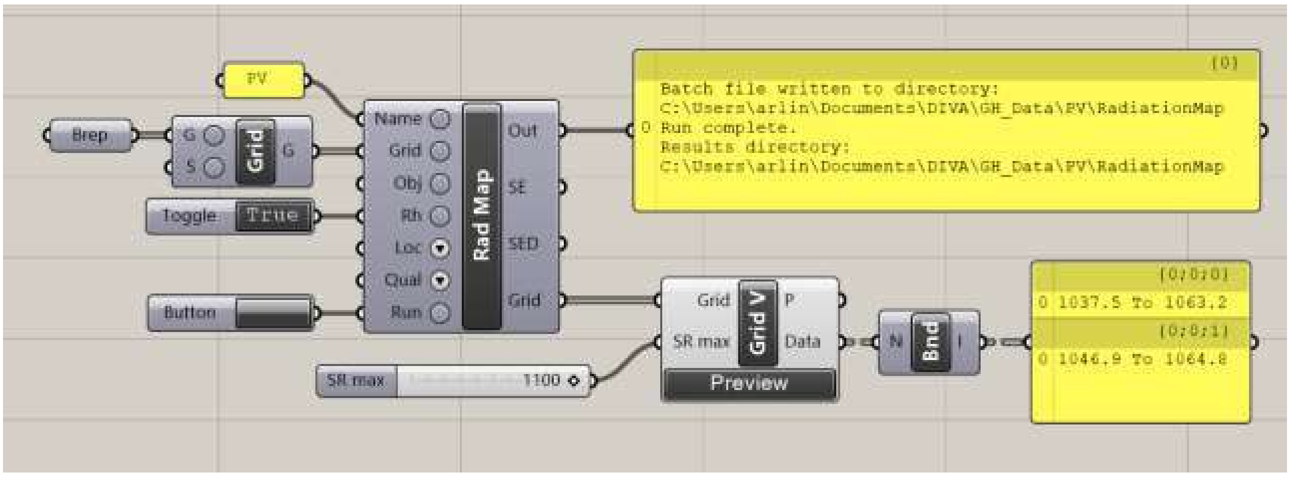


Figure 5. 83: DIVA for Grasshopper code for Annual Solar Radiation Map.

The output panel in Grasshopper displays the range (Bounds node) of minimum and maximum values received on the two analysis grids. The highest radiation is 1064.8 kWh/m^2 in a year. The lowest radiation received on the horizontal surface is 1037.5 kWh/m^2/year.

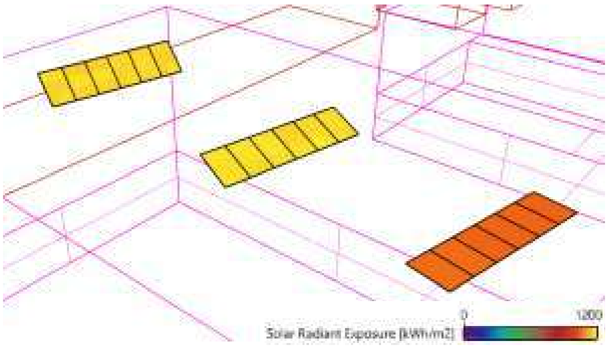


Figure 5. 84: Radiation Map for horizontal, 23° and 46° angle position PV panels.

The inclined panels receive around 100kWh more radiation than the horizontal ones. The difference between 23° and 46° is not noticeable at the level of detail of the legend bounds.

Figure 5. 85: Finding distance of area affected by shadows with Radiation Map and list of values.

The radiation map on the panel and roof surface is used to find the impact of the shadows cast by panels on other panel rows. The minimum offset to optimize panel distance distribution is 4 m.

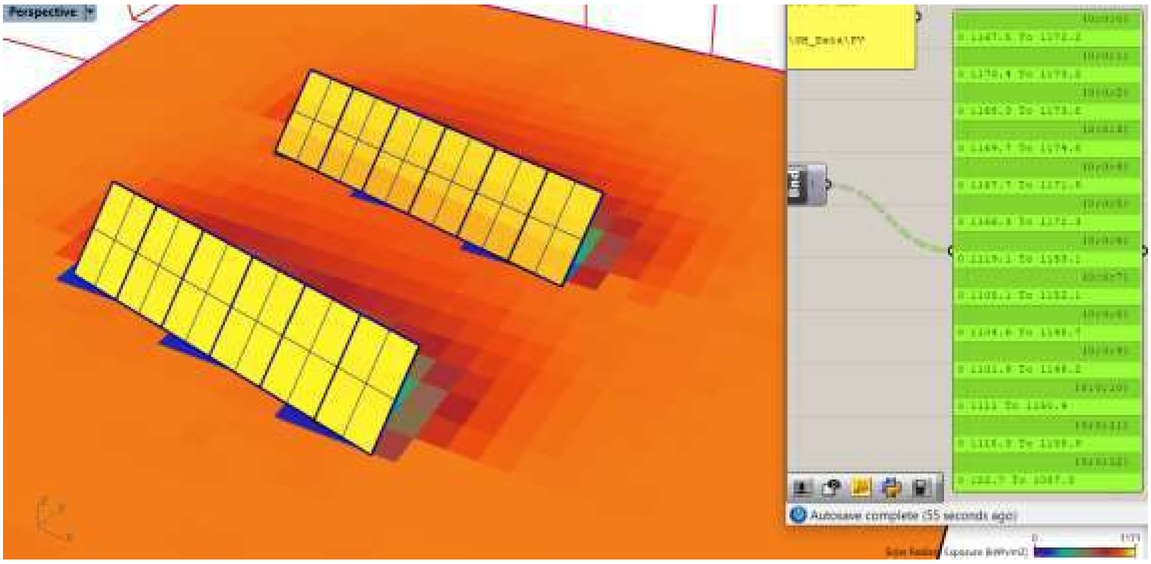


Figure 5. 86: Radiation Map and Panel values for panel offset at 4 m.

The impact of shadows on the second row of panels is around 40-50 kWh lower compared to the front row panels. A second analysis with panels at 4.5 m distance is performed to determine if there is an improvement in the panels yield.

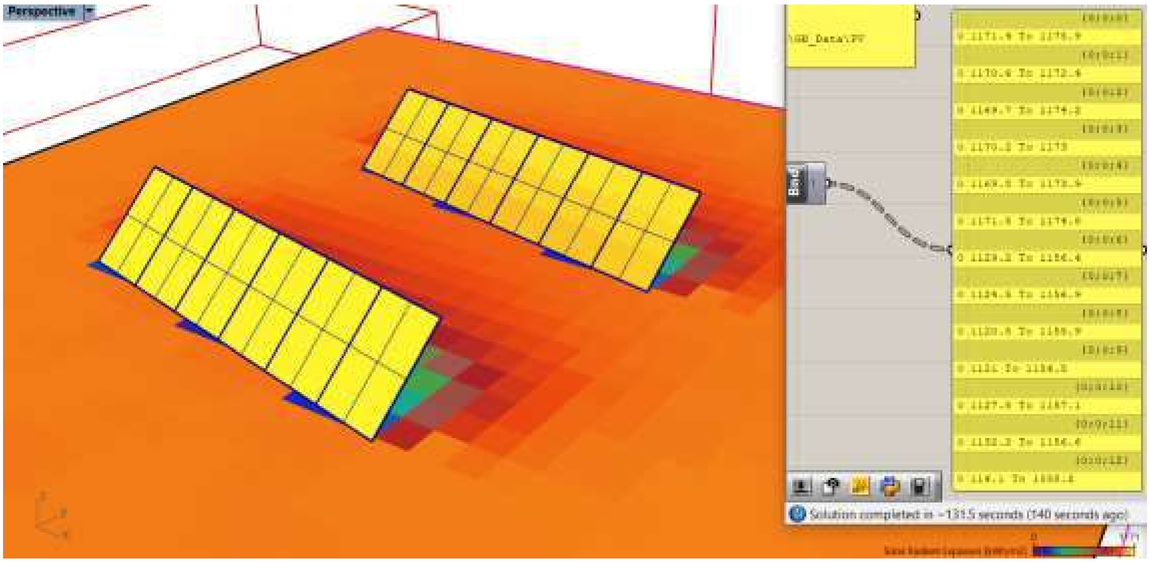


Figure 5. 87: Optimizing distance of panels. Radiation map and values for distance at 4.5 m.

When the distance is increased to 4.5 m per panel row, there is an acceptable yield difference of 10-20 kWh per panel row. The optimized panel distance will be used to place the panels on the roof surfaces. It is not possible to use the whole roof since the project needs space for the vertical smokestacks and HVAC system. A total of 136 PV panels is placed on both roofs of the Gerbiceva project.

Archsim, an energy modelling plugin for Rhino-Grasshopper that links parametric design with EnergyPlus simulations, is used to calculate the PV Panels energy production.

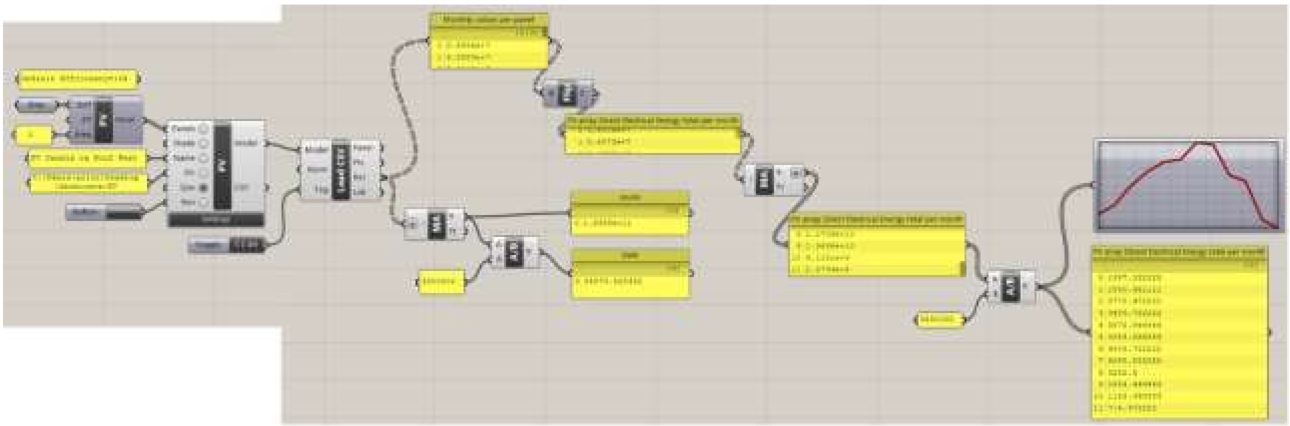
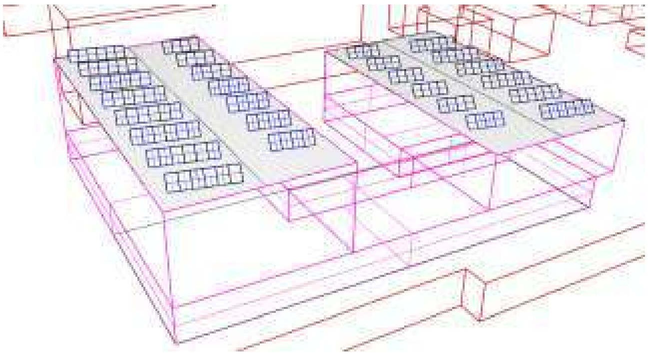


Figure 5. 88: Archsim for Grasshopper code for PV panel annual yield.

The output of the simulation is in Joules. To convert Joules into kWh, the list values are divided by 3’600’000. The results can be checked instantly with a list of 12 monthly values and a graph in Grasshopper.



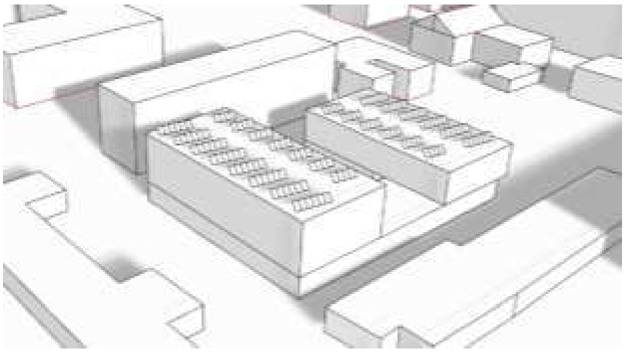


Figure 5. 89: Roof panels with analysis grid-points. Figure 5. 90: Shadows study on Winter Solstice

A shadow study is performed to verify the validity of results with the final Cumulative insolation map.

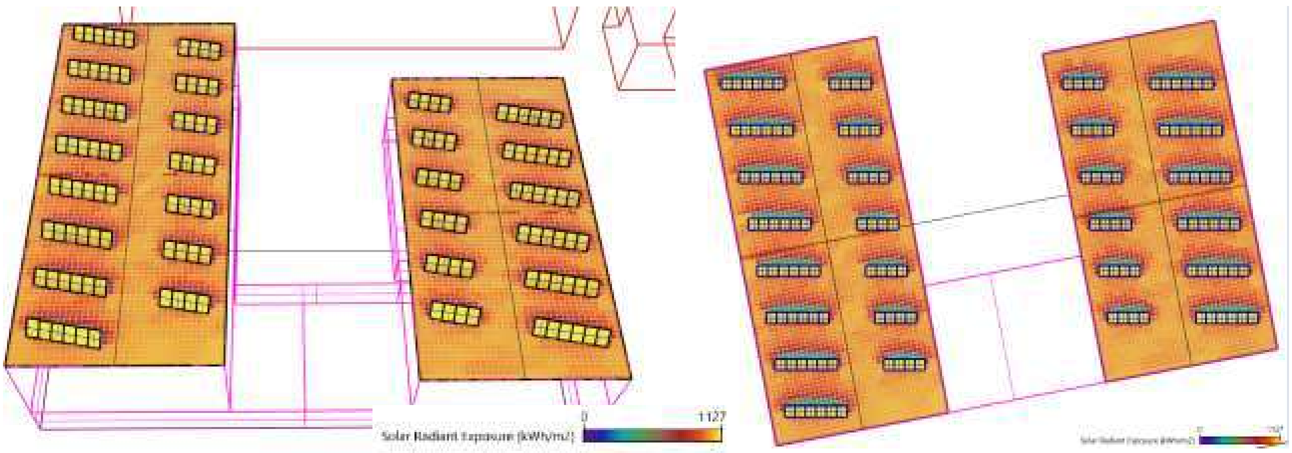


Figure 5. 91: Radiation Map of the roof with PV Panels system.

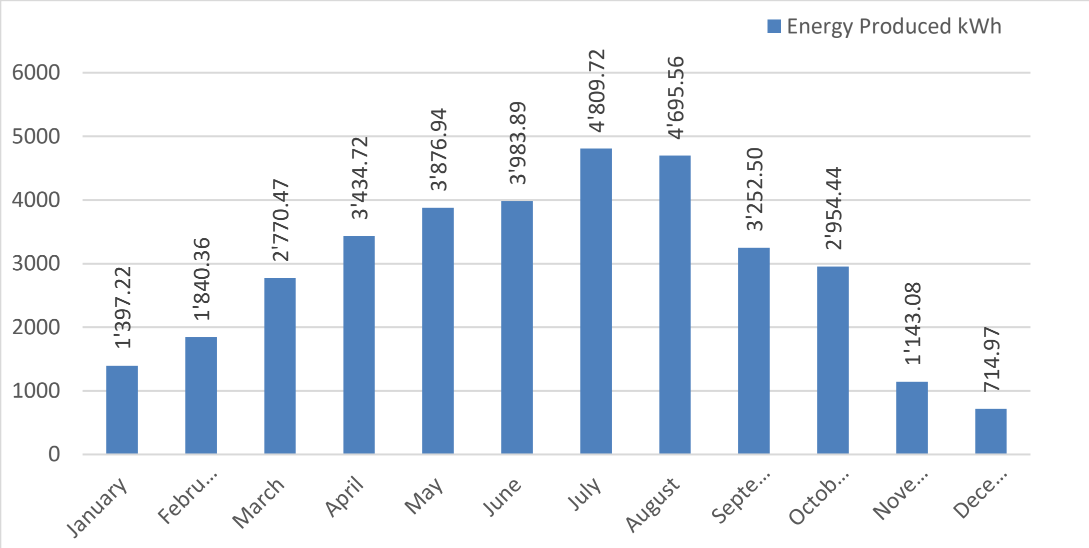


Table 5. 22: DC Electric Energy total monthly output of Roof PV Panels in kWh.

The data is exported into an excel spreadsheet. The Total DC Energy that can be produced by the system in a year is 34873.89 kWh. A total of 136 panels of 1 m by 1.5 m are placed on the roof. The system has a yield of 256 kWh/panel. The total panel surface is 204 $m^{2,}$ and normalized energy output is 171kWh/m^2/year.

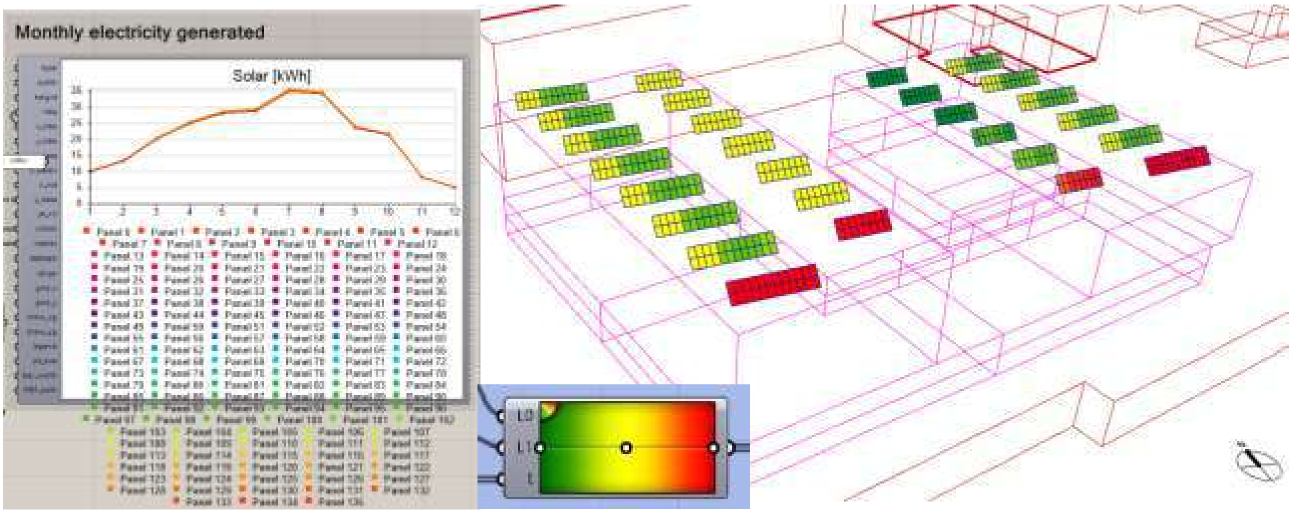


Figure 5. 92: PV panel simulation chart and colour for each panel with Climate Studio.

The simulation was repeated with Climate Studio and Archsim components. The results are the same. The chart is detailed with a colour-coded legend of the yield for each panel. A colour mapping node is added to the results to see the yield of each panel. The electricity production of panels ranges from 254 kWh to 260 kWh per panel in a year. The red colour is the high bound, and the green colour is the lower bound of the range. A slight difference of 6 kWh between the highest and least productive panel demonstrates that the Radiation study to optimize distances between panels worked well.

5.10.1 *Comparison with Solar Analysis in Revit*

Revit can perform Solar Analysis in the cloud with Autodesk Insight plugin. The functionality of Solar Analysis is done on the roof surfaces. Revit Solar Analysis can be performed for any selected building surface. The benefit of Revit is that performing the analysis does not require specialist knowledge or waiting time to simulate and have results. The use of a BIM model makes it possible to use the geometry available in Revit with any level of geometrical information.

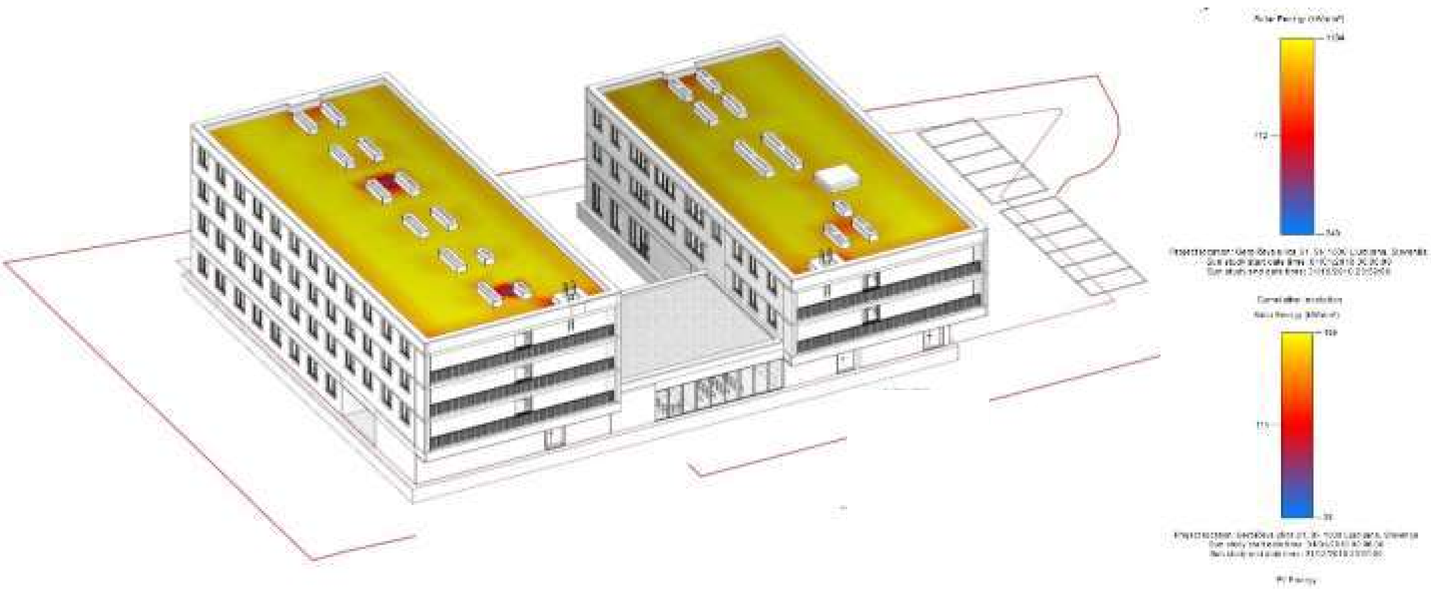


Figure 5. 93: Revit Solar Analysis. Cumulative Insolation and PV Energy.

The maximum cumulative insolation from the simulation for a year is 1184 kWh/m2. The maximum PV Energy on the horizontal surfaces is 189 kWh/m^2/year.

Figure 5. 94: Comparison of PV Energy in Revit based on roof surface parameter.

Table 5. 23: Comparison of Revit and DIVA-Archsim PV Panels energy output.

	AUTODESK REVIT	DIVA
Total radiation (horizontal plane)	1184 kWh/m^2	1065 kWh/m^2
PV Energy per panel	189 kWh/m^2/year (0° plane)	171 kWh/m^2/year (46° plane)
Total panel surface	212 m^2 (on roof surface)	204 m^2 (46° PV panels)
PV Energy total	40027 kWh/year	34873.89 kWh/year

The results of Revit Solar Analysis overshoot the real PV energy output by **more than 10%.** However, it is a useful tool in understanding site conditions and fast feedback for the PV potential of given surfaces. DIVA and Archsim can produce accurate results that can inform the detailed design of the building and integrated PV Energy system on building surfaces.

5.11 Climate Based Daylight Modelling with DIVA

DIVA is a climate based daylighting and energy modelling plugin for Rhinoceros. It also features advanced controls within Grasshopper interface for conducting a more advanced analysis. CBDM can provide control and detailed results for many Daylighting metrics based on local climate and the entire year. The modularity and orientation of the accommodation units into five typologies allow to take advantage of this feature for detailed simulations with DIVA. The five accommodation units were re-modelled in Rhino following the BIM Model provided in IFC.

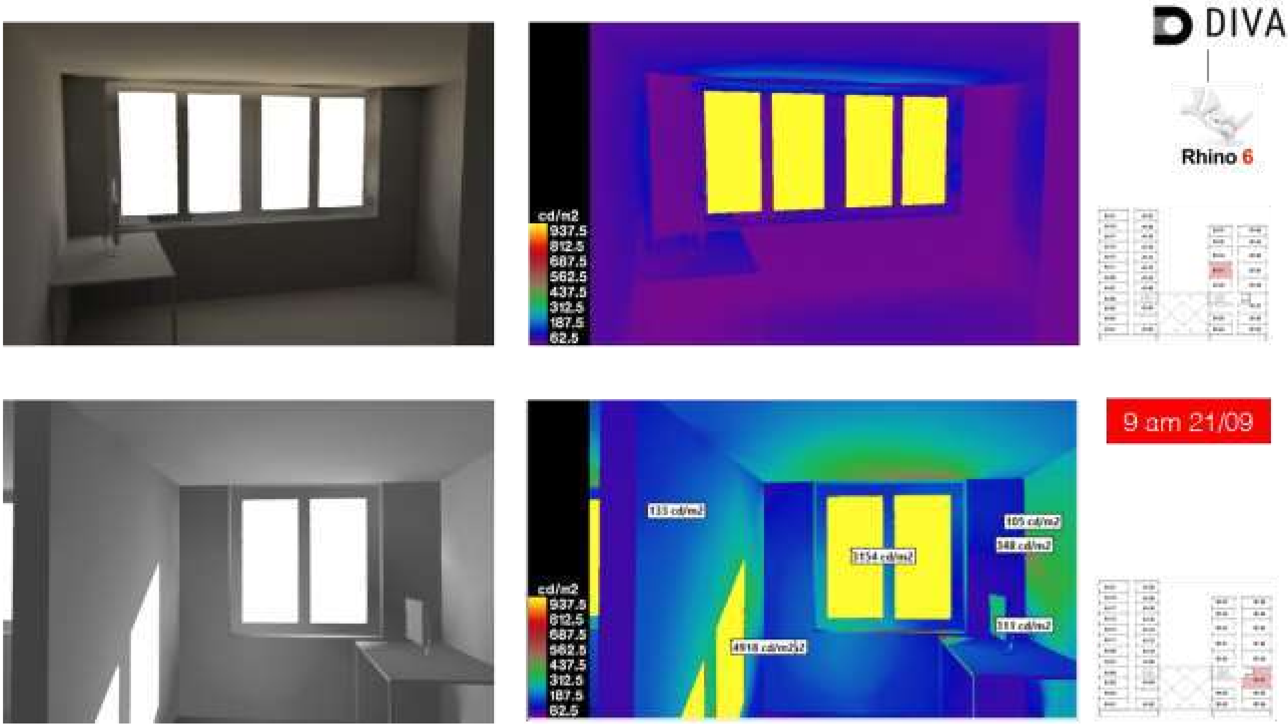


Figure 5. 95: DIVA Radiance-based renderings and Luminance false-colour maps.

False-colour maps can be used to verify glare condition of a particular view in a time of the year.

For the Climate Based Daylight simulations, a grid (called fraction $F_{plane,\%}$ in EN 17037) of at least 95% is used. CBDM metrics should be used for the entire daylit space. When using a grid plane of 95%, the minimum target illuminance or corresponding Daylight Factor (to exceed 100 lux) can be verified. For a minimum illuminance of 300 lux the corresponding DF_T = 1.8% ($F_{plane,\%}$=50%) and minimum target DF_{TM}=0.6% ($F_{plane,\%}$=95%) are to be verified for Slovenia. The mean DF with DIVA with $F_{plane,\%}$=95% for all accommodations is 1.8%, which is above the recommended value of 0.6% and equal to the DF_T. The CBDM simulations are different from the Daylighting performed with Velux Daylight Visualizer. When assigning zones in the Velux tool, the space accounted is more than 50% but less than 95%, which can be used to validate the target Daylight Factor (not the min. target) according to the EN 17037:2018 Daylight in buildings.

Figure 5. 96: Daysim automatic reports after simulation.

The five units are within the EN 17037 recommendation for Ljubljana of 1.8% DF from the Daysim report. LEED v4.1 credit of DA>55% is achieved for only one unit.

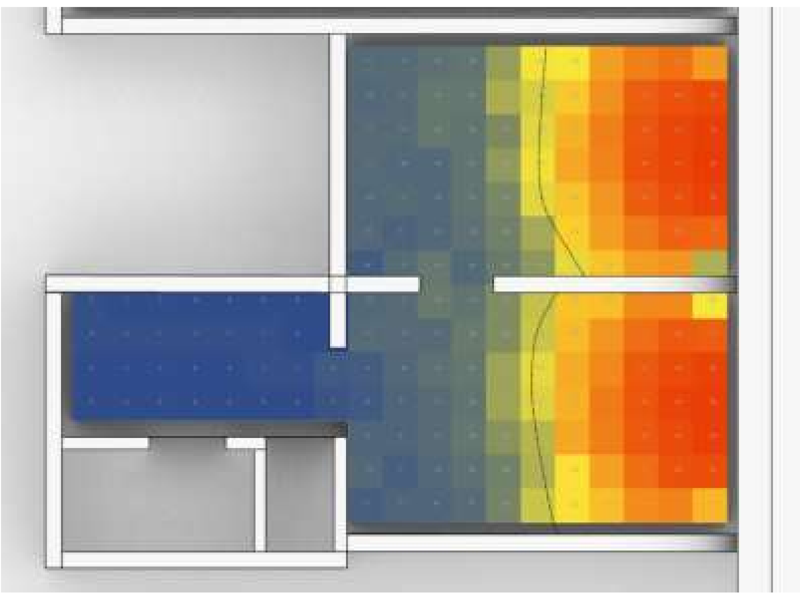


Figure 5. 97: sDA (300 lux) [50%] isolines for the east 2+1 unit.

Isolines of sDA target of 50% can be drawn to determine the spaces well-daylit- These spaces can be assigned to functions that require daylight such as reading and studying. The areas below sDA50% indicate the need for integrative artificial lighting throughout the year.

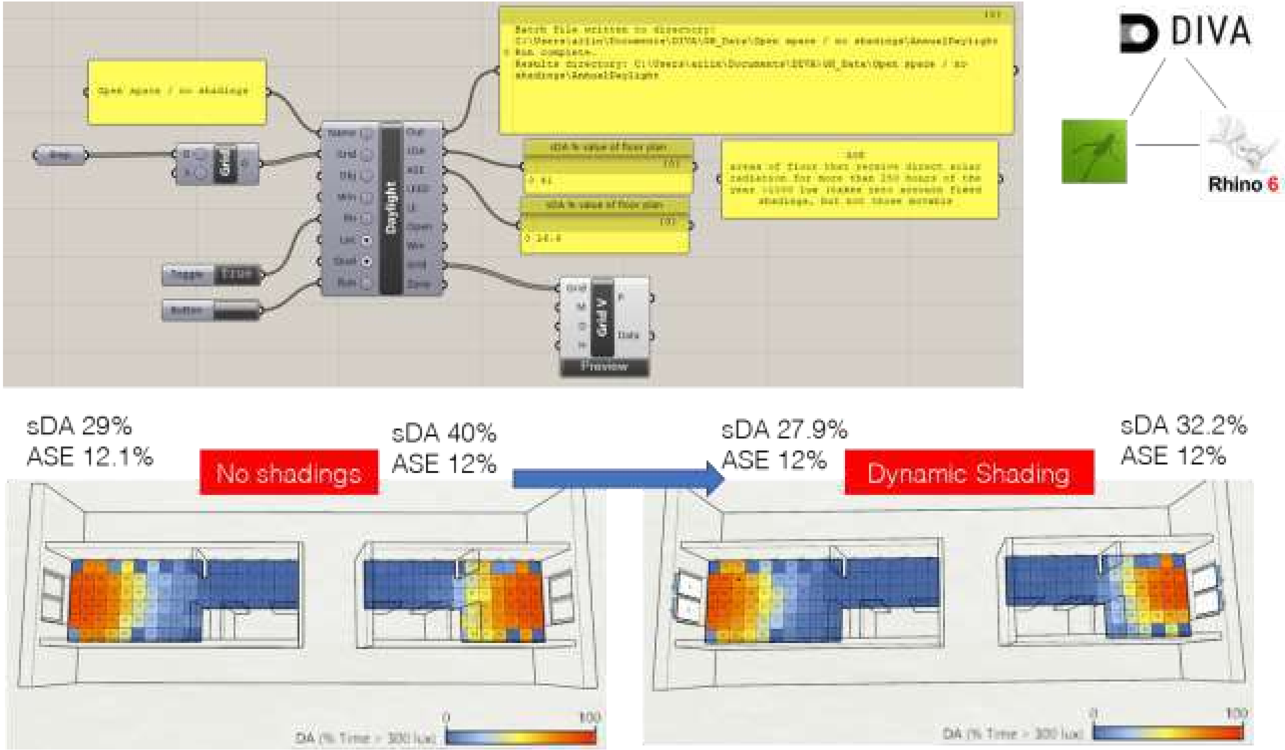


Figure 5. 98: DIVA for Grasshopper algorithm and simulations of units for conditions with no shadings for windows and with dynamic shadings.

The Gerbiceva Youth Housing Community project features external occupant operated movable blinds for each window. The Dynamic Shadings controls in DIVA has been set accordingly following the design, occupancy input for the shading control algorithm and the maximum distance of control points from the window of three meters.

Figure 5. 99: Climate Based Daylight metrics for two units with no shadings.

Figure 5. 100: Climate Based Daylight metrics for two units with Dynamic Shadings.

DIVA for Grasshopper allows choosing between the preferred Climate Based Daylight metrics available within the same simulation result. It can be beneficial to organize space when designing for specific requirements, e.g. to avoid Illuminance of over 3000 lux, reduce ASE hours, UDI underlit or overlit areas. ASE (annual sunlight hours) is a metric to be limited within 10% for the LEED credit. However, in another situation of using Solar Passive Gains, can be used as a metric to indicate the achieved solar insolation of given surfaces.

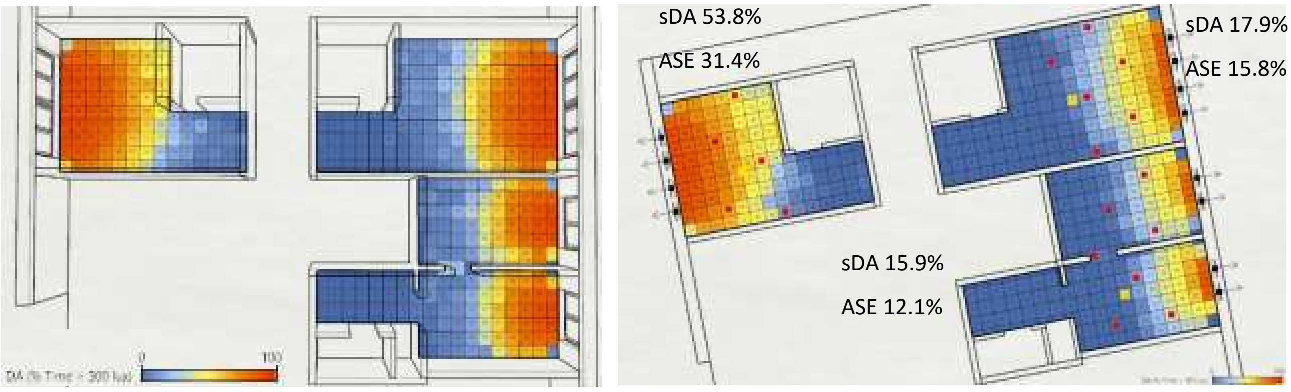


Figure 5. 101: spatial Daylight Autonomy comparison of units with No Shadings/Dynamic Shading.

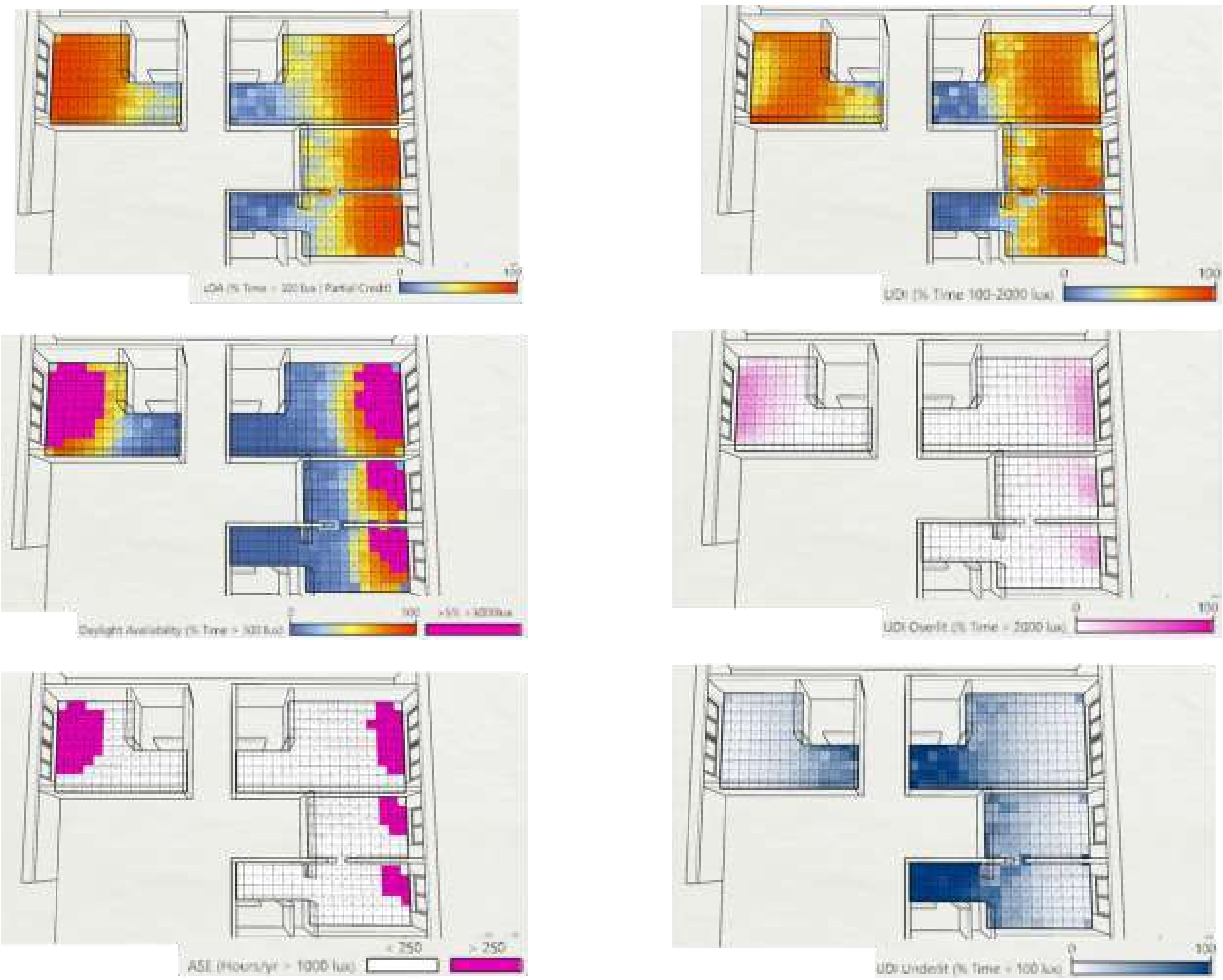


Figure 5. 102: cDA, UDI, Daylight Availability and Annual Sunlight Hours for no shadings condition.

The Annual Sunlight Hours does not change with the use of blinds. The use of dynamic shading, in our case blinds, reduces the spatial Daylight Autonomy, as blinds will be used during hours of the day that result in excessive illumination and direct sunlight. The distribution and service spaces (entrance, kitchen, toilet, shower) do not benefit from daylight in any of the Daylight metrics available. These spaces will require electric lighting for the whole year. The performance of the West facing units is better compared to the East units. This improved performance comes with reduced comfort situations, as seen in the Daylight Availability metric of excessive illumination levels (glare) and high ASE hours (overheating).

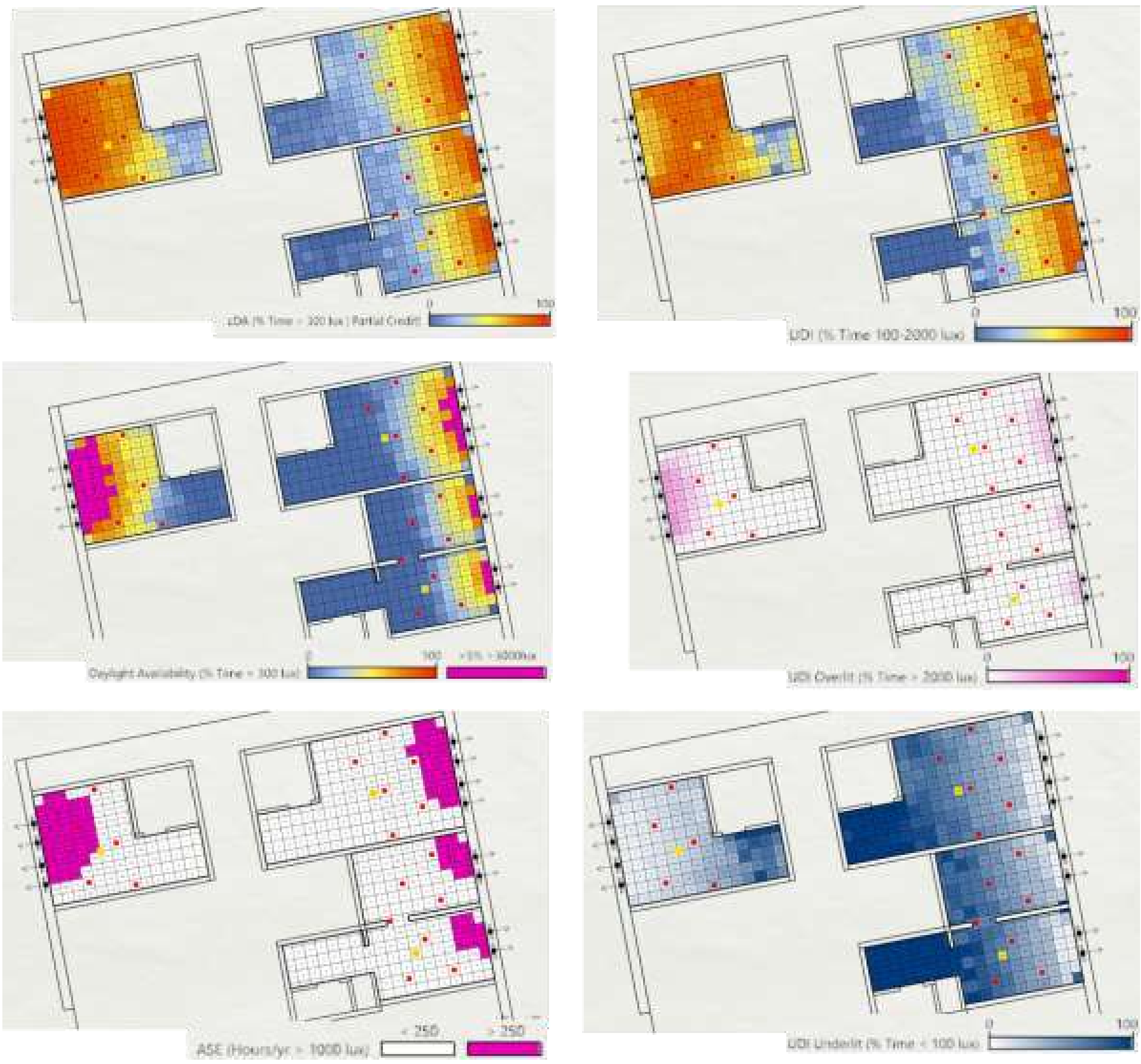


Figure 5. 103 : cDA, UDI, Daylight Availability, Annual Sunlight Exposure with Dynamic Shadings.

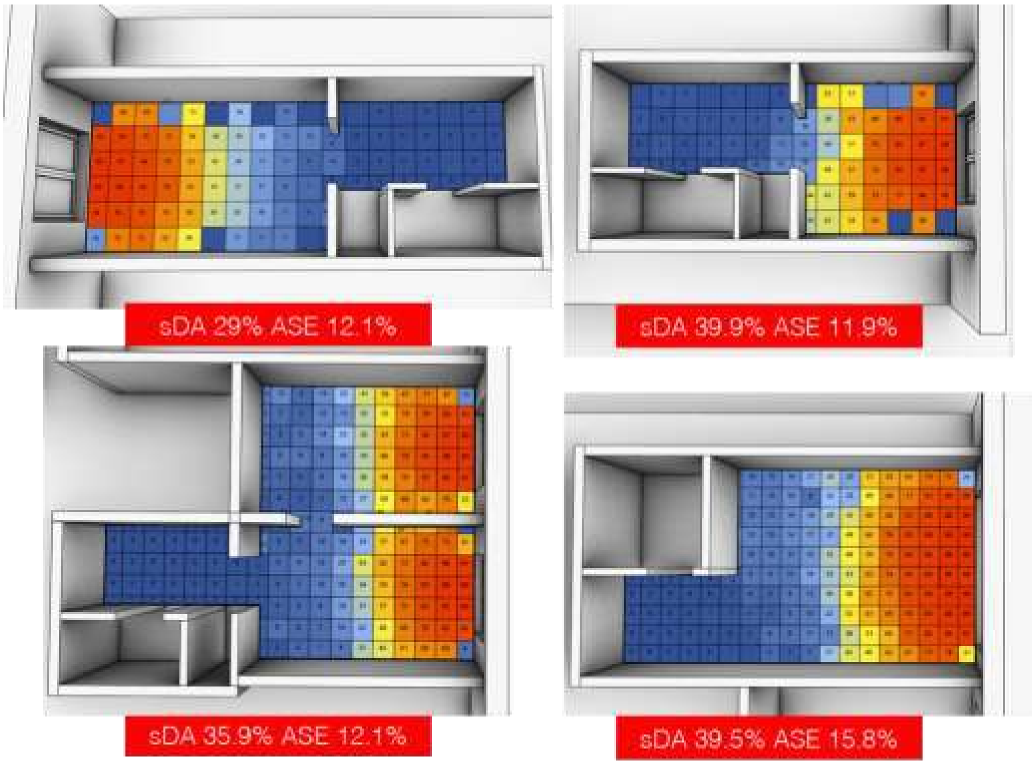


Figure 5. 104: sDA and ASE grid with values for the other units in No Shading condition.

Daylighting is a result of relations of space, openings and material properties. The above results of sDA and ASE indicate that there are different conditions of Daylight in every accommodation unit.

The West Unit that had high sDA and ASE will be examined in more detail.

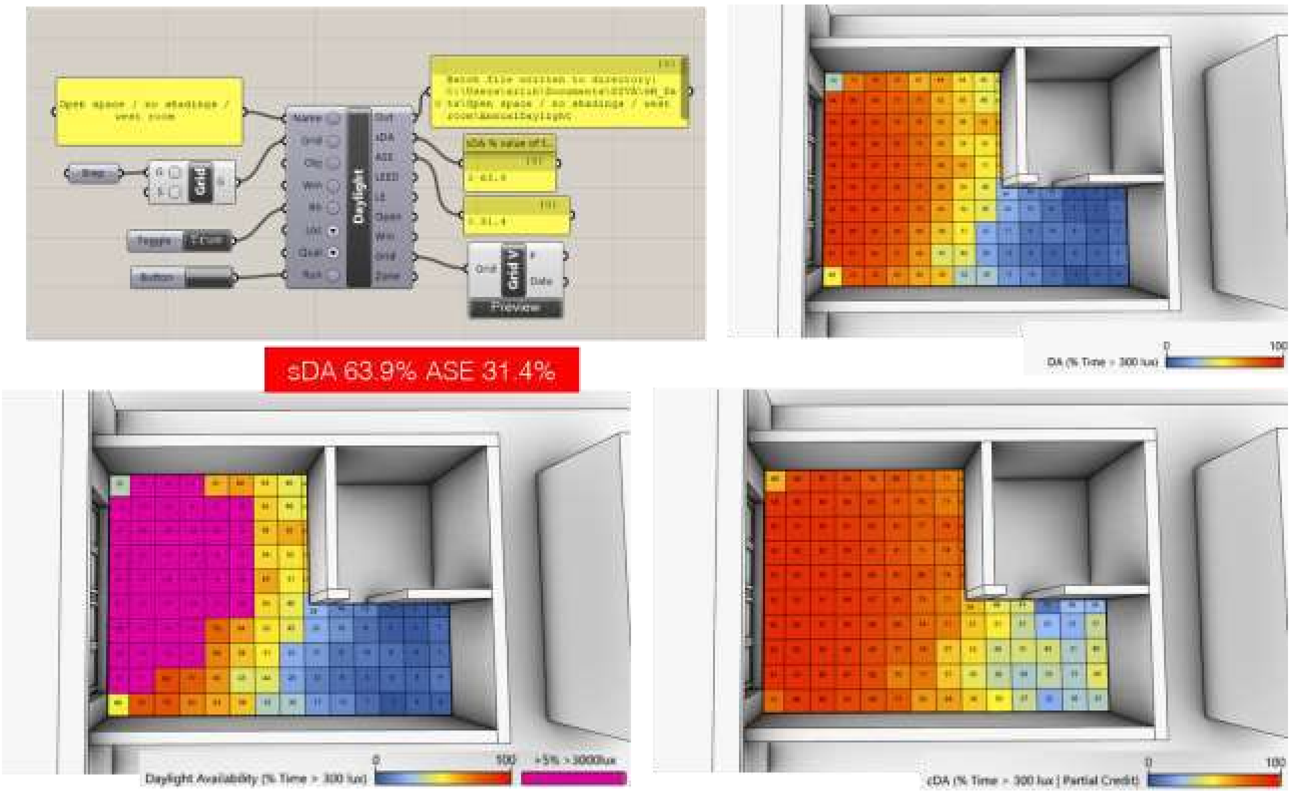


Figure 5. 105: West unit detailed simulation DA, cDA, Daylight Availability of no shading condition.

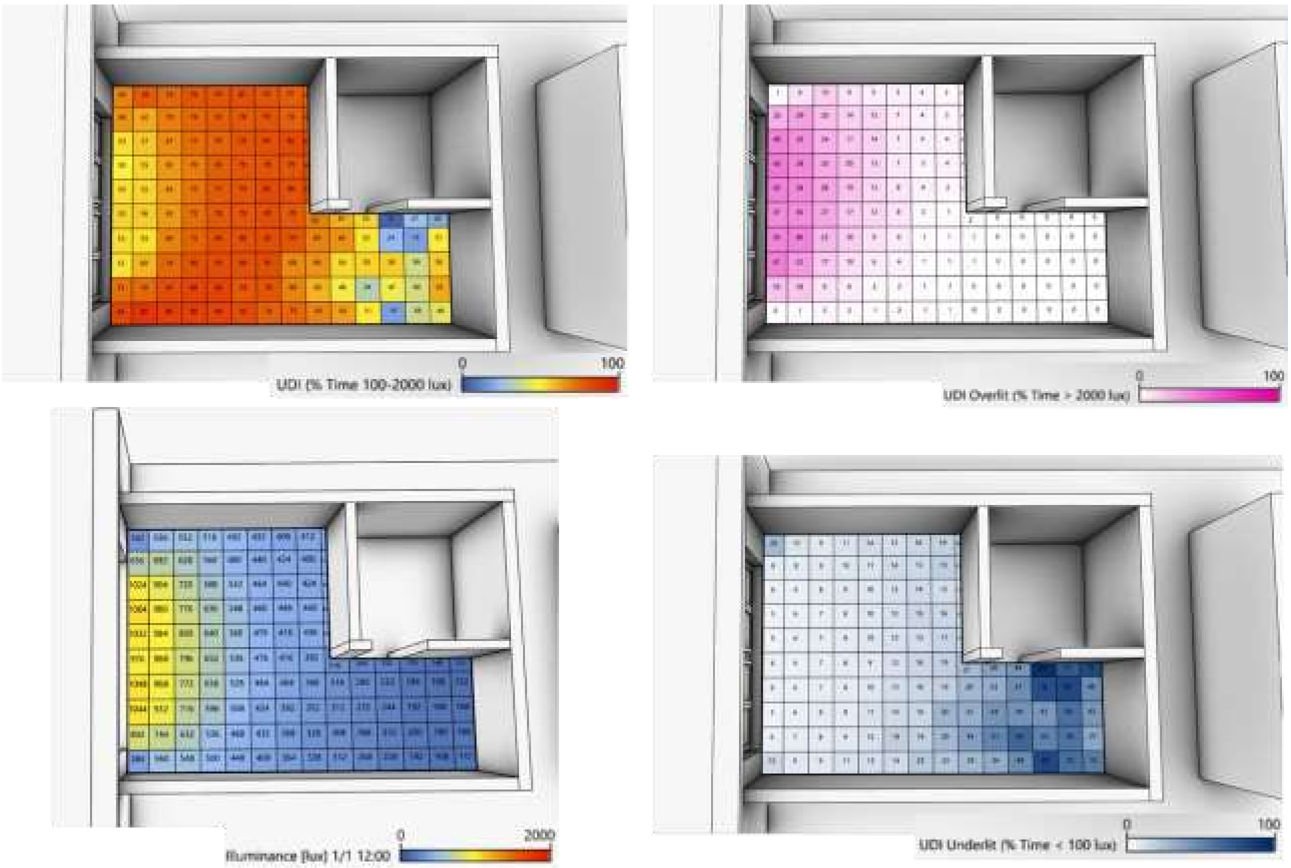


Figure 5. 106: West unit UDI, Overlit, Underlit, Illuminance at 1/1 12:00 of No Shading condition.

The unit is well daylit at the expense of some annual verification of glare and overheating from direct sun.

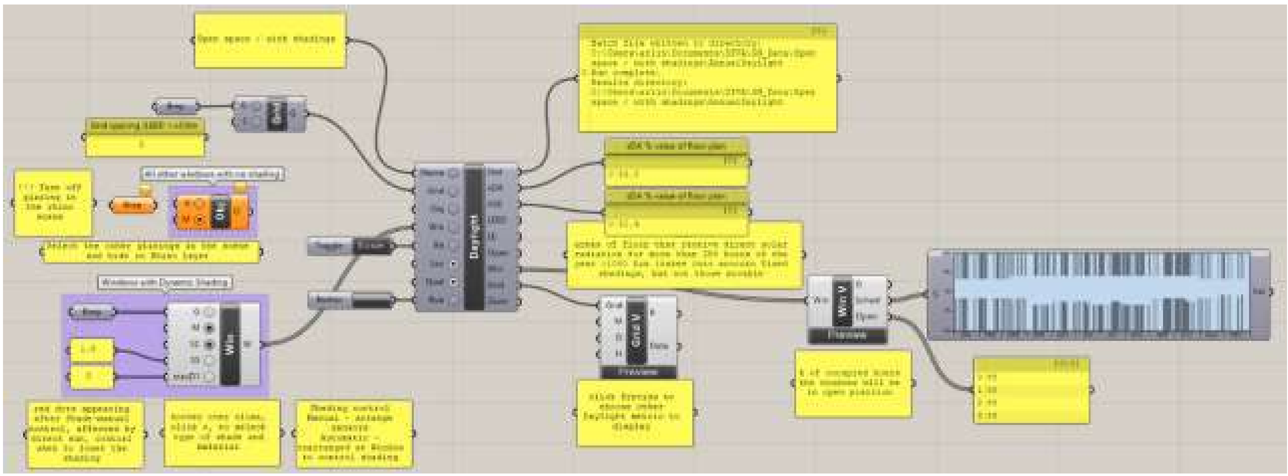


Figure 5. 107: DIVA for Grasshopper algorithm for Dynamic Shading set up.

The performance of the west accommodation unit will be explored in detail with the use of Dynamic Shading (manually controlled blinds).

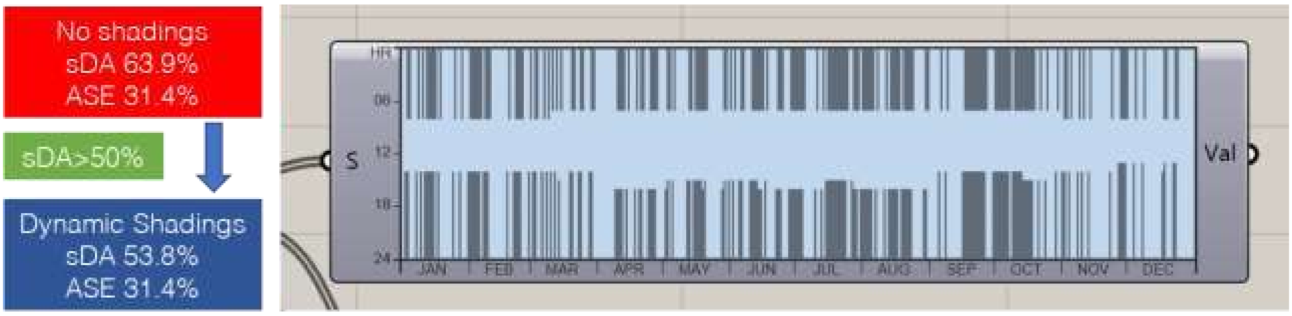


Figure 5. 108: Annual schedule of Shadings.

White colour represents the open position when shadings are not used. The black colour is the closed position of shadings to cover from glare and direct sunlight exposure. The sDA decreases by 10% with the use of shadings to provide for indoor comfort when needed. The overall value is above the target of sDA>50%.

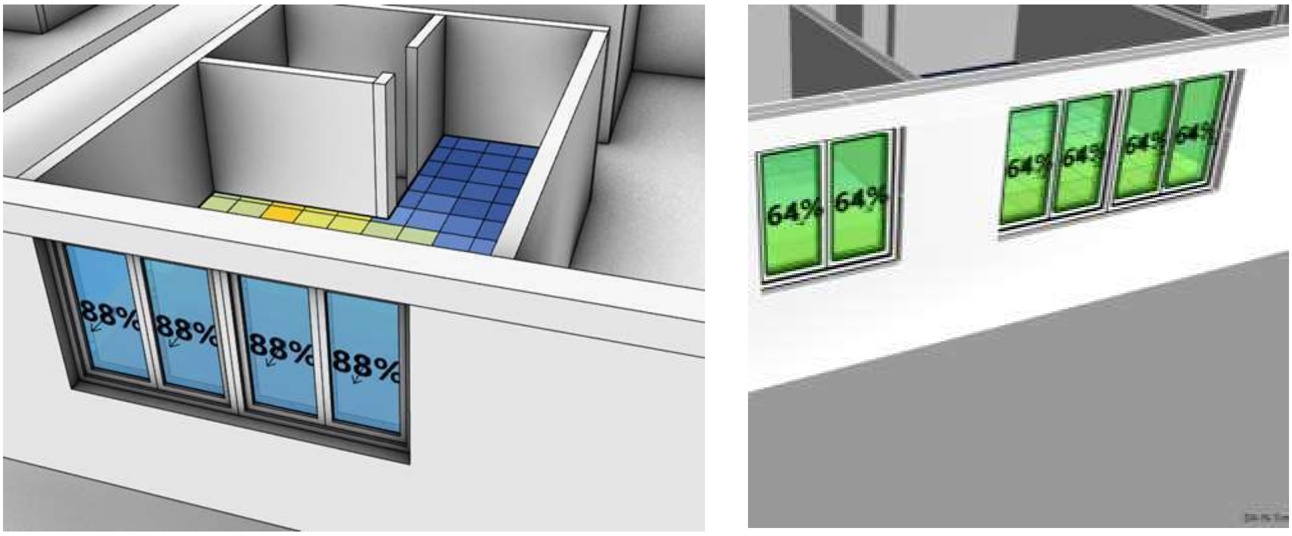


Figure 5. 109: West facing glazings are open 88% of the time of the year. East glazings result is 64%.

The use of Dynamic Shading does not affect ASE hours. The Daylight Availability and UDI overlit metrics are improved with controlled blinds. The other metrics such as sDA, cDA, UDI and UDI Underlit remain above good performance thresholds.

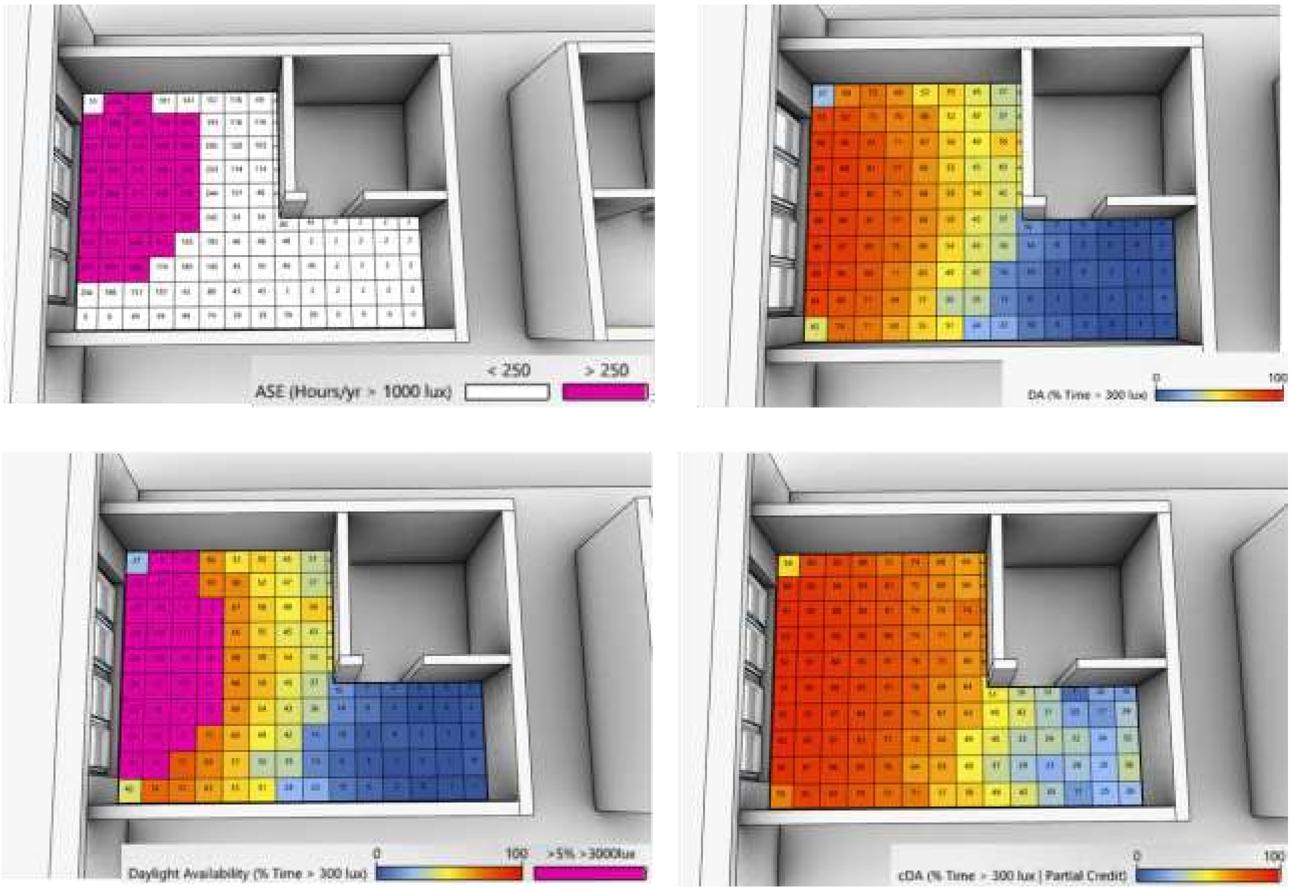


Figure 5. 110: West unit detailed simulation DA, cDA, Daylight Availability with Dynamic Shading.

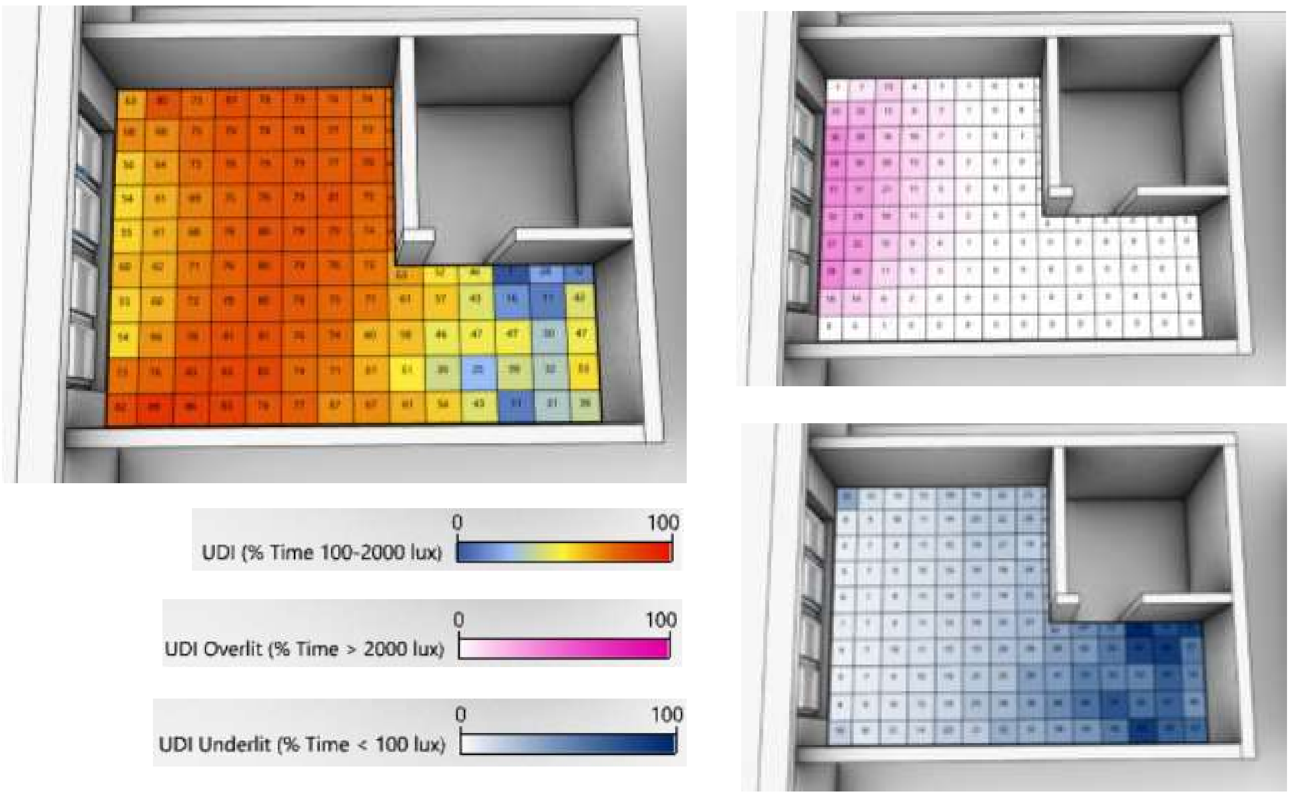


Figure 5. 111: Useful Daylight Illuminance, UDI Overlit, UDI Underlit analysis.

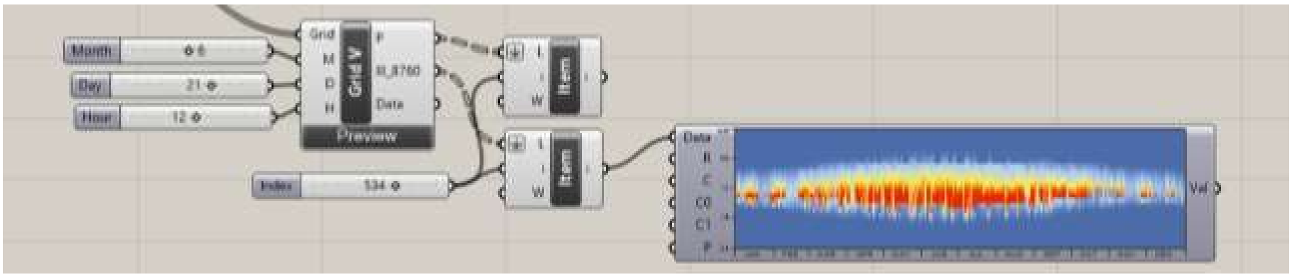


Figure 5. 112: DIVA Daylight and grid nodes for point-in-space Annual Illuminance graph.

Visualizing the annual Illuminance of a point in space can help understand the quality and usability of space for the entire year span. PCs, desks and furniture can be arranged following daylighting analysis recommendations.

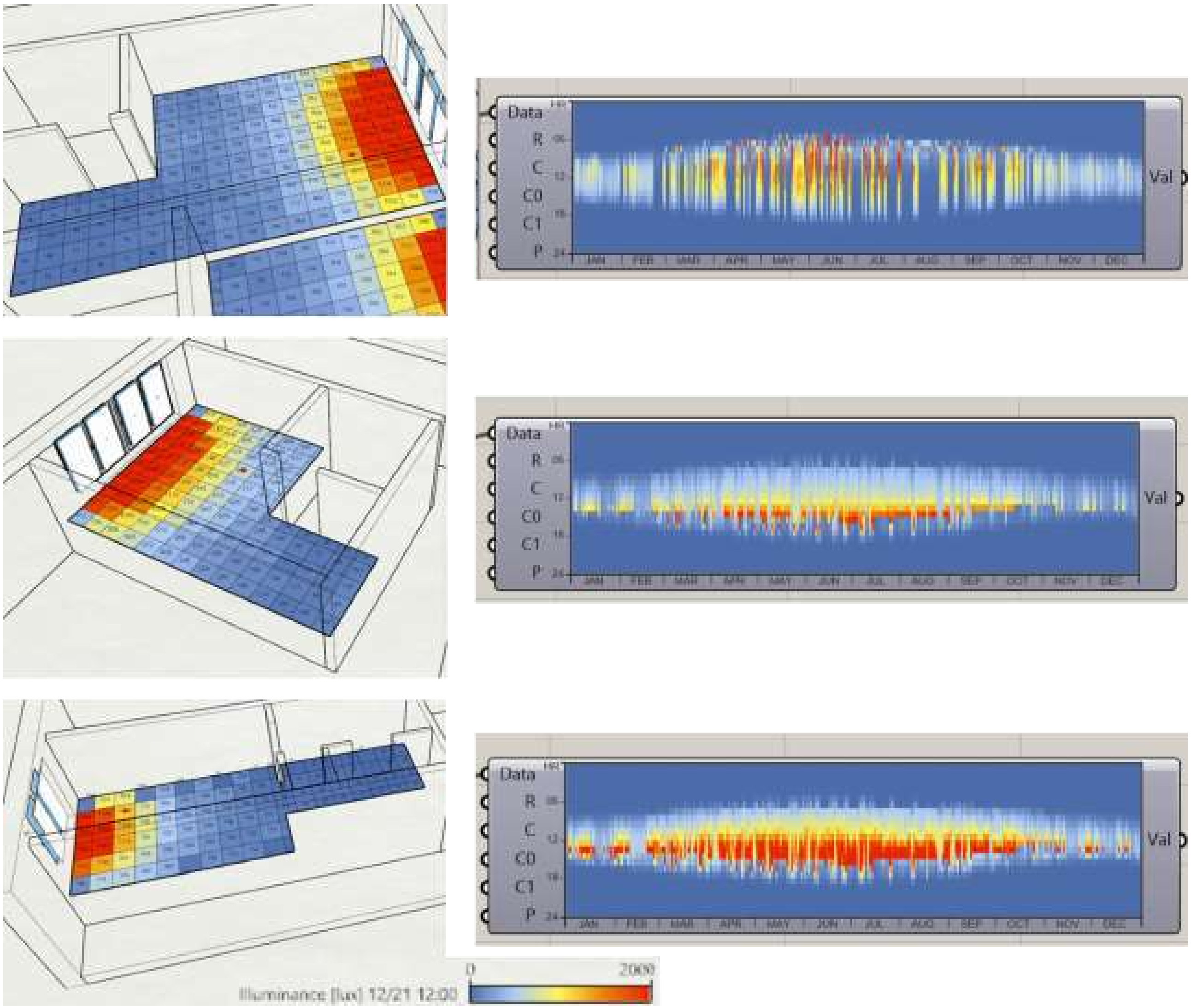


Figure 5. 113: Annual Illuminance graphs for a point-in-space of the grid.

The advanced computational features of DIVA in Grasshopper allow visualizing the illuminance levels of natural light for the entire year. It can be used as a relevant guideline when designing, placing and sizing electric lighting fixtures based on needs and feedback of daylight performance.

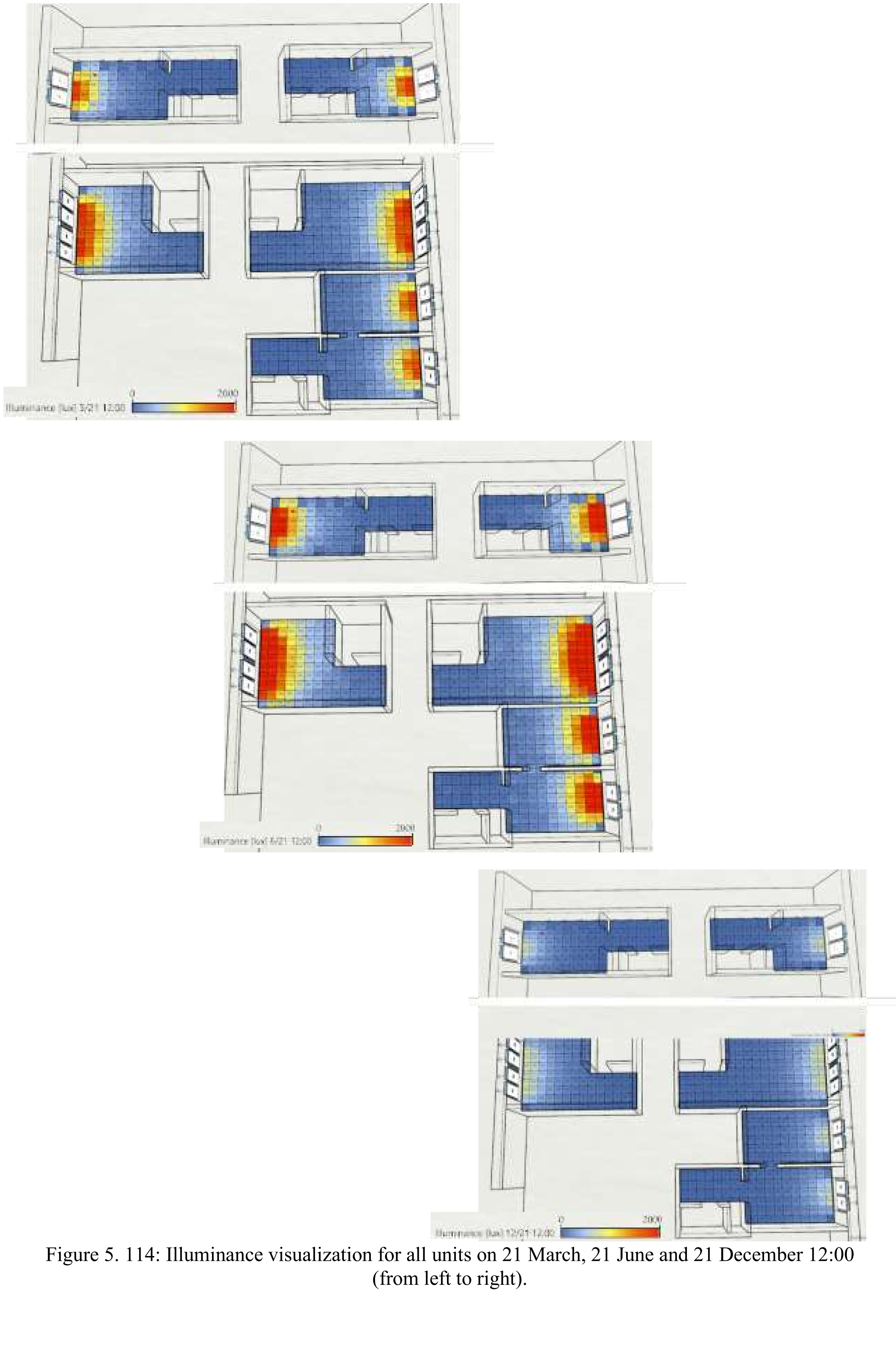


Figure 5. 114: Illuminance visualization for all units on 21 March, 21 June and 21 December 12:00 (from left to right).

Illuminance measures the amount of light on the work plane. It is the most widely used metric for designing daylit spaces and electric lighting systems. The possibility to switch easily between metrics in the DIVA results allows exploring the design performance for a given time of the year or annually The compliance with most standards, regulations and with most requirements of green building rating systems can be verified.

Benefits of Climate Based Daylight Modelling Model Use:

- Compliant with Generic Materials requirement during the design phase for Public Authorities
- Based on hourly climate data simulations and metrics
- Detailed feedback of performance, comfort, shadings, energy, costs
- Detailed analysis for building level/modular project unit/single space
- All daylight metrics (inform design and quality of spaces)
- Inform the design for integrative electric lighting

Exchange Information Requirements:

Geometry Requirements:

- Design Stage: RIBA 3 Spatial Coordination, 4 Technical Design, 7 In Use
- LOD200 - LOD300 (BIM Forum, 2019)
- One surface modelling for transparent surfaces of glazing (no thickness)
- Check surface normal of simulation grid, glazed surfaces, material surfaces
- Neighbouring obstruction (buildings and trees)
- Modelled window frames and mullions

Information Requirements:

- Validated simulation program
- Weather Data (Energy Plus .epw file)
- materials reflectance
- visible transmittance of the glazing
- Select the correct Sky Model for the simulation

5.12 Climate Based Daylight Performance and Visual Comfort with Climate Studio

Climate Studio is a new software that comes from the work and experience of developing DIVA for Rhino. It uses Radiance for simulations and produces fast results for annual illuminance, daylight metrics, glare spatial grid maps with eight view directions per grid-point, energy simulations and automatic reports for green building certifications such as LEED and BREEAM.

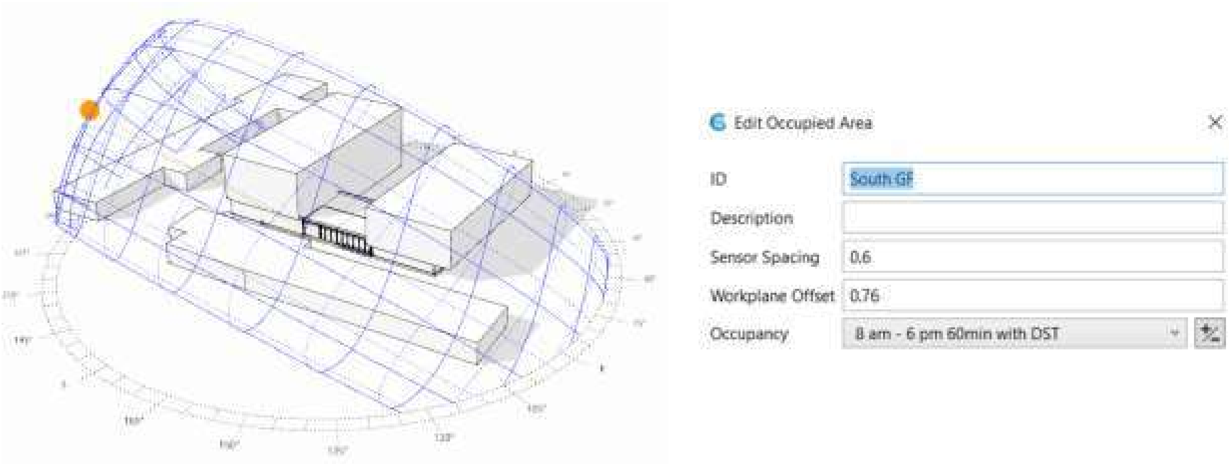


Figure 5. 115: Climate Studio Sun Path with Gerbiceva project and inputs for analysis grid.

The ground floor spaces (south and north) that are used as a residence hall, conference room, and private study room are represented in LOD200 detail for the simulation. The building's conceptual mass and nearby context are modelled to provide for accurate simulations of illuminance and shadow conditions.

Layer Materials

Layer	Objects	Material	Rvis	Tvis
overhang	1	Aluminium Grey Overhang	21.2%	0.0%
A-GROUND	1	Outside Ground LM83	10.0%	0.0%
ARL-Window-Frame	47	Window Mullion	22.6%	0.0%
ARL-Window-Glass	19	Solexia - Clear (Krypton)	12.6%	67.8%
B_Buildings context	12	Dupont Dirty White 114	34.1%	0.0%
A-ceiling	95	Ceiling LM83	70.0%	0.0%
A-FLOORS	8	Floor LM83	20.0%	0.0%
A-WALL-Exterior	58	Wall LM83	50.0%	0.0%
A-WALL-Interior	87	Wall LM83	50.0%	0.0%

Figure 5. 116: Assigning material properties from Climate Studio database to Rhino layers.

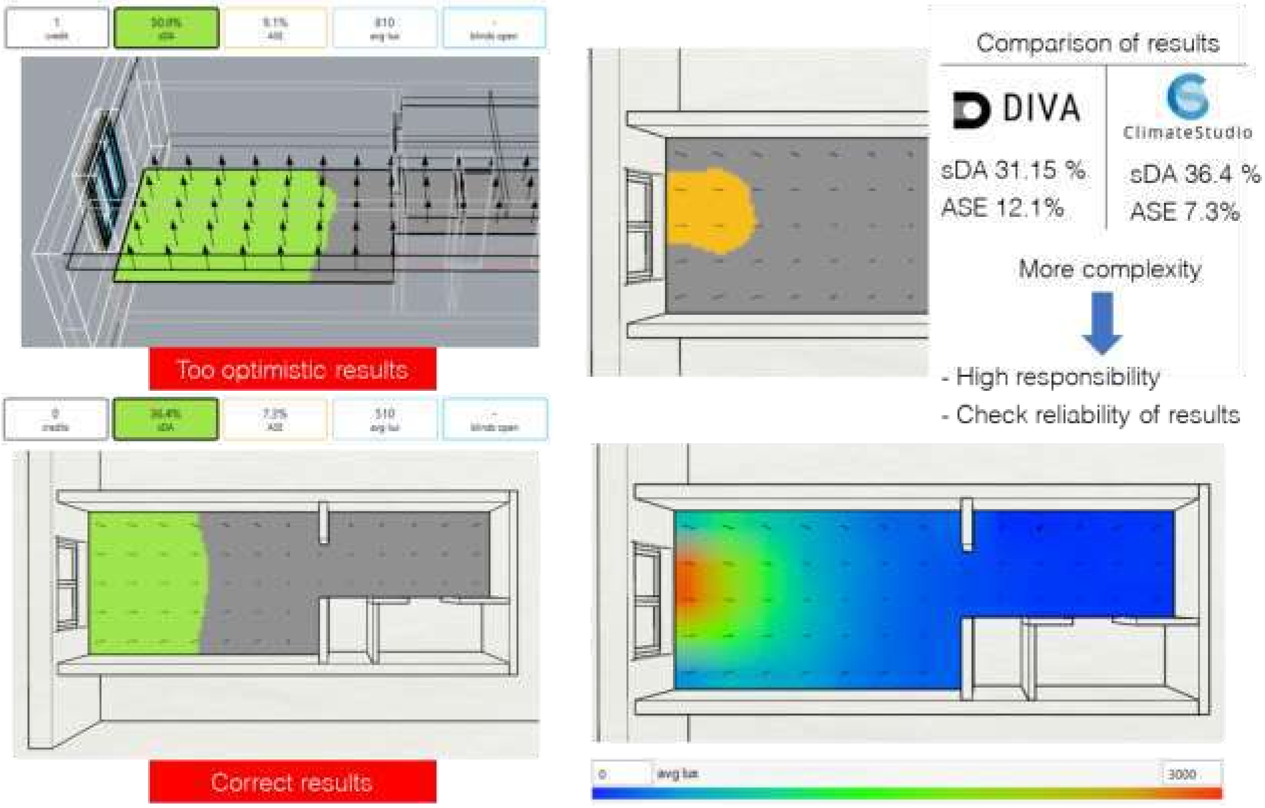


Figure 5. 117: Comparison of west unit daylight analysis of far better results with a corrected model.

The Daylighting study process should always control the reliability of results, adjusting surface normals if incorrect, material properties, and take into consideration visual transmittance of glazings. A change of a single property can produce different results. A sensitivity analysis should be done based on the project.

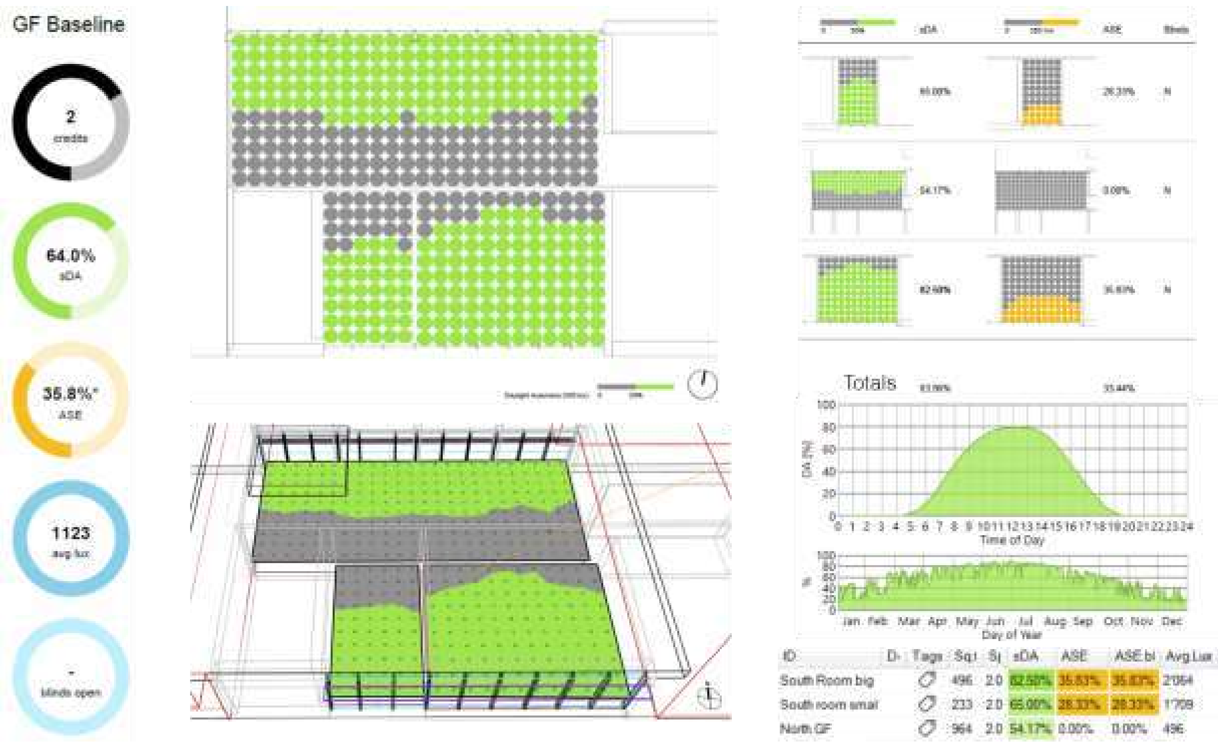


Figure 5. 118: LEED v4.1 Daylight option 1 results of baseline design for Gerbiceva.

The high 64% sDA >55% achieves 2 credits. When ASE>10%, the LEED credit requires to demonstrate how the design addresses glare. If no shading strategy is implemented, the zone will suffer overheating and glare.

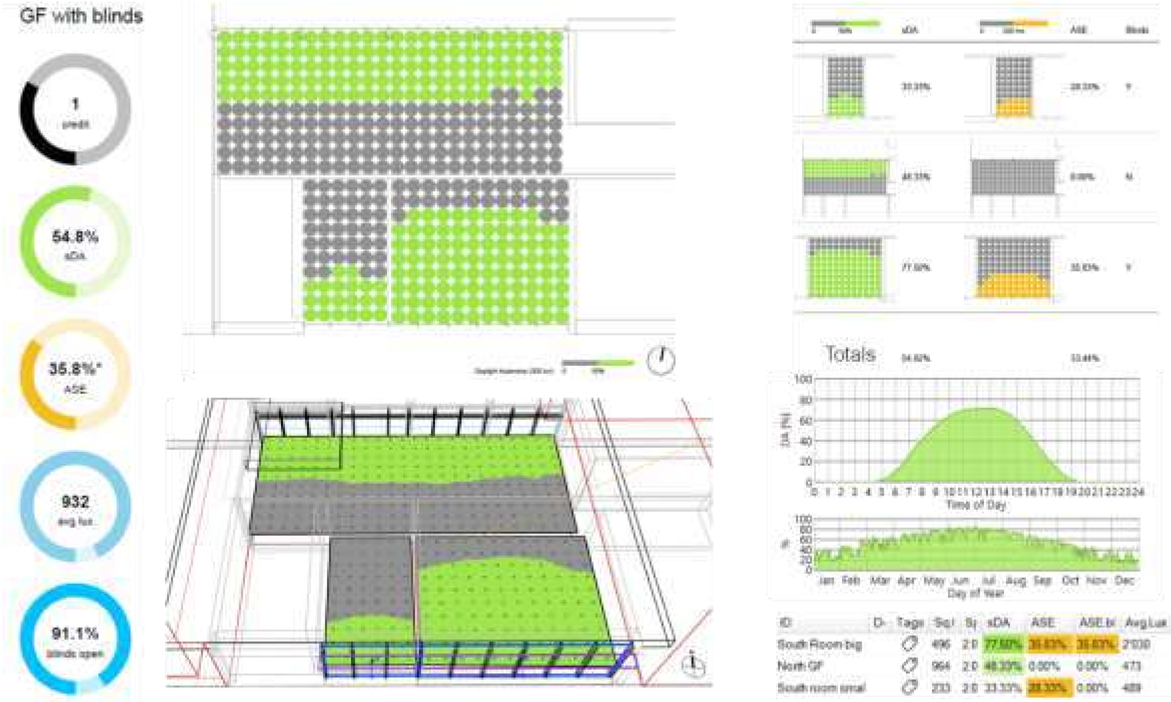


Figure 5. 119: LEED v4.1 Daylight option 1 of Design Option with blinds.

The interior comfort is improved with the use of manually controlled blinds. The illuminance LEED target is reached. Spatial DA at 54.8% is almost 55% with slightly more transparent glazing.

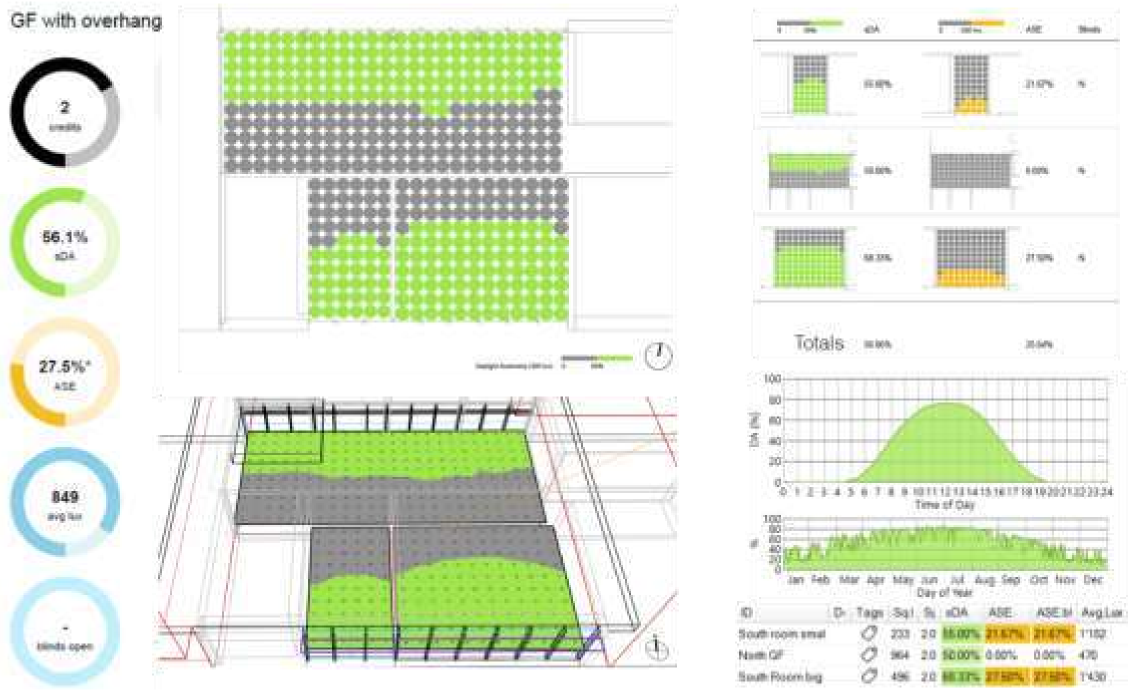


Figure 5. 120: LEED v4.1 Daylight option 1 of Design Option with 0.5 m overhangs.

Overhangs design returns an sDA above 55% and reduces ASE hours. However, an ASE of 27% for the south space can still produce local discomfort for a third of the space throughout the year.

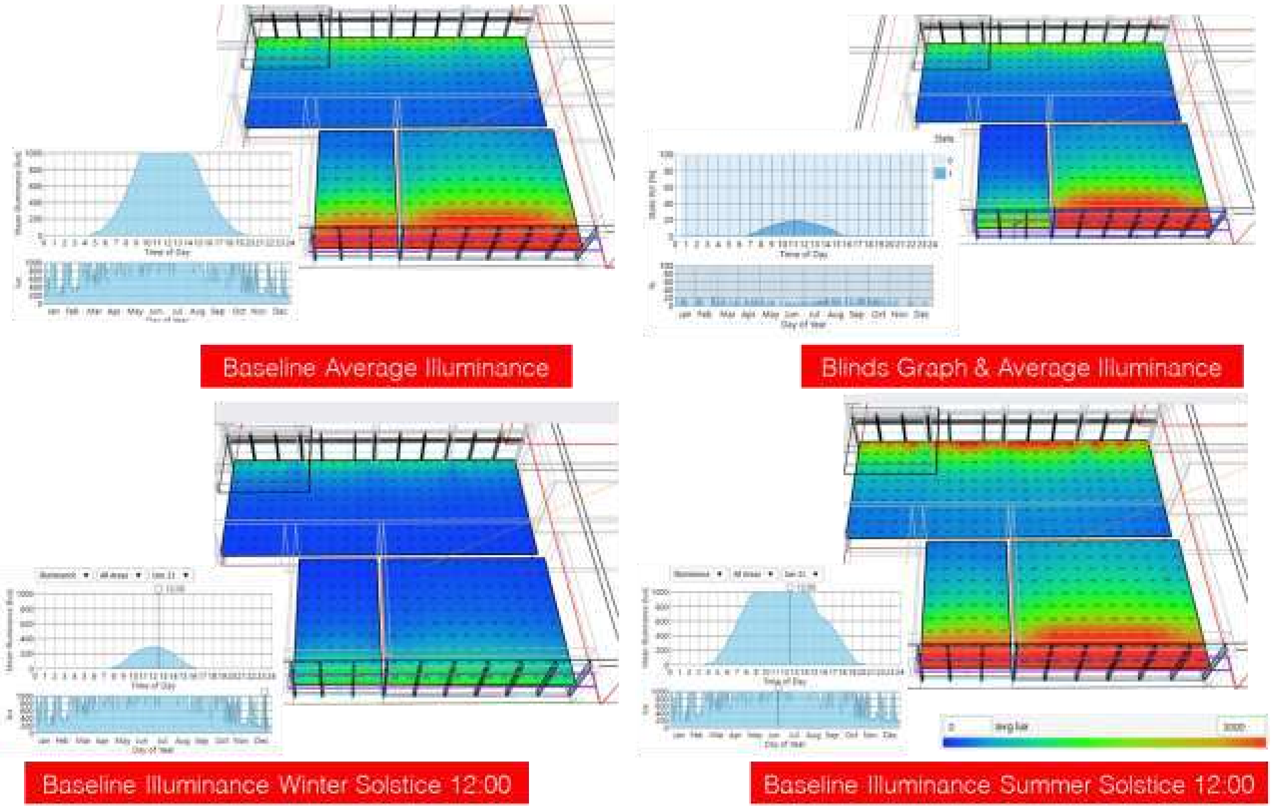


Figure 5. 121: Illuminance annual overview, at solstices and equinox for the ground floor.

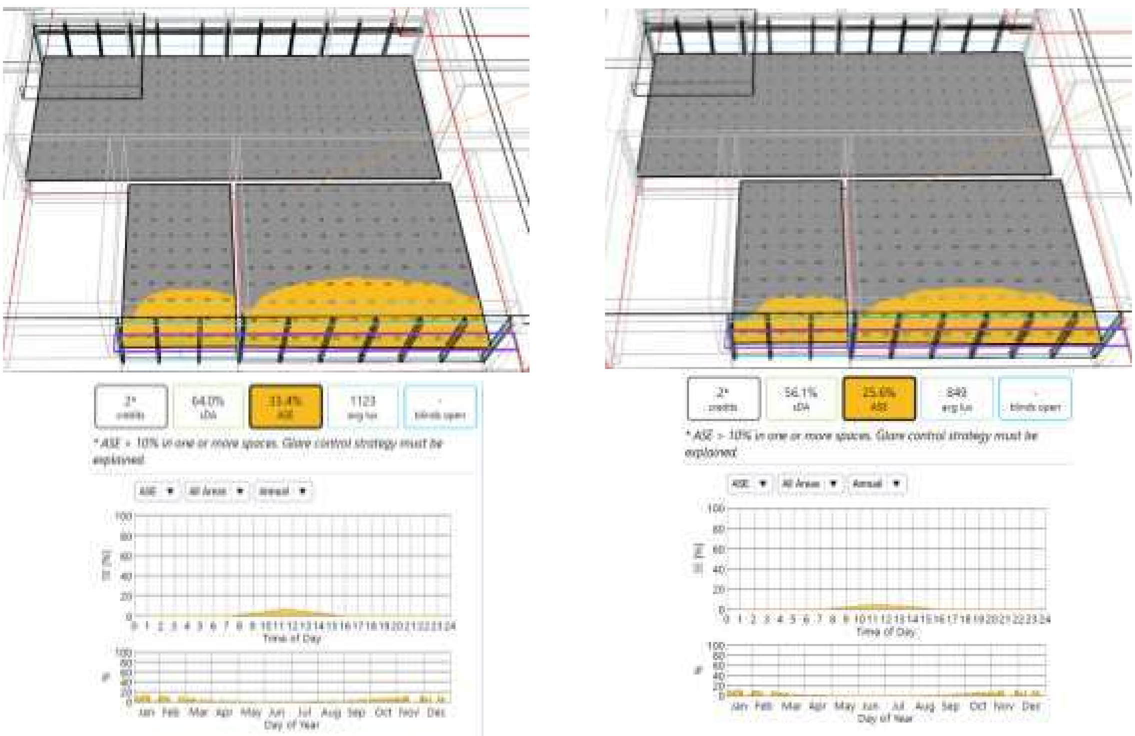


Figure 5. 122: Comparison of baseline and overhang improvement of ASE.

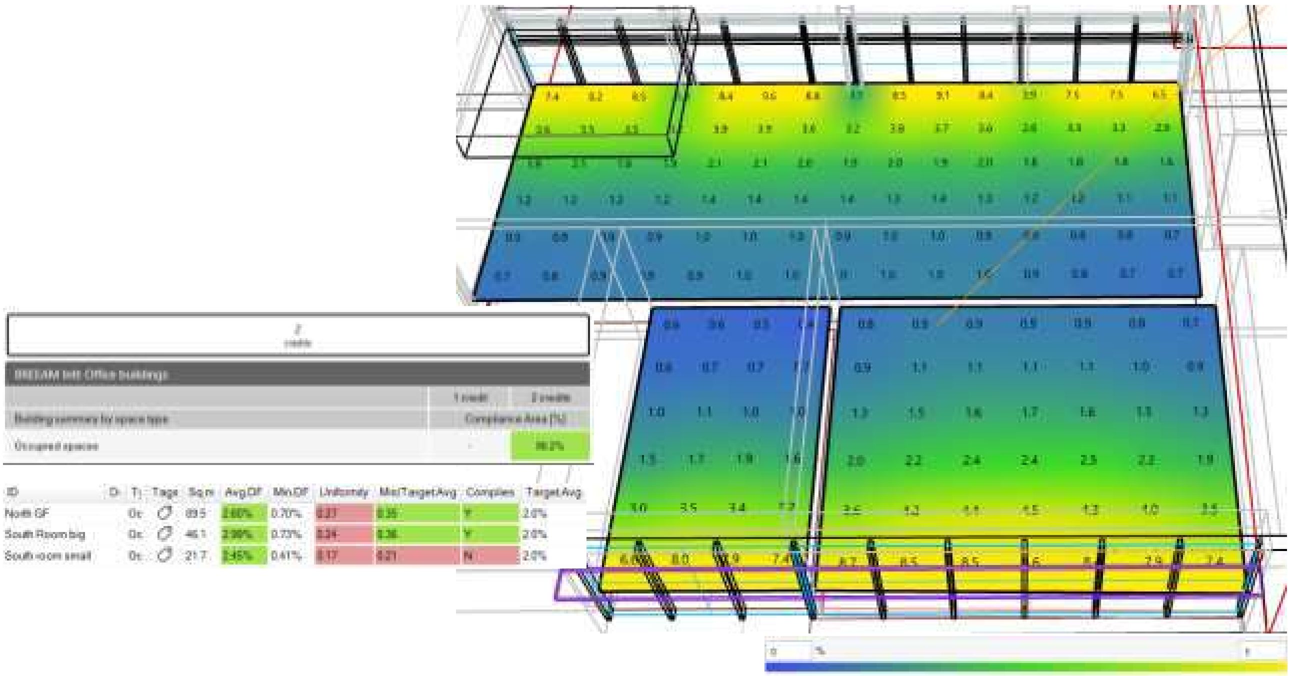


Figure 5. 123: BREEAM Intl: Office buildings credits. Daylight Factor at ground floor.

Daylight Factor provides insight for a well-daylit space. The uniformity ratio of DF below 0.3 indicates the need for integrative electric lighting over the year, improvement with skylights or other daylighting strategies.

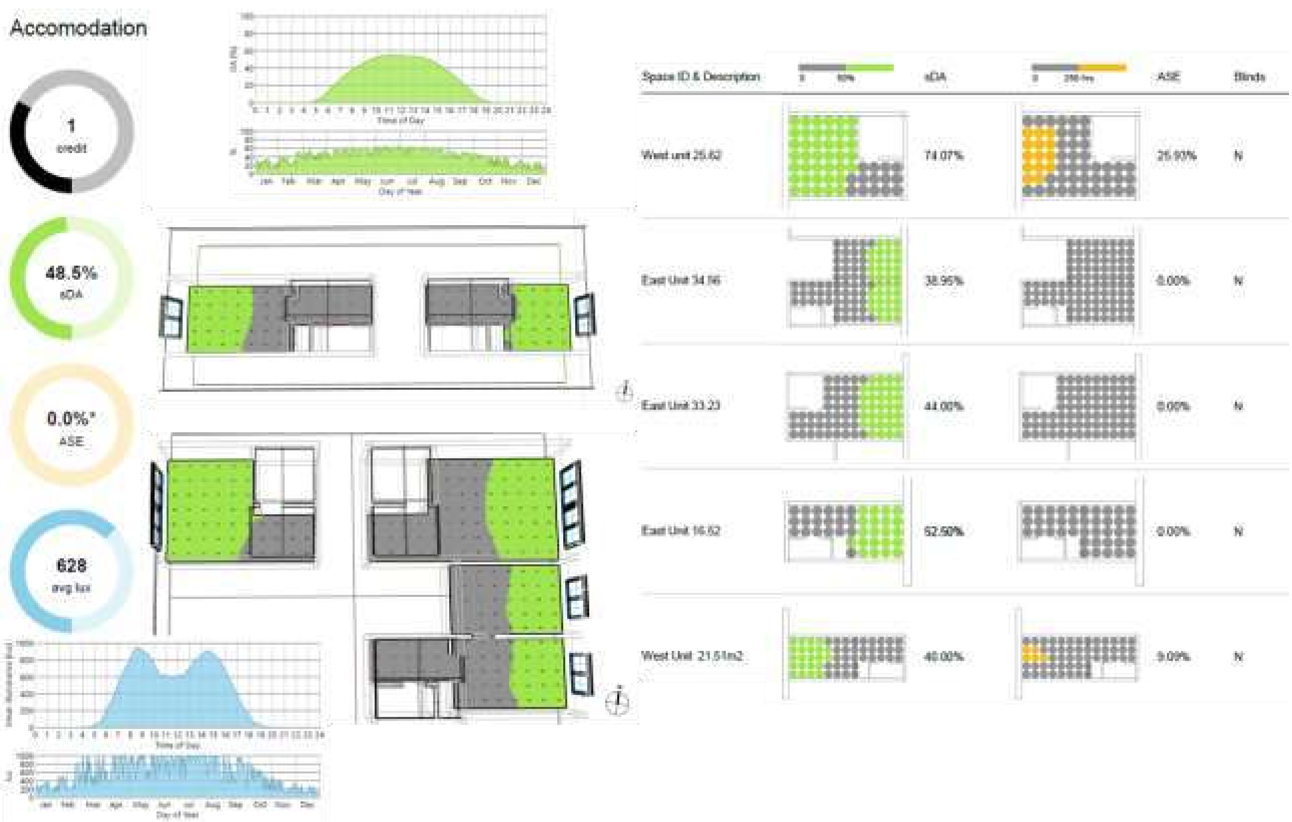


Figure 5. 124: LEED v4.1 option 1 for the five typologies of accommodation units.

The LEED Option 1 target sDA>40% is achieved for the accommodation units. Daylight Autonomy and ASE hours can be improved with design strategies.

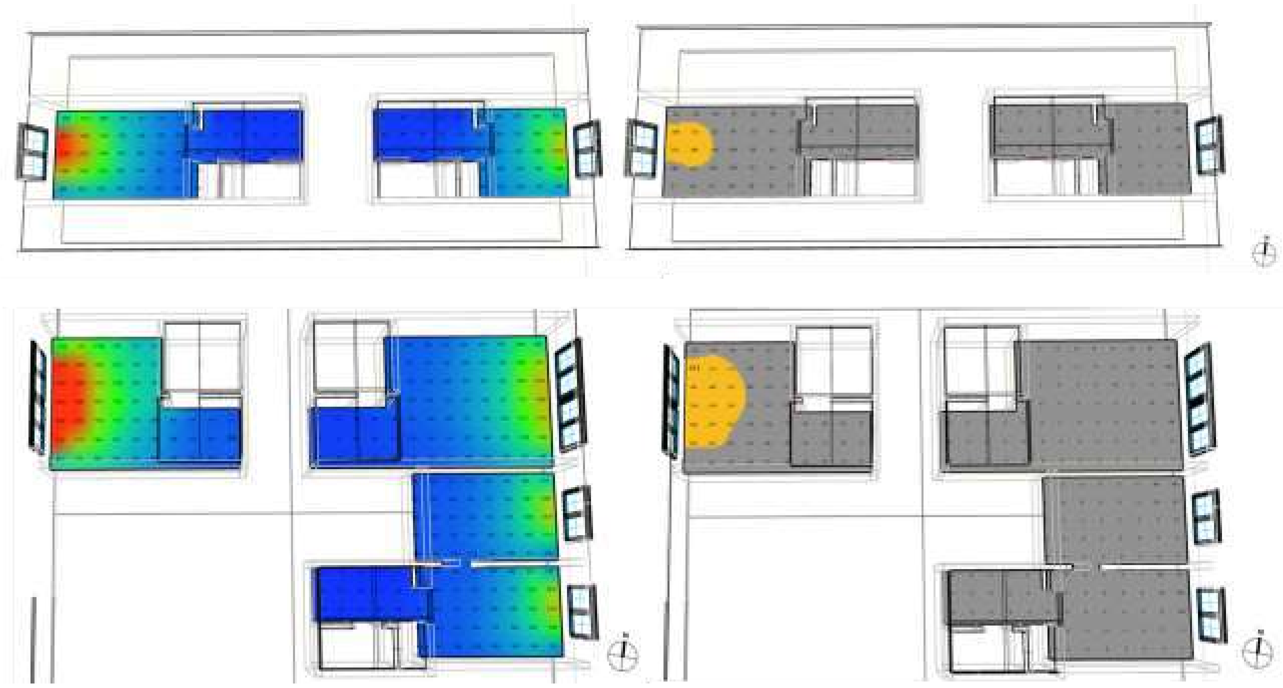
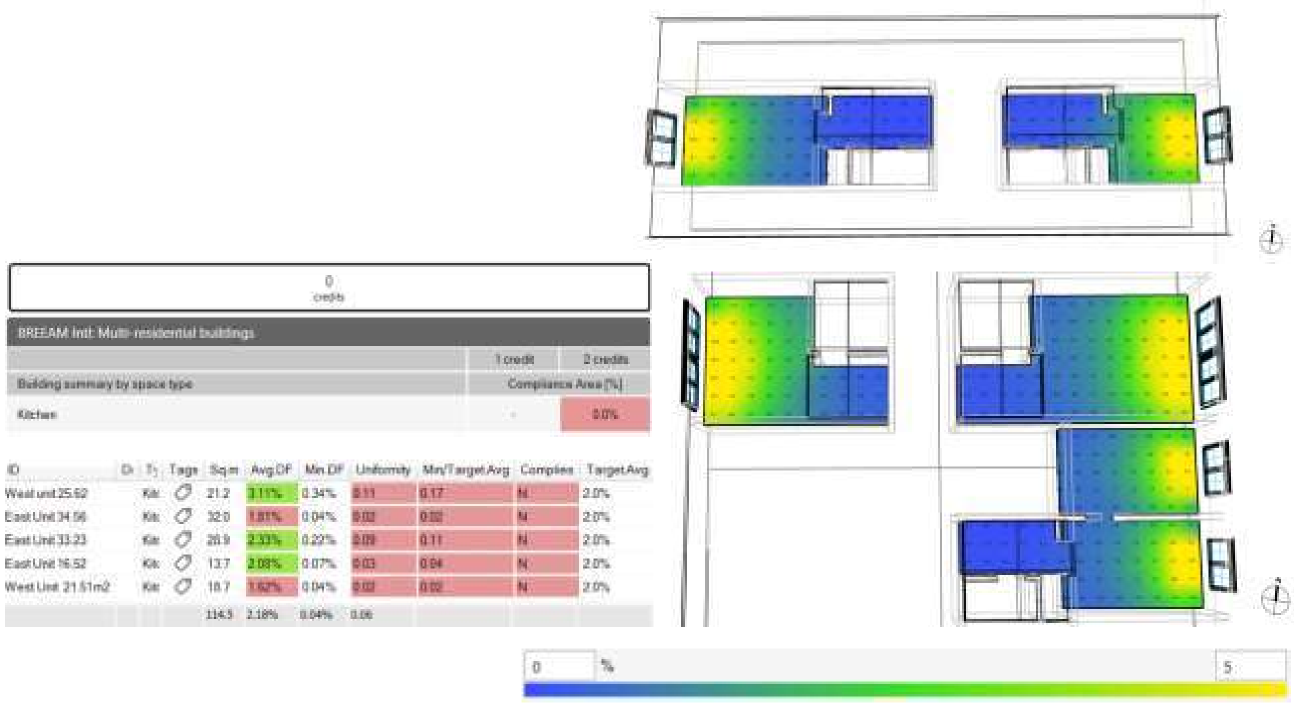


Figure 5. 125: Average Illuminance and ASE overview for the accommodation units.

High levels of illuminance above 3000 lux are found for the west units.

gg



ID	D	T	Tags	Sqm	Avg.DF	Min DF	Uniformity	Min/Target Avg	Complies	Target Avg
West unit 25.62		Kit		21.2	3.11%	0.34%	0.11	0.17	N	2.0%
East Unit 34.56		Kit		32.0	1.81%	0.04%	0.02	0.02	N	2.0%
East Unit 33.23		Kit		26.9	2.33%	0.22%	0.09	0.11	N	2.0%
East Unit 16.52		Kit		13.7	2.08%	0.07%	0.03	0.04	N	2.0%
West Unit 21.51m2		Kit		18.7	1.62%	0.04%	0.02	0.02	N	2.0%
				114.5	2.18%	0.04%	0.06			

Figure 5. 126: BREEAM Intl: Residential credits. Daylight Factor for accommodation units.

As the kitchen does not receive daylight, the uniformity ratio of DF is below the BREEAM requirement. Even though the results in Climate Studio are slightly higher than in DIVA, there are two units with DF below the BREEAM requirement of DF>2%.

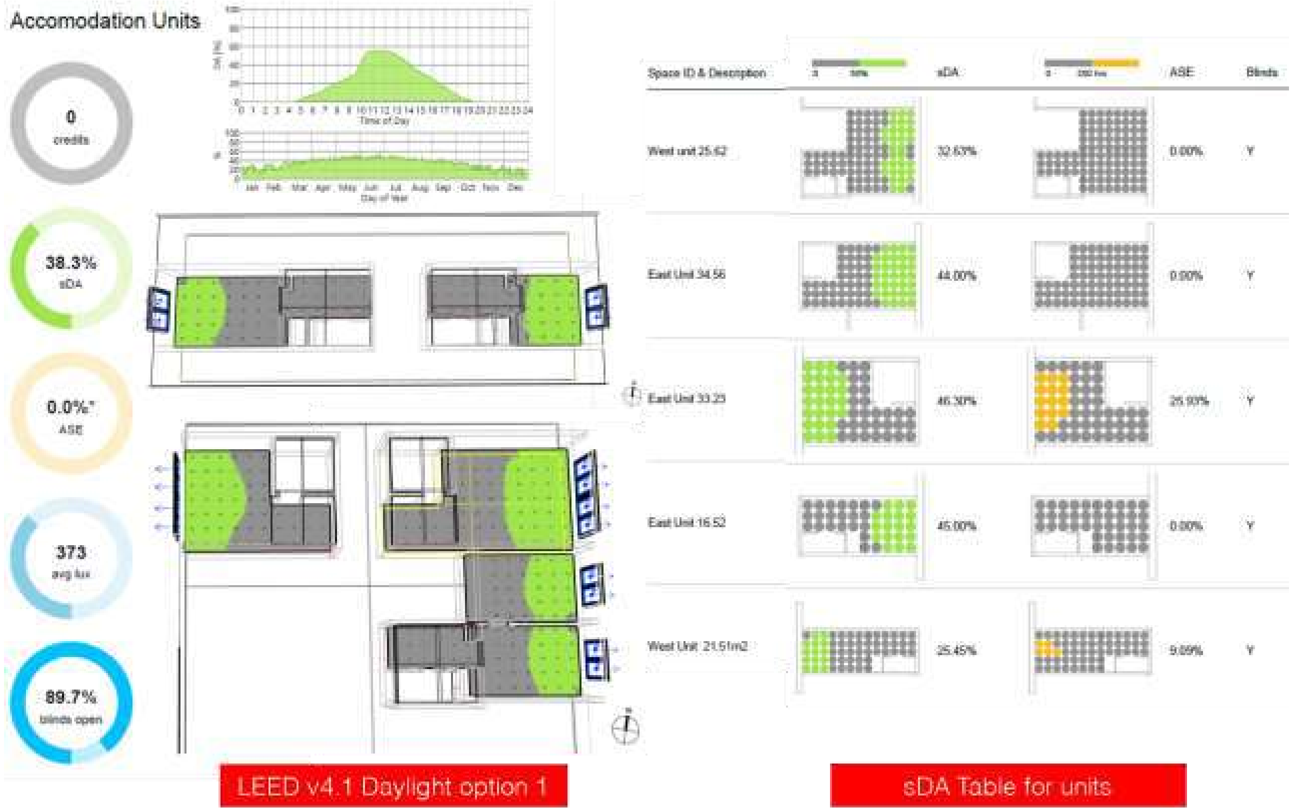


Figure 5. 127: LEED v4.1 option 1 of Design Option of units with blinds.

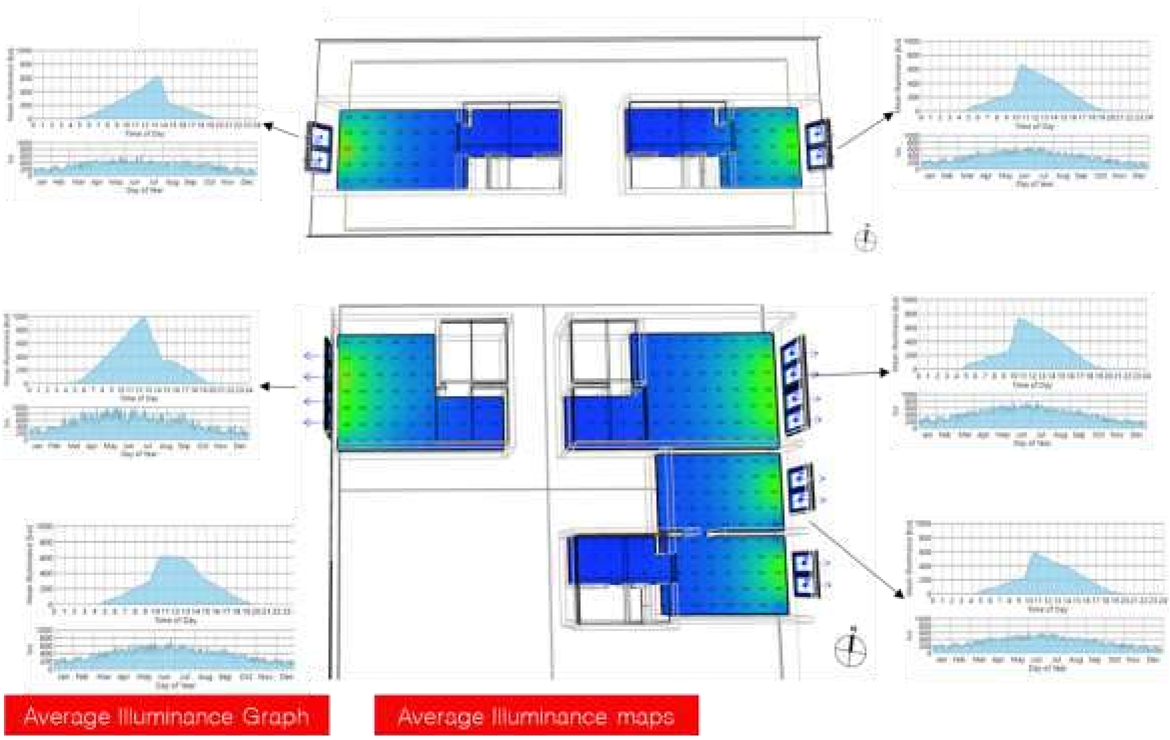


Figure 5. 128: Daylight performance with blinds, Illuminance maps and annual chart overview.

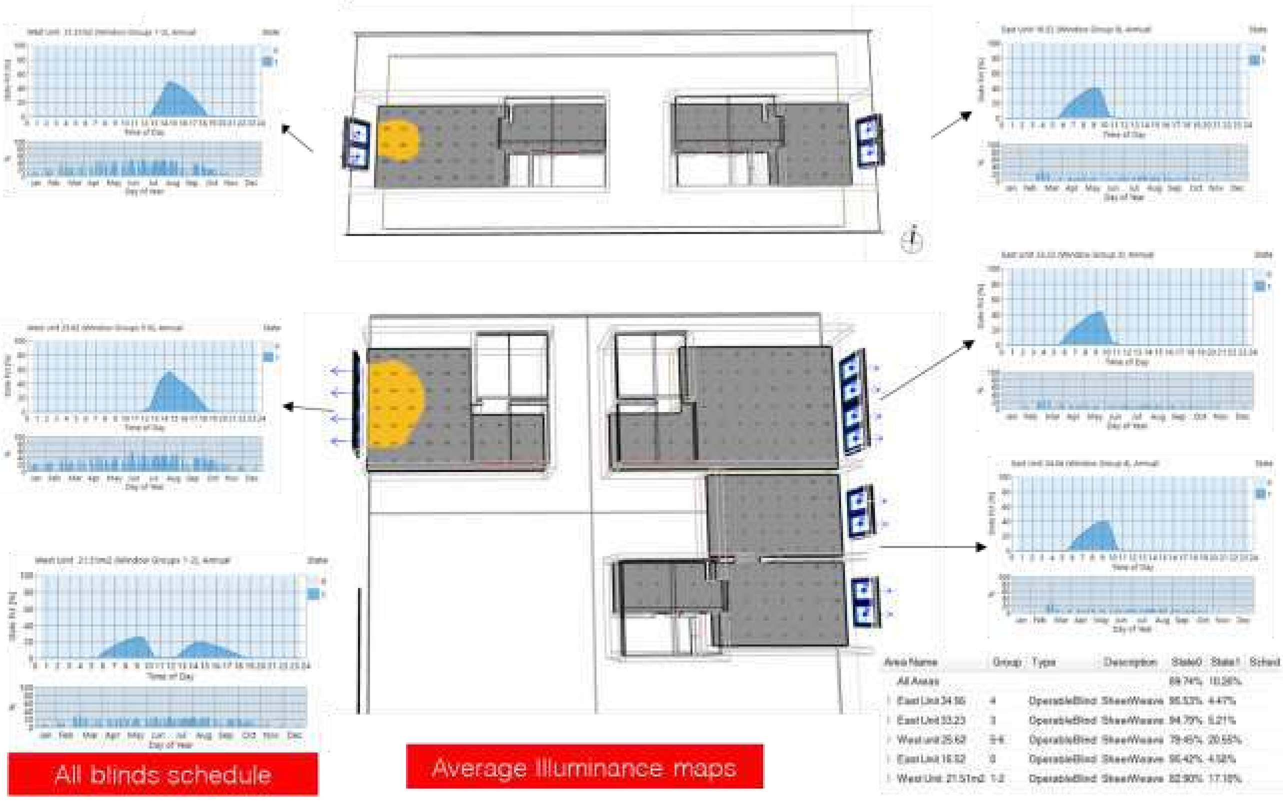


Figure 5. 129: Daylight performance with blinds, ASE maps and blinds annual schedules.

ID	D	Tags	Sq.ft	Spacing[ft]	sDA	ASE	ASE.b	Avg.Lux
West unit 25.62			228	2.0	74.07%	25.93%	25.93%	1'253
East Unit 34.56			344	2.0	38.95%	0.00%	0.00%	389
East Unit 33.23			311	2.0	44.00%	0.00%	0.00%	503
East Unit 16.52			148	2.0	52.50%	0.00%	0.00%	441
West Unit 21.51m2			201	2.0	40.00%	9.09%	9.09%	659

ID	D	Tags	Sq.ft	Spacing[ft]	sDA	ASE	ASE.b	Avg.Lux
East Unit 34.56			344	2.0	32.63%	0.00%	0.00%	313
East Unit 33.23			311	2.0	44.00%	0.00%	0.00%	401
West unit 25.62			228	2.0	46.30%	25.93%	0.00%	503
East Unit 16.52			148	2.0	45.00%	0.00%	0.00%	353
West Unit 21.51m2			201	2.0	25.45%	9.09%	0.00%	297

Figure 5. 130: Climate Studio tables of sDA, ASE, Avg. Lux for Gerbiceva project without shading and with roller blinds manually operated.

Table 5. 24: Comparison table of results in DIVA, DIVA-Grasshopper and Climate Studio.

Accommodation Unit	**DIVA**	**DIVA Grasshopper**				**Climate Studio**				
	No shading	**No shading**		**Dynamic Shading**		**No shading**		**Blinds**		**Min. Target**
	sDA	sDA	ASE	sDA	ASE	sDA	ASE	sDA	ASE	DF_{TM}
West Unit 21.51m2	31.15	29	12.1	27.9	12.1	40	9	25.45	9	1.62
West Unit 25.62m2	54.45	63.9	31.4	53.8	31.4	74	26	46.3	26	3.11
East Unit 16.52	41.91	40	12	32.2	12	52.5	0	45	0	2.08
East Unit 33.23	39.3	39.5	15.8	17.9	15.8	44	0	38.7	0	2.33
East Unit 34.56	35.25	35.9	12.1	15.9	12.1	38.95	0	32.63	0	1.81

The use of blinds can reduce the sDA by 5% up to 20% in some units. The sDA results between DIVA or DIVA-Grasshopper feature slight differences within 1-2%. The results with Climate Studio feature a slight difference of 3-4% for two of the east units, and 10% higher results for the 16.52 m2 unit. The west-facing units feature higher values in Climate Studio by 10%. It can be partly due to the difference of the Tvis of the different glazings found in their libraries. In DIVA a double-pane low-E with Tvis 65% is selected, while in CS a double-pane low-E Tvis 67.8%. A detailed sensitivity analysis of materials and glazings would be needed to understand how each tool accounts the contribution of the properties. The use of a modified version of Radiance with progressive path tracing, that produces faster results in CS could have a different sensitivity.

5.12.1 *Annual Glare overview, point in time glare, visual comfort with Climate Studio*

Glare is a condition of discomfort that can persist for many hours and throughout the year. Daylight software can analyze glare with point-in-time analysis. Climate Studio can simulate Annual Glare conditions on an analysis grid (usually at 1.2 m above floor at seated viewer height), and each point has eight view directions. Daylight Glare Probability is calculated for the whole space and individually for each of the viewpoints of the grid points.

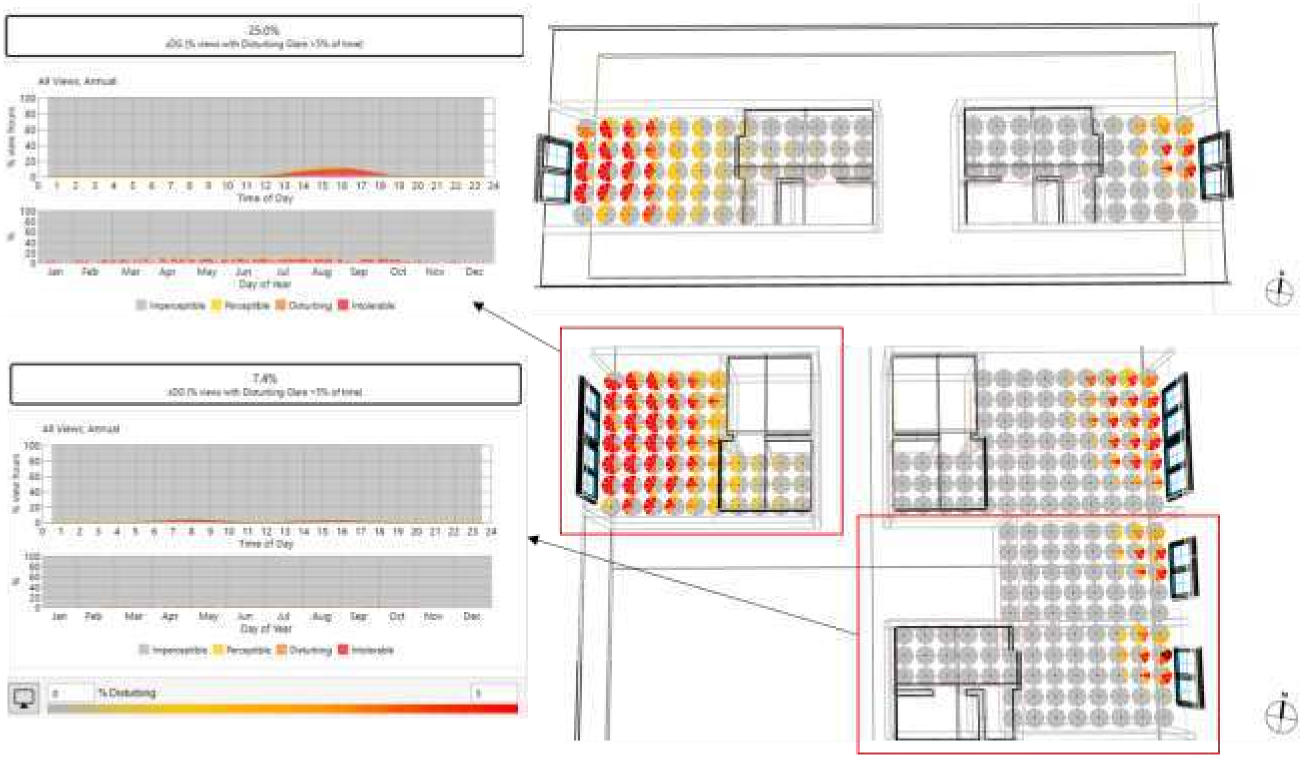


Figure 5. 131: Annual Glare overview of analysis grids and graphs for the accommodation units.

West and East units have glare. The spatial Daylight Glare (% views with Disturbing Glare >5% of the time) indicator for the west and east spaces selected is 25% and 7.4% respectively. The east-facing spaces do not require particular strategies for glare control. The high sDG value of the west units requires glare control with a design strategy, e.g. shading control.

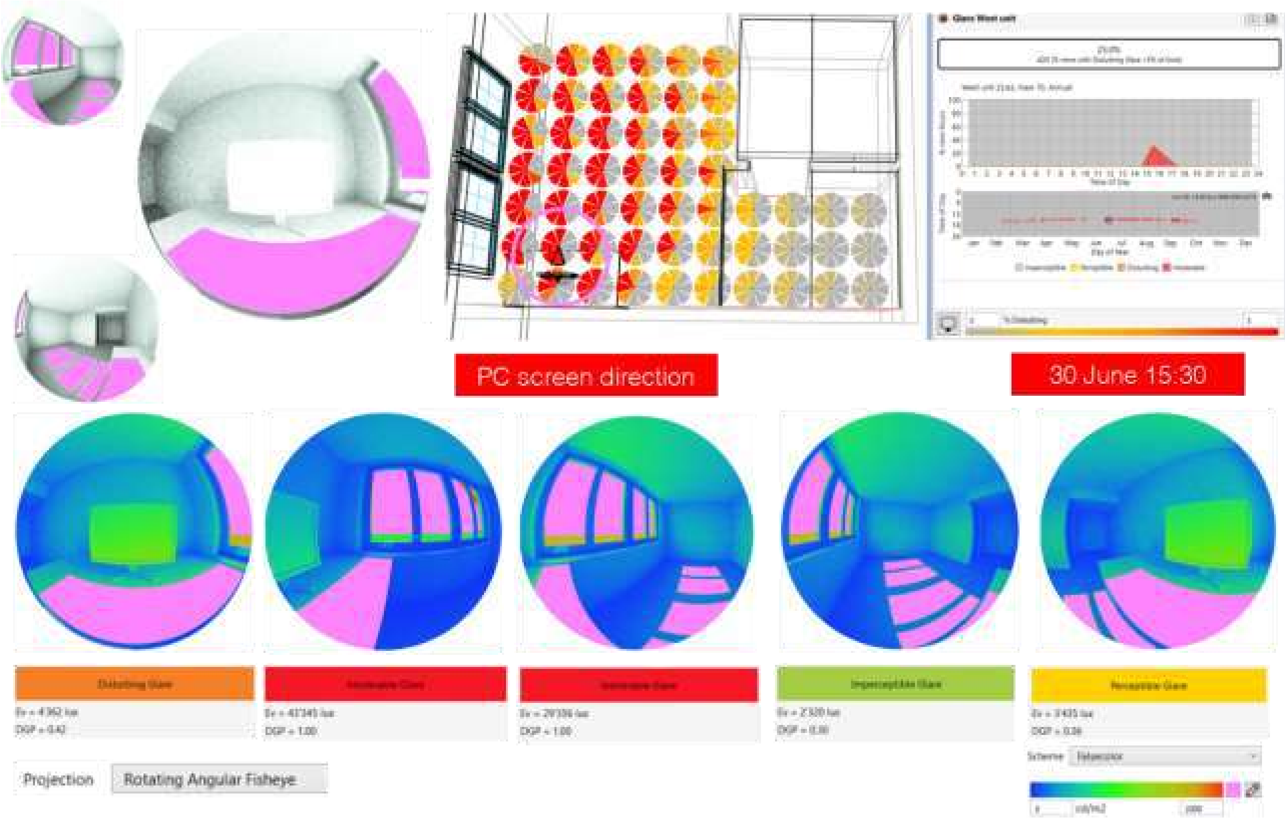


Figure 5. 132: Annual Glare analysis and point of view glare for computer table viewer position in the west accommodation unit.

Placing furniture improves the understanding of glare conditions in the space. Glare is present throughout the year from February – May and July – October months in the afternoon for the west unit. Surfaces with Luminance above 2000 cd/m2 are automatically coloured pink to indicate intolerable glare presence.

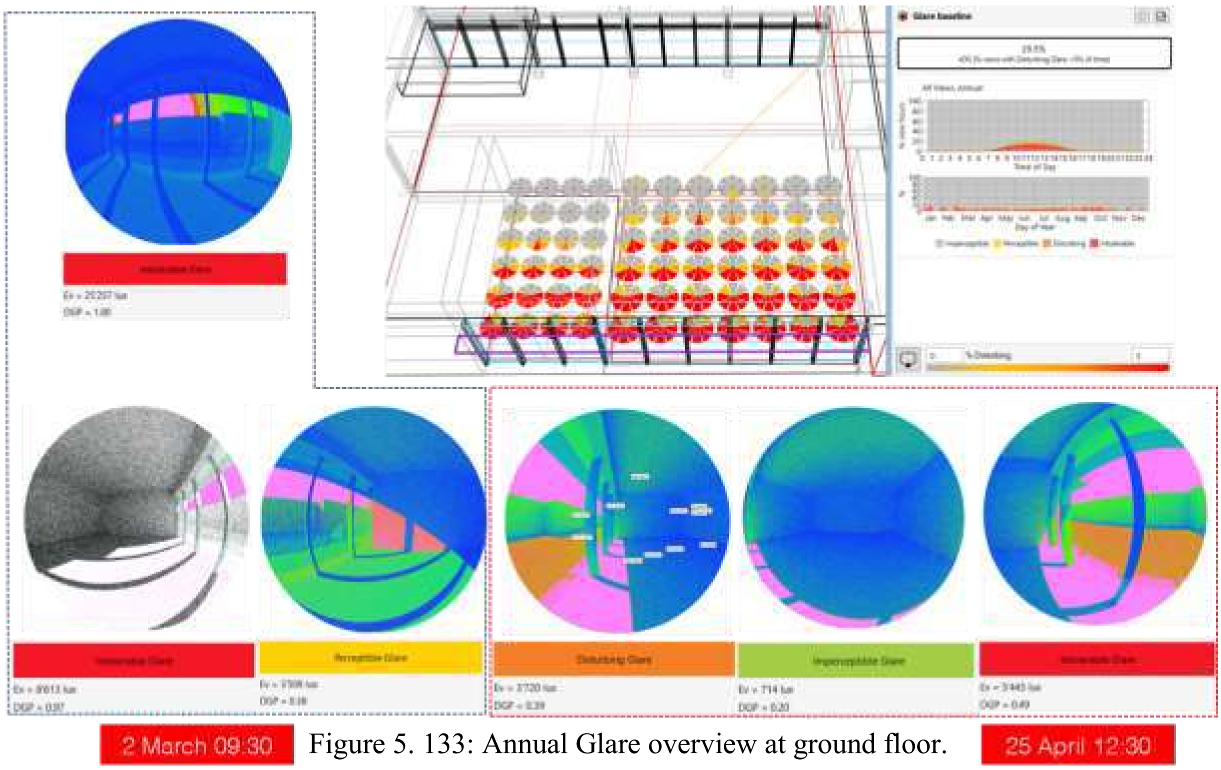


Figure 5. 133: Annual Glare overview at ground floor.

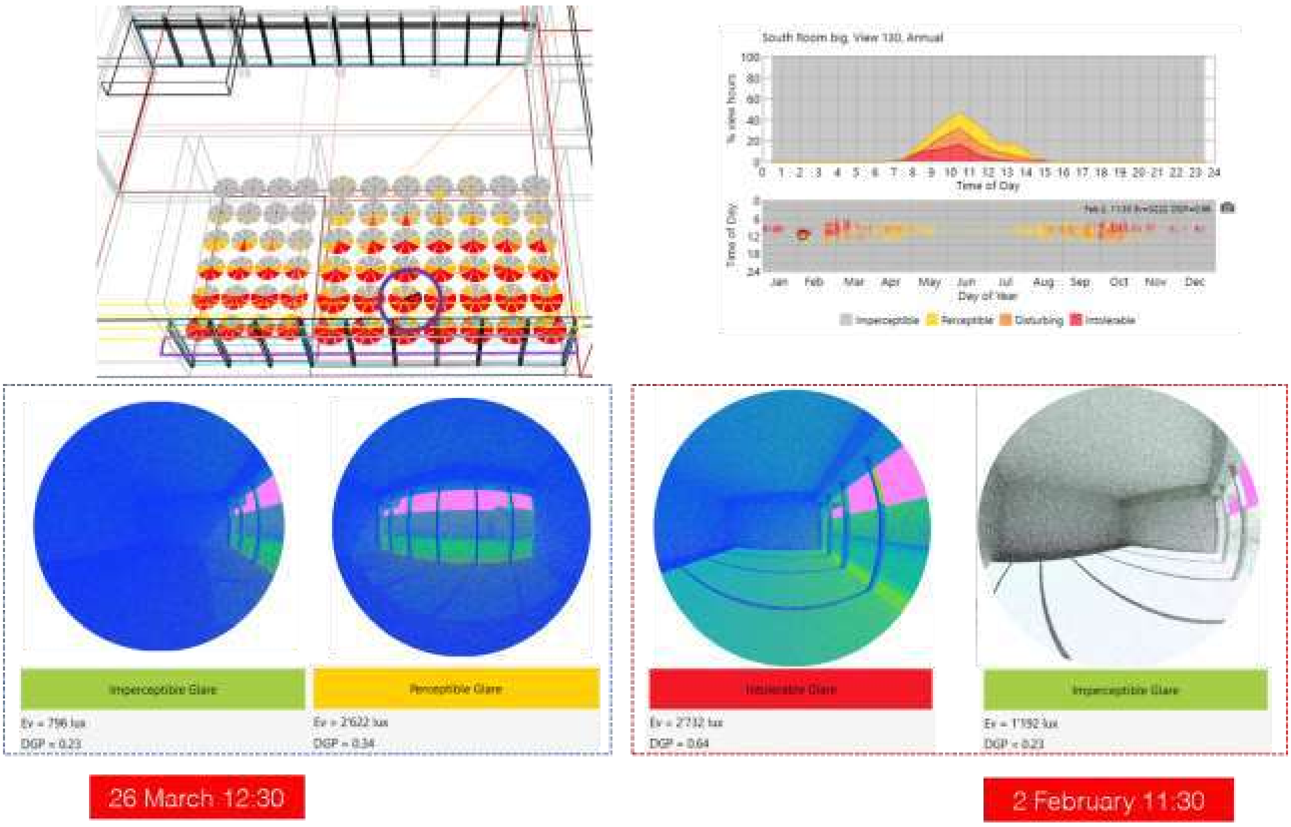


Figure 5. 134: Annual Glare and point in space glare analysis at ground floor.

5.12.2 *Daylighting qualitative exploration*

Vertical planes can give insight into the quality and distribution of light spatially, not just for the workplane.

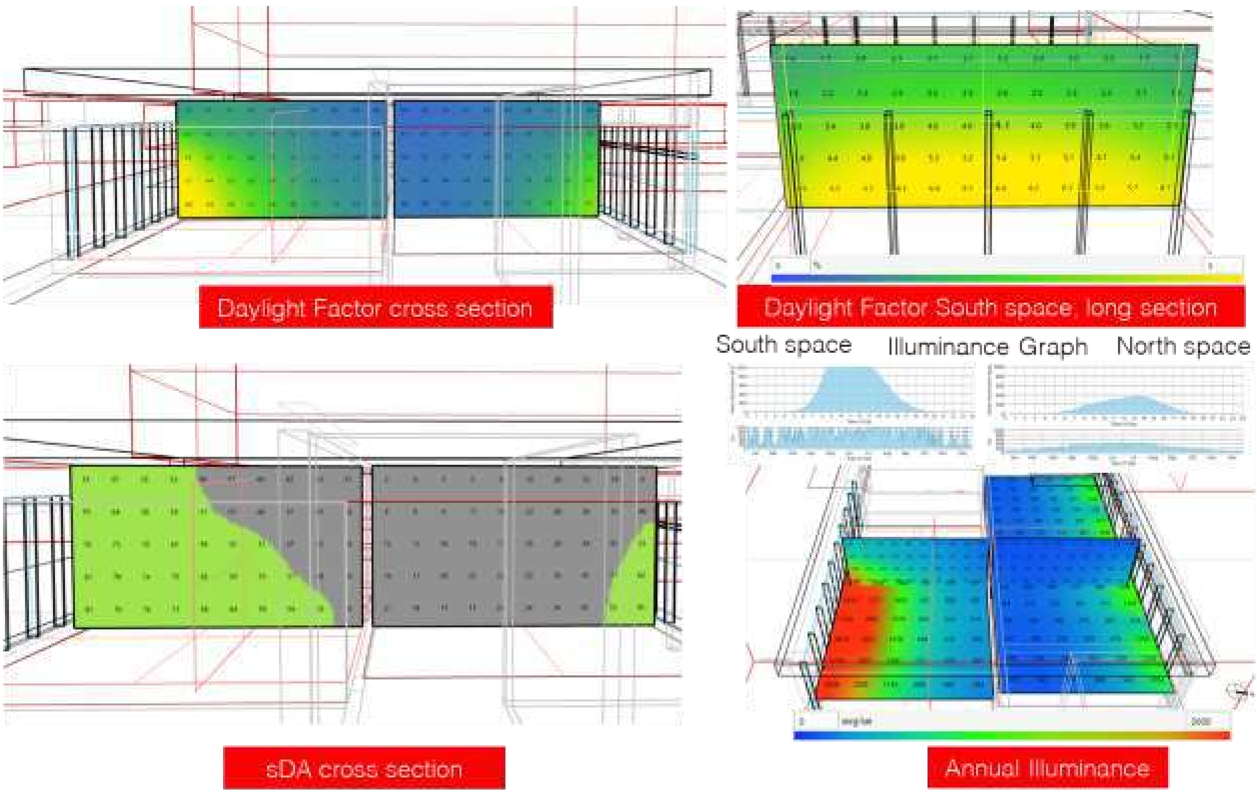


Figure 5. 135: Vertical Daylight exploration. Illuminance and Daylight Factor at ground floor.

The south spaces are overlit as conditions of sDA around 80% and DF above 5%. It is also an indication of high illuminance and overheating of spaces.

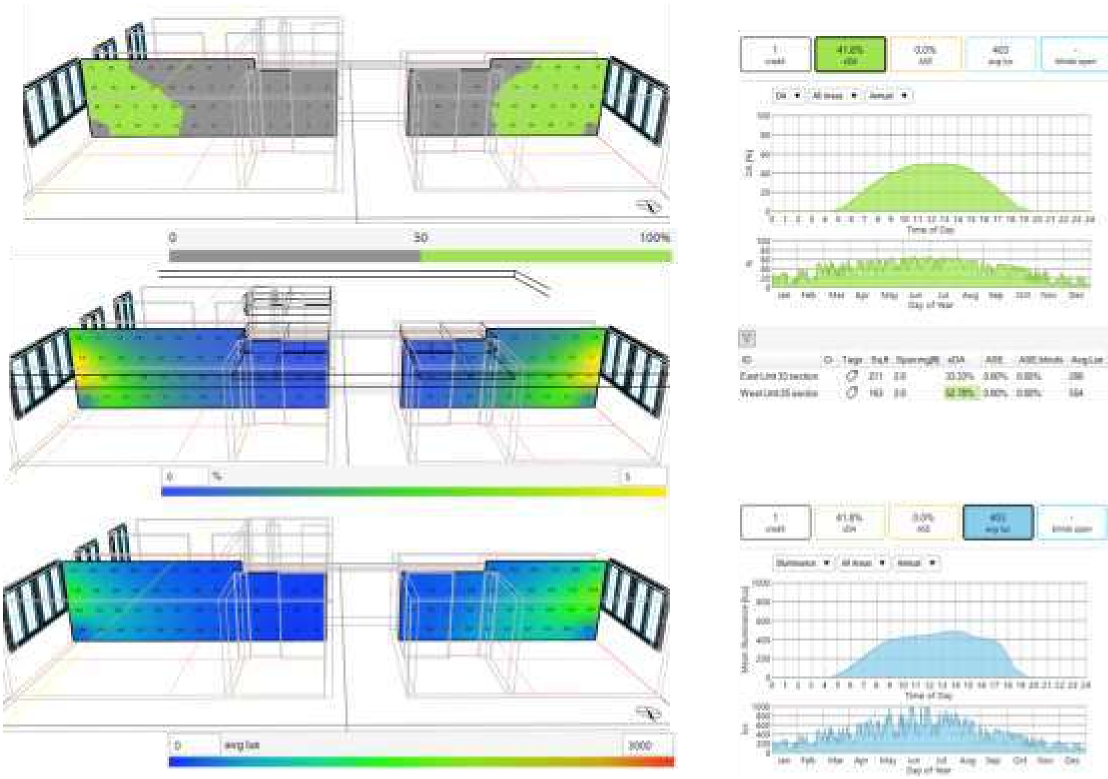


Figure 5. 136: Vertical Daylight exploration. sDA, Daylight Factor, and Illuminance for two units.

The placement of the window head at the same level as the ceiling produces a well-daylit space as seen in the section views of the sDA, illuminance and DF. The section view reaffirms the findings of the horizontal work plane analysis that the kitchen and corridor do not receive minimum lighting at any height level.

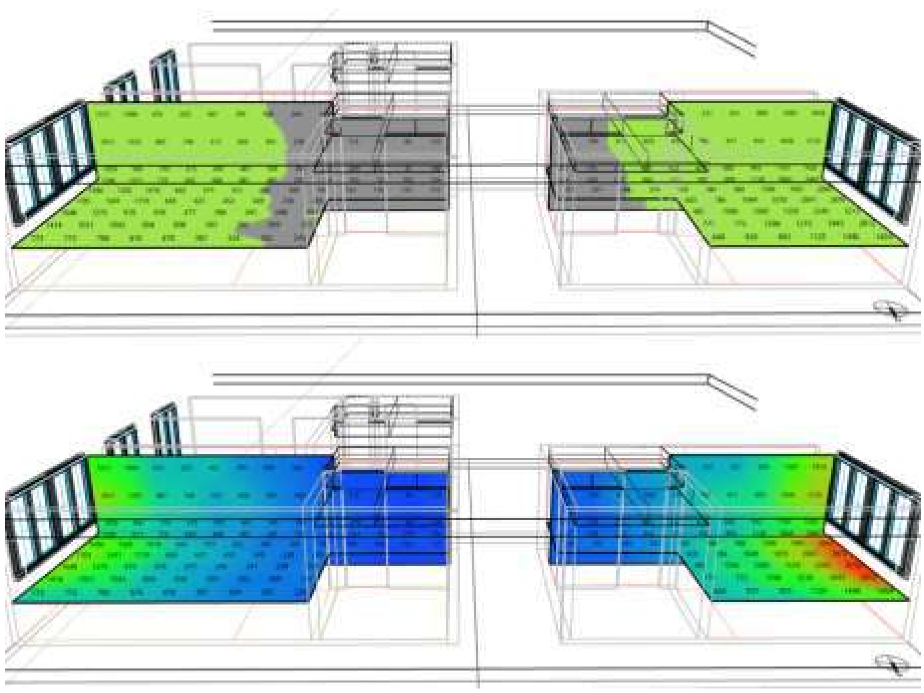


Figure 5. 137: Combined Horizontal and Vertical daylight grids analysis of sDA and Illuminance with Illuminance values.

Visualizing results in three dimensions with horizontal and vertical simulation planes improves the understanding of the distribution of daylight, and in turn can better inform the design decisions of window and material properties, WWR, shadings and space layout. The purpose of such studies is qualitative and to raise the quality and comfort of spaces. Daylight simulations are an essential contemporary digital method in exploring the design solution space, e.g. double-height spaces, apartments, atriums, sports venues. Qualitative daylight analysis can not be used with recommendations of EN 17037, LEED or other certifications as there are no lighting handbooks or studies that provide insight at this moment on recommended benchmark values or threshholds for vertical analysis of daylight.

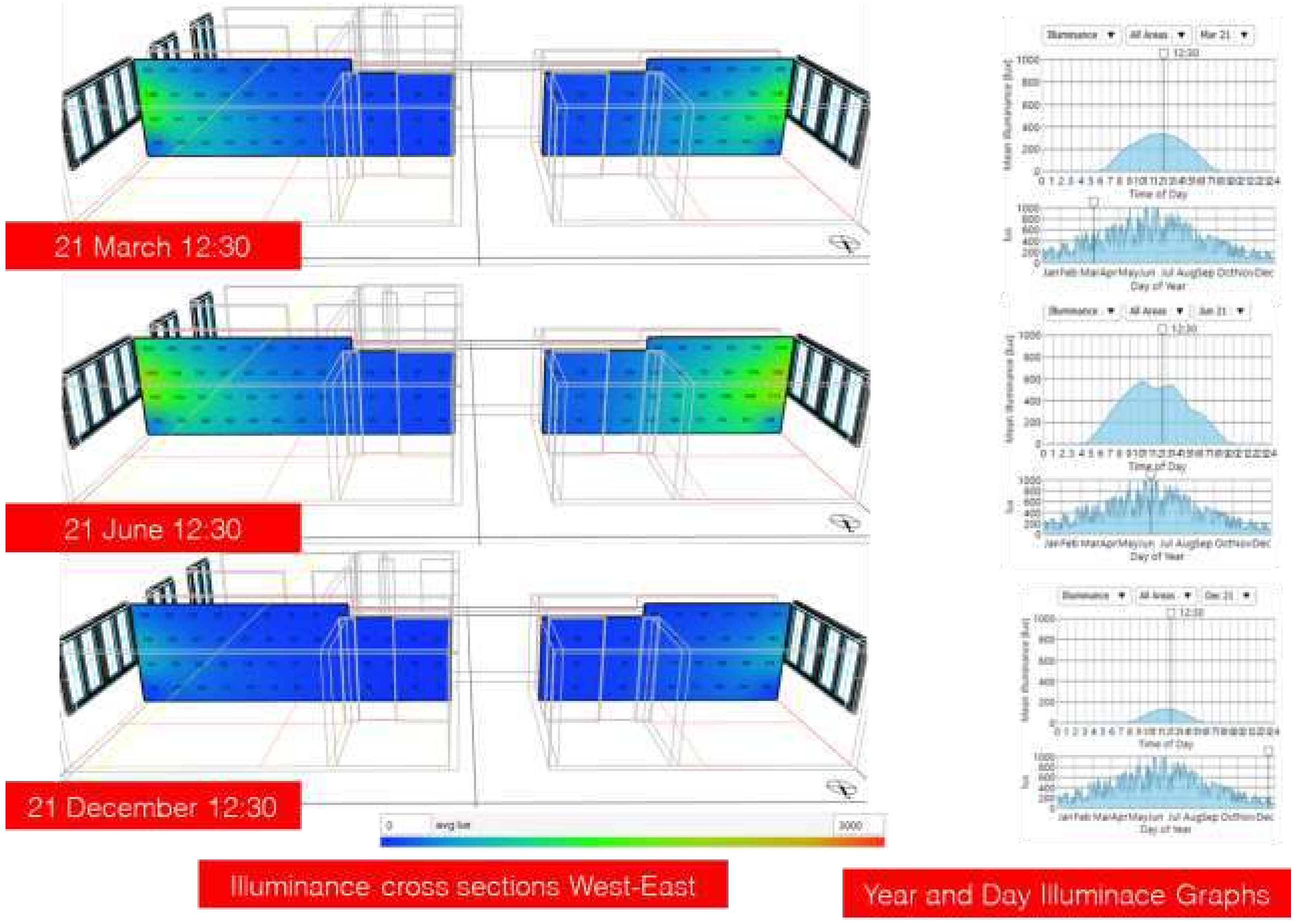


Figure 5. 138: Illuminance cross section West-East for two units.

Findings for Climate Based Daylight Modelling for Performance and Visual Comfort:

- Daylighting is a complex task
- Baseline conditions produce high sDA and ASE>10% with probable glare conditions
- Use of blinds improves comfort, but lowers sDA, and has a slight effect on Illuminance requirements
- Overhangs reduce the sDA slightly, reduce ASE but not enough to reach 10%, and affect illuminance
- Combined strategies are needed (orientation, façade design, shading devices, mechanic/manual blinds)
- Some Green Building Certification credits are achievable with the baseline condition
- Vertical section grids for analysis can give qualitative insights for the spaces

- Guide the design decisions selection of glazings, materials, furniture layout for low glare risk, integrate artificial lighting when needed (where to locate, maximize the use of daylight, lower cost of lighting)

Additional Benefits of Daylight Performance & Comfort with Climate Studio:

- Optimize the design goals of Performance and Comfort for Daylighting
- Green Building Certification daylight credits automatic reports
- Annual Glare Analysis
- Point-in-time Illuminance and Glare analysis
- Data-driven and informed design

5.13 Building Energy Modelling

The Building Energy Model will be created using two different approaches. The BIM integrated automated approach to BEM and the manual creation of BEM Model following recommendations in the ASHRAE Standard 90.1 with different perimeter thermal zones and core zones for each level.

5.13.1 *Automated BIM to Building Energy model with Revit and Insight*

The two possible ways with conceptual mass and building elements are tested to create the Energy model.

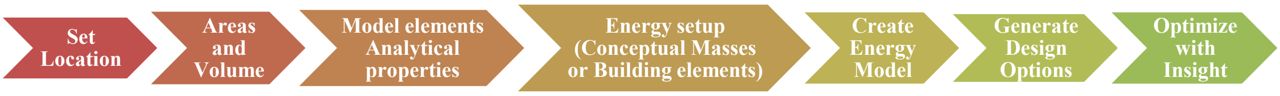


Figure 5. 139: Trajectory for automated BEM with Revit.

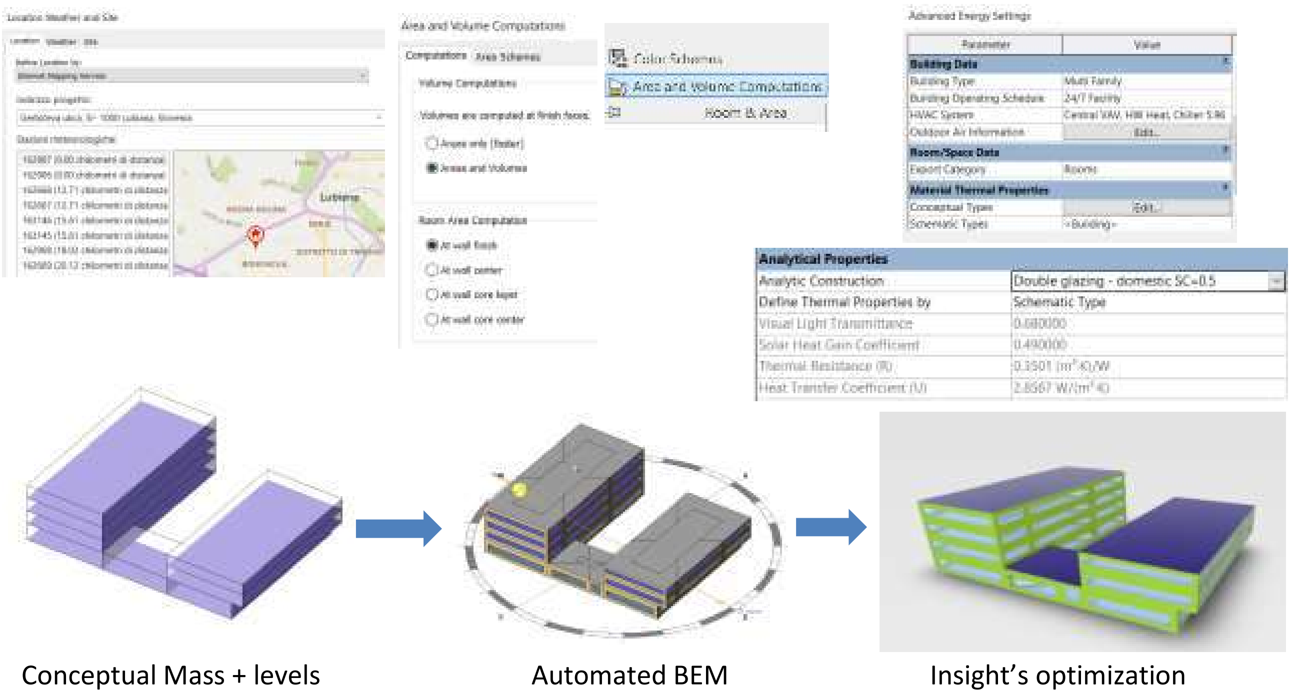


Figure 5. 140: Revit setup and modelling steps to create an Energy Model.

In order to prepare the Energy Model in Revit, project location must be set, and areas should be assigned to each space. For the thermal zones to be created, the spaces are to be computed by area and volumes in the model. If the model to be analyzed is an early concept, the Energy settings will be sufficient to define Building Systems, Program, Occupancy and target Window to Wall ratio (WWR). If a developed concept with building elements is used, the Energy settings can use the Revit elements and their analytical properties in the simulation for the constructions and glazings.

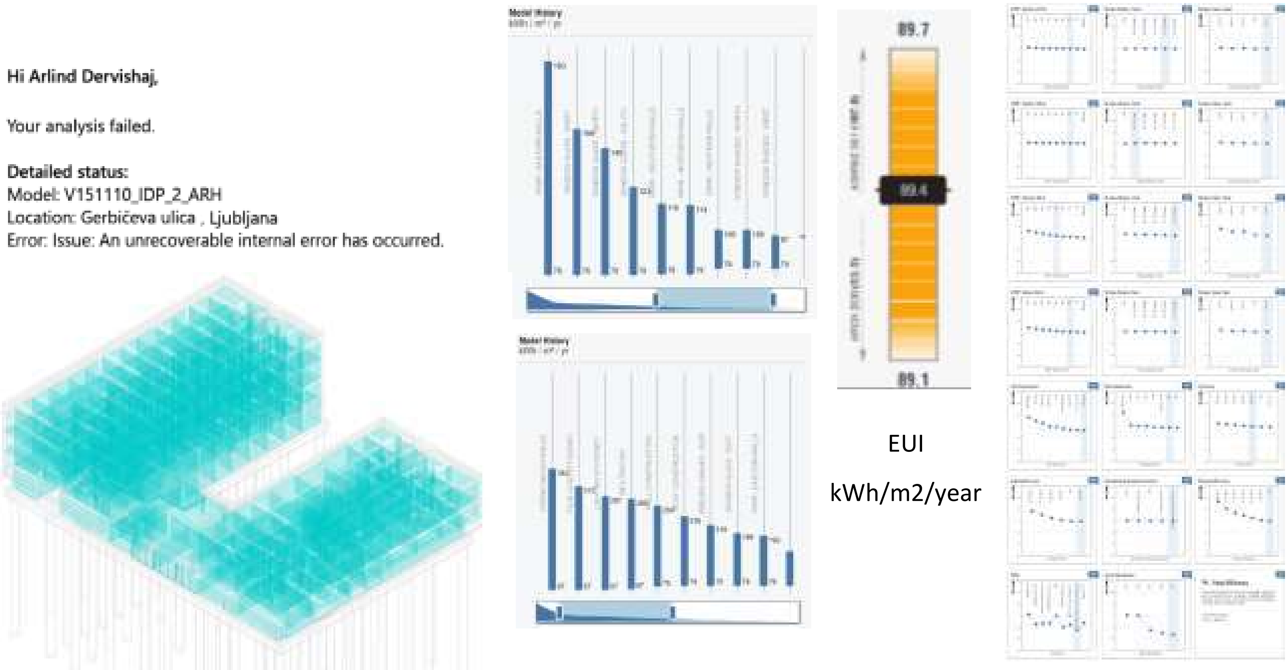


Figure 5. 141: Insight's optimization input charts, Optimization history for Conceptual BEM and message of failed analysis of Revit Multi-zone Model with Building Elements.

The Analytical Model created with the IFC failed to create results in Insight.

Table 5. 25. Automated BIM to BEM with Revit and Insight Pros and Cons.

Insight automated BEM Pros	Insight automated BEM Cons
- Simple and step by step quick procedure - Not time-consuming or costly - Applicable since early Concept stage to Detailed Design - Guidance towards optimization of design options - Automated Energy Model Creation - Applicable to every type of project	- Does not allow control to the user over the translation, to validate and correct the Energy Model. - Does not allow to assign thermal zones except in the general settings for the whole building - Might be problematic, incorrect and fail to analyze larger multi-zone thermal models

5.13.2 *Detailed BEM with Rhino, Grasshopper, and Climate Studio to Energy Plus connection*

An Energy Model was created with Rhino to simulate with Archsim and Climate Studio components that connect the geometry with the zones information needed to set up and simulate with Energy Plus for a whole building energy simulation. Two different thermal zone layers are used, one for the accommodation units and one for the distribution and common areas. The modularity and repetition of units allow modelling of a geometry that is compliant with rules for a Multi-zone Energy Model. Windows are modelled as surfaces of planar polygons and placed in a separate layer. The south balconies are modelled as shadings.

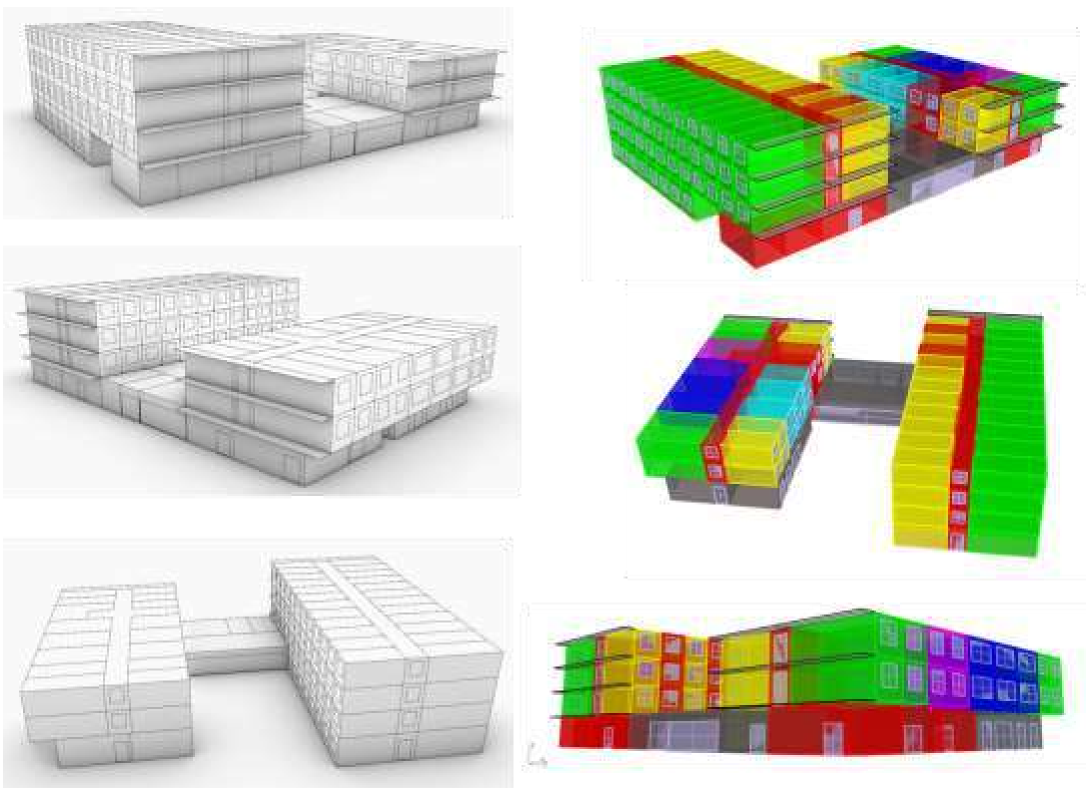


Figure 5. 142: Gerbiceva BEM visualized with CSShadows (left) and Rhino-Shaded (right) with thermal zones assigned to separate color layers.

Table 5. 26: Guidelines for Building Energy Modelling and Information Requirements.

How to Model Elements	Modelling rules	Input properties
-Windows as surfaces -Spaces as volumes -Shadings as separate elements -Boundaries as separate surfaces such as ground or adiabatic	-Surfaces as planar polygons -Surfaces can not contain holes -Volumes as complete polyhedrons -Assign model spaces to thermal zones, e.g. Residential, Office etc. -Co-planar faces of zones for partitions and floors -Assign materials to surfaces according to construction types -Co-planar Windows (surface) with walls (face of volume) of thermal zone	Constructions: - Resistance - U-value - Embodied Carbon Windows: - Air leakage -Visible transmittance -Solar Heat Gain Coefficient

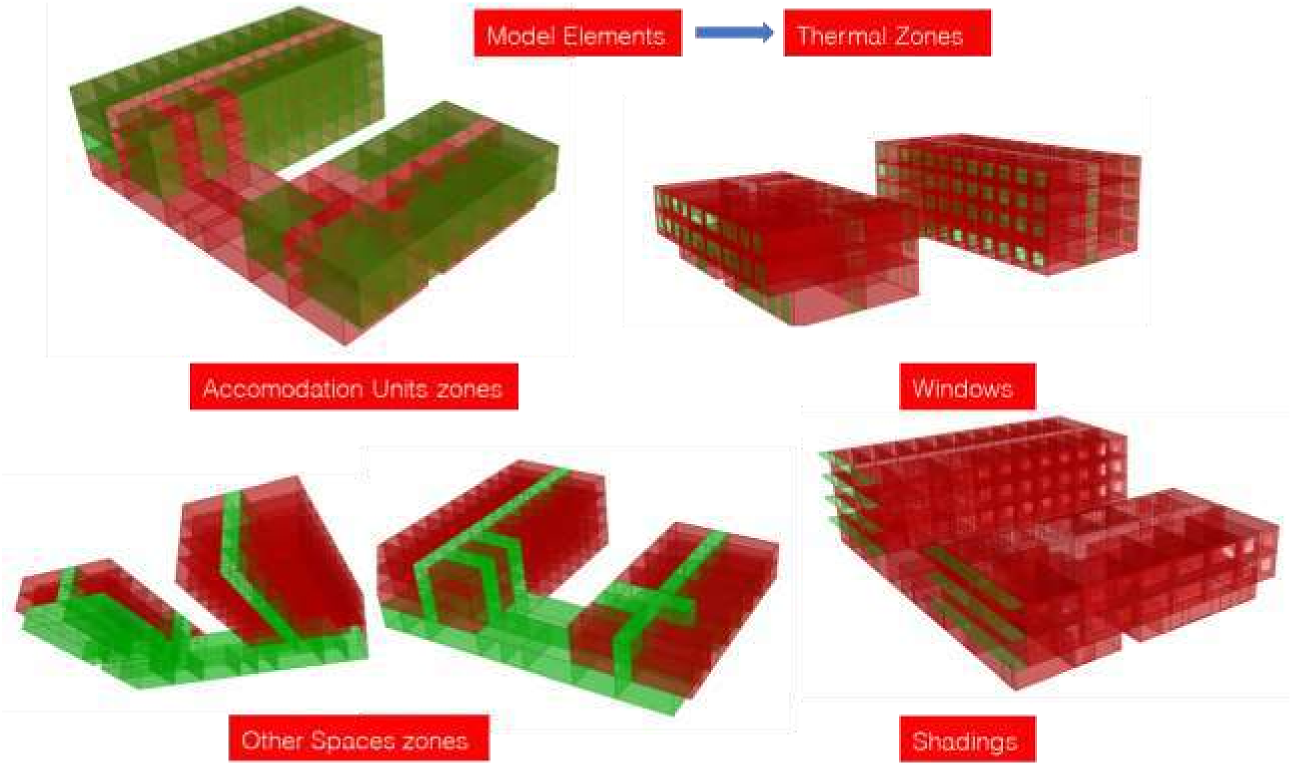


Figure 5. 143: Assigning geometry to Thermal Zones, Windows, Shadings, Boundaries with Archsim.

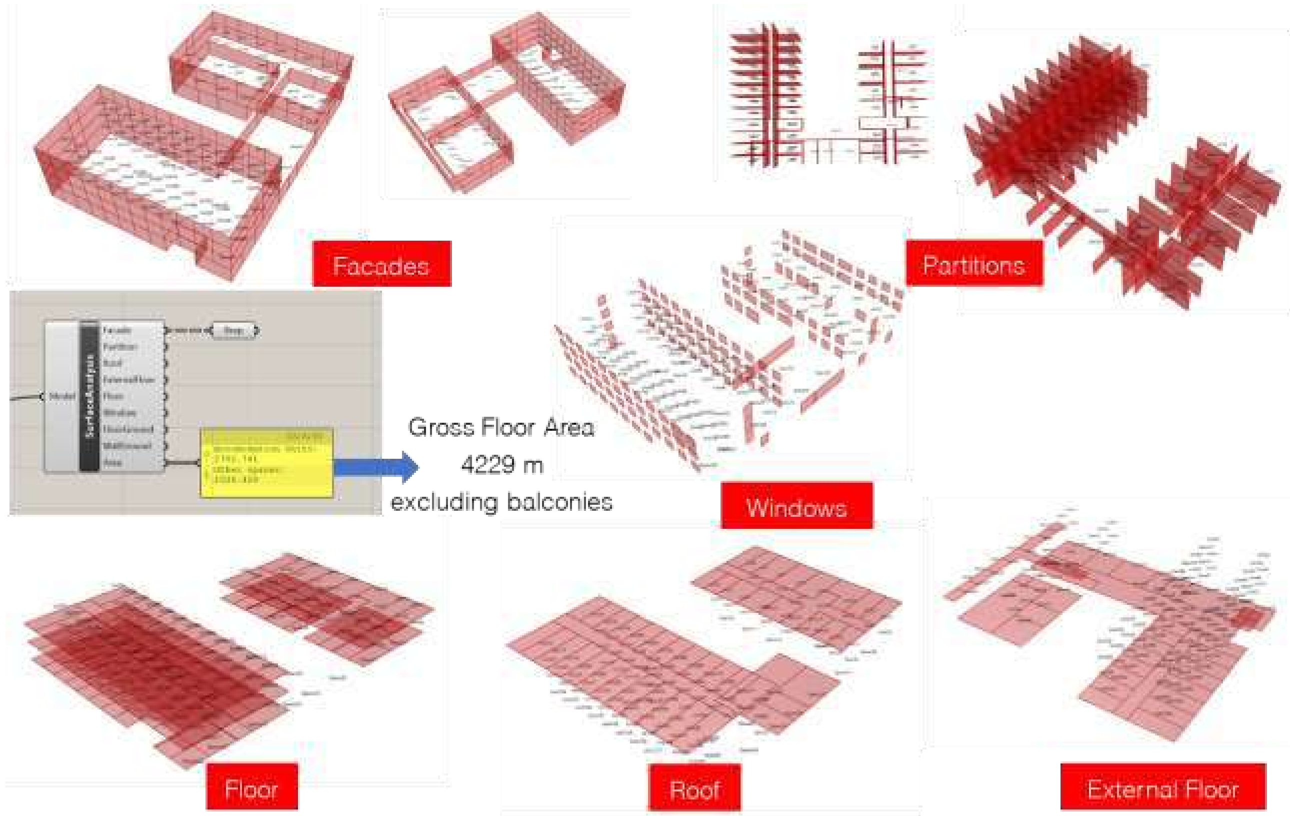


Figure 5. 144: Analysis of surfaces of the Energy Model.

The surfaces were recognized correctly in the model with naming based on the assigned thermal zone.

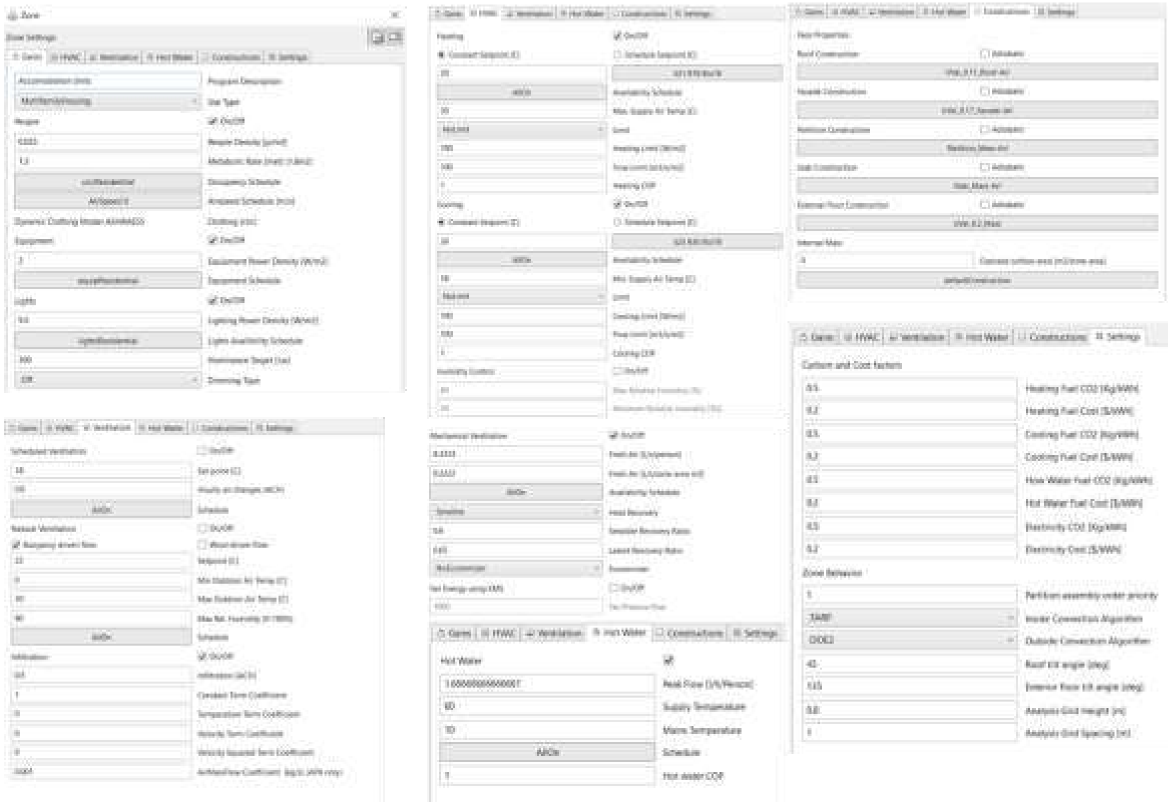


Figure 5. 145: Input data for Accommodation units Thermal Zones for Energy Plus.

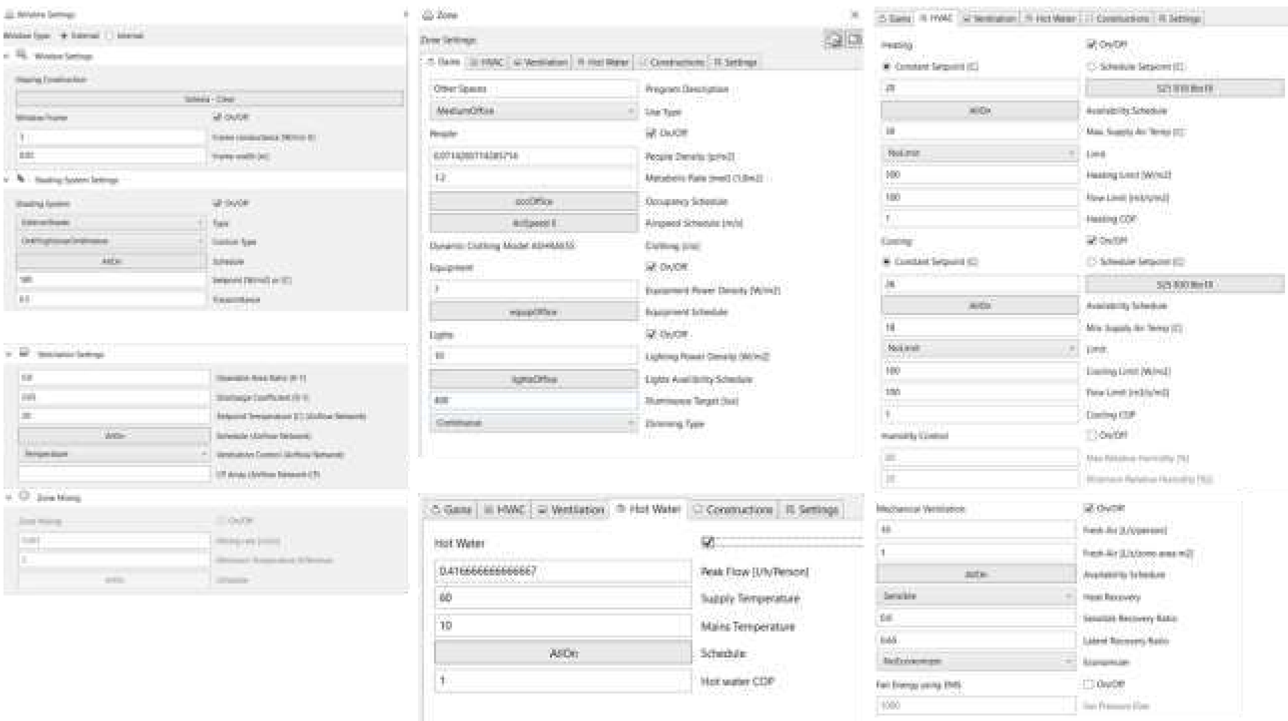


Figure 5. 146: Input data for the Other spaces Thermal Zones for Energy Plus.

An office template is used and adapted to reflect the approximate occupancy and other requirements for the facility. The templates used as a starting point are from the library of Climate Studio. The templates used are compliant with the SIA Merkblatt 2024: Standard conditions of use for energy and building technology of the Swiss Association of Engineers and Architects (SIA).

Figure 5. 147: Construction elements created with Climate Studio libraries.

The construction elements are modelled according to the Gerbiceva project's materials and thicknesses. In a heating-dominant climate such as Ljubljana, glazing with a balance between a low U-value and high Solar Heat Gain coefficient of 0.505 is selected to provide for insulation and solar gains in the winter months.

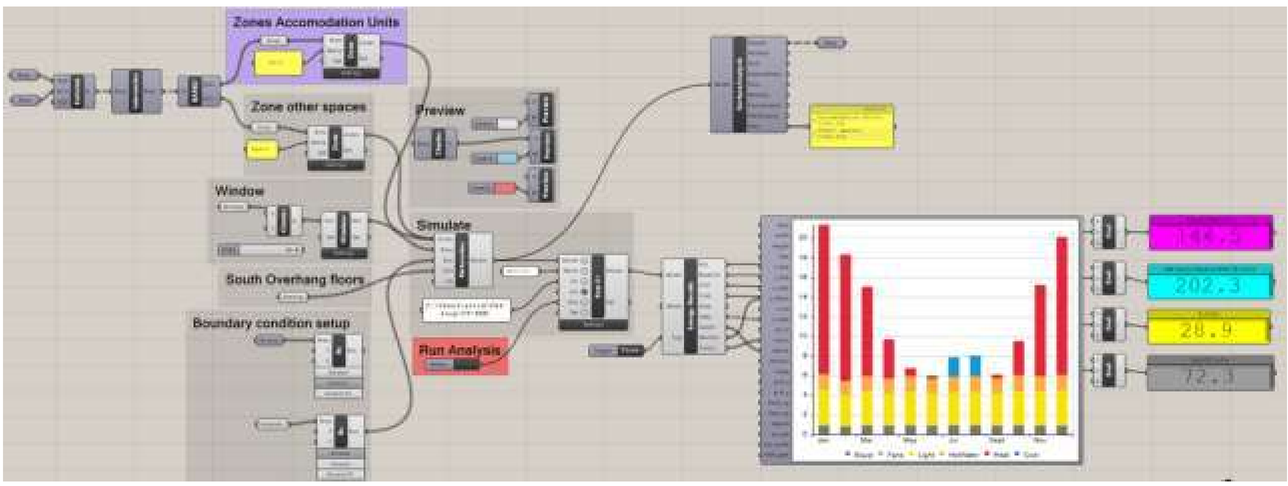


Figure 5. 148: Climate Studio in Grasshopper algorithm for Energy simulation.

The Baseline simulation uses standard template inputs approximated for the project and Office occupancy for the other spaces.

The total emissions, life cycle GWP normalized and social cost of carbon calculated are the following:

Total emissions for scope calculated

15 287 Tons CO2e

Total CO2/GFA/Period

72.3 kg CO2e / m2 / year

50€/ton CO2

764350 € Social cost of carbon

Figure 5. 149: Baseline's Energy Use Intensity (left) and Total Energy use (right) charts.

The highest energy demand comes from heating, followed by lighting, hot water, equipment and cooling.

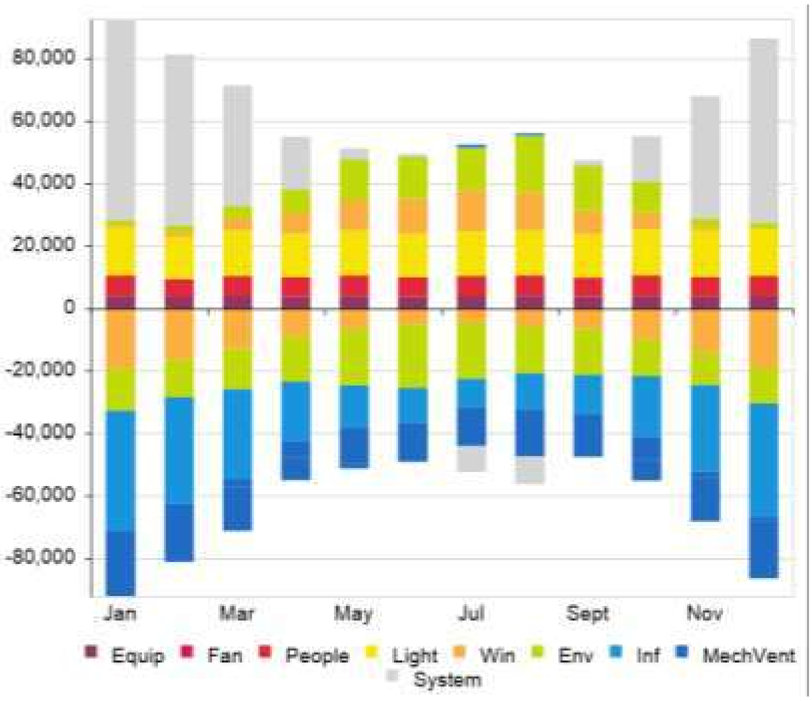


Figure 5. 150: Baseline's Energy balance chart.

The Energy balance provides additional insights on the energy flows of the design. In January there is heat loss from mechanical ventilation and infiltration (even with a moderate value of 0.5). Then, energy is lost through the envelope and more through the windows, in our case, given the compact shape and low U-value of units, the heat loss by windows becomes more relevant. The heat gains from equipment and people are constant throughout the year. In Winter the heat balance of windows is negative and in the other months the losses decrease, and solar gains increase, towards reaching unwanted solar gains in the summer months. The system provides the remaining load for the heat balance equation through Heating in winter and cooling in summer.

An improved design option with energy-efficient measures of air-tightness, efficient lighting, equipment and realistically lower occupancy for the Other spaces is input into the Thermal Zones settings for a second simulation.

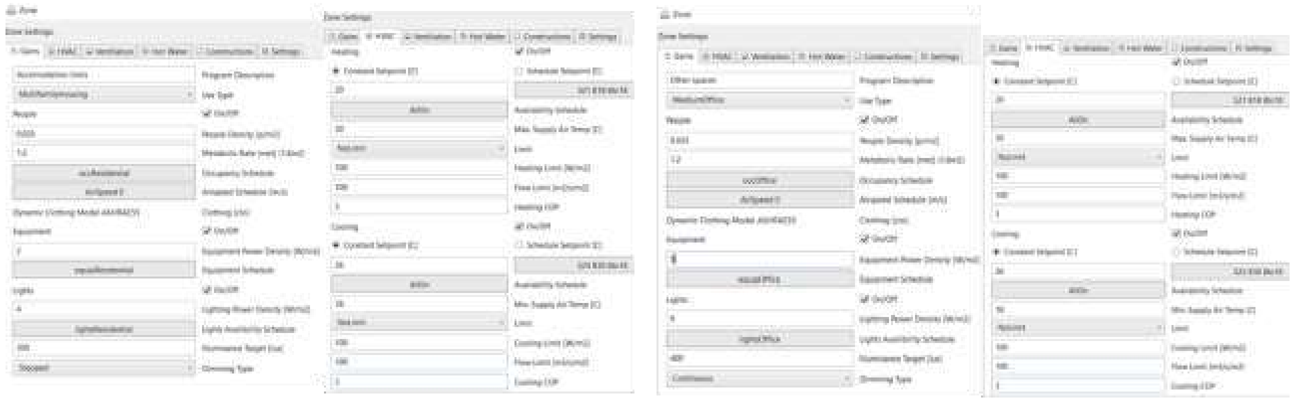


Figure 5. 151: Adapted input data for Thermal Zones for Energy-Efficient building.

The adapted input data takes into consideration real project data for Gerbiceva and from the insights provided from the Baseline's energy balance to reduce the operational energy demand of the design.

The total emissions, life cycle GWP and social cost of carbon calculated for the Energy-Efficient Design are:

Total emissions for scope calculated
6449 Tons CO2e

Total CO2/GFA/Period
30.5 kg CO2e / m2 / year

50€/ton CO2
322 450 € Social cost of carbon

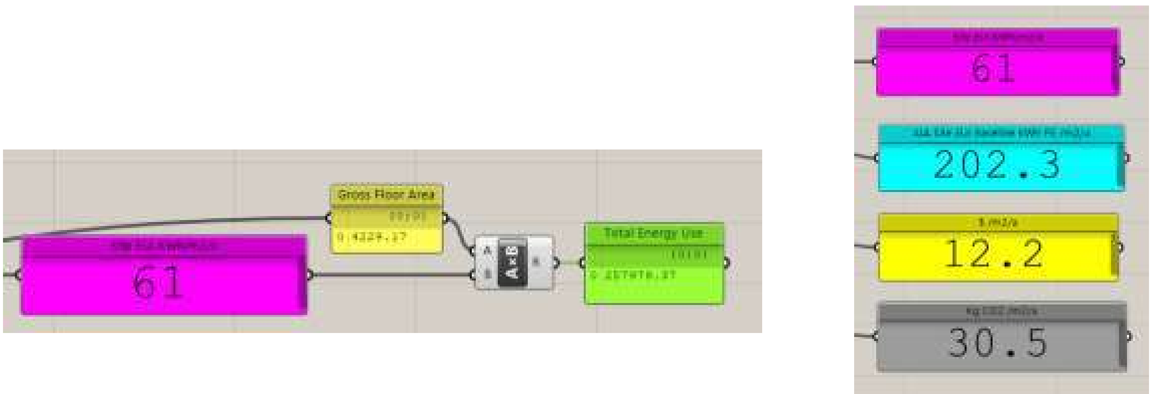


Figure 5. 152: Energy Efficient Design results normalized and Total Energy use output.

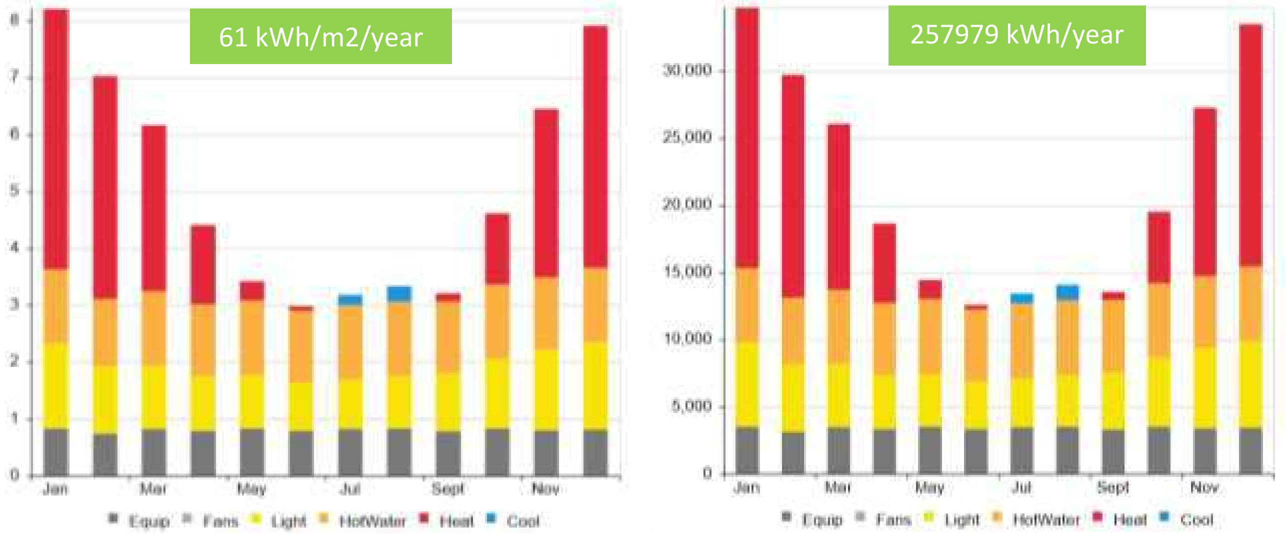


Figure 5. 153: Energy Efficient Design EUI (left) and Total Energy use (right) charts.

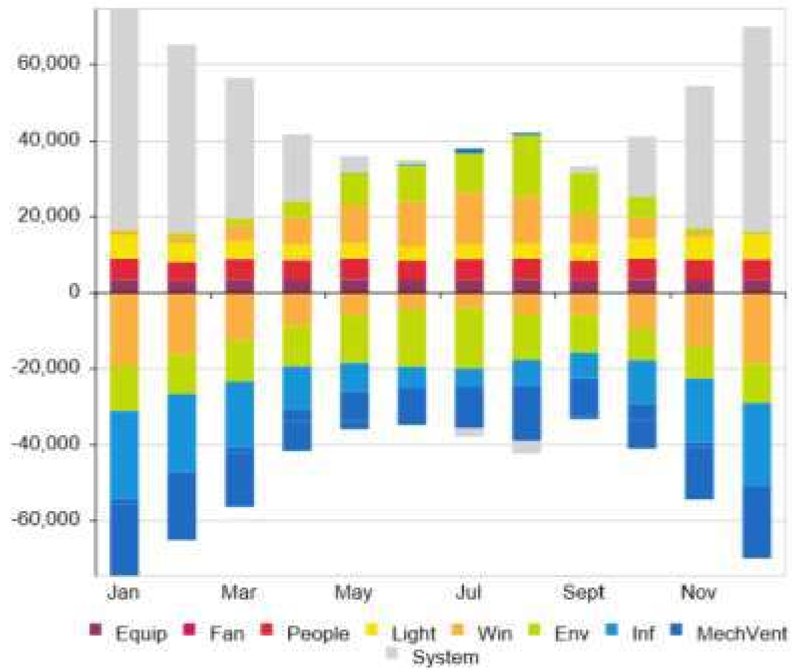


Figure 5. 154: Energy balance of Energy-Efficient Building design option.

The Energy-efficient design option with air-tight windows, energy-efficient lighting, heat recovery of sensible heat and highly efficient HVAC heat pump system reduces by more than half the energy demand compared to the Baseline created previously. When reducing high impact energy loads, such as mechanical ventilation, infiltration in our case, the contribution of every factor becomes relevant to optimize the design of low energy buildings.

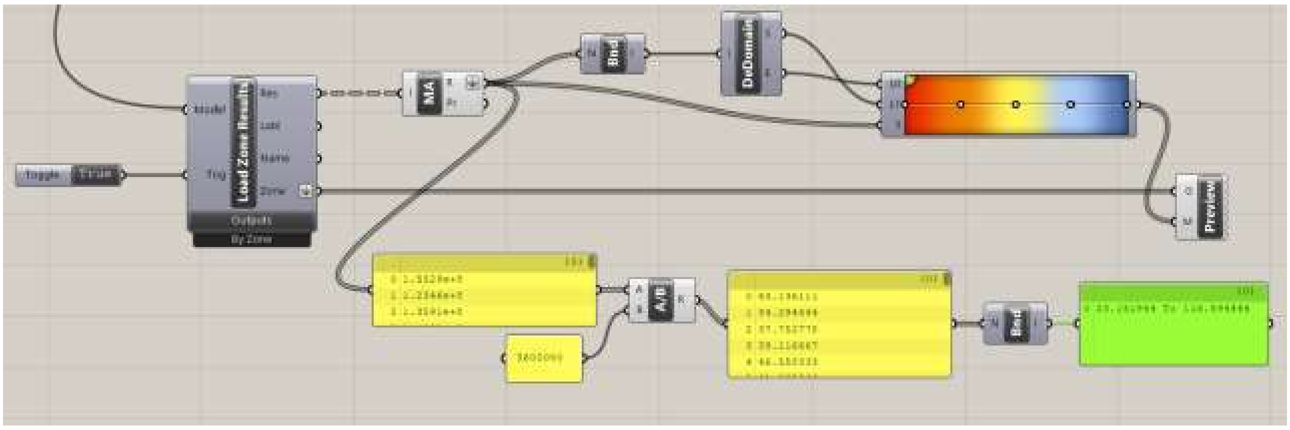


Figure 5. 155: Additional code to visualize results with a colour map on thermal zones.

The Load Zone Results and its related nodes to apply a colour map and identify the ranges of the most energy-demanding thermal zones per category are used.

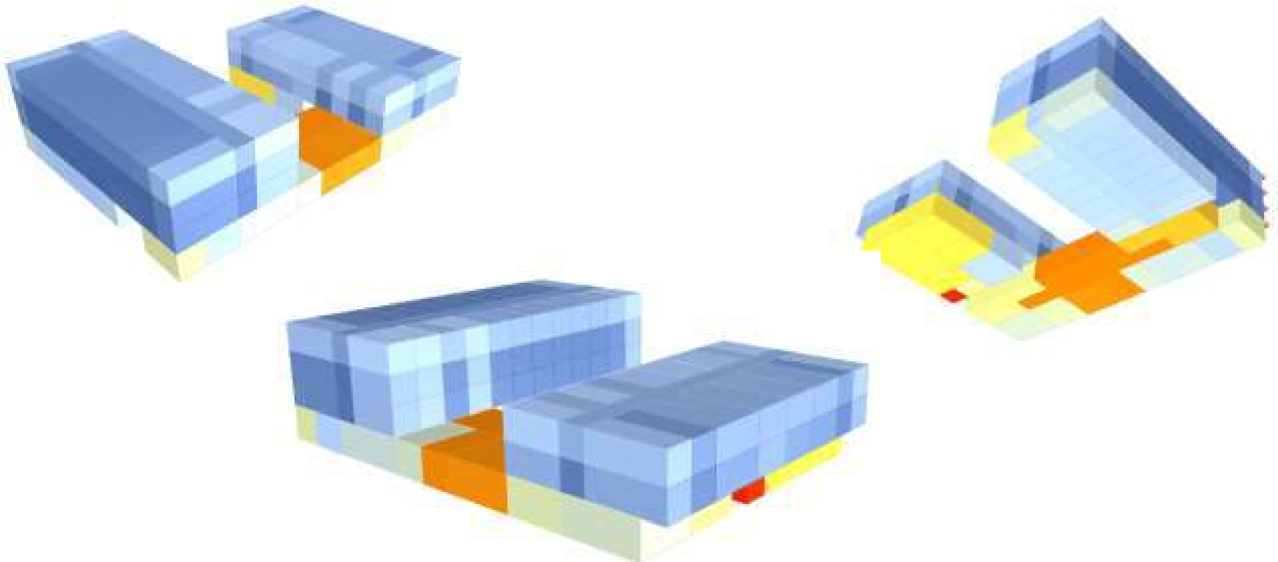


Figure 5. 156: Energy Heating Load normalized per floor area with a colour map.

The visualized colour results on the thermal zones give insight on the correct setup of the simulation. The first and second floor west facing units of the West Wing have a darker blue colour and have lower demand than their relatives of the third floor, which lose more heat through the roof. These west facing unit have one facade face and adiabatic partitions and floors. The Ground Floor space is coloured orange due to the higher energy demand and higher window to wall ratio. The East Wing ground floor space has a yellow colour, which accounts for their type of thermal zone, WWR, low solar gains and daylight availability from the overhang and inner courtyard. The small red coloured space is the buffer entrance zone with a glazed surface. The range of Heating load for the whole building thermal zones is from **23 to 117 kWh/m²/year**. The Gerbiceva Energy report predicted load for units ranges from **18.95 – 27 kWh/m2/year** only for the accommodation units which is close to the results obtained with the Building Energy Model.

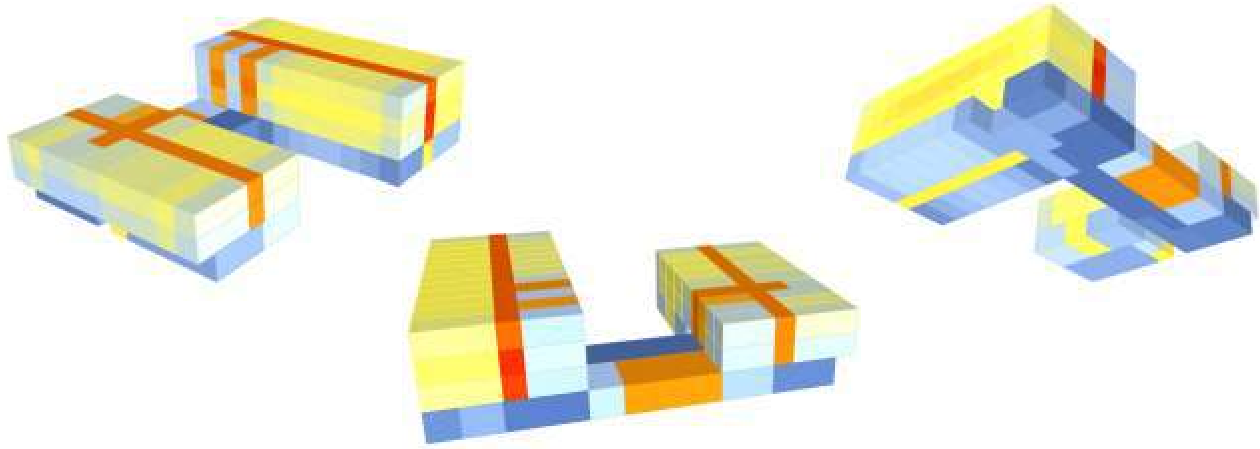


Figure 5. 157: Energy Cooling Load normalized per floor area with a colour map.

The building's tilt of 11° towards the south and its relation to energy load can be hinted in these results. The west-facing zones have a slightly stronger yellow to orange colour compared to the East facing ones due to the higher direct sun exposure and cooling needed. The distribution corridors have a high cooling load, which could be linked to their relative small losses through the Envelope, low infiltration coming from the two south and north surfaces and internal gains from lighting. Accommodation units on the ground floor have lower demand than their peers due to receiving less direct radiation. The Ground Floor north space is the one with the lowest load. The cooling load range is from 12 to 24 kWh/m^2/year.

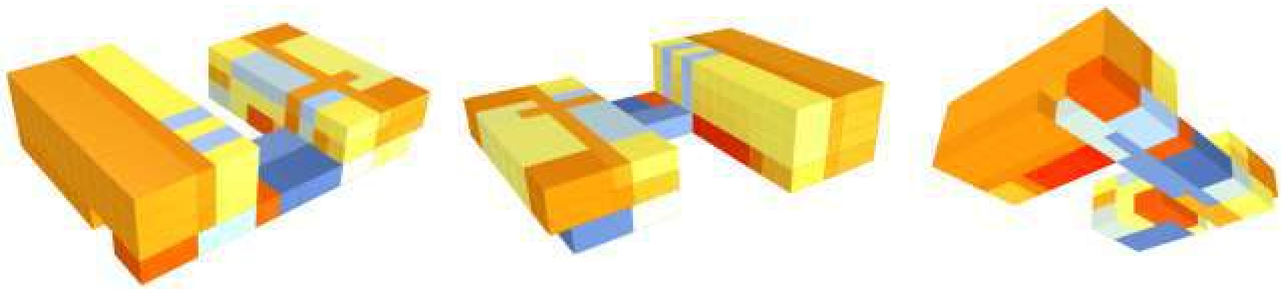


Figure 5. 158: Lighting + Equipment Load normalized per floor area with colour.

The west units have a higher load for Lighting compared to east units in the west wing, which can be attributed to the larger floor area, same windows size and lower sDA values from previous simulations. The west unit of the right-wing, which had the highest Daylight Availability have also a lower load compared to all other units. The ground floor areas which had the lowest DF values with Velux Daylight Visualizer, are coloured red with the highest need for artificial lighting throughout the year. The ground floor north and south zones which are fully glazed, with high sDA, have the lowest load compared to the whole building. The range of Electricity + Equipment load found is from 15 to 30 kWh/m^2/year.

Table 5. 27: Comparison of EUI, Energy Cost, Life cycle GWP with BEM for Baseline, Energy-Efficient Design Option, and Gerbiceva Energy report.

Energy Modelling workflow	Site EUI kWh/m2/yr	Energy Cost index €/m^2/year	Life cycle GWP $kgCO_2eq/m^2$/year	Total Energy Use kWh
Revit BEM	89.4	8.79	-	378072.5
Climate Studio-Energy+ Baseline	144.5	28.9	72.3	611090.5
Climate Studio-Energy+ Energy Efficient Buiding Design Option	61	12.2	30.5	257969
Gerbiceva Project Energy Report	74	-	41*	312658

*The Operational Carbon is estimated by the Energy report at 35 $kgCO_2eq/m^2$/year. The Upfront Embodied carbon for the purpose of the Whole Life Carbon calculation for the Gerbiceva project (or Life Cycle GWP as denominated by the EU Level(s) framework) is calculated from the mean value of LCA results of the Baseline and Optimized Design at 6 $kgCO_2e/m^2$/year. The Whole Life Carbon for the Gerbiceva project Energy report for the comparison with BIM integrated LCA is estimated at 41 $kgCO_2e/m^2$/year.

The BEM results of the Energy-Efficient Building compared to the actual detailed Gerbiceva Energy report are within an acceptable range with a difference of 17%. Given the high amount of data needed to input for an Energy model, calculation methodology and related differences that exist when using a BEM simulation with Energy Plus and the calculations following regulations for Ljubljana region, the results are reliable.

5.14 Life Cycle Assessment

The Environmental Performance of buildings through Life Cycle Assessment is an essential Sustainable Design approach towards a low carbon built environment. Non-integrated approach to LCA would require much time and in-depth specialist knowledge for calculation according to the standards. The object-oriented modelling in a BIM environment provides an opportunity to improve the LCA approach for building design, through automatic Quantity Take-Off, linking BIM objects (construction category and material) with EPD databases of LCA tools. The parametric and object-oriented BIM capabilities with LCA tools integration can be explored since the early design stage of buildings where the flexibility to make changes is higher to design low carbon structures.

Even though LCA is a standardized methodology, there is no performance target set by regulations at the city or national levels. For instance, Passive House and Nearly Zero Energy Buildings have clear targets defined in national and European directives. The reference study period of LCA is not standardized. Should a building be accounted to last for 50 years, 100 years, or following a national benchmark? It can be hard to predict with precision the life cycle of a building. The uncertainty of data and harmonization of approaches remains a challenge.

LCA should be used as a tool to inform design decisions and explore design options. The goal should not be to predict precisely the Embodied Carbon but rather reduce its environmental impacts. Buildings can last longer than the design intent. In other cases, they do not last because of degradation, low quality, disaster-related events such as earthquakes and floods, or housing programs that turned into bad neighbourhoods.

A significant challenge for future development is the semantic linking of the BIM model in native format or IFC with the LCA tools. LCA integrations can produce errors when reading volume or surface areas from BIM Models. Wrong data can have a significant impact on LCA results. The process remains semi-automated as there is a need from the modeller to check the quality of input data and find the equivalent material in the EPD database. How the model is created can have a high impact on the LCA translation of the data. A fully automated LCA integration is not yet possible.

IFC is the standard for drawing exchange in the construction industry. In many cases, the project exported to IFC for information exchange and analysis with teams or external consultants. In this exchange of information, errors occur in the export into IFC format. Even when read back into the design authoring tool that produced the model, components are not read with the same categories defined in a proprietary format. The Interoperability between Design Authoring and LCA applications requires further improvement. The exchange of BIM Models in IFC and their use for analysis remains a challenge to be improved by software in three directions a) export quality of the model (Information Delivery Manuals and Model View Definitions) b) import quality (reading IFC files) c) semantic linking BIM – LCA.

Tally is a plugin for Revit software, developed by Kieran Timberlake and PE International that allows designers to perform whole-building LCA and compare Revit design options. The Tally analysis accounts for the full cradle-to-grave life cycle, according to EN 15978. It can perform LCA calculations with Biogenic Carbon or excluding biogenic carbon from final results.

One Click LCA (2015), developed by Bionova, is an LCA and LCC (life cycle costing) software that allows users to perform whole building LCA and to earn certification credits for a range of systems (e.g. BREEAM, LEED)[64]. It features many integrations and plugins supporting native proprietary BIM Models and OpenBIM workflows through IFC and BIM Management tools.

One Click LCA provides access in its database to manufacturer EPDs or generic construction materials of the country. The use of generic databases for LCA is relevant for Public Authorities such as the Housing Fund of the Republic of Slovenia that needs to use Generic material information for some of the design stages. The manufacturer product has to be defined at a separate stage of the public tendering process. LCA Model Use can be requested to be performed for design by the Lead Appointed Party and included in the BIM Execution Plan as LCA Model use.

[64] One Click LCA (2015). Helsinki: Bionova Ltd. https://www.oneclicklca.com

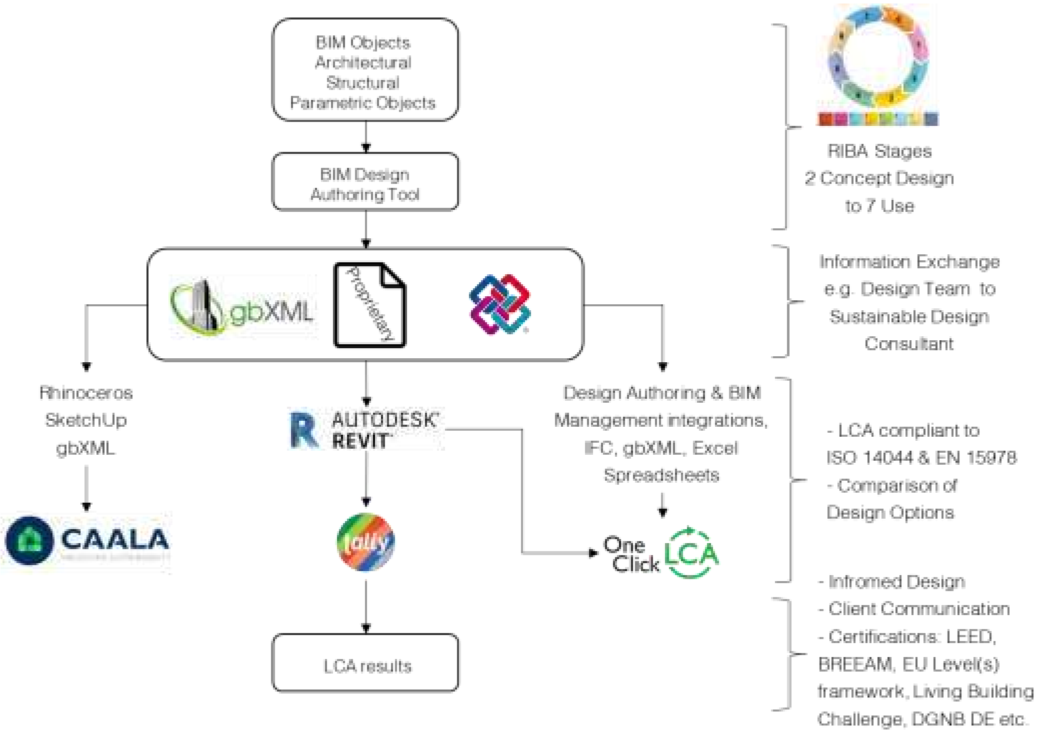


Figure 5. 159: BIM integrated LCA workflow interoperability.

The process starts in the Design Authoring tool, where BIM Objects are created, and a parametric approach to the Design can be used to explore alternatives. In case the LCA is to be performed within the design team, proprietary files can be used with direct integration of LCA tools as plugins such as Tally with Revit or gbXML for CAALA. In the scenario where another team or consultant is appointed to perform the LCA, an OpenBIM workflow needs to be established. IFC, gbXML or Excel Spreadsheets can be used for the Information Exchange with the selected LCA tool to be used. One Click LCA (2015) provides a broad range of integrations with BIM Design Authoring and BIM Management tools and supports OpenBIM workflows via IFC. It also supports integrations with Energy Modelling tools via gbXML integrations. The LCA process and results can be used to Inform Design Decisions and communicate with the Client during Design Development. If requested by the Client, the LCA results can be used for Sustainable Building Certifications such as BREEAM, LEED, EU Level(s) framework, Living Building Challenge or DGNB DE.

5.14.1 *Life Cycle Assessment with One Click LCA Carbon Designer*

Carbon Designer is an add-on to One Click LCA software for early-stage design and baseline generation for project and certifications such as LEED. It requires general information on building shape and size of early design stage where a Building Information Model would not have sufficient Level of Information Need for a whole building LCA. The tool can be used to study concepts, design alternatives and set targets for carbon reduction. Building parameters and construction types data are used as input to generate the conceptual carbon footprint of the design. The Carbon Designer approach uses benchmarks and average values of embodied carbon of building components for the input and calculations for the scope of concept design.

Figure 5. 160: One Click LCA (2015) Carbon Designer input data for Gerbiceva project.

The baseline design created has an Embodied Carbon Benchmark of 340 kgCO_2eq/m^2. The Carbon Designer's database of building elements and materials for calculating the carbon emissions for the design can be used to substitute the materials to reduce carbon emissions. The window frames, roof slabs and the concrete columns have been substituted with wood-based materials. The regular concrete slab has been substituted with a bubble deck assembly. The minor changes to the design achieve an 11% reduction of carbon. The LEED v4.1 Building Life Cycle Impact Reduction credit Option 4: whole-building life-cycle assessment (3 points) requires a 10% reduction in at least three of six impact categories. The Carbon Designer tool can guide in setting targets to be achieved for Sustainable Building Certifications, e.g. LEED credits at the following stages of design and whole-building LCA.

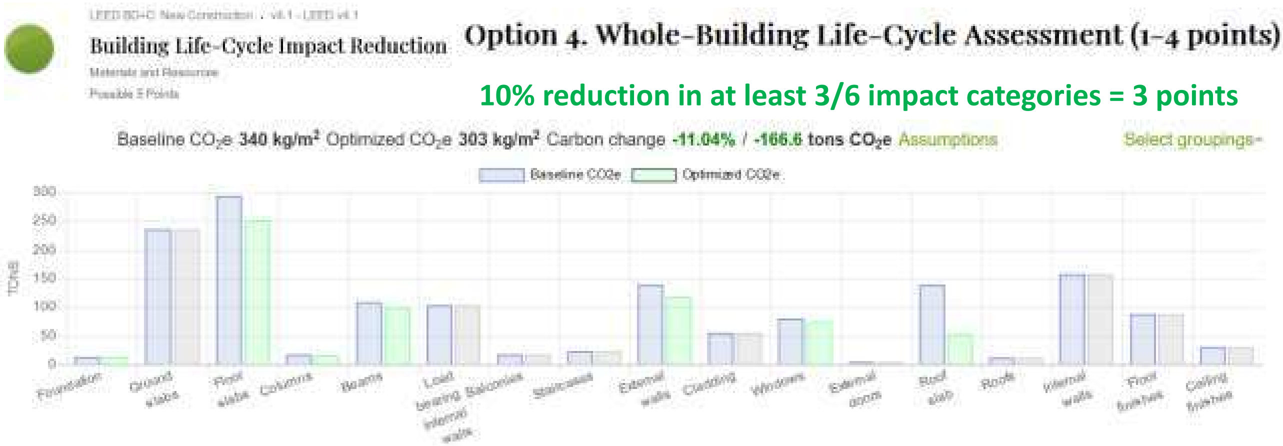


Figure 5. 161: Baseline & Optimized Design comparison by construction group. LEED v4.1 Building Life-Cycle Impact Reduction target.

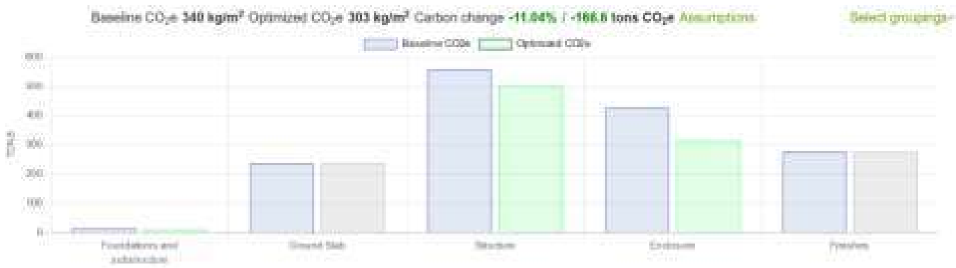


Figure 5. 162: Baseline & Optimized Design comparison by building elements

Figure 5. 163: Baseline & Optimized Design comparison by total embodied carbon

Figure 5. 164: Carbon Designer building elements and material input data.

The baseline and Optimized Design impacts of building elements can be compared and give insights into the reduction of the carbon footprint and share of each element. The baseline design has a carbon footprint of 1509 tons CO_2eq, while the optimized design has an 11% reduction at 1343 tons CO_2eq.

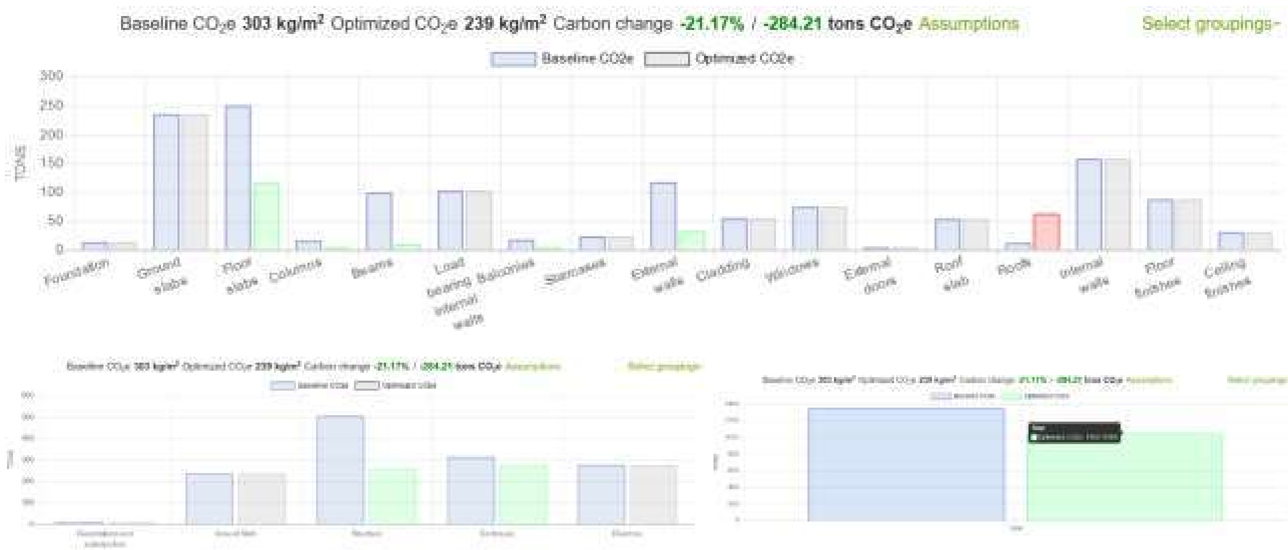


Figure 5. 165: Carbon Designer scenario of Wood building design with Baseline comparison.

A Wood design would result in an average carbon footprint reduction of 20% compared to a concrete one.

Figure 5. 166: Carbon Designer scenario of Steel building design with Baseline comparison.

A steel construction building would account for almost 10% more carbon than a concrete design. The results of Carbon Designer can be added in the input data of Whole-building LCA when certain elements may be missing from the Model, e.g. when the Architectural Model provided for LCA calculations does not feature foundations. The results of Carbon Designer can be used to account for the missing data.

5.14.2 *Whole-building life cycle assessment with One Click LCA*

One Click LCA (2015) plugin integration with Revit 2020 is used to quantify building elements and assign materials from the broad database of the tool. Where possible, generic materials for Slovenia are used for LCA calculation. When generic material data was not available, the materials of Slovenian manufacturer's were used. If a similar material was not available in the database for Slovenia, the closest alternative with minimal distance is used such as Generic materials from Italy, Austria, ÖKOBAUDAT (standardized database of the Federal Ministry of the Interior, Building and Community in Germany) were used.

Gerbiceva Project Baseline LCA

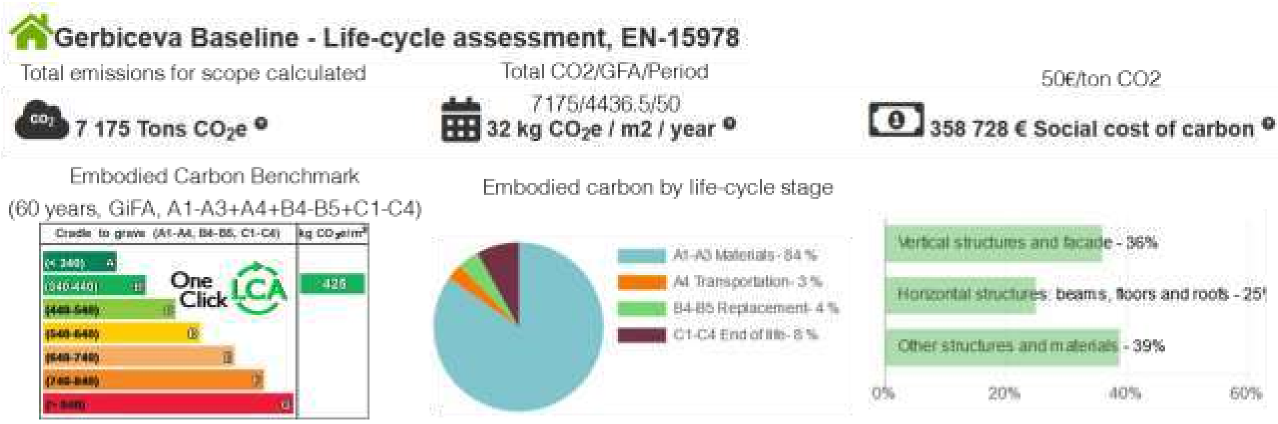


Figure 5. 167: Gerbiceva project LCA summary of results.

	Result category	Global warming kg CO2e	Acidification kg SO2e	Eutrophication kg PO4e	Ozone depletion potential kg CFC11e	Formation of ozone of lower atmosphere kg Ethenee	Total use of primary energy ex. raw materials MJ	
A1-A3	Construction Materials	1 595 743,53	4 052,6	527,36	0,2	473,61	11 673 607,72	Details
A4	Transportation to site	65 175,67	126,59	26,46	0,01	8,84	1 124 580,78	Details
A5	Construction/installation process							Hide empty
B1-B5	Maintenance and material replacement	66 247,5	140,93	21,69	0	16,74	1 148 264,25	Details
B6	Energy use	5 237 590,4	20 686,11	2 401,12	0,54	1 159,61	99 355 455,81	Details
B7	Water use	61 500	333,01	168,47	0,01	14,98	1 300 206,99	Details
C1-C4	Deconstruction	148 312,56	368,76	97,35	0,02	12,06	2 834 606,68	Details
D	External impacts (not included in totals)	−275 529,99	−553,62	−185,67	−0,01	−33,37	−1 702 307,79	Details
	Total	**7 174 569,67**	**25 739**	**3 242,47**	**0,78**	**1 686,05**	**117 637 014,22**	
	Results per denominator							
	Gross Internal Floor Area (IPMS/RICS) 4436,5 m2	1 617,17	5,8	0,73	0	0,38	26 515,73	

Figure 5. 168: LCA results per Life-cycle stages and total values.

One Click LCA (2015) features a completeness and plausibility checker review of the input data. The data of the project was within acceptable ranges of the checker of the tool.

No.	Resource	Cradle to gate impacts (A1-A3)	Of cradle to gate (A1-A3)	Sustainable alternatives
1.	Ready-mix concrete, normal-strength, generic ?	528 tons CO_2e	33.1 %	show sustainable alternatives
2.	Precast concrete wall elements (solid, uninsulated), generic ?	447 tons CO_2e	28.0 %	show sustainable alternatives
3.	Ready-mix concrete, normal-strength, generic ?	263 tons CO_2e	16.5 %	show sustainable alternatives
4.	XPS insulation board ?	92 tons CO_2e	5.8 %	show sustainable alternatives
5.	Ready-mix concrete, low-strength, generic ?	48 tons CO_2e	3.0 %	show sustainable alternatives
6.	Vitreous stoneware tiles for floors and walls ?	34 tons CO_2e	2.1 %	show sustainable alternatives
7.	Transparent board PVC ?	27 tons CO_2e	1.7 %	show sustainable alternatives
8.	Insulated glazing, double pane ?	25 tons CO_2e	1.6 %	show sustainable alternatives
9.	Insulation, EPS ?	24 tons CO_2e	1.5 %	show sustainable alternatives
10.	Ceramic tiles, glazed ?	18 tons CO_2e	1.1 %	show sustainable alternatives
11.	EPS insulation panel ?	16 tons CO_2e	1.0 %	show sustainable alternatives
12.	Plaster mortar - normal plaster / high grade plaster with special properties ?	11 tons CO_2e	0.7 %	show sustainable alternatives
13.	Glass façade , per m2 ?	9.1 tons CO_2e	0.6 %	show sustainable alternatives
14.	Plywood, generic ?	9.9 tons CO_2e	0.6 %	show sustainable alternatives
15.	Float glass, single pane, generic ?	7.3 tons CO_2e	0.5 %	show sustainable alternatives
16.	Gypsum plaster board, regular, generic ?	8.1 tons CO_2e	0.5 %	show sustainable alternatives
17.	Glass wool insulation panels, unfaced, generic ?	6 tons CO_2e	0.4 %	show sustainable alternatives
18.	Concrete masonry brick ?	5.2 tons CO_2e	0.3 %	show sustainable alternatives
19.	Extensive green roof system ?	4.6 tons CO_2e	0.3 %	show sustainable alternatives
20.	PVC waterproofing membrane ?	5.4 tons CO_2e	0.3 %	show sustainable alternatives
21.	Ceramic tiles, Italian average ?	3.2 tons CO_2e	0.2 %	show sustainable alternatives
22.	Thermally improved aluminium extrusions (profiles), mill finished ?	2.1 tons CO_2e	0.1 %	show sustainable alternatives
23.	Stainless steel sheet ?	0.85 tons CO_2e	0.1 %	show sustainable alternatives
24.	Mortar, pre-blended ?	0.34 tons CO_2e	0.0 %	show sustainable alternatives
25.	Vapour-proof membrane ?	0.73 tons CO_2e	0.0 %	show sustainable alternatives

Figure 5. 169: Most contributing materials (Global warming) for the Baseline Design.

The review of materials helps to understand the categories with the highest carbon impact and materials with high environmental impact.

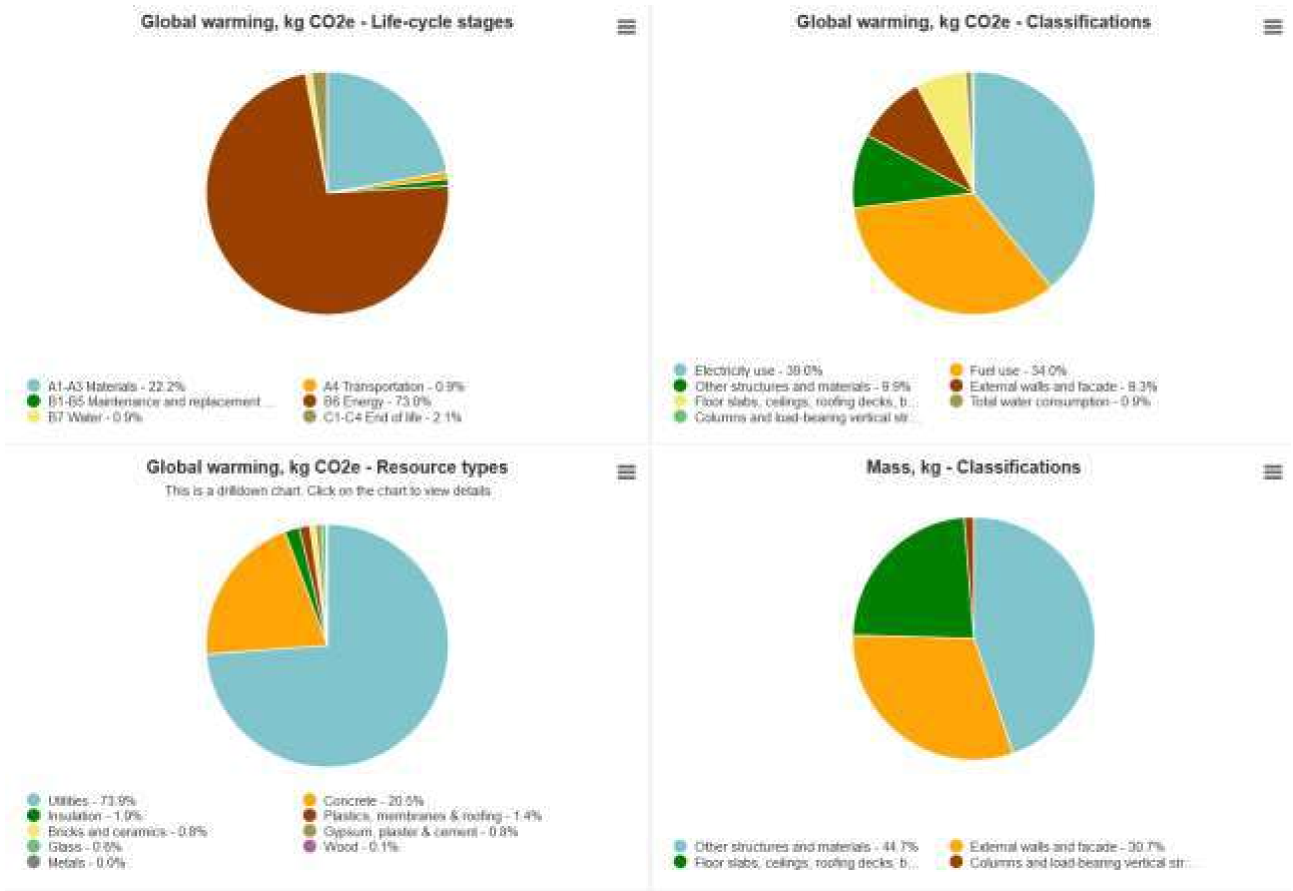


Figure 5. 170: LCA results of Global Warming Potential (GWP) for Baseline design.

The whole life-cycle of materials is responsible for 26% of GWP, while Energy consumption for a 50 years assessment accounts for 73%. Concrete is the material with the highest impact of 20.5%.

Table 5. 28: GWP by Life-Cycle stages. GWP by Resource types.

Global warming - Life-cycle stages

Item	Value	Unit	Percentage %
A1-A3 Materials	1 595 743,53	kg CO2e	22.24 %
A4 Transportation	65 175,67	kg CO2e	0.91 %
B1-B5 Maintenance and replacement	66 247,5	kg CO2e	0.92 %
B6 Energy	5 237 590,4	kg CO2e	73.0 %
B7 Water	61 500	kg CO2e	0.86 %
C1-C4 End of life	148 312,56	kg CO2e	2.07 %

Global warming - Resource types

Item	Value	Unit	Percentage %
Utilities	5 299 090,4	kg CO2e	73.86 %
Concrete	1 467 383,81	kg CO2e	20.45 %
Insulation	138 982,09	kg CO2e	1.94 %
Plastics, membranes & roofing	101 879,14	kg CO2e	1.42 %
Bricks and ceramics	56 541,56	kg CO2e	0.79 %
Gypsum, plaster & cement	55 379,7	kg CO2e	0.77 %
Glass	42 038,29	kg CO2e	0.59 %
Wood	10 277,83	kg CO2e	0.14 %
Metals	2 996,84	kg CO2e	0.04 %

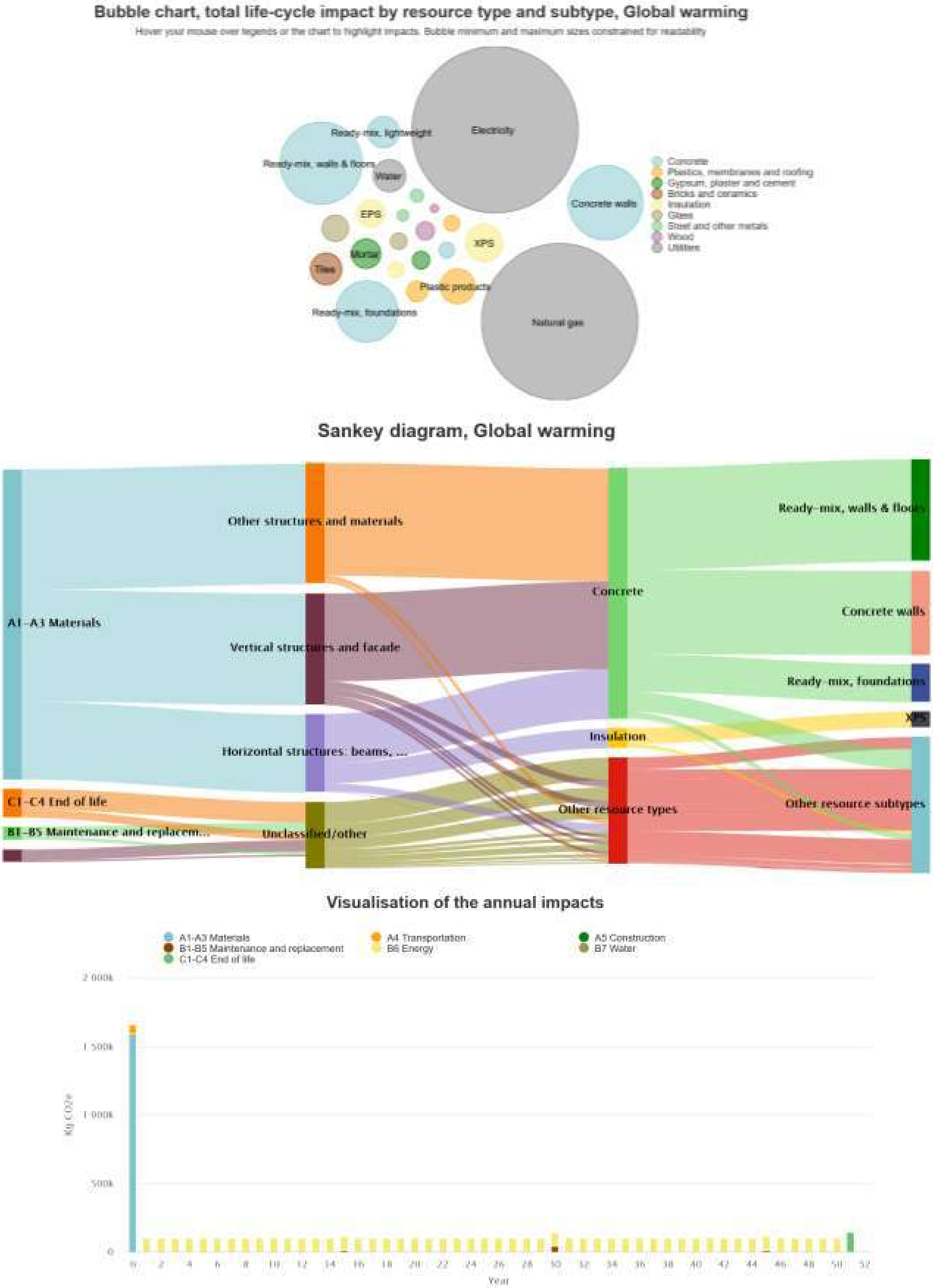


Figure 5. 171: Bubble Chart, Sankey diagram, Annual impacts chart of Life Cycle GWP.

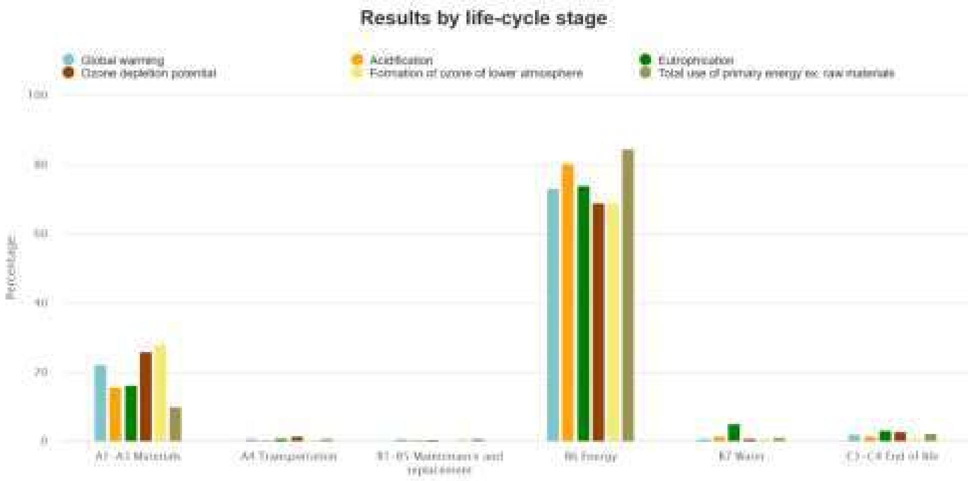


Figure 5. 172: LCA chart of results by life-cycle stage of the six impact categories.

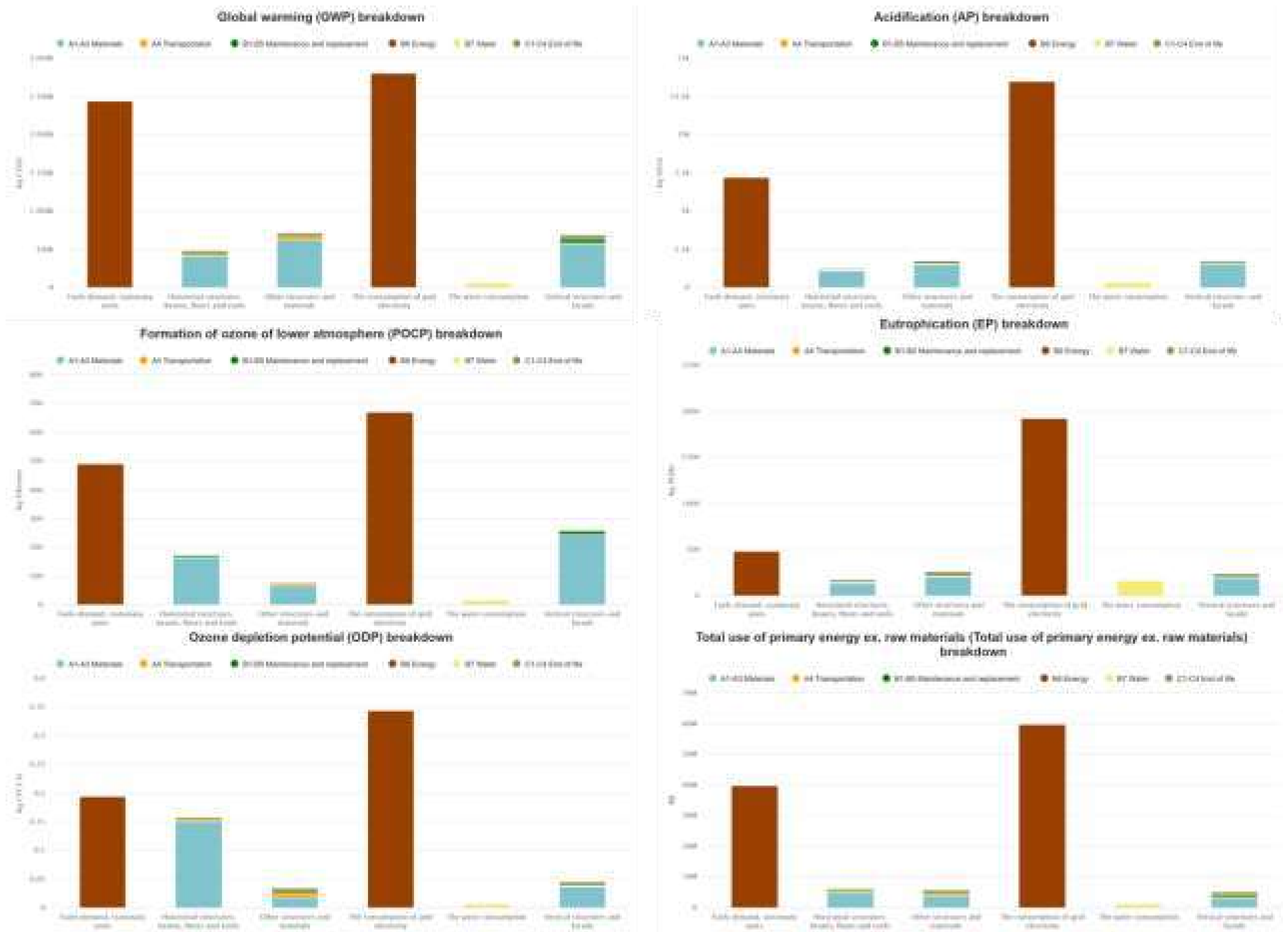


Figure 5. 173: Breakdown chart for each impact category by classifications.

B6 Electricity and Fuel demand have the highest impact on all six categories. The building components feature less noticeable differences or derivable trends from the charts by impact category that could provide insight into design decisions. The reduction of energy demand, e.g. nearly Zero Energy Buildings would result in a low carbon footprint of the design and increased relevance of Embodied Carbon.

Gerbiceva Design Option 1 LCA (optimized materials and concrete with recycled content)

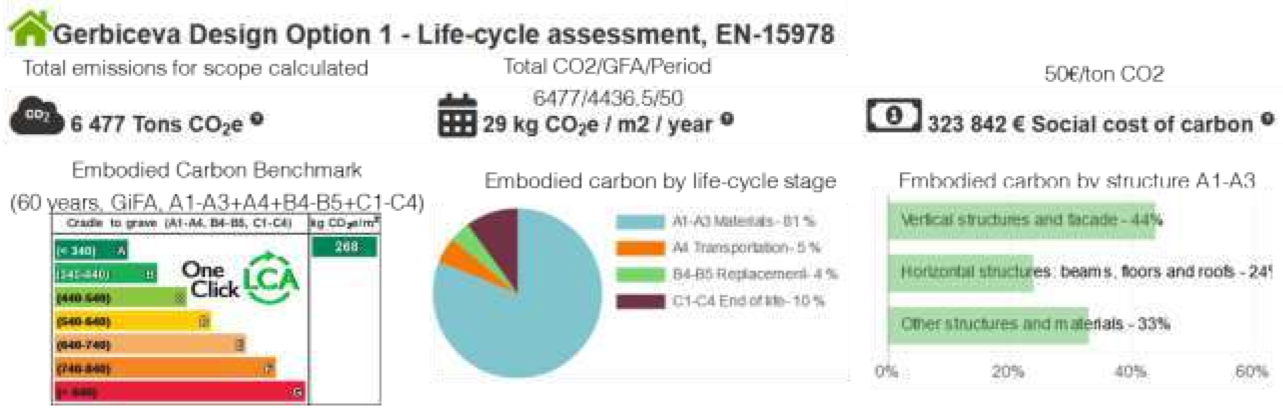


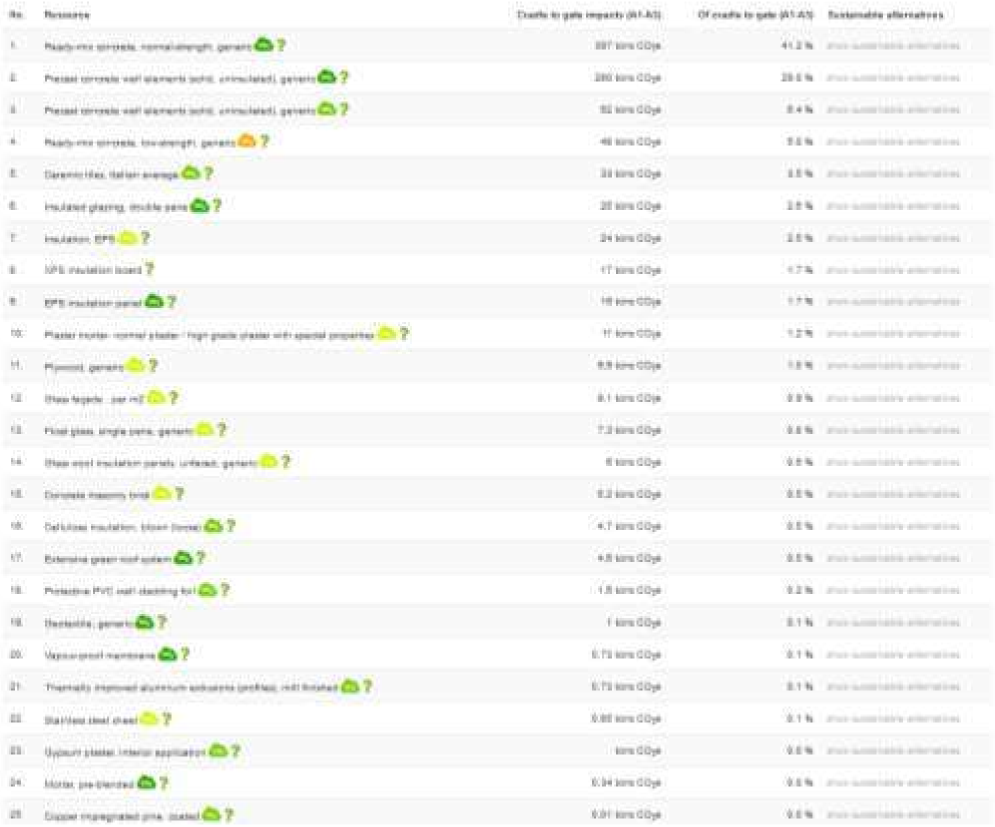
Figure 5. 174: Gerbiceva Design Option 1 (optimized materials and concrete with recycled content).

The materials with high impact have been substituted with lower impact alternatives of generic products in Slovenia or the European region. For this design option, regular concrete structures of any type have been substituted with concrete with recycled content (40% recycled binders in cement (300 kg/m^3 / 18.72 lbs/ft3). The Embodied Carbon Benchmark is reduced by 37% from the baseline and life cycle GWP by 9.7%.

	Result category	Global warming kg CO2e	Acidification kg SO2e	Eutrophication kg PO4e	Ozone depletion potential kg CFC11e	Formation of ozone of lower atmosphere kg Ethenee	Total use of primary energy ex. raw materials MJ	
A1-A3	Construction Materials	965 068,7 | -40 %	2 654,11 | -35 %	345,54 | -34 %	0,06 | -70 %	339,95 | -28 %	6 959 686,13 | -42 %	Details
A4	Transportation to site	61 962,98 | -4,9 %	120,4 | -4,9 %	25,18 | -4,9 %	0,01 | -4,9 %	8,41 | -4,9 %	1 069 363,34 | -4,9 %	Details
A5a	Site operations & site waste handling							Details
A5b	Site waste transportation							Details
A5	Construction/installation process							Details
B1-B5	Maintenance and material replacement	36 716,37 | -45 %	85,43 | -39 %	9,7 | -60 %	0 | +15 %	8,38 | -59 %	432 710,32 | -62 %	Details
B6	Energy use	5 237 590,4 | 0 %	20 686,11 | 0 %	2 401,12 | 0 %	0,54 | 0 %	1 159,01 | 0 %	99 355 456,81 | 0 %	Details
B7	Water use	61 509 | 0 %	333,01 | 0 %	168,47 | 0 %	0,01 | 0 %	14,98 | 0 %	1 300 208,99 | 0 %	Details
C1-C4	Deconstruction	114 010,65 | -23 %	369,89 | -4,9 %	98,22 | 0,8 %	0,02 | -3,6 %	10,88 | -9 %	2 712 620,53 | -4,3 %	Details
D	External impacts (not included in totals)	-239 074,82 | -13 %	-493,01 | -11 %	-167,45 | -3,8 %	-0,01 | -6,8 %	-29,14 | -11 %	-1 350 169,56 | -21 %	Details
	Total	**6 476 848,08**	**24 248,96**	**3 047,24**	**0,64**	**1 542,3**	**111 730 044,12**	
	Comparing total results with: 4 - Gerbiceva Baseline							
	4 - Gerbiceva Baseline Total	7 174 569,67	25 728	3 242,47	0,78	1 686,05	117 637 014,22	
	4 - Gerbiceva Design Option 1 compared with 4 - Gerbiceva Baseline	-9,7 %	-5,7 %	-6 %	-18 %	-8,5 %	-5 %	
	Results per denominator							
	Gross Internal Floor Area (IPMS/RICS) 4436,5 m2	1 459,9	5,47	0,69	0	0,35	25 184,28	

Figure 5. 175: LCA results per Life Cycle stages and total values for Design Option 1 with Baseline comparison in percentage.

The rich database of One Click LCA (2015) accounts for accurate building materials such as the URBANSCAPE Extensive Green Roof System found in the BIM Model. The Design Option 1 results of impact categories are sufficient to achieve LEED Building Life-Cycle Impact Reduction credits for Path 3 or 4. All A1-A3 Materials reduction is more than 20% for GWP and more than 10% in other impact areas.



No.	Resource	Cradle to gate impacts (A1-A3)	Of cradle to gate (A1-A3)	Sustainable alternatives
1.	Ready-mix concrete, normal-strength, generic ?	387 tons CO2e	41.2 %	Show sustainable alternatives
2.	Precast concrete wall elements (solid, uninsulated), generic ?	280 tons CO2e	29.8 %	Show sustainable alternatives
3.	Precast concrete wall elements (solid, uninsulated), generic ?	82 tons CO2e	8.4 %	Show sustainable alternatives
4.	Ready-mix concrete, low-strength, generic ?	49 tons CO2e	5.5 %	Show sustainable alternatives
5.	Ceramic tiles, Italian average ?	33 tons CO2e	3.5 %	Show sustainable alternatives
6.	Insulated glazing, double pane ?	25 tons CO2e	2.8 %	Show sustainable alternatives
7.	Insulation, EPS ?	24 tons CO2e	2.5 %	Show sustainable alternatives
8.	XPS insulation board ?	17 tons CO2e	1.7 %	Show sustainable alternatives
9.	EPS insulation panel ?	16 tons CO2e	1.7 %	Show sustainable alternatives
10.	Plaster mortar- normal plaster / high grade plaster with special properties ?	11 tons CO2e	1.2 %	Show sustainable alternatives
11.	Plywood, generic ?	9.9 tons CO2e	1.0 %	Show sustainable alternatives
12.	Glass façade, per m2 ?	8.1 tons CO2e	0.9 %	Show sustainable alternatives
13.	Float glass, single pane, generic ?	7.3 tons CO2e	0.8 %	Show sustainable alternatives
14.	Glass wool insulation panels, unfaced, generic ?	6 tons CO2e	0.6 %	Show sustainable alternatives
15.	Concrete masonry brick ?	5.2 tons CO2e	0.5 %	Show sustainable alternatives
16.	Cellulose insulation, blown (loose) ?	4.7 tons CO2e	0.5 %	Show sustainable alternatives
17.	Extensive green roof system ?	4.5 tons CO2e	0.5 %	Show sustainable alternatives
18.	Protective PVC wall cladding foil ?	1.8 tons CO2e	0.2 %	Show sustainable alternatives
19.	Geotextile, generic ?	1 tons CO2e	0.1 %	Show sustainable alternatives
20.	Vapour-proof membrane ?	0.73 tons CO2e	0.1 %	Show sustainable alternatives
21.	Thermally improved aluminium extrusions (profiles), mill finished ?	0.73 tons CO2e	0.1 %	Show sustainable alternatives
22.	Stainless steel sheet ?	0.65 tons CO2e	0.1 %	Show sustainable alternatives
23.	Gypsum plaster, interior application ?	[illegible] tons CO2e	0.0 %	Show sustainable alternatives
24.	Mortar, pre-blended ?	0.34 tons CO2e	0.0 %	Show sustainable alternatives
25.	Copper impregnated pine, coated ?	0.31 tons CO2e	0.0 %	Show sustainable alternatives

Figure 5. 176: Most contributing materials (Global warming) for the Design Option 1.

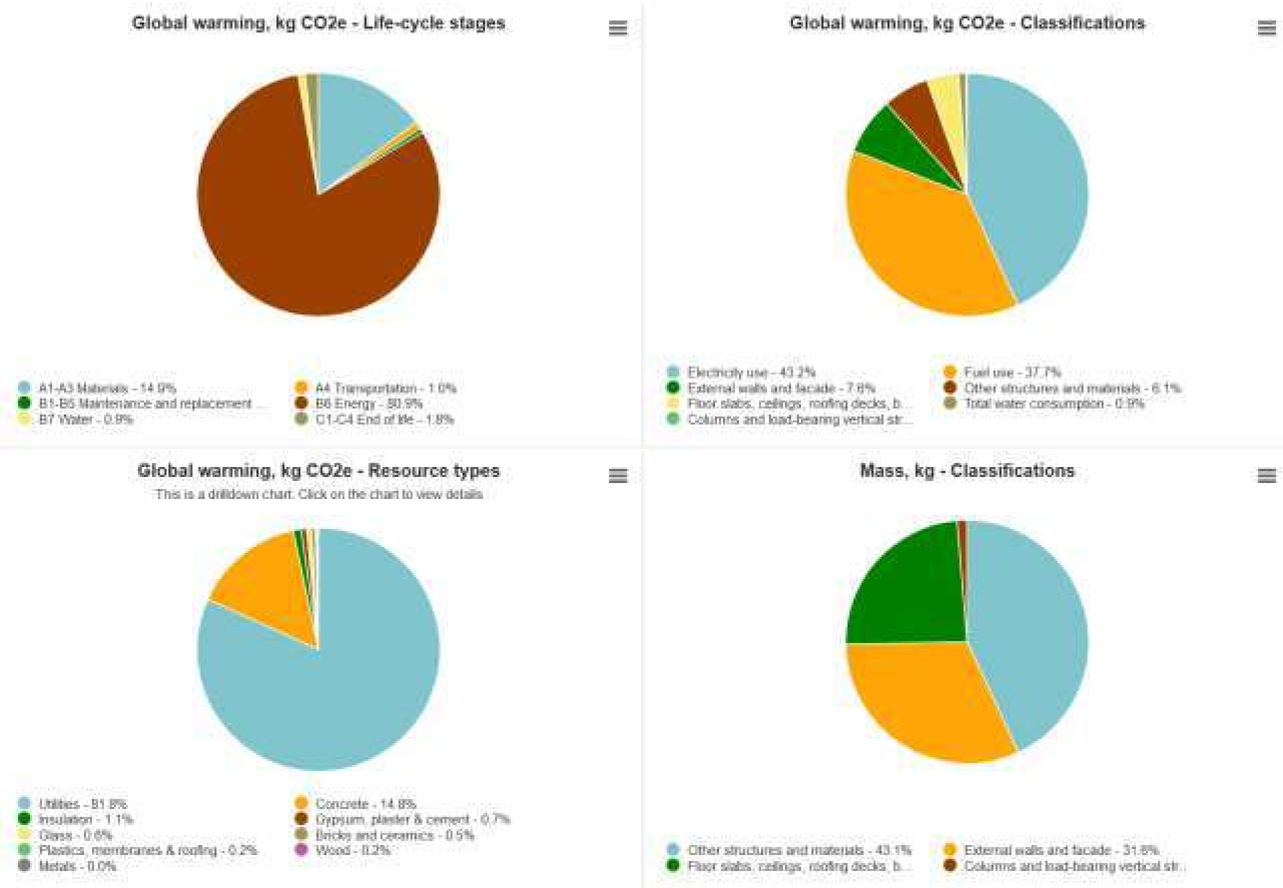


Figure 5. 177: LCA results of Global Warming Potential (GWP) for Design Option 1.

The reduced embodied carbon of materials results in a total share change from 26% of the baseline (A1-A3, A4, B1-B5, C1-C4 stages) to 18% of the Design Option 1. The energy share changes from 73 to 80.9%. The Operational Phase of the asset has the highest impacts. Optimizing design to reduce carbon should be integrated with Energy-efficient building design, bioclimatic strategies and renewable energy sources.

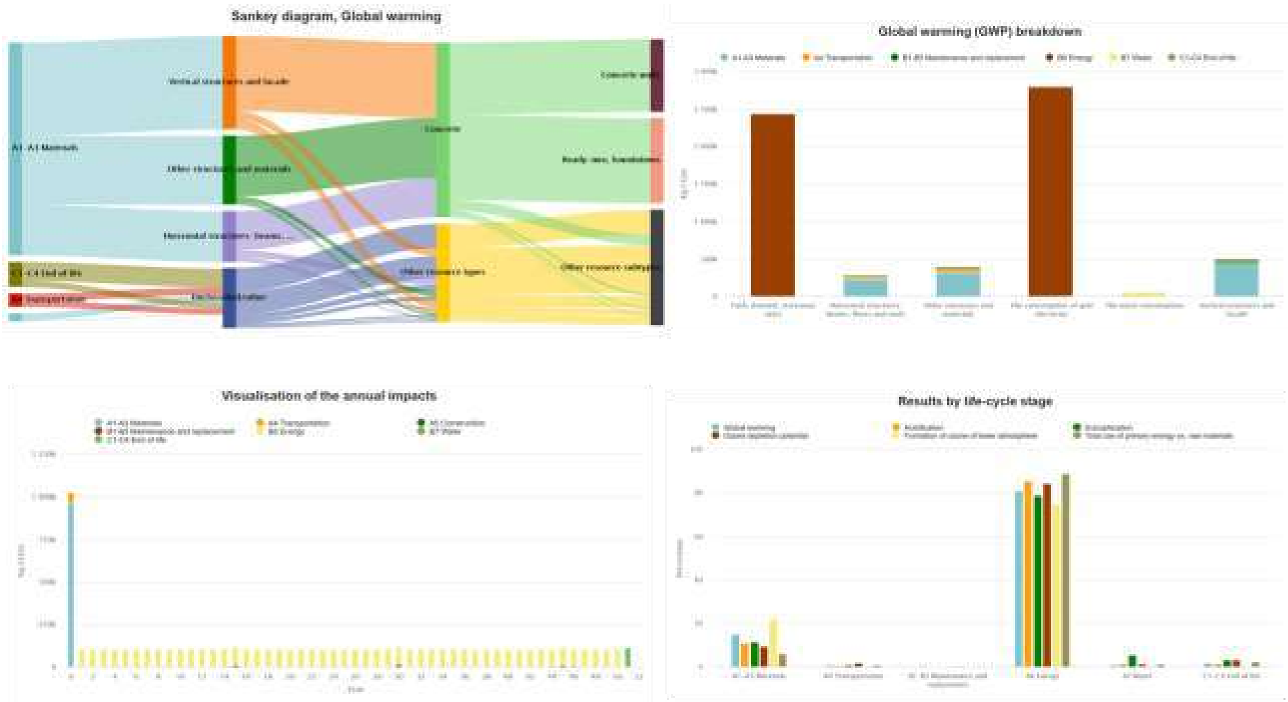


Figure 5. 178: Bubble Chart, Sankey diagram, Annual impacts chart, results by life-cycle stage of six impact categories chart of LCA for Design Option 1.

Gerbiceva Design Option 2 (CLT Wood and substitution with organic materials)

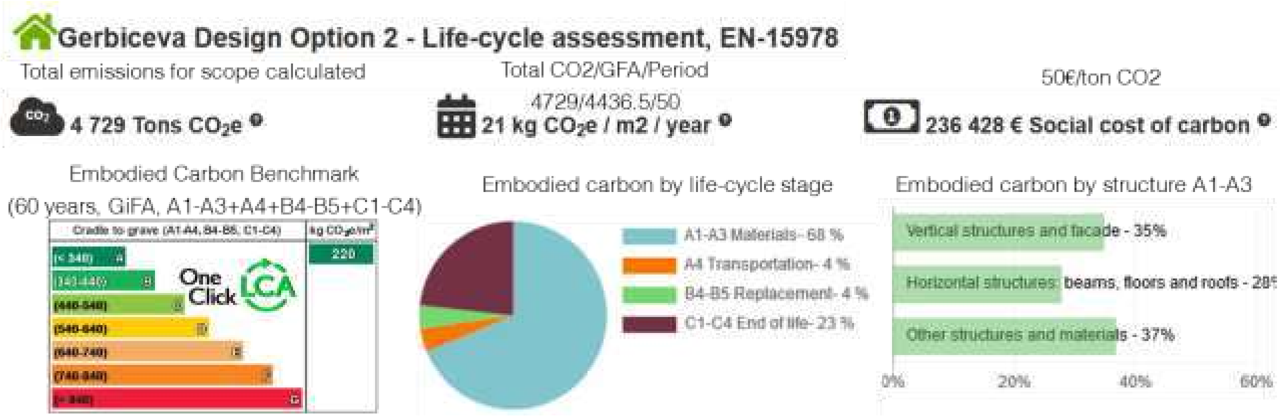


Figure 5. 179: Gerbiceva Design Option 2 (CLT wood construction and materials substitution).

A second Design Option for LCA has been explored where concrete structural materials are substituted with CLT wood elements. Insulation materials of EPS and XPS have been substituted by Cellulose-based insulation and recycled cotton for some components. Biogenic Carbon storage is not subtracted from A1-A3 GWP results or calculations in One Click LCA (2015). The Biogenic carbon storage data is separated from the original datapoint of the EPDs by Bionova to ensure comparability of results of design options. The Energy demand has been reduced by 50.000 kWh for the electricity and the heating demand of the alternative. The Life Cycle GWP is reduced by 34% and the Embodied Carbon Benchmark by 48% from the baseline.

	Result category	Global warming kg CO2e	Acidification kg SO2e	Eutrophication kg PO4e	Ozone depletion potential kg CFC11e	Formation of ozone of lower atmosphere kg Ethenee	Total use of primary energy ex. raw materials MJ	
A1-A3	Construction Materials	667 755,38 | -58 %	1 209,85 | -70 %	2 878,73 | +450 %	0,09 | -56 %	937,15 | +98 %	7 053 771,98 | -41 %	Details
A4	Transportation to site	43 205,39 | -34 %	85,08 | -33 %	17,81 | -33 %	0,01 | -34 %	5,83 | -34 %	750 379,34 | -33 %	Details
A5a	Site operations & site waste handling							Details
A5b	Site waste transportation							Details
A5	Construction/installation process							Details
B1-B5	Maintenance and material replacement	36 715,37 | -45 %	85,43 | -39 %	6,7 | -60 %	0 | +16 %	5,38 | -50 %	432 710,32 | -62 %	Details
B6	Energy use	3 695 060,27 | -29 %	14 390,74 | -30 %	1 641 | -32 %	0,37 | -30 %	813,82 | -35 %	69 549 553,87 | -33 %	Details
B7	Water use	61 500 | 0 %	333,01 | 0 %	168,47 | 0 %	0,01 | 0 %	14,98 | 0 %	1 300 208,99 | 0 %	Details
C1-C4	Deconstruction	224 325,06 | +51 %	323,36 | -17 %	85,14 | -13 %	0 | -83 %	24,8 | +116 %	947 628,82 | -67 %	Details
D	External impacts (not included in totals)	-980 230,93 | -203 %	-1 060,65 | -62 %	-174,72 | -5,8 %	-0 | -34 %	-110,4 | -200 %	-17 096 545,77 | -480 %	Details
	Total	**4 728 561,46**	**16 427,48**	**4 799,86**	**0,48**	**1 804,96**	**80 034 253,32**	
	Comparing total results with: 4 - Gerbiceva Baseline							
	4 - Gerbiceva Baseline Total	7 174 569,67	25 728	3 242,47	0,78	1 686,05	117 637 014,22	
	4 - Gerbiceva Design Option 2 compared with 4 - Gerbiceva Baseline	-34 %	-36 %	+48 %	-39 %	+7,1 %	-32 %	
	Results per denominator							
	Gross Internal Floor Area (IPMS/RICS) 4436.5 m2	1 065,93	3,7	1,08	0	0,41	18 039,95	

Figure 5. 180: LCA results per Life-cycle stages and total values for Design Option 2 and Baseline comparison.

The change of building design would reduce the Embodied Carbon by more than half at 58%, and A1-A3 impacts of Acidification potential by 70%, Ozone depletion potential by 56%, and Total Primary Energy by 41%. Interestingly though, the substitution to wood materials does not come only with benefits. The Eutrophication potential is increased drastically by 450%, and the formation of ozone of lower atmosphere is increased by 98% for Construction Materials.

The LEED credits can be achieved with Design Option 2, as four impact categories have achieved a reduction of more than 10% from the Baseline.

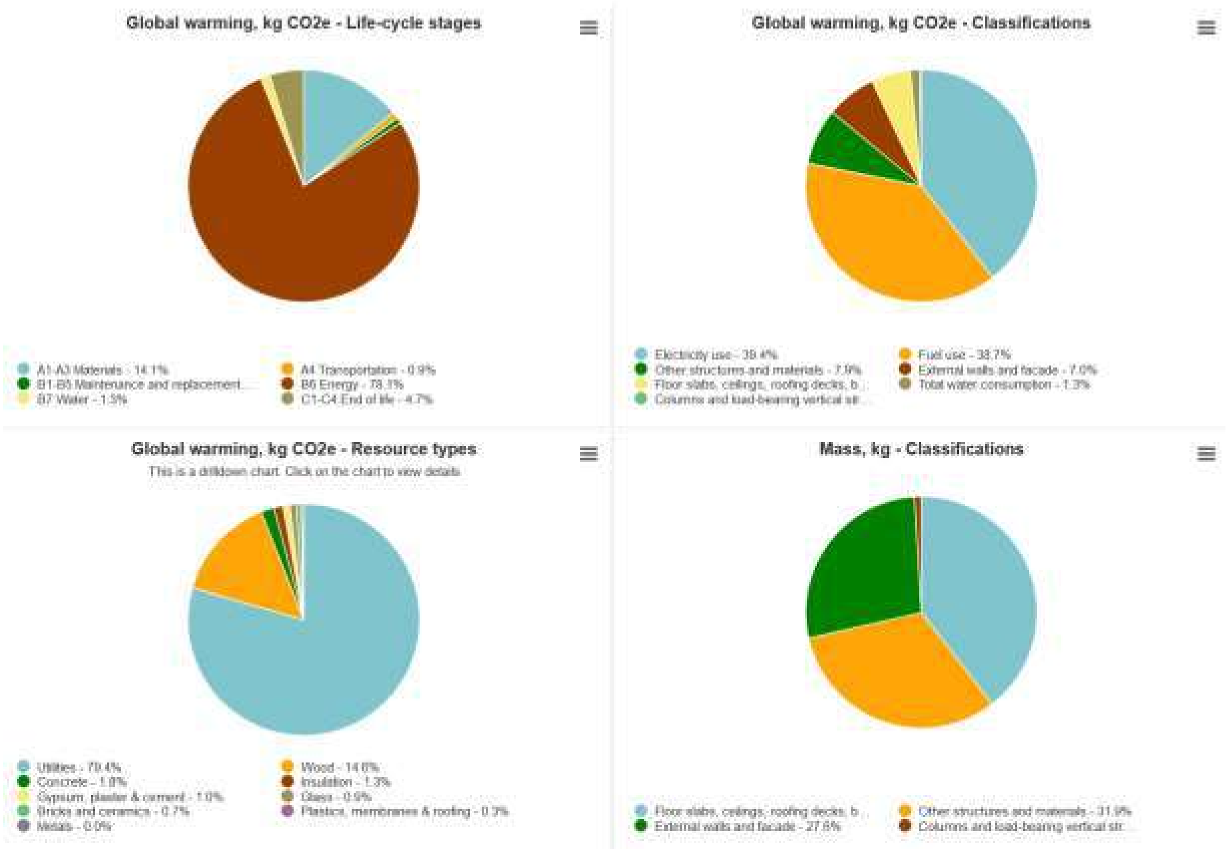


Figure 5. 181: LCA overview of Global Warming Potential (GWP) for Design Option 2.

The shares of the different pie charts for GWP impacts are similar compared to Design Option 1 of optimized materials and concrete with recycled content.

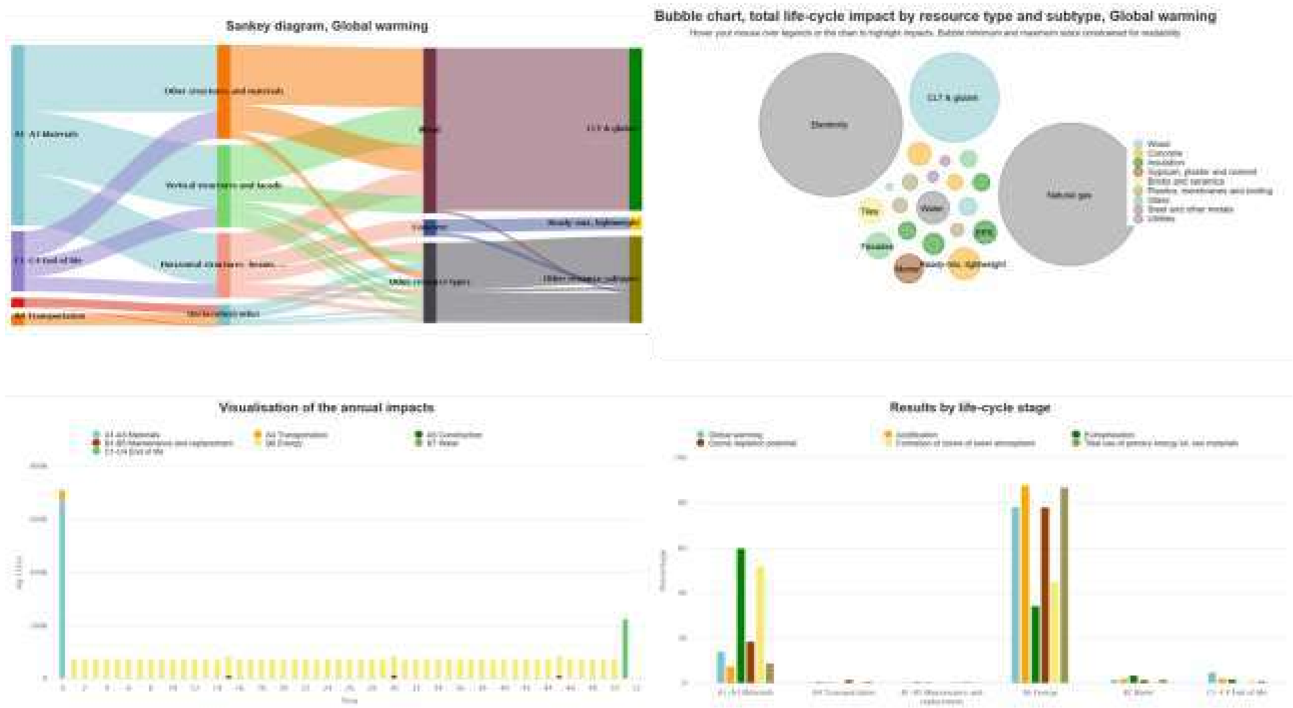


Figure 5. 182: Bubble Chart, Sankey diagram, Annual impacts chart, results by life-cycle stage of six impact categories chart of LCA for Design Option 2.

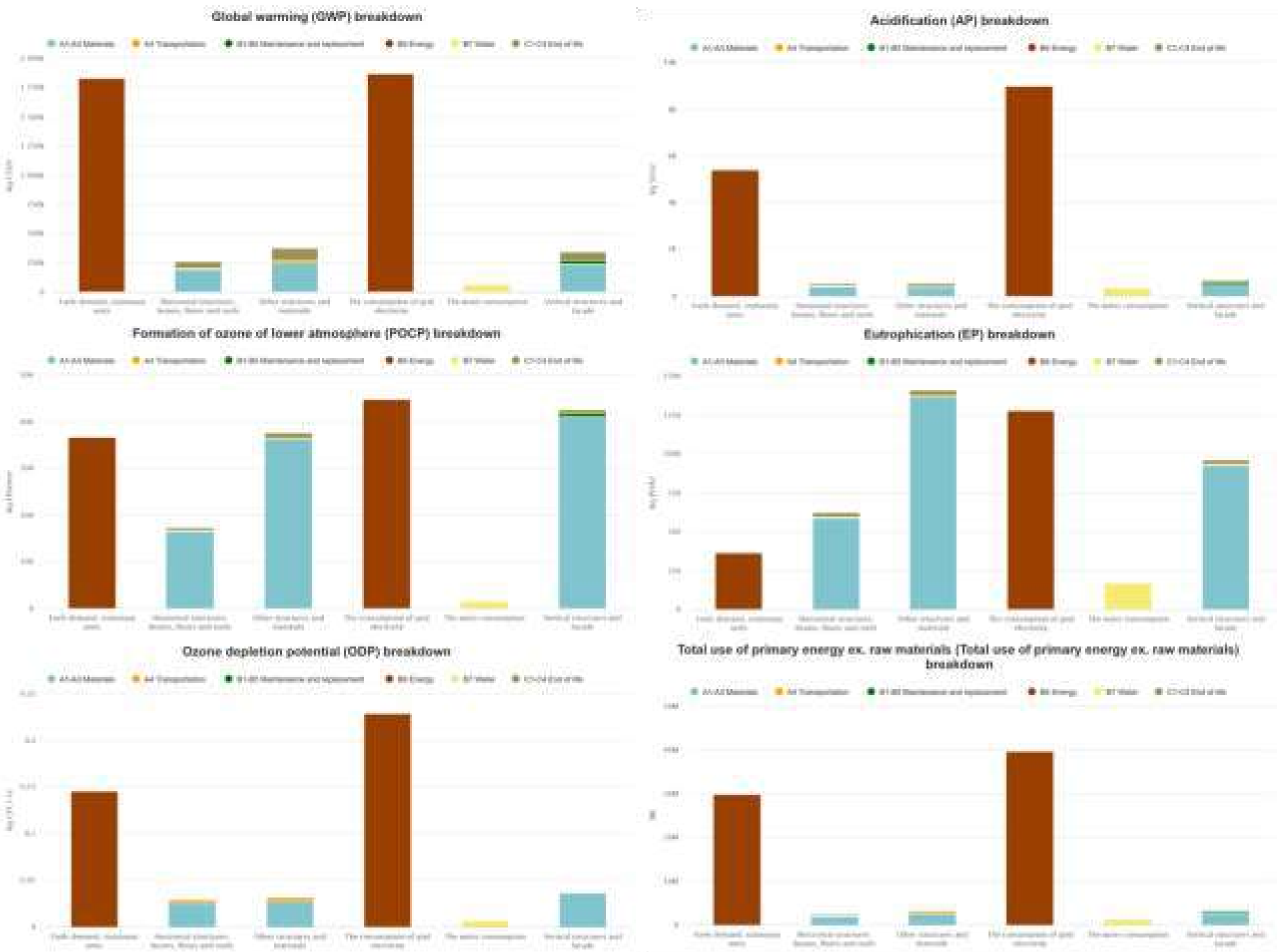


Figure 5. 183: Breakdown chart for each impact category by classifications for Design Option 2.

The Design Option 2 has similar but reduced values for GWP, AP, ODP and Total use of primary energy as found in the results summary table. The CLT wood elements and cellulose-based insulations account for increasing the Eutrophication and POCP potentials of the design.

Summary of results and comparison of designs

Licenses	One Click LCA Student (International)
Address	Gerbiceva Ulica 51, Slovenia
Type	Apartment buildings
Gross Floor Area (m²)	4 436,5

Tool	Unit	4 - Gerbiceva Baseline	4 - Gerbiceva Design Option 1	4 - Gerbiceva Design Option 2
LCA, EN-15978 ? Help	kg CO2e	7 174 570	8 470 840	4 720 061

The Baseline and the design alternatives can be compared through tables and charts by LCA results and impact categories.

Figure 5. 184: Input data for Energy and Water consumption, annual values.

Average results of building demands from Urban Modelling Interface previous simulations are used. The Gerbiceva Energy report estimates the Total Energy load at 312658 kWh/yr, which could be higher as the report indicates for the heating demand. The total 350000 kWh/yr input for the LCA is acceptable. Energy and Water data are essential in order to account for whole-building life-cycle assessment. The average consumption of Tap water in Slovenia is 122 litres/person[65]. An average of 100 litres/person is used for the calculation, approximating for efficient new building systems and occupancy of 111 people for 365 days of the year.

Figure 5. 185: LCA comparison, EN-15978 - by All impact categories.

[65] Drinking water in the EU: better quality and access. (2020, February 19). European Parliament. Retrieved May 25, 2020, from https://www.europarl.europa.eu/news/en/headlines/society/20181011STO15887/drinking-water-in-the-eu-better-quality-and-access

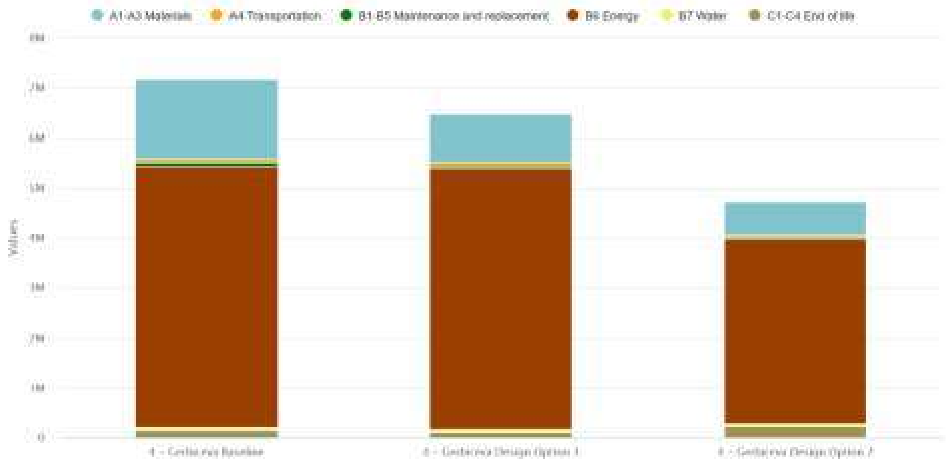


Figure 5. 186: LCA comparison by Life-cycle stages, EN-15978 - Global warming.

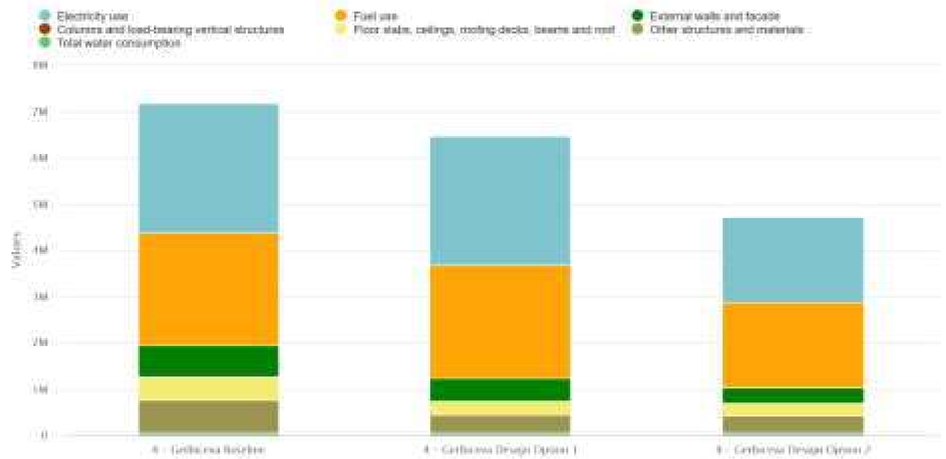


Figure 5. 187: LCA design comparison with elements, EN-15978 - Global warming.

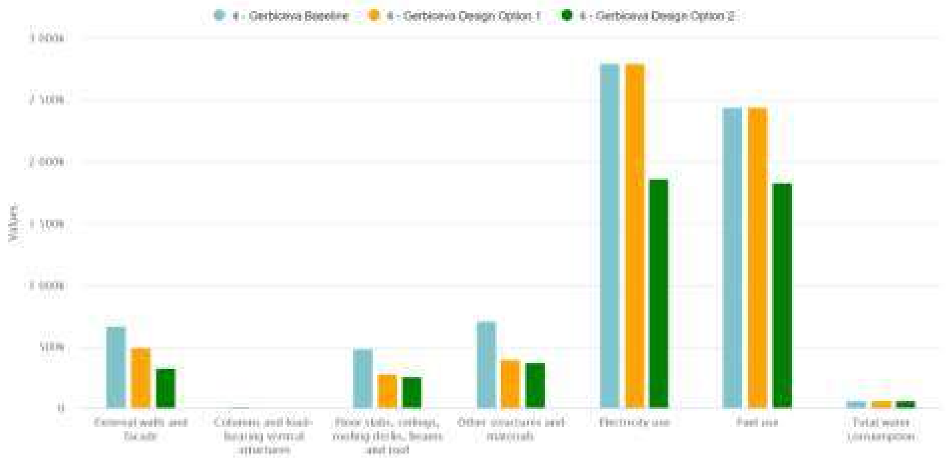


Figure 5. 188: LCA compared elements of designs, EN-15978 - Global warming.

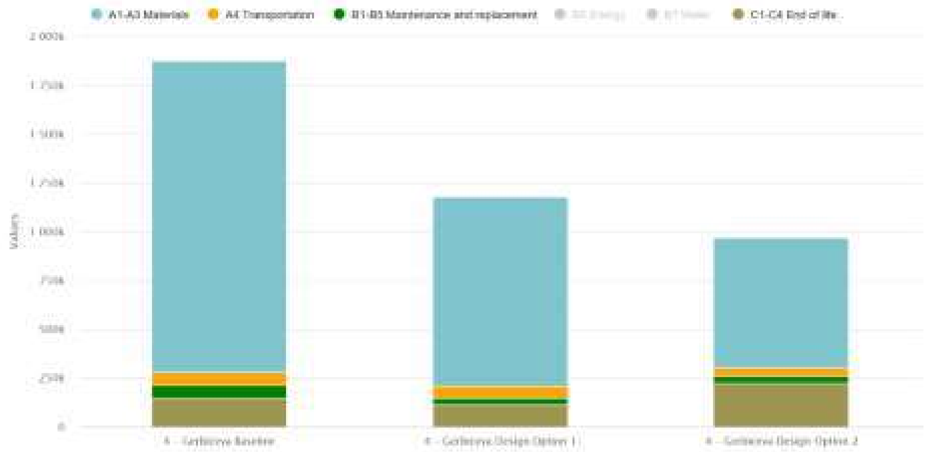


Figure 5. 189: LCA comparison of construction elements and their life-cycle stages.

The availability of generic materials in the LCA database for countries is a relevant feature. Public Authorities can request to the lead appointed party for the design to explore design options and carbon footprint of buildings since the early concept design stage. The materials and EPDs can be downloaded for detailed reporting of the results to the Client and keeping track of project progress. LCA done since the early design stage can inform project decisions of materials and resources, but also in setting targets to reduce Upfront Carbon, Energy Use Intensity (EUI) and integration of Renewable Energy Systems (photovoltaic, solar thermal, heat pumps) into the design.

5.14.3 *Whole-building life cycle assessment with Tally*

Report Summary

Created with Tally
Non-commercial Version 2020.02.28.01

Goal and Scope of Assessment
Life-cycle assessment, EN-15978

Author	Arlind Dervishaj
Company	BIM A+
Date	23/05/2020
Project	Gerbicev Youth Housing Community
Location	Gerbiceva Ulica 51 Ljubljana, 1000
Gross Area	4436 m²
Building Life	50
Boundaries	Cradle to grave, inclusive of biogenic carbon; see appendix for a full list of materials and processes
Operational Energy [B6]	150000 kWh annual electricity use 200000 kWh annual heating energy use

Total emissions for scope calculated
7 145 Tons CO2e

Total CO2/GFA/Period
32 kg CO2e / m2 / year

50€/ton CO2
357 250 0 € Social cost of carbon

Figure 5. 190: Tally report general summary data and derivated LCA outcomes (total emissions, normalized emissions, social cost of carbon)

Embodied Carbon
(cradle to grave)
481.5 $kgCO_2e/m^2$

Environmental Impact Totals	Product Stage [A1-A3]	Construction Stage [A4]	Use Stage [B2-B6]	End of Life Stage [C2-C4]	Module D [D]
Global Warming (kg CO_2eq)	1'840'173	24'239	5'223'420	148'938	-91'716
Acidification (kg SO_2eq)	6'149	112.3	10'972	652.9	-399
Eutrophication (kg Neq)	374.9	9.145	700.0	53.78	-8.46
Smog Formation (kg O_3eq)	100'588	3'711	159'515	11'445	-2'754
Ozone Depletion (kg CFC-11eq)	0.003034	8.302E-010	0.002891	3.429E-008	3.429E-004
Primary Energy (MJ)	2.374E+007	352'487	1.140E+008	2'073'600	-1'247'527
Non-renewable Energy (MJ)	2.182E+007	344'052	9.239E+007	1'939'011	-958'007
Renewable Energy (MJ)	1'920'008	8'524	2.169E+007	136'861	-290'228
Environmental Impacts / Area					
Global Warming (kg CO_2eq/m^2)	414.8	5.464	1'178	33.57	-20.7
Acidification (kg SO_2eq/m^2)	1.386	0.02532	2.473	0.1472	-0.08994
Eutrophication (kg Neq/m^2)	0.08451	0.002062	0.1578	0.01212	-0.001907
Smog Formation (kg O_3eq/m^2)	22.68	0.8366	35.96	2.580	-0.6207
Ozone Depletion (kg CFC-11eq/m^2)	6.840E-007	1.871E-013	6.516E-007	7.729E-012	7.730E-008
Primary Energy (MJ/m^2)	5'351	79.46	25'707	467.4	-281
Non-renewable Energy (MJ/m^2)	4'920	77.56	20'827	437.1	-216
Renewable Energy (MJ/m^2)	432.8	1.921	4'890	30.85	-65.4

Figure 5. 191: Tally summary of LCA results for Gerbiceva project.

The Embodied Carbon results of Tally are separated by life-cycle stages, to compare data with One Click LCA, the results of A1-A3 Construction Materials, A4 Transportation to Site, B1-B5 Maintenance and Replacement, and C1-C4 Deconstruction have been summed. The Embodied Carbon Benchmark with Tally is 481.5 $kgCO_2e/m^2$.

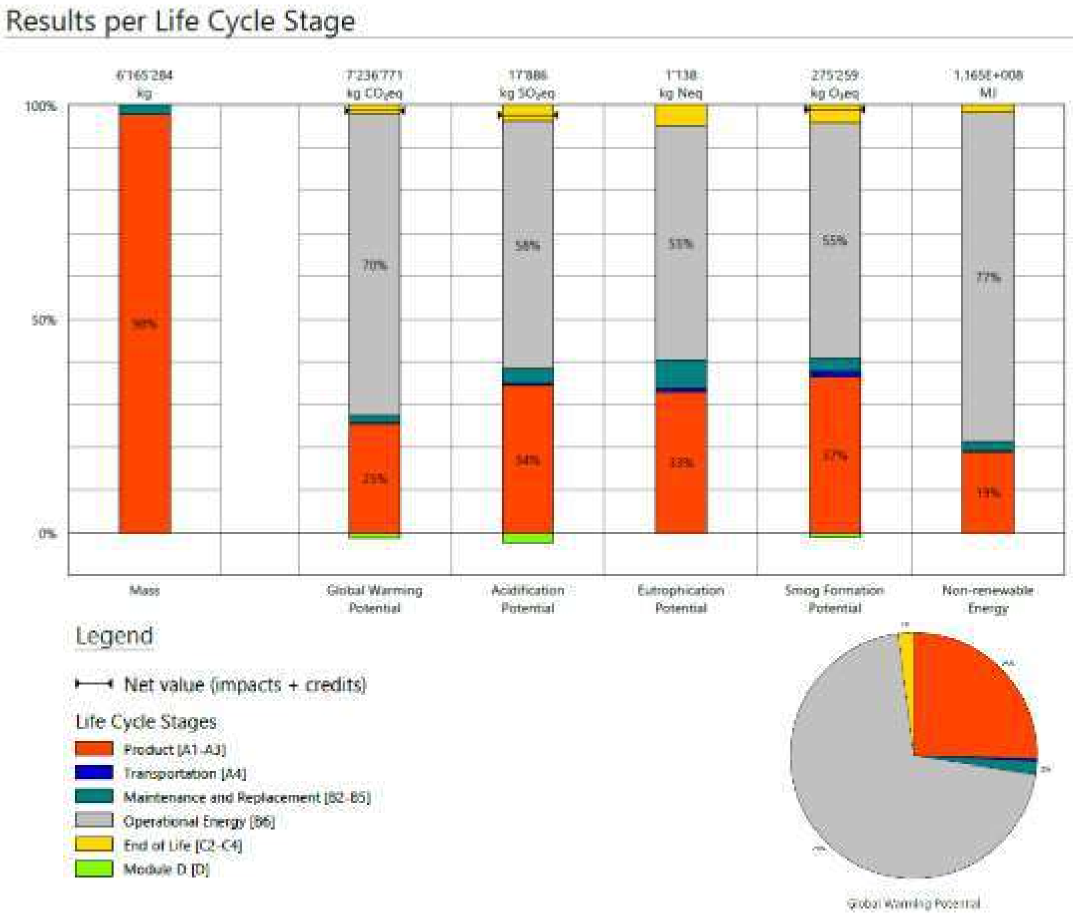


Figure 5. 192: Tally results per Life Cycle Stage.

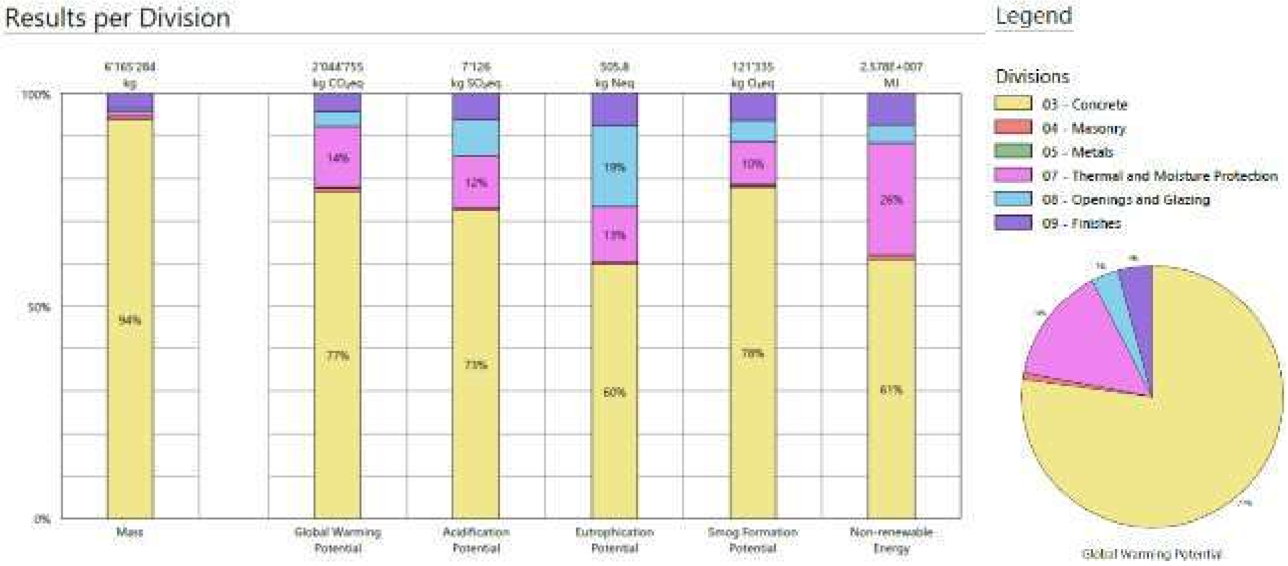


Figure 5. 193: Tally results by Material category.

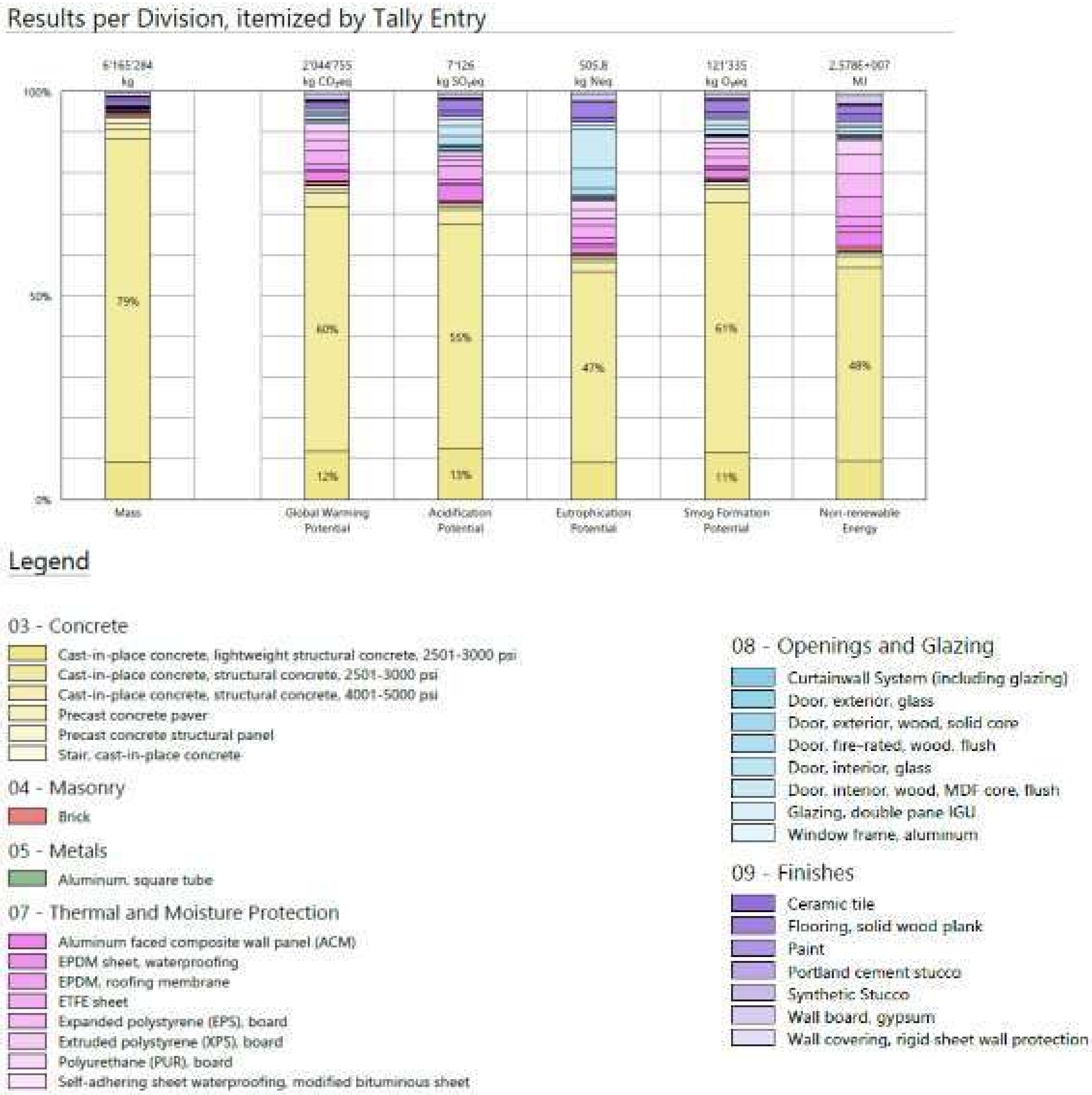


Figure 5. 194: Tally results by Material entry.

Concrete makes up 97% of the total mass and contributes to 77% of materials GWP and 61% of Energy consumption for Materials. Openings and Glazing account for 1% of the building mass but 19% of the Eutrophication potential. Insulation is just 1% of the mass but accounts for 14% of GWP and 26% of Energy.

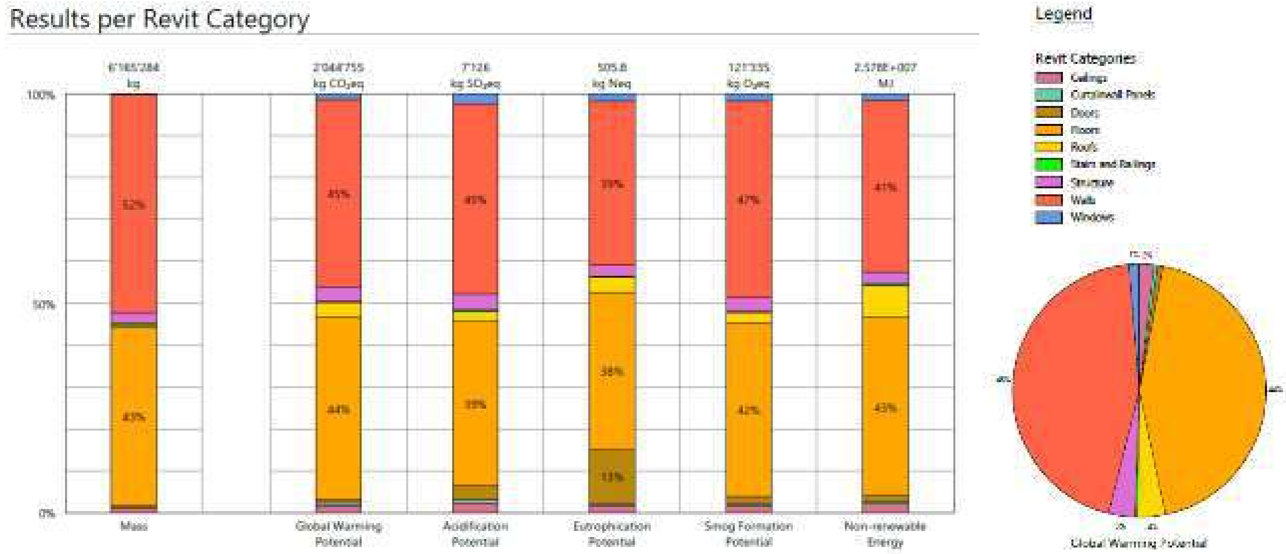


Figure 5. 195: Tally results by Revit category.

The Wall and Floor categories have the highest impact at 45% and 44% respectively. Walls account for high impact because they have a load-bearing structural function in the design.

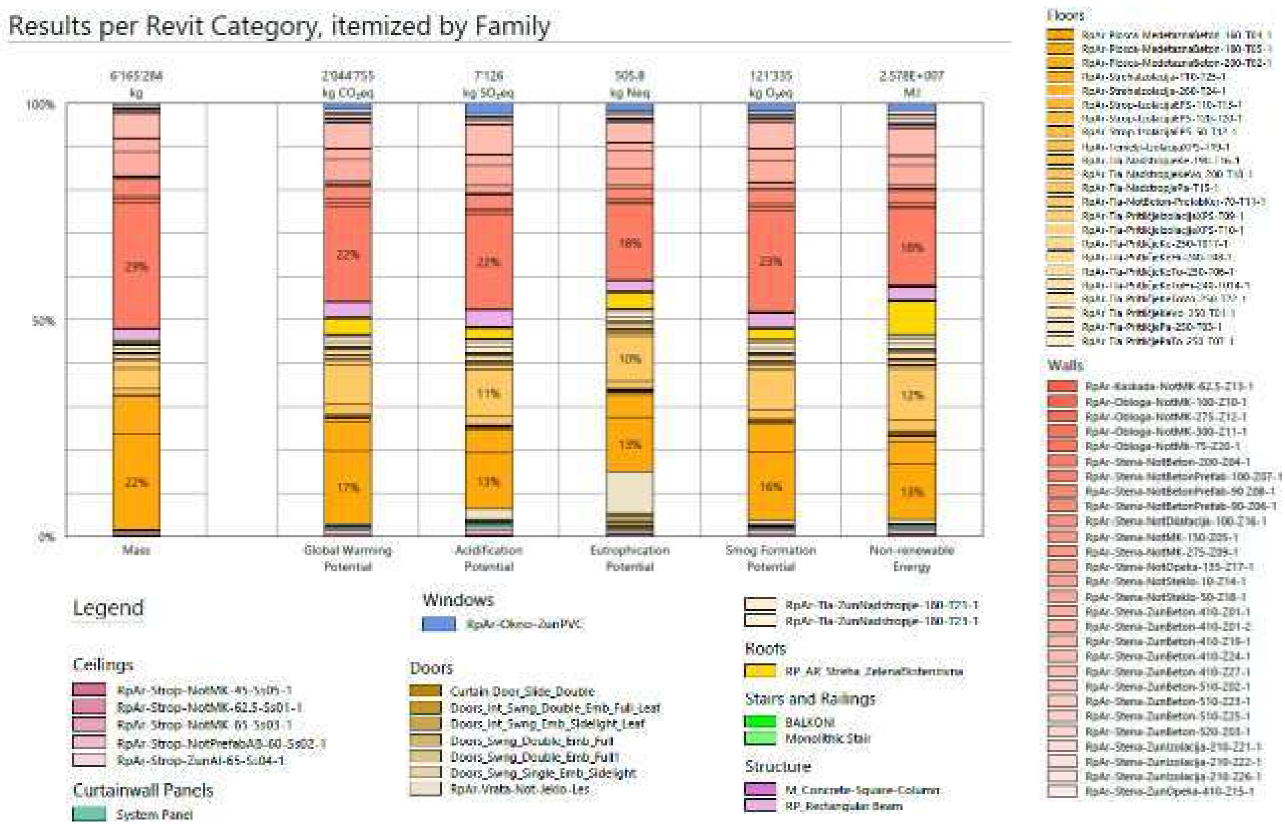


Figure 5. 196: Tally results by Revit category.

Tally Design Option 1 (concrete with recycled content)

Environmental Impact Totals	Product Stage [A1-A3]	Construction Stage [A4]	Use Stage [B2-B6]	End of Life Stage [C2-C4]	Module D [D]
Global Warming (kg CO_2eq)	1'559'942	24'011	5'223'487	148'876	-87'734
Acidification (kg SO_2eq)	5'475	111.3	10'972	652.6	-391
Eutrophication (kg Neq)	326.1	9.059	700.0	53.76	-8.14
Smog Formation (kg O_3eq)	86'540	3'676	159'517	11'439	-2'640
Ozone Depletion (kg CFC-11eq)	0.003119	8.223E-010	0.002892	3.427E-008	3.149E-004
Primary Energy (MJ)	2.164E+007	349'165	1.140E+008	2'072'534	-1'212'712
Non-renewable Energy (MJ)	1.988E+007	340'810	9.239E+007	1'938'018	-920'714
Renewable Energy (MJ)	1'759'281	8'443	2.169E+007	136'791	-292'785
Environmental Impacts / Area					
Global Warming (kg CO_2eq/m²)	351.7	5.413	1'178	33.56	-19.8
Acidification (kg SO_2eq/m²)	1.234	0.02508	2.473	0.1471	-0.08817
Eutrophication (kg Neq/m²)	0.07352	0.002042	0.1578	0.01212	-0.001834
Smog Formation (kg O_3eq/m²)	19.51	0.8288	35.96	2.579	-0.5952
Ozone Depletion (kg CFC-11eq/m²)	7.032E-007	1.854E-013	6.520E-007	7.726E-012	7.099E-008
Primary Energy (MJ/m²)	4'878	78.71	25'707	467.2	-273
Non-renewable Energy (MJ/m²)	4'483	76.83	20'827	436.9	-208
Renewable Energy (MJ/m²)	396.6	1.903	4'890	30.84	-66.0

Figure 5. 197: Tally summary of LCA results for Design Option 1.

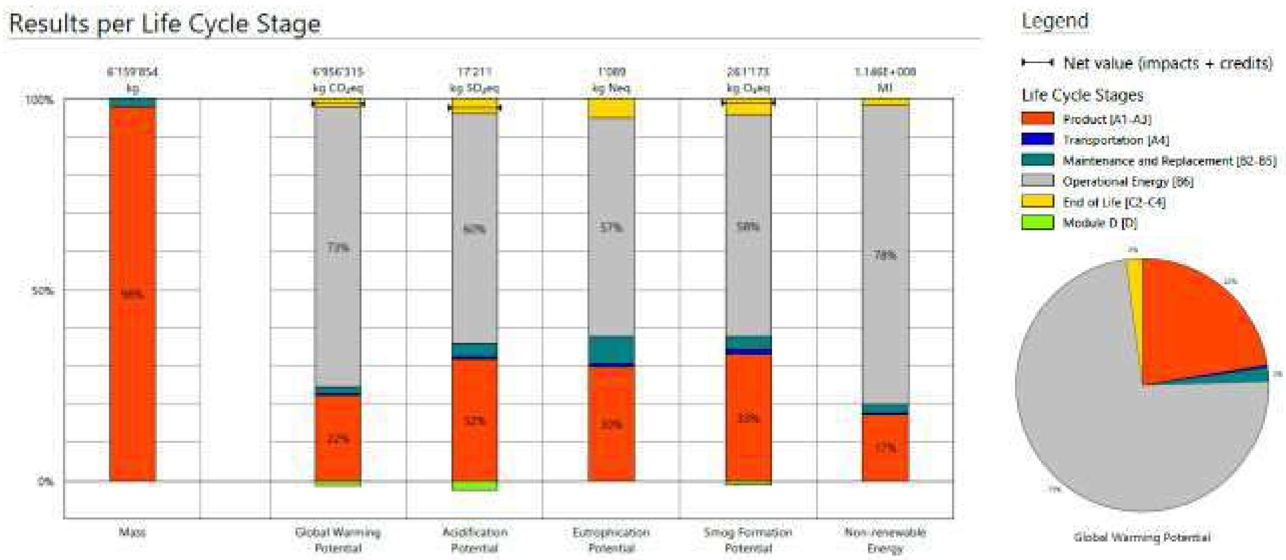


Figure 5. 198: Tally results per Life Cycle Stage, Design Option 1.

The substitution of regular concrete makes a reduction of the Life Cycle Product A1-A3 stage GWP by 15% from the Baseline design. The Embodied Carbon Benchmark (materials cradle to grave) is reduced by 13%.

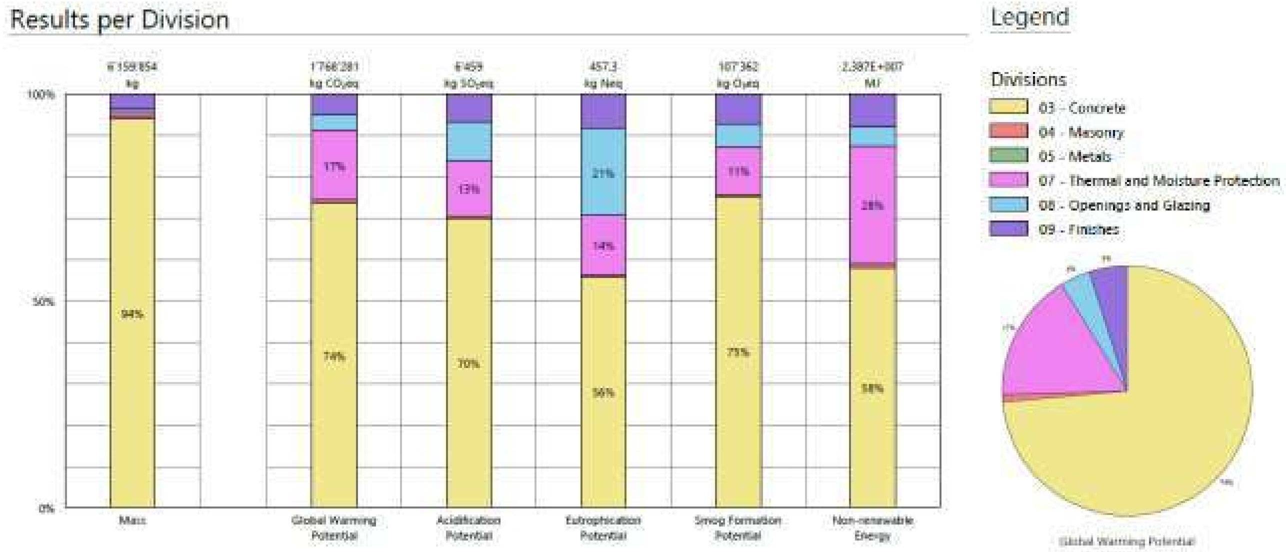


Figure 5. 199: Tally results by Material category, Design Option 1.

Tally Design Option 2 (CLT wood, excluding biogenic carbon)

Total emissions for scope calculated
6764 Tons CO2e

Total CO2/GFA/Period
30.4 kg CO2e / m2 / year

50€/ton CO2
338 200 € Social cost of carbon

Embodied Carbon
(cradle to grave)
428.38 $kgCO_2e/m^2$

Environmental Impact Totals	Product Stage [A1-A3]	Construction Stage [A4]	Use Stage [B2-B6]	End of Life Stage [C2-C4]	Module D [D]
Global Warming (kg CO_2eq)	1'096'045	39'373	5'295'978	569'634	-236'132
Acidification (kg SO_2eq)	6'583	183.4	11'130	5'019	-1'046
Eutrophication (kg Neq)	501.7	14.94	708.3	1'320	-35.9
Smog Formation (kg O_3eq)	87'771	6'062	162'555	18'403	-11'270
Ozone Depletion (kg CFC-11eq)	0.06758	1.356E-009	0.002892	2.614E-008	7.871E-006
Primary Energy (MJ)	3.133E+007	575'726	1.150E+008	1'069'634	-5'700'503
Non-renewable Energy (MJ)	1.692E+007	561'949	9.329E+007	1'003'604	-3'394'875
Renewable Energy (MJ)	1.441E+007	13'922	2.179E+007	66'115	-2'316'204
Environmental Impacts / Area					
Global Warming (kg CO_2eq/m^2)	247.1	8.876	1'194	128.4	-53.2
Acidification (kg SO_2eq/m^2)	1.484	0.04135	2.509	1.132	-0.2358
Eutrophication (kg Neq/m^2)	0.1131	0.003367	0.1597	0.2975	-0.008085
Smog Formation (kg O_3eq/m^2)	19.79	1.367	36.64	4.148	-2.54
Ozone Depletion (kg CFC-11eq/m^2)	1.524E-005	3.057E-013	6.520E-007	5.892E-012	1.774E-009
Primary Energy (MJ/m^2)	7'063	129.8	25'933	241.1	-1'285
Non-renewable Energy (MJ/m^2)	3'815	126.7	21'031	226.2	-765
Renewable Energy (MJ/m^2)	3'248	3.138	4'911	14.90	-522

Figure 5. 200: Tally summary of LCA results for Design Option 2.

The Embodied Carbon of a CLT building without accounting for biogenic carbon is slightly higher than the Design Option of a concrete structure with recycled content. The total emissions, normalized per year, and social cost of carbon is slightly lower compared to the Design Option 1. The CLT has an 11% reduction of the Embodied Carbon Benchmark from the baseline and a high reduction in Product A1-A3 GWP of 40%.

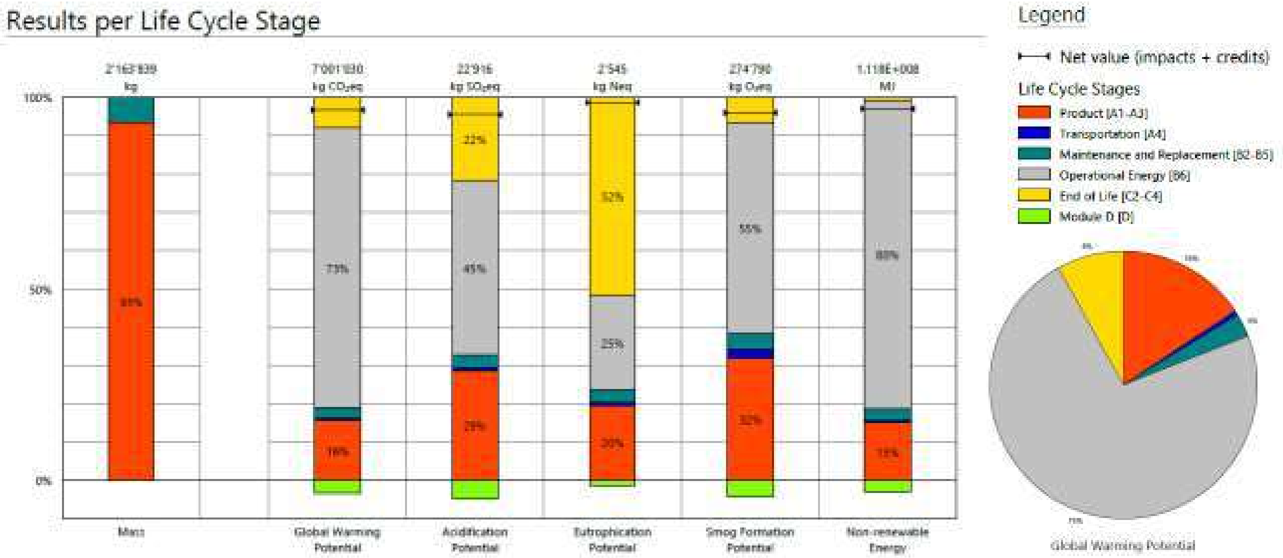


Figure 5. 201: Tally results per Life Cycle Stage, Design Option 2.

For Design Option 2, the share of materials goes down from 25% in the baseline to 16%. The Maintenance contribution increases from the baseline from 2 to 3%, and for End of Life from 2 to 8%

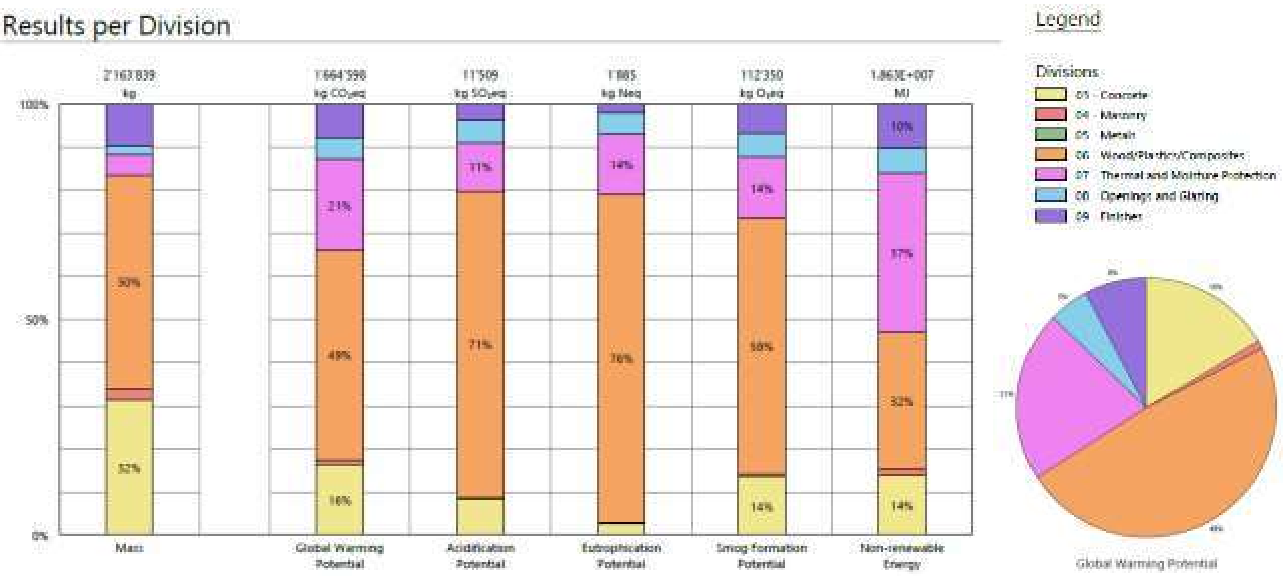


Figure 5. 202: Tally results by Material category, Design Option 2.

When choosing structural materials with recycled content and lower impact in LCA categories, the other materials impacts share becomes more significant than in the baseline scenario. The careful evaluation of building components and their impacts should not be limited to structural and insulating materials which have the highest impacts.

Tally Design Option 2 (CLT wood, including biogenic carbon)

Total emissions for scope calculated
5698 Tons CO2e

Total CO2/GFA/Period
25 kg CO2e / m2 / year

50€/ton CO2
284 900 € Social cost of carbon

Embodied Carbon
(cradle to grave)
124 $kgCO_2e/m^2$

Environmental Impact Totals	Product Stage [A1-A3]	Construction Stage [A4]	Use Stage [B2-B6]	End of Life Stage [C2-C4]	Module D [D]
Global Warming (kg CO_2eq)	-944'211	39'590	5'265'611	1'289'680	47'460
Acidification (kg SO_2eq)	6'583	183.4	11'130	5'019	-1'046
Eutrophication (kg Neq)	501.7	14.94	708.3	1'320	-35.9
Smog Formation (kg O_3eq)	87'771	6'062	162'555	18'403	-11'270
Ozone Depletion (kg CFC-11eq)	0.06758	1.356E-009	0.002892	2.614E-008	7.871E-006
Primary Energy (MJ)	3.133E+007	575'726	1.150E+008	1'069'634	-5'700'503
Non-renewable Energy (MJ)	1.692E+007	561'949	9.329E+007	1'003'604	-3'394'875
Renewable Energy (MJ)	1.441E+007	13'922	2.179E+007	66'115	-2'316'204
Environmental Impacts / Area					
Global Warming (kg CO_2eq/m^2)	-213	8.925	1'187	290.7	10.70
Acidification (kg SO_2eq/m^2)	1.484	0.04135	2.509	1.132	-0.2358
Eutrophication (kg Neq/m^2)	0.1131	0.003367	0.1597	0.2975	-0.008085
Smog Formation (kg O_3eq/m^2)	19.79	1.367	36.64	4.148	-2.54
Ozone Depletion (kg CFC-11eq/m^2)	1.524E-005	3.057E-013	6.520E-007	5.892E-012	1.774E-009
Primary Energy (MJ/m^2)	7'063	129.8	25'933	241,1	-1'285
Non-renewable Energy (MJ/m^2)	3'815	126.7	21'031	226.2	-765
Renewable Energy (MJ/m^2)	3'248	3.138	4'911	14.90	-522

Figure 5. 203: Tally summary of LCA results for Design Option 2 (with biogenic carbon).

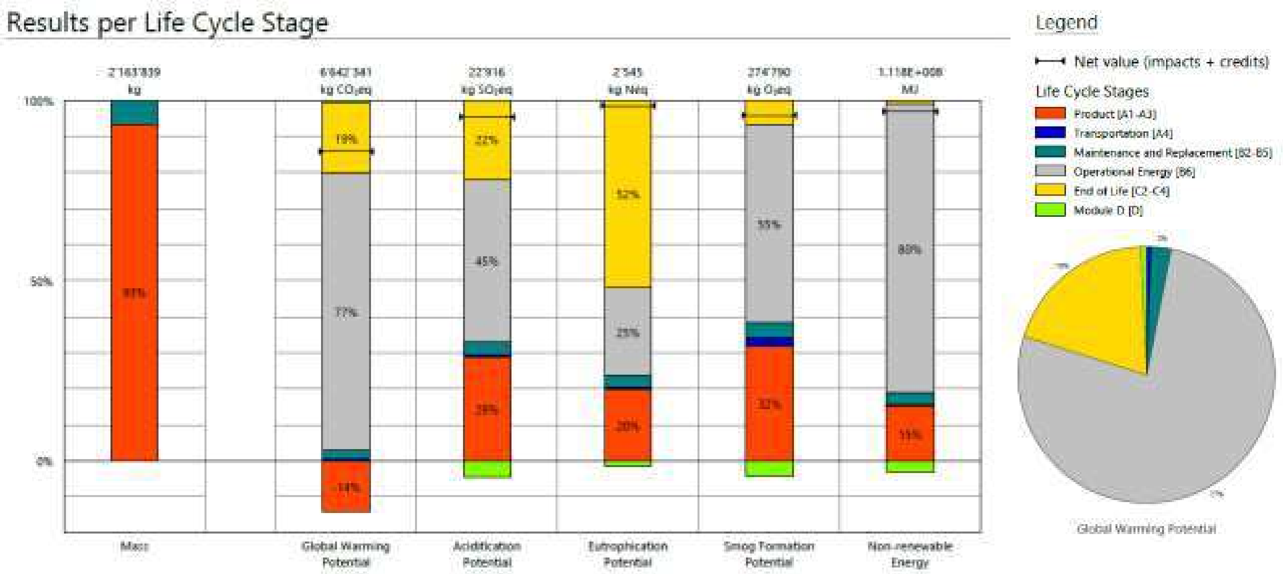


Figure 5. 204: Tally results per Life Cycle Stage, Design Option 2 (with biogenic carbon).

The use of biogenic carbon for LCA calculations would result in a negative GWP for materials of -944211 $kgCO_2e$ for the design. Biogenic carbon represents -14% of the total GWP of this Design Option. The use of CLT wood for construction can have a significant positive impact only in the GWP category, while the other five categories do not show improvements. The materials share of GWP may be -14%, but the share of C2-C4 End of Life increases to 19% of GWP. The acidification and eutrophication are more than double than the concrete solutions. The Embodied Carbon is reduced by 74%, which is interestingly close to the 78% UMI reduction. The Product A1-A3 GWP results in carbon sequestration by -51% from the Baseline. End of Life stage increases from 2%, to 8% (excl. Biogenic carbon), to 19% (incl. Biogenic carbon).

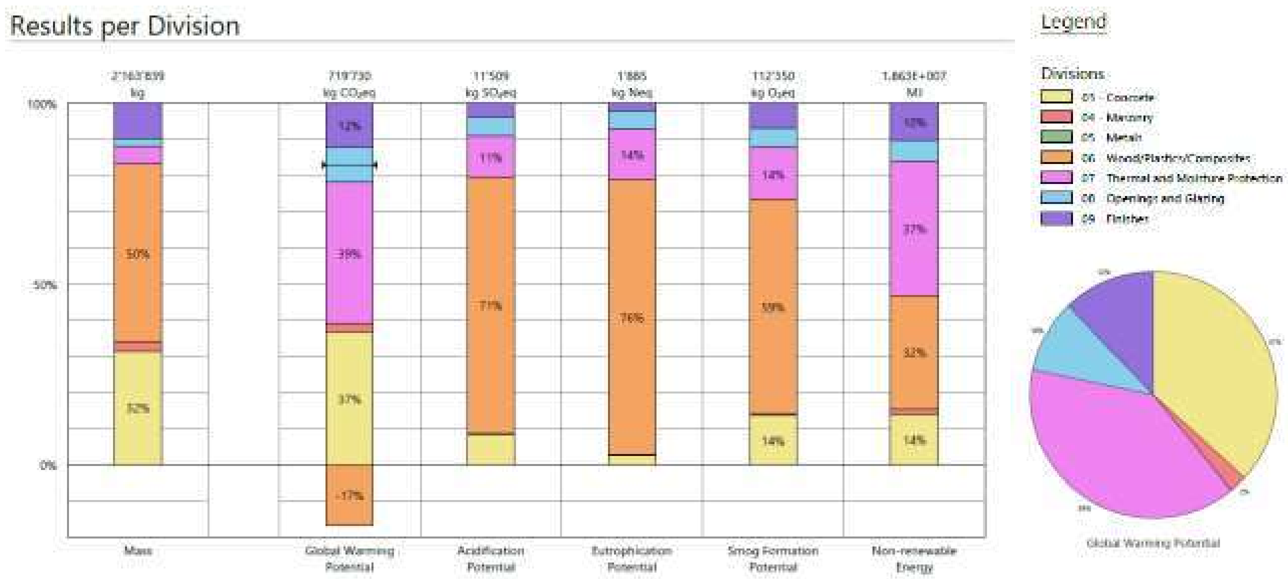


Figure 5. 205: Tally results by Material category, Design Option 2 (with biogenic carbon).

5.14.4 *Comparison of results between BIM integrated LCA workflows*

The results of Carbon Designer, One Click LCA (2015) and Tally have been organized in table form for comparison.

Table 5. 29: Comparison of LCA results with One Click LCA, Tally, Climate Studio, Energy report.

LCA of Design variant	GWP A1-A3 Materials kg CO_2e	Embodied Carbon Benchmark kg $CO_2e/m^2/year$	Total Emissions Tons CO_2e	Life Cycle GWP kg $CO_2e/m^2/year$	Social Cost of Carbon € (50€/ton CO_2)	Share of A1-A3 to Total GWP %	Most impacting material share to A1-A3 GWP %	B6 Primary Energy MJ
Carbon Designer Baseline	1509000	340	-	-	-	-	-	-
Carbon Designer Optimized	1343000	303	-	-	-	-	-	-
One Click LCA Gerbiceva	1595743	425	7175	32	358728	22.2	78.2	99355455
One Click LCA Option 1 (RC)	965068	268	6477	29	323842	14.9	81.6	99355455
One Click LCA Option 2 (CLT)	667755	220	4729	21	236428	14.1	70.9	69549553
Tally LCA Gerbiceva	1840173	481.5	7145	32	357250	25	77	114000000
Tally LCA Option 1 (RC)	1559942	418.3	6869	30.9	343450	22	74	114000000
Tally LCA Option 2 (CLT)	1096045	428.3	6764	30.4	338200	16	49	115000000
Tallyg LCA Option 2 (CLT, biogenic carbon)	-944211	124	5698	25	284900	-14	39	115000000
CS-E+ BEM Energy Efficient	-	-	6449	30.5	-	-	-	-
Energy report	-	-	8815	41 (6+35)	-	-	-	-

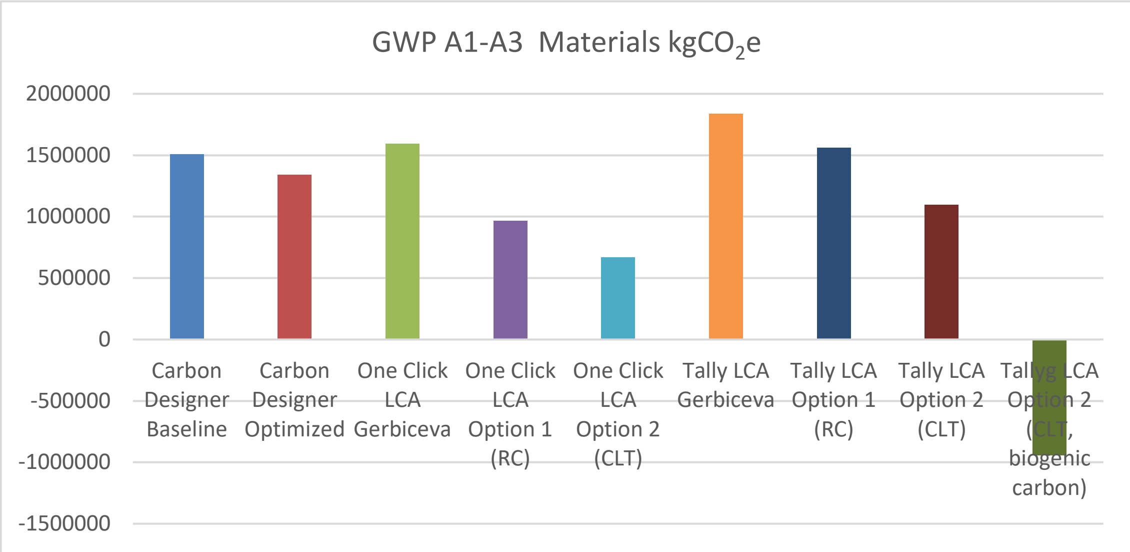


Figure 5. 206: Chart comparison of GWP A1-A3 Materials (kgCO_2e).

Carbon Designer results are close to the baseline's whole building LCA embodied carbon. The vast database of One Click LCA can assist in reducing the footprint of the design by 40% in the case study (option 1). One Click LCA (2015) and Tally account the CLT Design Option GWP differently. Tally results can exclude biogenic carbon for comparability or include biogenic carbon to demonstrate desired design goals.

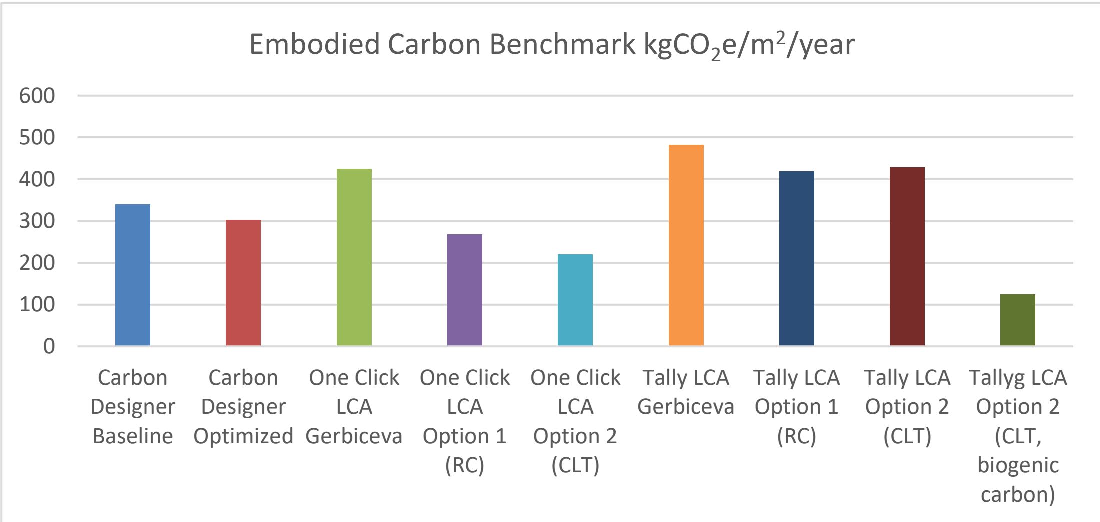


Figure 5. 207: Chart comparison of Embodied Carbon (kg CO_2e/m^2/year).

The Baseline's Embodied Carbon results are lower with One Click LCA (2015) by 11%. While the reduction with One Click LCA (2015) achieved is 37% (option 1) and 48% (option 2), Tally's results show small improvement as 13% (option 1) and 11% (option 2) from its baseline. The difference can be attributed to the database that gives more alternatives in One Click LCA to reduce the footprint or to different values in embodied carbon of materials selected in the two workflows.

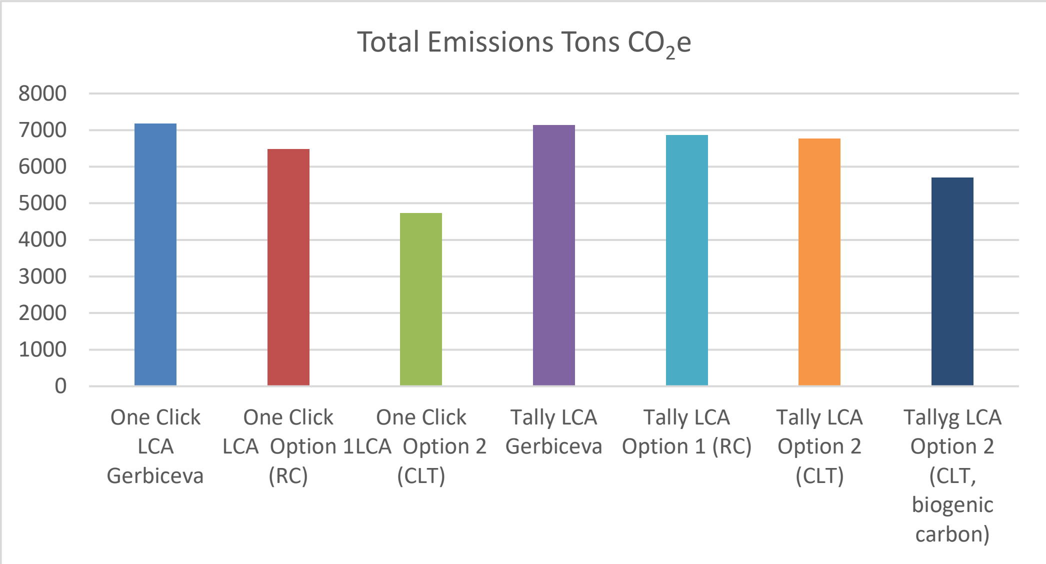


Figure 5. 208: Chart comparison of Total Emissions (CO_2e)

In relation to previous charts, the reduction of total emissions is higher in the design options with One Click LCA (2015), which achieved a 10% (option 1) and 34% (option 2) from the baseline. In Tally, the reduction in emissions is just 4% (option 1) and 5% (option 2), or at 20% (biogenic carbon) from its baseline.

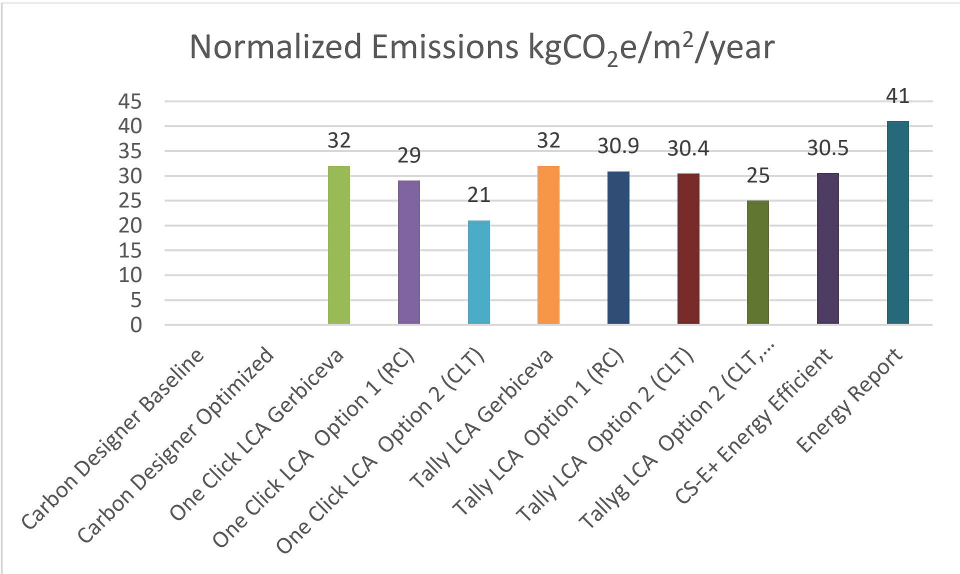


Figure 5. 209: Chart comparison of Life Cycle GWP ($kgCO_2e/m^2/year$).

When it comes to life cycle GWP normalized by floor area, the results of One Click LCA and Tally are similar for the Baseline. The difference between the other design options is less pronounced. The CLT design option provides the most considerable reduction, respectively. Interestingly the results of the Energy report area are the highest.

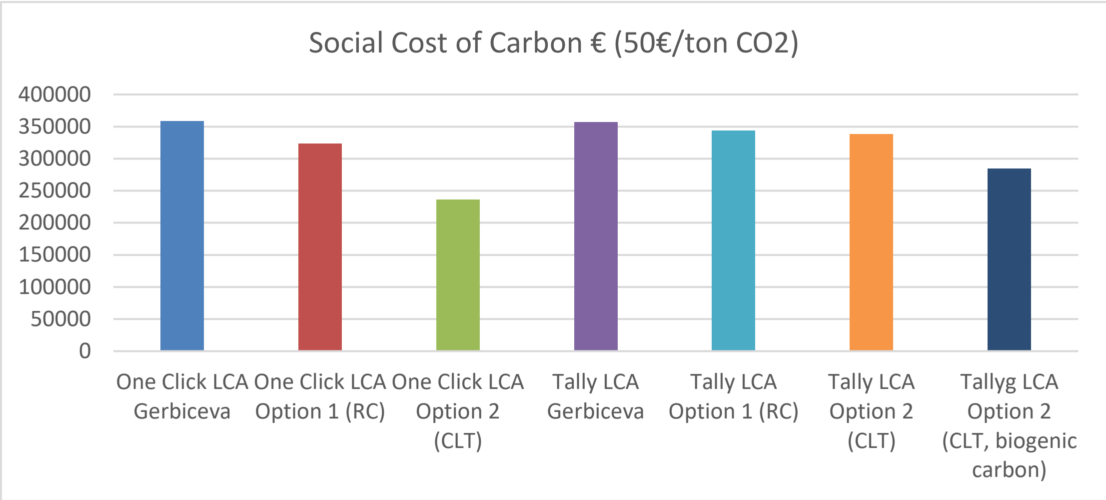


Figure 5. 210: Chart comparison of Social cost of carbon (€).

The social cost of carbon follows the trend of GWP life cycle with which it is related.

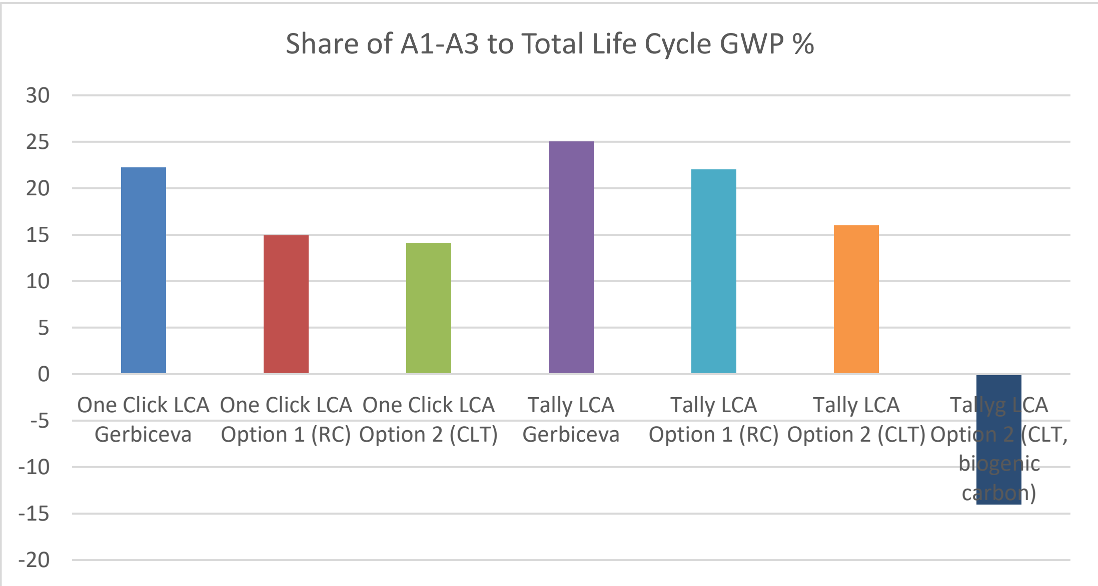


Figure 5. 211: Share of A1-A3 materials to Total Life Cycle GWP (%).

The final chart, showing the GWP contribution share of Products A1-A3 to the total life cycle GWP provides similar insights to the other charts, thus reaffirming the previous findings and validity of results with the two workflows. If accounted for biogenic carbon, the design can be categorized as Positive Carbon Design. In order to make a Regenerative Development, for real Climate Positive Design, renewable energies integrated into the project, that produces more energy than it consumes are needed. The only path towards Regenerative Design is to reduce both embodied and operational carbon towards reaching positivity through design optimization using LCA and a combination of design strategies.

Table 5. 30: Comparison table of BIM integrated LCA workflows.

Comparison areas	One Click LCA	tally
Type of solution	Software as a Service, several BIM integrations	Design Authoring Plugin
Integrations	Design Authoring, BIM Management, Energy Modelling Tools plugins	Plugin
OpenBIM workflows	IFC, gbXML, Excel Spreadsheets	Revit proprietary files, IFC
Material Databases	Generic or Manufacturer materials, Filter by Material, By Country, By Source, By C02 Impact	custom designed LCA database based on GaBi databases and modelling principles.
Strengths	- Large databases of materials - Completeness and plausibility checker - Sustainable Building Certifications - Many ways of visualization of results	- Excellent integration with Revit (Categories, families) - A good comparison of Embodied Carbon designs or materials
Comparing of designs	- Carbon Designer tool - Copy and modify baseline design - Import design for comparison	- Compare designs using Revit "Design Options" feature

5.15 Computational Fluid Dynamics

Two types of CFD simulations will be performed. One CFD analysis for outdoor comfort at urban level ad a CFD of mechanical ventilation of an accommodation unit as predicted in the Gerbiceva project.

5.15.1 *CFD for Outdoor Comfort*

A conceptual urban model of the Gerbiceva project and surroundings is prepared for analysis. Based on the wind visualized data for Ljubljana previously, the prevailing wind directions from the west and the east will be used at a maximum speed of 10 m/s to verify local discomfort around the open spaces of Gerbiceva project.

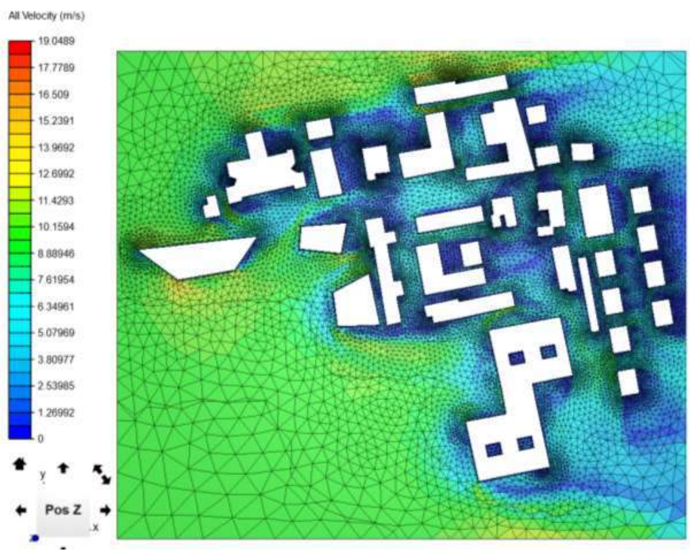


Figure 5. 212: Wind simulation with visible mesh in Simscale.

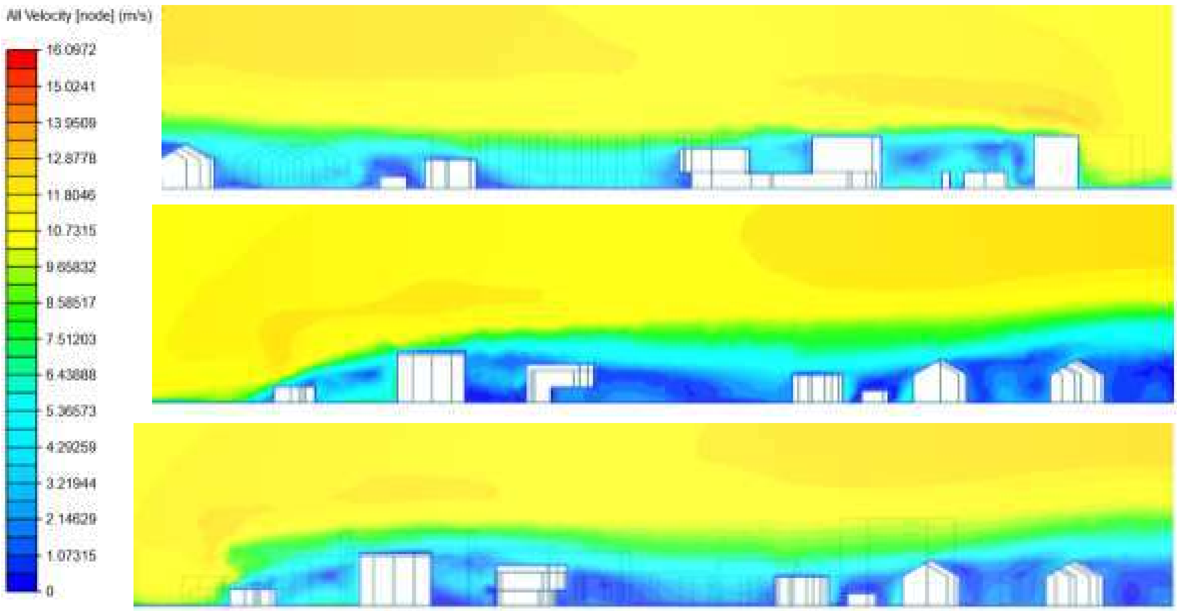


Figure 5. 213: Sections with West-direction wind velocity results.

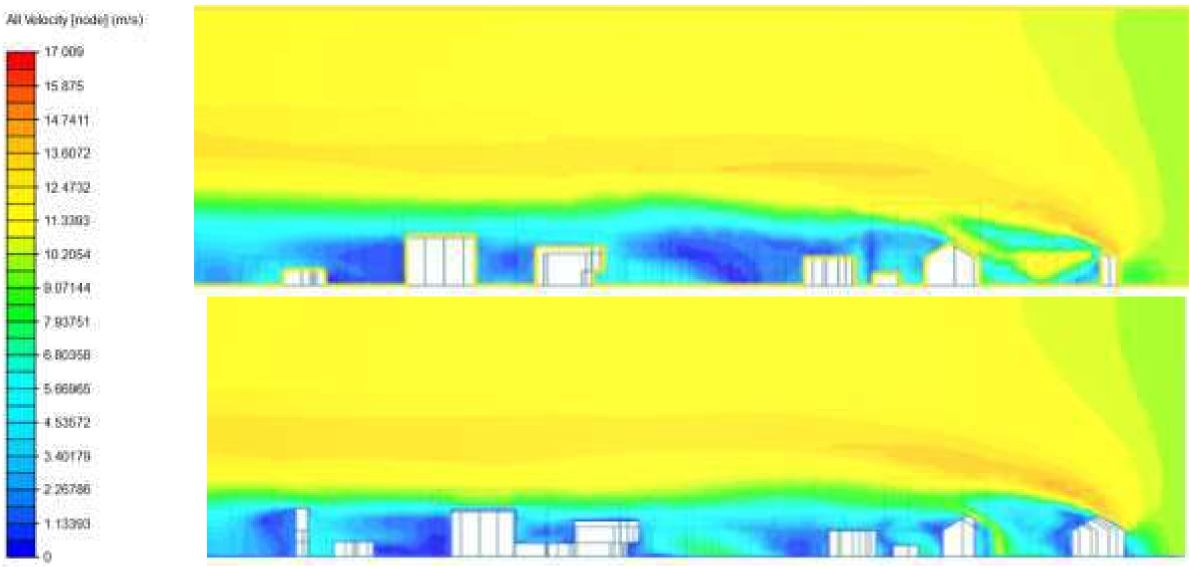


Figure 5. 214: Sections with East-direction wind velocity results.

In the sections and pedestrian level plan views, the wind direction in urban contexts gets reduced from 10 m/s to 6 m/s or lower values. Most spaces are below the 5 m/s threshold used by most wind comfort metrics, whereas a presence of winds above 5 m/s can be seen locally in the east open space of the Gerbiceva project which represents a larger unobstructed by buildings open area. However, due to the presence of vegetation and trees in the urban space, the wind speed can be expected to be lower than the simulation results, which account only for building geometry.

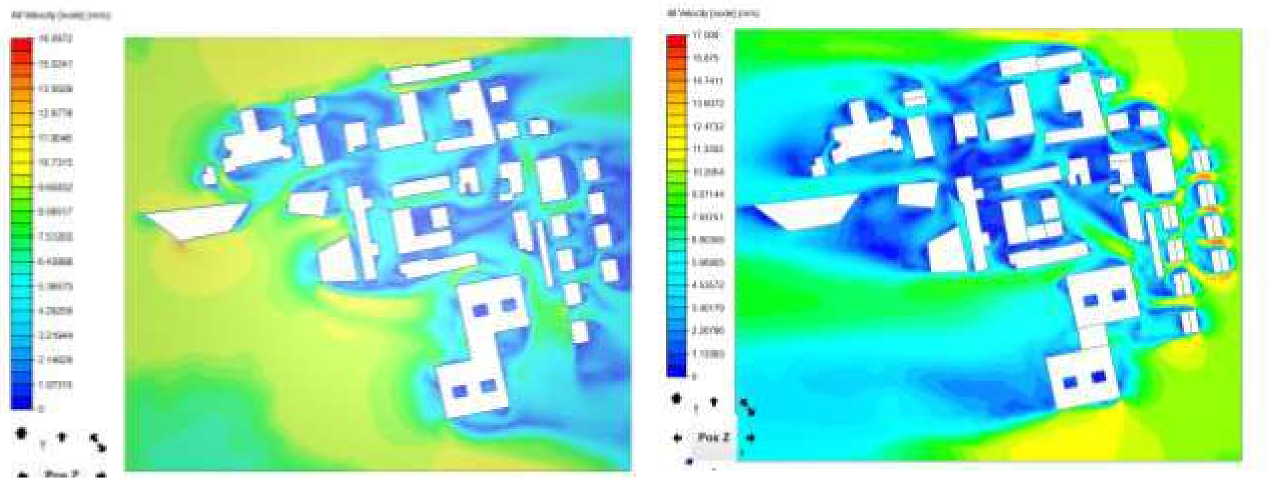


Figure 5. 215: Plan view with west and east wind blowing velocity results.

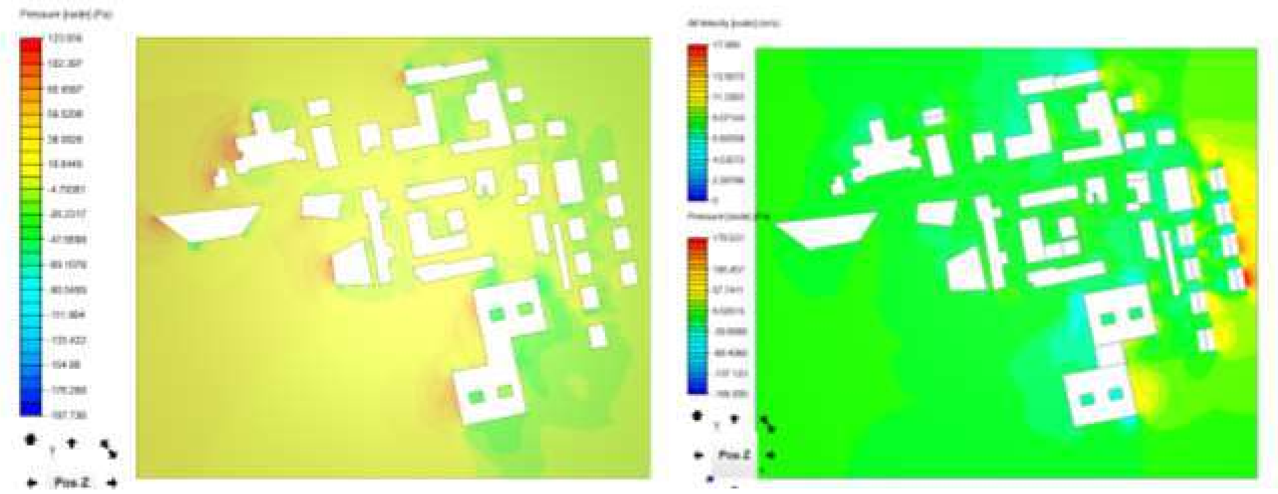


Figure 5. 216: Plan view with west and east wind blowing pressure results.

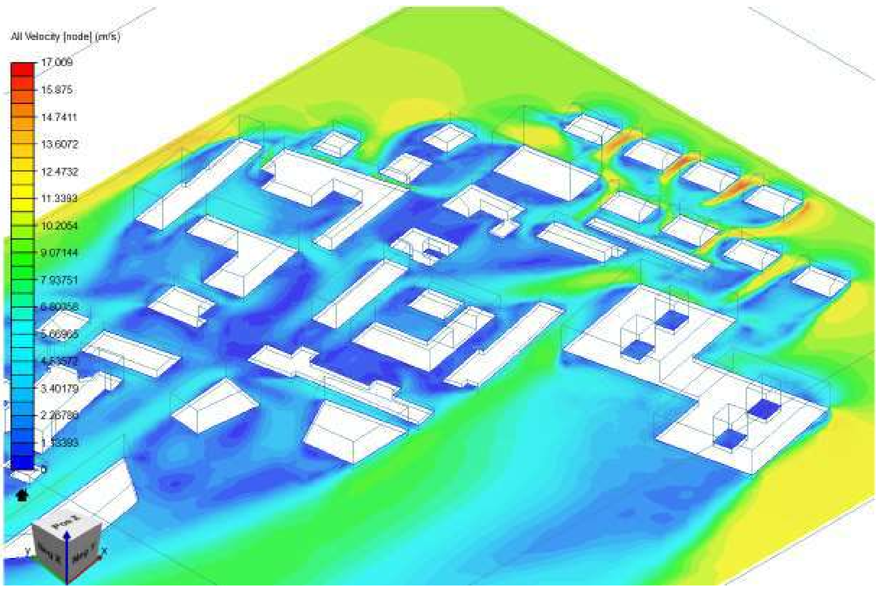


Figure 5. 217: Perspective view of wind simulation with velocity results.

5.15.2 *CFD for mechanical ventilation and indoor thermal comfort*

CFD simulations will be performed following recommendations of the new European standard EN 16798-1:2019. The Gerbiceva project predicts air conditioning with mechanical ventilation of accommodation units for the whole year, in winter and summer. The PMV and PPD model of Thermal Comfort will be used as output for the simulation results. The Adaptive model of natural ventilation is not predicted in the project, and output of thermal comfort with the adaptive model is not possible at this moment in time with simulation platforms. Table 4 in EN 16798-1 provides the categories for indoor environmental quality for buildings related to the level of expectation of the users. A normal level of expectation is usually selected for new buildings and renovations. The category II is used for Gerbiceva project.

Table 5. 31:Categories of indoor environmental quality.

Category	Level of expectation
IEQ_{I}	High
IEQ_{II}	**Medium**
IEQ_{III}	Moderate
IEQ_{IV}	Low

Table B.1 of EN 16798 recommends a PPD of less than 10% and a PMV between -0,5 and 0,5 to maintain thermal comfort for the design of mechanical heated and cooled buildings of medium IEQ_{II}.

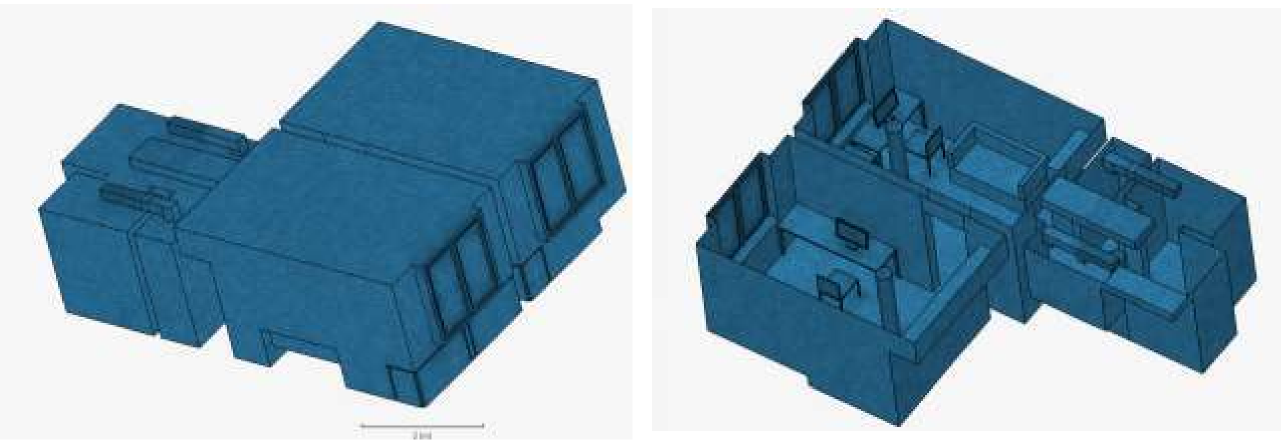


Figure 5. 218: Mesh geometry and inspection of air flow extracted volume for CFD.

CFD simulations have strict requirements for geometry such as solids and surfaces with no intersecting geometry and based on the type of simulation. It was not possible to create a flow region or mesh with IFC or other formats with Rhino exporting capabilities. The accommodation unit 02+1 34,56 m2 is tested for the simulation. It was recreated with Rhino and imported directly in Simscale platform. The Mesh control inputs are set up in the platform, and the mesh is generated on cloud-based computers. A Convective Heat Transfer type of simulation is set up with no radiation as a baseline. Additional simulations were performed to test the effect of convection and radiation, with occupants, walls and windows heat transfer in the indoor environmental parameters.

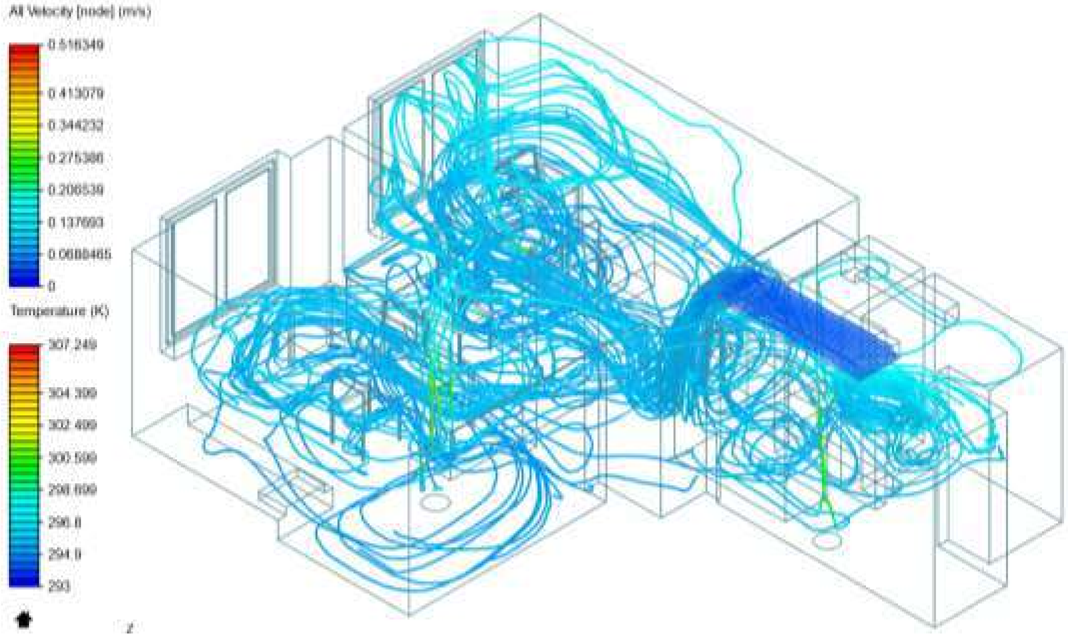


Figure 5. 219: Particle flow results of the velocity vector with Temperature scalar.

The particle flow allows understanding the changing temperature from the inlet of 21° to the outlet of kitchens and shower space. We can see that the temperature difference is less than 3° from inlet to outlet.

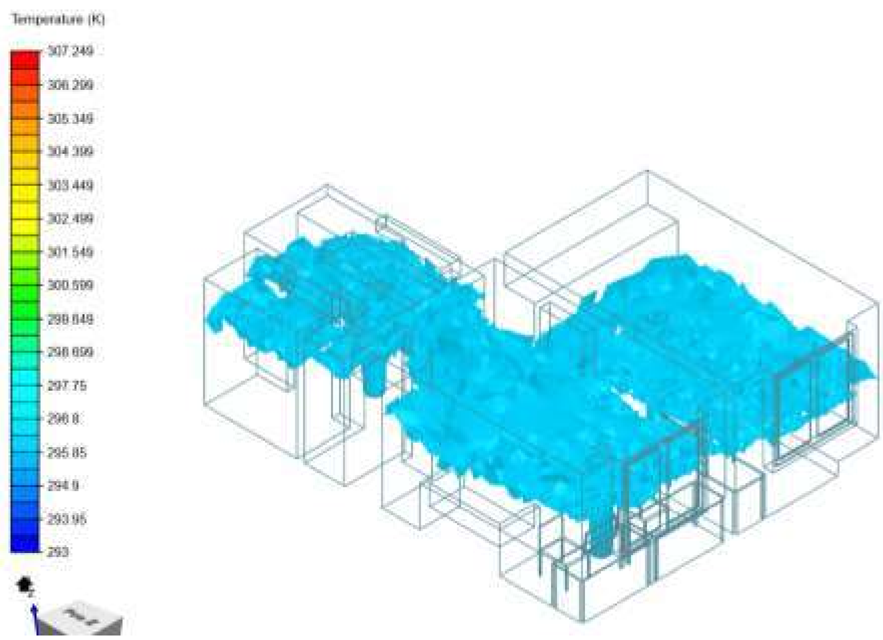


Figure 5. 220: CFD Isovolumes of Temperature in the accommodation unit.

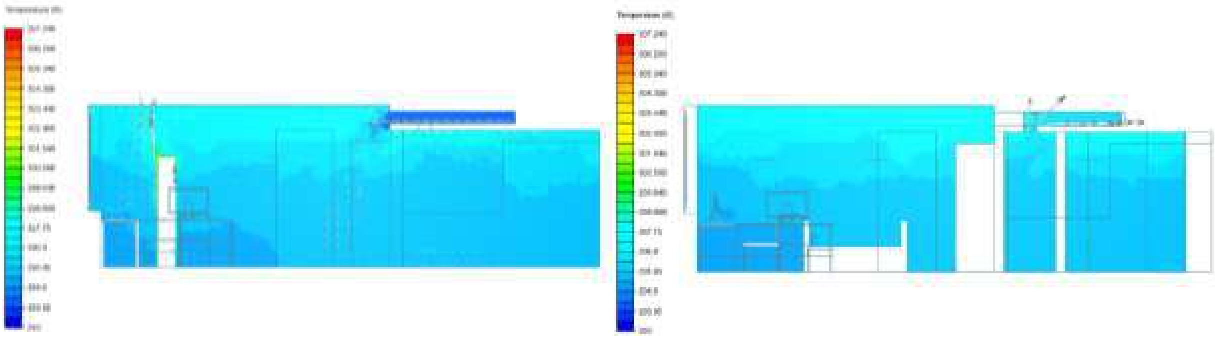


Figure 5. 221: CFD sections with Temperature colour coding.

The temperature difference from the ground to ceiling is within the 3° limit of vertical air temperature difference (head to ankle) required by EN 16798-1 for IEQ category II .

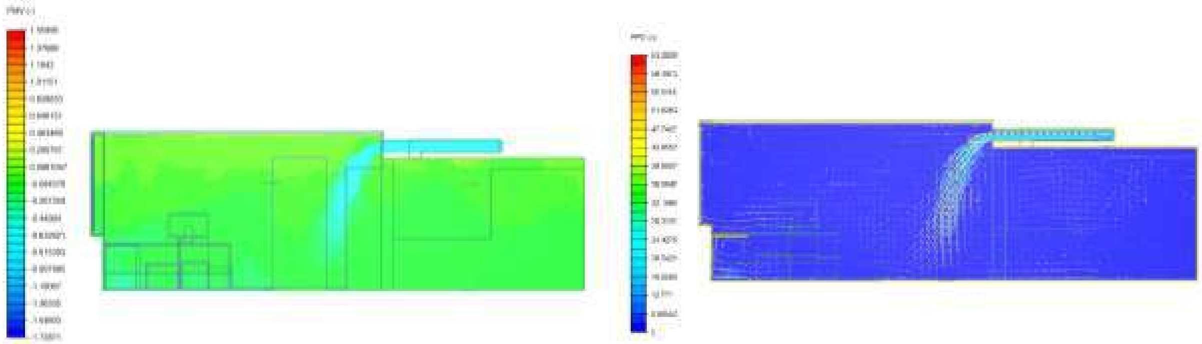


Figure 5. 222: CFD sections with metrics PMV and PPD.

The PMV results show a neutral thermal sensation, with a green colour that is an indication of a slightly warm sensation of 0,1 just above the neutral 0. The PPD is below the 10% target and at 15-20% in the proximity of the air inlet. A Clothing Coefficient of 1 clo, Metabolic Rate of 1 met, and Relative Air Humidity at 50% is set. The Air inlet speed is 0,2 m/s with a temperature of 21°.

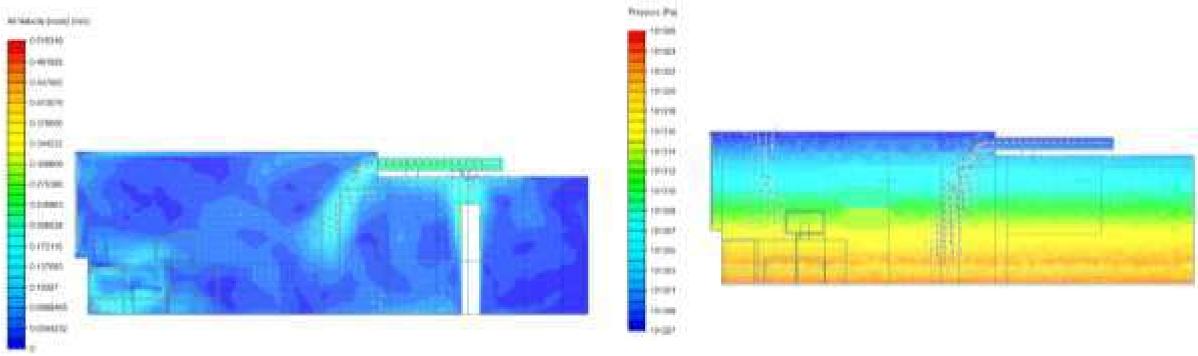


Figure 5. 223: CFD sections with metrics of Air Velocity and Pressure.

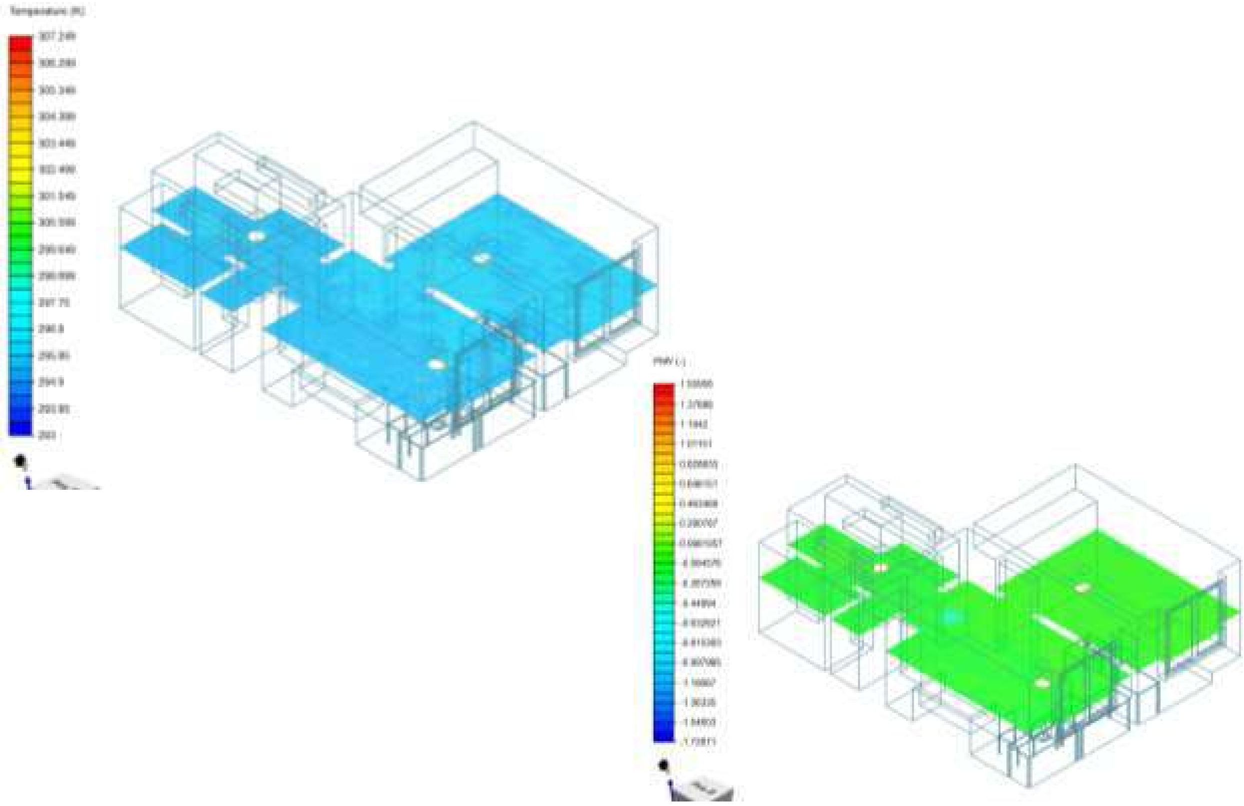


Figure 5. 224: CFD axonometry and sections of Temperature and PMV metric.

The simulation was repeated to account for effects of radiation of people and heat flux of walls and windows. The use of CFD with sensitivity analysis of the results for building components such as wall properties can be used to understand the level of insulation needed for winter or summer design. The HVAC system and energy savings that changing external insulation properties can bring can be explored with CFD simulations.

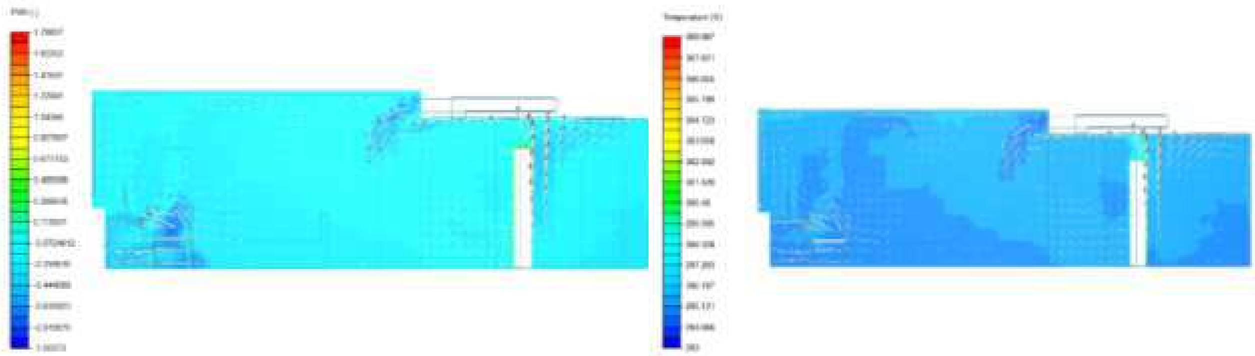


Figure 5. 225: CFD cross sections with metrics of PMV (left) and Temperature (right).

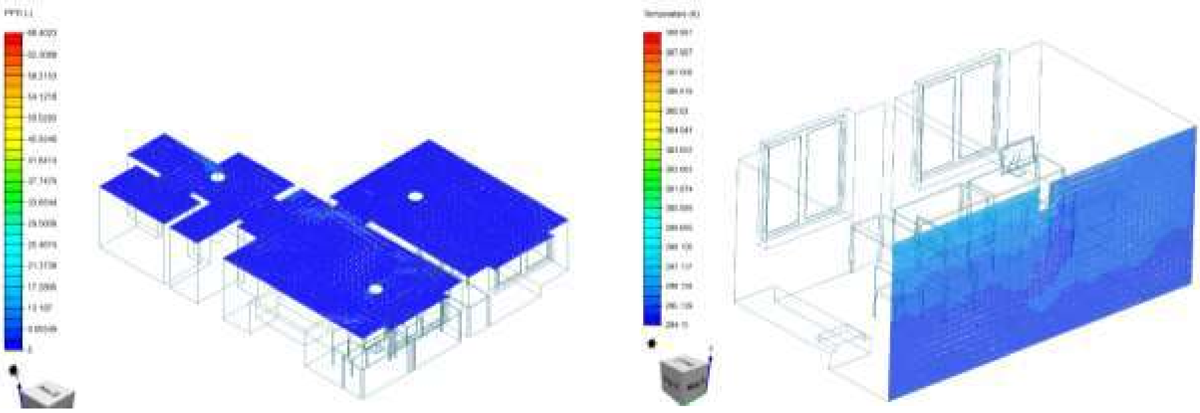


Figure 5. 226: CFD results in axonometry with sections of PPD (left) and Temperature (right).

CFD simulations require knowledge and skills to be performed by a specialist in the design team. As the tools improve, and object-oriented modelling approach is introduced, CFD analysis will become simpler and require expert knowledge to a less extent, with reduced time to prepare models for information exchange and more comprehensible inputs for simulation for non-expert design professionals.

6 INFORMATION REQUIREMENTS BASED ON ISO 19650 SERIES

Working with BIM for projects requires from the Client-side the development of high-level and detailed level information needs based on the assessment of organizational goals and strategic objectives, project scope, tender process, for project-related appointments, and the project delivery. In other words, the Information needs to be part of a managed process during the delivery phase of assets. ISO 19650: 2018 Part 1 provides guiding concepts and principles for information management with Building Information Modelling.

The standard's diagram of the hierarchy of requirements indicates that at the top are the business-related high-level Organizational Information Requirements and project-related Project Information Requirements. PAS 1192-2, now withdrawn with the arrival of EN ISO 19650, used to define the Level of Definition, which was composed of the Level of Detail (LOD) and Level of Information (LOI). The BIM Forum Level of Development (LOD) Specification 2019 defines the levels of development and the requirements. In ISO 19650, the LODs do not exist anymore. The standard defines the Level of Information Need (LOIN) as the new framework to determine the quality, quantity and granularity of information appropriately according to the defined scope for the Information Requirements. Metrics are needed to define LOIN, at least two, for the geometrical and alphanumerical content of the information. These metrics need to be used with consistency across the delivery phase and within OIR, AIR, PIR, EIR and for every trigger event of information exchange.

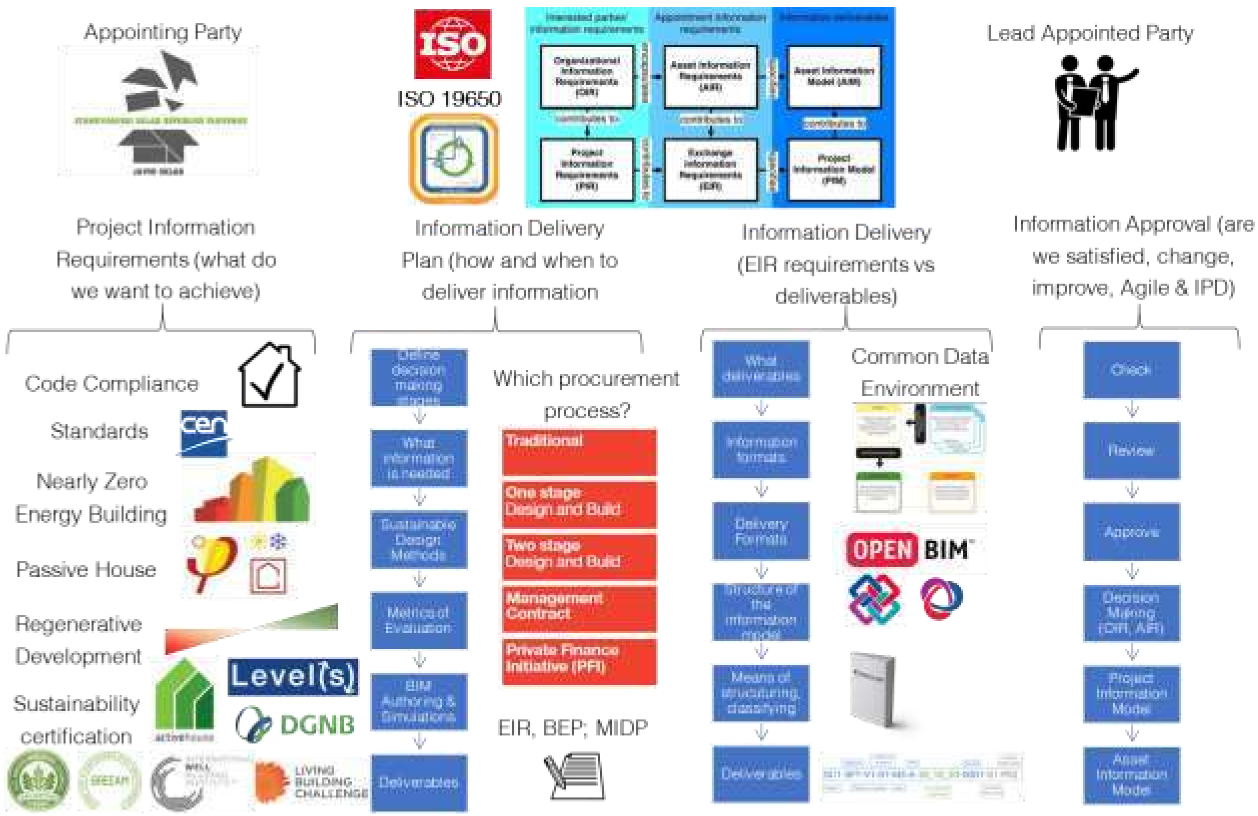


Figure 6. 1: Information Management for public procurement diagram based on ISO 19650 series for the information delivery life cycle.

Key Performance Indicators (KPIs) and Plain Language Questions (PLQ) can be used for Infomation Requirements. The diagram in Figure 6.1, illustrates the information delivery process that could be used by a public authority such as the Housing Fund of the Republic of Slovenia, and how a BIM managed process and requirements need to be established within the Organization, for the Project appointment, Information deliverables, exchanges and approvals. When defining Project Information Requirements, the OIR provides input along with the project scope requirements. What do we want to achieve? E.g. Code Compliance, implementation of standards, a Nearly Zero Energy Building and Districts, a Passive House certified project, pursuing reporting or certifications such as the novel EU Level(s) framework, the DGNB, LEED, BREEAM, WELL or the Living Building Challange. When PIR are defined, they provide input to the EIR. The EIR is used in project-related activities and defined wherever there are information exchanges, including exchanges between task teams. The Information management processes can be sub-divided based on the appointment or decision making stages of the client, e.g. for the activities of procurement, planning and production stages. The high-level requirements will guide specifying the Level of Information Need, the Sustainable Design Methods to follow, BIM Model Uses, and analysis needed, e.g. Whole Building Life Cycle Assessment. The metrics for Regenerative Design prepared in the previous chapter can be used as KPIs and information needs. If no green building certification is pursued, Regenerative Design goals can still be pursued, e.g. embodied carbon, operational energy, human well-being, daylighting and glare control. The Regenerative Design metrics can be selected for the alphanumerical information. The geometrical information of LOIN is strongly related to the requirements of the design stage, type of Sustainable Design Analysis to be performed and related alphanumerical metrics. The workflows in the previous chapter and cross-checked results are lessons learned to help in selecting the most appropriate workflows and types of analysis based on the complexity and scale of the project. For every project stage, the information requirements can be made of questions and measurable KPIs, e.g. Is the analysis-simulation validated, geometrical and alphanumerical information and documentation needed to answer to Exchange Information Requirements.

A role and responsibility matrix can be used to set out the responsibilities of the lead appointed party, appointed parties and team members for each task-related information containers and set out collaborative working. The Client has to specify the Exchange Information Requirements, Project information protocols, standards and production methods.

A table of BIM Uses by Project Stages can be used. BIM Uses such as Daylighting can be performed at different stages. The level of quality, quantity and granularity of information changes with each design stage. The scope of analysis changes as well. The goal is to inform design decisions and pass valuable information to the following project stage.

The Lead Appointed Party prepares the Master Information Delivery Plan. It should comply with the documents prepared by the Client. What needs to be delivered, information formats, delivery formats, structuring and classifying the information should be defined in the EIR, included in the BIM Execution Plan, and followed in every information exchange and approval process. The Client can require the Lead Appointed Party to document the data, inputs, approximations and missing information for the analysis, in the deliveries, to ensure consistency and comparability with their information and business needs. Existing asset information, Benchmarks and Templates can be used if needed during project per appointment activities, e.g. to provide a common ground of alphanumerical inputs, geometrical inputs and shared resources needed during the procurement and pre-appointment phase to ensure comparability of proposals and evaluation, e.g. potential to achieve project goals, scoring of pre-appointment BEPs, delivery teams capability and capacity.

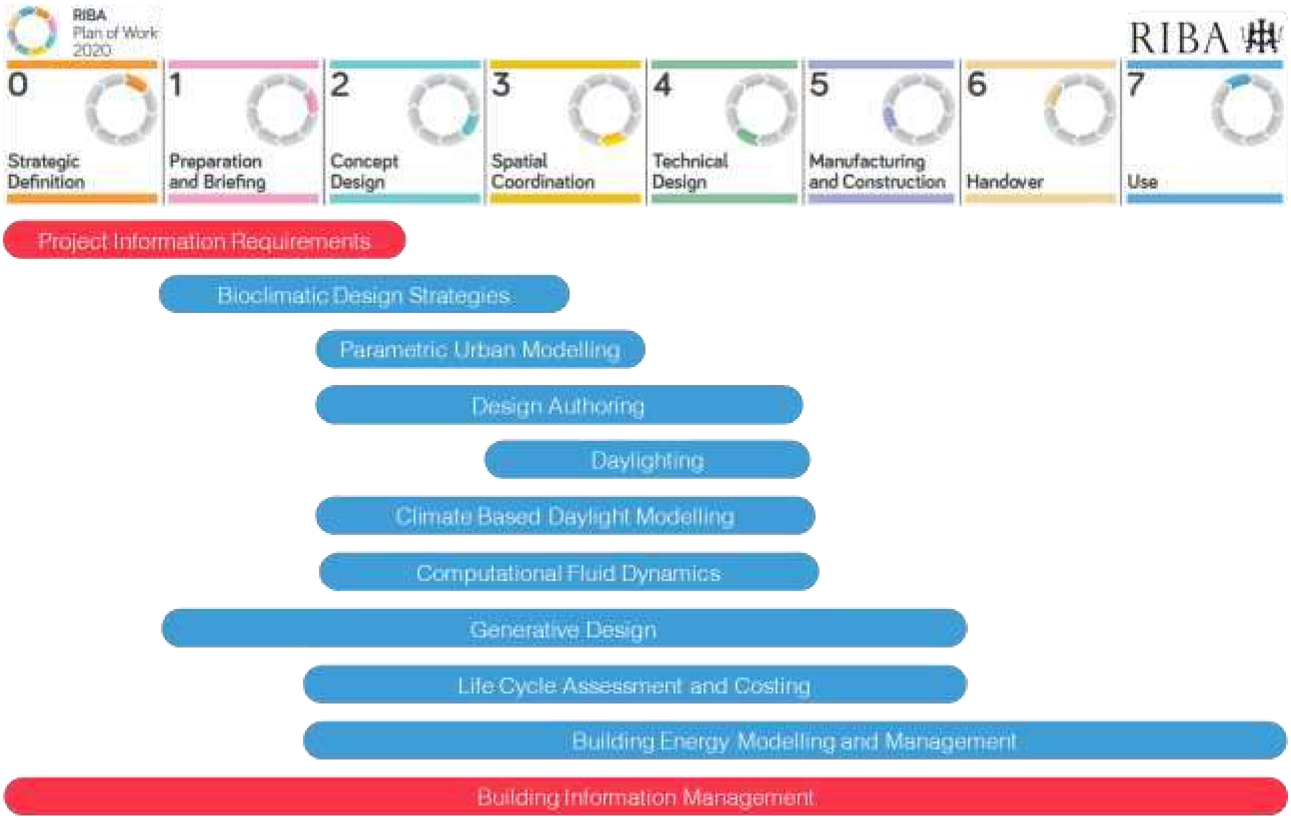


Figure 6. 2: BIM requirements for Regenerative Design based on ISO 19650 & RIBA Plan of Work 2020.

<u>*General Requirements for Project and Asset Information Requirements*</u>

- *Software requirements*
- *Team/Specialist competency or required credentials for the type of Analysis/Simulation/Certification*
- *Benchmarking*
- *Established goals and targets*
- *Baseline and Design Optimizations*
- *Input Data*
- *Sensitivity analysis by varying building characteristics, e.g. Geometry, orientation, WWR, properties.*
- *Reporting*
- *Quality Assurance (data quality and uncertainty, approximations, missing data)*

The RIBA Plan of Work 2020 template is used for the scope of planning the identified BIM Uses for Sustainable Design within RIBA's project stages[66]. The Project Information Requirements are identified early in the Strategic Definition, to limit their modification on later stages of Preparation and Brief or at most within Concept Design. Building Information Management practice needs to be part of the competencies and organizational procedures from the Client-side and appointed parties for meeting project goals and schedules. The RIBA Sustainable Outcomes Guide provides information on the contribution of the professional practice to the achievement of the 17 SDGs[67]. The guide gives metrics and benchmarks, organized based on the three sustainability dimensions of environmental, social and economic aspects for achieving the RIBA 2030 Climate Goals. The whole range of metrics of design performance is simplified and converged into the Net Zero Operational Carbon, Net Zero Embodied Carbon and Water Cycle. Life Cycle Cost is included, which most of the Green Building rating systems fail to include. The other metrics of social and economic sustainability, which are not possible to quantify with Digital Tools are measured with Post Occupancy Evaluations and other approaches. Land Use and Ecology could be explored in the future with the new concept and metric of Biodiversity Net Gain. The real world and its digital counterpart are becoming more and more interconnected. POEs, Energy and Asset Management will be included in Digital Twins to support future Client decisions for maintenance, refurbishment and deconstruction at asset End of Life, supporting recycling of building materials in a Circular Economy. The guide includes targets to be achieved in the following years in the RIBA 2030 Climate Challenge and detailed principles for the metrics.

[66] Royal Institute of British Architects. (2020). RIBA Plan of work 2020 Overview. https://www.architecture.com/knowledge-and-resources/resources-landing-page/riba-plan-of-work
[67] Royal Institute of British Architects. (2019, December 12). RIBA Sustainable Outcomes Guide. https://www.architecture.com/knowledge-and-resources/resources-landing-page/sustainable-outcomes-guide

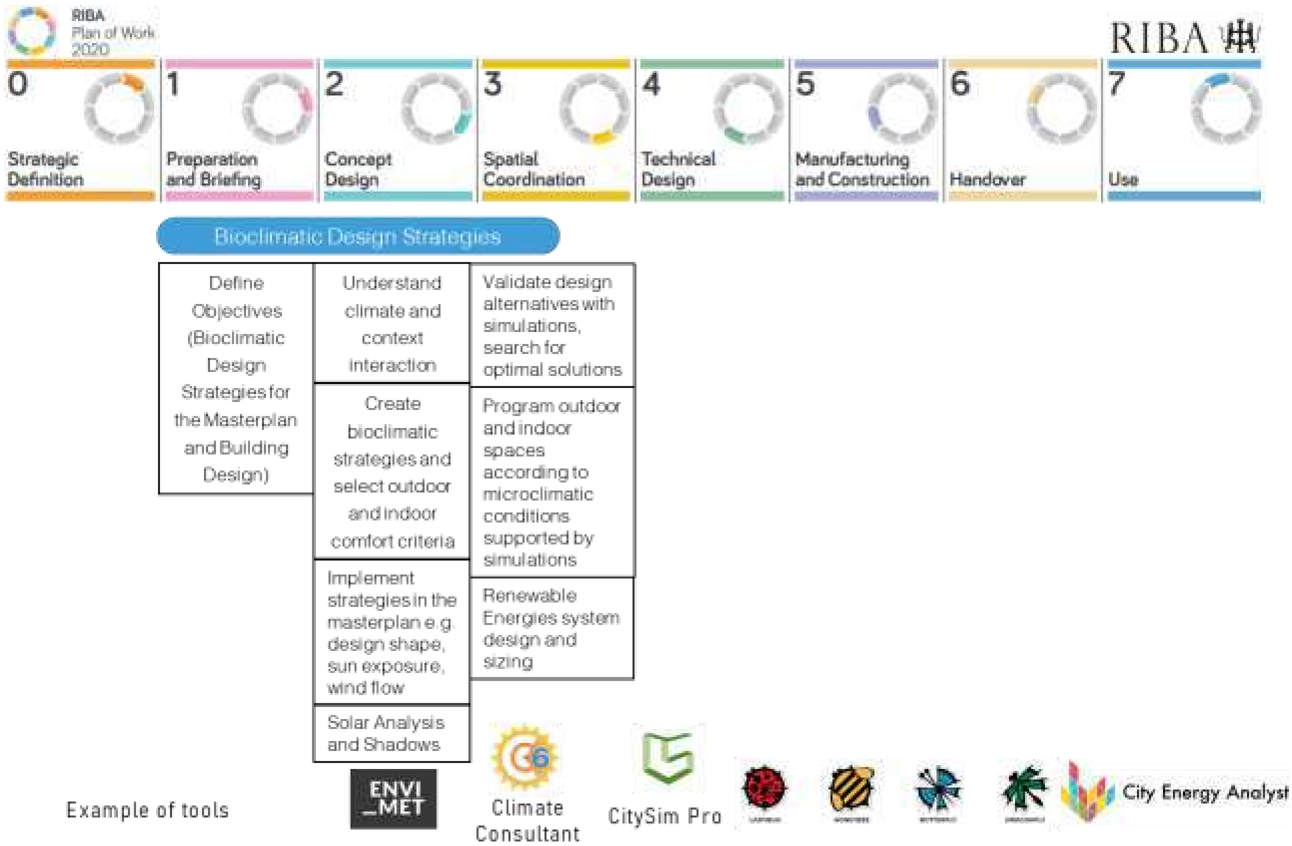


Figure 6. 3: Information Requirements for Bioclimatic Design Strategies.

Information Requirements for Bioclimatic Design Strategies

- *Provide information about the source of data, e.g. Type of weather file used and publisher*
- *Provide Input data used for the analysis performed*
- *Provide a Diagram/Chart/Visualization with the legend of metrics supporting the design strategy/concept/guideline*
- *Describe the analysis/findings*

Example of Analysis

- *Plot the Psychrometric and Bioclimatic Chart*
- *Define Bioclimatic strategies with the chart*
- *Urban Heat Island effect*
- *Outdoor Thermal Comfort*
- *Wind Comfort*
- *Solar Analysis, Radiation, Shadows*

While the RIBA guide focuses on outcomes, the intent of this academic work is also to shift the Client and design practice towards the new BIM paradigm and Regenerative Design thinking for real projects. The Architectural Design principles and concepts are to be framed within the project stages. The framing of design methods is to be seen through the lens of Regenerative Design and related Analysis for the project stage. The design methods framed inside the squares and stage of the BIM Use inform the next design stage. The Methods identified are to be seen from a qualitative designer's point of view, coupled with modelling requirements and KPIs of information needs. The geometrical needs are defined and measured based on the project stage, type of analysis, related information requirements, and a sample of tools that support such workflows. For the identified BIM Uses and related Design Methods, high-level Information Requirements and Examples of Analysis are identified. The Client PIR, EIR, Information protocols and standards provide input for the preparation of the BIM Execution Plan and MIDP by the Lead Appointed Party and task information delivery plans by appointed parties. Roles and responsibilities, software, naming conventions, information formats and classification systems are to be specified for every information exchange.

The Bioclimatic Design Strategies are presented as a separate BIM Use. The importance of Bioclimatic approach Information requirements since preparation and briefing can not be stressed enough. The focus needs to shift from solely using building technology to solve problems, increase efficiency and reduce impacts, but using the site's free energy flows of sun, wind, vegetation and water cycles. Bioclimatic strategies can improve performance significantly, support regeneration, reduce costs, and allow for the building technologies to be used in support of achieving comfort throughout the year, and not as one climate fits all as done in most cases of building design.

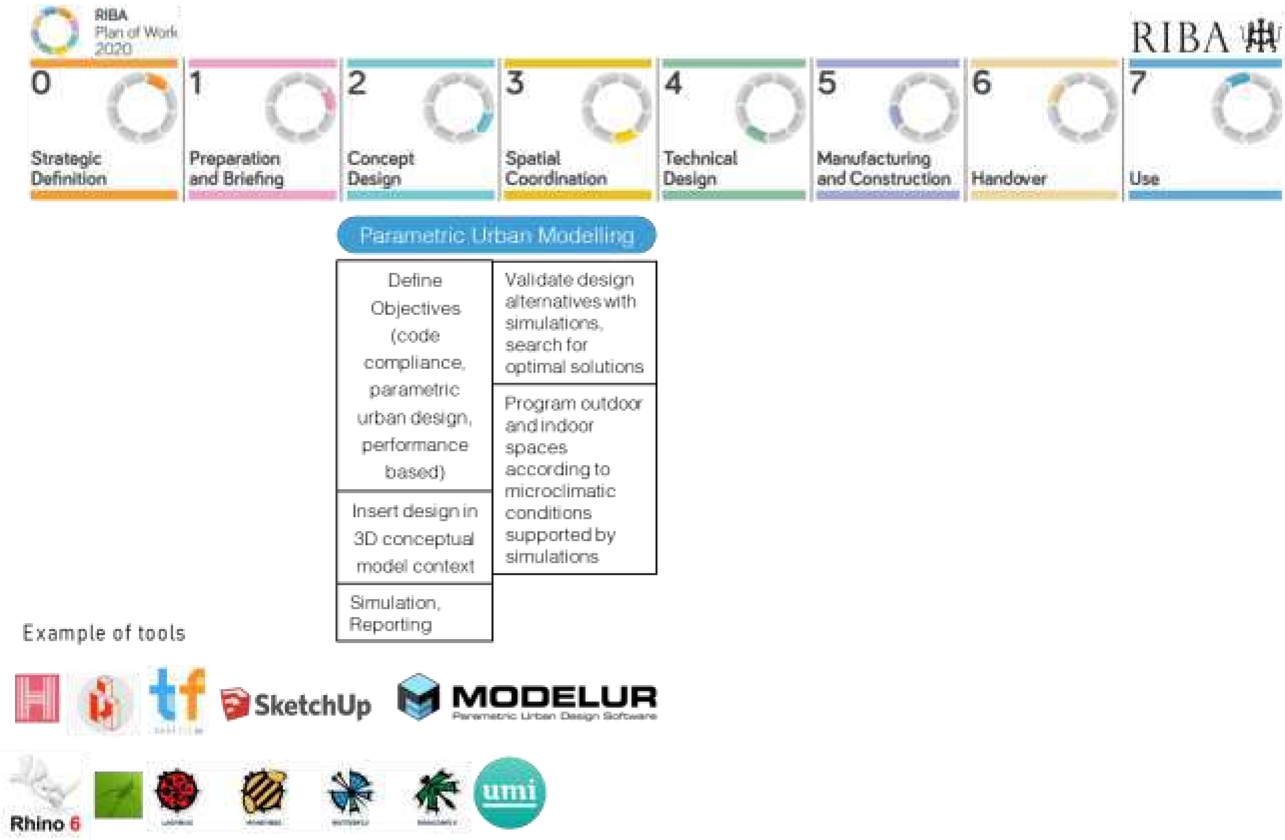


Figure 6. 4: Information Requirements for Parametric Urban Modelling.

<u>*Information Requirements for Parametric Urban Modelling*</u>

- *Provide information about the source of data, e.g. Type of weather file used and publisher*
- *Provide Input data used for the analysis performed*
- *Provide a Diagram/Chart/Visualization with the legend of the metric for the Analysis performed*
- *Describe the analysis/findings*

- *Provide guidelines insights for next project stage (Masterplan, spatial distribution, building program, targets for certification to pursue*

<u>*Example of Analysis*</u>

- *Design Optimization of goals, e.g. Form Factor, Heat Loss Form Factor, Floor Area Ratio, Open Space Ratio, Height, Building Distances Site Coverage, No. of people, parking, units.*
- *Right to light, right to landmark/nature views*
- *Daylighting Potential (sDA, cDA, DA)*
- *Energy Use (kWh/m2)*
- *Solar Potential (kWh/m2)*
- *Outdoor Comfort (UTCI, Davenport, Lawson)*
- *Embodied Carbon + Operational Carbon (kgCO_2e)*
- *Shadow studies, sunlight hours*

Regenerative Design requires a holistic approach. Currently, no single software can support the vast amount of requirements for Code Compliance, urban design form or performance. The concurrent use of tools based on their potential is needed for holistic design. While Tools add functionalities and become more interoperable, the time and effort required to make simulations and get results will be reduced for Design Optimisation and ultimately Generative Design exploration with Computational approach.

Design Authoring has a crucial role to play as a BIM use for Sustainable Design. It handles all exchanges for the other BIM uses and Downstream analysis, and it needs to reflect those changes to the information-containers and federation strategy within the Common Data Environment (CDE). The BIM Execution Plan, naming conventions and classifications should be present since the concept stage. It is best practice to use the Technical Design stage to reflect all the feedback of previous stages, coordination and findings. Exchanges with simulation tools at this stage should be limited as they would increase costs, create delays and issues at later stages. A physical model to validate simulation results can be done during the Technical Design Stage, e.g. Wind tunnel test.

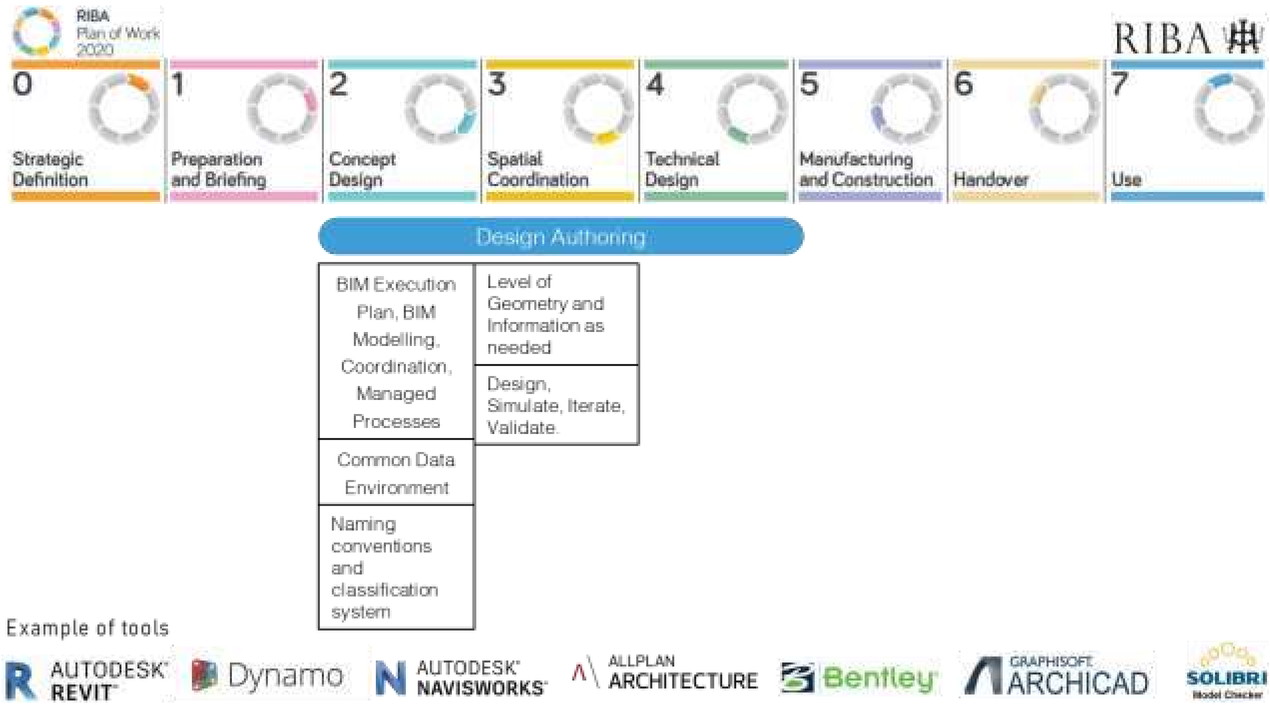


Figure 6. 5: Information Requirements for Design Authoring.

<u>*Information Requirements for Design Authoring*</u>

- *Are the bioclimatic design strategies /analysis/guidelines being reflected in the design and how?*
- *Provide a Diagram/Chart/Visualization on the integration and compliance of developed design with the previous stage*
- *Provide a description of the compliance*
- *Provide BIM Model and drawings for review*

<u>*Example of Analysis*</u>

- *Generative Design Optimization of Design Goals*
- *Develop Design Options for Analysis*
- *Reflect changes in the design from the analysis findings*

We spend 90% of our time indoors[68]. Therefore Daylighting is a must to improve health and well-being. Research studies and Post Occupancy Evaluations have linked good daylighting with increased productivity, activating the natural circadian rhythms and improve well-being by contact with nature. Daylighting is strongly related to Bioclimatic Design, Energy, Thermal and Visual Comfort, Biophilia, and discomfort from overheating. It can influence urban form, shadings, glazing, and material selection. If applied for all design stages, can inform better design decisions and smarter choices in other areas of the design process.

[68] Velux. (2019). Healthy Homes Barometer: Growing up in (un)healthy buildings.

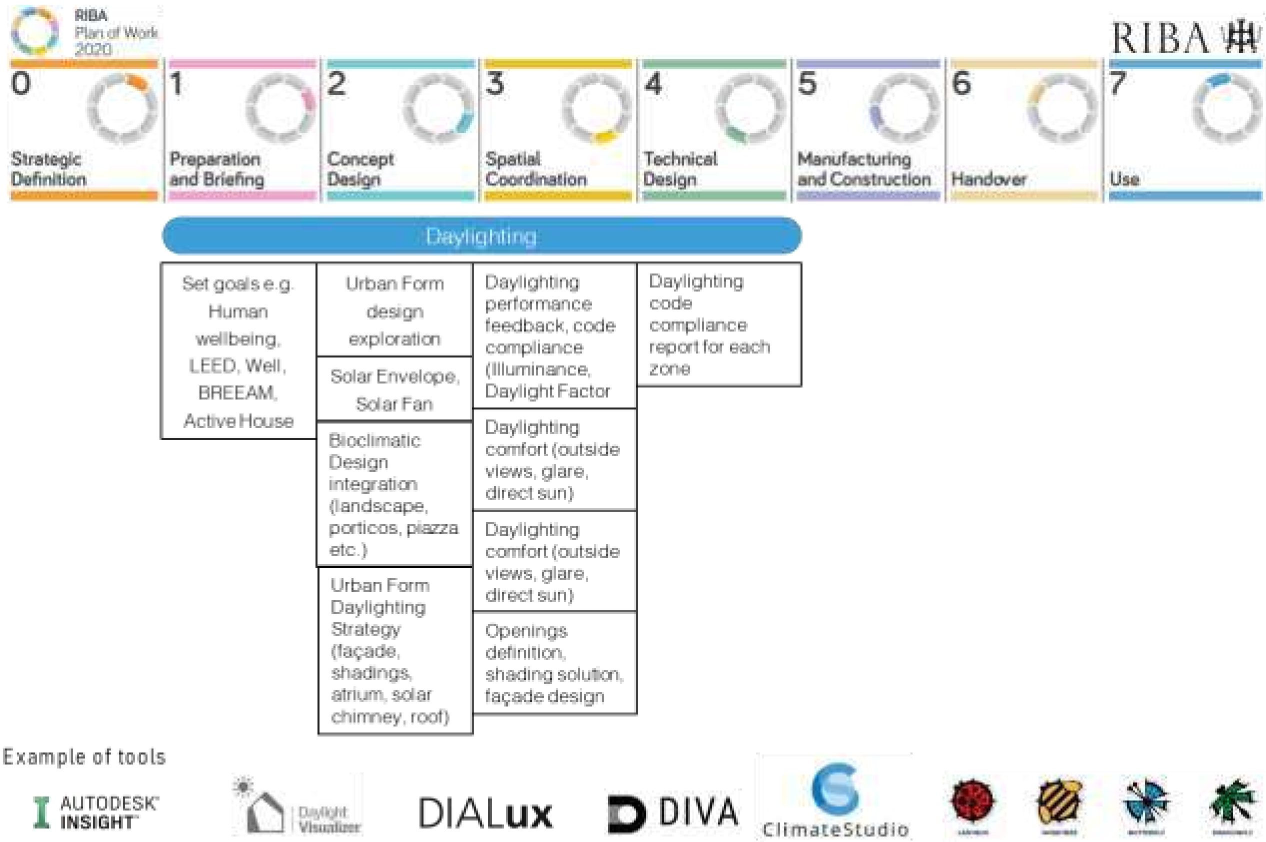


Figure 6. 6: Information Requirements for Daylighting.

<u>*Information Requirements for Daylighting*</u>

- Are the bioclimatic design strategies /analysis/guidelines being reflected in the daylighting design and how?

- Provide input data (materials reflectance and Tvis of glazing within EN 17037-2018 "Daylight in buildings" recommended values

- Provide simulation screenshot with legend, alphanumerical metrics for each zone.

- Mark results if pass min. Target illuminance or corresponding Daylight Factor

<u>*Example of Analysis*</u>

- Daylight Factor for each zone following EN 17037 recommendations

- Illuminance value for each zone following EN17037 recommendations

- Annual Overview (monthly) of Illuminance on workplane, Luminance false-colour maps

- Views to the outside

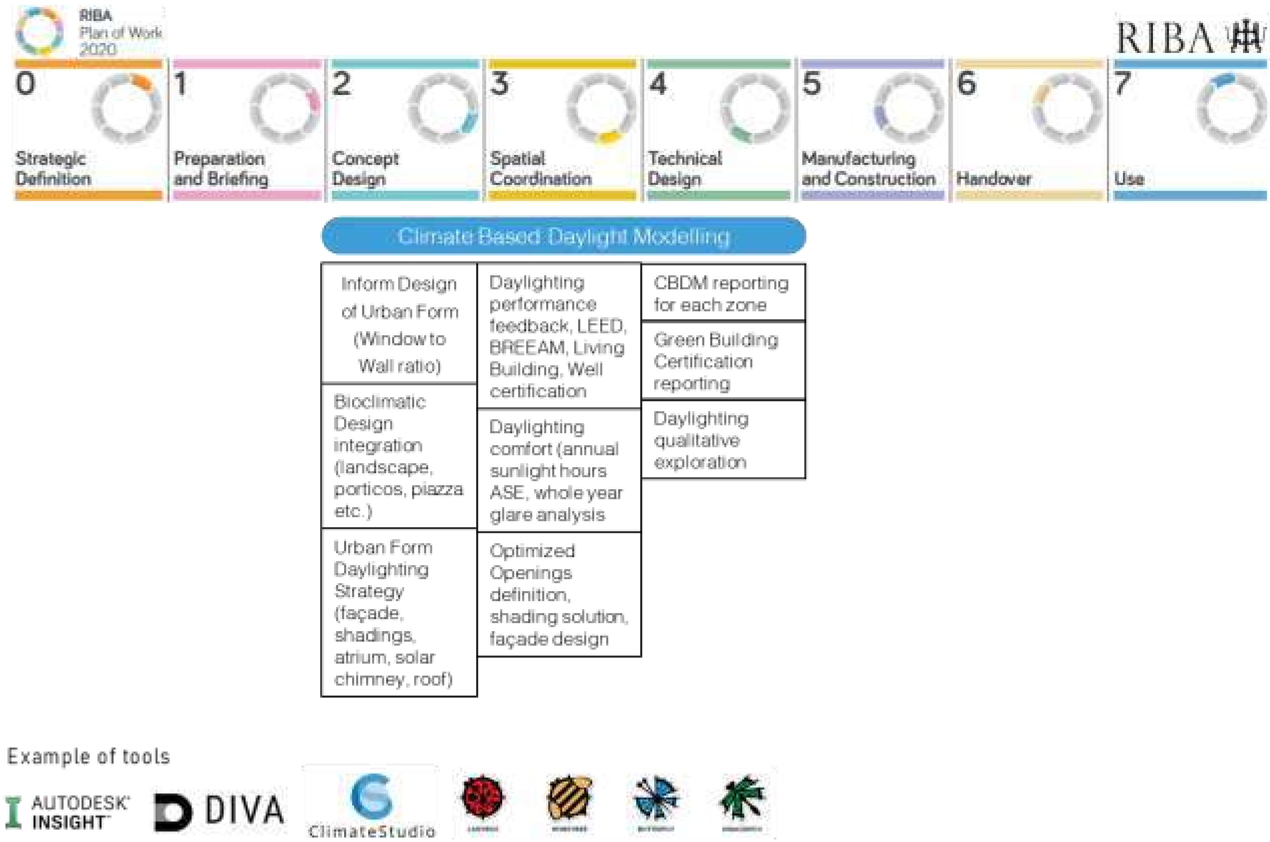


Figure 6. 7: Information Requirements for Climate Based Daylight Modelling.

<u>*Information Requirements for CBDM*</u>

- What CBDM metrics will the designer use to check performance and comfort?
- Provide input data (materials reflectance and Tvis of glazing within EN 17037-2018 "Daylight in buildings" recommended values
- Provide simulations of design options, e.g. No shading, with shading, overhang, facade
- Provide selected design simulation screenshot with legend, the alphanumerical metric for each zone.
- Mark results if pass Daylight credits of selected Certification System
- Provide interpretation of results and qualitative findings, how it has influenced the interior design

<u>*Example of Analysis*</u>

- CBDM performance (DA, ASE, UDI)
- Daylight Glare Probability Annual overview
- Illuminance and Shading annual overview maps and charts.

Climate Based Daylight Modelling is introduced as a separate BIM Use. Only some green building rating systems require projects to comply with credits based on CBDM. Design team require knowledge and skills to perform and understand CBDM. Knowledge from the Client-side is also needed to require the right level of information need. The insights provided by CBDM can inform the design based on performance and comfort in a complementary way. For example, ASE hours and DGP are different metrics, but they both impact the comfort of occupants and can be an indication for the other because they are inter-related. The computational approach can help the design explore the tradeoffs of different solutions. The exploration of design options and optimization strives to find the optimal balance. The Client team should have a good understanding of the concepts and application of CBDM if they intend to include in Information Requirements. It is not only the duty of designers to perform simulations and report results. Decision making requires improved collaboration and communication with meaningful information exchange.

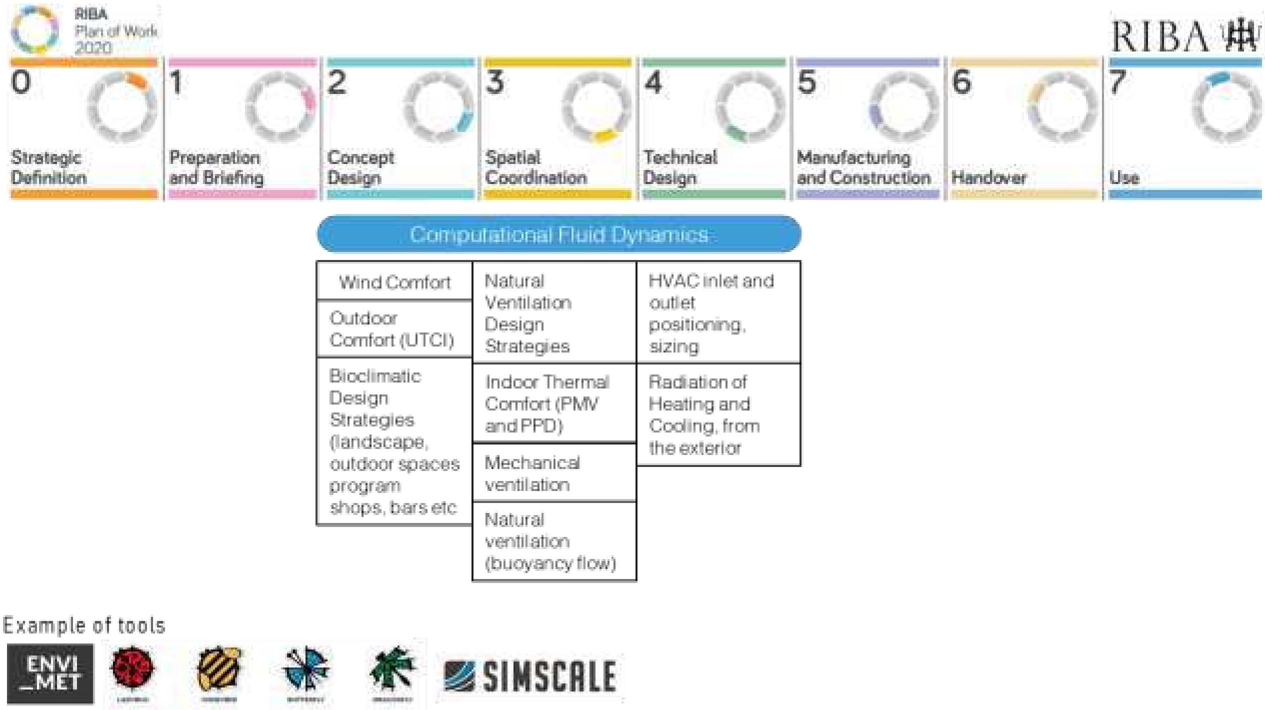


Figure 6. 8: Information Requirements for Computational Fluid Dynamics.

<u>*Information Requirements for CFD*</u>

- What climate data is being used?
- Provide input data (pre-processing, solver)
- Provide simulation screenshot with legend, colour maps and other types of representations available in 3D, plan, section.
- Provide alphanumerical metrics and the recommended values in standards.
- Provide a description of the solution and results

<u>*Example of Analysis*</u>

- Wind Rose
- Pedestrian Wind Comfort (Lawson, Davenport, NEN 8100)
- Outdoor Comfort (UTCI)
- Natural Ventilation with PMV and PPD or Adaptive model of Thermal comfort.
- Mechanical Ventilation with PMV and PPD

CFD is highly accessible to design practice through open source tools and cloud-based solutions. The design team can rely on more than just tacit knowledge, but anticipate behaviour, comfort and well-being for design solutions from the urban level down to the single space thermal sensation in a season for a defined space.

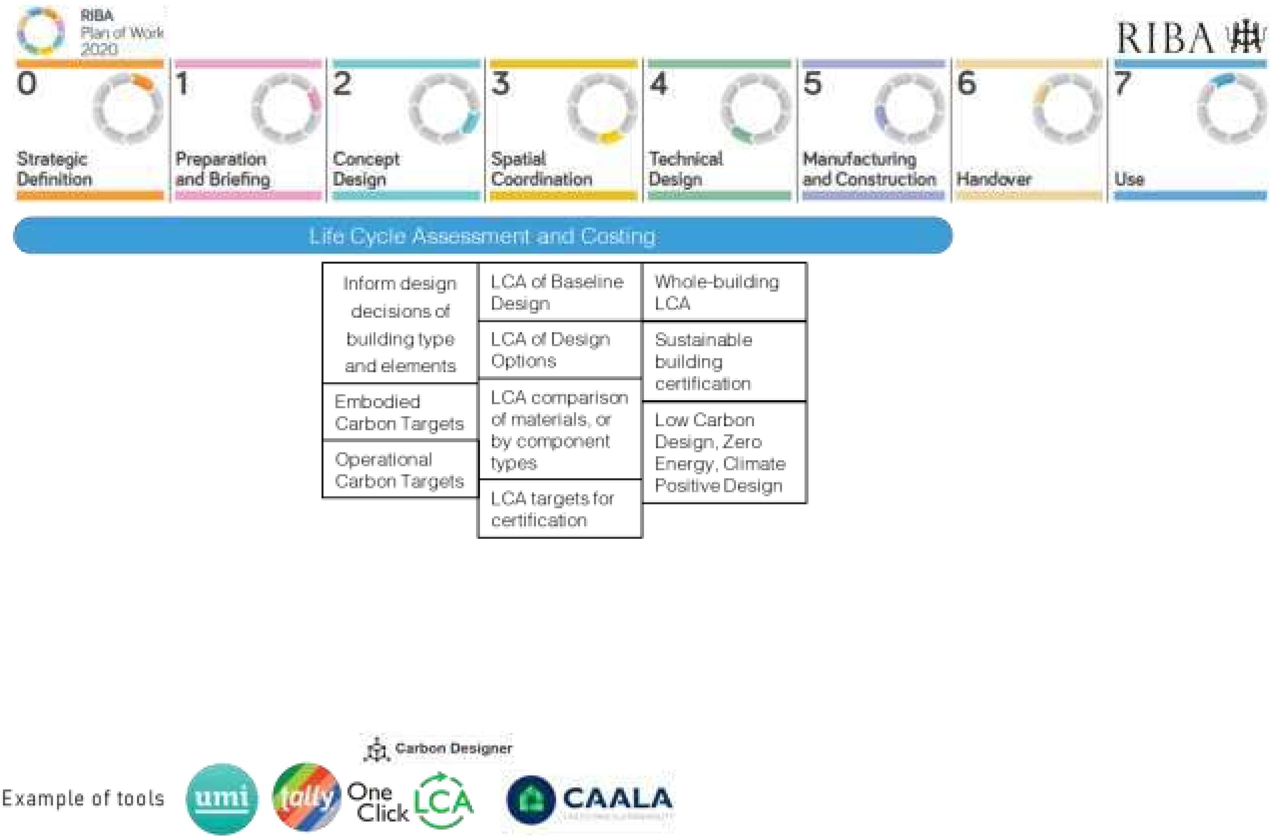


Figure 6. 9: Information Requirements for Life Cycle Assessment and Costing.

<u>Information *Requirements for LCA*</u>

- *What LCA database is being used?*
- *What are the criteria of selection, e.g. 1 Generic Materials 2 of the country 3 near the region*
- *Provide complete data set of materials coupled with LCA database and EPDs*
- *Provide information on missing data, approximations, integrations.*
- *Provide results of LCA (metrics+charts)*
- *Provide results of comparable metrics, e.g. Is biogenic carbon accounted? Are all material life cycle accounted in the Embodied Carbon?*

<u>*Example of Analysis*</u>

- *Material or building component LCA comparison*
- *Baseline and target optimization*
- *Whole building LCA (embodied+operational)*
- *Pursuing Sustainable Building Certification*

LCA and LCC are becoming increasingly relevant, and probably the most important way to measure the Sustainability of Constructions over the whole life, as it includes embodied carbon, construction phase, operation of an asset, water use and total energy use. LCA can be approached since the concept stage, with new BIM integrated tools and parametric models. LCA addresses not only the performance of a single building but can be part of high level strategic and portfolio management needs of an organization. Lessons learned from projects and LCA results can inform OIR, PIR and AIR of future developments.

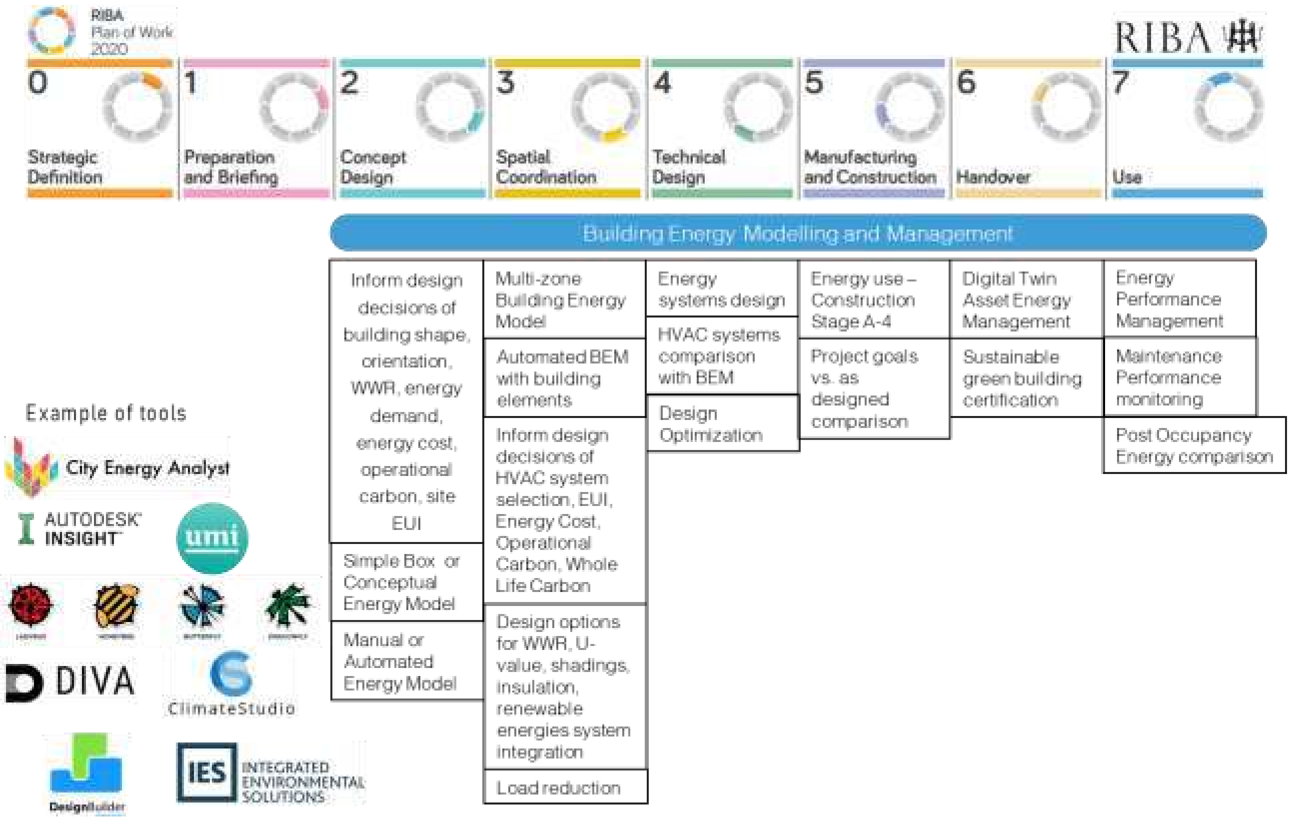


Figure 6. 10: Information Requirements for Building Energy Modelling and Management.

<u>Information *Requirements for BEM*</u>

- *What standards are followed to model and input data?*
- *Document standards used, templates, input data, model surfaces, constructions, thermal zones, geometry and information.*
- *Provide information on missing data, approximations, integrations.*
- *Provide BEM results (EUI, Cost, Total Energy, Source Energy, Normalized Energy, Carbon Emissions alphanumerical data, charts, report, and other if relevant.*
- *Provide results of comparable metrics, e.g. Is gross floor area or gross internal floor area used? Life Cycle Period?*

<u>*Example of Analysis*</u>

- *Conceptual Energy Modelling and Carbon*
- *Multi-zone Building Energy simulations (as-designed, as-built)*
- *Baseline and target optimization*
- *Sustainable Building Certification, e.g. Passive House, LEED, Living Building Challenge*.

Building Energy Modelling and BIM integration are expanding to all project stages. BEM can be used in the delivery phase, in Energy Management with the Digital Twin and for maintenance and through new models of collaboration that go from design to asset operation with Energy Performance Management contracts. The alphanumerical metrics need to be used with consistency, and clear description of input data, e.g. is the gross floor area or gross internal floor area used for the Energy Use Intensity. Consistency and comparability of data are crucial to the project and organizational information needs.

7 CONCLUSIONS

Throughout history, architecture has been a product of human collaboration, historical context, and climate. The evolution of making cities and buildings has been shaped by traditions passed from people to people, written documents, the scientific revolution and later with formal university education. The need for sustainable development within planetary boundaries and the new paradigm of Building Information Modelling are transforming the Design and Construction practice and the built environment.

The second chapter served to understand and connect concepts needed for Regenerative Design, from the evolution of design methods in history, highlighting key milestone contributions in Architecture and Urban Planning in the 20th century, and reviewing the current Sustainable Design Methods. From the Bioclimatic approach to Regenerative Design, principles of Biomimicry, Passive House standard, Nearly Zero Energy Buildings, Climate Change adaptation, Circularity contribute for the development of a sustainable built environment for society and nature to thrive. The most relevant concepts, frameworks, certifications, and built examples are reviewed. Even though Regenerative Design has been introduced since the 1990s as a distinct discipline, only recently given our current unsustainable and human-centred economy, it is gaining significant momentum. We can no longer be concerned only on limiting our damage to the environment and just reducing human health risks but should go beyond the Brundtland definition of Sustainability to do better. Meeting the Paris Climate Agreement, Sustainable Development Goals of the United Nations, IPCC target of limiting Global Warming to 1.5° and most recent European Green Deal, requires a shift towards a Circular Economy and become Climate Positive by 2050. Buildings are responsible for nearly 40% of energy consumption and greenhouse gas emissions globally. The culture of designing and building needs to change from one that consumes resources and energy towards circularity, resilience, plus energy buildings, reduced embodied carbon, and in harmony with natural systems. In other words, from merely reducing environmental impacts, towards creating positive outcomes for the planet. Where in the past, natural and human systems have been regarded as separate, the correlation of ecosystem degradation, biodiversity loss and our reliance on the planet resources is more than ever evident and on the agenda of policymakers globally. The natural and man-made environments are to be regarded as one. The regeneration and co-evolution of these systems lie at the heart of regenerative design.

While Regenerative Design is relevant to today’s societal challenges, few built examples exist of truly regenerative developments. The Digital Revolution and Computer-Aided Design helped design and document better but has been good only at substituting paper drawings with digital ones. The fourth industrial revolution and BIM are creating new opportunities, integrating physical and digital systems. Building Information Modelling and Management improve collaboration, productivity and supports holistic design. Data is utilized and transformed into information with the support of digital models. Design thinking and human creativity can turn the information into meaningful design knowledge.

Clients, designers and builders come together early on the project table to collaborate and set project scope and requirements. An Integrated Project Delivery and BIM are imperative to achieve goals for a Regenerative Development. Interactions and synergies are built from the start, e.g. mapping activities, who needs to work with whom, at what stage, about what, the exchange information needs, how to deliver it, and when. Scope, budget, schedules are prepared for project and construction processes to meet the Client's needs. No one holds all the information and skills. The collaboration of all parties is imperative in a holistic approach. The right level of information needs is crucial for each trigger event of client-lead appointed party and between appointed parties information exchanges during the project life cycle.

Literature review, design methods, tools and metrics used were essential to creating a framework and applied methodology for holistic Digital Design to achieve Regenerative goals. Concepts, tools, criteria based on metrics, process diagrams and road maps are proposed throughout the work. KPIs are organized around the three dimensions of Climate, People and Nature. Widely accepted standards and metrics such as the Daylight Factor can guarantee a good daylighting performance. In contrast, new climate based daylight modelling and research bring new insights and KPIs to understand the performance and comfort of daylight based on climate, location, orientation, space layout, and occupant needs for well-being. New concepts and metrics are being developed, such as Biodiversity Net Gain or Circadian Lighting Design based on the biological effect of light in humans.

The fifth chapter explores the BIM integrated methodology with Regenerative concepts, tools and KPIs for measuring and optimising designs for performance, comfort, and regenerative outcomes. The beginning of every project should start with exploring design goals, understanding climate, finding a suitable location for the development. Bioclimatic Design Strategies, Outdoor and Indoor Comfort studied through the use of Weather Data, the Psychrometric Chart, computational tools, alphanumerical evidence and visualizations that can support an informed design process. Tools and metrics and tested to guarantee the reliability of data based on the types of analysis and related exchange information requirements. Multiple workflows and their results are cross-checked. Workflows, parametric models, automation and algorithms can be used with confidence when validated for simulation, compliant with industry standards and by the designer's critical review of the process and results.

The findings of BIM integrated Regenerative Design are synthesized into a comprehensive framework for formulating Information Requirements for Clients and the project team based on the ISO 19650 series. The objective is to use these requirements when needed for Organizational and Project high-level Requirements, detailed Asset and Exchange information needs for the delivery phases of the Project Information Model and Asset Information Model. A BIM managed process begins with the Strategic Definition, supports Procurement, information processes, down to asset maintenance and use.

Limitations of this study remain in the application of Regenerative Digital Design on Nature's (circular and resilient) aspects of the proposed framework, as the related KPIs would require design strategies and policies concerning the construction and operation phase of built environments. The performance of Nature and Human (well-being) aspects of the framework can only be partly explored through Digital Tools and metrics. Regenerative Development and outcomes on human well-being and co-evolution with natural systems can not be measured without doing patient science that requires longer timeframes that go beyond the design phase, construction, and the first years in the life of developments.

Summary

This study makes a review of Sustainable Design Methods, from Bioclimatic to Regenerative, with links to a Circular Economy, and the new paradigm for the design and construction with Building Information Modelling. Different frameworks have local, national or international reach with variable focus on environmental performance, social and economic sustainability. Climate Change response and meeting the SDGs for all and supporting the evolution of life on the planet requires new ways of thinking and designing. Regenerative Design holds the promise for shifting from the current approach focused on reducing environmental impacts and increasing efficiency towards designing a built environment that is regenerative, climate neutrality, restored ecosystems to a healthy state, allowing human and natural systems to co-evolve.

The main highlights of this academic work:

- Review the development of Sustainable Design Methods, from the foundational Bioclimatic approach to Regenerative Development and Design

- Progressive principles and concepts of the paradigm shift from CAD to BIM

- Framework for Regenerative Design following BIM principles and management

- Key Performance Indicators for Regenerative Design defined at the urban and building level.

- Demonstrating how BIM and Regenerative Design can support in meeting the SDGs, Paris Agreement climate goals, and European Green Deal

- BIM integrated workflows for Regenerative Design applied to a case study in Ljubljana

- Modelling requirements and different types of building performance simulations for Sustainable Outcomes.

- A comprehensive framework for developing Information Requirements based on ISO 19650 series for Regenerative Development and Design.

The Regenerative Design framework is based on a holistic approach with the most advanced digital design tools following Building Information Modelling and Management processes. The Methodology relies on sustainable design principles, BIM-integrated workflows, tools and KPIs that are used and cross-checked on a public residential development of the Housing Fund of the Republic of Slovenia. The Information Requirements that could be used by public authorities for project activities during procurement, planning and

delivery phase are taken into consideration and incorporated in the development of the requirements. The research is a contribution to the selection of design methods, tools and Information needs for Clients, Architects and everyone involved in the project delivery, based on ISO 19650 series for Regenerative Development and Design in an Integrated Project Delivery.

Recommendations

Knowledge, skills, and open explorer's culture is required from the Client, architects and all figures involved in the construction of the buildings. The responsibilities and ways of designing are changing to respond to global climate action goals. Limitations remain in the functionalities of tools, data quality, processing of data from solvers, and interoperability. Urban level or building simulations are not real-time and do not integrate both ways yet. As the tools approach real-time maturity and two-way interoperability, the industry will benefit from increased productivity and applied generative design. The designer will continue to rely on tacit knowledge. The simulations will support the process, in confirming design choices and reconsider the solutions which do not achieve desired outcomes. The synthesis will use multiple design criteria with concurrent KPIs from simulation results for design optimization. It is up to the design team and client to follow a holistic approach for better outcomes for human health and well-being and the environment. Building simulations need to reach the broader practice of architectural design and not remain within a few examples of the best practice. All buildings have an impact on the human and natural systems. The simulations need to be performed from the early design stage and not just in the end for code compliance and certification. Performance simulations will be done across multiple design stages, adapting to a holistic approach in every stage.

Future work

Regenerative Design and BIM can be seen as a set of tools, processes and policies. As tools and data evolve, it will create new opportunities to add new metrics from the Architect's point of view and as Information Requirements from the client-side. The findings of Regenerative Design for Ljubljana are not exhaustive of everything that can be achieved. Design is a creative process. Every time there is an opportunity to do things differently, improve processes and draw lessons learned for future work. The proposed Information Requirements are to be selected based on real needs and aligned to high-level Organizational and Project Information Requirements and specified in greater detail for each appointment and information exchanges.

New metrics such as Biodiversity Net Gain, Equivalent Melanopic Lux, human health and ecosystems impacts are still to be explored and understood fully. Different research fields and societal challenges provide new ways to understand and improve "what good architecture should look like". As human knowledge increases, new metrics will start to be included in Regenerative workflows and BIM requirements. The ISO 19650 Part 3 Operational phase of the assets, Part 4 Information exchange, and Part 5 Security-minded approach to information management that are under development will need to be included in practice. Simulations will not be done only when the design is complete to report performance but will move horizontally across all project stages. The holistic approach to Regenerative Design will take advantage of real-time interoperability, Computational and Generative Design.

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LIST OF ACRONYMS AND ABBREVIATIONS

Abbreviation or acronym	Term
AIA	American Institute of Architects
AIM	Asset Information Model
AIR	Asset Information Requirements
ASE	Annual Sunlight Exposure
BEM	Building Energy Model, Building Energy Modelling
BEP/BxP	BIM Execution Plan
BIM	Building Information Modelling, Building Information Management
BREEAM	Building Research Establishment Environmental Assessment Method
CAD	Computer-Aided Design
CBDM	Climate Based Daylight Modelling
CDE	Common Data Environment
CFD	Computational Fluid Dynamics
CLT	Cross-laminated Timber
CO2	Carbon Dioxide
DA, cDA, sDA	Daylight Autonomy, continuous Daylight Autonomy, spatial Daylight Autonomy
DF	Daylight Factor
DG, sDG	Daylight Glare, spatial Daylight Glare
DGNB	German Sustainable Building Council
DGP	Daylight Glare Probability
DHW	Domestic Hot Water
EIR	Exchange Information Requirements
EU	European Union
EUI	Energy Use Intensity
FAR	Floor Area Ratio
GFA	Gross Floor Area
GHG	Greenhouse Gas
GWP	Global Warming Potential
HLFF	Heat Loss Form Factor
HVAC	Heating, ventilation, and air conditioning
IEA	International Energy Agency
IEQ	Indoor Environmental Quality
IFC	Industry Foundation Classes
IPCC SR1.5°C	Intergovernmental Panel on Climate Change: Special Report on Global Warming of 1.5°C

IPD	Integrated Project Delivery
ISO	International Organization for Standardization
KPI	Key Performance Indicator
kWh	Kilowatt-hour
LBC	Living Building Challenge
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LEED	Leadership in Energy and Environmental Design
LOD	Level of Development (BIM Forum, 2019), Level of Definition (former PAS 1192-2)
LOIN	Level of Information Need
MIDP	Master Information Delivery Plan
MVD	Model View Definitions
NBS	Nature-Based Solutions
NO2	Nitrogen Dioxide
NZEB	Nearly Zero Energy Building
OIR	Organizational Information Requirements
PAS	Publicly Available Specification
PIM	Project Information Model
PIR	Project Information Requirements
PLQ	Plain Language Questions
PM2.5	Particulate Matter 2.5
PM10	Particulate Matter 10
PMV	Predicted Mean Vote
POE	Post Occupancy Evaluation
PPD	Predicted Percentage of Dissatisfied
PV	Photovoltaics
RIBA	Royal Institute of British Architects
SDG	Sustainable Development Goals
Tvis	Visible transmittance
UDI	Useful Daylight Illuminance
UHI	Urban Heat Island
UMI	Urban Modelling Interface
UN	United Nations
UTCI	Universal Thermal Climate Index
VPL	Visual Programming Language
WWR	Window-to-wall Ratio

APPENDIX A: BUILDING PERFORMANCE SIMULATIONS

Some of the simulations presented in chapter 5 – BIM integrated Regenerative Design are shown in the appendix in full resolution and size as permitted by the thesis document format. The images are organized based on the sub-sections of the chapter they belong with a detailed description.

5. 7 Design validation according to EN 17037:2018 Daylight in Buildings

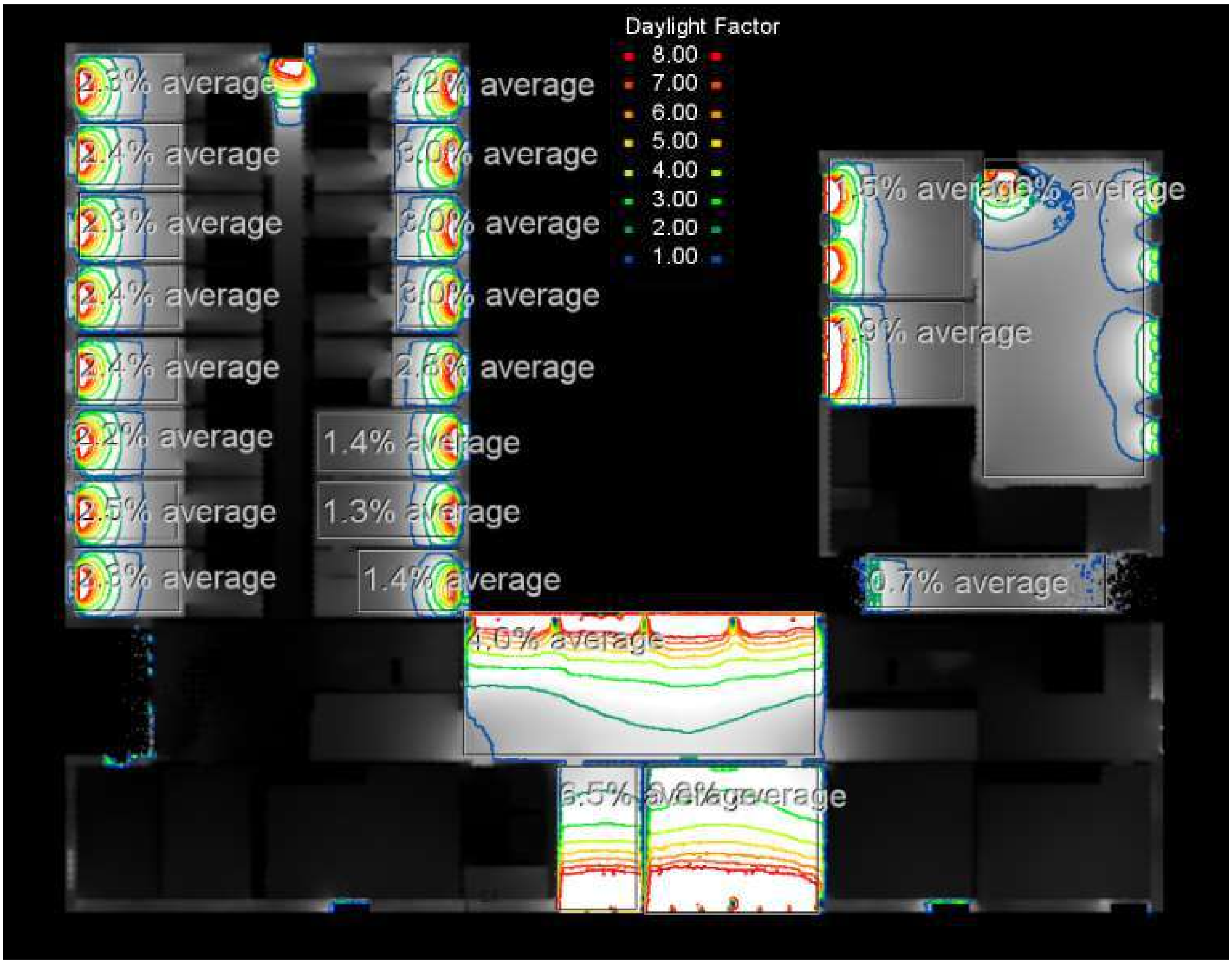


Figure A. 1: Daylight Factor simulation for the ground floor level with isolines and DF values.

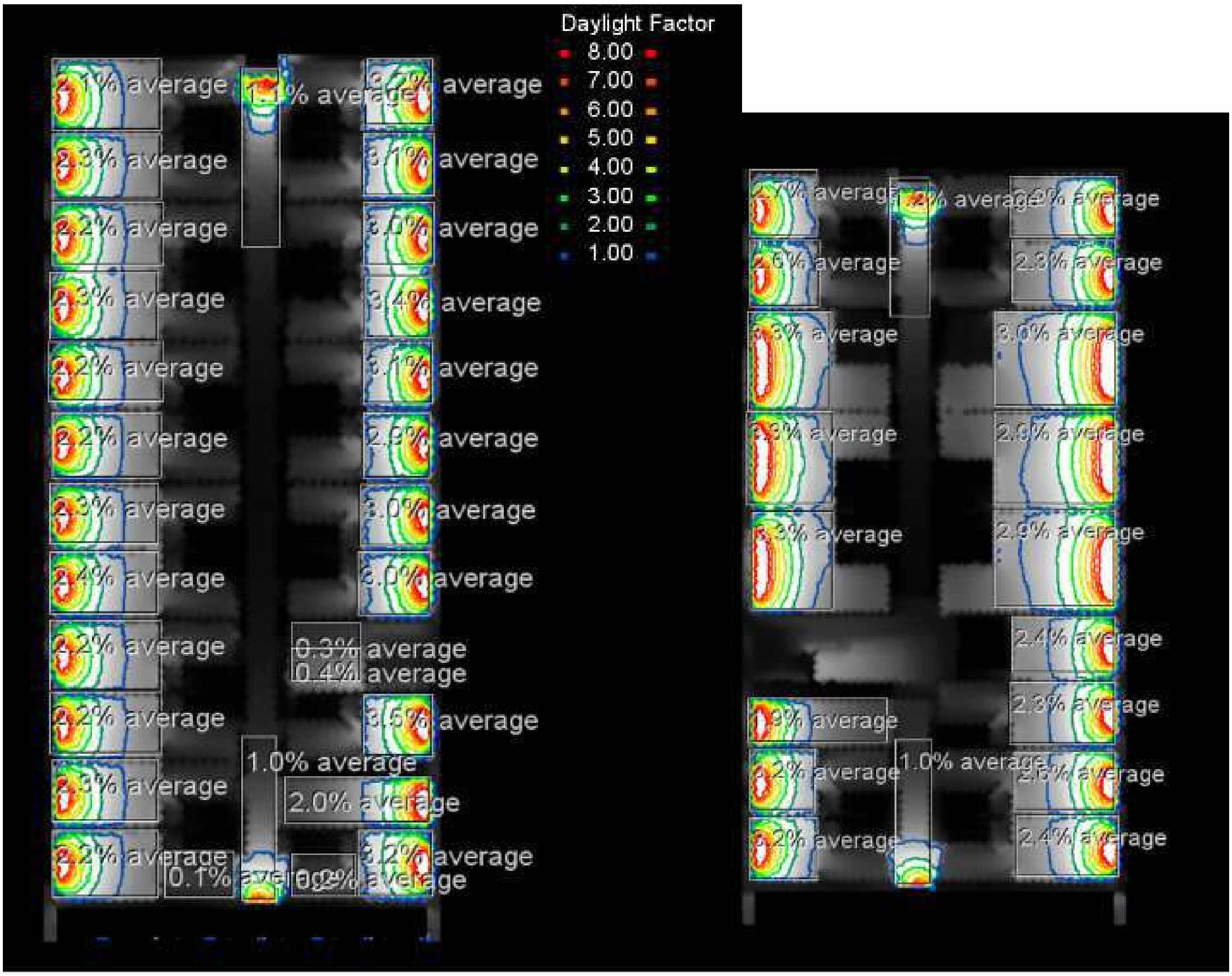


Figure A. 2: Daylight Factor simulation for the first floor level with isolines and DF values.

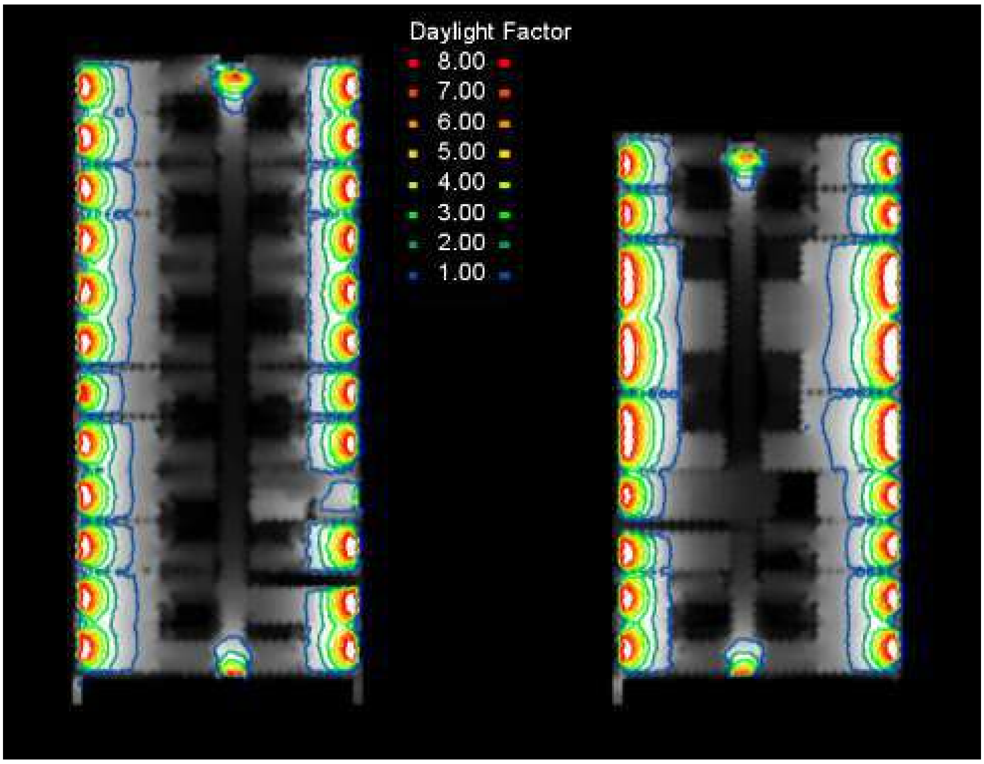


Figure A. 3: Daylight Factor simulation for the second floor level with isolines.

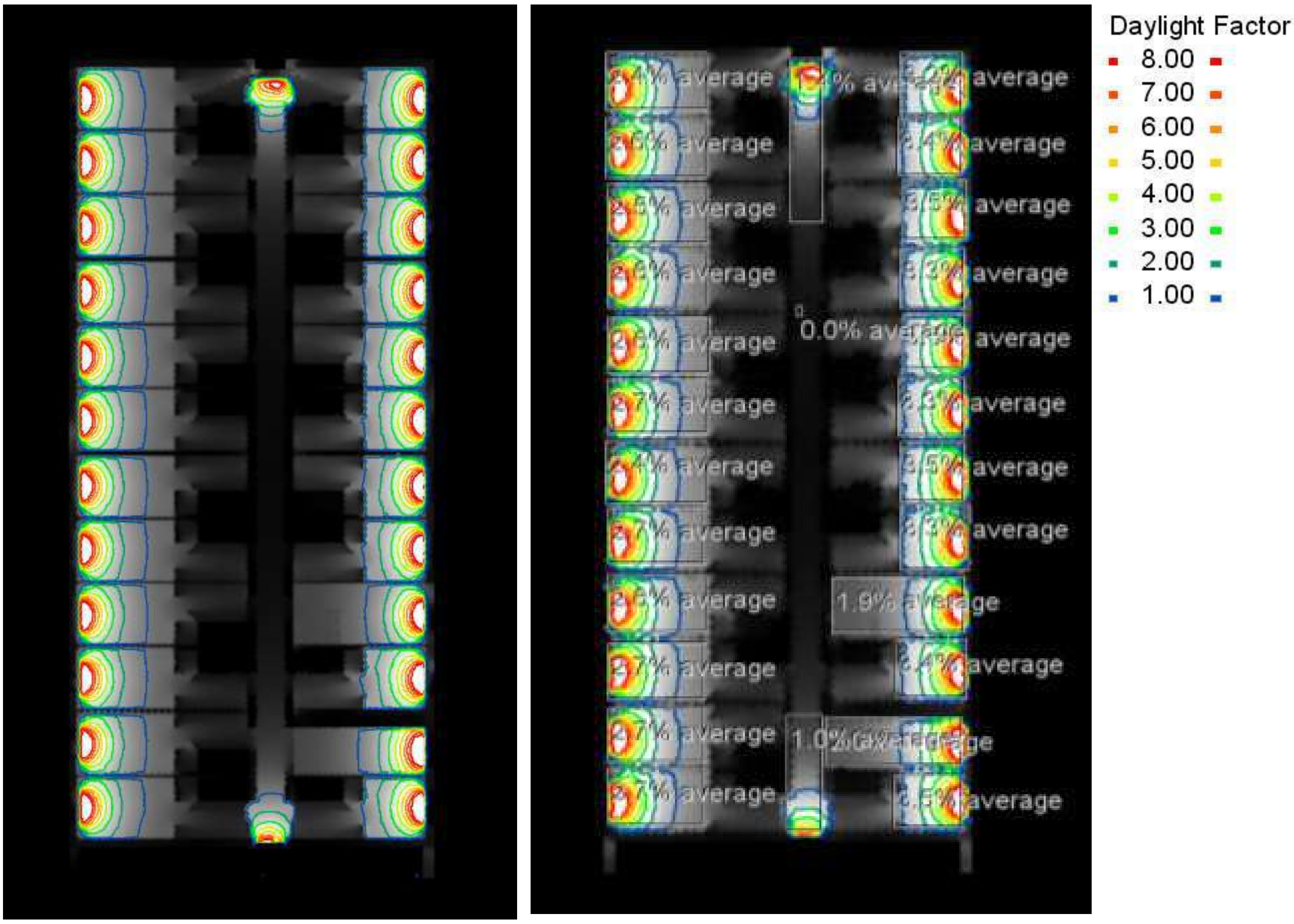


Figure A. 4: Daylight Factor simulation for the third floor level with isolines (left) and DF values (right).

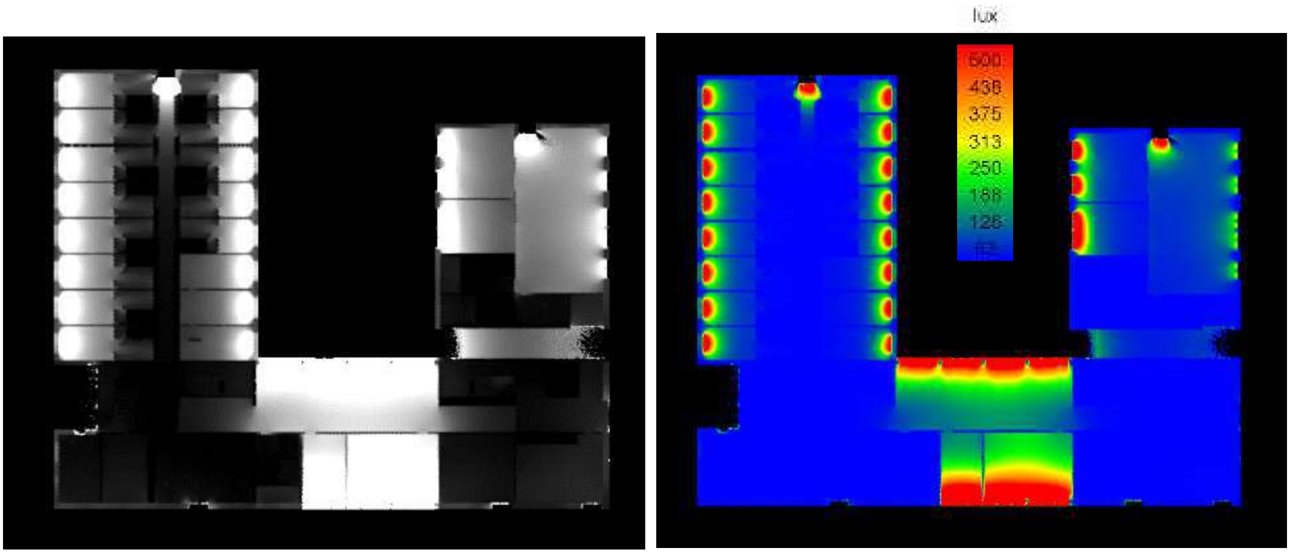


Figure A. 5: Illuminance rendering at ground floor level (left); Illuminance false-colour rendering with legend results in range 0-500 lux (right).

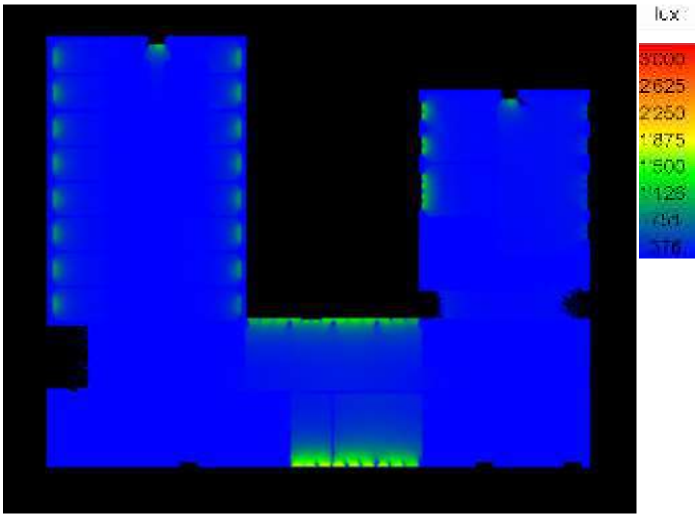


Figure A. 6: Illuminance false-colour rendering with legend results in range 0-3000 lux.

5.8 Sunlight hours with Computational Design

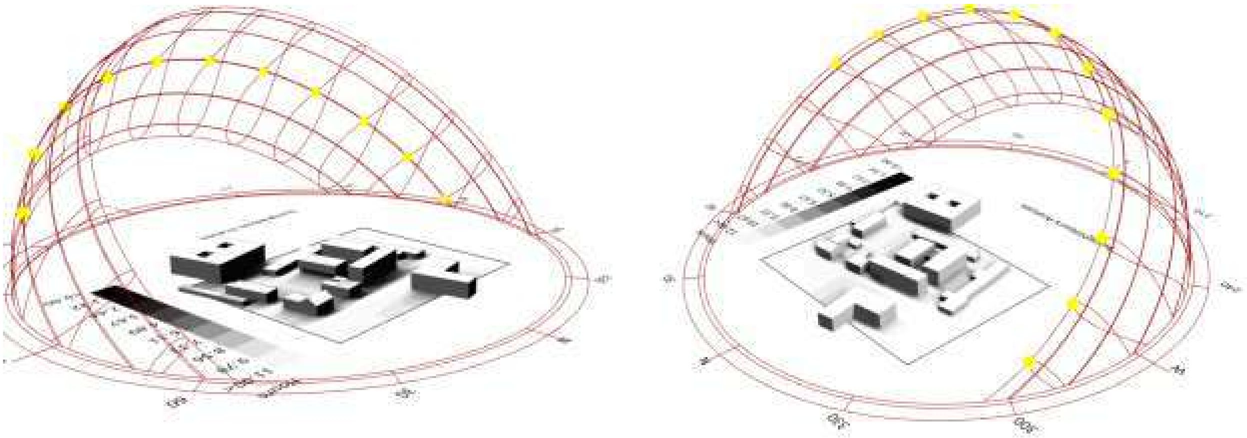


Figure A. 7: Gerbiceva project with Ladybug Tools sun Path and Sunlight Hours on 21 March (left) and 21 June (right).

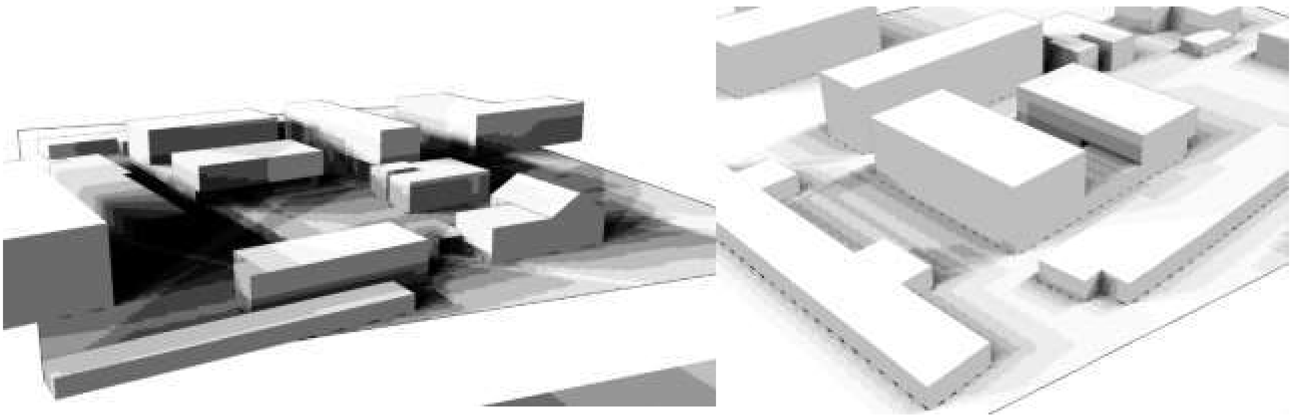


Figure A. 8: Comparison of Single day sunlight hours on 21 December and 21 June, black and white colour mapping.

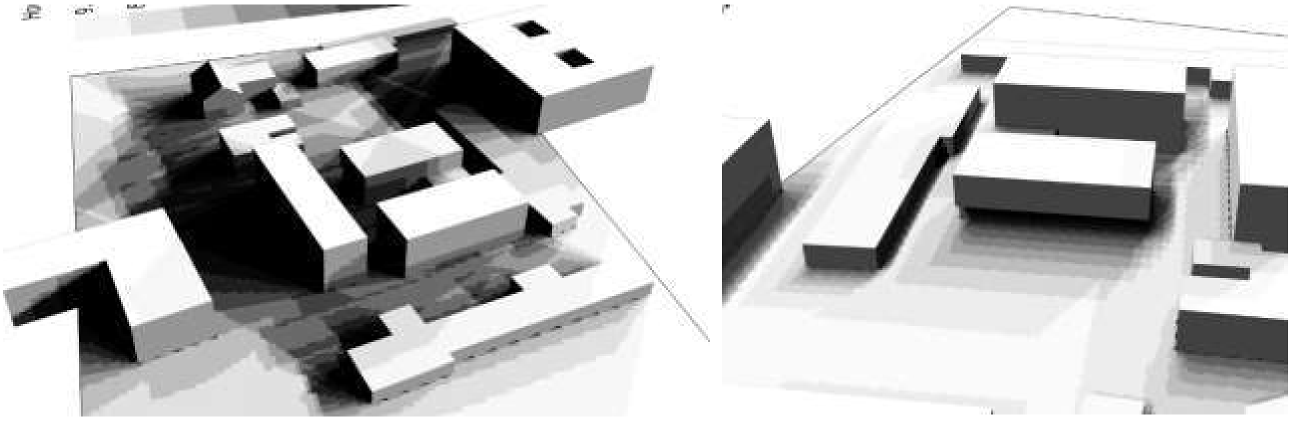


Figure A. 9: Perspective comparison of minimum sunlight hours on 21 December and 21 June.

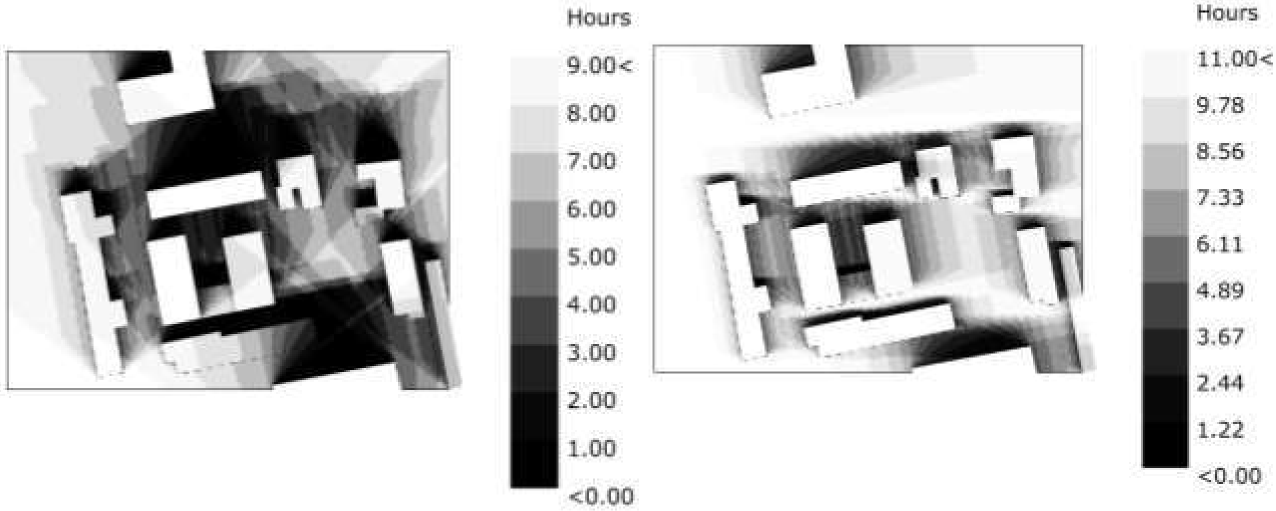


Figure A. 10: Sunlight Hours comparison on 21 December with 21 June, black and white colour map.

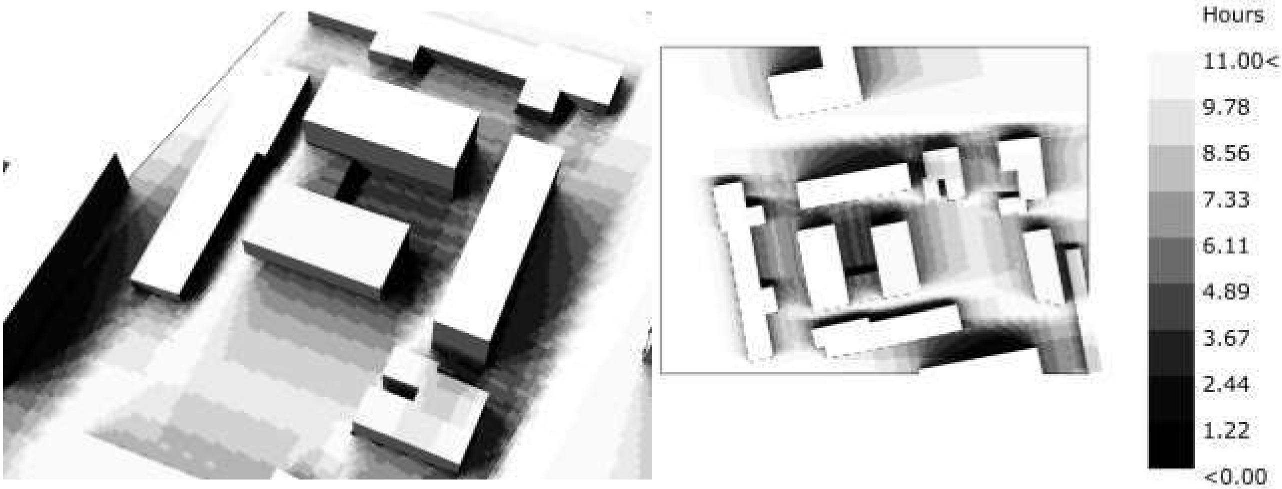


Figure A. 11: Sunlight hours perspective and plan view on 21 March, black & white map.

5.9 Algorithmic process for Shadow studies

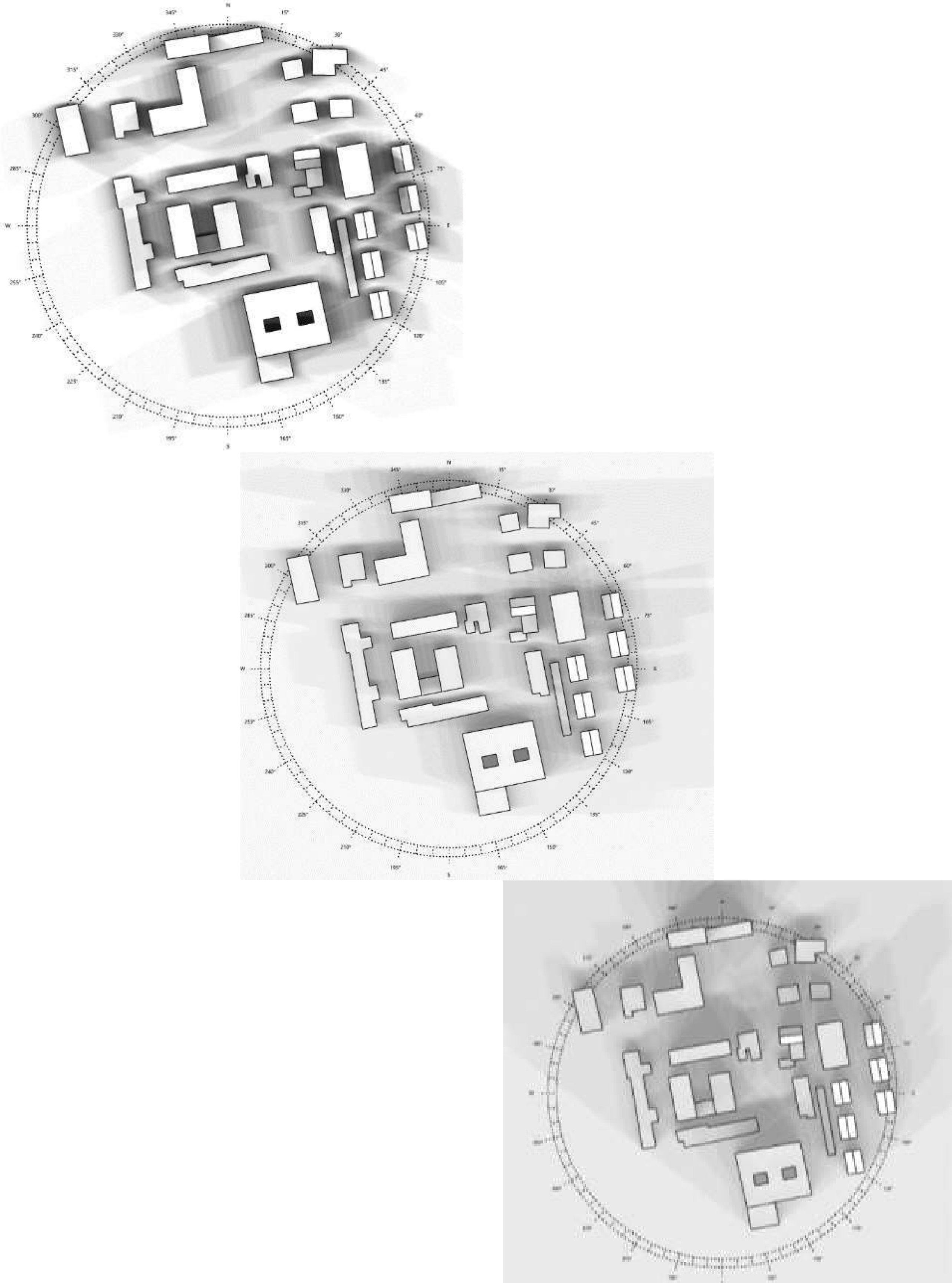


Figure A. 12: Shadows study for Summer Solstice, Equinox and Winter Solstice (from left to right).

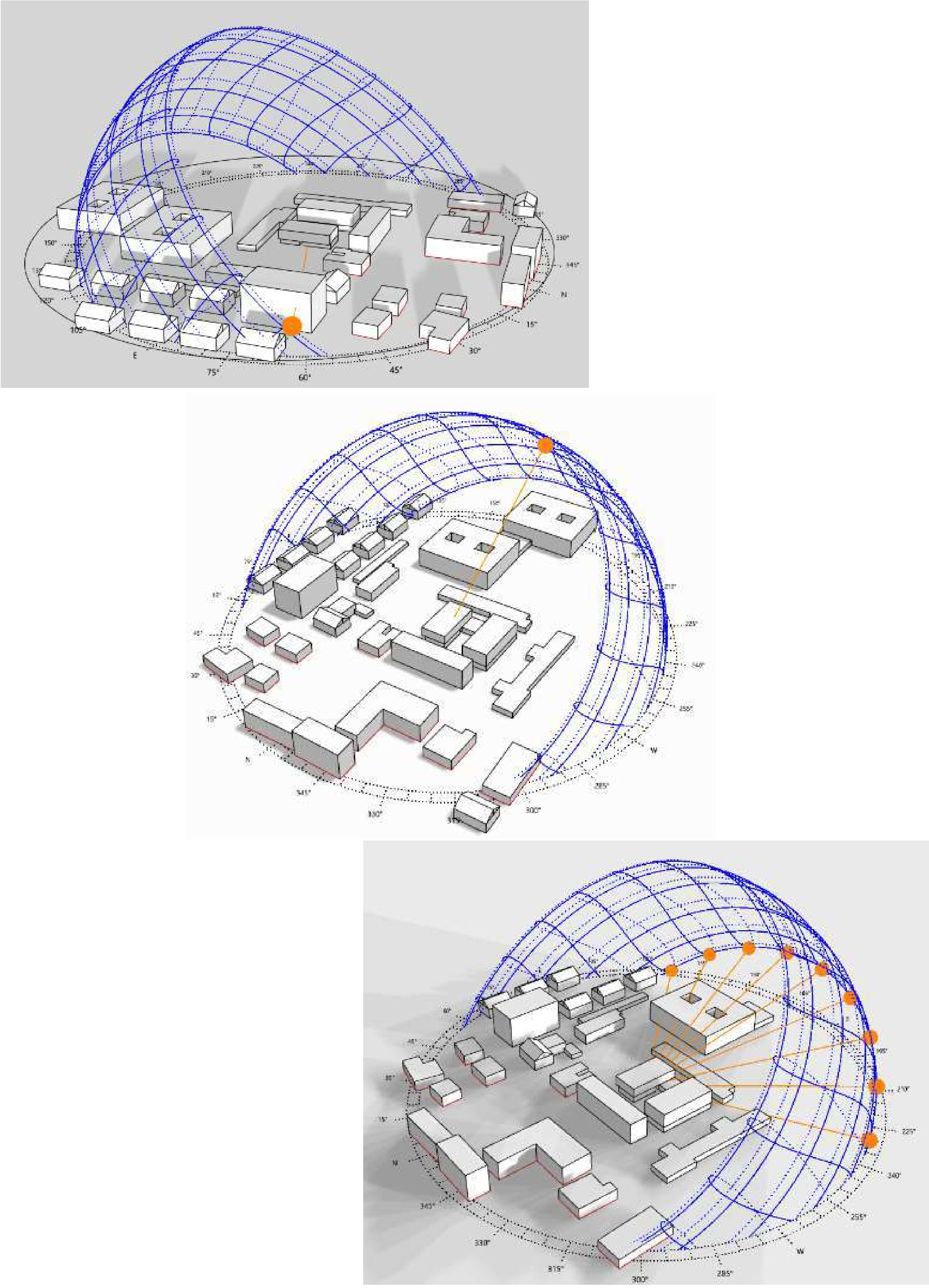


Figure A. 13: Sun Path with vectors - 5 am 21 June, 1 pm 21 June, 24 h on 21 December (left to right).

5.10 PV system design in a computational process

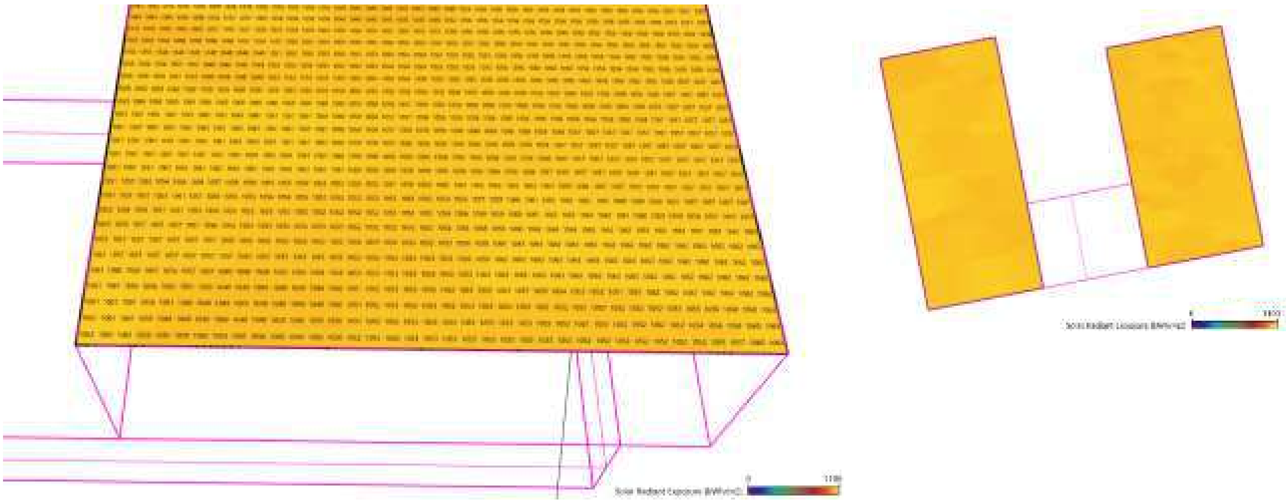
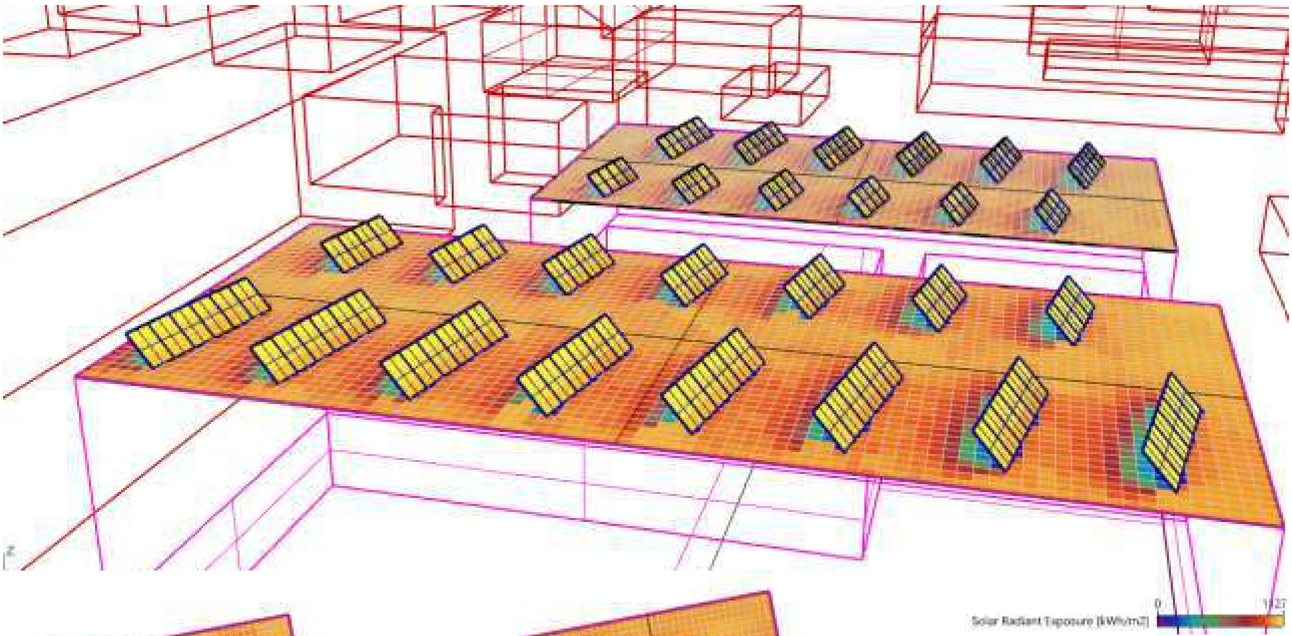


Figure A. 14: Radiation Map top view and detailed view with grid-point values.



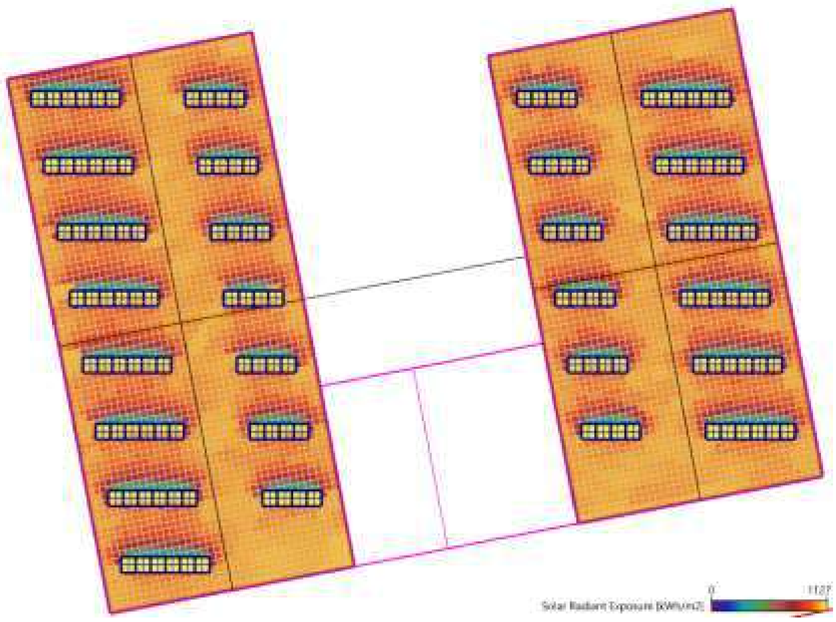


Figure A. 15: Radiation Map with Colour mapping of analysis to verify the optimal distribution of panels.

5.11 Climate Based Daylight Modelling with DIVA

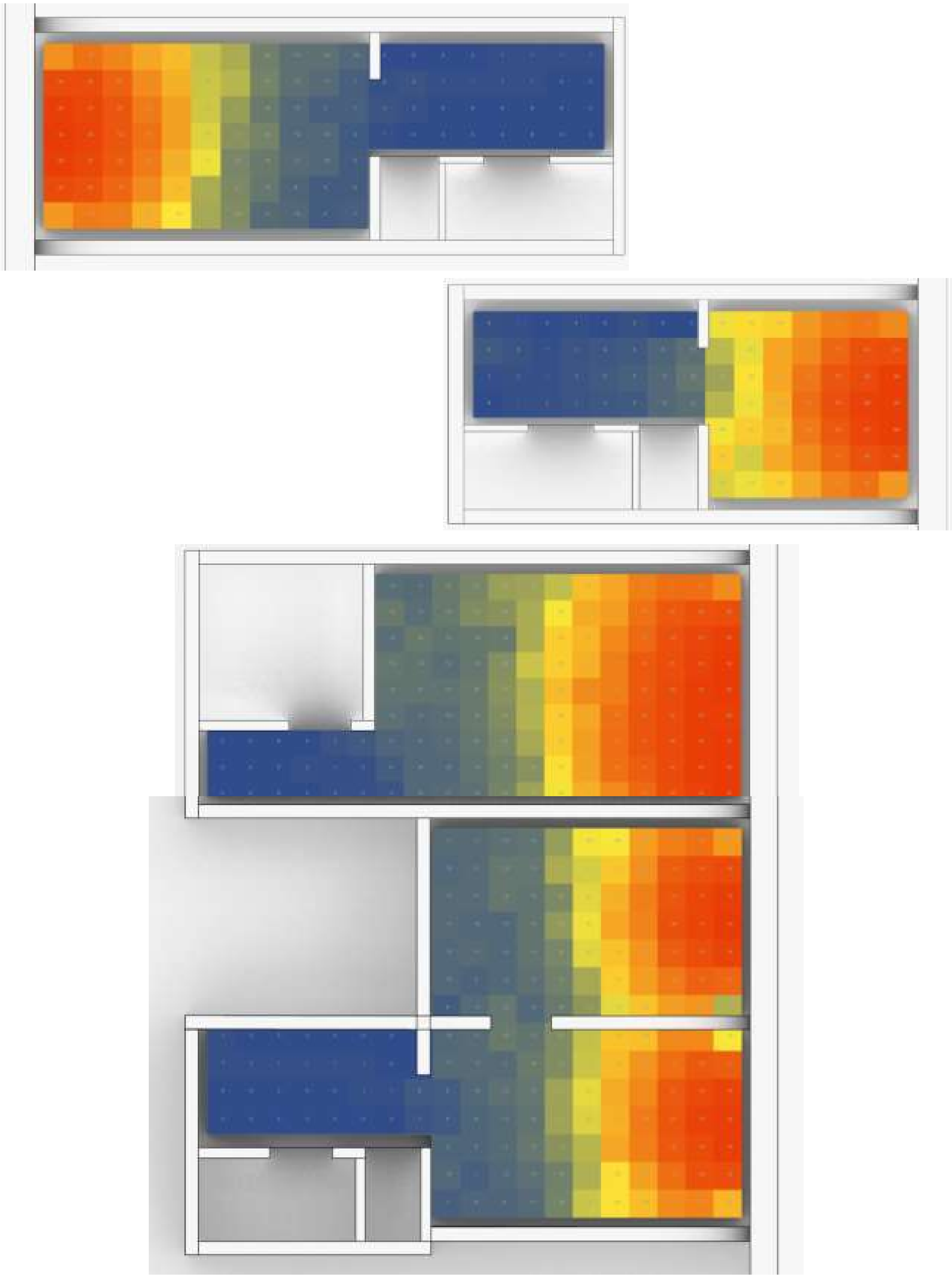


Figure A. 16: sDA (300 lux) [50%] with DIVA for four of the accommodation units.

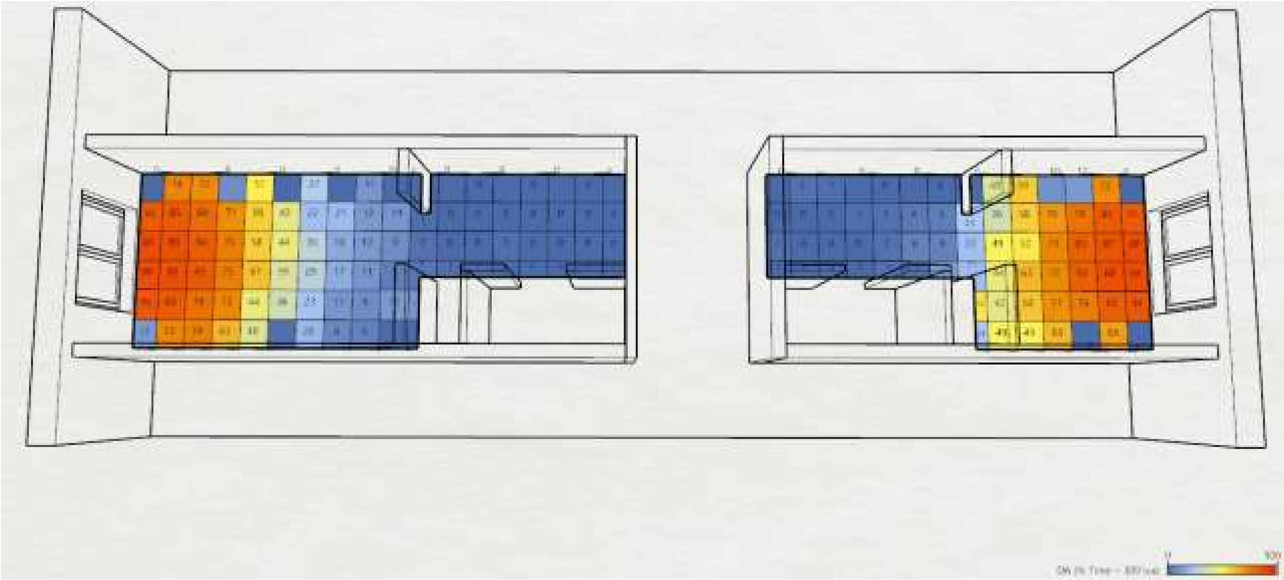


Figure A. 17: DIVA for Grasshopper simulations of sDA with no shading condition.

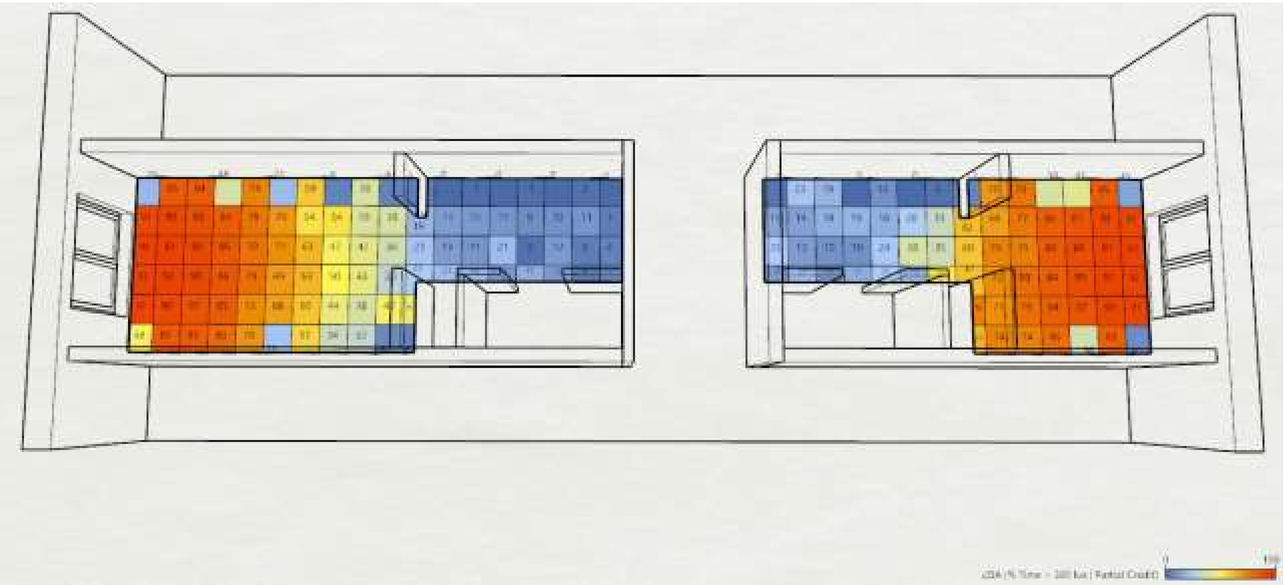


Figure A. 18: DIVA for Grasshopper simulations of cDA with no shading condition.

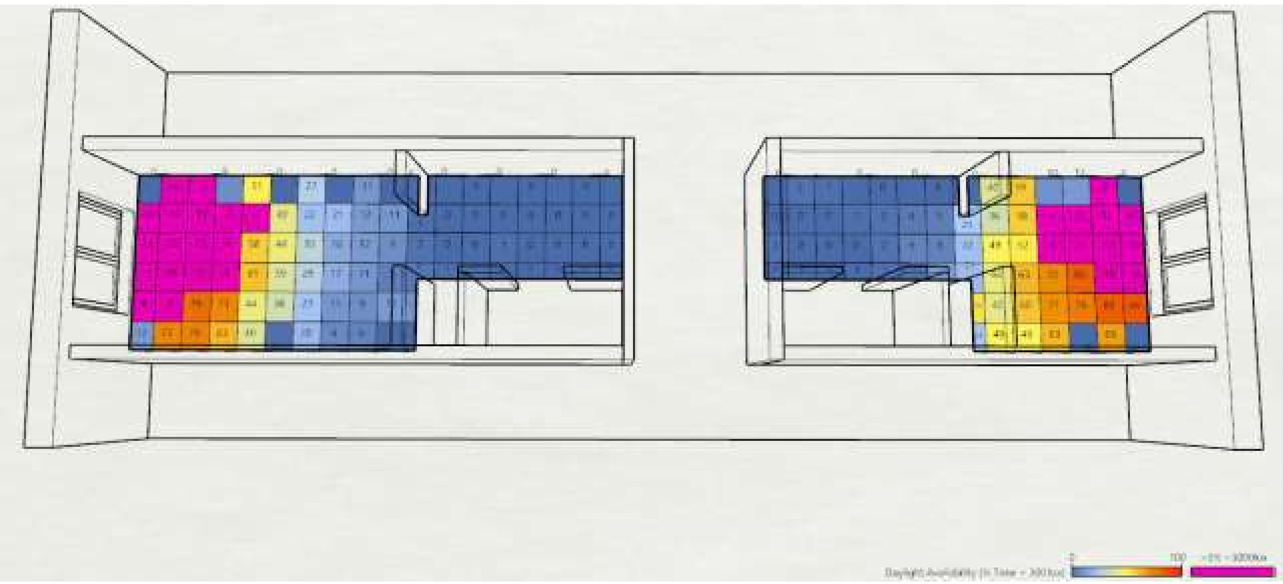


Figure A. 19: DIVA for Grasshopper simulations of Daylight Availability with no shading condition.

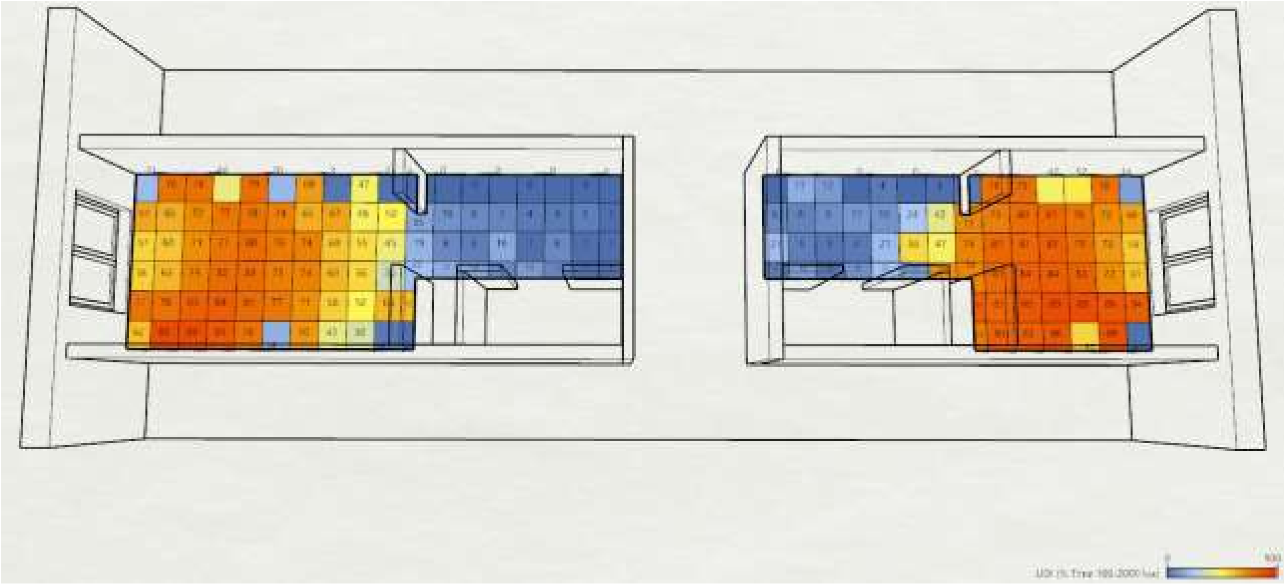


Figure A. 20: DIVA for Grasshopper simulations of UDI with no shading condition.

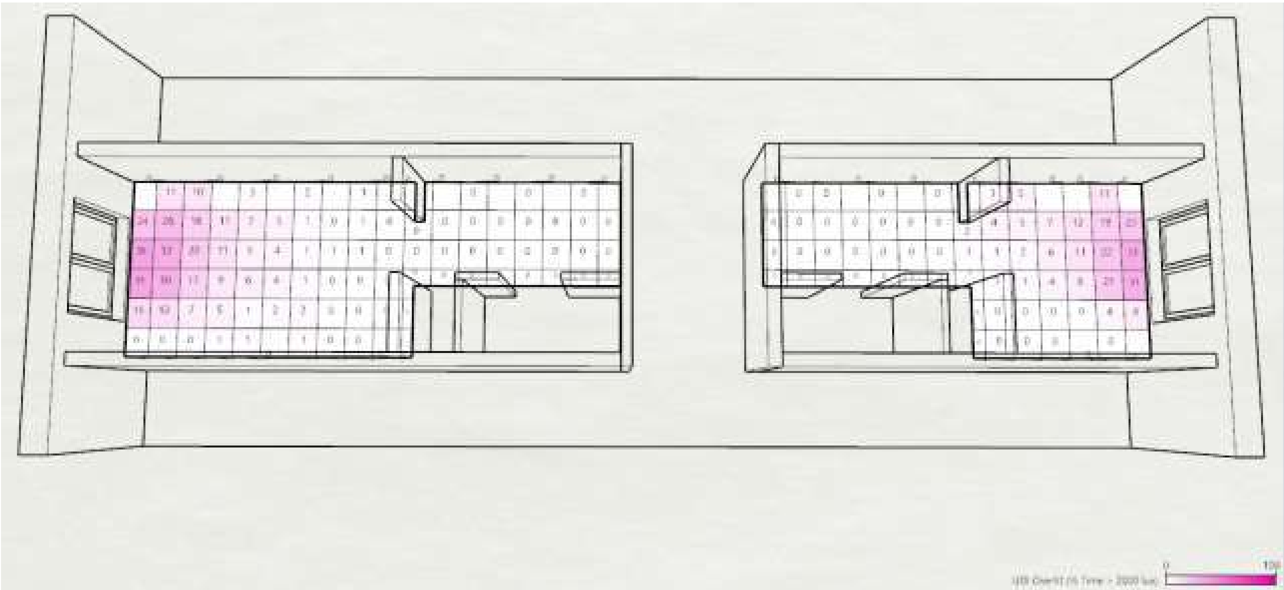


Figure A. 21: DIVA for Grasshopper simulations of UDI Overlit with no shading condition.

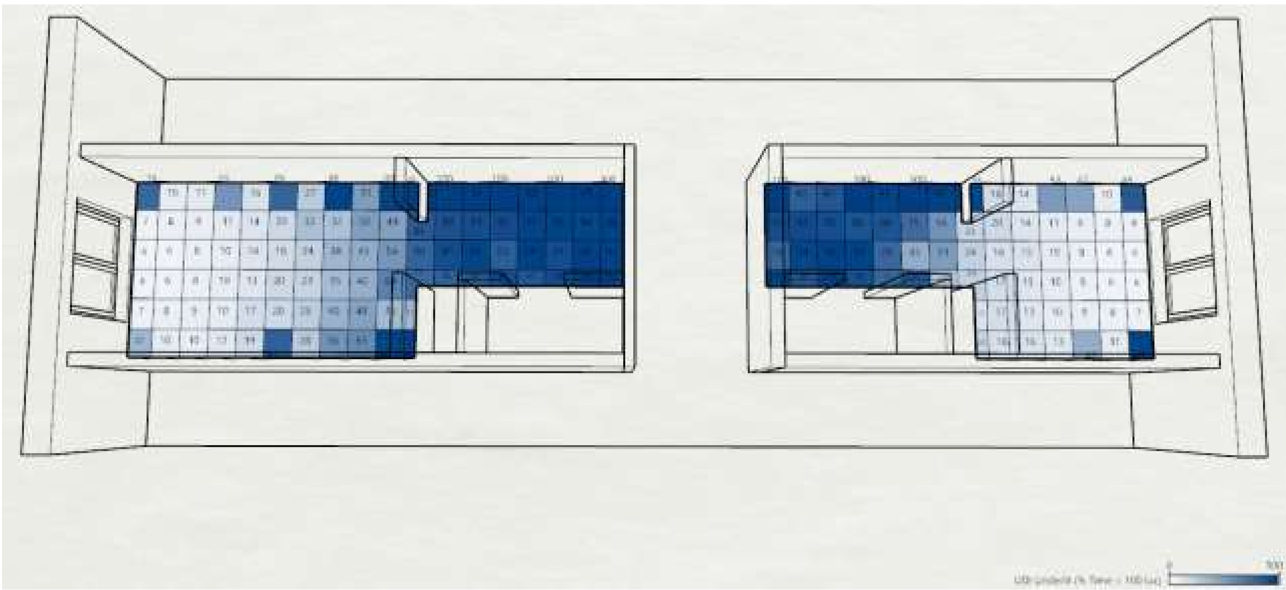


Figure A. 22: DIVA for Grasshopper simulations of UDI underlit with no shading condition.

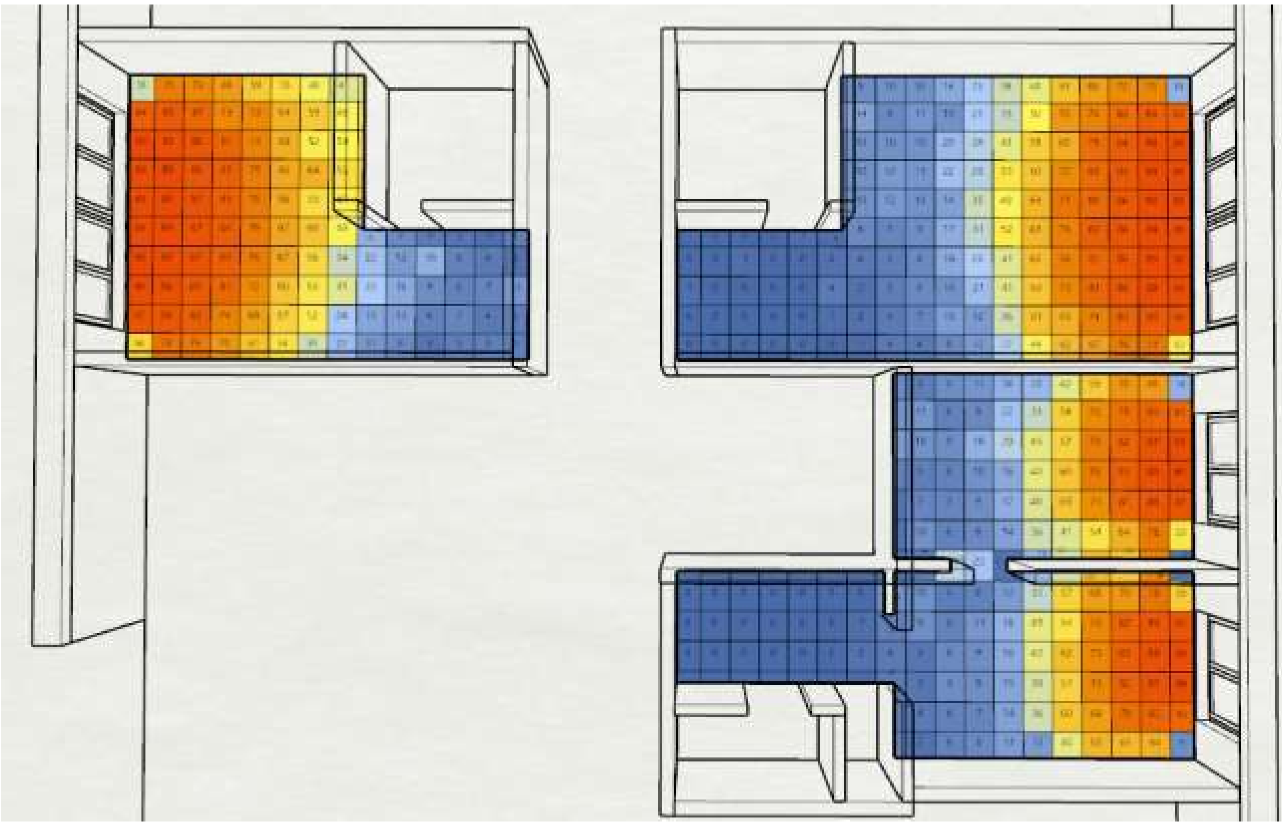


Figure A. 23: DIVA for Grasshopper simulations of sDA with no shading condition.

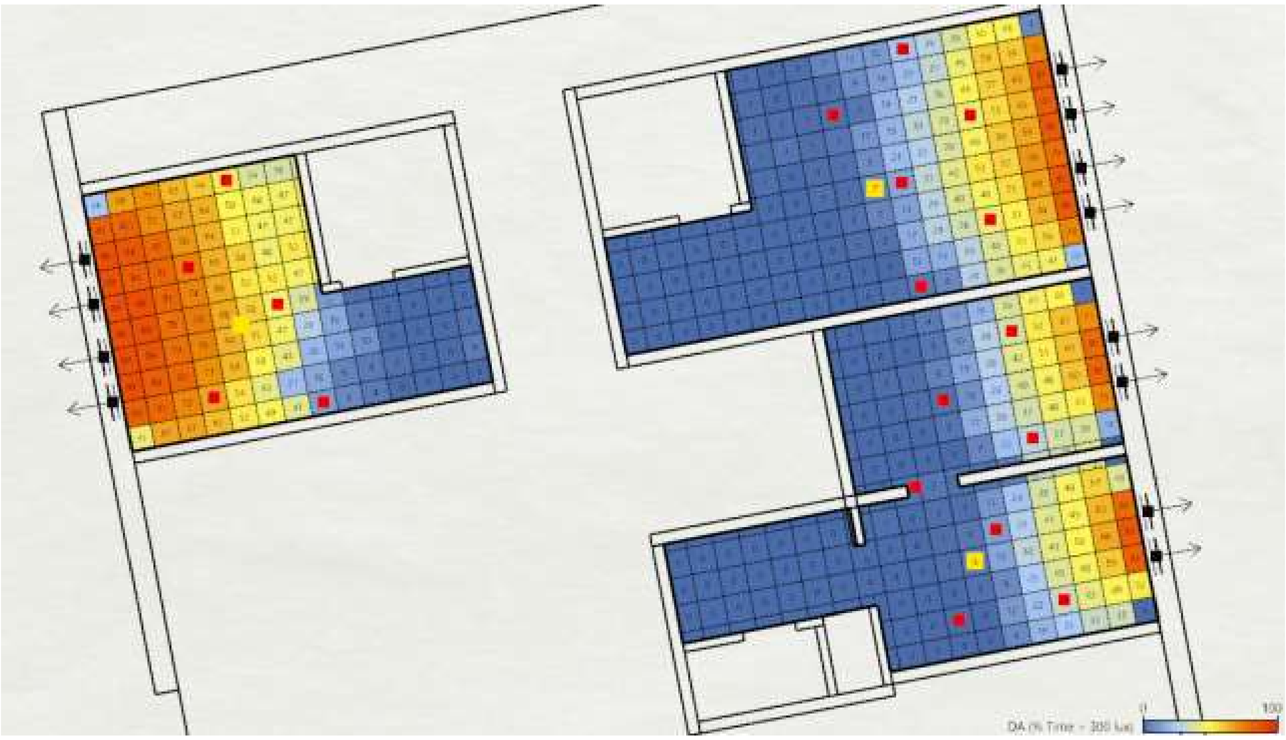


Figure A. 24: DIVA for Grasshopper simulations of sDA with shading condition.

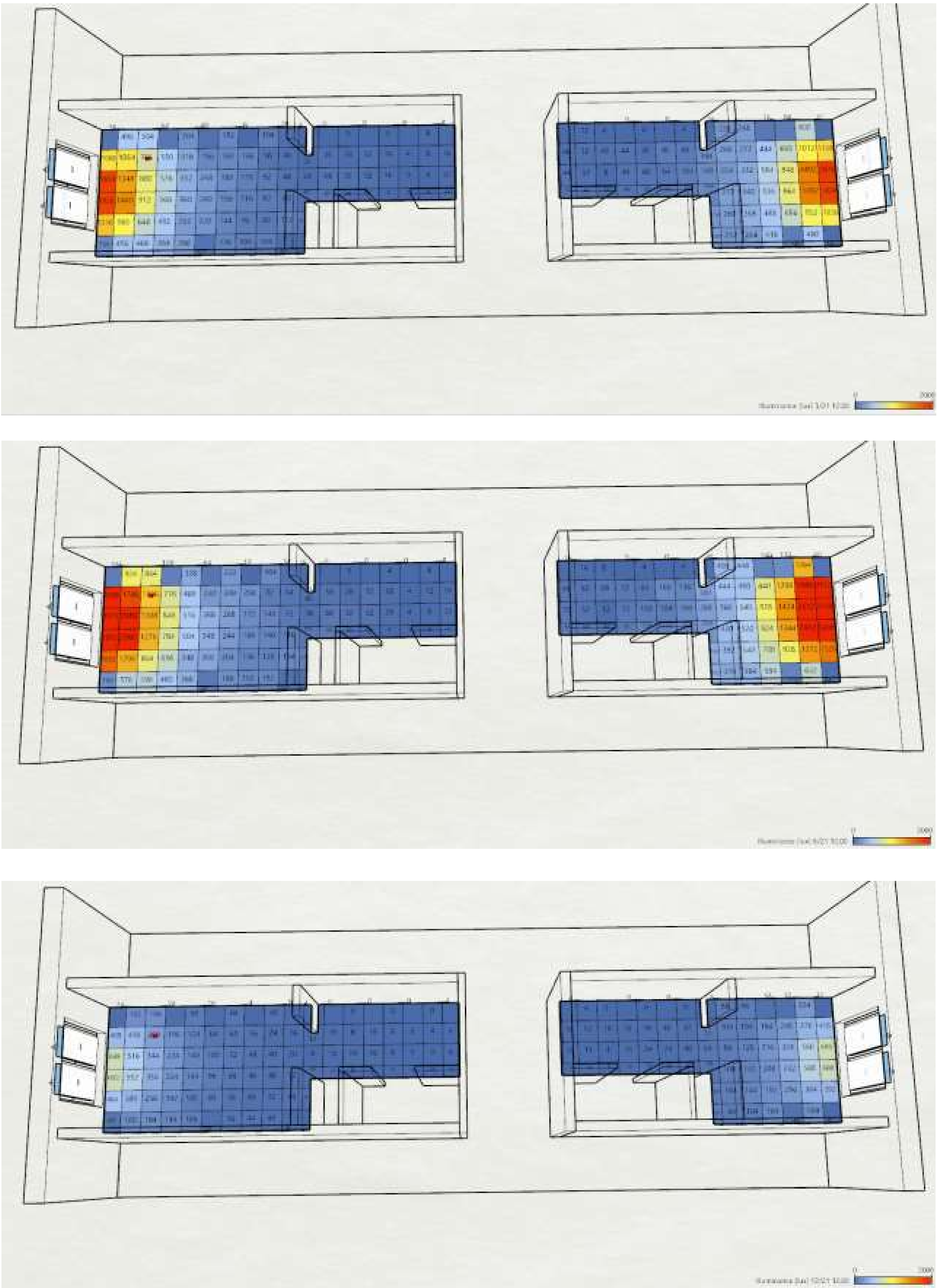


Figure A. 25: Illuminance visualization for units on 21 March (equinox), 21 June (summer solstice) and 21 December (winter solstice) at 12:00 with shading condition.

5.12 Climate Based Daylight Performance and Visual Comfort with Climate Studio

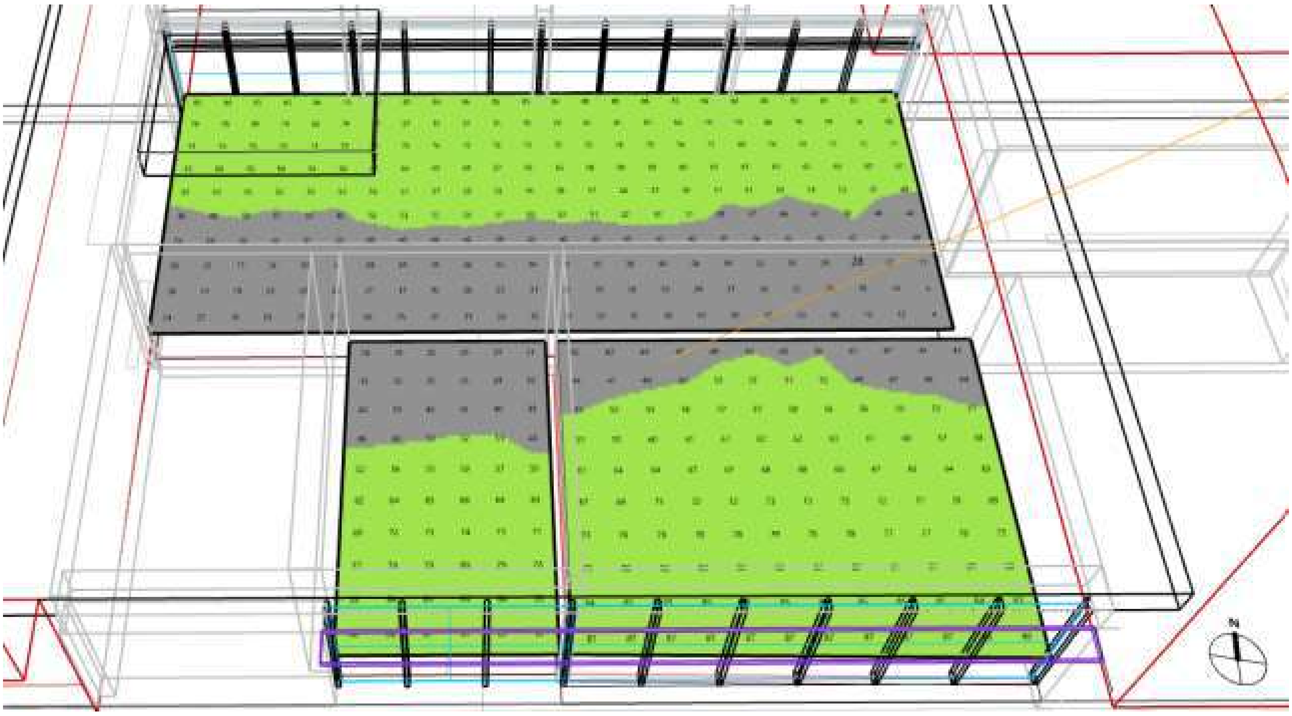


Figure A. 26: sDA and LEED v4.1 Daylight option 1 results of baseline design for Gerbiceva.

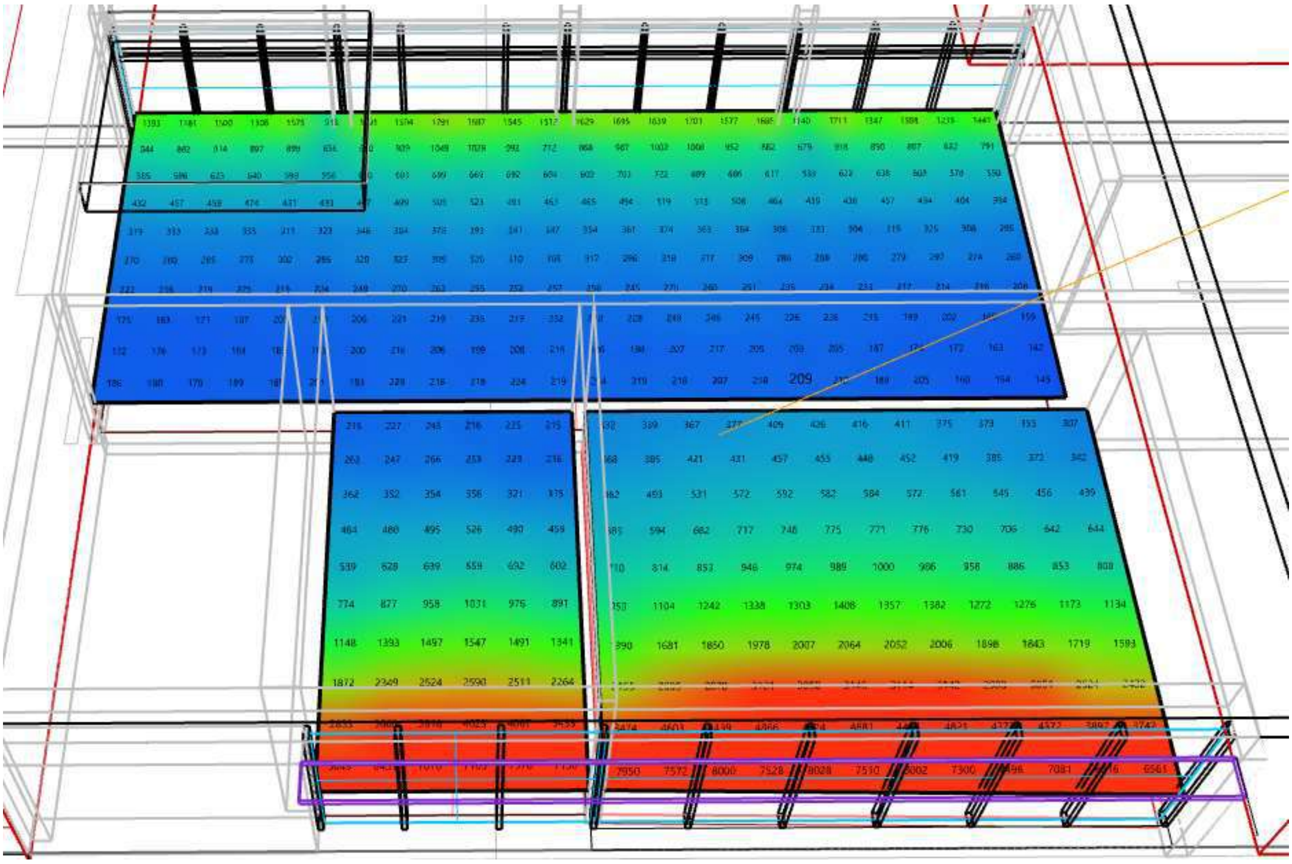


Figure A. 27: Average illuminance of ground floor spaces.

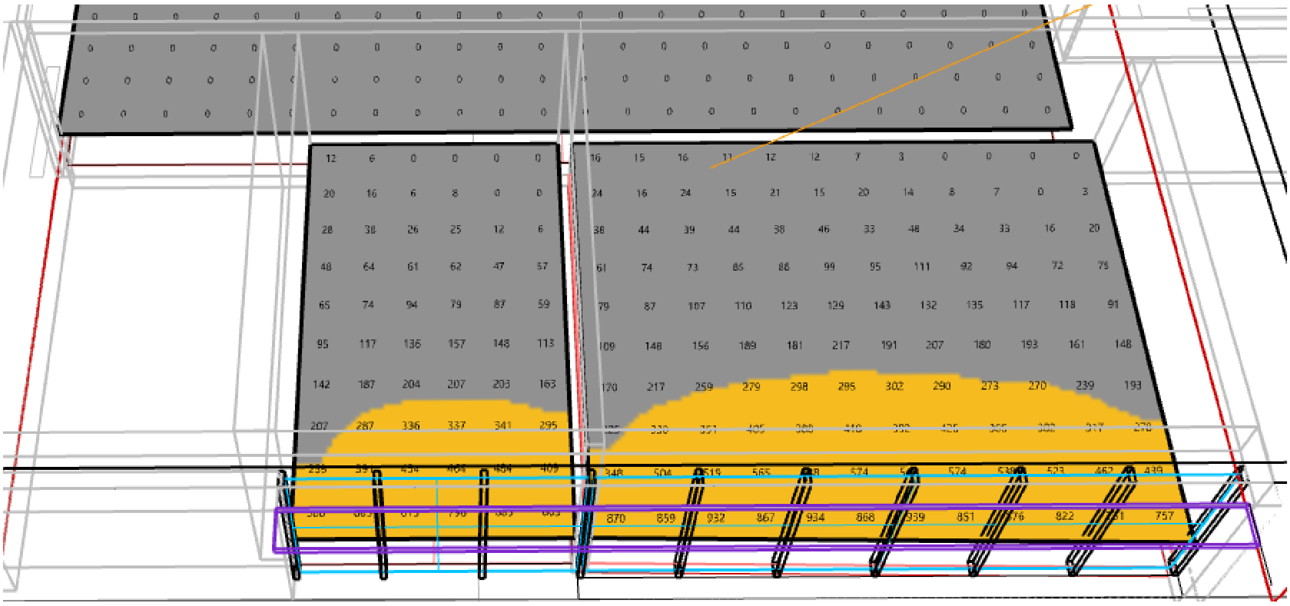


Figure A. 28: Annual Sunlight Exposure (ASE) of ground floor spaces.

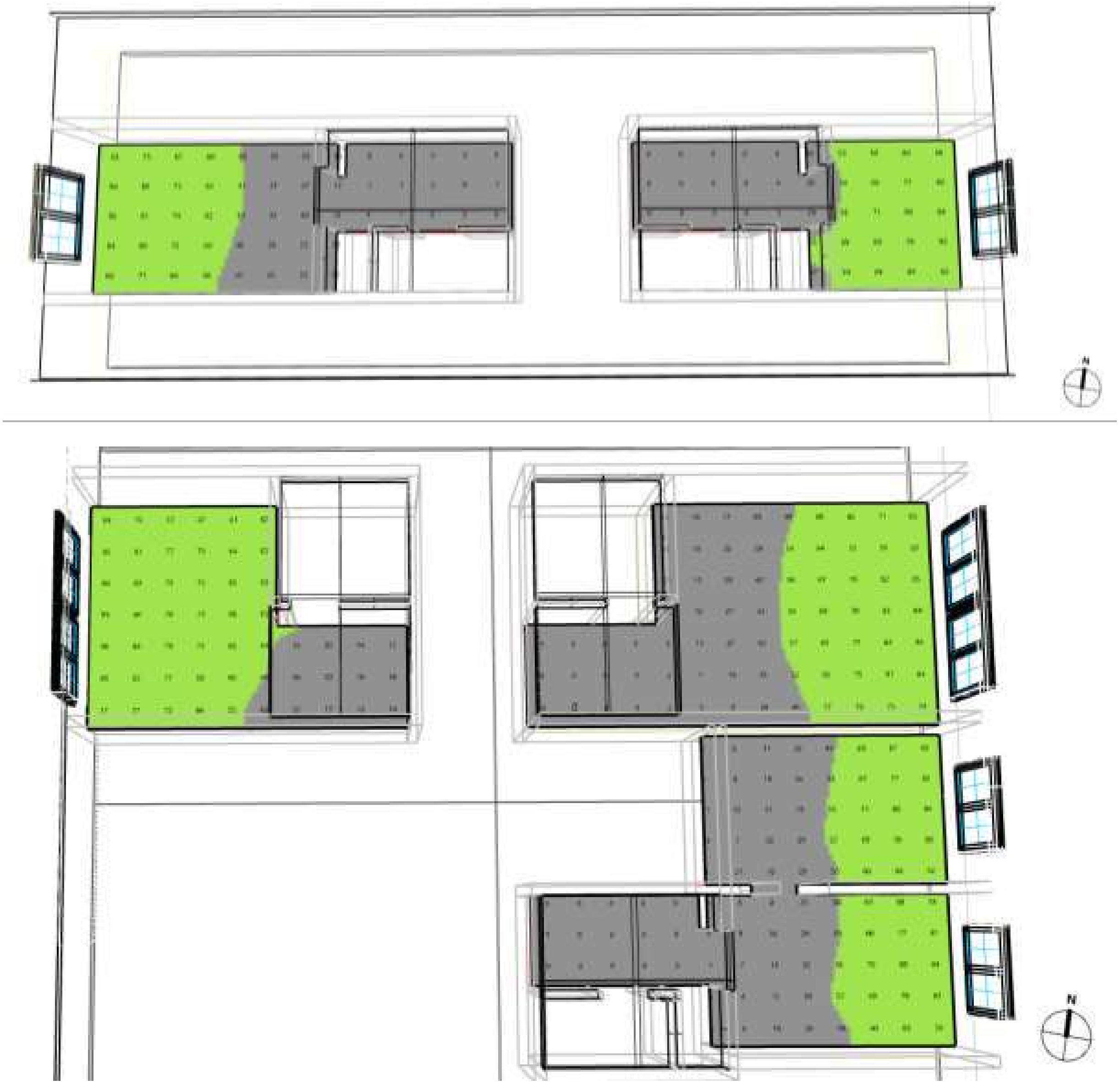


Figure A. 29: sDA with Climate Studio for accommodation units.

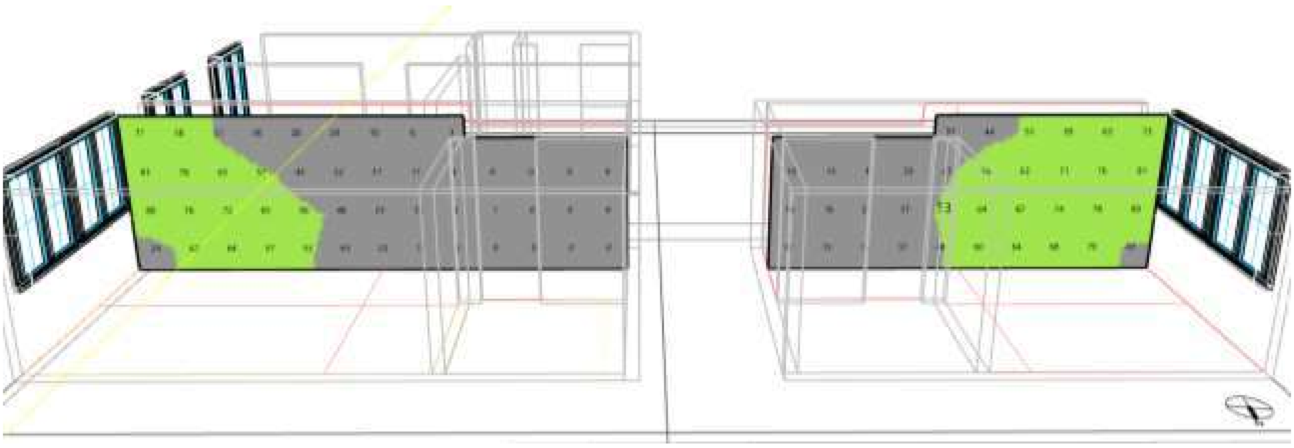


Figure A. 30: Daylight Autonomy cross section for two West and East units.

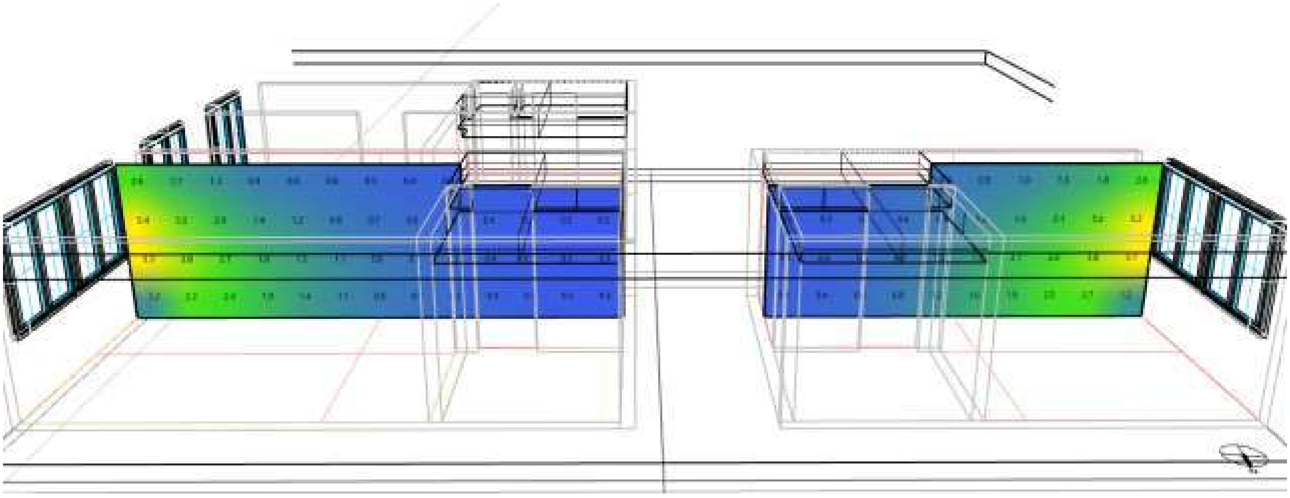


Figure A. 31: Daylight Factor cross section for two West and East units.

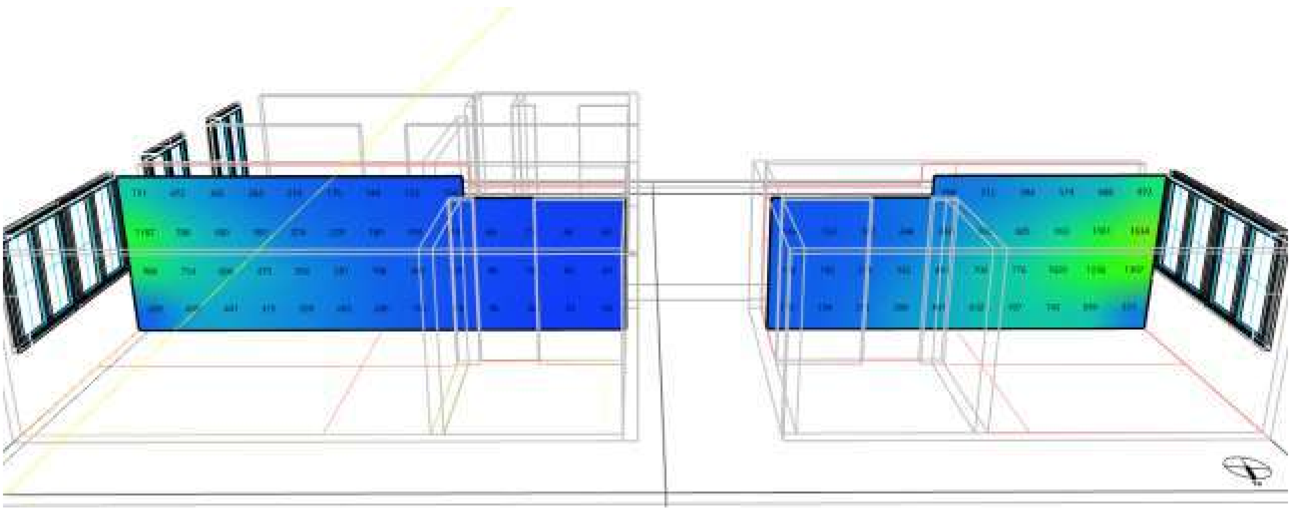
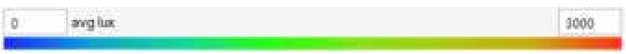


Figure A. 32: Average Illuminance cross section for two West and East units.



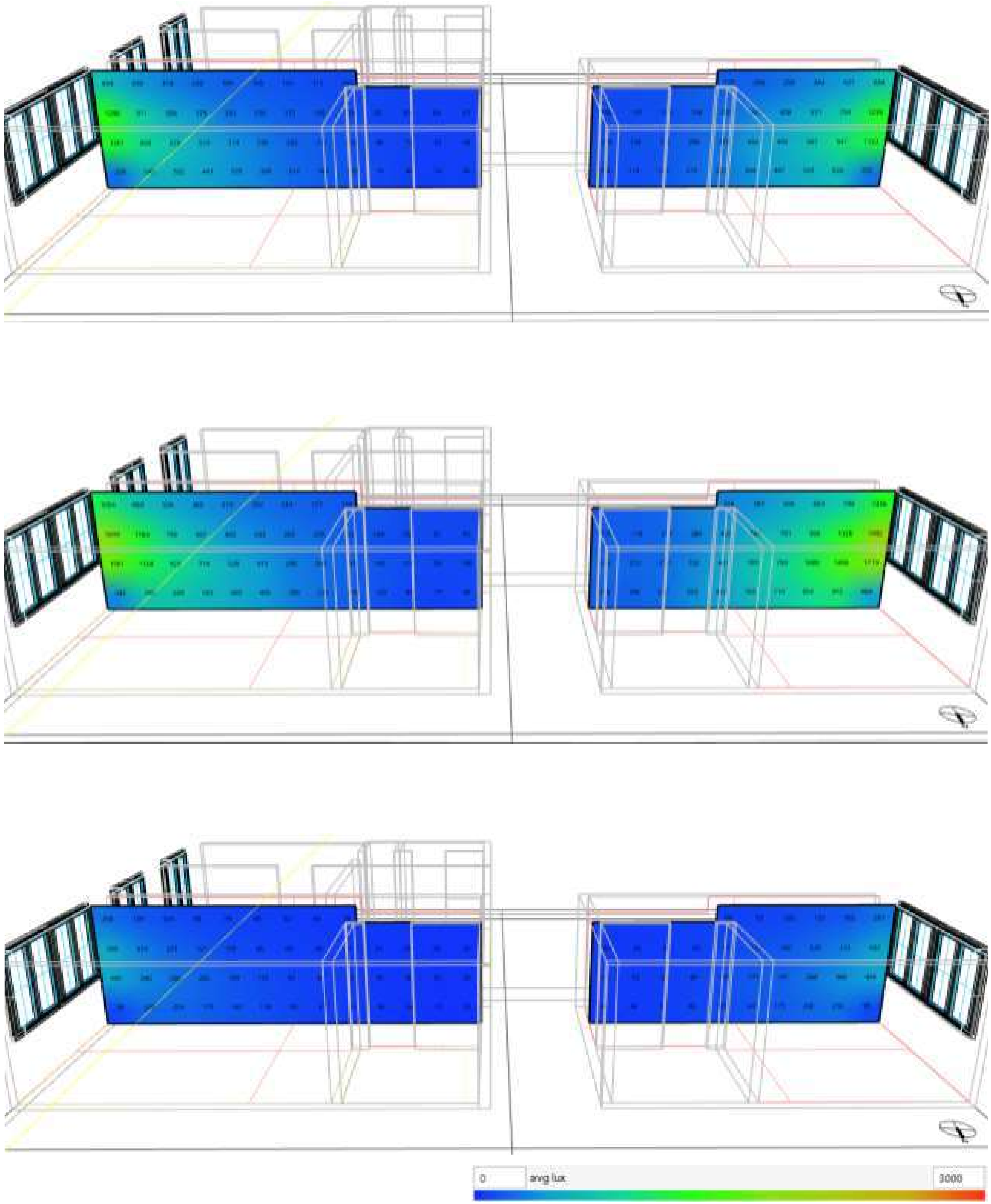
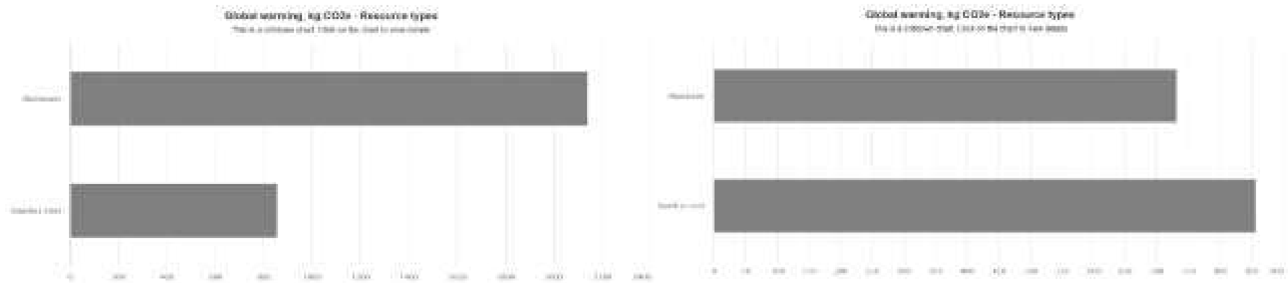
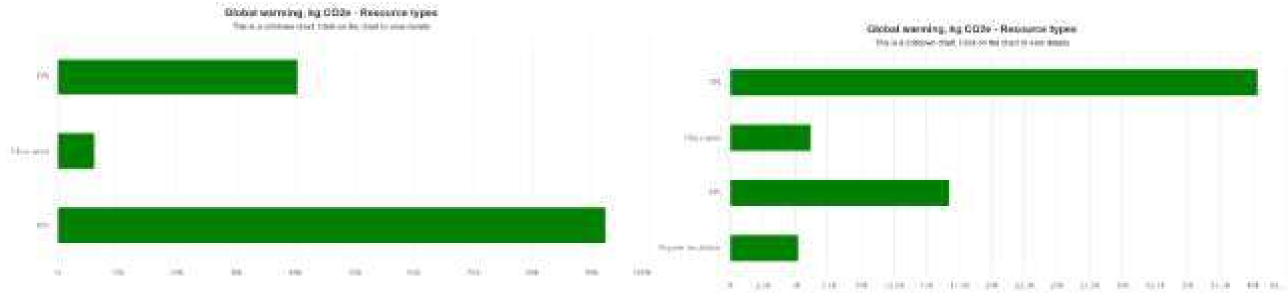


Figure A. 33: Illuminance cross section for two West and East units on 21 March, 21 June, 21 December at 12:30.

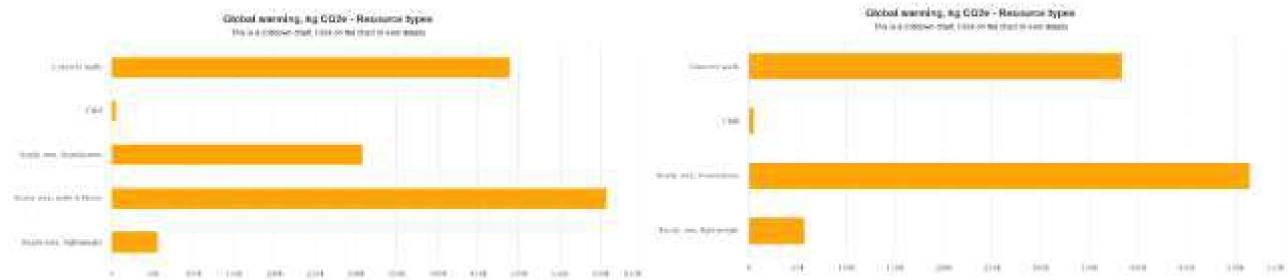
5.14.2 Whole-building life cycle assessment with One Click LCA



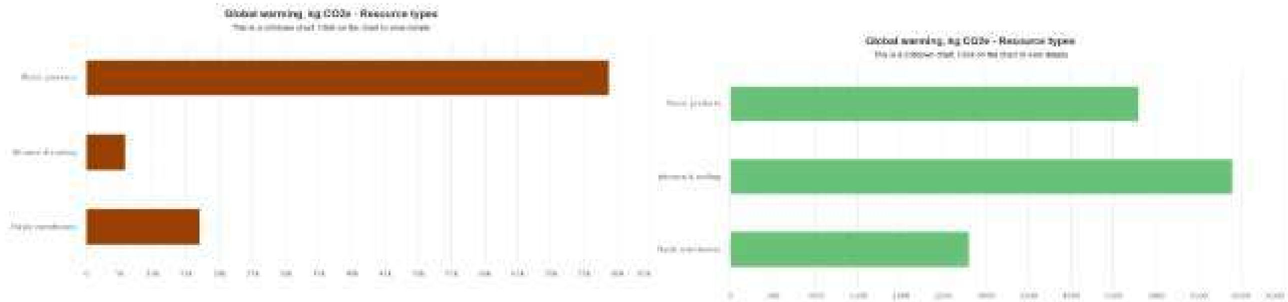
Aluminium (top bar) and Stainless steel (bottom bar)



EPS, Glass Wool, XPS and Organic insulations



Concrete material elements



Plastic products, bitumen & roofing and plastic membranes

Figure A. 34: GWP by Resource types. Comparison of Baseline (left) and Optimized Design Option 1 (right) charts.

5.15 Computational Fluid Dynamics

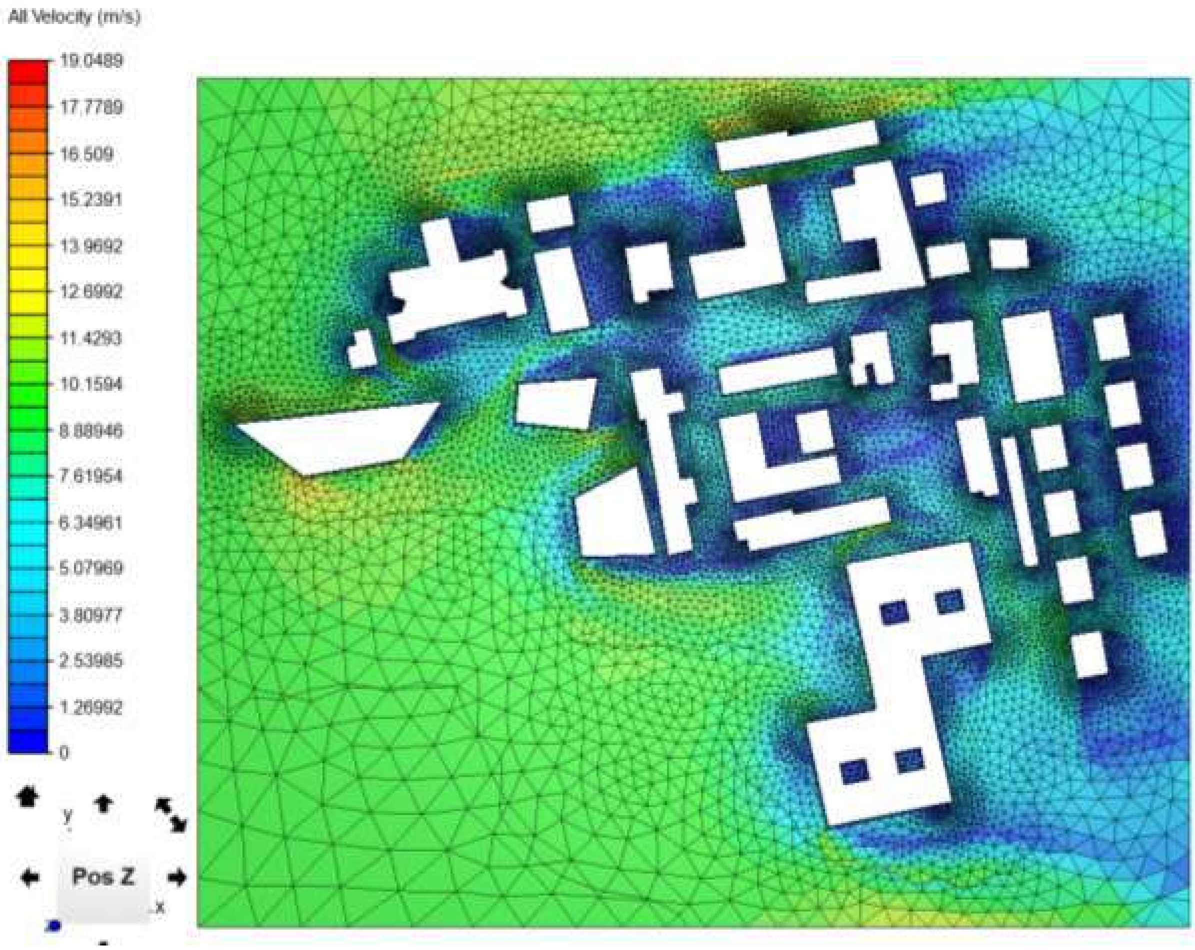


Figure A. 35: Wind simulation with visible mesh in Simscale.

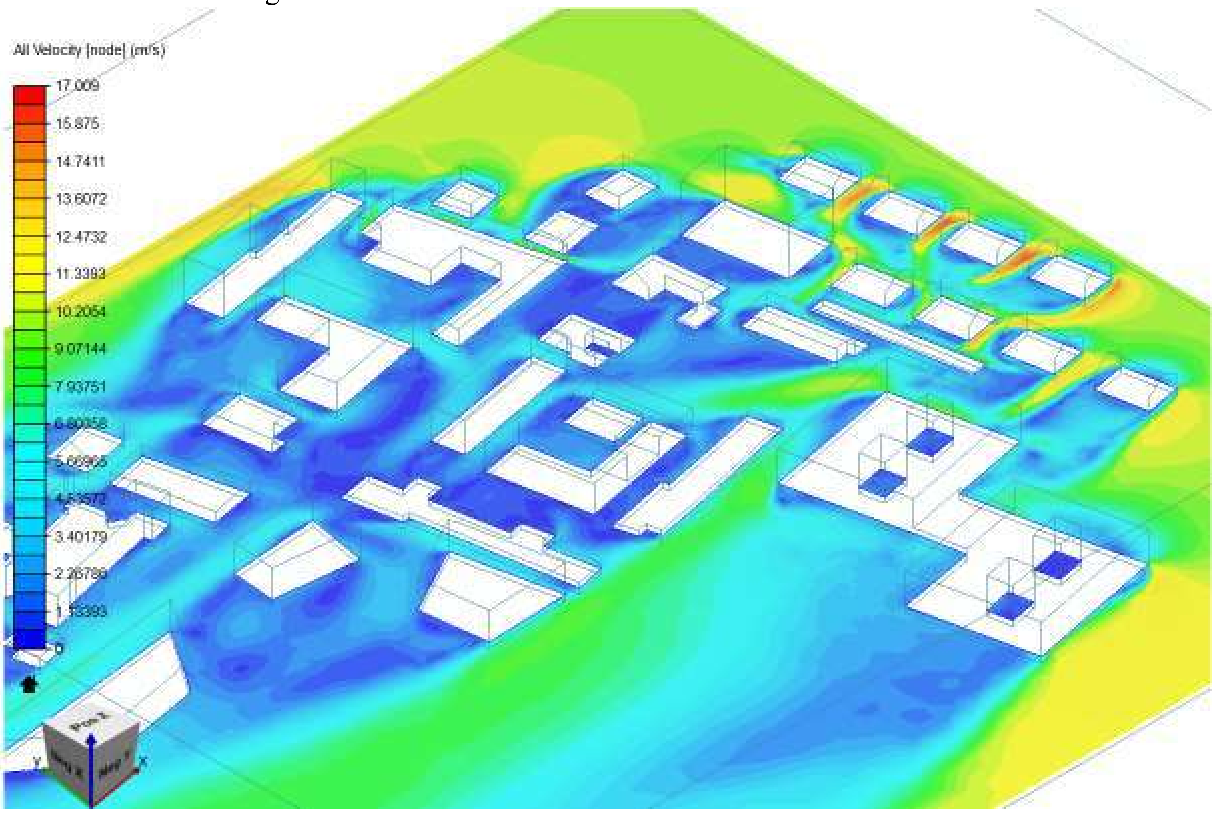


Figure A. 36: Perspective view of wind simulation with velocity results.

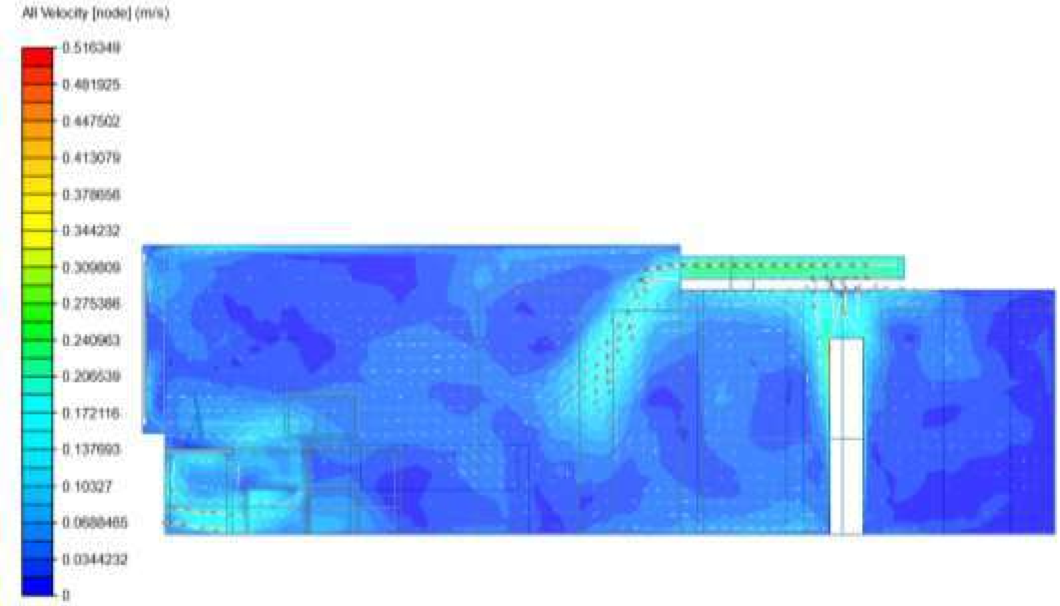


Figure A. 37: CFD section with results of Air Velocity and velocity vectors.

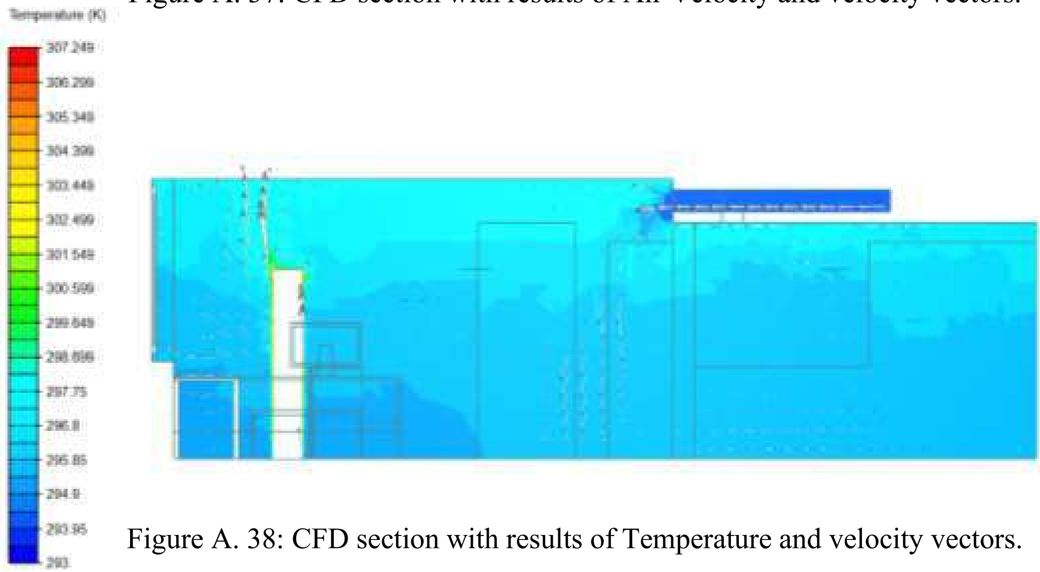


Figure A. 38: CFD section with results of Temperature and velocity vectors.

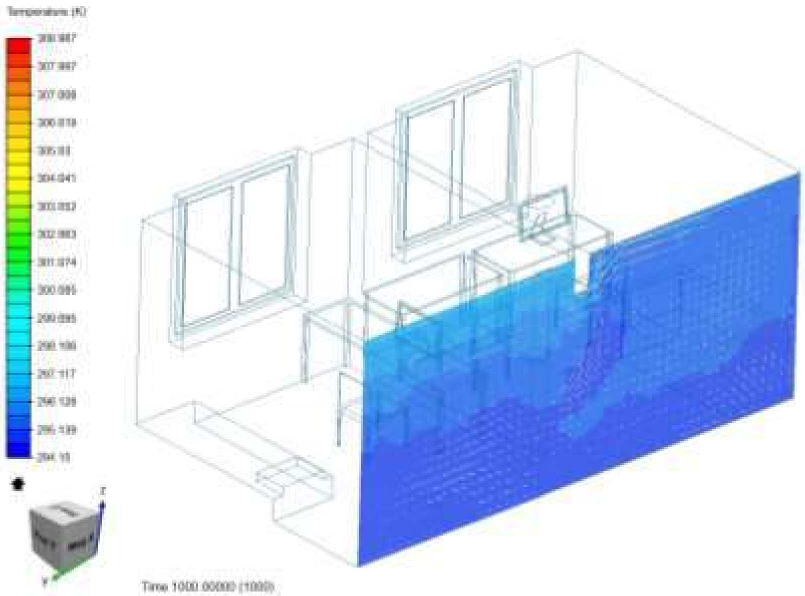


Figure A. 39: CFD axonometry with results of Temperature and velocity vectors.