# POLITECNICO DI MILANO

## Master in

Building Information Modeling

BIM A+ European Master in Building Information Modelling

# Using Building Information Modeling (BIM) for Environmental Simulation: Improving Sustainable Design Considerations in Residential Buildings

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# SOMMARIO

Il Building Information Modeling (BIM) rappresenta una trasformazione fondamentale nel settore dell'Architettura, dell'Ingegneria e della Costruzione (AEC), offrendo un quadro digitale integrato per la gestione completa del ciclo di vita degli edifici, compresi i processi di progettazione, costruzione, gestione e manutenzione. Un aspetto rilevante e distintivo della metodologia BIM risiede nella possibilità di creare simulazioni ambientali, fornendo così ai progettisti l'opportunità di esaminare e ottimizzare le prestazioni degli edifici in termini di efficienza energetica, qualità ambientale interna e sostenibilità. Questa tesi presenta un'indagine accademica incentrata sull'utilizzo del BIM per la simulazione ambientale, in particolare nell'ambito della progettazione sostenibile relative agli edifici residenziali.

La metodologia dello studio implica un approfondimento completo della letteratura sui principi della progettazione di edifici sostenibili, concentrandosi sul ruolo della progettazione dell'involucro edilizio nel raggiungimento di obiettivi energetici, sulla selezione dei materiali, sull'efficienza delle risorse, sulle scelte progettuali per promuovere una buona qualità ambientale interna e sulle strategie per ottimizzare le prestazioni energetiche. Lo studio analizza inoltre sistemi di valutazione e standard, come LEED, PEER, EDGE, WELL e ICP, e la loro possibile applicazione sulle scelte progettuali sostenibili in edifici residenziali.

I risultati dello studio dimostrano l'efficacia del BIM per la simulazione ambientale nel migliorare le scelte di progettazione sostenibile in edifici residenziali. La tesi presenta casi studio di progettazione di edifici residenziali creando scenari ambientali, considerando simulazioni di illuminazione naturale, energetiche, di qualità dell'aria interna, ventilazione e simulazioni acustiche. Lo studio sottolinea anche l'importanza della prospettiva del ciclo di vita e dell'uso delle tecnologie Virtual Design and Construction (VDC), Internet of Things (IoT) e Digital Twin per migliorare l'efficienza, la sostenibilità e la gestione e manutenzione della costruzione.

**Parole chiave:** (Building Information Modeling (BIM), Efficienza Energetica, Simulazione Ambientale, Qualità Ambientale Interna, Edifici Residenziali, Progettazione Sostenibile)

# ABSTRACT

Building Information Modeling (BIM) represents a transformative paradigm shift within the Architecture, Engineering, and Construction (AEC) domain, affording an integrated digital framework for the holistic management of building lifecycles, encompassing design, construction, operation, and maintenance phases. A prominent hallmark of BIM lies in its capacity to empower environmental simulations, thereby furnishing designers with the instrumental capability to scrutinize and optimize building performance across dimensions pertinent to energy efficiency, indoor environmental quality, and sustainability. This thesis conveys a scholarly investigation centered on the utilization of BIM for environmental simulation, specifically within the purview of sustainable design considerations vis-à-vis residential structures..

The study's methodology involves a comprehensive literature review of sustainable building design principles, the role of building envelope design in achieving sustainable buildings, material selection and resource efficiency, design considerations for promoting good indoor environmental quality, and strategies for optimising energy performance. The study also analyses rating systems and standards, such as LEED, PEER, EDGE, WELL, and ICP, and their applicability to sustainable design considerations in residential buildings.

The study's results demonstrate the effectiveness of BIM for environmental simulation in improving sustainable design considerations in residential buildings. The study presents case studies of residential building design using environmental simulation, including daylight simulation, energy simulation, indoor air quality and ventilation simulation, and acoustic simulation. The study also emphasises the importance of life cycle perspective and the use of Virtual Design and Construction (VDC), Internet of Things (IoT), and Digital Twin technologies for enhanced construction efficiency and sustainability.

**Keywords**: (Building Information Modeling (BIM), Energy Efficiency, Environmental Simulation, Indoor Environmental Quality, Residential Buildings, Sustainable Design)

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# 1. INTRODUCTION

Building Information Modeling (BIM) has become increasingly popular in the construction industry as a modern approach to building design and construction (Mahdavi et al., 2014). BIM involves creating a digital representation of a building's physical and functional characteristics that can be used throughout its life cycle, from design to operation. Since the building industry is a significant contributor to greenhouse gas emissions and resource depletion, sustainability is a crucial aspect of construction. BIM can significantly achieve sustainable building design principles.

This study investigates how BIM can contribute to sustainable building design through a comprehensive review of literature, case studies of residential building design, and life cycle assessment using environmental simulation. The objective is to provide an overview of the current state of the art in sustainable building design using BIM and to identify the challenges and opportunities in this field.

BIM offers a more efficient and collaborative approach to building design and construction, with a significant potential impact on sustainable building design. This research focuses on using BIM for environmental simulation in improving sustainable design considerations for residential buildings. The study provides a comprehensive review of sustainable building design principles, including the role of building envelope design and material selection in achieving sustainability. It explores various strategies for optimizing energy performance, including thermal comfort, lighting, and water conservation. The work also covers using simulation techniques for environmental analysis, data analysis, and optimization. Finally, the study discusses the role of life cycle assessment in sustainable building design and the importance of using Virtual Design and Construction (VDC), the Internet of Things (IoT), and Digital Twin Technologies for enhanced construction efficiency and sustainability.

**This research aims to answer the following questions:**

1. How can BIM support sustainable building design and construction practices?
2. What are the challenges and opportunities of using BIM for sustainable building design and construction?
3. What are the environmental and economic benefits of using BIM for sustainable building design and construction?

**The hypotheses for this research are:**

1. The use of BIM in sustainable building design and construction can improve energy efficiency, reduce waste, and promote the use of renewable resources.
2. The integration of BIM with other sustainable design tools and rating systems can enhance the sustainability performance of buildings.
3. The adoption of BIM for sustainable building design and construction can reduce project costs, improve project delivery times, and enhance collaboration among project stakeholders.

This research aims to investigate the potential of BIM in sustainable building design and construction, identify the benefits and challenges of using BIM for sustainable building design and construction, and provide recommendations for improving the sustainability performance of buildings through the use of BIM.

Through a mixed-methods approach that employs literature review, case studies, and data analysis, this study explores the potential of Building Information Modeling (BIM) in sustainable building design. To evaluate the impact of sustainable design on residential buildings, advanced software tools such as Revit and Dynamo were utilized to conduct environmental simulations. The study's findings are presented in an easily accessible format, using charts, graphs, and tables. This research effectively demonstrates the efficacy of these methodologies in assessing the performance of sustainable designs in residential buildings.

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# 2. LITERATURE REVIEW

The application of green building practices and the construction of green buildings offer numerous benefits. Firstly, they minimize the ecological footprint of the built environment, which greatly benefits the environment. Green buildings conserve resources by using environmentally friendly products and technologies, reducing waste generation, and minimizing energy and water consumption. This practices helps mitigate global warming, reduce greenhouse gas emissions, and safeguard natural resources. In addition, prioritizing energy efficiency is essential in creating eco-conscious buildings, resulting in lower expenses for occupants and building proprietors.

Moreover, green buildings focus on the health and well-being of occupants. This welling achieved by incorporating improved ventilation systems, non-toxic building materials, maximized natural lighting, and robust indoor air quality control measures. Studies have shown that individuals living in green buildings experience improved productivity, enhanced focus, and overall well-being.

Green buildings also enjoy higher marketability and value. They are in high demand in the real estate market, attracting tenants and buyers and often commanding premium market value. Sustainability is important to individuals and businesses, prompting them to invest in green buildings as a tangible display of their commitment to environmental stewardship. Regulatory authorities endorse sustainable practices within the construction sector by mandating green building prerequisites in building codes and standards, fostering the adoption of eco-conscious initiatives.

Builders and owners can benefit from financial incentives, tax benefits, and grants that support green building initiatives. Adopting green building practices aligns with social responsibility goals, improves companies' public image, and shows their commitment to sustainability and a greener future.

Professionals in the built environment industry are crucial in promoting sustainability and energy efficiency in tenant fit-outs. The growing awareness of environmental concerns has increased demand for high-performance, energy-efficient buildings and spaces. Market dynamics and evolving regulations drive this trend. Various jurisdictions are implementing stricter standards to reduce carbon emissions and enhance energy performance.

Architects have a unique opportunity to shape the sustainability of the built environment, particularly since a significant portion of commercial buildings leased. They can contribute to leased spaces' efficiency and environmental impact right from the design phase by prioritizing energy-efficient design. The Urban Land Institute's Tenant Energy Optimization Program (TEOP) offers a structured approach to achieve substantial energy savings during tenant fit-outs or significant renovations. Architects can benefit from this program's guidance, developed in collaboration with the American Institute of Architects (AIA). The AIA strongly emphasises sustainability and energy efficiency through initiatives like the Framework for Design Excellence and the 2030 Commitment. These initiatives have already demonstrated effectiveness, with architecture firms reporting substantial energy savings and potential cost reductions.


**Figure 1 – ASHRAE Standard 209 outlines 11 cycles for whole-building energy simulation, with single-aspect simulations by architects playing a crucial role in informing these phases.**

Energy Modeling, also known as building performance simulation, is pivotal in optimising the efficiency of entire structures and leased spaces. It encompasses utilising specialised software to evaluate the impact of design strategies on a building's energy consumption. The Architect's Guide to Building Performance, provided by the AIA, is a comprehensive reference for comprehending energy Modeling and facilitating the development of high-performance buildings. Although it predominantly targets new construction projects, the principles articulated in this guide are adaptable to a spectrum of endeavours, encompassing interior fit-outs, such as TEOP initiatives.

Energy Modeling entails quantifying how design decisions influence energy utilisation. It empowers project teams to pose pertinent inquiries, evaluate design strategies, and methodically refine performance. In the context of tenant improvements, Modeling can replicate factors like daylighting, ventilation systems, control systems, and programmatic choices, including the strategic placement of a server room adjacent to an office area to harness waste heat for thermal comfort. Additionally, incorporating historical and anticipated climate data, encompassing variables such as air temperatures, humidity levels, and wind speeds, assures the thermal well-being of occupants.

To ensure the practical application and optimisation of building performance simulation, project teams may adhere to ASHRAE's Standard 209. While certain architects may inherently incorporate energy considerations into their designs, the counterintuitive nature of energy usage necessitates the indispensable role of Modeling in harmonising aesthetics and energy efficiency.

The integration of energy Modeling into architectural workflows varies across firms. Some firms consistently employ it across all projects, often employing it early in the design phase to illustrate potential cost savings to clients. Conversely, others establish close collaborations with engineers from the project's inception, facilitating continuous discourse to convey and elucidate Modeling outcomes to clients. Initial-stage Modeling can commence with limited data and evolve with the design's maturation.

Alternatively, clients can enlist energy Modeling consultants to collaborate with architects. Architects utilise specialised software, such as the U.S. Department of Energy's COMcheck, to simulate energy code compliance. Others employ proprietary software to engage clients in decision-making processes on energy efficiency measures, promoting a participatory model conducive to innovation, distinct from the more predefined options offered by certifications like LEED.

When navigating energy Modeling, architects should regard the array of energy performance measures as decision trees rather than mere options catalogues. Energy Modeling assesses diverse strategies to curtail a building's energy requirements. Financial constraints may preclude the immediate implementation of all energy performance measures, and some measures can impact the efficacy of others. Architects must exercise strategic discernment in prioritising design recommendations grounded in Modeling insights. Collaborative interactions with fellow team members, including engineers and lighting designers, are crucial for evaluating how energy performance measures interact. For instance, modifications in daylighting may influence lighting demands, while variables such as window-to-wall ratios and insulation impact HVAC system sizing.

The sequence of energy enhancements holds significance. Initiating efficiency enhancements to the building envelope, insulation, and lighting can lead to the adoption of smaller HVAC systems, augmenting efficiency and cost-effectiveness. Architects should also consider integrating multiple redundant power systems to ensure seamless building operation during power disruptions.

## 2.1. Sustainable building design principles

This chapter emphasises incorporating sustainable development principles in residential building design, highlighting its importance. It underscores the need to consider environmental, social, and economic factors to achieve sustainable outcomes. The chapter explores minimising ecological footprints, improving energy efficiency, enhancing occupant comfort, and promoting long-term economic viability (Iwaro & Mwasha, 2013).

By integrating environmental, social, and economic considerations, sustainable design practices aim to minimise the ecological footprint of buildings and optimise energy performance. Strategies like MEP design with a BIM workflow, collaboration, data automation, and interoperability enable the evaluation and implementation of innovative solutions for sustainable building design (Iwaro & Mwasha, 2013).

Successful sustainable building requires the early involvement of stakeholders and the consideration of various sustainable development factors. Strategies encompass environmental quality, indoor comfort conditions, and efficient resource use, including daylighting, indoor air quality, passive solar heating, natural ventilation, energy efficiency, waste minimisation, water preservation, and renewable energy (Iwaro & Mwasha, 2013).

Sustainable design principles like Biomimicry, Human Vitality, Ecosystem, Seven Generations, Conservation, and Holistic approaches are integral to building design. Integrating sustainable design into construction processes enables the realisation of sustainable construction goals. Sustainable development in building envelope design is interconnected with four areas: environment, equity, participation, and futurity, encompassing intergenerational equity, public participation, ecosystem preservation, energy conservation, and equal access to resources.

Focusing on environmental sustainability in residential building design is an ethical responsibility and a strategic approach that enhances project quality, efficiency, and long-term value. Sustainable design practices contribute to global efforts to mitigate climate change, conserve natural resources, and foster healthier, resilient communities (Iwaro & Mwasha, 2013).

### 2.2. The Role of Building Envelope Design in Achieving Sustainable Buildings.

The importance of building envelope design in achieving sustainable buildings cannot be overstated. Integrating sustainable design principles into the building envelope makes it possible to minimise the ecological footprint, enhance energy efficiency, and promote long-term economic viability. The building envelope acts as a crucial interface between the external and indoor environment, protecting the indoor environment and ensuring occupant comfort. It significantly regulates solar and thermal flow, moisture control, and indoor air quality. Furthermore, building envelope design interacts with other building components, making it a critical factor in overall sustainability. Optimising the sustainable performance of the building envelope through appropriate assessment methods helps reduce resource consumption, environmental degradation, and reliance on supplementary mechanical energy. The significant building envelope design is essential for enhancing project quality, efficiency, and long-term value in sustainable buildings (Iwaro and Mwasha, 2013).

### 2.3. Importance of sustainable design in the context of residential buildings.

Buildings consume energy and resources throughout their lifecycle, impacting greenhouse gas emissions and the environment. Awareness of climate change necessitates that building designers consider the energy performance of their designs. Sustainable buildings can achieve significant energy savings and outperform traditional buildings (Asman et al., 2019).

The exploration of alternative energy sources, such as solar and wind, should be prioritised during the design stage. Energy-efficient appliances and equipment are vital, considering their lifetime operational costs may exceed the building's construction cost. Additionally, the utilisation of improved HVAC systems contributes to enhancing energy efficiency (Asman et al., 2019).

### 2.4. Material selection and resource efficiency.

The selection of building materials involves considering their potential impact on human health and the environment. It is crucial to prioritise materials that meet specific restrictions related to hazardous substances. These restrictions include ensuring that newly installed building materials are mercury-free, meet specified mercury content limits for lamps, are certified as lead-free for plumbing products, and contain less than 90 ppm total lead in indoor paints and surface coatings. It is also recommended to adopt cleaner production practices, consult with third-party-certified building product verifiers or materials transparency databases, and choose products that best support human and environmental health. Additionally, the concept of Materials Optimization promotes the selection of products with expanded chemical restrictions, such as limiting asbestos content to less than 1% by weight. Adhering to these guidelines aims to create safer and more sustainable buildings that prioritise the well-being of both humans and the environment (Well v2: Evidence behind the Material Concept, 2021).

When designing sustainable buildings, use durable and natural materials to reduce waste and promote a healthier indoor environment. Select renewable materials with low embodied energy and minimal volatile organic compounds (VOCs) to promote overall sustainability.

Designing for humane adaptation involves addressing waste management in the construction and operation of buildings. The construction industry generates significant waste, and designers can play a vital role in waste reduction. By focusing on waste minimisation strategies and considering waste management practices during the design stage, the overall environmental impact of a building can be significantly reduced (Asman et al., 2019).Designing for humane adaptation involves addressing waste management in the construction and operation of buildings. The construction industry generates significant waste, and designers can play a vital role in waste reduction. By focusing on waste minimisation strategies and considering waste management practices during the design stage, the overall environmental impact of a building can be significantly reduced (Asman et al., 2019).

Efforts should be made to reuse and recycle building waste whenever possible. The utilisation of recycled materials serves a dual purpose, encompassing the conservation of natural resources and reducing energy demand during production processes. Moreover, recycling is pivotal in diminishing the waste destined for landfills, advocating for a more sustainable and environmentally responsible waste management approach (Asman et al., 2019).

## 2.5. Design considerations for promoting good indoor environment quality.

The issue of sustainability is becoming increasingly important in the fields of architecture and MEP (mechanical, electrical, and plumbing). The theoretical basis of sustainable development in building design and MEP systems is increasingly recognised, even if not all theories are applicable in practice.

Initially, sustainable development primarily revolved around resource limitations, particularly energy, to curtail the adverse impact on the natural environment. Nevertheless, over the past decade, the emphasis has gradually shifted towards addressing technical intricacies pertaining to architecture and building services. These include considerations such as the selection of materials, building elements, construction techniques, and energy efficiency, all of which are critical to promoting good indoor quality.

Today, sustainability considerations in architecture and building services go beyond technical aspects. Economic and social factors are highlighted as important indicators of sustainable development. In designing for sustainability, economic viability and social well-being must be considered in the indoor environment.

Several strategies are proposed to achieve sustainable architecture and building services. These encompass meticulous building material selection guided by sustainable principles and the incorporation of cutting-edge building technology systems, including industrial manufacturing and prefabricated methods. These strategies are designed to achieve environmental objectives, enhance occupant comfort and well-being, and foster a favourable—indoor environmental quality.

By integrating these approaches into design considerations, architects and MEP professionals can balance environmental responsibility, economic viability, and the creation of a healthy indoor environment. The focus goes beyond technical aspects to embrace a holistic approach that recognises the broader influence of architecture and MEP in promoting good indoor quality for occupant well-being.

### 2.5.1. Air Quality

Indoor air quality (IAQ) constitutes a salient concern, given the substantial duration individuals spend within enclosed environments. The diminishment of IAQ in indoor spaces poses a substantial threat to human health, manifesting in various maladies, including respiratory afflictions, allergies, and enduring health hazards (Kanchanamayoon et al., 2019). Prioritizing IAQ amelioration is imperative for individuals, institutions, and facility managers alike. The implementation of effective ventilation systems, the routine cleaning and maintenance of HVAC (Heating, Ventilation, and Air Conditioning) systems, and the judicious mitigation of noxious chemicals and pollutants are pivotal measures that can markedly augment IAQ in indoor settings (Bornehag et al., 2019). These proactive measures hold the potential to engender healthier and more comfortable indoor environments that foster the well-being of their occupants.

Indoor air quality represents a paramount consideration within the construction sector, with a particular emphasis on residential structures, owing to the growing prominence of sustainable architectural practices. Suboptimal air quality has the potential to exert deleterious effects on human well-being, manifesting in respiratory ailments, allergic reactions, and various health-related maladies. Consequently, architects and designers assign considerable significance to the incorporation of ventilation systems, advanced filtration mechanisms, and judicious material choices to guarantee the attainment of an optimal indoor air quality standard. The integration of Building Information Modeling (BIM) technology offers a comprehensive framework for conducting simulations of diverse design scenarios, thereby facilitating a rigorous assessment of their ramifications on indoor air quality.

The strategies outlined in "Well v2: Evidence Behind the Air Concept" prioritize creating a smoke-free environment, proper ventilation, and basic air quality The fundamental Air Quality Overview is predicated upon the imperative of preserving a healthful indoor milieu, a goal contingent upon the rigorous observance of permissible concentration thresholds for various airborne constituents, including but not limited to particulate matter with diameters less than 2.5 micrometers (PM2.5), particulate matter with diameters less than 10 micrometers (PM10), volatile organic compounds (VOCs), carbon monoxide (CO), ozone (O3), and radon. In pursuit of this objective, the steadfast monitoring of pollutant levels and steadfast adherence to established regulatory standards assume paramount importance..

In Europe, ventilation standards and associated tariffs are determined by the European Committee for Standardisation (CEN) or the Chartered Institution of Building Services Engineers (CIBSE). These European standards generally require higher minimum ventilation rates than the indoor air quality standards set by ASHRAE in the United States (Well v2: Evidence behind the Air Concept, 2021).

### 2.5.2. Energy

In the pursuit of sustainable and efficient building design, it is crucial to consider synergies across disciplines and building systems, starting from pre-design and throughout the design phases. By doing so, we can identify and capitalise on opportunities for integration and optimisation. This approach will inform several critical documents, including the owner's project requirements (OPR), the basis of design (BOD), design documents, and construction documents.

During the discovery phase, two aspects to be analysed are energy-related systems. To ascertain a well-defined energy performance target, it is imperative to establish an energy use intensity (EUI) metric no later than the schematic design phase. Viable options for this metric encompass kWh per square meter-year of site energy use, kWh per square meter-year of source energy use, kg per square meter-year of greenhouse gas emissions, or cost per square meter-year of energy.

The project requirements are contingent on the type in the Residential- Multifamily rating system. For Mixed-use projects encompassing a non-residential area exceeding 20,000 ft2, adherence to requirements in sections 2, 3, and 4 is considered obligatory. Conversely, for Projects with a non-residential area of less than 20,000 ft2, compliance with requirements in sections 2 and 3 is deemed required.
Residential - Multifamily" rating system and commissioning (Cx) activities are crucial for ensuring the optimal performance and sustainability of non-residential areas in buildings. ASHRAE Guideline 0-2013 and Guideline 1.1-2007 serve as established protocols guiding these commissioning efforts. Guideline 0-2013 provides a structured framework for commissioning building systems, emphasising adherence to fundamental requirements and procedures to enhance energy efficiency, indoor environmental quality, water efficiency, and durability, all while meeting the owner's project requirements (OPR). Guideline 1.1-2007, on the other hand, focuses explicitly on commissioning HVAC&R systems, emphasising energy efficiency, indoor air quality, and thermal comfort.

Commissioning activities systematically assess the energy performance, water efficiency, indoor environmental quality, and overall durability of HVAC&R systems and other buildings in non-residential areas by identifying potential issues and optimising system performance.

Section 1 involves engaging a qualified professional to complete commissioning process activities for mechanical, electrical, plumbing, and renewable energy systems and assemblies in non-residential areas.

Section 2 deals with testing and verification activities for two critical areas: shared and common area systems and centralised HVAC and Domestic Hot Water systems serving dwelling units. In buildings with shared spaces, verifying the performance of these systems and documenting findings and recommendations for the owner are required. Similarly.

Section 3 outlines additional on-site inspection and verification activities for qualified professionals, depending on their relevance. Projects certified under Certified PHIUS or ENERGY STAR Multifamily New Construction automatically meet these requirements. The activities include Thermal Enclosure Inspection and verification of ducted heating and cooling systems, ensuring proper air sealing and compliance with specified duct air leakage rates.

#### 2.5.2.1. Minimum Energy Performance

Perform comprehensive unit-by-unit load calculations for each distinct unit type. Based on the results of these calculations, select equipment sizes for all individual systems serving dwelling units, adhering to the specified equipment selection sizing guidelines or opting for the next nominal size as appropriate:

**Cooling Equipment:**

The selected size should fall within 90% to 130% of the total heat gain for systems equipped with a Single-Speed Compressor.

For systems featuring a Two-Speed Compressor, the selected size should be 90% to 140% of the total heat gain.

Systems incorporating a Variable-Speed Compressor should have a selected size within 90% to 160% of the total heat gain.

**Heating Equipment:**

The selected size for heating equipment should be 100% to 140% of the total heat loss.

These specified equipment selection sizing guidelines ensure that the chosen equipment sizes align optimally with the calculated load requirements, enabling efficient and effective performance of the cooling and heating systems within the dwelling units.

Applicable to projects falling within the scope of ASHRAE 90.1-2016, compliance is required with ANSI/ASHRAE/IESNA Standard 90.1–2016, incorporating any relevant errata or a USGBC-approved equivalent standard. The compliance pathways specified in Section 4.2.1.1 of ASHRAE 90.1-2016 include the following options:

a) Compliance with all mandatory provisions of ASHRAE 90.1-2016.

b) Compliance with one of the following approaches:

   1. Prescriptive provisions outlined in Sections 5 through 10 of ASHRAE 90.1-2016.

   2. Section 11 Energy Cost Budget Method, as the standard details.

   3. Utilizing the Performance Rating Method in Normative Appendix G of ASHRAE 90.1-2016.

For projects opting for the Performance Rating Method (Appendix G), a critical requirement is that the Performance Cost Index (PCI) must not exceed or be equal to the Performance Cost Index Target (PCIt), as per the methodology specified in Section 4.2.1.1. The documentation should include values of PCI, PCIt, and the percentage improvement achieved, using metrics based on cost or greenhouse gas (GHG) emissions.

Adhering to these compliance pathways and documentation requirements ensures the project meets the prescribed energy efficiency standards outlined in ASHRAE 90.1-2016, promoting sustainability and environmental responsibility in the building's design and operation.

### 2.6. Rating systems and standards.

In the context of sustainable design, rating systems and standards have become increasingly important for evaluating and certifying buildings' environmental performance. These systems provide a framework for assessing a building's sustainability across several categories, including energy efficiency, water conservation, indoor air quality, and materials selection. Moreover, they also provide guidance for architects and designers to incorporate sustainable design principles into their building design process. In this section, we will explore some of the most commonly used rating systems and standards in the AEC industry, including LEED, PEER, EDGE, WELL, and ICP. We will examine their criteria for certification, their strengths and limitations, and their potential impact on the built environment.

#### 2.6.1. LEED

The U.S. Green Building Council (USGBC) introduced the Leadership in Energy and Environmental Design (LEED) framework as a comprehensive system for classifying and quantifying sustainable buildings within the sustainable building industry. LEED has evolved and developed rating systems tailored to specific building typologies, sectors, and project scopes.

For residential buildings, there are three central LEED rating systems to consider:

##### 2.6.1.1. LEED for New Construction (LEED NC):

- Use LEED NC for new residential buildings, such as apartment complexes or condominiums, that are under construction or undergoing major renovations.
- LEED NC addresses design and construction activities for new buildings and major renovations of existing buildings.

##### 2.6.1.2. LEED for Homes (LEED BD+C Multifamily):

- Use LEED Homes for single-family homes or low-rise multi-family buildings (up to three stories) undergoing construction or major renovations.
- LEED Homes is tailored explicitly for residential projects and considers various aspects, including site selection, energy efficiency, water conservation, indoor air quality, and sustainable materials.

##### 2.6.1.3. LEED for Existing Buildings: Operations & Maintenance (LEED EBOM):

- Use LEED EBOM for residential buildings that are already built and operational, focusing on optimising ongoing operations and maintenance practices.
- LEED EBOM addresses existing buildings' operational and maintenance aspects and promotes sustainable practices in areas such as energy efficiency, water conservation, waste management, and indoor environmental quality.
- When deciding which rating system to pursue for a residence building, consider the stage of the project (new construction or existing), the extent of renovations, and the specific goals and priorities of the project. Each rating system offers different requirements and strategies to achieve certification.

- The LEED rating systems evaluate the environmental performance of buildings from a holistic perspective throughout their life cycle. They cover various types of commercial, institutional, and residential buildings, emphasising energy and environmental principles while balancing established practices and emerging concepts. Each rating system comprises five environmental categories: Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, and Indoor Environmental Quality. Additionally, the Innovation in Design category recognises sustainable building expertise and design measures beyond the scope of the five environmental categories.
- LEED provides a comprehensive framework for assessing and promoting sustainable practices in the design, construction, and operation of buildings. Its widely recognised status as a global standard reflects its commitment to minimising carbon emissions, preserving resources, decreasing operational expenses, prioritising sustainable practices, and fostering a healthier environment.

The design phase plays a pivotal role in the LEED certification process by establishing project goals, assessing credit achievement likelihood, and ensuring the faithful execution of design intent. It also facilitates the collection of necessary documentation and consideration of credit synergies and trade-offs and serves as an early marketing and financing tool. By prioritising sustainability during the design phase, project teams lay the groundwork for a successful LEED certification, resulting in a building that embodies environmental responsibility and offers long-term benefits.

#### 2.6.2. PEER

The PEER Rating System is designed to assess and enhance power system performance and electricity infrastructure. Its objective is to promote adopting reliable, resilient, and sustainable practices within the utilities sector. By utilising the PEER Rating System, utilities can address challenges related to ageing infrastructure, identify opportunities for cost savings, share best practices, prioritise resiliency, and improve monitoring mechanisms to prevent system failures (GBCI, 2021a).

#### 2.6.3. EDGE

An innovation of IFC, a member of the World Bank Group, EDGE is a green building certification system focused on making buildings more resource-efficient. EDGE provides developers and builders with a powerful tool to efficiently identify the most cost-effective strategies for reducing energy consumption, water usage and embodied energy in building materials. The certification process for EDGE is overseen and administered by GBCI (Green Business Certification Inc.) in more than 160 countries worldwide. By leveraging EDGE, professionals in the construction industry can make informed decisions to create sustainable and resource-efficient buildings that align with global environmental goals (GBCI, 2016).

#### 2.6.4. WELL

WELL, v2 is an upgraded version of the WELL Building Standard™ that promotes human health and well-being in buildings and organisations, which sets performance requirements in seven categories: air, water, nourishment, light, fitness, comfort, and mind. It incorporates the latest scientific research and input from stakeholders to provide an accessible and equitable framework. The development process involved pilot testing, public comments, and stakeholder reviews. The rating system is based on six principles and consists of ten concepts with specific features addressing health goals. Projects can be owner-occupied or WELL Core, with different certification levels. Multifamily residential projects can pursue WELL Certification under certain criteria. Overall, WELL v2 is a comprehensive and flexible system focusing on evidence-based strategies and third-party verification to create healthier environments.

#### 2.6.5. ICP

The Investor Confidence Project (ICP), along with its Investor Ready Energy Efficiency Certification (IREE), is administered by the Green Business Certification Inc. (GBCI). ICP serves as a worldwide underwriting standard, offering guidelines for developing and assessing energy efficiency retrofits in commercial and multifamily residential buildings. Through its IREE certification, ICP aims to standardise energy efficiency upgrades (GBCI, 2021b).

### 2.7. Strategies for optimising energy performance.

The Strategies for Optimising Energy Performance section focuses on the various strategies that can be implemented to optimise the energy performance of residential buildings. These strategies are critical in promoting sustainable building design, reducing energy consumption, and minimising carbon emissions. The section covers topics such as thermal comfort, lighting, air quality and ventilation, water conservation, and acoustics. In each of these areas, the section highlights the key design considerations and technologies that can be utilised to optimise energy performance. The section also provides a comprehensive overview of the various rating systems and standards that are available to assess and promote sustainable building design. By implementing the strategies outlined in this section, designers and builders can create energy-efficient residential buildings that promote sustainable living while reducing the impact on the environment.

#### 2.7.1. Thermal Comfort

Thermal comfort is a crucial aspect of indoor spaces that significantly influences the well-being of occupants. The perception of comfort in an environment is intricately influenced by numerous variables, encompassing air temperature, mean radiant temperature, air velocity, humidity, metabolic rate, and clothing insulation. It is noteworthy that certain populations, such as children, individuals with specific medical conditions, and the elderly, are particularly vulnerable to the impact of extreme temperatures. Therefore, maintaining an optimal temperature range is paramount to ensure overall comfort.

In conjunction with temperature, indoor air quality is significantly influenced by humidity and air velocity. It is advised to uphold indoor humidity levels within 30-60% relative humidity (RH) for an equilibrium in indoor conditions. This contributes to fostering a harmonious and conducive indoor environment. Adequate humidity control improves thermal comfort and air quality and reduces the spread of viruses.

1. To increase occupant satisfaction, it is essential to give them control over the thermal environment. Easy-to-use temperature control allows residents to personalise their thermal conditions and increase satisfaction.

2. A preliminary "simple box" energy Modeling analysis is conducted before finalising the schematic design to optimise energy efficiency. This analysis explores ways to reduce energy loads in the building and achieve sustainability goals by challenging default assumptions. The following strategies are assessed:

3. Site conditions: This includes evaluating factors like shading, exterior lighting, hardscape, landscaping, and adjacent site conditions, all of which can impact energy consumption.

4. Massing and orientation: The building's massing and orientation can affect HVAC sizing, energy consumption, lighting, and opportunities for renewable energy integration.

5. Basic envelope attributes: Insulation values, window-to-wall ratios, glazing characteristics, shading, and window operability are considered to enhance the building envelope's performance.

6. Lighting levels: Interior surface reflectance values and lighting levels in occupied spaces are assessed to optimise lighting efficiency.

7. Thermal comfort ranges: Different thermal comfort range options are evaluated to strike a balance between occupant comfort and energy use.

8. Plug and process load needs: By assessing and optimising plug and process loads through programmatic solutions (e.g., equipment and purchasing policies, layout options), energy consumption can be minimised.

9. Programmatic and operational parameters: The potential for multifunctioning spaces, operating schedules, space allotment per person, teleworking, building area reduction, and anticipated operations and maintenance practices are explored to enhance sustainability.

### 2.7.2. Lighting

Light is crucial in our daily lives, impacting comfort, productivity, and well-being. To ensure optimal exposure, guidelines should be established for both natural light and regulated electric illumination. Maintaining a minimum light transmittance (VLT) of 40% in residential units is vital, and at least 70% of building residents should receive adequate daylight through well-designed interior areas and facades. Balancing natural and artificial light sources is essential, with workplace settings typically ranging from 300 to 500 lux. Visual comfort is crucial to avoid headaches, migraines, and glare. Offering pleasing lighting fixtures and the option to double light in work areas can enhance employee comfort (Schools-EBOM-v4 EQc5: Daylight and quality views | LEEDuser, 2020).

Light profoundly influences health and happiness, with daylight being the best source for regulating circadian rhythms, affecting hormone levels, sleep cycles, alertness, and mood. Electric illumination can mimic sunlight and offer comparable benefits. Access to natural light and outside views is linked to reduced pain, shorter hospital stays, and improved overall health. Proximity to windows, larger windows, and views of greenery contribute to greater well-being and positive emotions. Allowing residents to control lighting parameters such as intensity, colour temperature, and colour enhances visual comfort and satisfaction. A balance should be struck to avoid suboptimal lighting situations, and the introduction of automatic systems with manual override ensures a productive lighting environment while accommodating individual preferences (Well v2: Evidence behind the Light Concept, 2021).

Two methods are proposed to demonstrate compliance with illuminance level requirements: computer Modeling or daylight measurements. The following criteria should be met:

1. Minimum access to daylight in each living space: Ensure that at least 90% of the floor area of each regularly occupied space in all residential units receives a minimum of 10 lux of daylight. Each space is evaluated individually for this requirement.

2. Adequate daylight for the building: Achieve illuminance levels ranging between 150 lux and 5,000 lux for at least 50% of the regularly occupied floor area in the building. Spaces equipped with blinds or shades for glare control may only demonstrate compliance for the minimum 150 lux level. The assessment for this requirement considers the overall percentage of all regularly occupied spaces in the building.

For calculating illuminance levels, the following steps are suggested:

1. Calculate two specific time points on a clear-sky day at the equinox: 9 a.m. and 3 p.m.

2. Use a maximum 1500-millimetre square grid for calculations.

3. Exclude the influence of blinds or shades from the Modeling process but consider the presence of permanent interior obstructions. Movable furniture and partitions may be omitted from the calculations.

For measuring illuminance levels, adhere to the following guidelines:

1. Conduct measurements during the day between September 1st to October 30th or March 1st to April 30th.

2. Take measurements of 76 millimetres above the floor in all regularly occupied spaces, excluding kitchens.

3. In kitchens, measure illuminance levels at the height of the kitchen counter.

4. Use a maximum 1500-millimetre square grid for taking measurements.

### 2.7.3. Air quality and ventilation

Tuomaala and Lictech proposed a network-based multi-zone air infiltration and ventilation simulation strategy in their research article titled "New Building Air Flow Simulation Model: Theoretical Basis." This strategy divided the building into a series of connected zones, each representing a different place. Flow components like ducts or apertures enhanced the airflow between the zones. The flow equations were solved using a fully implicit formulation in Tuomaala's model, which made it possible to handle both steady-state and dynamical issues. The model used momentum equations to calculate pressure and velocity and mass balance equations to predict air and pollutant flow rates. Notably, the current model assumes constant and uniform air temperatures throughout and ignores the thermal behaviour of the building. Tuomaala examined the program's convergence by conducting steady-state simulations and verified that the mass balance and momentum equations were satisfied. Additionally, we discussed upcoming tasks concerning the model's enlargement to simulate indoor air quality. This would make it possible to evaluate various ventilation and air cleaning techniques to enhance indoor air quality. (Tuomaala & Lictech, 1993).

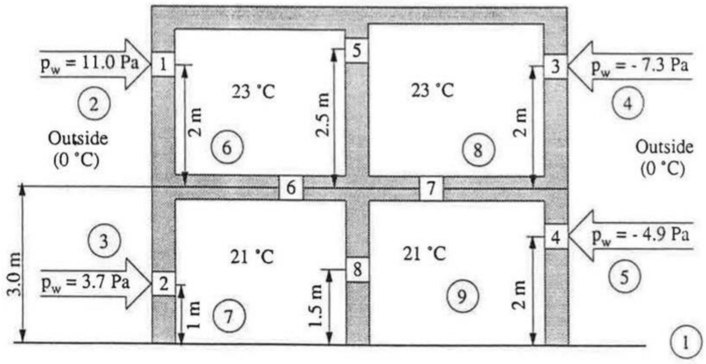



**Figure 2 – A four-room building of the second numerical example. Node numbers are inside the circles, and flow CD element numbers are inside the squares (Tuomaala & Lictech, 1993).**

The optimisation of air quality involves several key steps:

- Identification of sources: The first step is to identify the sources of indoor air contaminants. Understanding the sources helps in targeting specific areas for improvement.
- Assessment of exposure pathways: It is essential to assess how these contaminants enter the indoor environment and the paths through which individuals are exposed.
- Setting goals and thresholds: The next step involves establishing goals and thresholds for reducing contaminant levels. Limits are also set for carbon monoxide and nitrogen dioxide levels. These goals and thresholds surpass existing standards to enhance indoor air quality.
- Implementation of mitigation measures: Various mitigation measures must be implemented to achieve the set goals. These measures include improving ventilation systems, implementing air filtration technologies, and adopting cleaner energy sources using low-emission building materials.
- Monitoring and evaluation: Regularly monitoring indoor air quality is crucial to assessing the mitigation measures' effectiveness. This entails measuring contaminant concentrations and evaluating if they meet defined thresholds. Essential measures include using carbon monoxide (CO) monitors in all units, regardless of the equipment present, and ensuring indoor fireplaces and woodstoves have closing doors or solid glass enclosures. For combustion-involved space and water heating equipment, meeting specific requirements such as closed combustion, power-vented exhaust, or placement in detached utility buildings or open-air facilities is essential. These measures effectively minimise the risk of CO exposure.
- Implemented ventilation must be a demand-controlled system.
- Opening windows and doors effectively reduces indoor pollutant levels and encourages the circulation of fresh airflow.

- Implement displacement ventilation and advanced air distribution that introduces air through floor diffusers, providing fresher air in the breathing zone compared to ceiling supply systems.

The "Construction Activity Pollution Prevention - Sustainable Sites" requirement within LEED BD+C: New Construction v4.1 is designed to proactively mitigate the adverse environmental impacts stemming from construction activities, with a particular emphasis on safeguarding frontline communities. The primary objective is to proactively address issues associated with soil erosion, waterway sedimentation, and the dispersion of airborne dust, all of which can disproportionately affect these communities.

To fulfill these sustainability requirements, the project is required to formulate and execute a comprehensive erosion and sedimentation control plan that encompasses all construction activities associated with the project. Key components of this plan include (Santos et al., 2022):

- Compliance with Regulatory Standards: The plan must align with the 2017 U.S. Environmental Protection Agency (EPA) Construction General Permit (CGP) stipulations or adhere to any applicable local equivalents, consistently adhering to the more stringent of the two standards. This ensures that the project complies with established environmental regulations.
- Universal Applicability: Irrespective of the project's size or scale, the project must adhere to the guidelines set forth by the CGP. This underscores the commitment to environmental stewardship regardless of project scope.
- Effective Implementation: The plan must also articulate the specific measures and strategies undertaken to successfully implement erosion and sedimentation controls. This proactive approach aims to minimise the negative environmental footprint associated with construction activities.

For projects utilising the Normative Appendix G Performance Rating Method, specific guidelines govern the calculation and assessment of GHG emissions for both the baseline and proposed building performance ratings. The percentage improvement is determined based on carbon dioxide equivalent emissions. The approach to calculating GHG emissions depends on the project's location:

For projects in the US and Canada:

a) Use the U.S. Environmental Protection Agency's (EPA) regional grid mix coefficients to calculate GHG emissions by energy source or

b) Utilize hourly emissions profiles from the U.S. EPA's Avoided Emissions and Generation Tool (AVERT).

For international projects:

Use national grid mix coefficients from the International Energy Agency CO2 Emissions from Fuel Combustion 2017 report to calculate GHG emissions by energy source.

Furthermore, ISO Standard 52000-1:2017 is employed to consistently determine greenhouse gas emission factors for each building energy source published for the country or region of the project.

An exception to the requirements of Mandatory Measures is permitted for provisions quantified in the Appendix G Performance Rating Method. These provisions may include lighting occupancy sensor controls, lighting daylighting controls, and automated receptacles controls). Projects may model the Proposed Building Performance control parameters identically to the Baseline Building Performance control parameters instead of directly complying with the mandatory provisions.

#### 2.7.3.1. Supply Air-Flow Testing

The study mandates third-party testing of HVAC fan airflow in residential dwelling units to ensure compliance with specified criteria. The measured airflow should align with either the installer's measured fan airflow within a 10% margin or the design HVAC fan airflow within a 15% margin. Supply air-flow requirements must meet the higher cooling or heating designed air flow for each room. Residential buildings with non-ducted and radiative systems automatically fulfil credit requirements.

LEED certification for residential HVAC systems offers various compliance options. For radiative systems, install an HVAC system with at least two zones, each equipped with independent thermostat controls. For multifamily buildings, the criterion necessitates a demonstration of a pressure difference not exceeding 3 Pa relative to the main house body. Alternatively, bedrooms with a design airflow of at least 150 CFM are permitted a pressure differential of no more than 5 Pa. Multi-speed fan systems should use the highest design fan speed for verification. (LEED Certification for Homes, 2020).

### 2.7.4. Water conservation.

Water conservation is crucial due to the growing global population and limited resources. Sustainable water management practices are essential for efficient use of water, particularly in buildings. This part explores strategies for water conservation in buildings, including technologies and design considerations that promote water efficiency and reduce waste.

Water conservation stands as an urgent imperative within academic settings, as universities, as bastions of knowledge and research, hold a pivotal responsibility to champion sustainable practices. By deploying water-saving strategies such as low-flow faucets and toilets, academic institutions can notably diminish water consumption, alleviate environmental impacts, and contribute substantively to safeguarding this irreplaceable resource (Dwivedi et al., 2019; Johnson, 2018). Beyond tangible savings, water conservation fosters a culture of sustainability among students, faculty, and staff through awareness campaigns and educational initiatives (Schoeman et al., 2017). Implementation of water-efficient technologies like rainwater harvesting systems and greywater recycling further reduces academic buildings' water footprints (Gupta et al., 2020). Moreover, integrating water-saving practices into research projects and curricula cultivates environmental stewardship among students, preparing them to tackle future water conservation challenges (Dwivedi et al., 2019). In a world grappling with water scarcity, it is incumbent upon academic communities to prioritize concerted efforts toward water conservation, forging a path toward the preservation of this invaluable resource.

Given the global concern regarding water resource depletion, it is crucial to conserve water through sustainable construction methods that prioritize water efficiency. Water-efficient practices have both environmental and economic benefits by reducing energy consumption in water and wastewater systems. Implementing water-efficient procedures leads to cost savings in distribution, treatment, and abstraction. To achieve water efficiency, the 5R principle guides practices, which emphasises consumption reduction, loss and waste reduction, reuse, recycling, and seeking alternative sources. Following these principles fosters sustainability, and adverse water-related impacts are mitigated (Asman et al., 2019).

Maintaining water quality is crucial, necessitating regular monitoring of water quality parameters and implementing a Legionella management plan. Water testing ensures treatment efficacy and verifies the presence of Legionella bacteria, which can pose a risk of respiratory illness transmission. Monitoring pH, turbidity, and coliforms in drinking water is essential for preventing health issues. A comprehensive management plan with risk assessment and control measures is necessary to prevent Legionella-related illnesses. Considering water system complexities and relevant risk factors is vital in effective water management (Well v2: Evidence behind the Water Concept, 2021).

1. A preliminary water budget analysis is conducted before the schematic design phase to identify opportunities for reducing potable water consumption in the building. This analysis also aims to lessen the strain on municipal water supply and wastewater treatment systems.
2. The water budget analysis involves a careful assessment and estimation of potential nonportable water supply sources and water demand volumes, considering the following aspects as applicable:
3. The analysis of flow and flush fixture design case demand volumes is conducted as per the requirements outlined in the WE Prerequisite Indoor Water Use Reduction. This assessment allows for optimising indoor water use and reducing the reliance on potable water sources.
4. Outdoor water demand: The landscape irrigation design case demand volume is calculated by WE Credit Outdoor Water-Use Reduction. Evaluating outdoor water requirements helps to identify ways to minimise water usage in landscaping while preserving a green and sustainable environment.

A comprehensive water management strategy plays a vital role in achieving sustainability goals aligned with LEED BD+C: New Construction v4.1 standards. This strategy involves a detailed analysis of process water demand specific to equipment and facilities, such as kitchens, laundry, and cooling towers, to identify opportunities for efficient water use. Concurrently, the assessment explores potential nonpotable water sources like rainwater, greywater, municipally supplied nonpotable water, and HVAC equipment condensate, assessing their integration to meet water demand components.

To qualify for the "Optimize Water Use for Cooling" option, the designated baseline system must include a cooling tower by ASHRAE 90.1-2016 Appendix G Table G3.1.1. Implementing axial variable-speed fan cooling towers with maximum drift control and operating with three cooling tower cycles ensures enhanced cooling tower water efficiency. Furthermore, optimising water resources in mechanical processes entails conducting a one-time potable water analysis, calculating maximum cooling tower cycles, and incorporating a minimum percentage of recycled nonpotable water in cooling tower makeup, leading to efficient and environmentally responsible cooling systems.

Simultaneously, the Water Metering prerequisite within LEED BD+C: New Construction v4.1 aims to bolster water efficiency efforts by continuously monitoring and benchmarking water usage patterns. To comply, a comprehensive whole-house water meter must be installed in residential properties, accurately measuring water consumption.

Additionally, homeowners or tenants are encouraged to actively participate in this initiative by sharing their water usage data with USGBC via an approved third-party platform or system.

This collaborative approach fosters a deeper understanding of water usage trends and facilitates the implementation of targeted conservation strategies. However, homes relying solely on well water and lacking connections to municipal water systems are exempt from this particular prerequisite. The amalgamation of both strategies fosters a holistic and effective approach toward water conservation and sustainable building practices.

In the context of LEED ranking, if the building is for a single family, the Total Water Use criterion emphasises the significance of water conservation by aiming to achieve a minimum 20% reduction in indoor and outdoor water consumption compared to standard practices. To achieve indoor water savings, the Water Reduction Calculator determines the average flush or flow rate for each fixture type and estimates the daily usage. The baselines for indoor water consumption are outlined in Table 1, providing reference values for evaluating water conservation efforts within the project. The objective is to encourage sustainable water management practices contributing to resource efficiency and environmental responsibility within the built environment.

The regulation necessitates using at least R-4 insulation on all domestic hot water piping, including sub-slab pipes, while ensuring adequate insulation around piping elbows and tees. For buried piping, a protective, waterproof raceway, channel, sleeve, or path must be employed, with dimensions allowing easy removal and replacement of the piping and insulation without compromising their integrity. However, as per the manufacturer's guidelines, this waterproof sleeve is not obligatory for below-grade piping if the insulation manufacturer confirms its insulating value in damp soil conditions. This exception does not apply to piping that passes through or beneath building slabs**.**

**Table 1– Indoor water baseline consumption (per person per day) (USGBC, 2022).**

| **Fixture** | **Baseline flush or flow rate** | | **Estimated Fixture Usage** | **Estimated water usage** | |
|---|---|---|---|---|---|
| **Shower (per compartment)** | 2.5 gpm | 9.5 lpm | 6.15 minutes | 15.4 gallons | 58.4 liters |
| **Lavatory, kitchen faucet** | 2.2 gpm | 8.3 lpm | 5.0 minutes | 11 gallons | 41.5 litres |
| **Toilet** | 1.6 gpf | Six lpf | 5.05 flushes | 8 gallons | 30.3 liters |
| **Clothes washer** | 9.5 IWF | 9.5 IWF | 0.37 cycles @ 3.5 ft3 (@0.1 m3) | 15.1 gallons | 57.1 liters |

| | | | | | |
|---|---|---|---|---|---|
| **Dishwasher** | 6.5 gpc | 24 lpc | 0.1 cycles | 0.7 gallons | 2.4 litres |

By the LEED guidelines, the water pressure within the residential property must undergo testing, ensuring the absence of any detectable water leaks. Furthermore, installed water softeners should be demand-initiated to promote efficient water utilisation.

1. Installation of smart scheduling technology, with a potential maximum reduction of 30%, is contingent on employing a soil moisture sensor control system or a weather-based irrigation control system to regulate all landscape water usage effectively.

2. Utilization of captured rainwater as an alternative water source for outdoor applications.

3. Incorporation of reclaimed water, which refers to treated wastewater, into outdoor water usage to minimise reliance on potable water resources.

4. Implementation of water treated on-site or conveyed by a public agency specifically for nonportable uses while excluding water sourced from naturally occurring surface water bodies (e.g., streams and rivers) and groundwater (e.g., well water) from consideration.

Water conservation and sustainable building practices require all faucet aerators and lavatory faucets to bear the Water Sense branding. To earn one point, the average rated flow volume for all bathroom faucets must not exceed 1.5 gallons per minute (5.6 litres per minute).

Similarly, each showerhead fitting and fixture must display the Water Sense label. To gain one point, the mean flow rate in every shower unit must exceed 7.5 litres per minute. However, it is preferred to get an average flow rate of 6.6 litres per minute.

Moreover, all toilet fittings and fixtures must also be labelled with WaterSense. For one or two points, all toilets' average rated flush volume must not exceed 4.8 litres per flush or 4.1 litres per flush, respectively. In addition, clothes washers used in projects outside of the United States must be ENERGY STAR certified or equivalent, earning one point. For European initiatives, residential appliances with the EU A+++ mark are permissible. If outside the US, WaterSense may be replaced with a local equivalent.

These regulations apply to all housing unit spaces and non-unit facilities within multifamily complexes, encompassing both residential-associated and nonresidential spaces. Compliance with these standards encourages indoor water conservation and supports environmentally friendly multifamily housing designs. It is noted that no additional credit is given for more effective fixtures and fittings in non-dwelling unit spaces compared to dwelling unit spaces.

A Water Reduction Calculator is utilised to determine the average flush or flow rate for each fixture type and the estimated daily usage for indoor water savings. The baseline water consumption levels for indoor fixtures and fittings are detailed in Table 2.

**Table 2– Baseline water consumption of fixtures and fittings**

| Fixture or fitting | Baseline (IP units) | Baseline (SI units) |
|---|---|---|
| **Toilet (water closet)** | 1.6 gpf | Six lpf |
| **Urinal** | 1.0 gpf | 3.8 lpf |
| **Public lavatory (restroom) faucet** | 0.5 gpm* | 1.9 lpm* |
| **Dwelling unit lavatory and public and private kitchen faucets (excluding faucets used exclusively for filling operations)** | 2.2 gpm* | 8.3 lpm* |
| **Showerhead** | 2.5 per shower stall or compartment | 9.5 lpm**per shower stall or compartment |
| **Clothes washer** | 9.5 IWF | 9.5 IWF |
| **Dishwasher** | 6.5 gpc | 24 lpc |
| **Toilet (water closet)** | 1.6 gpf | Six lpf |

### 2.7.5. Acoustic

The significance of acoustics in residential building design cannot be overstated, as it has a direct impact on the well-being of those who reside within. Excessive noise can lead to stress, sleep disruptions, and hindered productivity. Thus, it is imperative to prioritize acoustic design in the early stages of building planning, ensuring a tranquil and comfortable living space. This design includes considering sound transmission through walls, floors, and ceilings and controlling external noise sources such as traffic and aircraft noise. This text will explore various aspects of acoustic design in residential buildings and investigate how environmental simulation can improve sustainable design considerations.

The acoustic environment in residential buildings is a critical determinant of overall quality of life for its occupants. As Smith points out, residential buildings must adhere to specific acoustic design principles to ensure an environment conducive to relaxation, productivity, and well-being. This includes the implementation of noise control measures, sound insulation techniques, and optimizing room acoustics (Smith, 2017).

In the study by Johnson and Williams (2019), the subjective perception of sound in residential environments is examined. Their research highlights that residents' well-being is profoundly affected by the acoustic environment. The study underscores the importance of minimizing noise levels, enhancing privacy, and fostering comfort to promote tranquillity and reduce distractions.

Lee and Chen's study (2021) delves into the adverse consequences of poor acoustic environments in residential buildings. It reveals that such environments can lead to increased stress levels among residents, often due to noise pollution and associated sleep disturbances. This emphasizes the necessity for effective acoustic interventions in residential buildings to create a healthy living environment.

#### 2.7.5.1. Sound mapping and noise level requirements

The combination of information from the Sound Mapping and Maximum Noise Levels overviews emphasises the critical role of acoustical planning and meeting specific sound pressure level requirements in architectural spaces. Sound is characterised as pressure fluctuations between particles, with frequencies ranging from 20 to 20,000 Hz. The human ear is sensitive to sound frequencies within this range. Sound pressure levels are measured in decibels (dB), with values ranging from 10 dB (near silence) to 130 dB (pain).

Various strategies are recommended to effectively manage acoustical stressors, including source control, sound-blocking or absorbing materials, sound-masking techniques, and intentional space design based on different activity types. Maintaining sound levels below 55 dBA for routine work and below 45 dBA for tasks involving deep concentration or in enclosed spaces such as meeting rooms is advisable.

Moreover, it is crucial to consider the health effects associated with environmental noise exposure. The threshold of human hearing is determined to be 20 micro pascals ($2.0 \times 10^{-5}$ Pa), and sound pressure level (SPL) is measured in decibels (dB). 0 dB equivalent to $2.0 \times 10^{-5}$ Pa. To prevent irreversible hearing loss, avoiding noise exposure levels exceeding 75-85 dBA is recommended. Furthermore, excessive noise can contribute to elevated stress responses, cardiovascular problems, hypertension, tinnitus, and sleep disturbances.

The site noise assessment requires qualitative or quantitative evaluations to assess noise levels and consider adjacent residential buildings. Exterior noise sources must be designed to meet specific noise level limits at the project boundary. For residential projects, bedroom noise limits should not exceed a maximum interior noise level (Lmax) of 45 dBA and an average interior noise level (Leq, eighth) of 30 dBA for HVAC background noise. The acoustic performance of walls, partitions, floor/ceiling assemblies, windows, and entrance doors must meet minimum sound transmission class (STC) ratings of 55, 34, and 30, respectively. Penetrations or openings in construction assemblies should be appropriately treated to maintain the required rating. Conforming sound level meters conforming to ANSI S1.4 for precision or general-purpose sound measurement instrumentation.

#### 2.7.5.2. The Reverberation Time

The importance of designing spaces that meet specific thresholds for enhancing speech intelligibility is highlighted. Reverberation time (RT60) quantifies the duration, measured in seconds, for the average sound pressure level in a space to decay by 60 decibels (dB) once the sound source has stopped.

To promote health and well-being, it is crucial to achieve optimal reverberation time based on factors such as room volume, intended use, and transmitted sound frequencies. Designing spaces with shorter reverberation times enhances comprehension and memory recall of spoken information, as excessive reverberation causes temporal smearing of speech signals, making them harder to understand. Addressing both reverberation and ambient sound pressure levels is essential for improving speech intelligibility, as these factors can synergistically exacerbate each other.

Implementing strategies for achieving optimal reverberation time involves the use of sound-absorptive materials that effectively absorb direct sound and reduce reverberation time—additionally, incorporating textured surfaces. By incorporating these strategies, spaces can create a more favourable acoustical environment that supports speech intelligibility, minimises distractions, and enhances well-being.

#### 2.7.5.3. Background sound

The appropriate levels of sound masking play a crucial role in residential buildings to ensure optimal speech intelligibility. In areas designated as Quiet zones and/or Circulation zones within open spaces, it is recommended that sound masking levels do not exceed 48 dBA. For enclosed rooms specifically labelled as Quiet zones, the limit is set at 42 dBA.

The site noise assessment requires qualitative or quantitative evaluations to assess noise levels and consider adjacent residential buildings. Exterior noise sources must be designed to meet specific noise level limits at the project boundary. For residential projects, noise limits in bedrooms should not exceed a maximum interior noise level (Lmax) of forty-five dBA and an average interior noise level (Leq, eighth) of thirty dBA for HVAC background noise. The acoustic performance of walls, partitions, floor/ceiling assemblies, windows, and entrance doors must meet minimum sound transmission class (STC) ratings of 55, 34, and 30, respectively. Penetrations or openings in construction assemblies should be appropriately treated to maintain the required rating. Conforming sound level meters, conforming to ANSI S1.4 for type 1 (precision) or type 2 (general purpose) sound measurement instrumentation, or the International Electrotechnical Commission (2013) IEC 61672-1:2013 Electroacoustics – Sound Level Meters – Part 1: Specifications, or a local equivalent, are essential for accurate measurements during assessments.

# 3. CASE STUDIES OF RESIDENTIAL BUILDING DESIGN USING ENVIRONMENTAL SIMULATION

During our training period, we had the opportunity to work on an exciting project situated in Milan. The project consisted of four residential towers, each with nine floors, and two additional towers, each with five floors. With a total of 300 unique apartments that varied in location, design, and area, the project presented us with an excellent opportunity to showcase our skills.

Our primary responsibility in this project was to calculate the energy requirements, model necessary equipment, and ensure that it was appropriately placed in the designated areas and connected to the relevant sections. To achieve this, we carried out the necessary calculations and developed codes and scripts that streamlined the entire process. Our work focused on energy calculations and Modeling, which will prove to be instrumental in the advanced stages of the project.

In this section, we discussed the mathematical operations of an apartment with code B.02.S1.02 on the second floor of Building B.

## 3.1. Simulation

Simulation has become an increasingly popular tool in the field of construction and building design, allowing architects and engineers to test and evaluate the performance of a building before construction even begins. Simulation can be used to analyse a wide range of factors, from energy efficiency and indoor air quality to acoustic performance and lighting. By providing insights into the behaviour of a building, simulation can help designers make informed decisions and optimize the design for the best possible performance. In this part, we explore the use of simulation for improving sustainable design considerations in residential buildings, focusing on the environmental aspects of building information Modeling (BIM) and the benefits that simulation can bring to the design process.

To create a 3D model, it is necessary to properly prepare and acquire the necessary information to present and enhance the model accurately. First of all, in the Architecture model, the spaces were created to host the information by Placing Spaces Automatically, as shown in Figure 3. The spaces placed not useful spaces automatically in this step, like vertical shafts and ducts, were deleted by the dynamo script after copying the room data from the linked file. See Figure 4, Figure 5 and Figure 6.

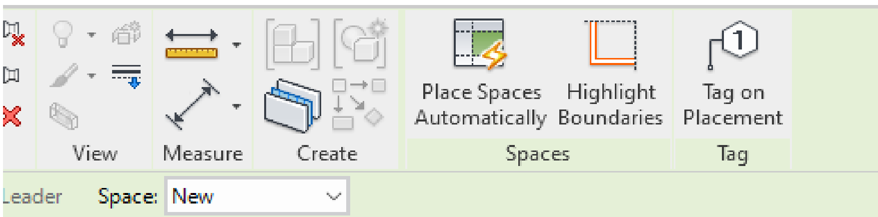



**Figure 3 – Place Spaces in the Simulation model.**

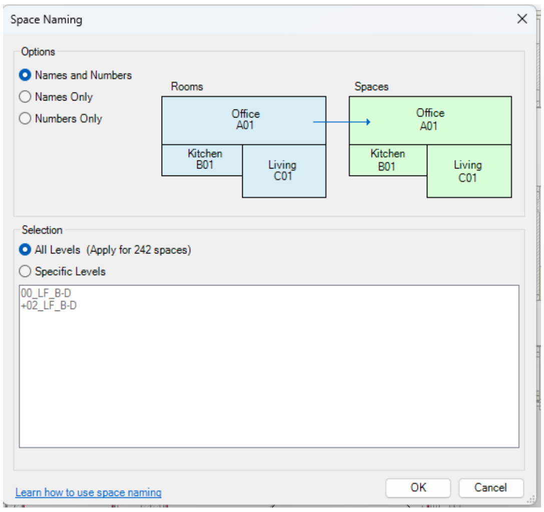



**Figure 4 – Copy Rooms' names and numbers to the Spaces.**

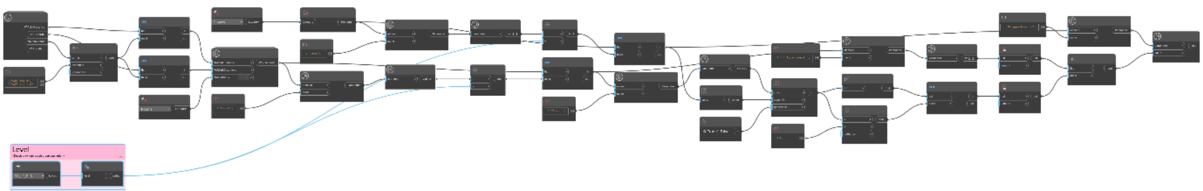


**Figure 5 – Copy data from Rooms' parameters inside the linked file to Spaces' parameters.**

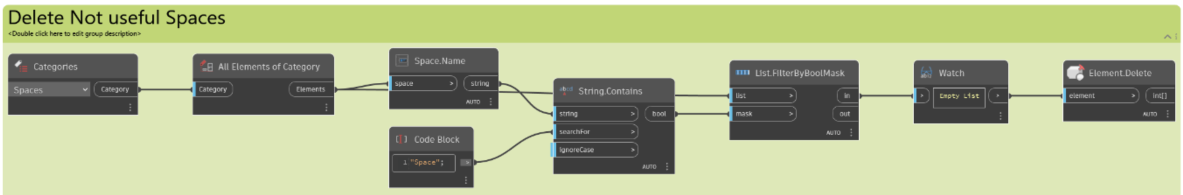



**Figure 6 – Delete not useful spaces using the dynamo script.**

### 3.1.1. light simulation

Lighting simulation is an essential aspect of building design, as it plays a crucial role in determining the overall energy consumption and visual comfort of occupants. The use of Building Information Modeling (BIM) for environmental simulation has become increasingly popular in recent years, as it enables designers to create accurate digital models of buildings and simulate various scenarios to optimize energy efficiency and occupant comfort. This approach allows designers to evaluate the impact of different lighting systems and configurations, daylighting strategies, and shading devices, among other factors, to improve sustainable design considerations in residential buildings. In this part, we explore the use of BIM for lighting simulation and its potential benefits for sustainable building design.

The square grid was created following the LEED standard with dimensions of 75 x 75 mm to make the measurement accurate; see Figure 7, which shows the unit created as a family to host the data related to the light. Figure 8 shows the family parameters that are going to host metadata. Utilising Dynamo, the chosen apartment for simulation was identified, and sensors were allocated to each space within it. See Figure 9.

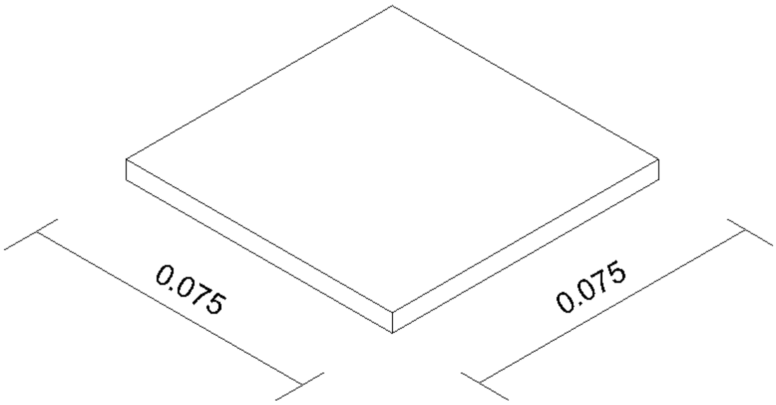



**Figure 7 – 75mm square family unit for hosting data and metadata.**

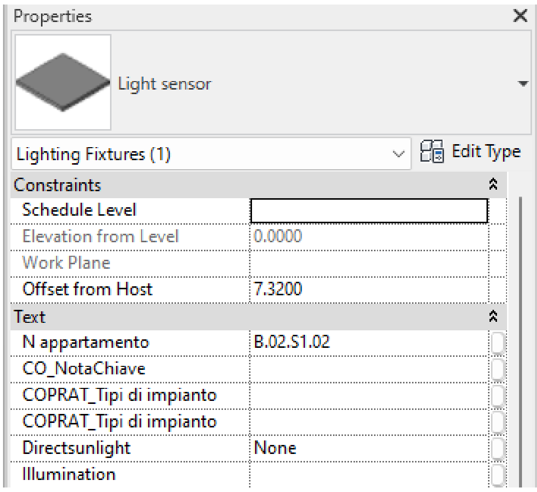



**Figure 8 – Family parameters.**

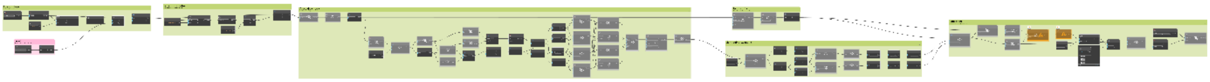


**Figure 9 – Creating a square grid in the apartment using dynamo script.**

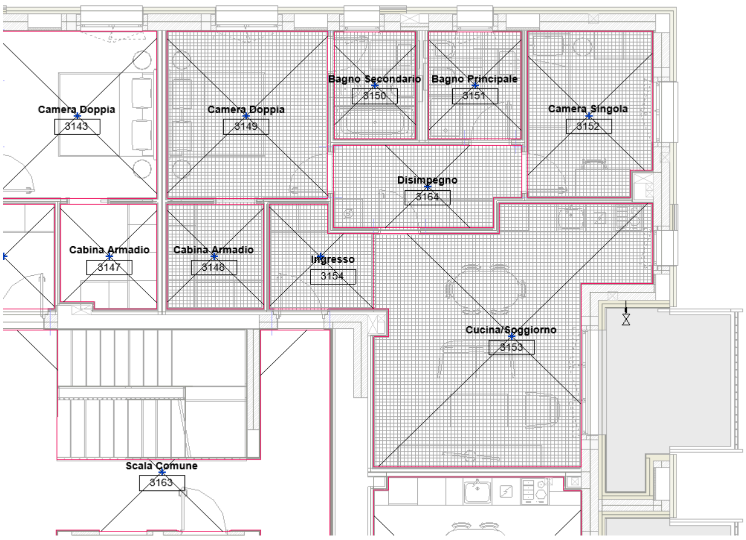



**Figure 10 – The grid created within the selected apartment.**

#### 3.1.1.1. Daylight simulation

Daylight in buildings comprises a combination of components: direct sunlight, diffuse skylight, and light that is reflected from the ground and surrounding elements. The daylighting design must encompass factors such as building orientation and site attributes, characteristics of facades and roofs, dimensions and positioning of window openings, glazing and shading mechanisms, and the geometry and reflectivity of interior surfaces. A well-executed daylighting design guarantees the provision of sufficient illumination during daylight hours.

Skylight is defined by sunlight scattered by the atmosphere and clouds, creating a gentle and diffused illumination. The illuminance levels from an overcast sky might range from 10,000 lux in winter to approximately 30,000 lux on a luminous overcast day during summer. In regions with cloudier climates, the diffuse sky frequently constitutes the primary source of beneficial daylight.

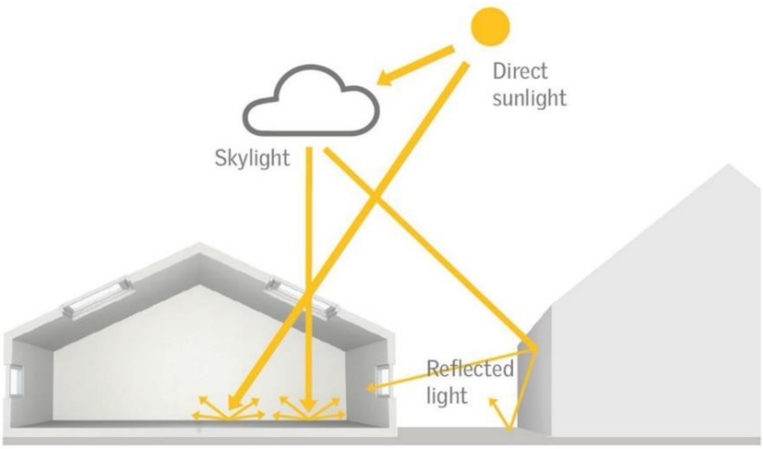



**Figure 11: The components of daylight (Velux, 2021).**

#### 3.1.1.2. Natural light simulation

Solar irradiance emerges as a perturbing exogenous thermal stimulus, yielding consequential implications for the functionality of optical instruments and allied systems. The quantum of incident and absorbed radiant flux is contingent upon the geometric attributes, spatial alignment, and surface microstructure of the optical apparatus or containment structure. The determination of solar azimuth hinges upon the judicious application of astronomical algorithms, intrinsically encompassing geodetic latitude, solar declination, and temporal parameters. Surface bidirectional reflectance, denoted as albedo, serves as a scalar manifestation of the bidirectional reflectance distribution function, signifying the partitioning of incident solar irradiance. The computation of solar insolation entails mathematical formalisms that integrate solar radiant exposure, zenith incidence angle, and the substratum's spectral-hemispherical reflectance properties. Solar insolation is an influential determinant underpinning the ontogenesis and operation of telescopic assemblages, heliogenic energy platforms, architectural structures, agrarian pursuits, and comprehensive climate simulations (Greve & Bremer, 2010).

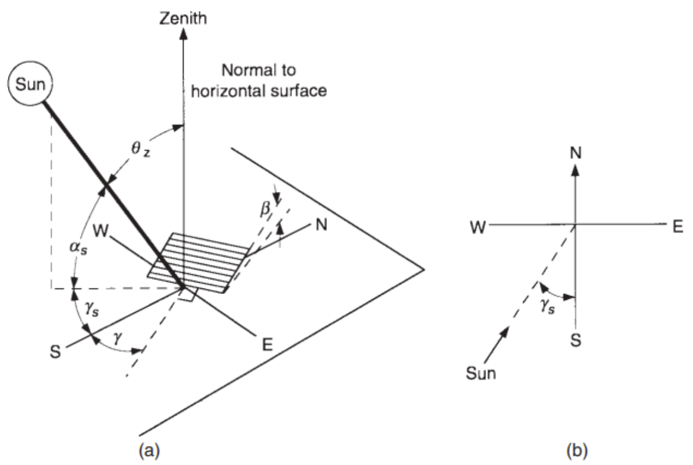



**Figure 12 (a) Zenith angle, slope, surface azimuth angle, and solar azimuth angle for a tilted surface. (b) Plan view showing solar azimuth angle.**

A procedure must be followed to calculate the illuminance caused by the sun. This involves calculating the total solar irradiance under clear sky conditions and the total daily solar irradiance on a surface, regardless of its orientation. Subsequently, the calculated solar irradiance needs to be converted into illuminance, taking into account the sensitivity of the human eye to different wavelengths of light.

To calculate the illuminance due to the sun, you generally follow these steps:

a) Calculate the total solar irradiance under clear sky conditions, considering the sun's position, the sphere's effects, and other factors.

b) Determine the orientation of the surface you're interested in.

c) Calculate the total daily solar irradiance on that surface, considering the angle of incidence of sunlight over the course of the day.

d) Convert the solar irradiance to illuminance by accounting for the human eye's sensitivity to light at different wavelengths. This involves applying a luminous efficacy factor, which represents the efficiency of human vision in perceiving light at different wavelengths.

Two angles identify the position of the sun in the sky, the solar altitude $\alpha_s$ and the solar azimuth $\gamma_s$, which are calculated automatically using Revit software with Dynamo node after choosing the site's location. But, when making calculations over the long term, equations must be used to speed up the process. In this case, some available parameters are used, such as the corners of windows and walls.

Solar Radiation at the surface can be calculated as:

$$G_{cb} = \tau_b . G_{on}. \cos\Theta = \tau_b . G_{on}. (\cos\varphi . \cos\delta . \cos\omega + \mathrm{Sin}\varphi . \sin\delta) \quad (1)$$

$$\tau_b = a_0 + a_1 . e^{(-k/\cos\theta z\,(ti)})} \quad (2)$$

$$\omega(t_i) = (t_i - 12).15^o \quad (3)$$

$$a_0 = r_0 \cdot (0.4237 - 0.00821 \cdot (6 - A)^2) \quad (4)$$

$$a_1 = r_1 \cdot (0.5055 - 0.00595 \cdot (6.5 - A)^2) \quad (5)$$

$$k = r_k \cdot (0.2711 - 0.01858 \cdot (2.5 - A)^2) \quad (6)$$

It is important to take into the factors of climate-type correction. Where the values vary during the year. See Table 3.

**Table 3– Correction Factors for Climate Type**

| Climate Type | $r_0$ | $r_1$ | $r_k$ |
|---|---|---|---|
| **Tropical** | 0.95 | 0.98 | 1.02 |
| **Midlatitude summer** | 0.97 | 0.99 | 1.02 |
| **Subarctic summer** | 0.99 | 0.99 | 1.01 |
| **Midlatitude winter** | 1.03 | 1.01 | 1.00 |

Before converting the value of light radiation, the value of the incident radiation on the unit used in the Modeling and whose dimensions are 7.5 x 7.5 cm must be taken.

$$\text{Indoor Irradiance on the Face} = G_{cb} \times \text{Window Transmittance} \times (0.075)^2 \quad (7)$$

Various datasets cover a wide range of photon wavelengths. For example, the AM1.5 ASTM G173 data is available at different intervals: 0.5 nm between 280 nm and 400 nm, 1 nm intervals from 400 nm to 1700 nm, and 5 nm intervals from 1705 nm to 4000 nm. Similarly, the CIE data includes intervals of 1 nm from 360 nm to 830 nm, followed by subsequent data spanning 380 nm to 780 nm with 1 nm intervals, and another data set with 0.1 nm increments from 390 nm to 830 nm. The study's core calculations regarding solar irradiance are based on the ASTM AM1.5 G173 data. Other datasets are either interpolated to fill gaps or adjusted to match the specific wavelengths of the G173 data. An approach involving binary truncation is used for power density calculations, and weighted data are incorporated for further analyses. The study employs CIE photopic luminosity curves, each curve assigned a weight that peaks at 555 nm and gradually decreases toward longer and shorter wavelengths, with values reaching zero outside each curve's range. The methodology outlined by Preston guides the computation process, highlighting the significant role of the CIE curve in limiting the power density of AM1.5 solar irradiance (Michael et al., 2020).

The CIE Standard Skies encompass a standardised array of atmospheric configurations meticulously devised to encapsulate prevailing meteorological circumstances across distinct geospatial locales and temporal epochs. These models find extensive utility within illuminative science and diurnal illumination analysis, facilitating the emulation of natural luminous comportment across indoor and outdoor settings. In the present exposition, the authors availed themselves of the CIE Standard Skies as a foundational framework for assessing the efficacy of their proposed analytical construct aimed at predicting solar radiant flux and luminous flux density upon inclined planes. The resultant outcomes evinced the fidelity of the introduced model in appraising the solar irradiance and illuminance distributions over inclined surfaces, thereby catering to the imperatives of solar energy harnessing and luminous characterisation within daylighting investigations (Lou et al., 2020).

$$\text{Illuminance} = k \int_{380}^{780} V_\lambda E_\lambda d_\lambda \quad (8)$$

The equation integrates the product of the spectral luminous efficiency and solar irradiance over the wavelength range to calculate illuminance. This equation considers the human eye's sensitivity to different wavelengths and provides a way to convert irradiance to illuminance.

Michael provided a summary of the conversion results, where the table shows the Conversion results.

**Table 4– Conversion results (Michael et al., 2020).**

| Source | k |
|---|---|
| **CIE 2008 data calculation** | 1 W/m2 = 116 lx |
| **Indoor laboratory simulation** | 1 W/m2 = 116 ± 3 lx |
| **Outdoor solar measurement** | 1 W/m2 = 122 ± 1 lx |

##### *3.1.1.2.1. Direct Sunlight*

Direct sunlight is distinguished by its exceptionally high intensity and continuous motion. The illuminance it imparts on the Earth's surface can surpass 100,000 lux. The luminosity of direct sunlight fluctuates based on factors including season, time of day, geographical location, and atmospheric conditions. In regions with abundant sunshine, effective architectural planning demands meticulous attention to provisions for admission, diffusion, shading, and reflection (Velux, 2021).

Employing a dynamo-based approach for locating sunny points proves advantageous for quantifying the proportion of sunlit areas. This methodology facilitates the computation of aggregate surface-reflected irradiance. This technique considers various parameters to enhance filter efficacy, encompassing factors such as wall function (exterior and interior walls), number of apartments for residential units featuring windows and doors, name of building and number of apartments for each floor, and wall.

Select the ray that came in through the windows in the linked file. Next, link the line with the family that it intersects with. If it does intersect, change the Direct sunlight parameter to 0. If not, write "None" as shown in Figure 13. Figure 14 shows the sunny area inside the Room in the selected apartment.

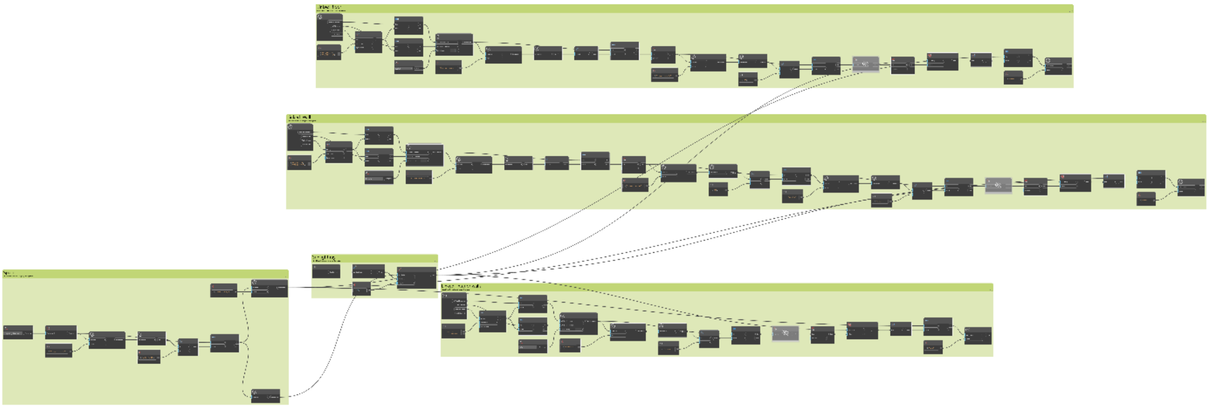


**Figure 13 – Finding the sunny points using the dynamo script.**

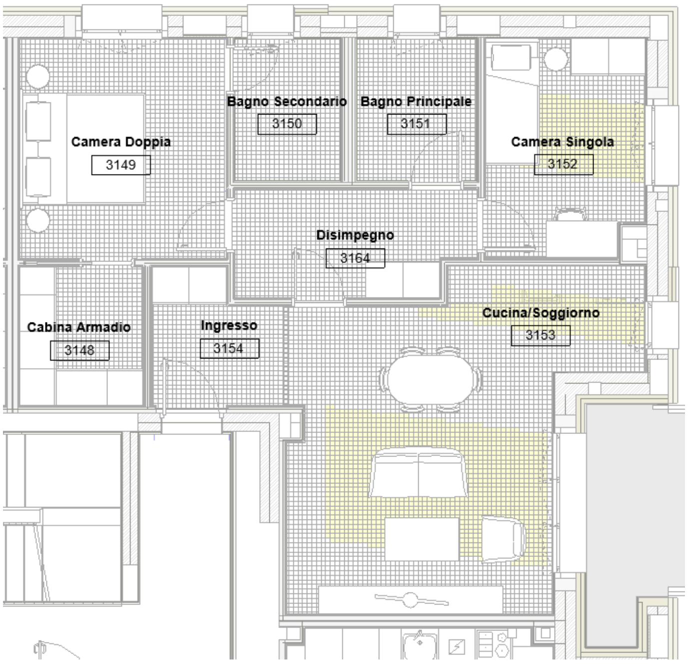



**Figure 14 Sunny area inside the rooms.**

### *3.1.1.2.2. Direct Sunlight reflection*

The reflected light is distinguished by the presence of photons originating from natural sources, such as sunlight and skylight, that undergo reflection upon interaction with terrestrial elements like terrain, trees, vegetation, neighbouring structures, and similar objects. The reflective characteristics of the immediate environment dictate the extent to which reflected light influences the luminous flux reaching the exterior surface of a building. Notably, in densely constructed urban settings, the contribution of luminance resulting from the reflection of light off the ground and surrounding elements can emerge as a substantial constituent of indoor daylight provisioning (Velux, 2021).

This study undertook the task of ray tracking, encompassing the trajectory of incident light rays and their subsequent reflections until their return to the room's floor. Adhering to the principles of reflection, encompassing the angles formed by incident rays, the vertical axis of surfaces, and the inherent reflectance properties, guided this analysis. Sunlight's path was traced by establishing the angle of solar incidence and the ensuing reflection for each surface, considering their inclination and orientation.

Illustrated in Figure 15, the dynamo script for ray tracing—without specific numerical values—assists the design process by facilitating the inclusion of surfaces or elements to enhance lighting derived from solar reflection during specific days and hours.

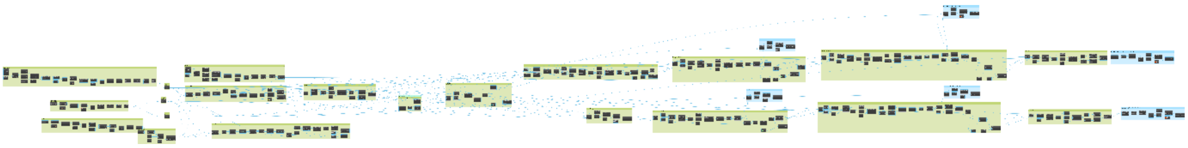
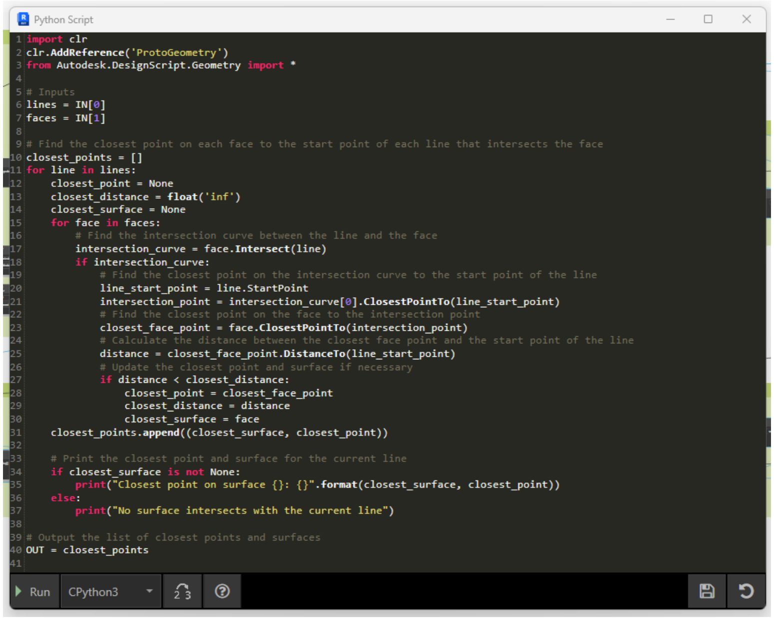


**Figure 15 Dynamo workspace showing the Sunlight reflection tracking.**



```python
import clr
clr.AddReference('ProtoGeometry')
from Autodesk.DesignScript.Geometry import *

# Inputs
lines = IN[0]
faces = IN[1]

# Find the closest point on each face to the start point of each line that intersects the face
closest_points = []
for line in lines:
    closest_point = None
    closest_distance = float('inf')
    closest_surface = None
    for face in faces:
        # Find the intersection curve between the line and the face
        intersection_curve = face.Intersect(line)
        if intersection_curve:
            # Find the closest point on the intersection curve to the start point of the line
            line_start_point = line.StartPoint
            intersection_point = intersection_curve[0].ClosestPointTo(line_start_point)
            # Find the closest point on the face to the intersection point
            closest_face_point = face.ClosestPointTo(intersection_point)
            # Calculate the distance between the closest face point and the start point of the line
            distance = closest_face_point.DistanceTo(line_start_point)
            # Update the closest point and surface if necessary
            if distance < closest_distance:
                closest_point = closest_face_point
                closest_distance = distance
                closest_surface = face
    closest_points.append((closest_surface, closest_point))

    # Print the closest point and surface for the current line
    if closest_surface is not None:
        print("Closest point on surface {}: {}".format(closest_surface, closest_point))
    else:
        print("No surface intersects with the current line")

# Output the list of closest points and surfaces
OUT = closest_points
```



**Figure 16 Python code to print each point and its surface.**

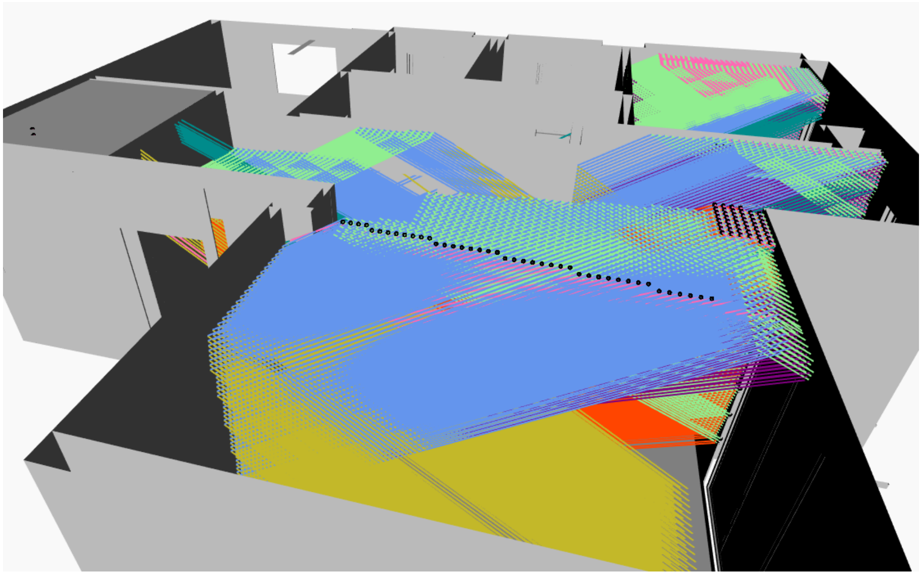


**Figure 17 Dynamo background 3d view showing the reflected rays.**

In the crucial architectural design phase, simulating the path of solar rays is essential to achieve the desired lighting effect. This can be achieved by incorporating elements such as light-reflecting or refracting surfaces, or modifying walls through breaking or wrapping. In later stages, the use of Equation (8) can aid in calculating the amount of illumination gained from the sun. Precise determination of work surfaces and external floors is crucial when reflecting sunlight effectively into the building. Overall, this work demands a high level of precision.

### 3.1.2. Energy simulation

Energy simulation is a powerful tool that is used to optimize energy efficiency, thermal comfort, and indoor air quality of buildings. The use of energy simulation in building design allows architects and engineers to analyze the energy performance of a building before construction, and identify areas where energy-saving measures can be implemented. This section of the paper presents an overview of energy simulation, including its importance in sustainable building design, the different types of energy simulation, and the factors that influence energy simulation results. Additionally, this section will discuss the role of energy simulation in the context of residential buildings, and explore some of the strategies that can be used to optimize energy performance.

The first step of energy calculation is the high and low temperatures of building spaces, which is essential to calculate the heating and cooling needed. In this case, the average monthly temperature of the surrounding environment corresponds to the temperature of an area or environment not served by a thermal system by estimating the day diffuse. Beam radiation on the building faces to obtain the energy gained from the sky that affects the building in one way or another through absorption and re-emission to the interior.

The subsequent step in the energy calculation process involves the determination of the U-value for each wall component. The U-value, also known as the thermal transmittance, plays a pivotal role in assessing the energy performance of a building's envelope. By calculating the U-value for each wall, which quantifies the heat transfer rate through the material, we gain essential insights into the thermal behaviour of the building's structural elements. This information is a foundation for accurate energy simulations and enables informed decisions regarding insulation strategies and overall building energy efficiency.

The interaction of solar radiation with building walls constitutes a pivotal mechanism with significant implications for architectural structures' thermal behaviour and energy dynamics. Upon impingement of sunlight on a wall's surface, a fraction of the incident the material assimilates solar radiation. This occurrence induces an elevation in the temperature of the wall's exterior, manifesting as solar heating.

The commencement of solar radiation absorption initiates a cascade of heat exchange events intrinsic to the building envelope. After the absorption of solar energy, the temperature of the material begins to ascend, thereby ushering in a solar-induced warming phenomenon of paramount consequence for the overall thermal equilibrium of the structure. Emanating from this absorbed thermal energy, a transference is instigated towards the internal strata of the wall, thereby orchestrating the establishment of a thermal gradient that extends from the external to the internal domain.

This transmission of absorbed thermal energy to the interior domains exercises a material influence over the energetic characteristics of the building. Now subjected to elevated temperatures, the wall functions as a thermal energy reservoir, gradually diffusing heat to adjoining regions via conduction mode. This process emerges as an indispensable determinant of the indoor climate, imparting pertinence to room temperatures and the perceptible levels of thermal comfort.

Moreover, the rate and amplitude of the thermal energy's translocation from the heated wall towards the internal space are contingent upon an amalgamation of variables. The thermal attributes of the wall, its thickness, the inclusion of insulation, and the presence of supplementary modalities of heat exchange—such as convection and radiation—culminate in an intricate interplay that underscores the complex facets of building energy dynamics.

The comprehension of solar radiation absorption by building walls and its ensuing ramifications, encompassing wall heating and the facilitation of heat propagation to interior realms, represents a fundamental enabler for the integrity of energy simulations and the discernment of performance attributes. The attainment of this comprehension equips architects, engineers, and designers with the capacity to devise strategies conducive to the maximisation of energy efficiency, the attenuation of overheating vulnerabilities, and the enhancement of the comprehensive indoor thermal experience.

#### 3.1.2.1. Beam radiation

In solar process design methodologies, it is imperative to acquire diurnal and monthly mean solar irradiation data impacting surfaces. This encompassing task entails the aggregation of contributions from direct solar irradiance, the constituents of diffused solar radiation, and solar irradiance that undergoes reflection from the terrestrial surface. It is, however, essential to acknowledge that the degree of advancement attained in enhancing computational methodologies for horizontal solar irradiation is not necessarily commensurate with the progress achieved in the realm of oblique solar irradiation.

The procedural approach involves formulating mathematical equations within the Python programming framework, thereby generating vectors that faithfully emulate the trajectory of solar rays. These vectors are subsequently incorporated into an iterative construct, wherein the objective is to ascertain the temporal intervals during which a specific surface remains exposed to solar irradiation. This information is elucidated through quantifying angular values, which are then printed. The parameters primarily at play within this framework are exclusively the day and the month.

Subsequently, Equation No. (1) is enlisted to derive the magnitude of direct solar irradiation impacting the designated surface. The ensuing step involves the computation of daily irradiance values, culminating in deriving a daily aggregate. This iterative process is diligently replicated over the entire expanse of a given month, thereby culminating in the evaluation of a monthly aggregate. The distinguishing hallmark of this approach lies in its inherent universality, signifying a departure from methodologies contingent upon specific temporal or geographical attributes.

$$\omega_s = \cos^{-1}(-\tan\varphi \tan\delta) \tag{9}$$

$$\delta = \left(\frac{180}{\pi}\right)(0.006918 - 0.399912\,cosB + 0.070257\,sinB - 0.006758\,cos\,2B + 0.000907\,sin\,2B - 0.002697\,cos\,3B + 0.00148\,sin\,3B) \tag{10}$$

$$B = (n - 1) \cdot \left(\frac{360}{365}\right)$$

$$\cos\theta = \alpha_s = \sin\delta \sin\varphi \cos\beta - \sin\delta \cos\varphi \sin\beta \cos\gamma + \cos\delta \cos\varphi \cos\beta \cos\omega + \cos\delta \sin\varphi \sin\beta \cos\gamma \cos\omega + \cos\delta \sin\beta \sin\gamma \sin\omega \qquad (11)$$

#### 3.1.2.2. Diffuse radiation

In this part, solar radiation will be calculated by formulas which are crucial for applications in solar energy systems, environmental Modeling, and climate studies, where the goal is to determine the amount of energy due to diffuse radiation that reaches a specific location on the surface, taking into account factors like Earth's orbit, atmospheric conditions, and the position of the Sun.

$$t_d = 0.271 - 0.294\, t_b \qquad (12)$$

$$G_{on} = \mathrm{Gsc}(1.000110 + 0.034221 \cos B + 0.001280 \sin B + 0.000719 \cos 2B + 000077 \sin 2B) \qquad (13)$$

$$G_{cd} = G_{on} \cos\theta_z \times t_d \qquad (14)$$

#### 3.1.2.3. Calculation

In the comprehensive assessment of energy ingress via windows, a meticulous methodology necessitates concurrently considering both direct solar irradiation (beam radiation) and diffuse solar radiation. The computational process entails the determination of incident solar radiation for discrete time intervals facilitated by utilising pertinent solar geometries and atmospheric conditions. The salient determinant in direct solar irradiation is the angle of incidence, denoted as the solar zenith angle, which signifies the angle between solar rays and the window surface's normal vector. This angle becomes instrumental in conjunction with the direct solar irradiance for calculating energy penetrating through the window aperture. Concomitantly, the component of diffuse solar radiation, stemming from molecular scattering in the atmosphere, serves as a contributive factor to the overall energy influx through the window interface.

The distinct attributes of the window itself engender a substantive influence. The window's transmittance and reflectance coefficients directly influence the proportion of energy transversing the window aperture and the quantum of energy being retroverted. By amalgamating these coefficients with the solar radiation dataset, a more refined depiction of the energy ingress through windows ensues. The contextual intricacies expand when contemplating insulated windows, entailing the assimilation of heat transfer dynamics resulting from temperature differentials between the interior and exterior environments.

The intricate interplay of energy among walls, solar radiation, and insulation constitutes a multifaceted realm within the ambit of building energy analysis. When solar radiance encounters walls, it imparts an allocation of energy onto their surfaces. This energy absorption process is a composite phenomenon involving direct solar irradiation and the diffusely scattered component. This amalgamation instigates an influx of thermal energy that permeates the structural fabric of the walls. The resultant elevation in temperature within the wall materials engenders consequential shifts in their thermal disposition.

Within this framework, the concept of energy storage within walls assumes prominence. The assimilation of solar energy, consequent to absorption, imparts elevated temperatures to the wall constituents. This rise in thermal energy levels engenders an accrual of power over temporal trajectories within the walls. Emanating from this accumulation, the walls exhibit characteristics akin to thermal reservoirs, conferring sway over indoor temperature dynamics. This thermal interplay reverberates across indoor environments, potentially influencing occupant comfort levels and the operative functioning of heating, ventilation, and air conditioning (HVAC) systems.

In pursuing a comprehensive analysis, deploying building energy simulation software emerges as a prudent course of action. This computational toolset embraces a spectrum of variables, including solar radiation, wall material attributes, insulation effects, thermal mass considerations, and indoor temperature oscillations. The synergistic amalgamation of these constituents enables a truthful depiction of energy influx, propagation, and consequential impacts on the internal milieu. Such insights inform the delineation of energy-efficient design strategies, thus catalysing the augmentation of sustainable architectural paradigms.

### *3.1.2.3.1. Sunset and Sunrise Angle*

The first step in calculating energy involves the angles of sunrise and sunset times. At this juncture, angles are ascertained in accordance with solar time rather than local time. Subsequently, the angles are subjected to iterative computation within a loop from sunrise to sunset. Employing the supplied equations, the angles corresponding to sunrise and sunset were computed for all designated days of the month, wherein the intended calculations are to be executed. Figure 18 depicts the dynamo script, wherein the sunrise and sunset angles are calculated through the utilisation of Python code.

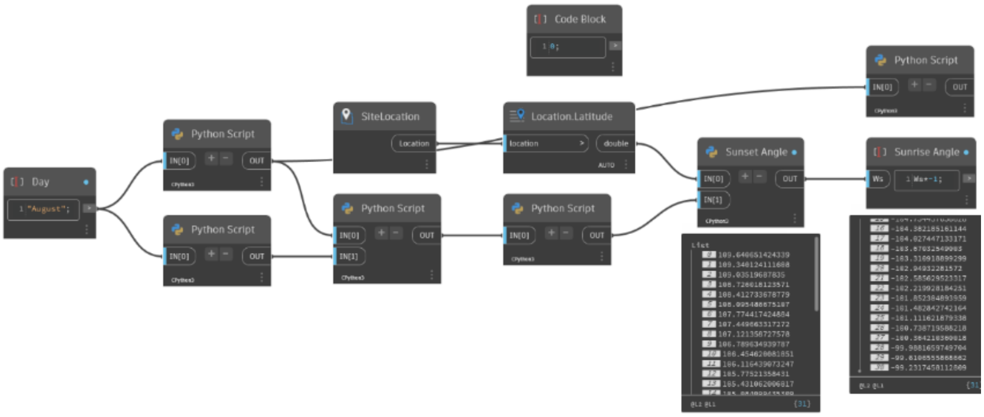



**Figure 18 Sunrise and Sunset angles.**

In Figure 19, the Python code is presented, elucidating the determination of the initial and concluding day indices within the span of 365 days in a year. Similarly, within Figure 20 resides a code snippet pertinent to the computation of one of the requisite equations facilitating the angle calculation process.

The variation of the solar angle occurs continually and diurnally. Determining solar angles during periods of sunlight within a given month is imperative for the comprehensive computation of solar irradiation throughout the project. Subsequently, the calculation of monthly averages ensues. Utilising the Python code shown in Figure 21, the solar angles relative to vertical elements are calculated hourly, commencing from sunrise and concluding at sunset.

Further calculations need to be performed for the filtration of solar angles beyond the surface's expanse. Determining the angle between the southern direction and the solar beam is imperative (Solar azimuth angle), followed by excluding surface azimuth and gamma threshold by 90 degrees, as necessitated.

$$\gamma_s = \sin(\omega)\left|\cos^{-1}\left(\frac{\cos\theta_z \sin\varphi - \sin\delta}{\sin\theta_z \cos\varphi}\right)\right| \tag{15}$$

Figure 22 shows the Python code for calculating the Zenith angle needed in the solar azimuth formula (15). This section of the thesis addresses the calculation of the radiation incident on surfaces, including windows and walls. Each wall or window is associated with its unique value, subject to variation based on the surface azimuth angle and surface area.

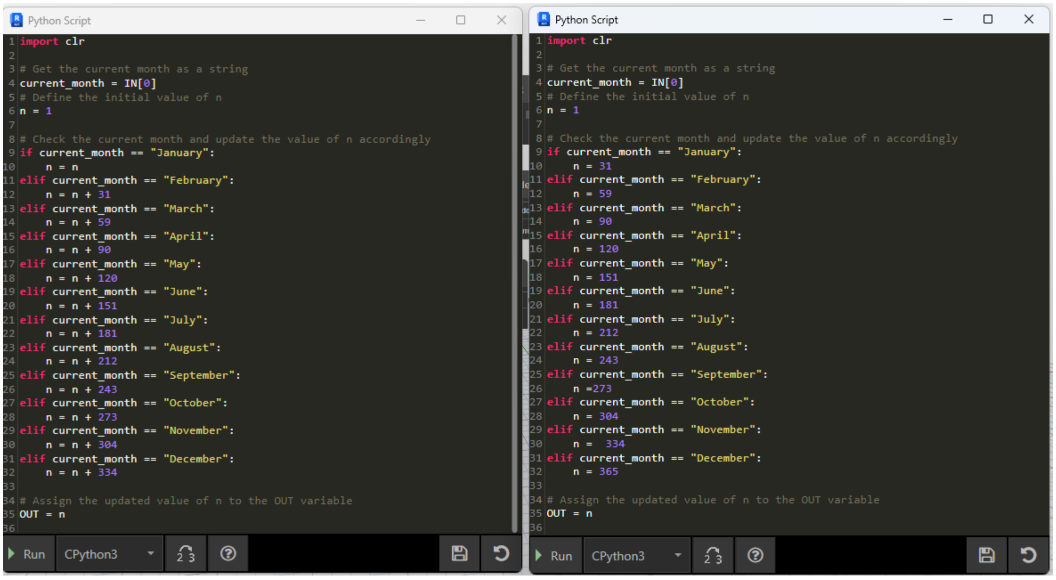



**Figure 19 Determining the first and the last day of the selected month.**

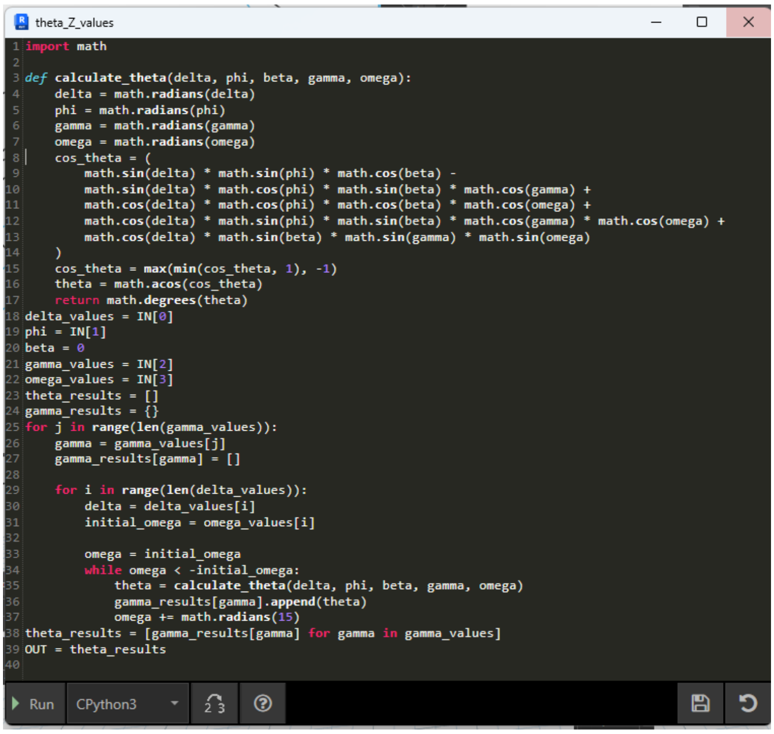
```python
import math

B_list = IN[0]

results = []

for B in B_list:
    B_rad = math.radians(B)
    delta = (180 / math.pi) * (0.006918 - 0.399912 * math.cos(B_rad) +
    0.070257 * math.sin(B_rad) - 0.006758 * math.cos(2 * B_rad) + 0.000907
    * math.sin(2 * B_rad) - 0.002697 * math.cos(3 * B_rad) + 0.00148 *
    math.sin(3 * B_rad))
    results.append(delta)

OUT = results
```

**Figure 20 Python code to calculate $\delta$.**

After that, the architectural elements will be connected to the spaces via the utilisation of an external family for data hosting. Subsequently, calculations will be executed to determine the daily energy gain or loss. In this phase of the study, the quantity of gained energy that needs to be dissipated is computed.

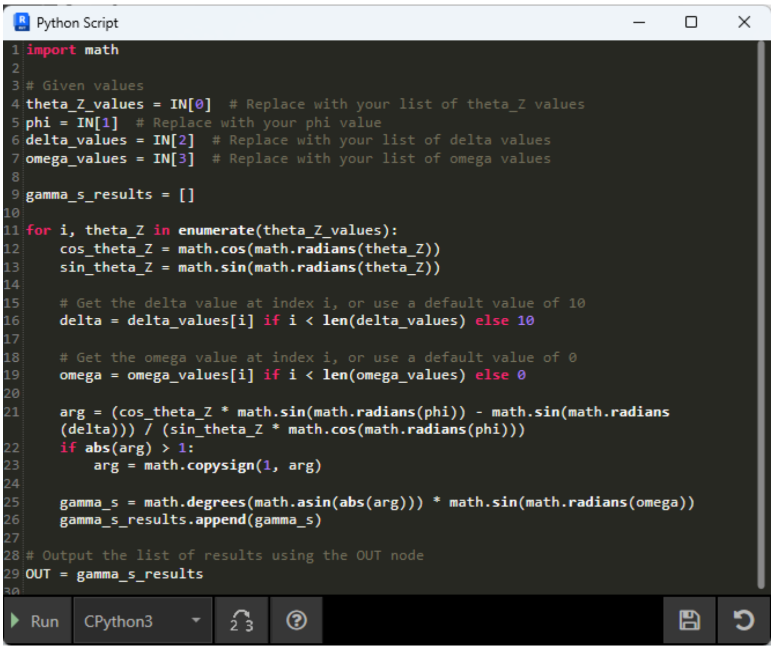
```python
import math

def calculate_theta(delta, phi, beta, gamma, omega):
    delta = math.radians(delta)
    phi = math.radians(phi)
    gamma = math.radians(gamma)
    omega = math.radians(omega)

    cos_theta = (
        math.sin(delta) * math.sin(phi) * math.cos(beta) -
        math.sin(delta) * math.cos(phi) * math.sin(beta) * math.cos(gamma) +
        math.cos(delta) * math.cos(phi) * math.cos(beta) * math.cos(omega) +
        math.cos(delta) * math.sin(phi) * math.sin(beta) * math.cos(gamma) * math.cos
        (omega) +
        math.cos(delta) * math.sin(beta) * math.sin(gamma) * math.sin(omega)
    )


    cos_theta = max(min(cos_theta, 1), -1)

    theta = math.acos(cos_theta)
    return math.degrees(theta)


delta_values = IN[0]
phi = IN[1]
beta = 90
gamma = IN[2]
omega_values = IN[3]

theta_results = []

# Loop through each delta value
for i in range(len(delta_values)):
    delta = delta_values[i]
    initial_omega = omega_values[i]

    omega = initial_omega
    while omega < -initial_omega:  # Loop until omega becomes larger than -initial_omega
        theta = calculate_theta(delta, phi, beta, gamma, omega)
        theta_results.append(theta)

        omega += math.radians(15)  # Add 15 to omega each iteration


OUT = theta_results
```

**Figure 21 Python code to Calculatet theta during the day.**



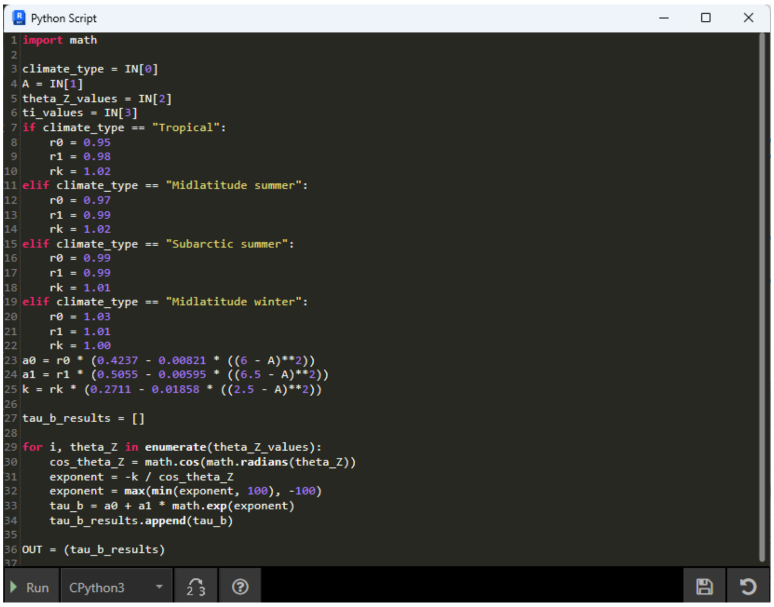
```
import math

def calculate_theta(delta, phi, beta, gamma, omega):
    delta = math.radians(delta)
    phi = math.radians(phi)
    gamma = math.radians(gamma)
    omega = math.radians(omega)
    cos_theta = (
        math.sin(delta) * math.sin(phi) * math.cos(beta) -
        math.sin(delta) * math.cos(phi) * math.sin(beta) * math.cos(gamma) +
        math.cos(delta) * math.cos(phi) * math.cos(beta) * math.cos(omega) +
        math.cos(delta) * math.sin(phi) * math.sin(beta) * math.cos(gamma) * math.cos(omega) +
        math.cos(delta) * math.sin(beta) * math.sin(gamma) * math.sin(omega)
    )
    cos_theta = max(min(cos_theta, 1), -1)
    theta = math.acos(cos_theta)
    return math.degrees(theta)
delta_values = IN[0]
phi = IN[1]
beta = 0
gamma_values = IN[2]
omega_values = IN[3]
theta_results = []
gamma_results = {}
for j in range(len(gamma_values)):
    gamma = gamma_values[j]
    gamma_results[gamma] = []

    for i in range(len(delta_values)):
        delta = delta_values[i]
        initial_omega = omega_values[i]

        omega = initial_omega
        while omega < -initial_omega:
            theta = calculate_theta(delta, phi, beta, gamma, omega)
            gamma_results[gamma].append(theta)
            omega += math.radians(15)
theta_results = [gamma_results[gamma] for gamma in gamma_values]
OUT = theta_results
```

**Figure 22 Python code to Calculate $\theta_z$ during the day.**



```
import math

# Given values
theta_Z_values = IN[0]  # Replace with your list of theta_Z values
phi = IN[1]  # Replace with your phi value
delta_values = IN[2]  # Replace with your list of delta values
omega_values = IN[3]  # Replace with your list of omega values

gamma_s_results = []

for i, theta_Z in enumerate(theta_Z_values):
    cos_theta_Z = math.cos(math.radians(theta_Z))
    sin_theta_Z = math.sin(math.radians(theta_Z))

    # Get the delta value at index i, or use a default value of 10
    delta = delta_values[i] if i < len(delta_values) else 10

    # Get the omega value at index i, or use a default value of 0
    omega = omega_values[i] if i < len(omega_values) else 0

    arg = (cos_theta_Z * math.sin(math.radians(phi)) - math.sin(math.radians
    (delta))) / (sin_theta_Z * math.cos(math.radians(phi)))
    if abs(arg) > 1:
        arg = math.copysign(1, arg)

    gamma_s = math.degrees(math.asin(abs(arg))) * math.sin(math.radians(omega))
    gamma_s_results.append(gamma_s)

# Output the list of results using the OUT node
OUT = gamma_s_results
```

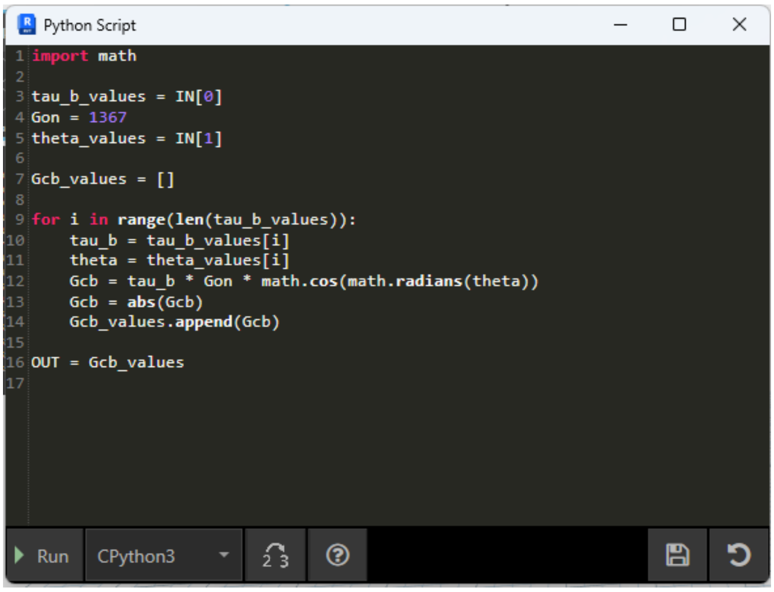
**Figure 23 Python code to Calculate $\gamma_s$ during the sunny times per day.**



```python
import math

climate_type = IN[0]
A = IN[1]
theta_Z_values = IN[2]
ti_values = IN[3]
if climate_type == "Tropical":
    r0 = 0.95
    r1 = 0.98
    rk = 1.02
elif climate_type == "Midlatitude summer":
    r0 = 0.97
    r1 = 0.99
    rk = 1.02
elif climate_type == "Subarctic summer":
    r0 = 0.99
    r1 = 0.99
    rk = 1.01
elif climate_type == "Midlatitude winter":
    r0 = 1.03
    r1 = 1.01
    rk = 1.00
a0 = r0 * (0.4237 - 0.00821 * ((6 - A)**2))
a1 = r1 * (0.5055 - 0.00595 * ((6.5 - A)**2))
k = rk * (0.2711 - 0.01858 * ((2.5 - A)**2))

tau_b_results = []

for i, theta_Z in enumerate(theta_Z_values):
    cos_theta_Z = math.cos(math.radians(theta_Z))
    exponent = -k / cos_theta_Z
    exponent = max(min(exponent, 100), -100)
    tau_b = a0 + a1 * math.exp(exponent)
    tau_b_results.append(tau_b)

OUT = (tau_b_results)
```



**Figure 24 Python code to Calculate $\tau_b$ during the sunny times per day.**



```python
import math

tau_b_values = IN[0]
Gon = 1367
theta_values = IN[1]

Gcb_values = []

for i in range(len(tau_b_values)):
    tau_b = tau_b_values[i]
    theta = theta_values[i]
    Gcb = tau_b * Gon * math.cos(math.radians(theta))
    Gcb = abs(Gcb)
    Gcb_values.append(Gcb)

OUT = Gcb_values
```



**Figure 25 Python code to Calculate radiation value $G_{cb}$ during the sunny times per month.**

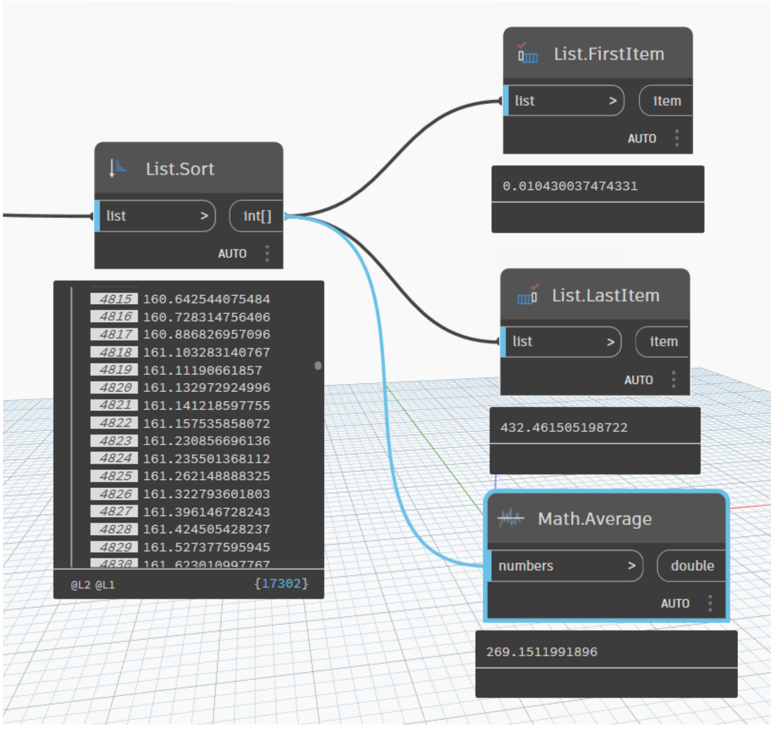



**Figure 26 Dynamo script to get the average value for the month.**

After completing the calculations, the total energy ingress into the room from external sources will be computed utilising energy balance equations. Concerning the stored weather data, an average temperature of 29 degrees Celsius is identified for August. Consequently, upon conducting the calculations, an internal temperature of 24 degrees Celsius will be considered the thermal comfort zone.

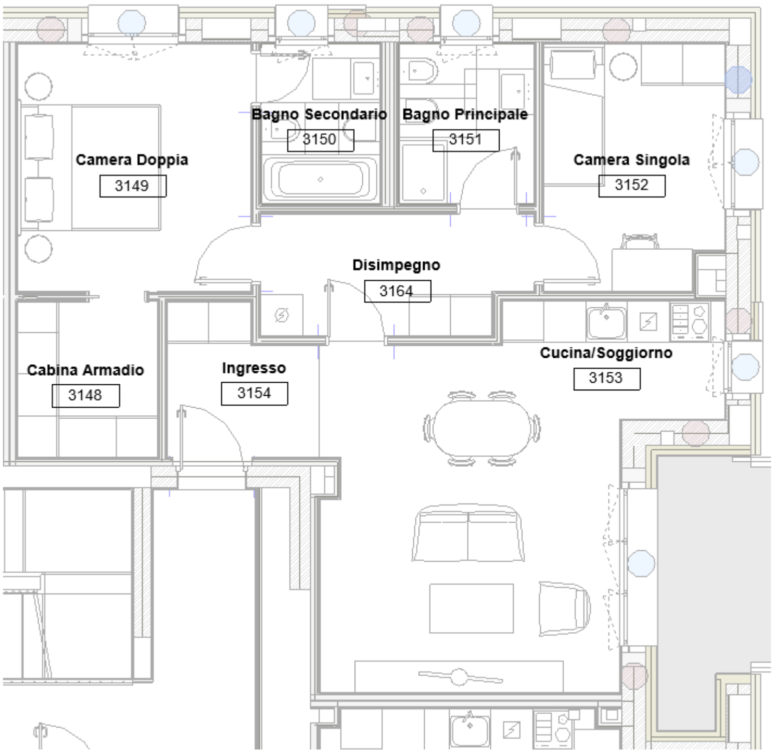



**Figure 27 2D plan view showing the family that hosts the data.**

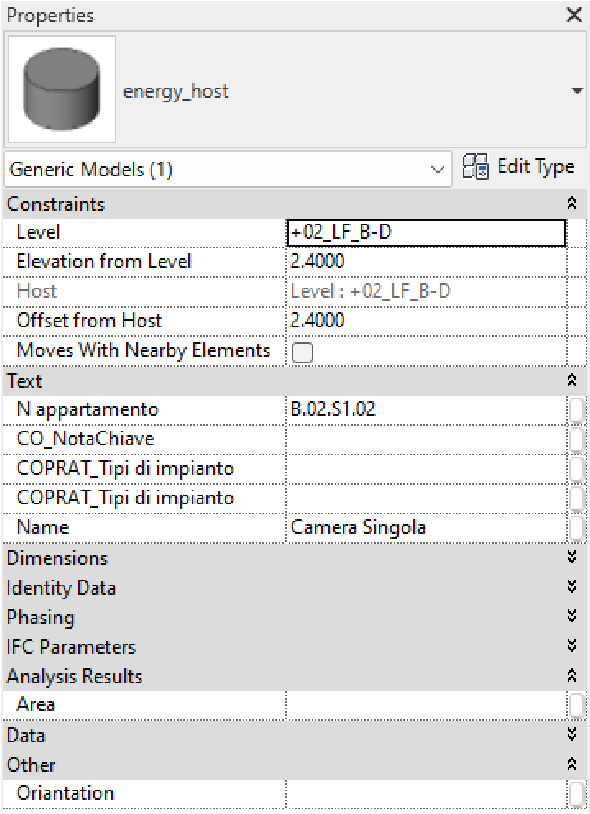



**Figure 28 Energy_host parameters.**

The following equations are employed for the execution of calculations, encompassing Energy Inflows such as solar energy through windows (both direct and diffuse) as well as heat from internal sources, and Energy Outflows comprising Energy_wall, heat dissipation through ventilation, and radiative heat transfer from walls.

$$\text{Energy\_solr\_direct} = \text{Solar Irradiance} \times \text{Window Area} \times \tau \tag{16}$$

$$\text{Energy\_solar\_diffuse} = \text{Diffuse Solar Irradiance} \times \text{Window Area} \times \tau \tag{17}$$

$$\text{Heat gain from people (in watts)} = \text{Number of people} \times \text{Specific heat gain per person} \tag{18}$$

$$\text{Heat gain from lighting (in watts)} = \text{Total lighting power} \times \text{Lighting heat gain factor} \tag{19}$$

$$\text{Energy\_wall} = (\text{Thermal Conductivity} \times \text{Wall Area} \times (\text{T\_indoor} - \text{T\_outdoor})) / \text{Wall Thickness} \tag{20}$$

$$\text{Radiative\_heat\_transfer} = \varepsilon \times \sigma \times \text{Wall Area} \times (\text{T\_wall}^{\wedge}4 - \text{T\_outdoor}^{\wedge}4) \quad (.21)$$

The calculation of specific heat gain per person typically depends on the individual's activity level. Specific heat gain quantifies the heat generation (in watts) attributed to metabolic activity and other contributing factors. It can fluctuate depending on whether the individual is at rest, engaged in light activity, or performing strenuous physical work. The subsequent are common specific heat gain values per person based on activity levels:

**At Rest:** Approximately 80-100 watts

**Light Activity:** Approximately 100-120 watts

**Moderate Activity:** Approximately 120-150 watts

These values are approximations and are subject to variation based on individual factors such as age, gender, and clothing. Furthermore, established standards and building codes may furnish specific values for energy calculations in the context of building design.

For a more precise determination of specific heat gain per person in a particular scenario, measurements or references to studies that provide comprehensive data on heat production for various activities may be necessary. Techniques like indirect calorimetry, which estimates energy expenditure by measuring the rate of oxygen consumption and carbon dioxide production, can be employed to measure heat production.

In most building energy simulations or energy Modeling endeavours for design purposes, using standard values contingent on activity level is a common and pragmatic approach. Nevertheless, if your project demands specific data or criteria, it is advisable to consult pertinent literature or undertake measurements to obtain more accurate values.

Once the data and values have been gathered and analysed, the subsequent task is to transform them into user-friendly formats. In order to determine the required collectors, and number of the circuits needed for heating the apartment and export them to an Excel file shown in Figure 29 Dynamo script to calculate the number of circuits. Figure 30 the exported data of the apartment in Excel sheets.

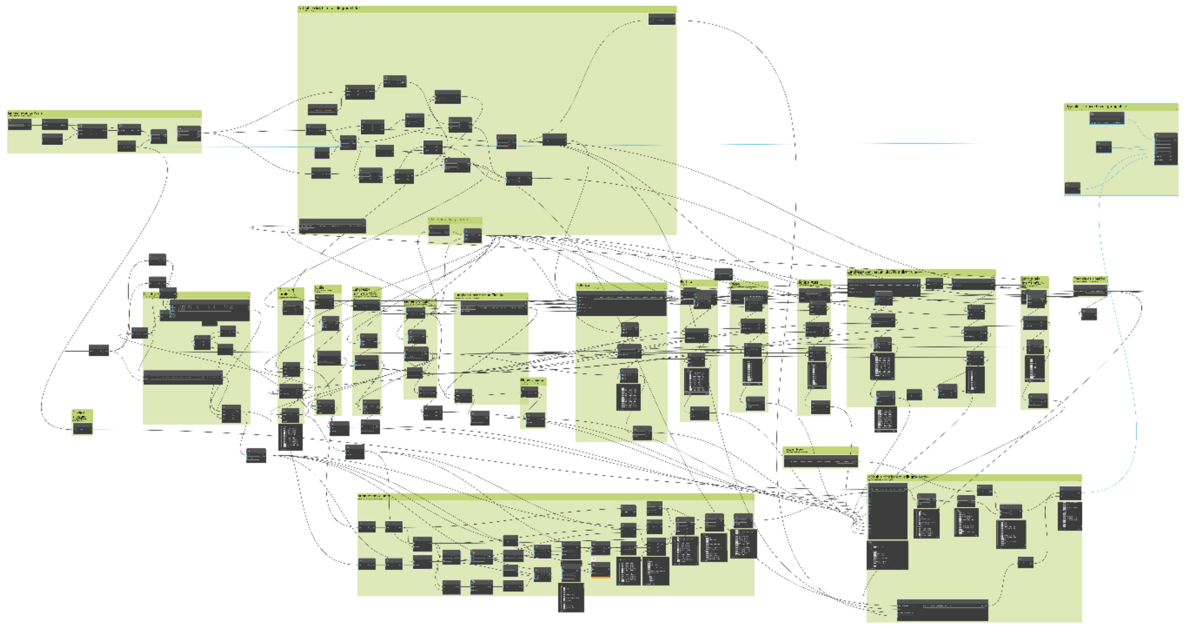
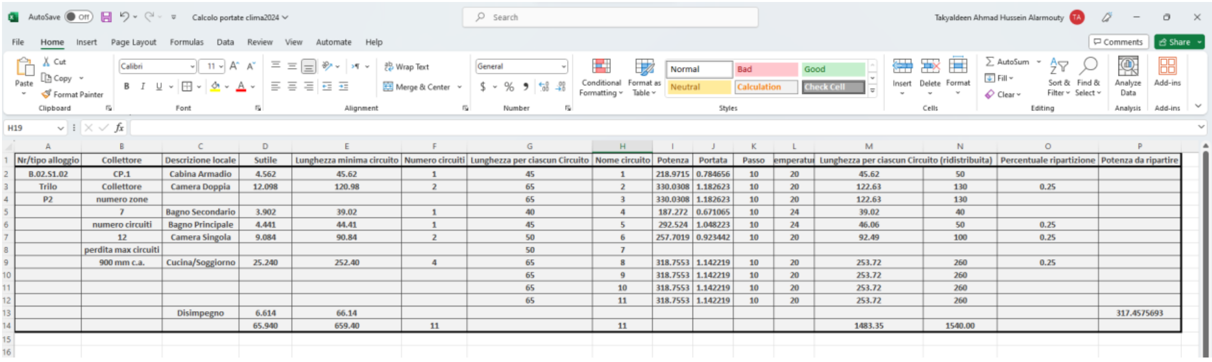


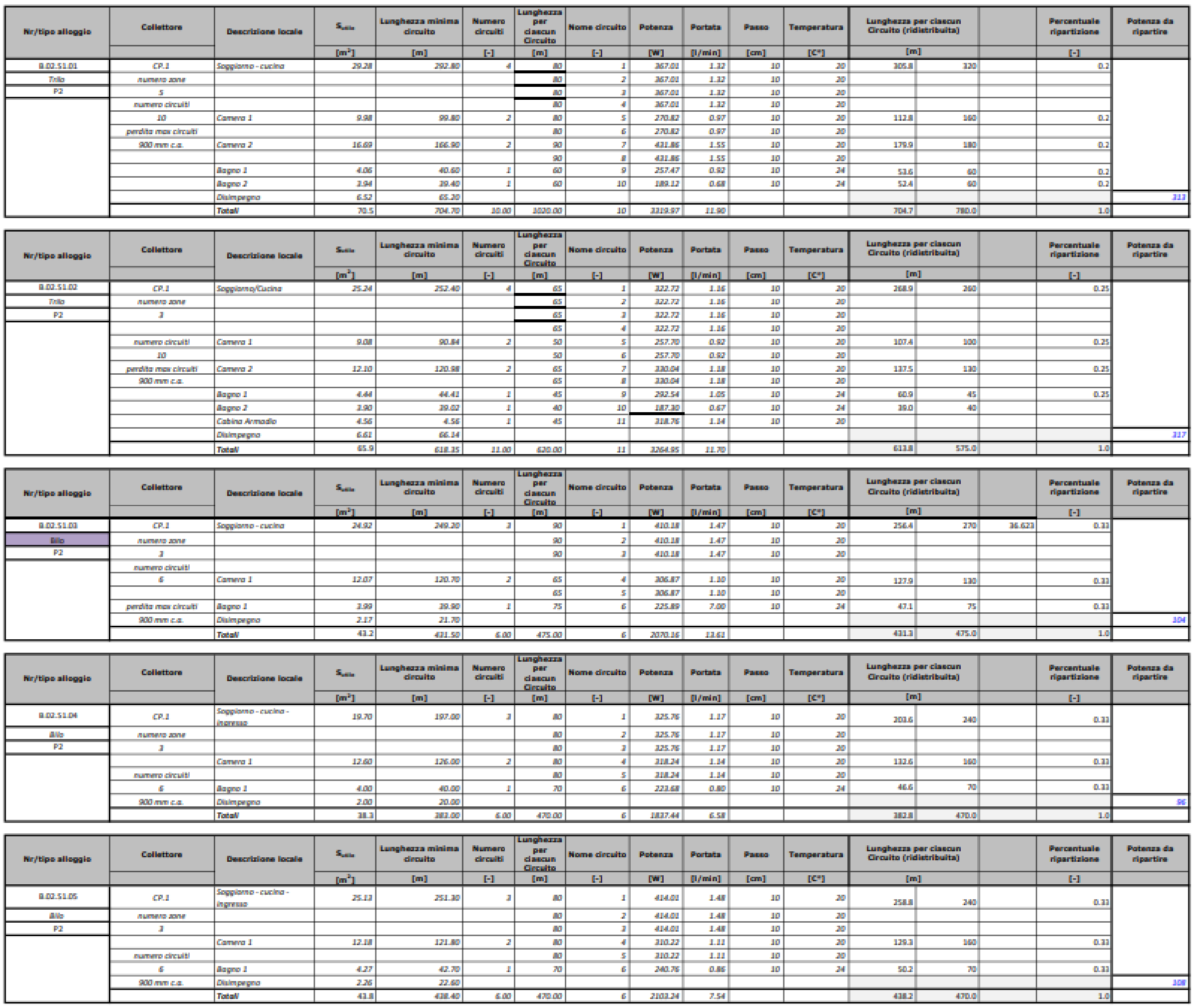
**Figure 29 Dynamo script to calculate the number of circuits.**



| | Nr/tipo alloggio | Collettore | Descrizione locale | Sutile | Lunghezza minima circuito | Numero circuiti | Lunghezza per ciascun Circuito | Nome circuito | Potenza | Portata | Passo | emperatur | Lunghezza per ciascun Circuito (ridistribuita) | | Percentuale ripartizione | Potenza da ripartire |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | B.02.S1.02 | CP.1 | Cabina Armadio | 4.562 | 45.62 | 1 | 45 | 1 | 218.9715 | 0.784656 | 10 | 20 | 45.62 | 50 | | |
| 3 | Trilo | Collettore | Camera Doppia | 12.098 | 120.98 | 2 | 65 | 2 | 330.0308 | 1.182623 | 10 | 20 | 122.63 | 130 | 0.25 | |
| 4 | P2 | numero zone | | | | | 65 | 3 | 330.0308 | 1.182623 | 10 | 20 | 122.63 | 130 | | |
| 5 | | 7 | Bagno Secondario | 3.902 | 39.02 | 1 | 40 | 4 | 187.272 | 0.671065 | 10 | 24 | 39.02 | 40 | | |
| 6 | | numero circuiti | Bagno Principale | 4.441 | 44.41 | 1 | 45 | 5 | 292.524 | 1.048223 | 10 | 24 | 46.06 | 50 | 0.25 | |
| 7 | | 12 | Camera Singola | 9.084 | 90.84 | 2 | 50 | 6 | 257.7019 | 0.923442 | 10 | 20 | 92.49 | 100 | 0.25 | |
| 8 | | perdita max circuiti | | | | | 50 | 7 | | | | | | | | |
| 9 | | 900 mm c.a. | Cucina/Soggiorno | 25.240 | 252.40 | 4 | 65 | 8 | 318.7553 | 1.142219 | 10 | 20 | 253.72 | 260 | 0.25 | |
| 10 | | | | | | | 65 | 9 | 318.7553 | 1.142219 | 10 | 20 | 253.72 | 260 | | |
| 11 | | | | | | | 65 | 10 | 318.7553 | 1.142219 | 10 | 20 | 253.72 | 260 | | |
| 12 | | | | | | | 65 | 11 | 318.7553 | 1.142219 | 10 | 20 | 253.72 | 260 | | |
| 13 | | | Disimpegno | 6.614 | 66.14 | | | | | | | | | | | 317.4575693 |
| 14 | | | | 65.940 | 659.40 | 11 | | 11 | | | | | 1483.35 | 1540.00 | | |

**Figure 30 exported data in excel sheet.**

After running the script comprehensively to include every apartment in the building and identifying Building B, we collected all the essential data required to ensure accurate equipment placement, which is now neatly organized in an Excel file, as shown in Figure 31.



| Nr/tipo alloggio | Collettore | Descrizione locale | $S_{utile}$ [m²] | Lunghezza minima circuito [m] | Numero circuiti [-] | Lunghezza per ciascun Circuito [m] | Nome circuito [-] | Potenza [W] | Portata [l/min] | Passo [cm] | Temperatura [C°] | Lunghezza per ciascun Circuito (ridistribuita) [m] | | | Percentuale ripartizione [-] | Potenza da ripartire |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B.02.S1.01 | CP.1 | Soggiorno - cucina | 29.28 | 292.80 | 4 | 80 | 1 | 367.01 | 1.32 | 10 | 20 | 305.8 | 320 | | 0.2 | |
| Trilo | numero zone | | | | | 80 | 2 | 367.01 | 1.32 | 10 | 20 | | | | | |
| P2 | 5 | | | | | 80 | 3 | 367.01 | 1.32 | 10 | 20 | | | | | |
| | numero circuiti | | | | | 80 | 4 | 367.01 | 1.32 | 10 | 20 | | | | | |
| | 10 | Camera 1 | 9.98 | 99.80 | 2 | 80 | 5 | 270.82 | 0.97 | 10 | 20 | 112.8 | 160 | | 0.2 | |
| | perdita max circuiti | | | | | 80 | 6 | 270.82 | 0.97 | 10 | 20 | | | | | |
| | 900 mm c.a. | Camera 2 | 16.69 | 166.90 | 2 | 90 | 7 | 431.86 | 1.55 | 10 | 20 | 179.9 | 180 | | 0.2 | |
| | | | | | | 90 | 8 | 431.86 | 1.55 | 10 | 20 | | | | | |
| | | Bagno 1 | 4.06 | 40.60 | 1 | 60 | 9 | 257.47 | 0.92 | 10 | 24 | 53.6 | 60 | | 0.2 | |
| | | Bagno 2 | 3.94 | 39.40 | 1 | 60 | 10 | 189.12 | 0.68 | 10 | 24 | 52.4 | 60 | | 0.2 | |
| | | Disimpegno | 6.52 | 65.20 | | | | | | | | | | | | 313 |
| | | Totali | 70.5 | 704.70 | 10.00 | 1020.00 | 10 | 3319.97 | 11.90 | | | 704.7 | 780.0 | | 1.0 | |

| Nr/tipo alloggio | Collettore | Descrizione locale | $S_{utile}$ [m²] | Lunghezza minima circuito [m] | Numero circuiti [-] | Lunghezza per ciascun Circuito [m] | Nome circuito [-] | Potenza [W] | Portata [l/min] | Passo [cm] | Temperatura [C°] | Lunghezza per ciascun Circuito (ridistribuita) [m] | | | Percentuale ripartizione [-] | Potenza da ripartire |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B.02.S1.02 | CP.1 | Soggiorno/Cucina | 25.24 | 252.40 | 4 | 65 | 1 | 322.72 | 1.16 | 10 | 20 | 268.9 | 260 | | 0.25 | |
| Trilo | numero zone | | | | | 65 | 2 | 322.72 | 1.16 | 10 | 20 | | | | | |
| P2 | 3 | | | | | 65 | 3 | 322.72 | 1.16 | 10 | 20 | | | | | |
| | | | | | | 65 | 4 | 322.72 | 1.16 | 10 | 20 | | | | | |
| | numero circuiti | Camera 1 | 9.08 | 90.84 | 2 | 50 | 5 | 257.70 | 0.92 | 10 | 20 | 107.4 | 100 | | 0.25 | |
| | 10 | | | | | 50 | 6 | 257.70 | 0.92 | 10 | 20 | | | | | |
| | perdita max circuiti | Camera 2 | 12.10 | 120.98 | 2 | 65 | 7 | 330.04 | 1.18 | 10 | 20 | 137.5 | 130 | | 0.25 | |
| | 900 mm c.a. | | | | | 65 | 8 | 330.04 | 1.18 | 10 | 20 | | | | | |
| | | Bagno 1 | 4.44 | 44.41 | 1 | 45 | 9 | 292.54 | 1.05 | 10 | 24 | 60.9 | 45 | | 0.25 | |
| | | Bagno 2 | 3.90 | 39.02 | 1 | 40 | 10 | 187.30 | 0.67 | 10 | 24 | 39.0 | 40 | | | |
| | | Cabina Armadio | 4.56 | 4.56 | 1 | 45 | 11 | 318.76 | 1.14 | 10 | 20 | | | | | |
| | | Disimpegno | 6.61 | 66.14 | | | | | | | | | | | | 317 |
| | | Totali | 65.9 | 618.35 | 11.00 | 620.00 | 11 | 3264.95 | 11.70 | | | 613.8 | 575.0 | | 1.0 | |

| Nr/tipo alloggio | Collettore | Descrizione locale | $S_{utile}$ [m²] | Lunghezza minima circuito [m] | Numero circuiti [-] | Lunghezza per ciascun Circuito [m] | Nome circuito [-] | Potenza [W] | Portata [l/min] | Passo [cm] | Temperatura [C°] | Lunghezza per ciascun Circuito (ridistribuita) [m] | | | Percentuale ripartizione [-] | Potenza da ripartire |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B.02.S1.03 | CP.1 | Soggiorno - cucina | 24.92 | 249.20 | 3 | 90 | 1 | 410.18 | 1.47 | 10 | 20 | 256.4 | 270 | 36.623 | 0.33 | |
| Bilo | numero zone | | | | | 90 | 2 | 410.18 | 1.47 | 10 | 20 | | | | | |
| P2 | 3 | | | | | 90 | 3 | 410.18 | 1.47 | 10 | 20 | | | | | |
| | numero circuiti | | | | | | | | | | | | | | | |
| | 6 | Camera 1 | 12.07 | 120.70 | 2 | 65 | 4 | 306.87 | 1.10 | 10 | 20 | 127.9 | 130 | | 0.33 | |
| | | | | | | 65 | 5 | 306.87 | 1.10 | 10 | 20 | | | | | |
| | perdita max circuiti | Bagno 1 | 3.99 | 39.90 | 1 | 75 | 6 | 225.89 | 7.00 | 10 | 24 | 47.1 | 75 | | 0.33 | |
| | 900 mm c.a. | Disimpegno | 2.17 | 21.70 | | | | | | | | | | | | 304 |
| | | Totali | 43.2 | 431.50 | 6.00 | 475.00 | 6 | 2070.16 | 13.61 | | | 431.3 | 475.0 | | 1.0 | |

| Nr/tipo alloggio | Collettore | Descrizione locale | $S_{utile}$ [m²] | Lunghezza minima circuito [m] | Numero circuiti [-] | Lunghezza per ciascun Circuito [m] | Nome circuito [-] | Potenza [W] | Portata [l/min] | Passo [cm] | Temperatura [C°] | Lunghezza per ciascun Circuito (ridistribuita) [m] | | | Percentuale ripartizione [-] | Potenza da ripartire |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B.02.S1.04 | CP.1 | Soggiorno - cucina - ingresso | 19.70 | 197.00 | 3 | 80 | 1 | 325.76 | 1.17 | 10 | 20 | 203.6 | 240 | | 0.33 | |
| Bilo | numero zone | | | | | 80 | 2 | 325.76 | 1.17 | 10 | 20 | | | | | |
| P2 | 3 | | | | | 80 | 3 | 325.76 | 1.17 | 10 | 20 | | | | | |
| | | Camera 1 | 12.60 | 126.00 | 2 | 80 | 4 | 318.24 | 1.14 | 10 | 20 | 132.6 | 160 | | 0.33 | |
| | numero circuiti | | | | | 80 | 5 | 318.24 | 1.14 | 10 | 20 | | | | | |
| | 6 | Bagno 1 | 4.00 | 40.00 | 1 | 70 | 6 | 223.68 | 0.80 | 10 | 24 | 46.6 | 70 | | 0.33 | |
| | 900 mm c.a. | Disimpegno | 2.00 | 20.00 | | | | | | | | | | | | 96 |
| | | Totali | 38.3 | 383.00 | 6.00 | 470.00 | 6 | 1837.44 | 6.58 | | | 382.8 | 470.0 | | 1.0 | |

| Nr/tipo alloggio | Collettore | Descrizione locale | $S_{utile}$ [m²] | Lunghezza minima circuito [m] | Numero circuiti [-] | Lunghezza per ciascun Circuito [m] | Nome circuito [-] | Potenza [W] | Portata [l/min] | Passo [cm] | Temperatura [C°] | Lunghezza per ciascun Circuito (ridistribuita) [m] | | | Percentuale ripartizione [-] | Potenza da ripartire |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B.02.S1.05 | CP.1 | Soggiorno - cucina - ingresso | 25.13 | 251.30 | 3 | 80 | 1 | 414.01 | 1.48 | 10 | 20 | 258.8 | 240 | | 0.33 | |
| Bilo | numero zone | | | | | 80 | 2 | 414.01 | 1.48 | 10 | 20 | | | | | |
| P2 | 3 | | | | | 80 | 3 | 414.01 | 1.48 | 10 | 20 | | | | | |
| | | Camera 1 | 12.18 | 121.80 | 2 | 80 | 4 | 310.22 | 1.11 | 10 | 20 | 129.3 | 160 | | 0.33 | |
| | numero circuiti | | | | | 80 | 5 | 310.22 | 1.11 | 10 | 20 | | | | | |
| | 6 | Bagno 1 | 4.27 | 42.70 | 1 | 70 | 6 | 240.76 | 0.86 | 10 | 24 | 50.2 | 70 | | 0.33 | |
| | 900 mm c.a. | Disimpegno | 2.26 | 22.60 | | | | | | | | | | | | 108 |
| | | Totali | 43.8 | 438.40 | 6.00 | 470.00 | 6 | 2103.24 | 7.54 | | | 438.2 | 470.0 | | 1.0 | |

**Figure 31 exported data of all the apartments in the second floor in excel sheet.**


**Figure 32 plan view of second floor in building B (B.02.S1.xx).**

Now that we have linked all the equations and extracted them into an Excel file, we can proceed with selecting the locations of the fan coils in accordance with the design requirements and calculations. However, this stage is rather intricate. Even though the values obtained from the calculations conducted through Revit and Dynamo are precise, we had to re-evaluate certain aspects due to the design requirements. Therefore, we had to combine some of the fan coils to have one instead of having two, such as in the bedrooms. The Figure 33 showcases the modified calculations and the final presentation in the Excel file.

| | | | | | | | | | Superficie [m2] | | | | | Fabbisogno Estivo [kW] | | | | | TAGLIE FCZI_P | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Numero | Taglio | Edificio | Scala | Piano | Appartamento | Tipologia | TIPOLOGICO | S.U. | Zona Giorno | Zona notte | S.Camera 2 | S.Camera 3 | Veranda/studio | S.Soggiorno + K | S.Camera 1 | S.Camera 2 | S.Camera 3 | Veranda/studio | S.Soggiorno + K | S.Camera 1 | S.Camera 2 | S.Camera 3 | Veranda/studio | PTOT (@Vmed)[kW] | Q(@Vmax) [l/h] | M.U. RBM Metis | Q montante [l/h] | Diametro |
| | | | | | | | | | | | | | | [w/m2] | | | | | | | | | | | | | | |
| EDIFICIO B-F PIANO SECONDO TIPOLOGICO | | | | | | | | | | | | | | 65 | 65 | 65 | 65 | 65/75 | | | | | | | | | | |
| 1 | B | F | 1 | 2 | F.02.S1.01 | 2KV1 | BILO | 44.59 | 24.2 | 13.0 | -- | -- | -- | 1.57 | 0.84 | -- | -- | -- | 300 | 200 | -- | -- | -- | 3.11 | 731 | 3/4" | 9,677 | 2+1/2" |
| 2 | T | F | 1 | 2 | F.02.S1.02 | 1KV1 | TRILO | 57.71 | 28.0 | 23.5 | -- | -- | -- | 1.82 | 1.53 | -- | -- | -- | 300 | 300 | -- | -- | -- | 3.91 | 912 | 3/4" | | |
| 3 | B | F | 1 | 2 | F.02.S1.03 | 2KV1 | TRILO | 57.44 | 23.7 | 22.7 | -- | -- | -- | 1.54 | 1.48 | -- | -- | -- | 300 | 300 | -- | -- | -- | 3.91 | 912 | 3/4" | | |
| 4 | T | F | 1 | 2 | F.02.S1.04 | 3KV2 | BILO | 47.23 | 27.2 | 13.6 | -- | -- | -- | 1.77 | 0.88 | -- | -- | -- | 300 | 200 | -- | -- | -- | 3.11 | 731 | 3/4" | 7,122 | 2" |
| 5 | T | F | 2 | 2 | F.02.S2.01 | 2KV1 | Trilo | 62.41 | 27.6 | 24.6 | -- | -- | -- | 1.80 | 1.60 | -- | -- | -- | 300 | 300 | -- | -- | -- | 3.91 | 912 | 3/4" | | |
| | B | F | 2 | 2 | F.02.S2.02 | 3KV2 | BILO | 35.56 | 17.3 | 12.0 | -- | -- | -- | 1.12 | 0.78 | -- | -- | -- | 200 | 200 | -- | -- | -- | 2.30 | 550 | 3/4" | | |
| 7 | T | F | 2 | 2 | F.02.S2.03 | 3KV2 | TRILO | 60.88 | 28.0 | 24.7 | -- | -- | -- | 1.82 | 1.61 | -- | -- | -- | 300 | 300 | -- | -- | -- | 3.91 | 912 | 3/4" | 4,929 | 2" |
| 8 | T | B | 1 | 2 | B2-1 | 2KV1 | TRILO | 70.47 | 29.3 | 26.7 | -- | -- | -- | 1.90 | 1.73 | -- | -- | -- | 300 | 300 | -- | -- | -- | 3.91 | 912 | 3/4" | | |
| 9 | T | B | 1 | 2 | B2-2 | 3KV2 | TRILO | 70.43 | 29.4 | 26.5 | -- | -- | -- | 1.91 | 1.72 | -- | -- | -- | 300 | 300 | -- | -- | -- | 3.91 | 912 | 3/4" | | |
| 10 | B | B | 1 | 2 | B2-3 | 2KA2 | BILO | 43.14 | 24.9 | 12.1 | -- | -- | -- | 1.62 | 0.78 | -- | -- | -- | 300 | 200 | -- | -- | -- | 3.11 | 731 | 3/4" | 2,193 | 1+1/4" |
| 11 | B | B | 1 | 2 | B2-4 | 4KV1 | BILO | 37.88 | 19.7 | 12.2 | -- | -- | -- | 1.28 | 0.79 | -- | -- | -- | 300 | 200 | -- | -- | -- | 3.11 | 731 | 3/4" | | |
| 12 | B | B | 1 | 2 | B2-5 | 4KA2 | BILO | 43.84 | 25.1 | 12.2 | -- | -- | -- | 1.63 | 0.79 | -- | -- | -- | 300 | 200 | -- | -- | -- | 3.11 | 731 | 3/4" | 731 | 1" |
| Num. Tagli residenziali | | | | | | | TOT. 12 (1M 5B 4T 2Q) | | | | | | | | | | | | | | | | | | | | | |
| TOTALE UNITA' | | | | | | | N. 50 - 2M (%) 19B(%) 22T(%) 7Q(%) | | | | | | | | | | | | | | | | | | | | | |
| Totale Superfici in Progetto | | | | | | | | 3,041.63 | | | | | | | | | | | | | | | Tot kW | 216.60 | 50,875 | | | |

**Figure 33 Fan coil capacity needed to cool the rooms in the buildings.**

When it comes to selecting the optimal placement for fan coils, there are several key considerations to keep in mind. Factors like the dimensions of the room, the distance between the fan coils and the opening of fan coil of room , the airflow, and the necessary duct measurements for proper air delivery all play a vital role. As depicted in Figure 34, the positioning of fan coils in ceiling view is highlighted. In the following section, we will delve into the impact of the fan coil's airflow on the circulation of air in the room.

**Figure 34 View of Ceiling plan shows the Fan coil location in the rooms.**

### 3.1.3. Indoor Air Quality and Ventilation Simulation.

In new residential constructions, both mechanical and natural ventilation systems can be employed to meet regulatory and performance requirements. Natural ventilation can serve as the primary mode of complementing mechanical ventilation. Bathrooms, which generate humidity and odours primarily during baths, benefit from efficient ventilation designs that enable high ventilation rates for brief periods. While bathrooms often feature mechanical extract ventilation, the inclusion of operable windows enhances the potential for effective airing. Efficient ventilation in bathrooms can be achieved with windows at different heights. Kitchen activities produce humidity, odours, and fine particles, all effectively addressed by timely and efficient ventilation during cooking. Kitchen hoods are essential, though their performance may degrade with grease buildup, making in-process ventilation a valuable practice. Optimal results are achieved when windows at different heights, such as facades and roofs, can be opened. The heat generated by ovens and stoves seldom results in cold drafts in kitchens. Sensing the need for ventilation based on odours and humidity is typically straightforward for occupants, facilitating timely ventilation. The addition of humidity-controlled electrically operated windows can further enhance the ventilation process.

Mechanical ventilation systems utilise electric fans for directing airflow within buildings. They can provide a consistent air exchange rate irrespective of external weather conditions but rely on electricity and generally lack the capacity to adapt ventilation rates to varying daily and seasonal demands. These systems come in several configurations, including those with both supply and exhaust components that can be augmented by heat recovery units, which reclaim and reuse heat from exhaust air, yielding energy recovery rates of up to 90%.

In many North European countries, it is standard practice for newly constructed houses to incorporate mechanical heat recovery ventilation systems to meet contemporary energy efficiency standards. While effective for winter heating, these systems may optimise energy consumption during the summer by transitioning to natural ventilation, constituting hybrid ventilation systems. Routine filter replacement is essential for maintaining indoor air quality in mechanical ventilation systems, as clogged filters can degrade air quality and occupant comfort.

Comparative research has suggested that air-conditioned buildings may be associated with a higher prevalence of Sick Building Syndrome (SBS) symptoms than naturally ventilated structures. Mechanical ventilation systems with heat recovery rely on airtight building envelopes for energy efficiency, as inadequate airtightness can lead to significant infiltration, bypassing heat exchangers and rendering them less energy-efficient for existing buildings.

#### 3.1.3.1. Mechanical ventilation systems

Mechanical ventilation systems can be categorised as either central or decentralized. Central systems feature a central unit equipped with supply and exhaust fans and, if required, a heat recovery unit integrated into the system, with ventilation ducts distributing air to various rooms. Decentralised systems, on the other hand, employ smaller units, some of which incorporate heat recovery, installed within individual rooms, eliminating the need for ductwork.

The calculation of the natural ventilation airflow rate can be more intricate than mechanical ventilation due to its dependency on various factors, including the size and placement of openings, prevailing wind conditions, temperature disparities, and the geometry of the building. Presented herein is a simplified methodology for approximating the airflow rate for natural ventilation:

Formula for Natural Ventilation (Simplified):

$$Q = A \cdot C_d \cdot V \tag{22}$$

Estimation of each component is elucidated as follows:

Effective Opening Area (A): Measure the area of the apertures that enable air exchange into or out of the space, including windows, doors, or other openings. Be sure to account for obstructions such as screens or grilles.

Discharge Coefficient ($C_d$): The discharge coefficient is a dimensionless parameter quantifying the efficiency of the opening in facilitating airflow. It relies on the type of opening, its shape, and other influencing factors. Empirical data or tabulated values for standard openings are typically employed to determine $C_d$.

Wind Velocity (V): Wind velocity signifies the speed of outdoor air, and it may fluctuate based on location, time of day, and weather conditions. Referencing local meteorological data or utilising estimates based on the site's exposure to prevailing winds may be necessary.

It is important to note that this simplified formula provides an approximation and does not encompass variations in wind direction, temperature discrepancies between indoor and outdoor air, and other factors that can influence natural ventilation. More comprehensive analyses may necessitate using computational fluid dynamics (CFD) simulations or specialised software to consider these factors accurately.

Furthermore, to ensure the effectiveness of natural ventilation, it is imperative to incorporate sufficient openings on both the inlet and exhaust sides of the space to facilitate the desired airflow. Designing for natural ventilation also entails building orientation, window placement, and indoor air quality management. For more precise calculations and design recommendations, consulting with a ventilation expert or an architect experienced in natural ventilation design is advisable.

#### 3.1.3.2. Hybrid ventilation

Integrating both natural and mechanical ventilation systems offer an effective approach, particularly in new residential buildings, particularly those with roof windows that facilitate the stack effect. Multiple variations of hybrid ventilation systems are in use:

##### *3.1.3.2.1. Combined Natural and Mechanical Ventilation:*

Mechanical ventilation operates during the heating season, while natural ventilation is employed throughout the rest of the year. This approach yields commendable energy efficiency in newly constructed houses and synergizes effectively with VELUX roof windows.

##### *3.1.3.2.2. Fan-Assisted Natural Ventilation:*

Primarily utilised in larger commercial structures where natural driving forces may prove insufficient during certain periods. Fans are employed to augment natural ventilation.

### *3.1.3.2.3. Stack-and Wind-Assisted Mechanical Ventilation:*

This approach is primarily employed in larger commercial buildings where the ventilation system incorporates ducts to convey air, with natural driving forces contributing significantly to airflow, augmented by fans as needed.

Hybrid ventilation serves to optimise indoor environmental conditions while concurrently curbing energy expenditures. As mentioned, mechanical ventilation with heat recovery is deployed in new residences to diminish heating requirements and meet energy heating standards. However, during warmer periods, shifting to natural ventilation reduces electricity consumption associated with electric fans and is generally favoured by occupants.

Hybrid ventilation amalgamates the advantages of both realms: commendable winter energy efficiency achieved through mechanical heat recovery ventilation and optimal summer performance through natural ventilation. In the realm of ventilation science, numerous significant considerations extend beyond purely technical aspects. Central among these is the fundamental human requirement for access to ventilation. Scientific research underscores that ventilation involving windows or 'fresh air from the outside' is not solely about 'freshness' or 'air'; rather, it revolves around cultivating a 'favourable indoor environment.' This concept encompasses various facets beyond the mere introduction of fresh air.

Typically, the subjects pertaining to the diverse aspects of fresh air can be categorised into three primary elements: a functional (practical) element, an aesthetic (relating to bodily and sensory experiences) element, and a social (about care and impression management) element. The functional element pertains to practical endeavours such as ventilating the space after bathing, floor cleaning, or bed-making. It also involves engaging with the weather and the dwelling itself.

The aesthetic element encompasses both bodily and sensory perspectives, encompassing factors like the regulation of body temperature and the capacity to perceive one's scent. This includes not only the olfactory environment within the house resulting from activities but also the enjoyment derived from the circulation of breezes within the home. The social element relates to the profound desire for control. It involves demonstrating concern for family members' well-being by ventilating the house, relishing the sense of freedom conferred by the ability to open windows, and even embracing the sounds and fragrances from the external environment.

These three vital aspects, all addressing non-technical considerations, underscore the indispensability of operable windows for the indoor environment across various dimensions of human experience. Another human aspect concerns the ability to open windows during transitional phases in our daily lives, such as transitioning from work to home, from sleep to wakefulness, or returning from vacation. Routines and reflexive actions are integral to these transitions, and opening windows have been identified as one of the necessary actions in these contexts.

The selection of a ventilation system in new residential buildings is often significantly influenced by energy regulations and the energy performance objectives of prospective homeowners. In Northern European countries, mechanical ventilation with heat recovery has increasingly become the de facto standard due to its capacity to reduce heating demands during the winter season. Across all European nations, natural ventilation continues to be the most energy-efficient system for the summer, as it entails no heat loss and necessitates no electricity for fan operation.

### 3.2. Results

The end result comprised a sequence of mechanical diagrams which showcase the equipment's positions, connections, capabilities, and other pertinent details. The ultimate presentation was structured around typology. Figure 35 outlines the collector's placement, emphasizing its importance inside the apartment, well away from external walls or structural partitions. To ensure accuracy, it's imperative that the collector is located far from sensors, as its high temperature can significantly impact measurement values.

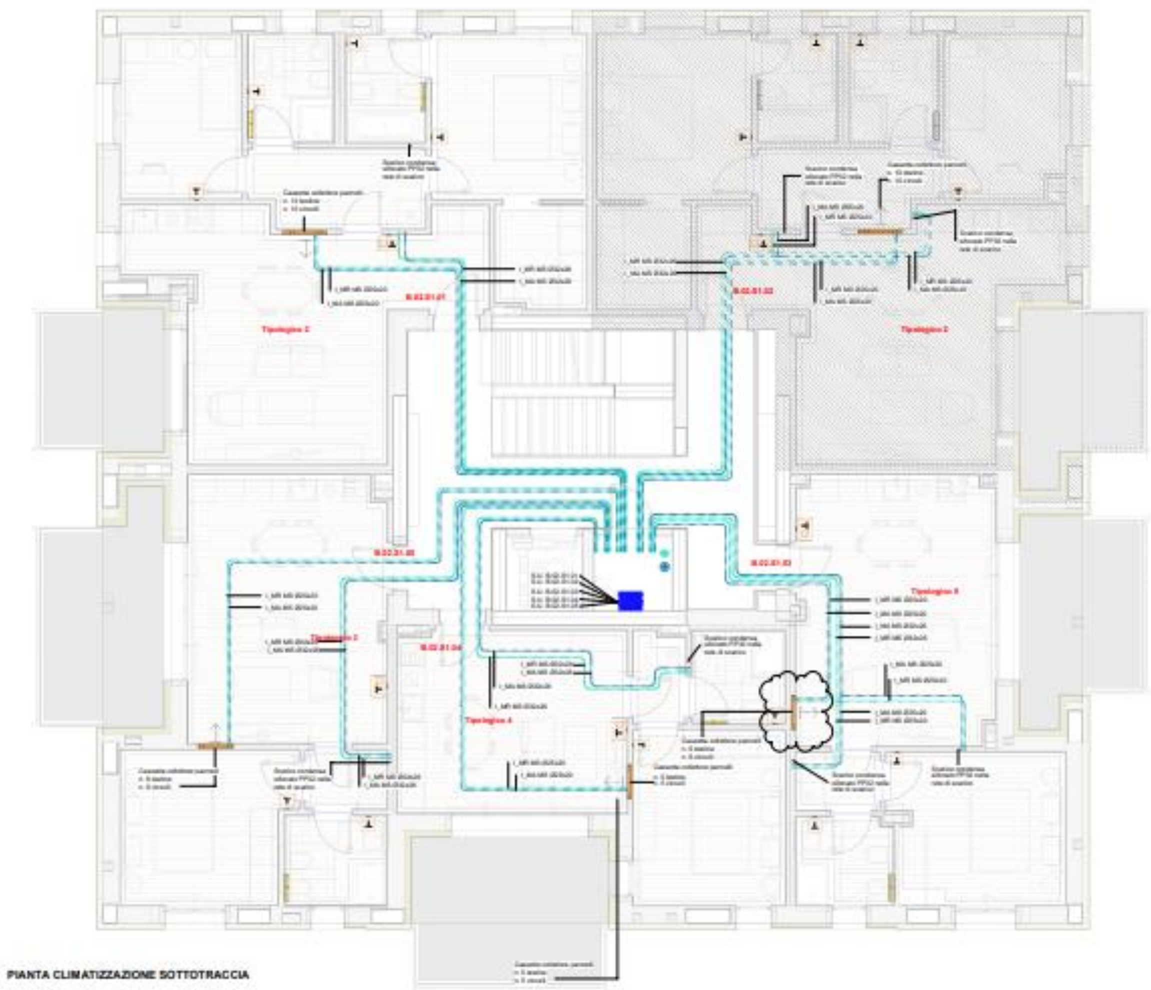



**Figure 35 Underground air conditioning system.**

Figure 36 renders a visual representation of the air conditioning system that has been integrated into the false ceiling. It showcases an array of equipment, including fan coils and pipes, as well as air outlets and a return hole. Furthermore, it illuminates the mechanical ventilation system that is utilized in bathrooms lacking windows. The information in fan coils legends contains crucial information regarding a fan coil unit. This data includes details about the unit's specifications, such as its heating and cooling capacities, airflow rate, power requirements, and dimensions. It is vital to keep this legend alongside the technical information to ensure accurate installation, maintenance, and operation of the fan coil. This comprehensive data enables HVAC professionals and technicians to make informed decisions and effectively integrate the unit into heating and cooling systems as shown in Figure 37.

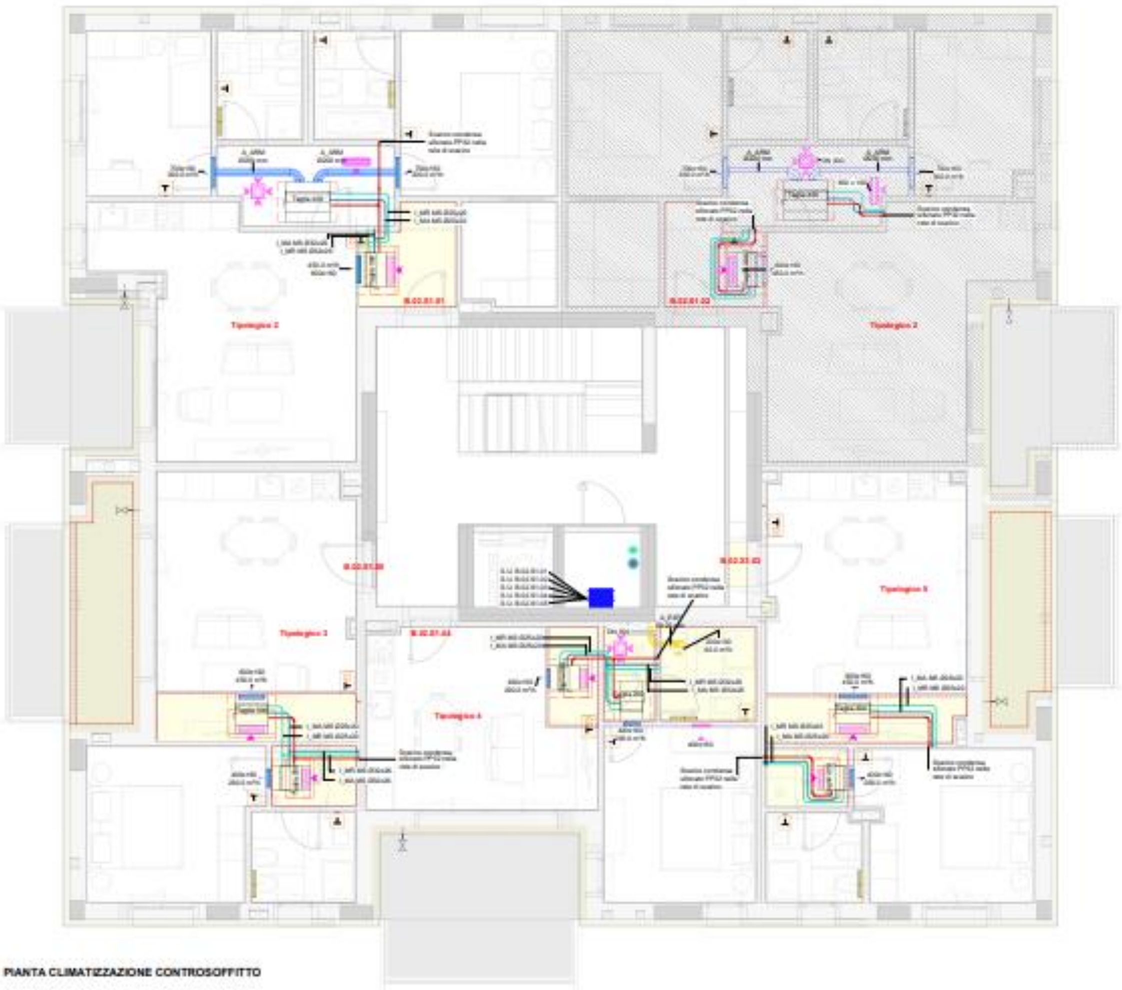



**Figure 36 False ceiling air conditioning.**

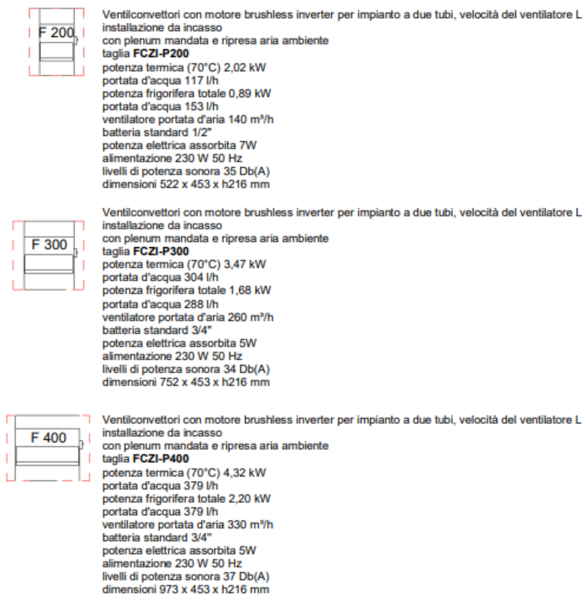



**Figure 37 Fancoil legends.**

Figure 38 depicts a diagram of a sanitary water system that displays the water collector. The capacity of each collector is determined by the number of waters points it needs to serve. Typically, there are two collectors in an apartment that has two bathrooms.

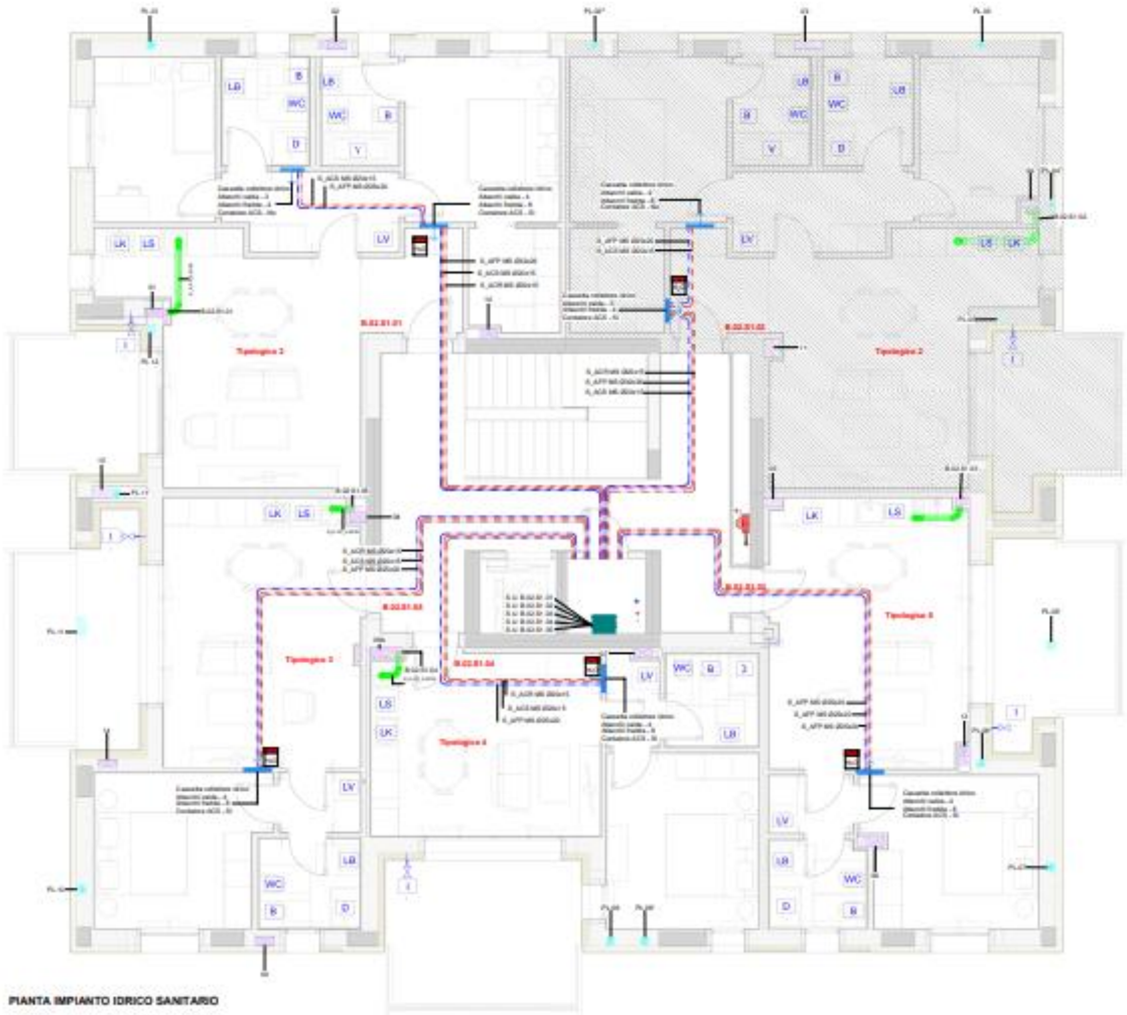



**Figure 38 Sanitary water system plan.**

# 4. LIFE CYCLE ASSESSMENT

The real estate industry has been working on reducing energy consumption in buildings to increase efficiency and sustainability for a long time. However, this approach only addresses some of the industry's carbon emissions. Embodied carbon is a significant factor that cannot be ignored. It accounts for emissions generated during the manufacturing and transportation of construction materials and the construction process itself. Buildings contribute to almost 40% of global greenhouse gas emissions, with 28% coming from building operations and 11% from embodied carbon. Experts use a recognized methodology called Life Cycle Assessment (LCA) to evaluate a product's environmental impact throughout its life cycle. This process involves assessing environmental goals, boundaries, and functional units, collecting energy, materials, and emissions data, and using impact assessment methods to evaluate environmental consequences. Utilizing LCA can help identify opportunities for environmental improvement, guide decision-making, and inform product development and design processes, particularly in the residential sector, to promote sustainability. (Iwaro and Mwasha, 2013).

Manufacturers provide EPDs to assess a product's environmental impact. EPDs evaluate emissions from mining, extraction, transport, and factory processes. LCAs are the gold standard for tracking a building's environmental impact. Carbon footprint calculations quantify total impact using EPD databases. Real estate professionals use LCA tools and consultants during the design stages of a project.

As more cities commit to decarbonization and buildings continue to significantly contribute to emissions, there is growing pressure to limit both operational and embodied carbon. Adopting low-embodied-carbon design practices now can protect firms from future challenges and costs associated with transitioning to low-carbon development. One potential policy that could influence real estate decision-making around embodied carbon is the future of carbon pricing. Although the United States currently has no federally legislated price on carbon, carbon taxes and pricing regulations are expected to become more common shortly. Developers who act now to reduce embodied carbon will have a strong financial incentive to do so once a carbon tax is passed.

Moreover, firms that operate in progressive markets likely to adopt carbon prices can benefit by aligning with the sustainability policies of cities and embracing upcoming policy goals. Establishing cooperative relationships with cities can also pave the way for future embodied carbon legislation. Examples of national and local policies driving embodied carbon reductions in real estate include the following.:

- The Netherlands Circularity Goals: To meet the country’s commitment to economic circularity by 2050, the goals set the intention of being 50 percent circular by 2030 and requiring that the building sector reduce its raw materials use by 50 percent by 2030. Since 2013, all new buildings are also required to conduct a whole-building life-cycle analysis.
- France: Currently in the pilot stage, the Positive Energy and Carbon Reduction (E+C-) voluntary labeling scheme uses whole-building life cycle assessments (LCAs) to assess performance. The country plans to regulate embodied carbon by 2020. Good performers are eligible for a density bonus.
- Buy Clean California: Signed into law by Governor Jerry Brown in 2017, this legislation mandates that all state agencies consider the carbon emissions of the full supply chain when

embarking on a new construction or infrastructure project, thus rewarding manufacturers that produce materials with lower embodied-carbon levels. Washington state is currently considering similar legislation.

- Bay Area Low-Concrete Carbon Codes Project: Based in Marin County, California, the project works to target local building codes to phase out highly polluting traditional forms of concrete.
- Vancouver's Zero Emissions Buildings: Perhaps the most rigorous embodied carbon policy to date, the policy sets the city on track to reduce embodied carbon by 40 percent by 2030.

## 4.1. Importance of Life Cycle Perspective

The life cycle perspective is crucial for sustainable decision-making, environmental impact assessment, resource efficiency, cost savings, innovation, regulatory compliance, and stakeholder engagement. Considering the entire life cycle, comprehensive information is obtained to inform sustainable choices, identifying environmental, social, and economic impacts at each stage. It enables thorough evaluation, highlighting areas for improvement and minimising negative environmental effects. The life cycle perspective promotes resource efficiency, reducing waste, and embracing circular economy practices. It assesses long-term cost implications, identifying potential energy consumption, maintenance, and disposal savings. The perspective drives innovation, encouraging environmentally friendly and socially responsible products and processes. It is increasingly essential for regulatory compliance and facilitates stakeholder engagement, transparency, and effective communication. Overall, the life cycle perspective empowers organisations to make informed decisions, reduce environmental impact, optimise resource use, achieve cost savings, drive innovation, comply with regulations, and engage stakeholders effectively (Iwaro and Mwasha, 2013).

## 4.2. VDC, IoT, and Digital Twin Technologies for Enhanced Construction Efficiency and Sustainability

VDC tools, the Internet of Things (IoT), and digital twin approaches are revolutionising the construction industry. VDC tools enhance various aspects of construction projects, such as design, planning, safety, resource management, visualisation, quantification, and data management, particularly in complex projects. By utilising VDC tools, valuable resources like time, cost, and manpower can be conserved during project construction.

The IoT enables real-time interaction between internet-enabled devices within buildings, benefiting residential and non-residential structures. This connectivity positively impacts every facet of operation and maintenance, resulting in smart, efficient, flexible, and real-time work management. Furthermore, IoT fosters collaboration and communication among project stakeholders and beneficiaries during pre-planning and design phases, enhancing overall project outcomes.

Digital twin technology provides a virtual replica of physical buildings and infrastructure, facilitating monitoring, control, and optimisation throughout the construction and operational phases. Its implementation in the architecture, engineering, and construction (AEC) industry improves efficiency, safety, and sustainability. For instance, digital twins enable remote monitoring and control of building systems like HVAC, lighting, and security, optimising their performance and reducing energy consumption. These approaches also aid in predicting and preventing equipment failures, reducing downtime, and improving maintenance planning. Moreover, digital twin technology allows for the simulation of various scenarios and testing design options before physical implementation, resulting in significant time and cost savings during construction.

Digital twin approaches for sustainability assessment in the AEC industry are gaining traction. Researchers propose frameworks leveraging digital twin technology to evaluate buildings' environmental, social, and economic impacts throughout their life cycle. These frameworks consist of modules for data collection, analysis, and visualisation, empowering decision-makers to identify the most sustainable design and operational choices. Digital twin technology offers a more accurate and comprehensive assessment of sustainability performance compared to traditional methods. Furthermore, it holds the potential for energy-saving measures in built environments. Future research should focus on developing digital twin approaches with enhanced functionalities for optimising monitoring processes, enabling predictive maintenance, and delivering top-notch services across various categories within the AEC industry (Rafsanjani & Nabizadeh, 2023).

Multifamily buildings must monitor energy and water systems, outlining measurement points and criteria in the commissioning plan. Acceptable values should be defined, and predictive algorithms incorporated where applicable. An action plan, training initiatives, and maintenance planning ensure operational efficiency. Regular analyses during the initial occupancy year are essential, with any changes recorded in the updated systems manual.

The life-cycle assessment should be clearly described, with any changes made for impact reductions detailed. Buildings should have similar size, function, and energy performance, with a service life of at least 60 years. Compliant ISO 14044 data sets and life-cycle assessment software tools should be used. Three out of six impact categories, including global warming potential, must be reduced.Upon site commissioning, a durable air quality monitoring infrastructure is recommended, incorporating commercial-grade sensors for real-time surveillance of four out of the six designated pollutants, with PM2.5 being mandatory. The targeted pollutants encompass PM10, SO2, NO2, O3, and CO. Concurrently, the monitoring system should display instantaneous comparisons with the prevailing National Ambient Air Quality Standards (NAAQS) in the respective project country for each measured pollutant. To ensure precision and reliability, periodic calibration of the sensors, either annually or per the specifications provided by the manufacturer, is mandated (LEED 2012 – 3rd Public Comment – MR (Materials and Resources) Section, 2012).

Furthermore, it is essential to conduct routine maintenance, perform audits, and validate the data generated by the sensors in compliance with the guidelines stipulated by the product manufacturer. The real-time air quality information available through the display shall serve as a valuable resource, offering pertinent guidelines and recommendations for the project's occupants.

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# 5. CONCLUSIONS

This study suggests that the use of Building Information Modeling (BIM) can greatly enhance sustainable design in residential construction through environmental simulation. The literature review highlights the importance of sustainable building design principles such as building envelope design, resource efficiency, material selection, and design features that promote good indoor air quality. The study also examines various rating systems and standards like LEED, PEER, EDGE, WELL, and ICP, which evaluate building sustainability.

Case studies of residential building design using environmental simulation have shown the importance of simulation for lighting, energy, indoor air quality, ventilation, and acoustics. The results of the simulation show that BIM can be used to optimize energy performance, enhance thermal comfort and lighting, conserve water, and reduce noise levels in residential construction. Additionally, the study emphasizes the importance of a life-cycle perspective and the use of VDC, IoT, and Digital Twin technologies to improve construction efficiency and sustainability.

While this study shows that BIM can significantly enhance sustainable design in residential construction, there is still room for improvement and unanswered questions. For example, more precise simulation tools and the integration of BIM with other technologies such as Artificial Intelligence (AI) and Machine Learning (ML) are necessary. These findings can be extended to other building types, such as commercial, industrial, and institutional buildings.

The integration of Python with the AEC field offers several benefits. Experts can use its capabilities for simulation, automation, and simplifying complex equations using tools like Dynamo. Python's computational power allows advanced models to simulate behavior, energy consumption, airflow, and other essential factors, resulting in valuable insights for superior design iterations and optimization. Python's data handling flexibility enables seamless integration with BIM software, leading to deeper insights and the automation of tedious tasks. Custom scripts and applications can be created to simplify formulas, automate tasks, and allow non-programmers to harness the power of Python, thereby improving productivity and driving innovation in the AEC industry.

In conclusion, architects, engineers, and other professionals involved in designing and constructing sustainable buildings can benefit significantly from this study's findings. The use of BIM for environmental simulation can help reduce energy consumption, improve indoor air quality and ventilation, and optimize lighting and acoustic conditions. By using BIM, it is possible to design and construct buildings that are sustainable, comfortable, and healthy for their occupants.Recommendations:

1. Expand the scope of the simulation to cover a wider range of building types and designs.
2. Utilize and develop the environmental simulation tools to generate more accurate and detailed results.
3. Conduct more extensive research on materials and construction methods to identify additional opportunities for improving sustainability in building design.
4. Explore the use of virtual reality technology to enhance the user experience and facilitate collaboration between designers, builders, and other stakeholders.

5. Incorporating real-time data collection and analysis to enable continuous monitoring and optimization of building performance.
6. Collaborate with experts in related fields, such as energy management and sustainable design, to further enhance the simulation model and its applications.
7. Conduct a thorough life cycle assessment of the simulated buildings to ensure that sustainability considerations are addressed throughout the entire lifespan of the structure.
8. Ensure that the simulation model is user-friendly and accessible to a wide range of stakeholders, including architects, builders, and building owners.
9. Continuously update the simulation model to reflect the latest advancements in building design, construction, and sustainability practices.
10. Document the simulation methodology, results, and recommendations thoroughly to enable others to replicate and build upon the research.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| A | The effective opening area ($m^2$). |
| AEC | Architecture, Engineering & Construction |
| AVERT | Avoided Emissions and Generation Tool |
| BIM | Building Information Modeling |
| $C_d$ . | Discharge coefficient (dimensionless) specific to the opening |
| CGP | Construction General Permit |
| cos $\theta_z$ | Cosine of the solar azimuthal angle |
| dB | Decibels |
| $d_\lambda$ | The infinitesimal change in wavelength over the integration range |
| EPA | Environmental Protection Agency |
| EUI | Establish an Energy Use Intensity |
| $E_\lambda$ | represents the solar irradiance data in $W/m^2$ at a specific wavelength λ |
| GBCI | Green Business Certification Inc. |
| GHG | greenhouse gas |
| $G_{on}$ | extraterrestrial normal solar irradiance per day n, [W/m2] |
| gpc | Gallons Per Cycle |
| gpf | Gallons Per Flush |
| Gpm | Gallons Per Minute |
| $G_{sc}$ | Constant solar irradiance equal to 1367 [W/m2]. |
| HVAC | Heating, Ventilation, and Air Conditioning |
| ICP | The Investor Confidence Project |
| IEC | International Electrotechnical Commission |
| IoT | Internet of Things |
| IWF | Integrated Water Factor |
| k | the conversion constant (lm/W) |
| LCA | Life Cycle Assessment |
| LCIA | Life Cycle Impact Assessment |
| LEED | Leadership In Energy And Environmental Design |
| lpc | Liters Per Cycle |
| lpf | Liters Per Flush |
| lpm | Liters Per Minute |
| MEP | Mechanical, Electrical, and Plumbing |
| Q | Airflow rate ($m^3/s$). |
| RH | Relative Humidity |
| SBS | Sick Building Syndrome |
| STC | Sound transmission class |
| SY | Statistical |
| ti | Solar hour |
| USGBC | The U.S. Green Building Council |
| V | Wind velocity (m/s). |
| $V_\lambda$ | represents the CIE luminosity function values. |

| | |
|---|---|
| $\delta$ | Latitude of the site |
| $\tau_b$ | Transmission coefficient of the atmosphere for normal direct solar radiation. |
| $\tau_d$ | Transmission coefficient of the atmosphere for diffuse isotropic solar radiation. |
| $\omega$ | Hour angle |