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Smart Workplace. Micro-Climatization and Real-Time Digitalization Effects on Energy Efficiency Based on User Behavior

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"If I can see farther it is only because I stand on the shoulders of giants".
Issac Newton (1642-1727)

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DEDICATION

This thesis is dedicated to my father, Parviz, and my mother, Shamsi.

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CHAPTER 1 INTRODUCTION

It is widely known that the built environment is responsible for various issues related to environmental pollution and energy consumption. In this context, regulations and standards represent significant steps to control and reduce them. The increasing global demand for energy is one of the major issues in the world today and the design of the built environment plays a crucial role in determining pathways of energy use. However, there are many available strategies to reduce energy-related demands. Users make significant contributions towards enhancing energy efficiency to such a degree that user behavior can sometimes lead to significant energy savings. Furthermore, building users have a considerable impact on the performance of indoor environments. Therefore, to improve energy efficiency and indoor environmental quality (IEQ) in buildings it is essential to understand and predict user behavior. It is worth mentioning the fact that indoor environmental quality (IEQ), user behavior and energy consumption are correlated.

1.1 Problem Definition and Specific Challenges

In the context of building performance and user satisfaction, indoor environmental quality (IEQ) is one of the major issues that should be taken into consideration. It can also be considered as a key aspect of assessment approach in the sustainable buildings. In order to evaluate indoor environmental quality (IEQ) performance, it is essential to determine factors that affect building users in the indoor environment (Figure 1.1).

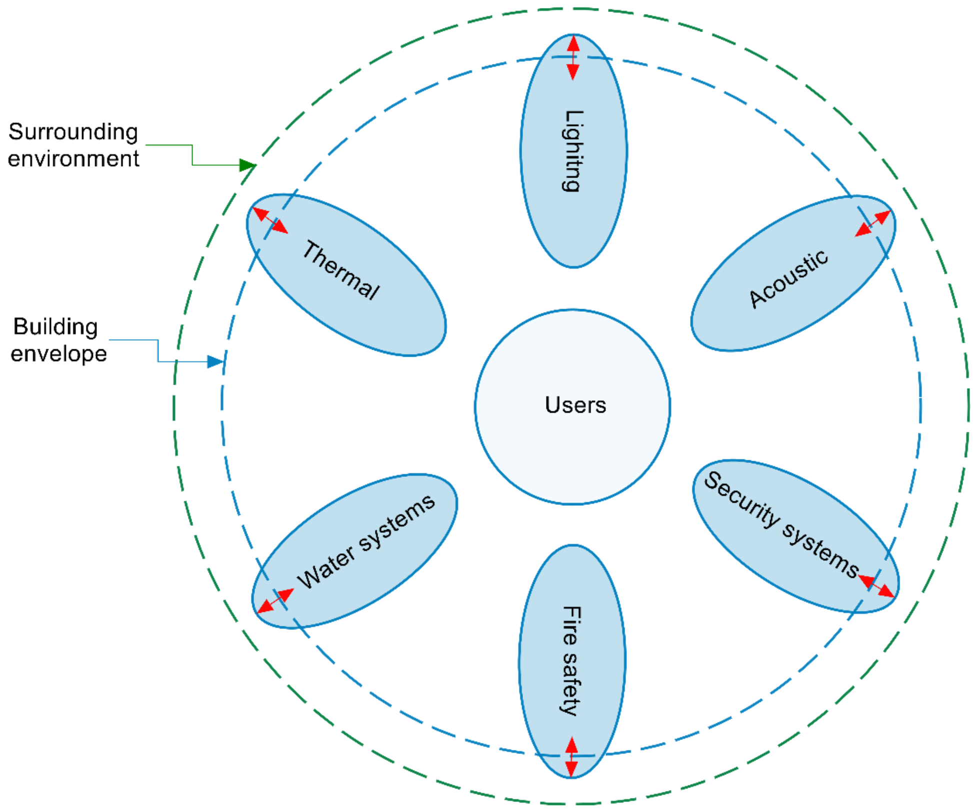


Figure 1.1: Important parameters affecting comfort levels for building users. Source: Author.

It is clear that there is no a comprehensive intelligence approach and environmental control method based on important factors such as thermal, acoustic, visual comfort. Nowadays, demand for energy management systems (EMSs), especially in smart buildings, is growing significantly. Smart buildings are commonly defined as buildings that are usually controlled automatically instead of using conventional controllers. In this respect, energy management systems (EMSs) are the most important structural framework for building automation and management systems. These systems include processes for determining the set-point temperature for each zone separately, forecasting future conditions, controlling HVAC systems and lighting and interaction with the outside temperature to prevent wasted energy building. However, there are some challenges regarding developing energy management systems (EMSs) in the buildings. For example, energy management systems (EMSs) are not continuously able to control individual needs in each area separately. It is necessary, therefore, to develop innovative technologies in architecture with a particular focus on improving energy efficiency on a micro scale level. Furthermore, it is important to design a new conceptual framework to address user behavior in process control and optimization applications. However, it is important to note that building management systems should be developed to increase energy efficiency and cost savings with respect to environmental conditions.

Today, smart systems integration (SSI) are emerging as innovative approaches and tools for promoting more effective development and use of technology in the built environment. In this context smart systems can be considered as integrated systems that not only are able to provide promotion systems, but also help make better decisions in critical conditions. In order to develop smart systems, especially in planning and building construction, it is important to highlight the main possibilities and challenges of systems to generate better environmental outcomes.

Smart systems according to their applications in buildings are classified into different categories. These categories can be transferred from architecture to other building fields such electrical and mechanical, etc. In recent times, examples of smart systems such as sensors are being used to monitor indoor and outdoor environmental condition. They are classified into three categories: self-sensing, self-diagnostic, and self-adapting sensors. Developed systems can also measure environmental factors such as mean air temperature, relative humidity, CO_2 concentration, light, reliable occupancy, ventilation, etc. Smart sensor systems as part of innovation platforms can not only improve energy efficiency and indoor environmental quality (IEQ) in residential buildings, office buildings and commercial buildings but they play a very important role in making smart cities.

In order to develop a new approach for enhancing indoor environmental quality (IEQ) and building user comfort, it is useful to investigate responsive design principles based on user needs. For example, workplace users within office buildings in particular are significantly affected by environmental conditions. It can therefore be advantageous for users to integrate smart system devices in a wide variety of applications to control environmental factors without having to interact with manual controls. In fact, in view of the importance of indoor environmental quality (IEQ), the strategy challenge is to create optimal comfort conditions for each individual user of a building.

This current work focuses on innovation technologies and methods through smart systems and sensorization to build improved indoor environmental based on users' behaviors and needs. In this respect, a hierarchical functional decomposition can be used to detect attributes and objectives of work framework (Figure 1.2). This approach makes it possible to study the challenges associated with smart energy management systems, mainly related to user behavior and energy use trends in the buildings as an integral part of architectural technology.

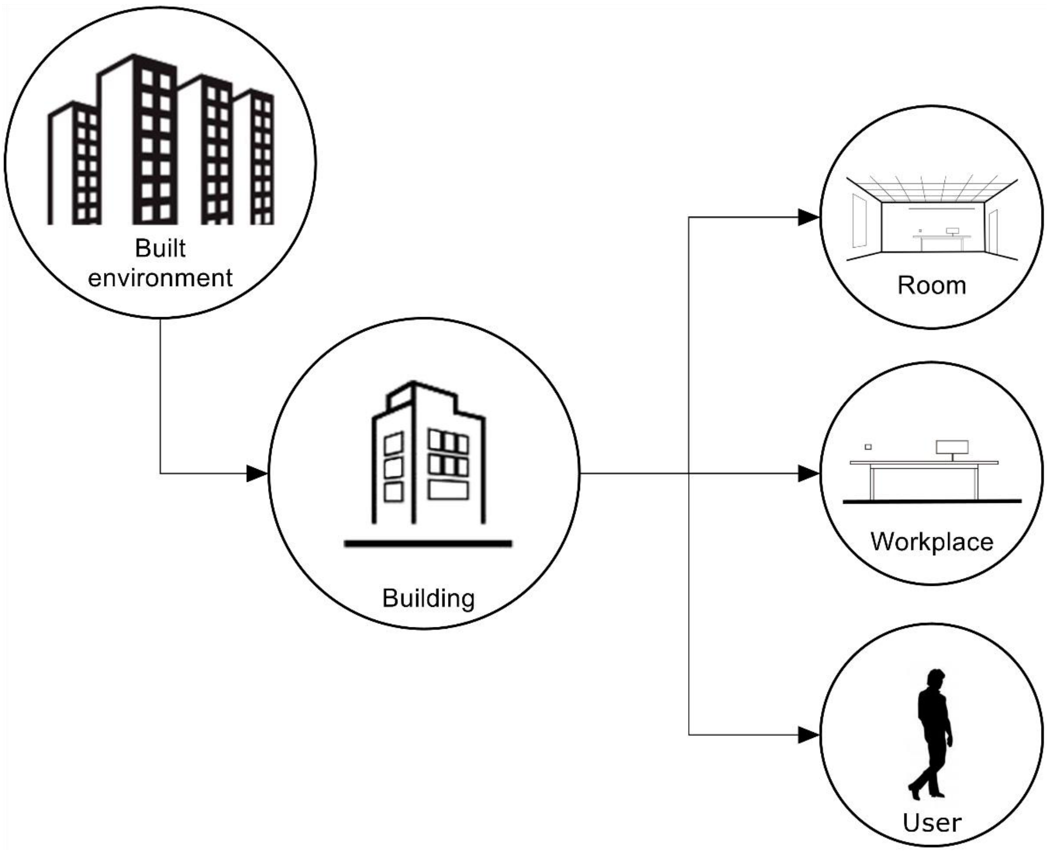


Figure 1.2: Hierarchical functional decomposition of the built environment with focus on room level, workplace level and user level. Source: Author.

There are a great many technical challenges that should be overcome to provide and monitor better indoor environmental quality (IEQ). It is clear that issues and challenges of involving smart systems within indoor and outdoor environments are becoming increasingly complex. For example, there are many problems related to user technology interaction in the field of smart and sustainable control systems. Within this context, particular control system functionalities are not always completely understood by users. Therefore, it is important to identify concept and scope of control systems in relation to their ability to manage and make sense of environmental data. This is one of the most important features of smart control systems that should effectively meet user needs.

Nowadays, there are various smart control systems such as smart thermostats, mechanized blinds, mechanized windows, etc. which can keep occupied zone within the comfort range (Figure 1.3). In the context of individual micro-climatization concept, it is clear that there is no improvement in actual performance toward optimizing energy consumption and user satisfaction on workplace level. It should also be noted that an appropriate energy management system (EMS) can be designed with particular focus on efficiency and individual control for user comfort and energy consumption with a view towards improving individual micro- environment.

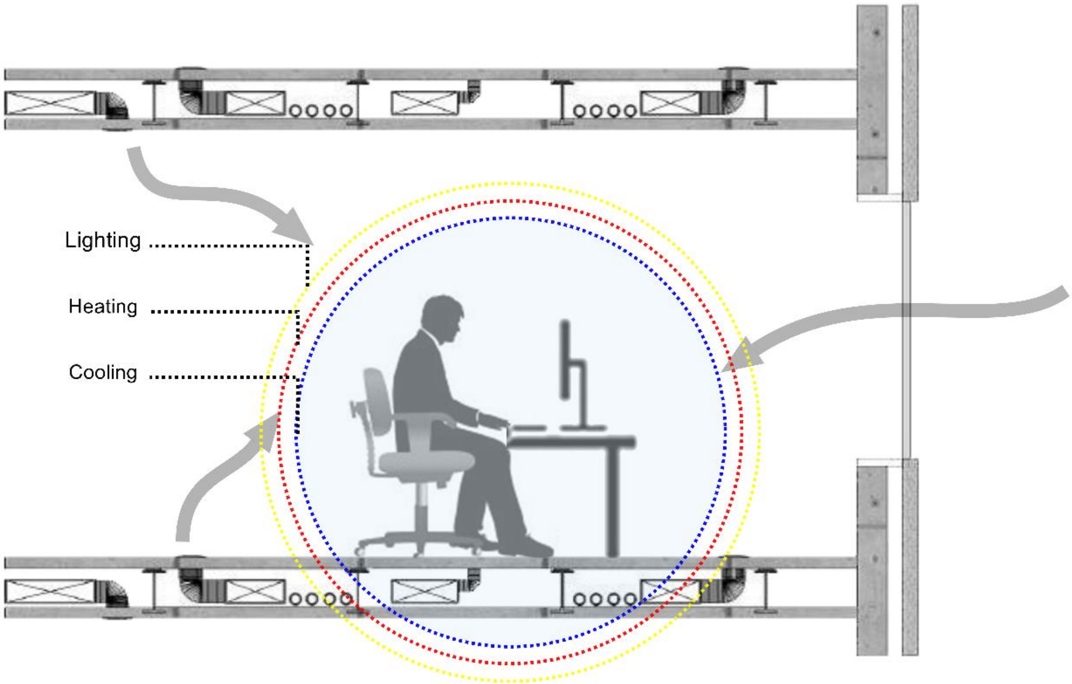


Figure 1.3: Individual micro-climatization concept on workplace level. Source: Author.

Individual micro-climatization systems need to be integrated with a series of smart sensor and controllers to create a comfort zone for a certain user. In summary, smart sensor systems involve a variety of economic and environmental objectives. They are also used for various different purposes as follows:

- Improving the level of automation in buildings
- Developing new opportunities for energy efficiency and comfort conditions
- Accelerating the use of renewable resources
- Enhancing indoor environmental quality (IEQ) and user-centered design concepts
- Determining acceptable comfort zone conditions in the built environment
- Evaluating responsive, adaptive and interactive environments
- Controlling artificial lighting, daylight and HVAC systems

Although smart sensor systems have proved to be effective and adaptable in the built environment, they still face difficulties and challenges in the process of gathering data and information directly from users. It therefore becomes essential to provide solutions to contribute toward achieving user needs and expectations in real-time.

It is possible to state that individual energy and comfort profiles can enable users to resolve problems in a new way and find creative solutions. In fact, the utilization of technologies to achieve a better understanding of user behavior and needs can facilitate integration process between energy supply and demand. In other words, smart building control systems can help develop a beneficial relationship between user, indoor and outdoor environments to achieve significant energy savings.

At this point, it is possible to claim that the development of more flexible and comfortable control systems can provide a simplified communication between users and built environment which encourage users to be involved and mindful of energy efficiency. On the other hand, control and optimization of indoor comfort conditions should be considered along with user needs. Furthermore, the use of outdoor environmental conditions (e.g. passive strategies) should be taken into account as possibilities and opportunities in enhancing energy efficiency and comfort.

1.2 Thesis Approach and Objectives

In order to enable user involvement strategies to improve indoor environmental quality, it is essential to develop smart adaptive systems for controlling environmental parameters. One approach is to develop a smart micro scale energy management system through smart sensor systems and building information modeling (BIM) that is based on user behavior. This uses new methods to study the interaction between user behavior, indoor comfort and outdoor climatic variation, particularly at the workplace. It is important to establish and maintain links between user behavior, digitalization and visualization technologies, optimization process and data transformation to create comfortable, smart and sustainable built environment (Figure 1.4).

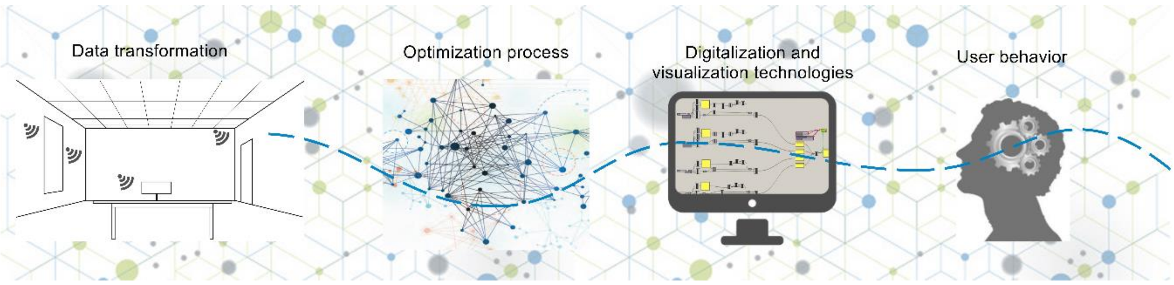


Figure 1.4: An illustration of correlation between user, information visualization, optimization and the processing performance. Source: Author.

The final work is focused on designing a user-oriented environmental control model. This includes processes for collecting and monitoring environmental data for finding solutions which are more efficient and suitable to users. It provides an effective method for determining and predicting user behavior and dynamic behavior of smart systems which can better promote interaction between the user and a smart environment. The approach mainly focuses on the development of low-cost smart systems and artificial interfaces (AIs) that will enable optimal individual comfort and energy profiles. In order to fulfil these aims, the following objectives will be addressed:

- Advances in the analysis of user behavior patterns in the built environment
- Development of a cost effective automation system
- Compilation of a user workplace and profile for climate responsive design strategies
- Digitalization and visualization of environmental data for improving energy efficiency
- Evaluation of user behavior and user interaction with smart sensor systems for determining an appropriate control strategy.

1.3 Main Research Questions

To fulfil the aims of this current research work, several important questions will be investigated from a design and architectural technology point of view. The following are examples of main research questions:

- Which methods can be applied to measure and monitor indoor environment quality (IEQ)?
- What are the fundamental principles for improving energy efficiency at the workplace level?
- What type of technologies and applications are necessary to develop smart buildings and smart cities?
- How can smart systems affect energy consumption and indoor environmental quality (IEQ)?
- How can we create low-tech systems with high smart perspectives in buildings?
- How to measure the role user behavior in buildings as potential smart energy consumers?
- What are the advantages of using building information modeling (BIM) and open-source environmental programs to improve building performance?
- How can smart sensor systems based on user behavior improve indoor environmental quality (IEQ) and user comfort?

The above mentioned research questions cannot be answered without considering various aspects of smartness which include smart people, smart buildings, smart environment, smart cities and sustainability. Therefore, this current research work will attempt to answer certain questions through scientific investigation. It will also highlight a range of methods for development of smart users and smart workplaces. The following questions are the major questions that are addressed in the research paper.

Chapter 2:

● What is environmental workplace comfort model in office buildings?

● What are the most important environmental factors affecting user satisfaction in buildings?

● What is the impact of smart manufacturing systems and smart process control on energy efficiency?

Chapter 3:

● What type of self-diagnostic smart system services are capable of controlling and monitoring environmental conditions?

● What strategies are appropriate to deploy smart system services in the built environment?

● What type of smart systems and scenarios are used extensively on sustainable refurbishment of office buildings?

Chapter 4:

● What are the potential benefits of sustainable design and adaptation strategies in the built environment?

● What type of smart system solutions have the most impact on achieving environmental sustainability goals?

● What are the challenges and opportunities in achieving smart sustainable cities and smart energy planning objectives?

Chapter 5:

● What are the most important methods and data analysis techniques?

● Which processing method can be used effectively to analyze climate data?

● How can energy modeling and environmental assessment tools influence building sustainability and performance?

Chapter 6:

● What are prime analysis needs in building performance simulation (BPS) tools for predicting buildings' energy performance?

● How can building information modeling (BIM) contribute to sustainable development?

● What are acceptable values of comfortable environmental conditions?

Chapter 7:

● What components are required in relation to smart system integration?

●What is the purpose of using intelligent algorithms and interfaces?

● What are the advantages of multi objective optimization approach?

Chapter 8:

● What is the difference with previous approaches to the same topic?

● What is the importance of research in the field of architectural technology?

● What are target research stakeholders?

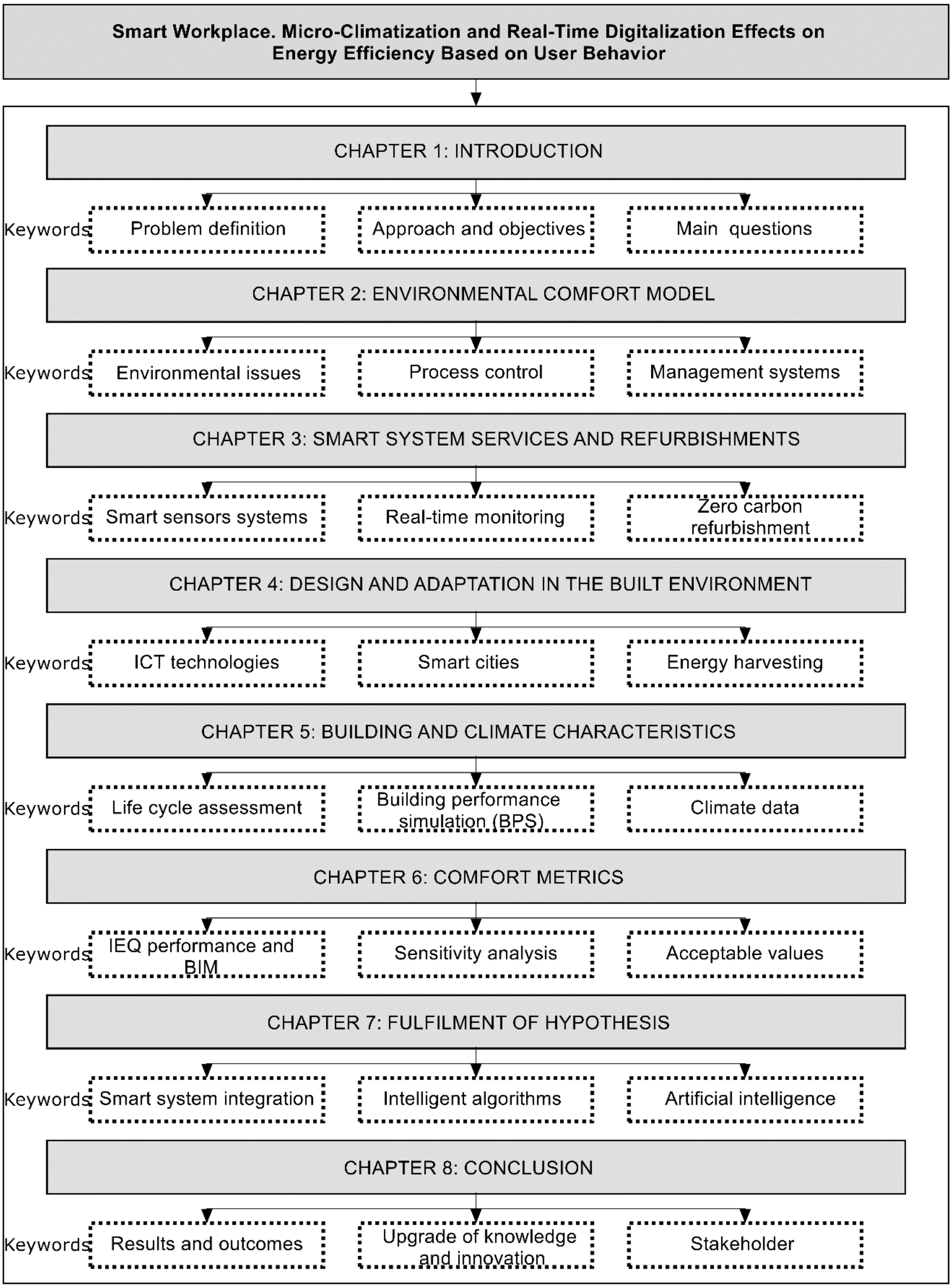


Figure 1.5: Outline and structure of current research work. Source: Author.

1.4 Methodology

To reach high performance buildings through climate responsive and smart systems, it is important to pay attention to environmental parameters and their impact on the built environment. Sustainable smart behavior is considered as a new method to investigate interaction between users and environmental parameters for improving comfort, efficiency and smart solutions in the built environment (Figure 1.6). This concept can also be used to explain how users can make a place sustainable and smart. X-axis and Y-axis are considered as the built environment and efficiency goals in the figure. This also shows the importance of making a place sustainable, then smart, then work on the behavior of the user in the building to meet efficiency goals.

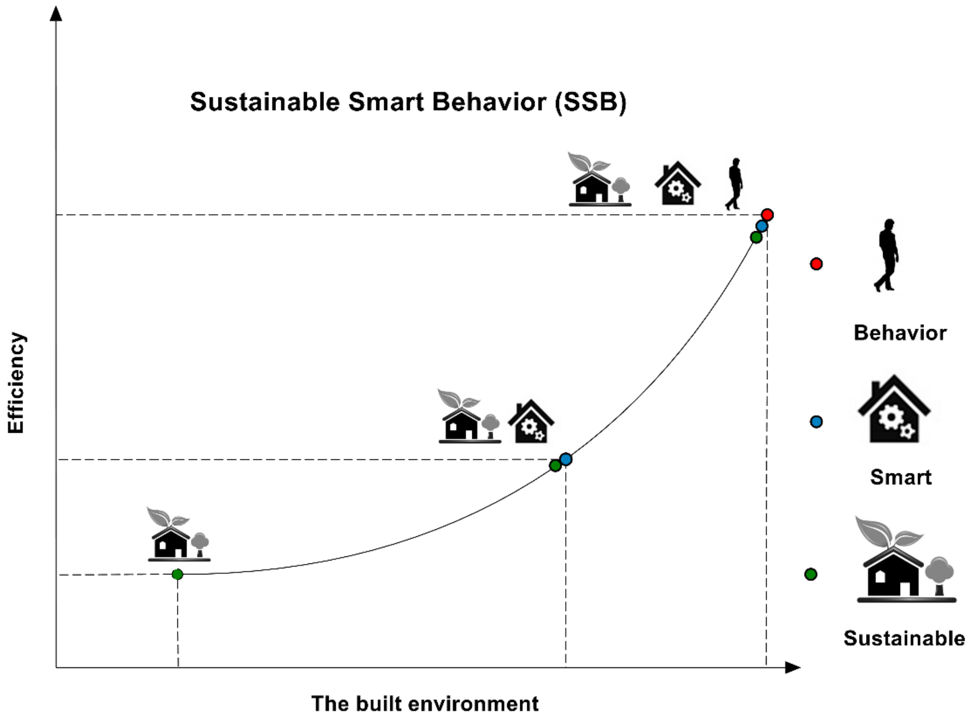


Figure 1.6: Overview of sustainable smart behavior methodology and influencing factors. Source: Author.

Sustainable smart behavior can offer significant opportunities for developing smart and sustainable built environment. However, its main contribution is to highlight the importance of users in addressing sustainable development and smart growth.

The aim of sustainable smart behavior methodology is to find optimal comfort conditions related to sustainable and smart systems. This can not only provide significant techniques for both new construction and retrofits, but also improve environmental attributes of renewable resources and users' comfort towards fostering sustainable smart buildings. Sustainable smart behavior methodology can be used for optimization of multi-energy systems and environmental parameters in buildings through sensorization or cost-effective smart systems.

To achieve an efficient environment, it is essential to find practical methods to take advantage of sustainable and smart facilities at the same time. To promote sustainable development objectives under smart systems, user behavioral patterns have significant potential to drive systems in the process. It is also important to take account of user needs, local climate conditions and living cultures in the implementation of sustainable smart behavior into built environment.

In addition to the above mentioned, performance assessment index (PAI) can be used along with sustainable smart behavior methodology to measure the state of sustainable and smart initiatives at each stage of the new construction and renovation projects (Table 1.1). Examples of such sustainable initiatives may include focus on passive and low-energy systems, use of sustainable building materials, renewable energy sources, etc. Smart initiatives can include automated building systems, wireless sensors, daylight harvesting, etc. The PAI can be explained by specific mathematical description and criteria evaluation in the following equation.

Table 1.1: Overview of performance assessment index (PAI).

	Sustainable building initiative	Intelligent building initiative	Interference issues
Abbreviation	SBI	IBI	η

$$PAI = \sum_{a=1}^{n} SBIa + \sum_{b=1}^{n} IBIb - \eta c \qquad (1)$$

(a= 1, 2, 3…n), (b=1, 2, 3…n), (c=1, 2, 3…n)

Where **SBIa** is the total quantity of sustainable building initiatives at each stage of any given project. Furthermore, **IBIb** stands for the total quantity of intelligent or smart initiatives. The varieties of sustainable and smart initiatives are denoted by (a) and (b) respectively. Interference issues (η) are disincentive factors for smart and sustainable growth. Therefore, they should be excluded from sustainable and smart initiatives, and only the factors that influence manufacturing sustainability and efficiency should be taken into account.

Sustainable and smart initiatives have the direct potential to increase the quality of built environment and well-being of the end users. However, some systems may have detrimental effects on sustainability performance. For instance, a smart window can cause a low daylight transmittance or increase heating load for internal. In this case, users can play a key role in maintaining optimal indoor environmental quality. Users can contribute to the development of appropriate smart systems in accordance with the desired sustainability and help mitigate interference issues in the process. In fact, interference issues must be resolved by users.

It is evident that interactive capabilities of smart materials and elements will change architectural styles and details in the future. It is, therefore, important to develop a deeper understanding of how user integration can enhance performance and efficiency.

The current work methodology includes 3 phases: 1) exploring principles of user-centered control systems; 2) analysis of smart and sustainable systems to develop an innovative solution at the workplace level; 3) development of smart micro-level approaches to improve energy efficiency and comfort conditions.

As mentioned before, the work aims to explore the use of user behavior, smart and passive systems to improve energy efficiency and indoor environmental quality (IEQ) in buildings (Figure 1.7). The presence of users within buildings can affect process improvement. For example, users can contribute to energy efficiency by switching off artificial lighting during daylight hours. Furthermore, they can reduce the use of energy by changing their behavior to act according to principles of sustainable development.

Building control systems are essential for achieving optimal desired conditions. In this respect, two types of feedback control systems such as smart systems and passive systems are used to meet user needs.

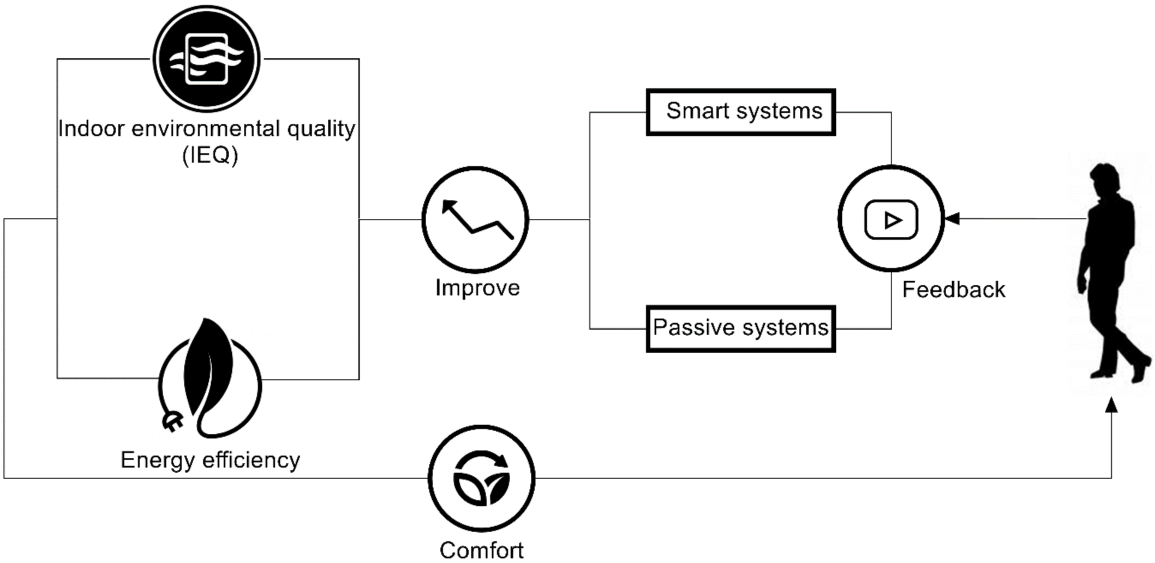
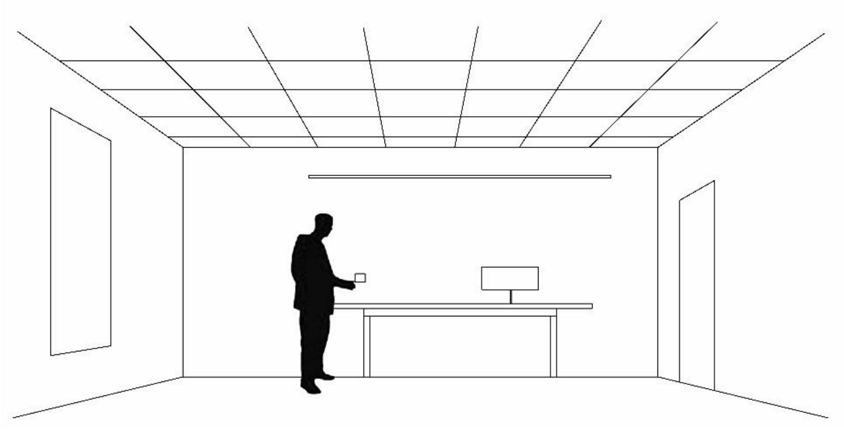
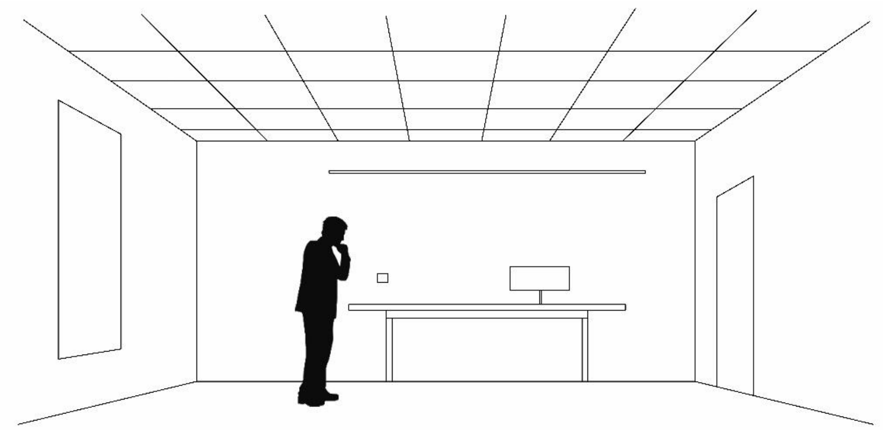


Figure 1.7: A schematic diagram of relationship between user and feedback control systems.
Source: Author.

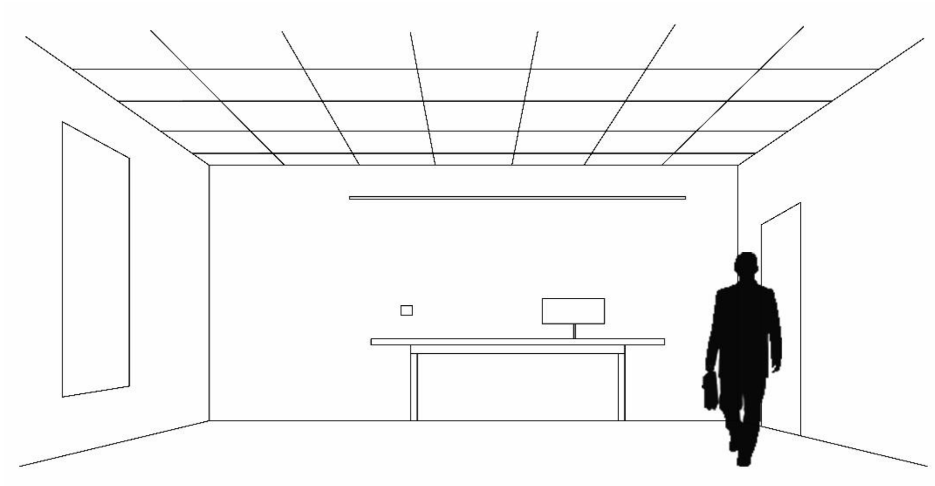
The analysis of user behavior patterns can be helpful to predict energy consumption and comfort conditions in buildings. It also can facilitate the process of executing a deep energy retrofit. In this regard, the current work proposes user behavior patterns of three main category types: 1) user is familiar with building control systems and can communicate with them individually 2) user has no actual knowledge of building control systems and is unable to set them 3) user is wasteful and does not care about building control systems (Figure 1.8). It is important to consider that user-level familiarity with control systems can be determined through a questionnaire approach or a smart learning approach. Understanding of user-level familiarity is an effective way to analyze user behavior in process control. It also can make a significant contribution to energy analysis methods. User behavior patterns should be used to understand correlation between the occupant behavior and the energy use.



a) Familiar with systems



b) Have no actual knowledge



c) Not care about systems

Figure 1.8: The user-level familiarity with building control systems. Source: Author.

In addition, the work attempts to address methods through building performance simulation (BPS) tools to determine optimal conditions of indoor and outdoor environments. To examine and identify key factors that affect building performance, preliminary simulation of models by setting relevant environmental conditions are conducted. Furthermore, for each case study, user comfort, energy requirements and indoor climate are investigated at the workplace level. The assessment processes are carried out with calculation methods using simulation programs such as IES-VE, Daysim/ Radiance, Ecotect and Revit. The following figure shows research design strategy and probabilistic modelling approach.

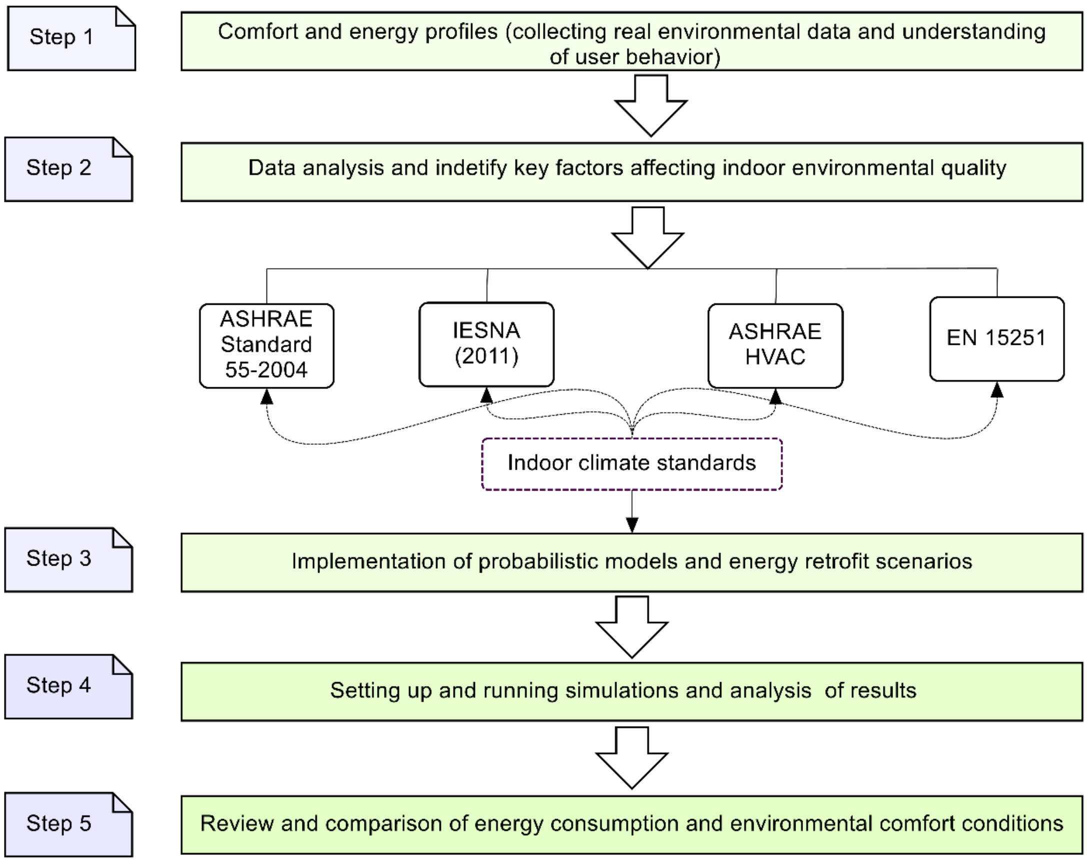


Figure 1.9: Research design methodology in relation to simulation process in case studies. Source: Author.

CHAPTER 2 ENVIRONMENTAL COMFORT MODEL

Rising energy costs and consumption in recent years, especially in buildings, have led researchers to consider new methods and approaches for reducing energy use. The building sector accounts for about 40% of total energy consumption and 38% of the CO_2 emissions in the U.S. [1] and the commercial and residential building sector account for 38.7% of the total energy consumption in Europe [2]. Energy efficiency in buildings nowadays has become a prime objective for energy policy at regional, national, and international levels [3].

Energy awareness programs have proven that they can lead to a reduction exceeding 10% of the energy demand in a work environment [4]. With the increasing energy crisis, energy management systems (EMSs) are considered as a real need. Furthermore, rising energy prices and the need to obtain detailed information about energy use has increased the importance of the EMSs. The proper distribution of HVAC systems and the supply of comfort conditions throughout occupied spaces are the most fundamental topics in energy management systems (EMSs).

In order to develop environmental comfort models with low energy consumption, especially in the workplaces, it is important to focus on strategies which provide better control of environmental conditions and create a comfortable workplace. There are many technologies that can be used to provide well-being conditions, but individual comfort systems have not been sufficiently taken into account in the buildings. User comfort and satisfaction should be considered as the most significant factors for individual comfort controls. However, in order to ensure that workplaces meet user needs, the main categories of environmental comfort such as physical, functional and psychological comfort should be included in the guidelines (Figure 2.1).

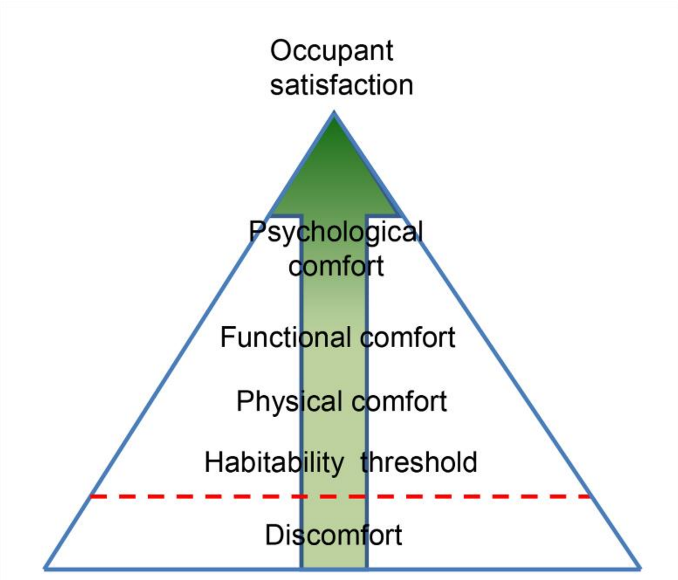


Figure 2.1: Environmental comfort model of workspace quality [5].

2.1 Environmental Control Systems

Improving indoor environmental quality at lower energy consumption has received considerable attention in recent years, with special emphasis on the use of advanced control methods for managing IEQ and energy use [6]. It is widely known that environmental control systems (ECSs) help to maintain the desired indoor environmental conditions. They also play an important role in making smart environments. It can be noted that the technological evolution in the field of environmental control systems has led to ongoing improvements in the indoor environment. For example, a smart control system can adjust automatically the air conditioners according to user needs and ensures the optimum temperature throughout a space. In fact, environmental control systems (ECSs) are solutions that assess and measure indoor conditions which can result in considerable energy savings. The main objective of environmental control systems (ECSs) is to minimize energy consumptions. Furthermore, environmental control systems (ECSs) are considered essential for enabling adaptive infrastructures. They can affect not only user comfort and indoor air quality (IAQ) but also potentially influence safety and security controls.

However, it is clear that conventional heating, ventilation, and air conditioning (HVAC) systems are unable to meet the needs of individual users. They are controlled and monitored separately which leads to higher prices and low performance. Furthermore, they often cannot communicate effectively with the system controllers and are not adequate to meet the needs of buildings. In the field of smart buildings, environmental control systems (ECSs) include a broad range of digital communications technologies which provide an opportunity to move from centralized to distributed control. In this respect, distributed control systems (DCSs) have become advanced tools useful in reducing costs in many situations. These are more flexible control systems and are used in various industries to monitor and control distributed applications. Furthermore, in order to optimize individual comfort in buildings, distributed environmental control systems have a significant impact on the process output.

Nowadays, real-time control (RTC) strategies are widely used in buildings. A real-time control (RTC) system (on-line optimization) provides efficient solutions for controlling complex environmental systems and is a suitable alternative to conventional methods. It has also become an accepted technique to control sensors-based systems in the context of large-scale automation. From an architecture and construction point of view, real-time control (RTC) can be particularly useful in optimizing device settings in accordance with standards. However, it should be noted that user satisfaction is a key performance indicator to evaluate the effectiveness of environmental control systems (ECSs). Therefore, the results of user satisfaction measurement should be used as the basis to analyze the performance of environmental control systems (ECSs).

2.1.1 User satisfaction

Buildings enable their users to work, play, meet, shop, sleep, eat, socialize, educate, and learn and a host of related activities. Consequently one of the performance criteria of a building should be how well it succeeds in satisfying its users. This involves their comfort, both physically and psychologically. The physical aspect is straightforward involving thermal comfort, appropriate lighting for the users' activity, the user's control of the lighting and air distribution, the workspace layouts and the technology systems available to the users to make their tasks easier. The physiological effect may relate to the building's image, appearance and aesthetics and how it impacts a user's perception of their environment [7].

In order to investigate user satisfaction and its relationship with parameters of indoor environmental quality (IEQ), it is essential to understand environmental factors that influence user comfort in the built environment considering the fact that user satisfaction has been defined as an independent criterion for indoor environmental quality (IEQ). However, user satisfaction in office buildings is associated with indoor environmental quality (thermal, visual, acoustic environment and air quality) and workspace and building features including size, aesthetic appearance, furniture and cleanliness [8]. In this context, a number of studies have investigated the principal factors influencing user satisfaction (e.g. [9, 10, 11, 12, 13]). The following table shows result of their investigations.

Table 2.1: List of studies about users' satisfaction parameters.

Study	Occupants / Users	Users' satisfaction
Humphreys, 2005	4655 responses in 26 office buildings in 5 European countries	▪Warmth ▪Air quality ▪Air movement ▪Noise ▪Humidity ▪Light
Astolfi and Pellerey, 2008	852 students in a secondary school in Italy	▪Acoustic environment ▪Thermal environment ▪Visual environment ▪Air quality
Wong et al., 2008	293 occupants of office buildings in Hong Kong	▪Thermal environment ▪Air quality ▪Noise level ▪Illumination level
Lai et al., 2009	125 occupants in 32 residential apartments in Hong Kong	▪Thermal environment ▪Acoustics environment ▪Lighting environment ▪Air quality
Cao et al., 2011	500 occupants in 5 buildings in Beijing and Shanghai	▪Thermal environment ▪Acoustic environment ▪Luminous environment ▪Air quality

As can be seen from the above mentioned studies, thermal environment, lighting and acoustic are the three most important factors influencing user satisfaction. Furthermore, the literature survey conducted by Frontczak and Wargocki [14] suggests that user satisfaction can also be influenced by other variables "*unrelated to environmental quality, that influence whether indoor environments are considered to be comfortable or not*", such as features of the building and the workspace, personal characteristics of the users, and their work activities. According to a study by Wagner et al. [15] user satisfaction is defined as the individual perception of the thermal, visual and audible environment, the air quality at the workplace and the office layout.

In this respect, it can be useful to point out that post occupancy evaluation of IEQ not only provides an initial step towards investigating physical and operational attributes of building systems, but also helps to measure the impacts on user satisfaction in relation to indoor environmental factors. In fact, the indicator of user satisfaction reveals a very close relationship between the social aspects of sustainable development and technical, economic or financial considerations [16]. In other words, the evaluation of user perception and satisfaction forms a significant aspect of probing the indoor environmental quality within the workplace [17].

2.1.2 Individual comfort controls

It is important to emphasize that user behavior is one of the key factors which can be used in enhancing indoor environmental quality (IEQ) of workplace environments. Furthermore, user behavior can have a significant impact on building adaptive performance. Therefore, user adaptive behaviors are needed in order to support adaptive building systems. Adaptive behaviors include different reactions and behaviors that can be categorized into three types, which are as follows: 1) behavioral adaptation (adjustment), 2) physiological adaptation (acclimatization), and 3) psychological adaptation (habituation) [18]. It is obvious that users adjust themselves to maintain and improve their well-being through physiological, psychological and behavioral reactions to the environmental stimuli. The behavioral reactions can lead to actions such as switching heating or cooling on/off, opening/ closing windows or blinds, the putting-on/taking-off of clothes, switching lights on/off, etc., which are also influenced by user's expectations about their actions' effects [19]. In order to provide individual comfort controls on workplace level, environmental conditions, such as thermal environment, lighting, acoustics and air quality which mostly affect user satisfaction, should be taken into account.

Although, air distribution systems can provide individual comfort control, they may consume more energy than a conventional system. Therefore, individual comfort controls are needed to incorporate user behaviors in order to reduce energy consumption and environmental impacts. However, due to variances in personal factors and behavior patterns, individual comfort levels may be different.

For example, in relation to individual thermal comfort, Lian et al. [20] indicate that in general, different individuals have different scales of thermal comfort due to physiological difference and variety of subjective sensation. In a comfortable thermal environment (based on the thermal comfort evaluation for most users), a user may still feel uncomfortable. In order to reduce these problems, individual comfort controls allow users to control environmental conditions in space or zone, individually and this can lead to improvement in thermal comfort. From an individual microclimate point of view, to achieve a comfort zone, users of the workplace need to monitor different environmental conditions. Therefore, it is of importance to understand the comfort needs of individuals and energy demands on workplace level. It might also be worth noting that function decomposition at workplace conditions can help develop individual microclimate control techniques in the process (Figure 2. 2).

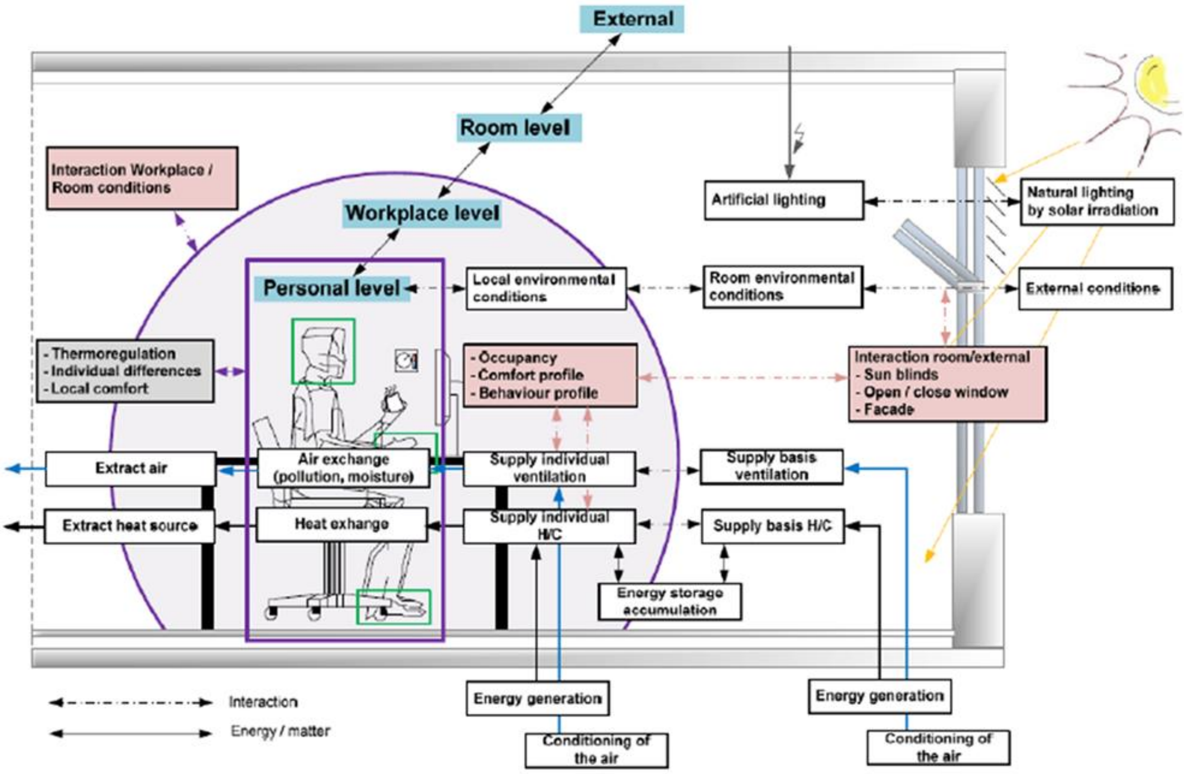


Figure 2.2: The function decomposition on the level of room, workplace and individual [21].

In this context, task/ambient conditioning (TAC) system is an alternative method to provide users with control of a local supply of air so that they can adjust their individual thermal environment. It can be defined as any space conditioning system that allows thermal conditions in small, localized zones (e.g., regularly occupied work locations) to be individually controlled by building users, while still automatically maintaining acceptable environmental conditions in the ambient space of the building (e.g., corridors, open-use space, and other areas outside of regularly occupied work space) [22].

From an energy efficiency point of view, individual control of temperature may be a practical means to improve user comfort and reduce energy consumption. It is clear the main aim of comfort control in the workplace, is adaptation to ambient environmental conditions. In this regard, it is possible to claim that users should adjust ambient environmental conditions to maintain personal comfort levels. In order to meet infrastructure requirements and individual user needs, a number of technologies and applications have been developed. One example of efficient applications is the Nest thermostat (Figure 2.3). In this approach application, individuals are given the chance to control environmental conditions within their local environment.

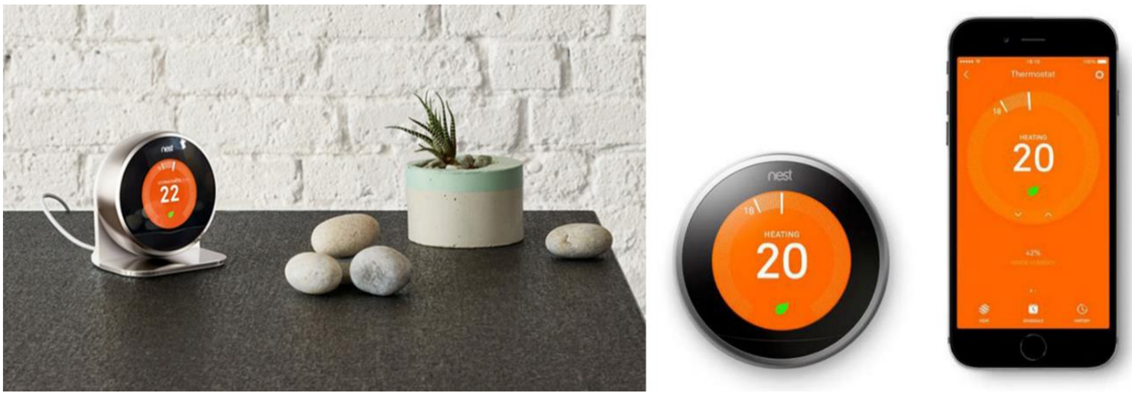


Figure 2.3: Some examples of Nest technologies [23].

2.1.3 Adaptive comfort model

In the last decade, the adaptive comfort theory has become a fundamental tool for evaluating thermal performance in buildings, most notably in the naturally ventilated and low energy design sector [24].The fundamental assumption of the adaptive approach is expressed by the adaptive principle: *if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort* [25]. According to Fabi et al. [26], the adaptive approach is based on the notion that the users' level of adaptation and expectation is strongly related to outdoor climatic conditions: in this way, at the base of adaptive model of comfort is the belief that the users consciously or unconsciously, play an active role in realizing indoor environmental conditions. In this regard, the adaptive model provides greater flexibility, especially for naturally ventilated buildings, in matching optimal indoor temperatures with outdoor climate [27].

Adaptive model of thermal comfort is one of the most important objectives of indoor environmental quality (IEQ). It is also one of the essential aspects of user satisfaction and energy consumption. Thermal comfort model was first presented by Fanger [28]. In the field of thermal comfort, Fanger's predicted mean vote (PMV) and Fanger's predicted percentage dissatisfied (PPD) are the basis of the most important indoor climate standards in Europe, ISO 7730-2005 (ISO 2005) and America, ANSI/ ASHRAE standard 55-2004 [29,30]. In this context, a number of studies have been carried out to analyze user satisfaction and preference in order to address the application of the adaptive approach to thermal comfort model [31, 32, 33, 34] .

The adaptive models are based on adaptive opportunities of users and are related to options of personal control of the indoor climate and psychology and performance [35]. Therefore, it is important that users are aware of which environmental conditions have the most impact on energy use and thermal comfort relative to the others. In the field studies of thermal comfort, adaptive comfort standard proposed by Dear and Brager [36] for ASHRAE standard 55-2004 is still widely used for naturally ventilated buildings (Figure 2.4). It allows warmer indoor temperatures for naturally ventilated buildings during summer. In fact, this comfort model can be applicable to buildings in which users control operable windows. Furthermore, it includes a regression equation that relates the neutral temperature indoors to the monthly average temperature outdoors.

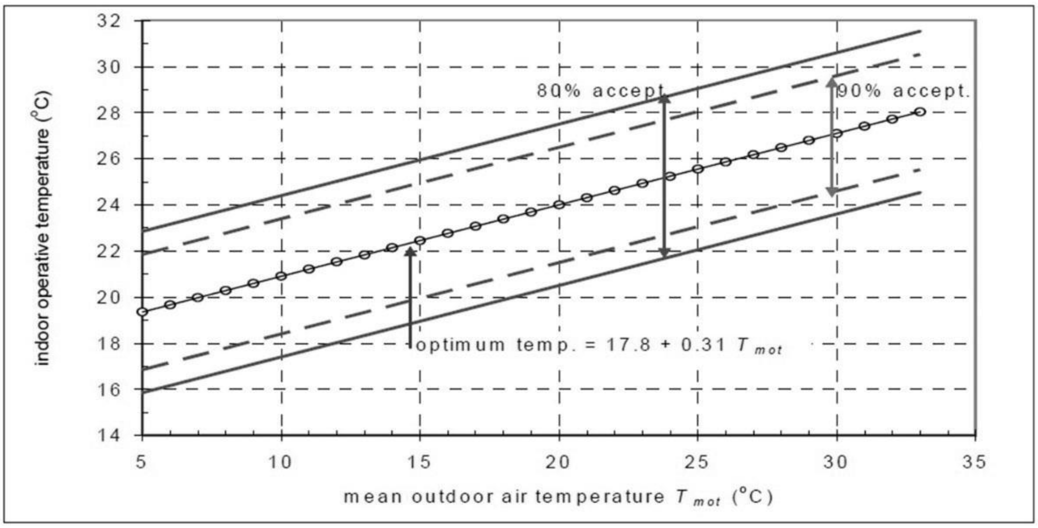


Figure 2.4: The adaptive comfort model used in ASHRAE standard 55-2004 [36]

However, due to lack of prompt response of users, the adaptive model can be associated with a delay. Therefore, it is important to develop systems that encourage information flow between users and building managers for promoting adaptive comfort models. It is a fact that adaptive comfort models can, not only have an effect in reducing total energy consumption, but also can maintain constant conditions for users. Furthermore, adaptive models are advantageous to energy decisions, particularly for specifying building temperature set points. In this respect, it is important to point out that the possibility of users to interference in the process control should be easy and flexible and can directly impact on user satisfaction, productivity and overall energy efficiency of the buildings.

Although buildings allow for fewer possibilities of individual control systems, they may provide opportunities for enhancing user interactions with environmental controls. Accordingly, users will be able to adjust the indoor climate based on their needs and expectations and to learn how to use adaptive comfort models.

2.2. Process Control Systems

Building process control is essential to maintain optimum environmental conditions. Nowadays, process control systems play a central role in monitoring and managing building operations. In particular, process control systems are necessary for enabling energy-efficient operations in smart buildings. They include various systems, such as field instruments, actuators, controllers and PID loops. In fact, process control systems are the means of controlling actuators based on data received from measurements (Figure 2.5). It is obvious that control of indoor comfort conditions is one of the most important steps in process building management systems. In order to make better use of building systems, it is important to integrate strategies through appropriate process control. For example, the performance of a building system can be improved by changing manual modes to adaptive modes which can result in energy efficiency and energy saving.

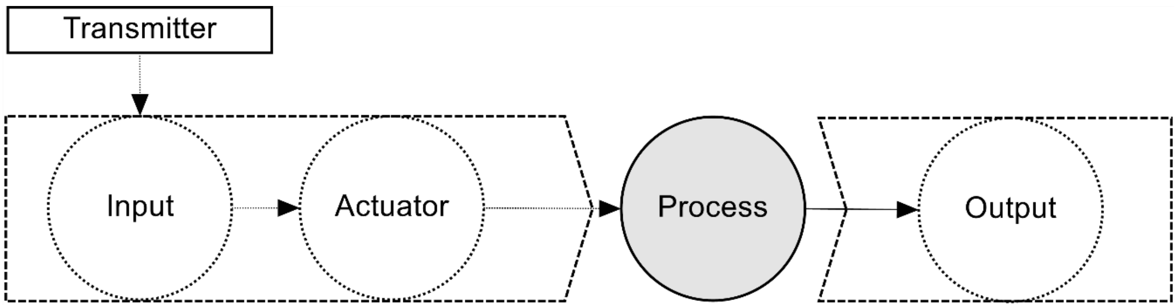


Figure 2.5: Illustration of a basic process control. Source: Author.

In order to reduce and control operating costs, smart control has become an effective necessity. Smart control can provide a deeper insight into process control and data monitoring and can be used for enabling economic growth and sustainable development. To achieve these goals, development of a smart approach is needed as the first step. In this context, the benefits of information and communications technologies (ICTs), sensors and algorithms are clear for promoting and achieving goals. For example, the smart control and thermal comfort project (SCAT), promoted by the European Commission aims to reduce energy use in air conditioning systems by varying indoor temperature through the use of an “adaptive algorithm” [37] . Furthermore, smart control can significantly accelerate the execution of process and reduce controls expenditure. It is obvious that process control is a complex discipline to evaluate and optimize systems such as the cooling/heating units, building ventilation systems and lighting control systems, but it can help to detect efficiencies and flexibility initiatives. In fact, smart controls are designed to create a sustainable operating model for controls.

2.2.1 Definition of smart building systems

Recent development and technologies in the domain of architecture, engineering and construction, have led to the emergence of so-called smart buildings and cities. Smart buildings are defined as buildings that should be sustainable, healthy, technologically aware, meet the needs of occupants and business, flexible and adaptable to deal with change [38]. The word “intelligent” was first used at the beginning of the 1980s to describe buildings, together with the American word “smart” [39] . In another definition of smart buildings, they are more efficient, comfortable, healthy, environmentally friendly, and economic. Achievement of desired indoor comfort conditions is one of the most important goals of smart buildings. In particular, control of environmental parameters plays a crucial role in providing indoor environmental quality (IEQ) and further opportunities for energy efficiency. Information and communications technology (ICT) can be a significant driving force for measuring and controlling indoor and outdoor conditions. It also can enhance management systems, energy savings, individual control systems and opportunities for real-time energy consumption data.

In fact, smart building systems offer certain facilities and comfortable conditions for users. For example, they can continuously adapt to variable environments, and also allow the end-users to use existing resources more effectively. In this context, smart building systems are managed in conjunction with each other and can lead to safety and security (Figure 2.6). They provide a dynamic environment through management systems and user interfaces. Smart building systems can not only adjust lighting and HVAC flows but also provide fire alarm and mass notification during an emergency situation. Furthermore, facility management system (FMS) is a principal system of a smart building that supports operations and performance processes.

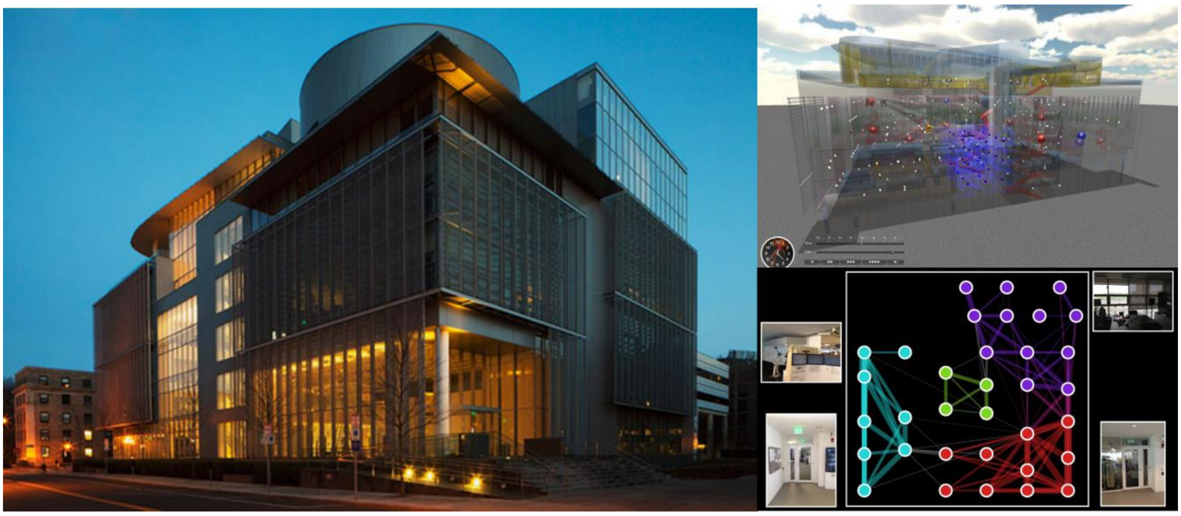


Figure 2.6: MIT Media Lab’s Joseph Paradiso [40].

2.2.2 Energy management systems (EMSs)

Nowadays, energy has become an increasingly important issue in the built environment. In order to use energy more efficiently, energy management systems (EMSs) can help identify saving opportunities and approaches. These systems can also significantly reduce energy consumption through an efficient control process which result in an increase in building energy performance. In fact, energy management system (EMS) is an advanced system which offers services oriented to monitor, control and manage. It is also capable of responding in real-time to devices in demand and provides significant potential for smart buildings and cities. In other words, energy management system is the framework of processes that can be used to achieve energy goals.

ISO 50001 – energy management systems (EMSs) is one of ISO standards that focuses on the management of energy in any infrastructure (large or small). Implementation of this standard can help building systems in reducing energy use through the utilization of best practices, measurement and reporting disciplines. Furthermore, it can reduce energy costs, greenhouse gas emissions and environmental problems. In fact, ISO 50001 follows the plan-do-check-act process of ISO 9001 and ISO 1400. It provides a framework for enhancing energy efficiency throughout the supply chain and implements energy management action plans. The figure below shows a schematic diagram of an energy management system (EMS).

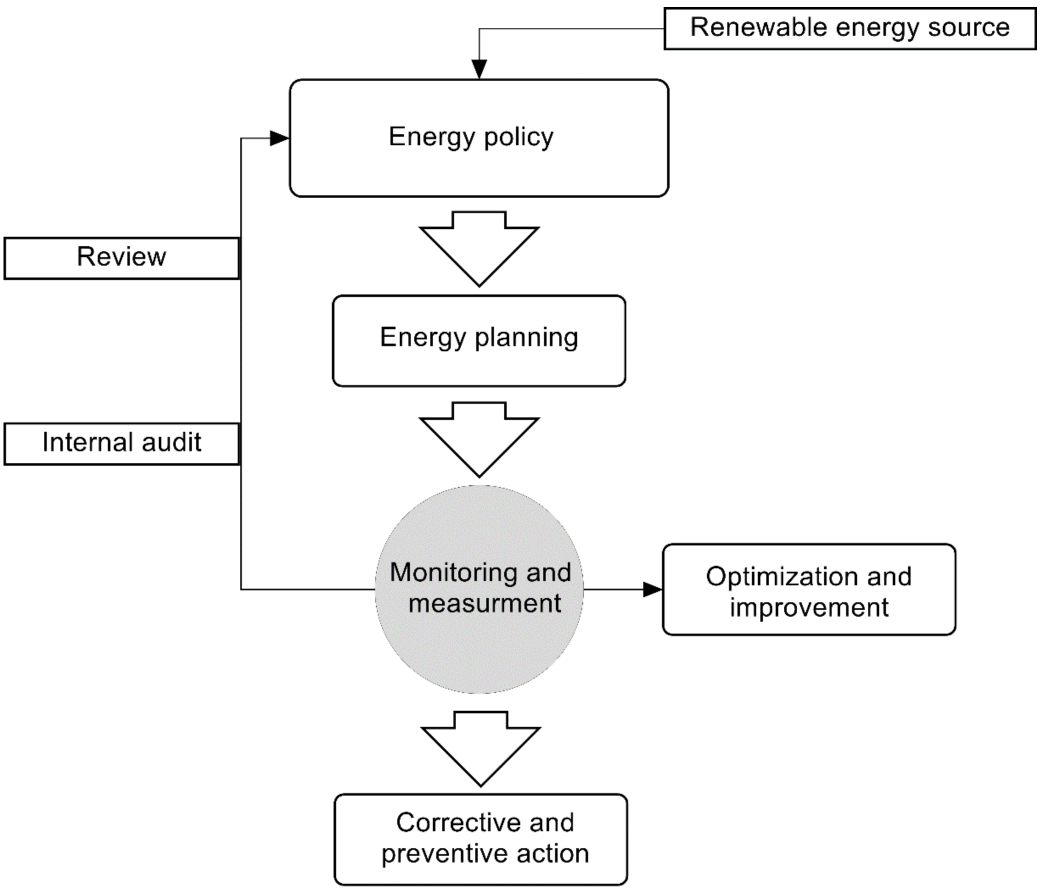


Figure 2.7: A schematic diagram of an energy management system. Source: Author.

2.2.3 Agent-based control systems

In order to increase energy efficiency for building energy management, agent-based control system has emerged as a vital solution. Furthermore, it has proved an efficient method in the building automation field due to its ability to deal with complex systems.
Within the contexts of smart buildings and cities, the concepts of agents and multi-agent systems (MASs) are very widespread (Figure 2.8). They are capable of independent action and mutual interaction. On the other hand, they are under user supervision and this flexibility can contribute to the achievement of objectives. Multi-agent systems (MASs) are called autonomous agents and are based on logic, neural networks and genetic algorithms. Currently, multi-agent systems (MASs) are increasingly being used in the field of smart grid research projects. They also are used in several application areas such as manufacturing and process control.

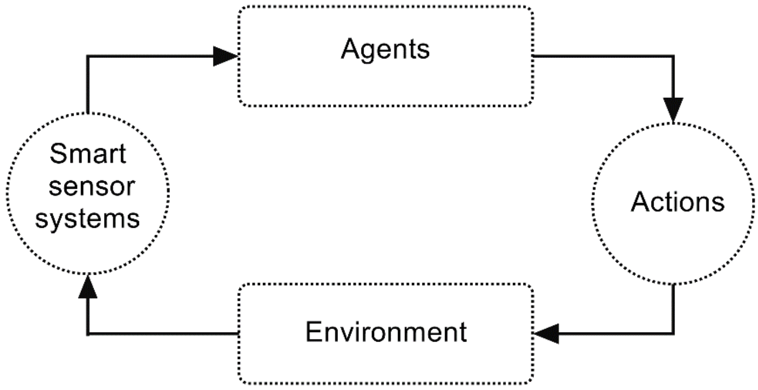


Figure 2.8: A schematic diagram of connections between agents and environment.
Source: Author.

In the context of smart buildings, the configuration of multi-agent control systems can aim to provide useful tools for environmental control. In this respect, there are many types of agents, such as personal comfort (PC) agents, room agents, environmental parameter (EP) agents and badge system agent (BSA) in the MASs that affect many aspects of smart buildings.

Although it is clear that multi-agent systems have gained increasing attention in smart buildings, they are still not adjusted according to behavior or feedback of users. However, in order to adapt to different user needs, multi-agent control systems should include learning capabilities related to users' behavior. In other words, they are capable of adjusting building environmental systems to meet user preferences, but cannot be adapted according to user behavior. Therefore, the ability to learn and predict users' behavior should be the main objective of multi-agent control systems. To improve the decision making process, learning algorithms can be embedded in the systems in a completely unsupervised manner. Furthermore, learning by user feedback and interaction can effectively improve the performance of multi-agent control systems and provide opportunities to improve smart building energy management.

2.3 Process Control on Workplace Level

As mentioned before, it is important to explore innovative solutions to improve energy efficiency and comfort in the workplace. Therefore, it is necessary to understand the process controls of the key factors affecting user satisfaction on workplace level. It is widely known that the environmental systems (HVAC), lighting (daylight and electric) and acoustics play important roles in the indoor built environment. However, in order to have more efficient performance in the systems, it is essential to use control strategies.

2.3.1 HVAC system control

Heating, ventilation, and air conditioning (HVAC) systems cause significant energy consumption in the buildings. According to Zavala et al. [41] optimal control of HVAC system can achieve energy savings of up to 45%. Therefore, efficient control strategies should be developed for HVAC systems in order to achieve cost-effective energy savings. Several studies have shown that some faults can increase building primary energy consumption and HVAC energy usage (Table 2.2). It is clear that including advanced control strategies can have a major impact in reducing energy consumption and technical faults. It is expected that more sophisticated algorithms and methods will be added as a higher level of hierarchical control using simulation models and numerical methods [42].

Table 2.2: The annual energy impact of faults selected for evaluation by Roth et al. [43].

Fault	Fault type	By percentage	Annual energy consumption [quads]
Duct leakage	Air distribution	30%	0.3
HVAC left on when space unoccupied	HVAC	2%	0.2
Lights left on when space unoccupied	Lighting	18%	0.18
Airflow not balanced	Air distribution	7%	0.07
Improper refrigerant change	Refrigeration circuits	7%	0.07
Dampers not working properly	Air distribution	6%	0.055
Insufficient evaporator airflow	Air distribution	4%	0.035
Improper controls setup/commissioning	Controls	2%	0.023
Control component failure or degradation	Controls	2%	0.023
Software programing error	Controls	1%	0.012
Improper controls hardware installation	Controls	1%	0.01
Air-cooled condenser fouling	Refrigeration circuits	1%	0.008
Valve leakage	Waterside issues	1%	0.007
Total	-	100%	1

2.3.2 Efficient light control

Light control and light-harvesting are the most important strategies that significantly enhance both energy efficiency and indoor environmental quality (IEQ). It is important to note that lighting control can not only improve user comfort but also reduce energy consumption. It also represents a significant contribution to energy efficiency.

The achievement of visual comfort is one of the most challenging tasks in the analysis of indoor conditions. Lighting level and illuminance are the major criteria that should be considered in order to enhance visual comfort in buildings especially at the workplaces. Lighting level and illuminance are dependent upon building orientation, daylight availability and season. However, details of the recommended illuminance values for buildings can be found in different national recommendations and standards. For example, SLL (Society of Light and Lighting) [44], CIBSE (Chartered Institution of Building Services Engineers) which involves LG3 (CIBSE Lighting Guide LG3: The visual environment for display screen use) and LG7 (CIBSE Lighting Guide 7: Lighting for Offices) [45] and IESNA (Illuminating Engineering Society of North America) [46] provide detailed horizontal and vertical illumination level recommendations for buildings. The following table presents a comparison of some current standards and recommendations.

Table 2.3: Comparison of standards and recommendation regarding office buildings. Source: Author.

Lighting purpose	Recommended range of illuminance (Lux)		
Office	IESNA (2011)	CIBSE (2005)	SLL (2012) / EN 12464-1
Workplace-offices	400	500	500
Conference and meeting rooms	300	500	500
	Limiting glare rating		
	IESNA (2011)	CIBSE (2005)	SLL (2012) / EN 12464-1
Workplace-offices		19	19
Conference and meeting rooms		19	19

In this context, illumination levels for most office buildings are assessed based on horizontal daylight illumination at the work plane about 800 mm above floor. According to standards horizontal illuminance of 500 lx is necessary for workplaces in office buildings.

Furthermore, in order to ensure visual performance and lighting comfort, glare control should be taken into consideration.

The daylight factor (DF) is the most widely applied metric used to assess daylight sufficiency based on this measure [47]. The daylight factor is defined as the ratio of the internal illuminance at a point in a building to the unshaded, external horizontal illuminance under a CIE overcast sky, [48] where an average DF of 2% across a given space is commonly considered to constitute sufficient daylight [49]. There are several studies that have been conducted on this topic to present performance based on the work plane illuminance metric such as daylight autonomy (DA) by Reinhart in 2001[50], useful daylight illuminance (UDI) conceived by Mardaljevic and Nabil in 2005 [47],and continuous daylight autonomy (CDA) conceived by Rogers in 2006 [51] (Figure 2.9).

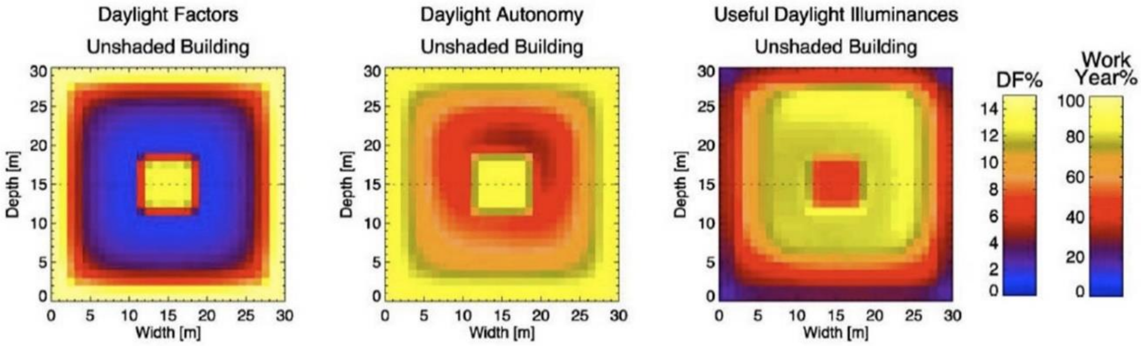


Figure 2.9: Daylight factor (DF), daylight autonomy (DA), and useful daylight illuminance (UDI) area plots for a generic building [47].

Daylight autonomy (DA), uses work plane illuminance as an indicator of whether there is sufficient daylight in a space to allow an occupant to work by daylight alone. Useful daylight illuminance (UDI) is an attempt to integrate the evaluation of daylight level and glare in one scheme. According to Nabil and Mardaljevic [47], UDI is defined as the annual occurrence of illuminance across the work plane that are within a range considered "useful" by occupants. Continuous daylight autonomy (DA_{con}), recently proposed by Rogers [51], is another set of metrics that resulted from research on classrooms.

In this context, leadership in energy and environmental design (LEED) v4 has released updates in relation to daylighting credit through which illumination calculations at desired points through the year can be considered. The prescriptive option based on a ratio of window space to floor space in previous versions of the LEED rating system has been eliminated in favor of a new performance metric based spatial daylight autonomy (sDA). The new criteria is $sDA_{(300/50\%)}$, which means that calculation points in regularly occupied areas have 300 lux or more 50% of the time. In this credit spatial daylight autonomy (sDA) is the percentage of the "work plane" above 300 lux (28 foot-candles) at least 50% of the time during occupied hours over the course of a whole year.

● **Shading devices**

Shading device can play a key factor in achieving quality indoor environment in terms daylight, thermal comfort, control solar heat gains and reduce glare (Figure 2.10). Shading devices have the potential to reduce peak cooling load and annual energy consumption so that they can control solar gain in achieving good indoor environmental quality (IEQ). Consequently, an adaptable shading device meet user, thermal and visual comfort requirements.

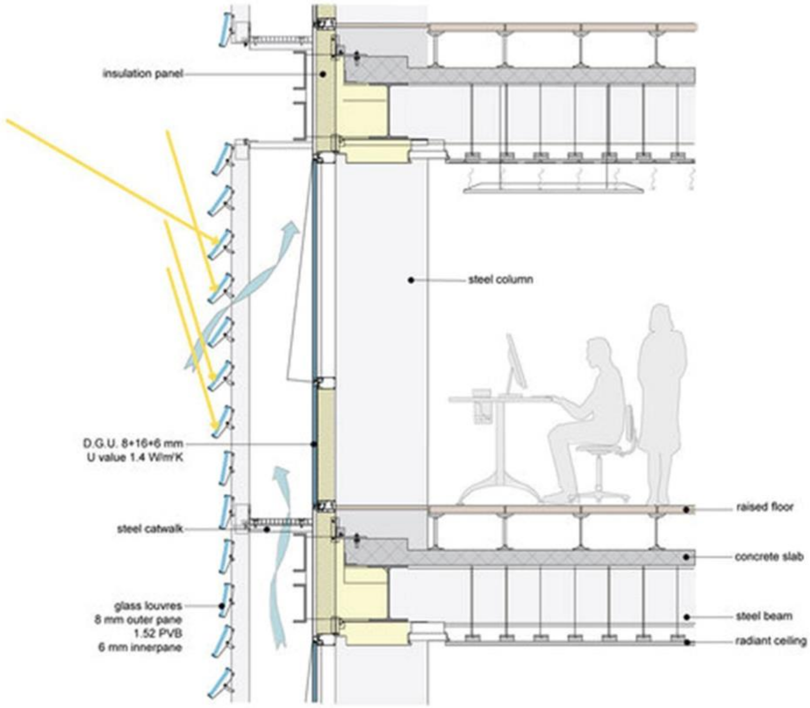


Figure 2.10: An example of a moveable exterior shading device [52].

In this context, David et al. [53] introduce techniques to assess effect of solar shading on illumination levels. The aim of their study was to investigate the relationship between some simplified performance indicators of thermal and visual comfort, i.e. the solar shading coefficient, cooling energy demand, daylight autonomy and sun patch index on work plane. In their study they show that the number of blades in the shading devices present the different useful daylight luminance in the proposed building. For instance, from 0 to 3 blades, the useful daylight illuminance is greater than 80%, from four and five blades is near to 40% and for more than 5 blades, the useful daylight illuminance is below 20%. The implications of the study are that it is not necessary to overprotect the window with a louver that experiences more than 5 blades which would reduce significantly visual comfort from daylighting without improving the efficacy of the solar protection [53].Therefore, in order to meet user requirements and indoor environmental quality (IEQ) at the same time, it is necessary to implement appropriate shading devices into buildings. The following figure represents louvers dimensional characteristics assessed by David et al.

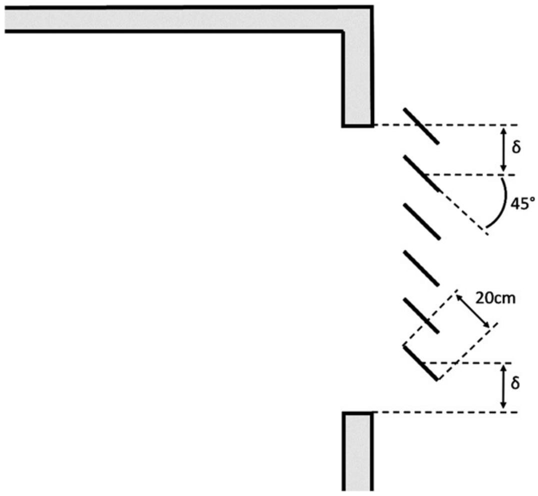


Figure 2.11: Louvers dimensional characteristics of shading device assessed by David et al. [53].

● **Electric lighting control**

Electric lights are an important part of building energy consumption in buildings. Analysis of the energy consumption buildings regarding electric lighting has shown that daylighting can be a good substitute for electric lighting and can be used as an energy-efficient solution to reduce considerable amounts of energy in the buildings. Although, daylighting can provide a considerable amount of users' needs in terms of lighting, it is not always possible to get the daylight to building interiors. Therefore, electric lighting must be provided in the buildings. It is clear that the amount of energy consumed by lighting systems need to be controlled. Nowadays, many studies have stated that smart control systems can be considered as innovative solutions compared to traditional methods. There are several examples of smart lighting controls for indoor environment such as systems based on the mathematical model, fuzzy control, adaptive control , etc. which can reduce electricity consumption for lighting systems.

According to Dubois and Blomsterberg [54], in order to achieve a "nearly zero or zero energy building" label, it is necessary to implement intelligent control systems and energy efficient technologies based on sensors and actuators. In this regard, the generation of smart light control systems aim to provide a comfortable environment while reducing energy consumption [55]. For example, wireless lighting control systems provide easier approaches for deploying effective lighting plans. They provide a cost-effective solution for switching off unnecessary electric lights to avoid usage energy. Furthermore, these systems play a key role in sensing information regarding occupancy and daylight. The following figure shows examples of smart lighting control systems that track the position of the building occupant by wireless to control lighting, and a microwave detector for the automatic control of lighting, heating and ventilation.

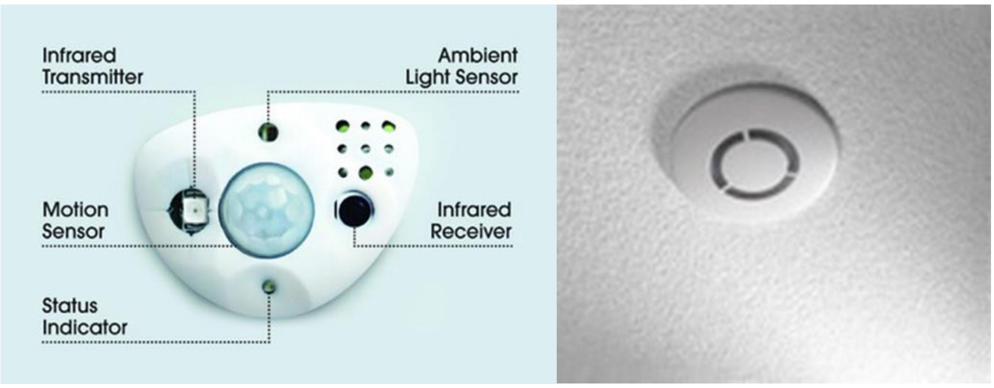


Figure 2.12: Intelligence-based lighting control (left) and microwave detector (right) [56].

It is possible to assert that energy efficient lighting systems not only reduce energy consumption but improve the indoor environment. Their performance depends on several factors such as lighting power density (LPD) values, high-efficiency equipment, lamps, luminaries and the appropriate light controller. Furthermore, it is important to consider power requirements for lighting systems. For instance, standards such as ASHRAE/IES 90.1-2010 [57] and LENI. Lighting energy numeric indicator (LENI) EN 15193 [58] have determined the limits on the amount of lighting power installed in the building as (W/ ft^2) and (W/m^2). In this regard, LENI (Lighting Energy Numeric Indicator) calculates the contribution of light to the overall energy consumption of a building as the following equation:

LENI = Energy Consumption for lighting / Square meter per year (in kWh/m2/a)

The following table shows lighting power density (LPD) value for office building functional according to ASHRAE/IES 90.1 and EN-15193 standards.

Table 2.4: Lighting power density (LPD) values from ASHRAE 90.1 [57] and EN-15193 [58].

Building type	Maximum lighting power density (W/ ft2.) ASHRAE/IES 90.1 standard	Maximum lighting power density (W/m2) EN-15193
Office	0.90	10

However in order to provide energy efficient lighting systems, lighting power density (LPD) should be limited. For example, in the European standard EN15193 there are limits to the LPD. For large office rooms (>12 m^2), this standard recommends an installed LPD under 12 W/m^2 with preferable target under 10 W/m^2 (Table2.5). Furthermore, several LPDs and reduction factors for a single office have been defined based on manual lighting control with manual on/off and occupancy control. In this regard, an annual time of usage of 2500 hours has been assumed. As can be seen in Table 2.5, a combination of occupancy sensors and daylight control provides the lowest energy intensity values.

It is clear that low LPD's and lighting control systems such as manual, switch on/off, dimming, etc. are required to comply with the energy requirements. However, it is possible to achieve energy savings for lighting control systems depending on control strategy with existing smart systems management.

Table 2.5: Guidelines for installed LPD (W/m^2), reduction factors and LENI (kWh/m^2 yr) [58].

Type of room	LPD (W/m^2)	Reduction factor			LENI (kWh/m^{2}yr)		
		Manual control	Absence/ presence control	Daylight control	Manual control	Absence/ presence control	Daylight control
Individual office rooms (>10 m^2)							
Obl.	10	0.8	0.75	0.56	20	15	8
Pref.	8	0.8	0.75	0.56	16	12	7
Large office rooms (>12 m^2)							
Obl.	12	1	0.90	0.77	30	27	21
Pref.	10	1	0.90	0.77	25	23	17
Corridor							
Obl.	8	1	0.75	0.57	20	15	9
Pref.	6	1	0.75	0.57	15	11	6

Indoor lighting components consist of fluorescent tubes, tungsten halogen lamps, LED lamps, T-12 lamps, magnetic ballasts, etc. Currently, to assess and predict the lighting situation in buildings simulation programs such as Daysim /Radiance, EnergyPlus, etc. are being used. To perform these simulations, it may become necessary to consider interior lighting energy consumption (kWh, kWh/m^2), peak interior lighting load (W, kW), operational lighting energy (kWh/h), lighting energy share (%), etc. Furthermore, luminaire types and segmentation of luminaires should be defined properly for simulation models (Figure 2.13).

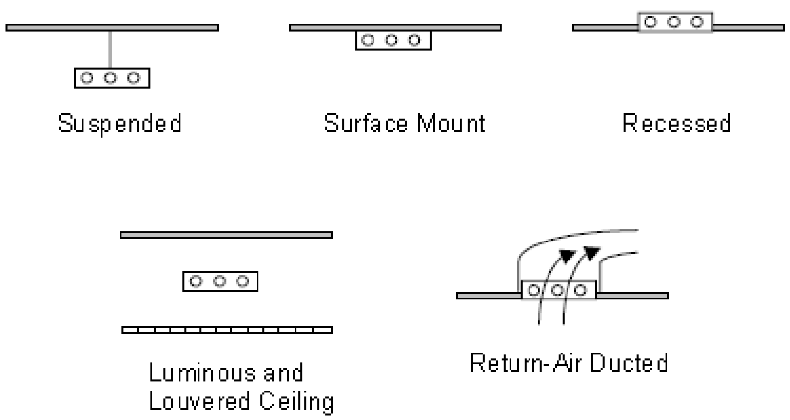


Figure 2.13: Different luminaire types [59].

In the context of lighting simulation programs, two types of control strategies such as continuous dimming control and step dimming are used. With continuous control, the overhead lights dim continuously and linearly from maximum electric power and stepped control allows users to switch lighting on/off according to the availability of natural daylight in discrete steps (Figure 2.14).

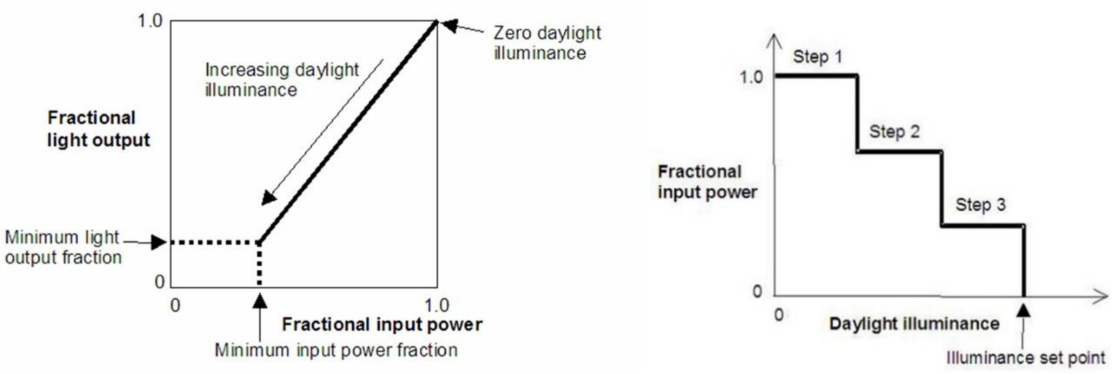
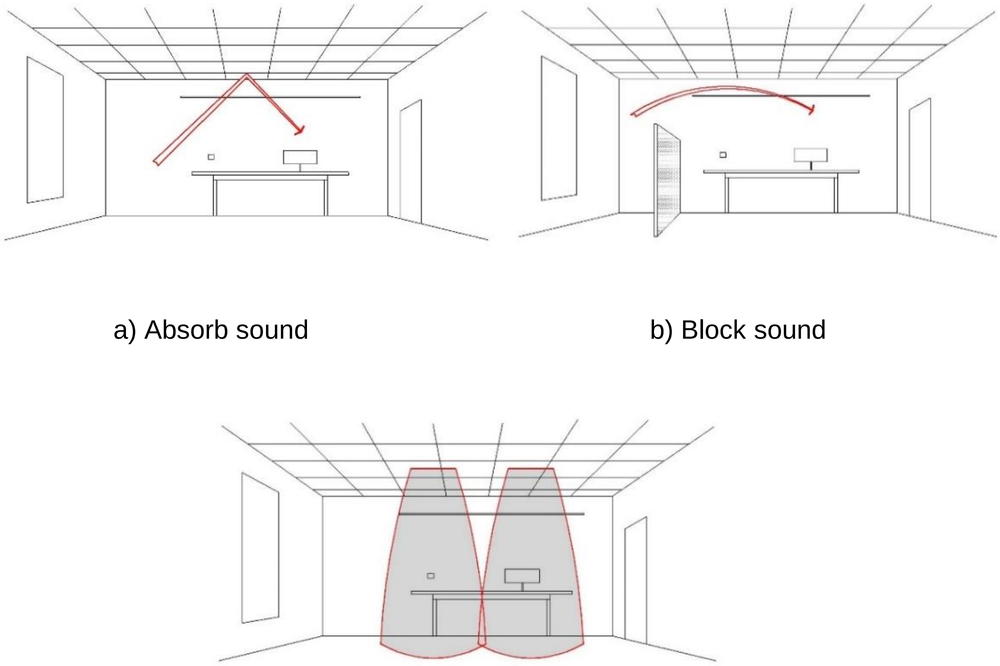


Figure 2.14: Illustrations of continuous and stepped controls [59].

2.3.3 Efficient acoustic control

Sound is one of the environmental factors that plays an important role in influencing user satisfaction especially in the workplace. It can also affect user's physical and psychological. To achieve significant sound reduction and acoustic comfort at the workplace, there are three main strategies which are as follows: absorb, block, and cover-up (Figure 2.15).These strategies can help create a comfortable work environment. In this regard, the selection of appropriate materials is one of the most important steps in the process of acoustic design and control. For example, an inappropriate acoustic material can lead to an uncomfortable environment. It is therefore necessary to consider appropriate acoustical materials.



a) Absorb sound

b) Block sound

c) Cover up sound

Figure 2.15: Illustrations of sound reduction through ABC strategies. Source: Author.

The U.S. general services administration recently published a comprehensive guide to acoustics in the workplace. According to this study, office acoustics is a key contributor to work performance and well-being in the workplace and acoustical comfort is achieved when the workplace provides appropriate acoustical support for interaction, confidentiality and concentrative work [60].

It is, however, obvious that the acoustical parameters such as reverberation time (RT), speech transmission index (STI) measurements and sound pressure level (SPL) need to be taken into account in evaluating the acoustical performance of space. Therefore, it is very important to use measurement approaches based upon these factors. The value of acceptable reverberation time of a workplace room is related directly to the size of room and amount of sound absorption used within rooms and working areas. The suggested time is between 0.5 and 0.8 seconds and should be minimized as much as possible. The values of the indicator of STI are accepted in the range between 0 and 1, where 1 indicates perfect intelligibility (EN ISO 9921) [61]. The value of sound pressure level (SPL) as $L_{Aeq,8h}$ should be less than 40 dB(A) in separate rooms/offices and be less than 45 dB(A) in open plan office [62].

The prediction of noise levels is an important step in improving the acoustic design of space. It also has a significant effect in determining desirability and sound quality. Noise criteria or NC curves and room criterion (RC) are two the most common standards to evaluate indoor noise and sound levels (Table 2.6). The range of these standards is from 63 to 8000 Hz octave band.

Table 2.6: Recommended criteria for indoor design RC or NC range [63].

Type of area	Recommended NC Level NC Curve	Equivalent Sound Level dBA
Office buildings		
Conference rooms	25-30	35-40
Private	30-35	40-45
Open-plan areas	35-40	45-50
Business machines/computers	40-45	50-55

It is of importance to mention that solutions to noise problems and acoustic comfort should be produced by analyzing the problem correctly alongside economical methods. Furthermore, evaluation of the acoustic properties of materials in the design stages should be targeted in terms of achieving indoor acoustic comfort. In this context, the sound insulating properties of building components should be designed in accordance with acoustical requirements. For example, the building envelope can be effective in reducing and absorbing sound energy by acting as a barrier to sound. Therefore, in order to investigate the effect of sound on the building envelope, it is necessary to determine the physical properties of sound absorption and insulation materials used in the building envelope.

CHAPTER 3 SMART SYSTEM SERVICES AND REFURBISHMENTS

Nowadays, there are a number of initiatives to provide guidance for building refurbishment. Even though building refurbishment is a complex process and there are challenges in incorporating the principles of energy efficiency and sustainability it can be practical and useful to develop concepts through smart systems to improve refurbishment processes. However, to investigate technical aspects of smart systems to reduce energy consumption and negative environmental impacts, it is essential to address their benefits and potentials.

3.1 Development of Smart Systems

Smart systems have a great effect on architecture in so far as they can manage several devices in buildings and cities. In this regard, smart management systems which include smart sensor systems, actuating systems, smart control systems and advanced sensory systems have the potential to cope with challenges of sustainable development in the built environment, but these have not yet been used in a fully operational. For example, smart sensor systems are being used to monitor and measure energy performance in buildings but they are not able to provide user behavior characteristics in relation to energy use directly.

However, smart sensor systems record reliable information on indoor environmental parameters; provide advice for the users to adjust their behavior, and enable optimum control for the services systems responsible for the energy management system in the building. Furthermore, the smart sensor systems supply multiple environmental and user information in real-time to enable control strategies based on multiple factors [64].

Smart systems are described as integrated systems which are able to: 1) sense and diagnose a situation and describe it, 2) mutually address and identify each other, 3) predict and decide, 4) operate in a discreet, ubiquitous and quasi-invisible manner, 5) utilize properties of materials, components or processes in an innovative way to achieve greater performance and new functionalities 6) interface, interact, and communicate with the environment and with other smart systems, and 7) perform multiple tasks and assist the user in different activities [65].

3.1.1 Environmental monitoring sensors

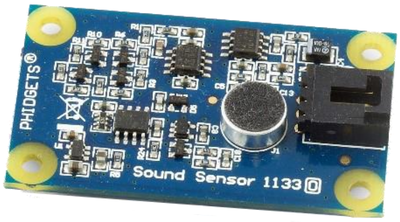
Smart sensors systems across several industries have played key roles in controlling and monitoring. For instance in the area of energy and building automation, smart sensors systems can track and monitor occupancy in real-time or offline position which can help develop sustainable mobility and smart energy profiles. Interaction of smart sensors systems with their environment is not always consistent, sometimes due to weather conditions or technical problems, they do not have the necessary capacity to yield information. However, embedded sensors on the built environment can contribute to the development of energy efficient systems.

In the domain of smart buildings, there are many examples of sensors that can monitor indoor temperature, humidity, CO_2 concentration, light, sound, motion , etc. (Tables 3.1 and 3.2). They not only measure environmental factors but also help users to understand their environment conditions. For example, Hailemariam et al. [66] developed an occupancy detection system that used light sensors, motion sensors, CO_2 sensors, and sound sensors. They embed a number of low-cost sensors of different types into the cubicle furniture to deduce the occupancy of the workspace at any given time and achieved an accuracy of 98.4% for using the motion sensor alone. In this context, it is worth mentioning that both the energy management and air quality monitoring paradigms are changing rapidly due to advances in the development of portable, low or medium cost sensors [67].

Table 3.1: Examples of IAQ and light sensors used in the buildings [68].

Indoor Air Quality sensors		Light sensors	
Sensor types		Sensor types	
Temperature		Lighting controls and integrated occupancy sensor	
RH meter		Lighting controls and Integrated daylight sensor	
CO_2 meter		Lighting controls and smart scheduling occupancy/ vacancy detection	

Table 3.2: Examples of sound level sensors used in the buildings [69, 70, 71].

Sound level sensors	
Sensor types	
Sound level sensor: By means of this device the ambient noise in a zone is measured and the masking sound level is adjusted based on this measurement. Source: [69]	
Sound level sensor: Detects sounds with frequency between 100 Hz and 8kHz and measures sound pressure level between 50dB to 100 dB. Source: [70]	
Temperature/Sound level/ Light sensor: This sensor can conduct all three measurements simultaneously and continuously. Source: [71]	

As mentioned before, smart sensor systems have a significant impact on the building sector, particularly in terms of providing a comfortable indoor environment. In addition, they offer low-cost environmental monitoring and can be installed individually. However, the implementation of multiple simultaneous sensors into buildings is still a complex process.

It is obvious that the combination of sensors installed in single device can be practical and useful. For instance, the National Research Council Canada (Newsham et al. [72]) has designed two different types of indoor measurement devices with environmental sensors referred as NICE Cart (National Research Council Indoor Climate Evaluator) and the Pyramids (Figure 3.1). In their study, they used the NICE cart to collect data at all possible occupant locations in the building as well as the pyramids to collect a subset of the parameters collected by the cart but at a fixed location. In fact, data collection from the sensors was semi-automated via software controlled by the researcher. In this context, Heinzerling et al. [73] indicate that these devices represent a wide range of abilities and size. Carts are primarily useful for their ability to move multiple sensors around a space, to have multiple wired sensors log to one location, and to keep sensors steady for the measurement period. With the advent of wireless sensors, this restriction of keeping sensors together is lifted. For example, wireless sensor network (WSN) is one of the devices that can monitor factors like mean air temperature, relative humidity and CO_2 concentration and aim to make devices disappear into the environments.

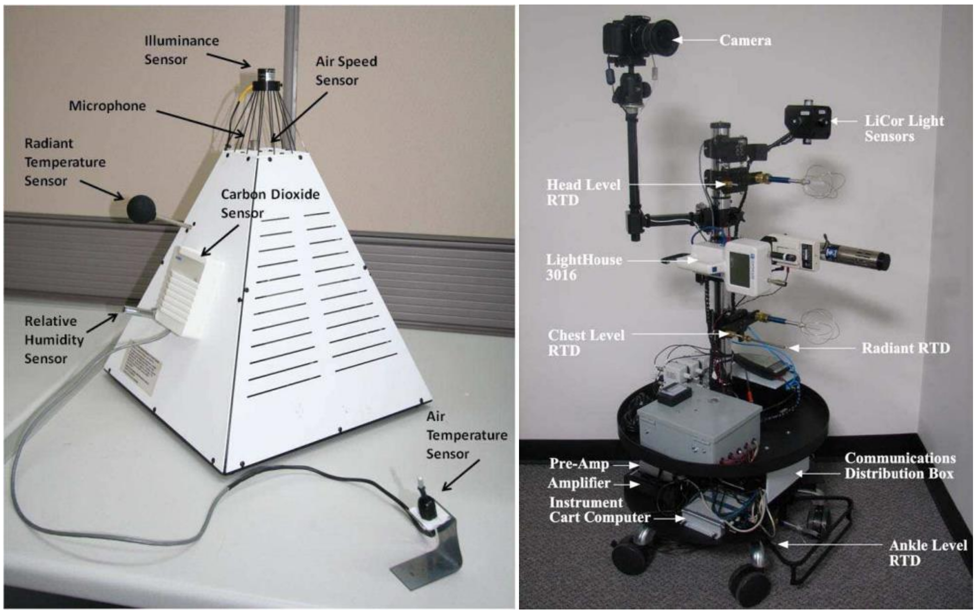


Figure 3.1: Examples of IEQ measurement cart and desktop: Pyramid desktop device (left) and NICE instrumented cart (right) [72].

● Outdoor monitoring applications

Nowadays, cities are facing unprecedented challenges such as environmental pollution, traffic, population growth and energy which directly affect human health and comfort. Thus, it may be helpful to collect and analyze environmental data for decision making related issues of buildings and cities. In order to measure and monitor the outdoor environmental parameters (temperature, humidity, illumination, etc.), the measurement process can be configured with a wide range of external sensors and smart applications. This process not only improves the quality of indoor environment, but can also contribute to the development of optimization strategies in the buildings.

Monitoring and evaluation of outdoor environmental data can be considered as important steps forward in adjusting indoor conditions. Although outdoor environmental parameters cannot be controlled easily, a monitoring of them may help users determine optimal solutions for indoor.

In this context, outdoor monitoring applications provide detailed insights into weather conditions. They act as automatic control systems that collect information data without supervision. They can also assess the impacts of air pollution, hot and cold temperatures, natural ventilation and wind speed on indoor areas. The following figure shows examples of outdoor monitoring applications that are used to measure outdoor environmental parameters.

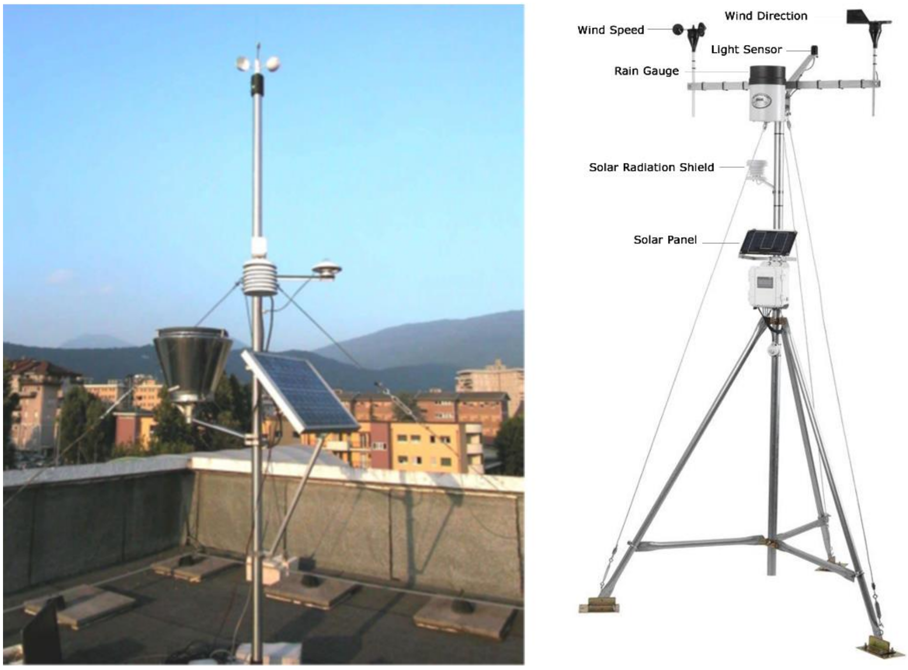


Figure 3.2: Examples of outdoor monitoring applications [74, 75].

3.1.2 Monitoring and collecting data in real-time and off-line modes

It is known that several buildings involve smart sensor systems such as motion, temperature, light, CO_2, air pressure and airflow. And yet many of these sensors have significant limitations that can impact the accuracy of building performance. In some cases, they cannot measure the data of users directly.

Smart sensor systems are usually used to monitor environmental parameters in two types of modes: real-time mode and off-line mode. The real-time mode is used to monitor data in a process control under natural and real conditions. It has continuous connection with smart sensor systems (Figure 3.3). As mentioned before, these real-time modes can play a constructive role in analyzing energy and user data while the off-line mode is performed by device demand and includes previously collected data: all calculation are made in an off-line environment.

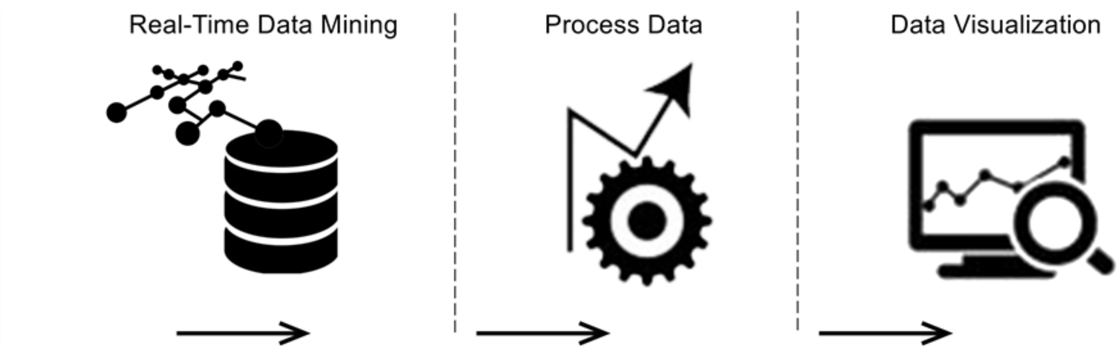


Figure 3.3: An example of schematic diagram for real-time systems. Source: Author.

In the field of building control systems, real-time occupancy information is a topic of utmost importance. It is an economical strategy to improve energy management systems

(EMSs). For example, occupancy information can be used for determining heating and cooling loads and controlling building services such as lighting and ventilation. However, lacking the capability of knowing accurate and real-time occupancy information, current facility management practices usually rely on assumptions to operate building systems, leading to more energy consumption than needed [76]. Monitoring of user behavior is one of the most efficient methods to reduce energy consumption and can be reached by an off-line mode approach. For example, in the off-line mode information is collected by smart sensor systems to provide inputs for user profiling. The basic function of the user profile is the characterization of user behavior so that some settings of the energy management system can be made automatically. Different types of profile can be created such as user presence profile, temperature profile, and light profile [77].

3.1.3 Smart systems: functions and technologies

At present, the architectural world with outstanding improvements in science and technology is changing our life. These changes in architecture are not only limited to smart buildings, smart cities and smart environments but also include significant progress in advancing materials, elements, structures, etc. For instance, several technical improvements have been made in building façades (Figure 3.4). In this regard, responsive façade is one of the design strategies that seeks to adjust the indoor environmental conditions with respect to the outdoor environment.The term responsive is often used interchangeably with adaptive, but most simply it is used to describe how natural and artificial systems can interact and adapt [78]. This process may include several steps such as sensing, actuation and adapting. It is clear that smart systems have been extremely influential in achieving responsive building elements especially in façades. Smart systems can not only lead to solutions in terms of functionality, but also have the potential of contributing to develop innovation strategies and technology.

Figure 3.4: One example of smart envelope made of the polymer ETFE [79].

● **Smart materials**

The emerging new technologies in architecture provide new possibilities for designing innovative building materials. Currently, there are two types of innovative building materials: smart materials and nano-materials. Different types of smart materials involve aerogels, thermoelectric, piezoelectric, magnetostrictive, shape memory alloys, etc.

In the context of design material, the term smart means frequently transparent, lightweight, malleable and responsive. In some cases, smart materials are not fully compatible with environmental, but they can easily be adapted to the built environment. Furthermore, smart materials can adapt themselves to the external environment in terms of moist, heat, light, pressure and other fundamental factors.

In general, it is debatable whether a material can be referred to as being smart or intelligent since materials do not have cognitive capabilities [80]. However, in practice smart materials have proven their performance not only to construct smart structures, but also to control the energy performance of buildings. Smart materials have significant advantages compared to conventional materials including small scale and prompt response time. In fact, smart materials have emerged as promising materials to contribute to energy reduction. Furthermore, they have been considered as solutions for improving energy efficiency and the productivity of automation.

In this context, Architect Sung [81] developed her research at the University of Southern California by focusing on new smart material which requires neither control and nor energy. This material is set to temperature and is a self-ventilating building skin with smart thermo bimetal which deforms and responds automatically to changes when heated or cooled (Figure 3.5).Thermo bimetals have been used since the beginning of the industrial revolution. A lamination of two metals together with different thermal expansion coefficients. Reacting with outside temperatures, this smart material has the potential to develop self-actuating intake or exhaust for façades.

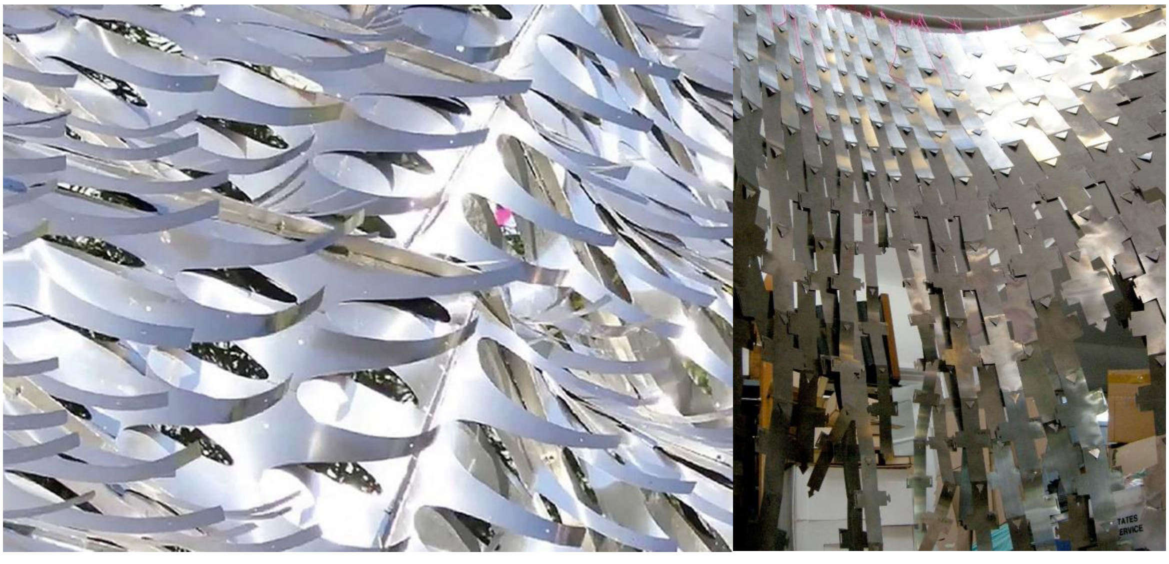


Figure 3.5: One example of smart thermo bimetal self-ventilation skin [81].

● **Building integrated photovoltaic (BIPV)**

Photovoltaics enable the active use of solar radiation by turning it into electrical energy; in addition they can also represent a form of passive solar protection [82]. The incorporation of photovoltaic cells into the building envelope is defined as building integrated photovoltaic (BIPV). In fact, BIPV systems are designed to reduce electricity use in the buildings. Furthermore, BIPV systems can be used as aesthetic elements which control indoor environment and harvest solar energy simultaneously (Figure 3.6). It is clear that BIPV systems can affect both the local environment and economy because they do not require separate support structure and environments.

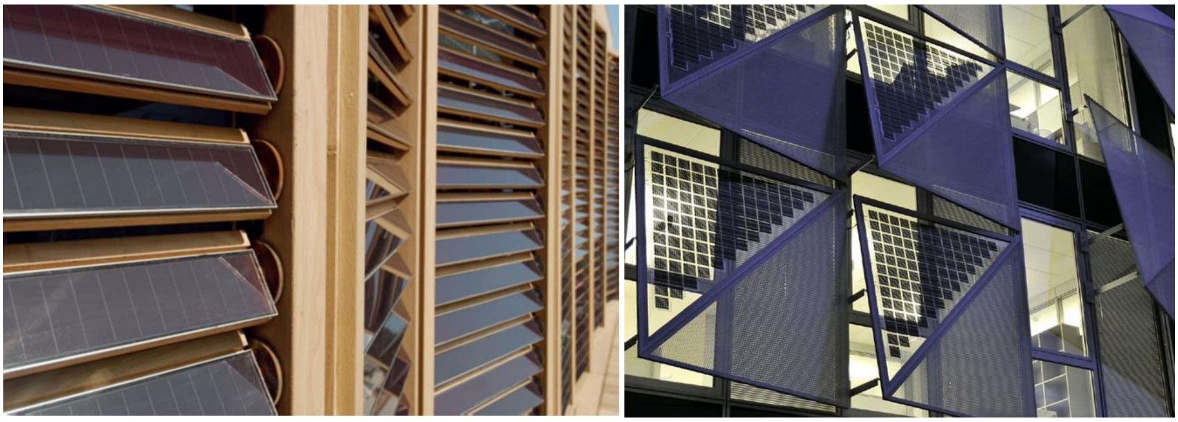


Figure 3.6: Examples of the photovoltaic panels are integrated in the building envelope: 1) TU Darmstadt's 2007 Solar Decathlon House (left) [83], 2) House of Music designed by COOP HIMMELB (L) AU, Denmark (right) [84].

According to Agrawal and Tiwari [85], BIPV systems can achieve significant cost reductions when they are used as part of the building envelope and thereby offset the cost of the building materials they replace. Furthermore, they can reduce energy consumption without preserving and commissioning. BIPV systems are capable of creating solar architectural elements which can result in multiple design options. For example, smart glazing like electrochromic (EC), liquid crystal (LC), and suspended particle device (SPD) may have a great impact on the aesthetic of BIPV systems in terms of color contras.

● **Nanomaterial**

It is clear that nanotechnology can bring some immense improvements in building performance and material. In the energy arena, it offers high potential for enhanced insulation. Today, nanotechnology is leading the way and affordable technologies to enable high level energy efficiency and sustainability in the buildings.

In the field of material science, the term 'nano' identifies the scale of morphological transformations that occur in the measure of one billionth of a meter. In this respect, it is the material itself that is being designed and engineered rather than the architecture which contains it. Nanotech materials are synthesized and calibrated to perform with the highest degree of specificity [86].

There is currently an extraordinary amount of interest in nanomaterial and nanotechnologies, terms now familiar not only to scientists, engineers, architects, and product designers but also to the general public. Nanomaterial and nanotechnologies have been developed as a consequence of truly significant recent advances in the material science community [87].

In architecture two fundamentally different design approaches prevail when dealing with materials and surfaces; these are divided into three main types such as: honesty of materials (what you see is what you get), fakes like artificial surfaces that imitate natural materials and functional nano surfaces which emancipated from underlying materials [88]. However, coating and insulation are the most significant research areas in nanomaterial and nanotechnology. In this context, European Commission is working on a project with the title “Functional Adaptive nano-Materials and Technologies for Energy Efficient Buildings” which includes nanotechnology approaches for multifunctional lightweight construction materials and components. The project is expected to develop external thermal insulation composite systems (ETICS) for new builds and retrofitting applications [89]. Under this project titles, such NanoPcm, Nanoinsulate, Aerocoins, HIPIN, NanoFoam, CoolCoverings are at research stage or have been completed. For instance, the Aerocoins project proposes new material composite and super-insulating such as aerogel that have great potential for various applications (Figure 3.7). It is used in various fields, such as architecture, engineering, chemistry science, etc.

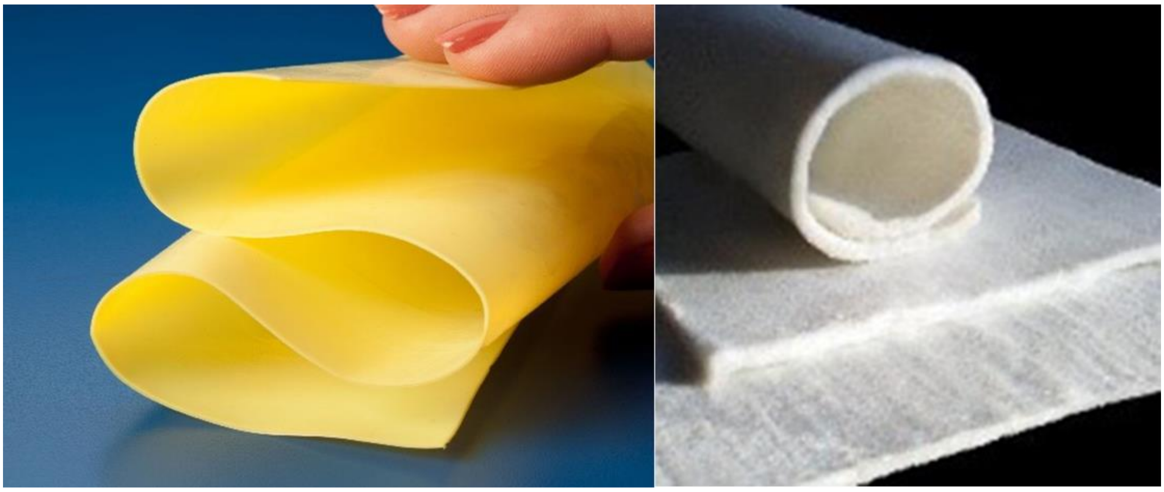


Figure 3.7: Examples of new flexible aerogel (left) [90], aerogel super insulation produced from silica (silicon dioxide) (right) [91].

Aerogels have a wide range of outstanding physical properties such as low thermal conductivity, good mechanical properties, low weight and high ability to absorb energy. For these reasons, aerogels can be used in the fields of thermal, sound insulation (Figure 3.8). Also, they play a role in light transmission due to their porous structure (Figure 3.9). Aerogels provide generally very good sound insulation. They can reduce range and velocity of sound waves and might be used in rooms and spaces that need not reflect sound. For example, monolith silica aerogels have a lower speed of sound than air. Sound velocities down to 40m/s have been measured [92]. Furthermore, granular aerogels are exceptional reflectors of audible sound, creating barrier materials [93, 94]. However, the high potential for aerogels may be found in its translucency and possible transparency and aerogels may provide large energy savings in future transparent systems [95].

Figure 3.8: Examples of aerogel insulation used in a building envelop [96].

Figure 3.9: Examples of translucent aerogel for thermal insulation and daylighting [97].

● **Advanced glazing and smart windows**

The glazing is installed in the façade of buildings to transform light and prevent heat loss and noise. Glazing can separate the outside and inside through façade and plays a constructive role in the exchange of heat and light and sound. In this regard, advanced glazing can significantly influence improved thermal, visual, and acoustic comfort.

Window U-factor (U-value) measures the rate of window heat loss depending on U-value of glazing. To meet heat loss reduction, currently low thermal conductive with multilayer glazing is mostly being used in office buildings. The most common glazing that gives a low U-value is triple glazing. Typically this is with a gas fill of either argon or krypton, with krypton producing lower U-values with less cavity or fill thickness (and volume) [98]. Glazing is classified and evaluated according to a series of factors which are essential for a understanding of quality and performance such as glazing U-value (Ug), solar transmittance (T_{sol}), visible solar transmittance (T_{vis}) and solar heat gain coefficient (SHGC).The Tables 3.3, 3.4 and 3.5 show examples of triple glazed windows, suspended film windows and vacuum glazed windows that are known as advanced glazing types.

Table 3.3: Examples of triple glazed windows in literature review [98].

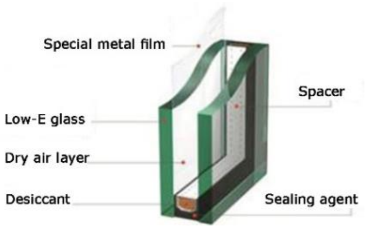
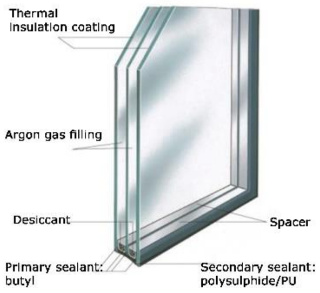
Product	Ug (W/m^2K)	T_{sol}	T_{vis} (%)	SHGC	Reference
Triple silver coating 	1.62		49.6	0.26	AGC Glass Company Asahi www.agc.com
Triple thermal insulation glass (iplus 3CE) 	0.5		72	0.47	INTERPANE Glas Industrie AG www.interpane.com

Table 3.4: Examples of suspended film windows in literature review [98].

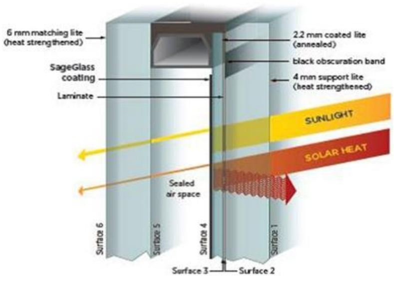
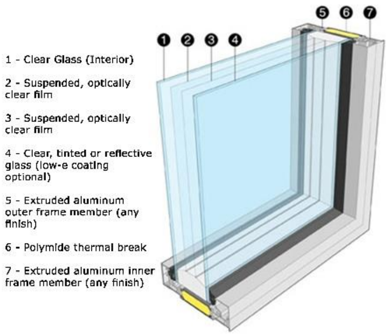
Product	Ug (W/m^2K)	T_{sol}	T_{vis} (%)	SHGC	Reference
SageGlass 	0.28		6	0.10	Sage glass www.sageglass.com
Visionwall Solutions Inc.Series 204, 4-Element Glazing System 	0.62		0.50	0.303	Visionwall Solutions www.visionwall.com

Table 3.5: Example of vacuum glazed windows in literature review [98].

Product	Ug (W/m^2K)	T_{sol}	T_{vis}	SHGC	Reference
SPACIA-21 vacuum glazing 	0.70	0.22	0.53	0.32	Pilkington/NSG company www.nsg-spacia.co.jp

It is estimated that buildings lose considerable energy through windows. Therefore, efforts should be made to reduce energy consumption on the windows. In this context, smart windows are considered as new technologies to adjust the indoor conditions and control environmental factors. For instance, smart windows are able to become black in color when outside temperature increases and are mostly transparent at low temperatures. In fact smart windows aim to reduce energy-performance issues in the buildings by controlling heat loss and managing daylight. Smart windows have also potential to reduce glare and improve the quality of natural light.

In addition to issues mentioned above, there are other important windows that filled by nanotechnology and smart materials to achieve autonomously responsive and light adjustment, such as photovoltaic (PV) glazing, aerogel glazing products , phase change material (PCM) filled glazing products, self-cleaning glazing products.

In this regard, Grobe et al. [99] examined four different glazing types such as glazing integrated blinds, electrochromatic glazing, aSi photovoltaic glazing, and clear glazing to monitor the daylighting performance by means of sensors and data acquisition systems (Figure 3.10). In order to assess daylighting performance of windows both in terms of energy savings and visual comfort, they analyzed the following parameters; daylight factor (DF), useful daylight illuminance (UDI), daylight autonomy (DA) and vertical illuminance, IES daylight glare index (DGI) and daylight glare probability (DGP). For example, regarding energy savings in lighting, the daylight autonomy of each testing chamber is proposed for initial studies [100]. In the study they assumed a baseline illuminance requirement of 300 lx accordingly at a working plane level of 0.85m and a daily occupancy period from 8 a.m. to 6 p.m.

Figure 3.10: Façade equipped with four types from left to right: glazing integrated blinds, electrochromatic glazing, aSi photovoltaic glazing, and clear glass [99].

The results of study showed that daylight autonomy (DA) during daytime was easily achieved by clear glazing and glazing with integrated blinds, even when the blinds were closed. They indicated that the aSi PV façade did not achieve transmittance to reach daylight autonomy at any time of the monitored period except for the position directly behind the glazing, when very high exterior illuminance was observed. Electrochromatic glazing could still achieve daylight autonomy levels of 40% during daytime when switched to clear, but dropped to 0% when switched to tinted.

It can be concluded from this study that glazing integrated blinds not only have the potential to be adaptable but they also are capable of spreading light evenly. Furthermore, the choice of appropriate façade glazing can affect energy savings. As a result, in order to select glazing in the buildings, it is essential to pay attention to user needs and indoor environment requirements.

● **Green roof**

In recent times, in order to enhance energy and water efficiency strategies in buildings, the number of green roofs has grown significantly. The main benefits of green roofs are their ability to improve ecological sustainability and local environment. Furthermore, they have significant impact on microclimatic, noise environment, energy consumption, CO_2 reduction and air purification (Figure 3.11).

Ambient and indoor temperature reduction brought about by vegetated roofs can reduce the energy and carbon footprint burden of cities, and offer a means for climate-change adaptation [101]. In a study by Liu and Baskaran [102], the green roof significantly moderated the heat flow through the roofing system in the warmer months. In addition, the average daily energy demand for space conditioning due to the heat flow through the roof was reduced by over 75%. In this study, the green roof was more effective in reducing heat gain than heat loss.

Figure 3.11: An example of a green roof project (left) and its detail (right) [103].

It is clear that green roofs have multiple environmental benefits and interest in these roofs is greatly increasing [104]. Recent studies have shown that thermal characteristics of green roofs significantly affect energy efficiency and may be an effective solution to reduce annual energy consumptions. For instance, Cabeza et al. [105] studied the thermal behavior and sustainability of extensive green roofs in three identical house-like cubicles located in Spain (Figure 3.12).

Figure 3.12: Energy savings potential of green roof studied by Cabeza et al. [105].

They used sensors to evaluate thermal behavior during the experiments. Each cubicle was equipped with a heat pump in order to provide both heating and cooling. The study found that extensive green roof cubicles show less energy consumption (16.7% and 2.2%, respectively) than the reference model during warm period. In the study, clear temperature difference between internal and exterior air temperature were found. The results of this study indicate that a properly designed green roof can reduce the cumulative electrical energy consumption for cooling period.

It may be useful to note that integrating photovoltaics (PVs) into green roofs can improve the efficiencies of both. According to Chemisana and Lamnatou [106], the combination of PVs with green roofs is a recent tendency. They have recently focused on a research which makes a comparison of PV-green with PV-gravel systems. The results obtained in their research show PVs installed on green roofs have generally increased efficiency and output power exceeding than of PVs installed on gravel roofs. There are several research studies based on PV-green. These studies have shown that the majority of photovoltaics (PVs) along with green roofs have more effectiveness and efficiency compared to roofs void of green area. For instance, in a study by Hui et al. [107], results showed a positive influence of PV panel integration on green roof surface. The findings of this study indicated that the PV-green roof generated 8.3% more electricity than the PV roof.

As a result, it can be concluded that the combination of green roofs with photovoltaics (PVs), can not only achieve significant energy efficiency but also bring considerable advantages compared with conventional installation.

Green roofs have potential to reduce noise pollution in the built environment. Multiple studies have shown that green roofs can insulate sound from outside. In this context, Connelly and Hodgson [108] found that green roofs can optimize the sound transmission loss (STL). The study was conducted on two extensive green roofs. Case studies indicated an increase of 5 to 13 dB in TL over the low and mid frequency range (50 Hz to 2000 Hz) and 2 dB to 8 dB increase in TL in the higher frequency range relative to the reference model.

In this context, Renterghem and Botteldooren [109] and Yang et al. [110] have investigated the effect of green roofs on noise propagation in an urban environment. In the study by Renterghem and Botteldooren [109], green roof acoustic effect was analyzed for propagation path lengths interacting with the roofs ranging from 2.5 m to 25 m. Measurements showed that green roofs might lead to consistent and significant sound reduction at locations. Also, Yang et al. [110] analyzed the effect of green roof systems on noise reduction at street levels and showed that the green roof system can be effectively used to reduce noise in urban spaces for diffracted sound waves. It can be deduced that the benefits of green roofs are not limited only to thermal scope, but have also remarkable features of noise reduction in the scale of buildings and cities.

As mentioned before, smart sensor systems and smart materials are being adapted for use in buildings to improve optimization strategies. However, these systems should perform multiple functionalities without disturbing balance between environmental and energy factors.

According to Schwartz [111], one of the major difficulties in incorporating smart materials into architectural design is the recognition that very few materials and systems are under single environmental influences. For example, he indicates that the use of a smart material to control conductive heat transfer through the building envelope may adversely impact daylight transmission. Furthermore, because most systems in a building are highly integrated, it is difficult to optimize performance without impacting the other systems or disrupting control system balancing. In this respect, he establishes four major categories of applications such as glazing materials, lighting systems, energy systems, and monitoring/control systems for smart materials (Table 3.6).

Although it is difficult to understand the major attributes of smart materials and systems, they have proven to be able to sense their environments and adapt to them. However, it is important to point out that smart materials and systems should not conflict with sustainable systems. In order to provide opportunities for a better understanding of smart materials and systems, it is important to discuss their behavior and properties.

It is clear that the development of design strategies based on smart materials, is able to significantly improve the sustainability of buildings. In fact, smart materials are considered as a substitute for conventional materials. They can also create new opportunists for ecosystems.

Nowadays, the latest technological trends in the field of architecture offer a number of features that contribute to the variability of the built environment. So far it can be concluded that smart materials and systems such as green roofs and photovoltaics help to reach the principles of sustainability and positively affect the built environment. Therefore, it is very important to consider the use of smart materials and systems as complementary concepts in architectural design.

Table 3.6: Mapping of smart materials to architectural requirements [111].

Building system needs	Relevant material or system characteristics	Representative applicable smart materials
Control of solar radiation transmitting through the building envelope	Spectral absorptivity/ transmission of envelope materials	Suspended particle panels Liquid crystal panels Photochromics Electrochromics
	Relative position of envelope material	Louver or panel systems - exterior and exterior radiation (light) sensors -- photovoltaics, photoelectrics - controls/actuators -- shape memory alloys, electroand magnetorestrictive
Control of conductive heat transfer through the building envelope	Thermal conductivity of envelope materials	Thermotropics, phasechange materials
Control of interior heat generation	Heat capacity of interior material	Phase-change materials
	Relative location of heat source	Thermoelectrics
	Lumen/watt energy conversion	Photoluminescents, electroluminescents, light-emitting diodes
Energy delivery	Conversion of ambient energy to electrical energy	Photovoltaics, micro- and meso energy systems (thermoelectrics, fuel cells)
Optimization of lighting systems	Daylight sensing Illuminance measurements Occupancy sensing	Photovoltaics, photoelectrics, pyroelectrics
	Relative size, location and color of source	Light-emitting diodes (LEDs), electroluminescents
Optimization of HVAC systems	Temperature sensing Humidity sensing Occupancy sensing CO_2 and chemical detection	Thermoelectrics, pyroelectrics, biosensors, chemical sensors, optical MEMS
	Relative location of source and/or sink	Thermoelectrics, phase-change materials, heat pipes
Control of structural systems	Stress and deformation monitoring Crack monitoring Stress and deformation control Vibration monitoring and control Euler buckling control	Fiber-optics, piezoelectrics, electrorheologicals (ERs), magnetorheologicals, shape memory alloys

3.2 Building Refurbishment

Refurbishment is one of the most efficient ways to improve the performance of existing buildings. It can contribute towards filling the gap between existing building conditions and environmental requirements. Furthermore, the refurbishment of existing buildings is believed to significantly contribute to the improvement of indoor environment and energy performance. Therefore, it is essential to establish methods of determining building and indoor environment conditions in refurbishment projects.

Nowadays, due to climate change and scarcity of natural resources, sustainable refurbishment has attracted much research attention in the building sector. In fact, sustainable refurbishment strategy can include tools to enable more efficient buildings.
In this respect, Mickaitytev et al. [112] indicate that sustainable refurbishment principles should include dimensions such as technical, economic, cultural, architectural, ecological and social factors (Figure 3.13). Therefore, in order to develop building refurbishment plans, a comprehensive planning process is needed to understand existing conditions.

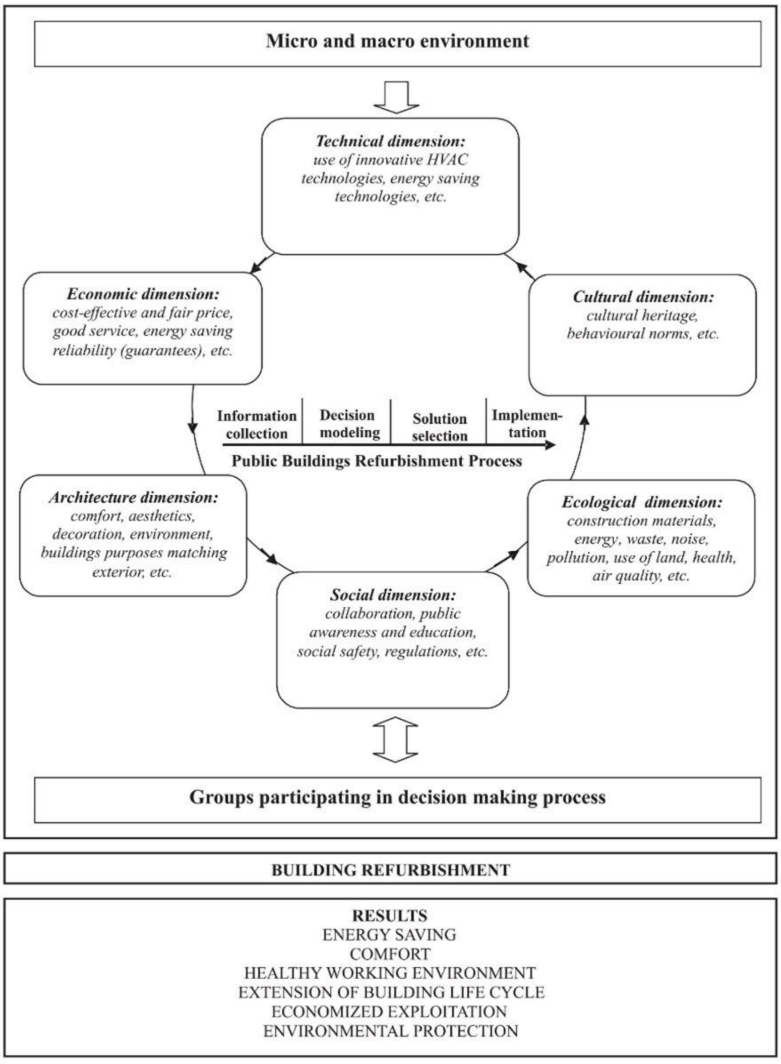


Figure 3.13: The conceptual model of sustainable buildings refurbishment [112].

In this context, a hierarchical approach to achieve zero carbon refurbishment is developed by Xing et al. [113]. It includes retrofitting fabrics, efficient equipment and micro generation (Figure 3.14). Achieving zero carbon should always be one of the core decisions in sustainable refurbishment. In fact, zero carbon refurbishment of existing buildings can significantly promote sustainable development in the built environment. It is a comprehensive strategy that combines the improvement of the building systems and renewable energy sources to enhance self-generation energy systems.

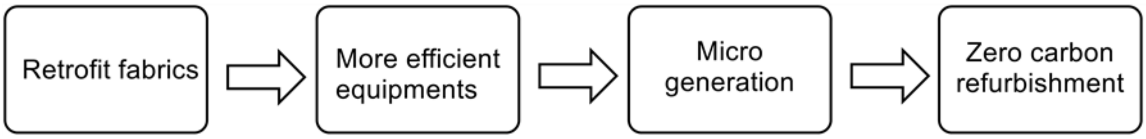


Figure 3.14: A hierarchical process toward zero carbon refurbishment [113].

In this context, decision-making tools play a key role in addressing the challenges involved in refurbishment process. In addition, they can meet the desired level of refurbishment and minimize risks in advance. For instance, TOBUS is one of evaluation tools that has been supported by JOULE III program in European commission [114]. It is a decision-making tool for selecting office building upgrade solutions and is an evaluation tool to meet building needs in compliance with sustainability issues such as energy performance and indoor environment.

3.2.1 Sick building syndrome (SBS)

In many office buildings, the entry of outside air pollution into indoor, a lack of proper ventilation, placed chemicals, contaminated materials (volatile organic compounds (VOCs)) and air pollution produced by office equipment can contribute sick building syndrome (SBS). In some cases, sick building syndrome (SBS) is caused by human activity (carbon dioxide, perfume) and HVAC (entry dust and polluted air of mechanical systems) which can significantly affect productivity. Therefore, this issue needs to be solved for the purposes of creating healthy, comfortable, and productive buildings.

There is considerable evidence that sick building syndrome (SBS) can affect building occupants. Regarding the analysis of a sick building, a rule of thumb has been that ventilation rates below or above standards per person in office buildings can increase the prevalence of SBS symptoms. It is, therefore, essential to ensure that buildings guarantee conditions which allow users to breathe optimally.

The symptoms of SBS may vary according to the users. However, it is important to emphasize that SBS symptoms may be related to poor or uncomfortable indoor thermal, light, noise and indoor air quality conditions. Furthermore, incorrect response from users can increase the complexity of SBS problem.

3.2.2 User behavior and retrofits

In recent times, energy retrofit strategies and initiatives have significantly improved reductions in energy use and emissions. It is important to focus on the fundamental principles and practices of buildings retrofits to increase energy efficiency. As mentioned before, the role and the importance of user behavior on the performance of the buildings cannot be denied. User behavior is a key factor for designing retrofit programs. For example, Fabi et al. [115] studied the robustness of building design with different operations of windows and movable shadings, and found that a description of user behavior allows a better defining of robust building designs.

Understanding user behavior in the buildings can not only assess user comfort requirements but also identify beneficial retrofit strategies. Today, energy simulation tools and experimental systems are used to investigate user requirements in buildings. However, several building simulation tools cannot calculate changes affected by the presence or absence of users. For instance, Knight et al. [116] studied energy profiles of education buildings based on simulation programs and experimental measurements. In their study, the questionnaires and simulation programs such as Ecotect and iSBEM were used to calculate the heating and cooling loads and predict yearly usage. The aim of the questionnaire was to assess when the users were present in the building, and when they used the small power and lighting under their control. But, questionnaire as conducted were not able to predict profiles of the electricity consumption. They indicated that Ecotect simulated proper results except for analyzing gas consumption which the model overestimated by 50%. The study showed that it is difficult to accurately estimate energy consumption without regard to correct statistics of user behavior. User behavior is a crucial factor in the evaluation of systems used in retrofits. It should be taken into account when conducting building energy simulation. It is important to pay attention to user behavior in detail in energy efficiency retrofitting of existing buildings.

3.2.3 Retrofitting existing buildings

The retrofit strategy represents an opportunity to upgrade the energy performance of buildings. Therefore, it is important to establish the optimal energy retrofit strategies for existing buildings. Ma et al. [117] stated that retrofitting of existing buildings offers significant opportunities for reducing global energy consumption and greenhouse gas emissions. Although there are a wide range of retrofit technologies readily available, methods to identify the most cost-effective retrofit measures for particular projects still present a major technical challenge. One of the biggest barriers to retrofit existing buildings is the lack of reliable data sources. In fact, retrofitting problems are related to multi-attribute decision issues and unfamiliarity with the existing systems. Furthermore, there are many challenges associated with the determination of real energy consumption. For example, the actual amount of energy used in the existing buildings is often uncertain due to climate change, user behavior change, building system changes, etc.

Building information modeling (BIM) can play a key role in analyzing and determining energy consumption in existing buildings. It has an important effect on the accuracy of estimates. As building information model (BIM) is a tool to estimate accurate building information it can be used to predict the energy performance of retrofit measures by creating models of existing buildings, proposing alternatives, analyzing and comparing building performance for these alternatives and modeling improvements [117, 118]. BIM is also accepted as a process and corresponding technology to improve the efficiency and effectiveness of delivering a project from inception to operation/maintenance [119].

In order to improve existing building retrofit strategies, a systematic approach to identification of appropriate retrofitting options is needed. It is also important to consider integrated steps that include reviewing requirements, identifying options and conducting techniques (Figure 3.15). In this context, a series of key factors such as building expectations, building information, user behavior, and retrofit technologies should be studied in deep.

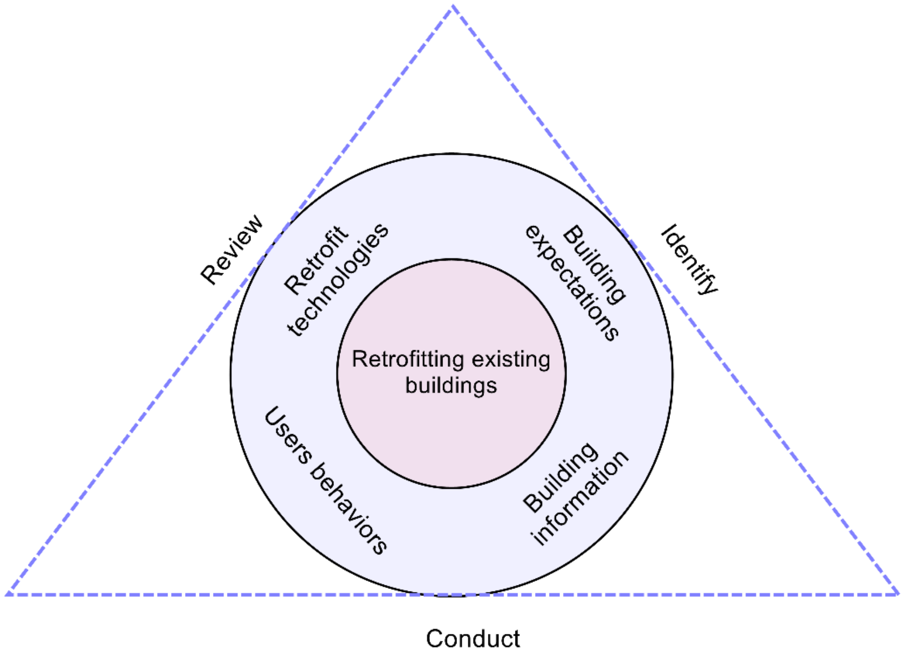


Figure 3.15: Key elements influencing building retrofits. Source: Author.

The key factors identified in the process of retrofitting buildings should be considered regarding their condition. Furthermore, building retrofits that replace equipment and components should offer more opportunities for existing buildings to improve their energy performance. In order to obtain the complete state of a retrofitting process, it is essential to assess conventional technologies, design analysis, existing HVAC systems and construction technologies. It can also be useful to provide a framework for retrofitting existing buildings under uncertainty which result in better understanding their condition.

3.3 Development of Smart Control Systems in Accordance with Protocols and Standards

Automation technologies used in smart buildings enable users to control their own environments. By using smart control systems, all devices and equipment are controlled according to characteristics and needs of users with respect to the environment. Smart control systems have the ability to undertake repetitive tasks and can provide more comfortable conditions for users. They can react quickly to user needs and connect with users to obtain significant feedbacks.

Advanced control systems are defined as smart control systems, and include two levels. The first level is a low-level feedback control of indoor conditions for each building's zone. The second level is a high-level supervision (smart coordinator) and planning. This high-level management provides optimal operation strategies for energy conservation and environmental comfort [120]. Therefore, it is important to understand how the capabilities of smart control systems can help users track energy consumption and comfort through sensors, actuators, and applications.

3.3.1 Building automation systems (BASs)

Building automation systems (BASs) are the main strategies used to improve performance and operational efficiency. It is clear that the BASs have a significant impact on energy saving. However, it is necessary to understand what kinds of building automation systems (BASs) can meet user requirements efficiently.

The BASs should achieve level of comfort by using the low energy use and real-time applications. They are designed to allow sufficient profits for operating and managing building systems. In fact, they make computing much easier compared to conventional systems. In general, they should include the following items:

- Ability to distinguish user-presence and user-absence mode
- Design principles for actively controlling to detect the active or semi-active systems
- Adjusting and balancing between demand and supply
- Accurate estimation of the energy consumption of lighting, heating, cooling and other mechanical and electrical systems.

BASs can be classified according to types of control systems which are summarized as follows:

- Centralized control and monitoring systems (CCMSs)
- Distributed control systems (DCSs)
- Autonomous decentralized control systems (ADCSs).

The use of wireless technology in the field of building automation systems is currently growing to monitor ambient conditions. Wireless technology due to the easy transfer process, has received a great deal of attention recently in the field of building control systems. It can also reduce construction, commissioning and operating cost over in the buildings. Visualization is one of the fundamental features of building automation systems. It enables users to track detailed energy audit and real-time information of environments to achieve a supply and demand balance in energy consumption. The following figures show examples of building automation systems that have real-time visualization and information data to manage energy in the buildings.

Figure 3.16: Examples of building automation systems visualization [121].

As shown in Figure 3.16, building automation systems (BASs) are performed automatically with a programmable logic controller (PLC) which by getting information via the input terminals provides an appropriate response to devices. It also has ultimate responsibility for controlling building automation systems. However, it is not easy for users to understand whether the PLC achieve the control objectives. It would be better to make systems more accessible for the users to control building systems.

3.3.2 Protocols and standards

Building automation systems (BASs) are often used to control and manage mechanical, electrical and lighting systems. They provide important functions such as data collecting, monitoring, and operating systems through smart sensor systems and actuators. It is clear that the installation and running of the systems should necessarily be in accordance with protocols and standards, which otherwise may lead to less efficiency. There are several standards and protocols such as the IEEE 1451.1 standard, ISA 100 created by the International Society of Automation (ISA) , LonWorks protocol, KNX, building automation and control network (BACnet), DALI protocol(lighting systems), Metasys N2, Modbus that can be used in the field of building automation systems (BASs). In fact, they are used for the development and implementation of smart sensor systems and communications networks. Since building automation systems (BASs) are produced by different manufacturers, it can be useful to control smart sensor systems in a standardized way. Figure 3.17 represents a simple schematic drawing of the current state-of-art in smart sensors systems and control systems.

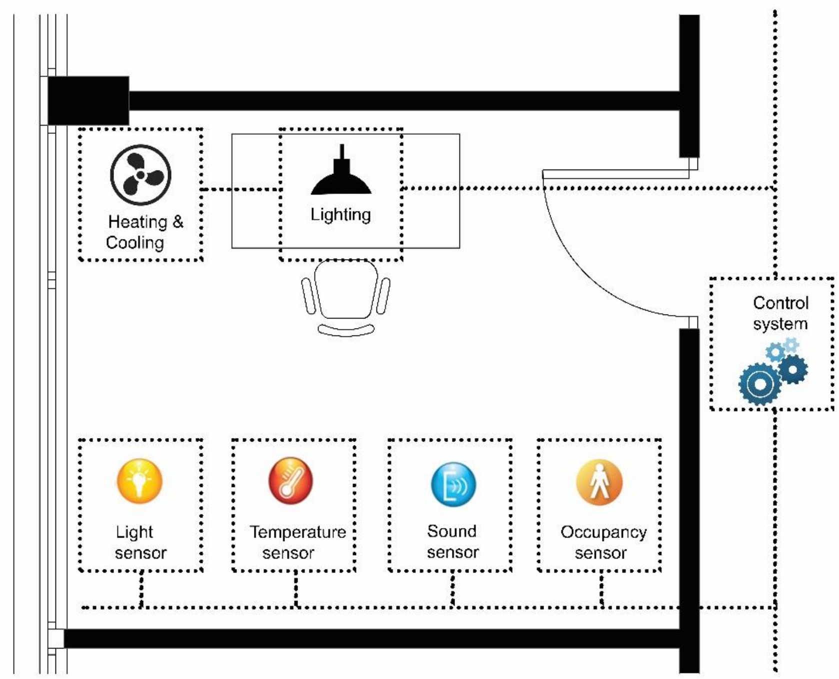


Figure 3.17: A simple schematic drawing of smart sensor systems, actuators and control system modules. Source: Author.

Active energy management tools and consistent coordinate systems play key roles in connecting building automation systems (BASs) to enterprise systems. In this context, using systems such as DALI, SMI, LON, KNX and BACnet can help enhance data transmission and avoid dependency on one manufacturer only.

Main network communications protocols used for smart buildings installations include the KNX, DALI and BatiBUS the European Installation Bus (EIB).They are used to control lighting, windows , shading control and air conditioning. For example the DALI which stands for Digital Addressable Lighting Interface, is a real stand-alone lighting control system and has made significant improvements in energy savings. Furthermore, KNX protocol management system which is a standardized (EN 50090, ISO/IEC 14543) can be used across a range of integrated systems in order to transfer control data to all building management systems. KNX systems are used by systems integrators to build smart integrated building control solutions. They provide a holistic approach to reduce energy consumption and are not limited to individual control of lighting, HVAC systems, etc.

According to Ruta et al. [122], project design of a KNX system initially does not differ from a typical electrical project. In the preliminary stages, several aspects must be clarified by the planner such as the type and use of the installation, the building system components to use, and their functions and special requirements stipulated by users.

Currently, several residential and office buildings are being fitted with KNX systems. In particular, they help to make buildings sustainable and more energy efficient. The following figure shows a schematic KNX smart building system. It includes several sensors, controller, interface and actuators to control the indoor environment.

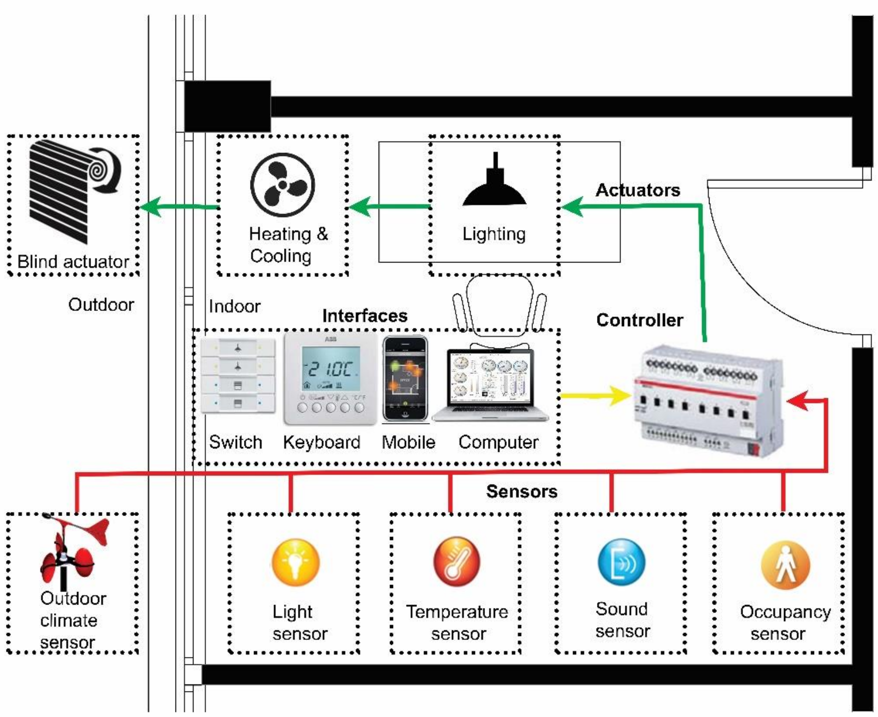


Figure 3.18: A schematic drawing of KNX smart building system. Source: Author.

It is known that building automation systems (BASs) can control both individual user needs and general building requirements. However, when the building is intelligently controlled to meet users' preferences by adjusting the heating/cooling and lighting level, these preferences need to be well interpreted and learned through the feedbacks or behaviors of users [123]. In this context, artificial intelligence as an efficient technique can contribute to the field of control and automation systems. It is capable of learning from its own environment and can help building automation systems to optimize goals.

Adoption of BASs with artificial intelligence techniques can lead to greater awareness of user behaviors on energy consumptions. Furthermore, it can lead towards the management of indoor environment according to kinds of user behaviors in the buildings.

It is worth mentioning that, the additional link between building automation systems (BASs) and environmental conditions and users provides great advantages. For example, it can encourage the users to take part actively in the operation of building automation systems (BASs). Furthermore, users can significantly reduce energy use and make corrective actions to BASs. At present, however, the interaction strategy between users and BASs is not sturdy. BASs need to communicate directly with an active user who has in-depth knowledge on controlling and managing. But, current standard systems (e.g. KNX, DALI, BatiBUS, etc.) and technologies are still far from that vision. Although users may have access for modifying building automation system, they still need to be coordinated by smart systems. As a result, the implementation of user profile and user characteristics into building automation systems (BASs) can provide the operational flexibility necessary to manage the actuators, sensors, and user interfaces.

3.3.3 Simulation-assisted and model predictive controls

Model-based control is one of key strategies in achieving optimal energy performance. It is a method of analysis that uses a model to predict and control energy consumption. It develops efficient and cost-effective processes to achieve energy performance goals. In this context, simulation-assisted control and model predictive control (MPC) in conjunction with building energy management systems (BEMS) use dynamic models to control mechanical, lighting, electrical and plumbing (MEP). Simulation-assisted control plays a significant role in enhancing the capabilities of building energy management systems. It can be used for evaluation of automation design and validation of system requirements. Furthermore, in order to facilitate automation applications, simulation-assisted helps improve an understanding of expectations from the performance of the system (Figure 3.19). The application of simulation-assisted control method in building performance involves the incorporation of explicit numeric performance simulation in the control core of buildings' environmental systems (e.g., for window ventilation and shading controls). Thereby, candidate control options (i.e., alternative combinations of the possible states of different control devices) for a future time instance are proactively accessed via performance simulation [124].

Simulation-assisted controller can contribute to optimize the set points in a certain range for different conditions. The objective of simulation-assisted control is to create effective and efficient ways to reduce energy consumption and increase user's comfort. A simulation-assisted control system includes building information model, data analysis and process control to achieve desired improvements and efficiency. Furthermore, it can help to generate optimum alternatives in control decision making.

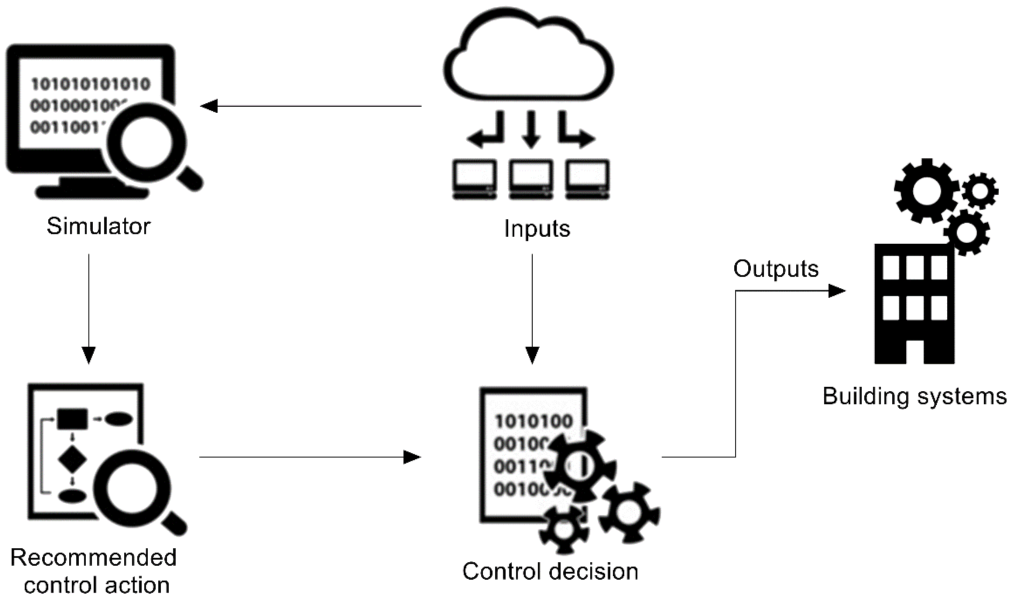


Figure 3.19: A schematic drawing of simulation- assisted control in the buildings. Source: Author.

Model predictive control (MPC) is a multivariable strategy for optimizing building energy consumption. It includes a series of replacement operations in the control schedule process relevant to climate prediction or climate forecast (Figure 3.20). Many studies have been conducted regarding the effectiveness of model predictive control (MPC) in reducing the energy consumption for buildings (e.g. [125, 126, 127, 128, 129, 130, 131]). For example, Hu and Karava [131], demonstrated that model predictive control (MPC) strategies for buildings with mixed-mode cooling (window opening position, fan assist, and night cooling schedule) can significantly reduce the cooling requirements compared to baseline night setback control during the occupied period within acceptable limits.

In general, the concept of model predictive control (MPC) includes query optimization methods based on the collection of set points. It can predict the best choice of comfort and environmental energy economics along with the existing conditions instead of conditions that have been set previously. One of the main difference between model predictive control (MPC) and simulation-assisted control is to interfere forecast and prediction vision which can provide the precautions necessary for a variation of conditions to users. Aside from its roles mentioned above, model predictive control (MPC) considers the demand response and solves user satisfaction problems in real-time mode. It helps to reduce peak loads in the buildings. In fact, it is an optimization-based control and manages the variability of energy generation. Furthermore, it makes a contribution towards more efficient operation of building energy management systems (BEMSs).

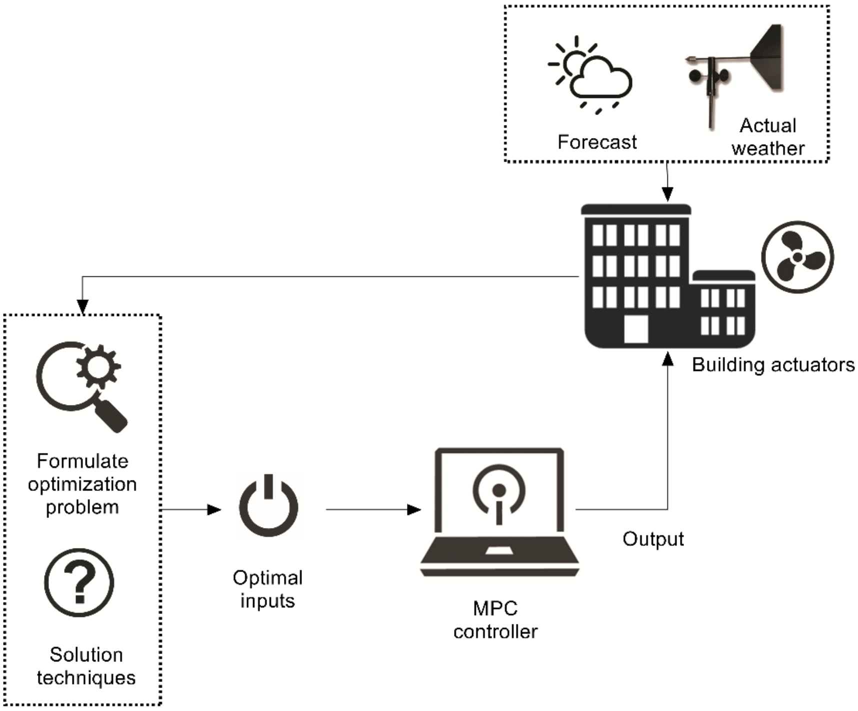


Figure 3.20: A schematic drawing of model predictive control (MPC). Source: Author.

CHAPTER 4 DESIGN AND ADAPTATION IN THE BUILT ENVIRONMENT

The built environment is facing challenges in relation to climate changes. It should be capable of adaptation to better respond to requirements and challenges. To enhance flexibility and efficiency, adaptation methods should refer to a natural environment. This can lead to the creation of comfort conditions and opportunities to improve the physical and mental conditions of living in the built environment. Although architectural technologies have taken steps to reduce energy consumption and environmental issues, several challenges of climate change and global warming have not been solved yet.

As mentioned in previous discussions, it is of great importance to identify the important variables that are needed for the adaptation in the built environment. For example, it is necessary to achieve adaptation to unexceptional parameters such as user behavior or weather conditions in the buildings. Within these considerations it can be useful to explore and understand the needs and expectations of users which can result in optimization of individual comfort. The built environment needs to adapt to users' needs. It is therefore of significant importance to identify predictive data.

According to Yang et al. [132], "people are not passive recipients of their immediate environment, but constantly interacting with and adapting to it". Indeed, some changes in indoor environment cause discomfort and dissatisfaction of building users and persuades them to adaptation strategies in physiological, behavioral and psychological aspects [133,134]. It is thus suggested that adaptation strategies should also be designed to address both the needs of end users and challenges of built environment. The following figure shows examples of key adaptation objectives in relation to the environmental issues that can contribute to more environment-friendly.

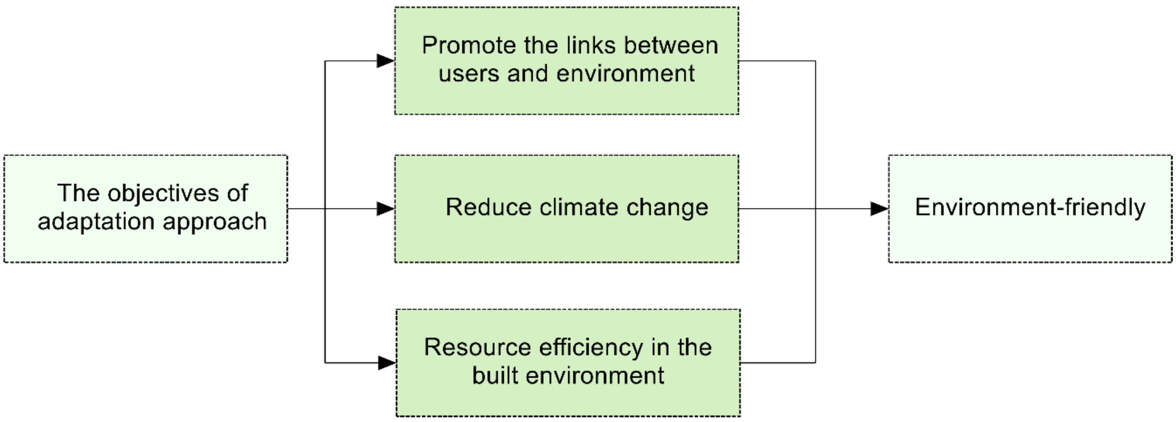


Figure 4.1: The objectives of adaptation approach in relation to environmental issues.
Source: Author.

On the other hand, user behavior can influence the achievement of adaptation objectives. In fact, users can help to facilitate the creation of adaptation strategies and actions in the built environment. Furthermore, inclusion of user is increasingly important to reduce the risk from climate change impacts. Climate change is recently becoming a major threat to the environment, future cities and buildings. Therefore, it is essential to develop adequate adaptation strategies regarding the reduction of CO_2 emission and climate change risks. Climate change can be controlled by a series of innovative technologies along with bioclimatic and passive design strategies. Gething [135] suggests that the impacts of the changing climate on the built environment can be grouped into three broad categories: 1) how they affect comfort and energy performance: warmer winters may reduce the need for heating, but keeping cool in summer without increasing energy use and carbon emissions may present a challenge 2) how they affect construction: resistance to extreme conditions, detailing, and the behavior of materials 3) managing water: both too much water (flooding) and too little (shortages and soil movement) water. Climate change may affect building design strategies. It is clear that the effects of climate change on the built environment consist of a series of technological challenges and behavioral challenge that more attention should be paid to address these problems.

The development of the adaptation strategy for the Technical Hub (also known as EBI2 building) is an example of a research strategy that is designed to cope with the impacts of extreme weather and a changing climate [136]. Figure 4.2 shows a detailed solution for reducing solar gain / glare. In this project, effects of climate change on building performance have been analyzed between three sets of weather data (e.g. the baseline, the 2050s and 2080s). The baseline weather tape uses past weather data from the period 1961 to 1990 to represent current day weather. The 2050s and 2080s tapes morph from the baseline tape to represent the projected future climates. Additional adaptation strategies were proposed and tested via modeling and simulation to demonstrate the further added benefit to the EBI2 building and the resilience it may have against changing Future climate. All in all, the EBI2 building should be able to adapt to climate change relatively without any major predicaments and should benefit its owner and occupiers through the provision of a building with acceptable thermal comfort and energy use [136].

Figure 4.2: Technical Hub at EBI, Cambridge [136].

4.1 Smart Cities. The Correlation between Smart Buildings and Smart Cities and The Impact on Smart Energy Planning Objectives

To deal with environmental and climate change issues, the development of smart cities is one of the most important concepts and principles in the field of urban design. According to the Climate Group [137], a smart city is a city that uses data, information and communication technologies strategically to provide efficient services to citizens, monitor policy outcomes, manage and optimize existing infrastructure, employ cross-sector collaboration and enable new business models.

Smart city has not only become more concerned with architectural science but has also been the area of interest for some designers and architects. The concept of the smart city concerns some fundamental dimensions as follows: 1) smart economy 2) smart mobility 3) smart environment 4) smart people 5) smart energy 6) smart governance 7) smart building. With respect to all relevant factors, smart building and smart people paly particularly important roles in the formation of smart city. For instance, all of the technologies associated with smart cities (e.g. smart lighting, sensors, wind turbines, LED lighting, smart building controls, etc.) are connected with people and buildings. In fact, a smart city provides smart infrastructures for people to make more smart decisions. In this context, different stakeholders and people are involved in creating smart cities. However, smart city consists of different communities for solving the challenges of the city.

The objectives of smart cities can be achieved through innovative applications, smart design principles and key features of environmental management system. The development of a theoretical model of smart city and its key conceptual components can provide useful guidance to achieve objectives (Figure 4.3). For example, smart buildings, smart people and smart energy are key components of a smart city. They are able to acquire effective, efficient and sustainable principles in smart cities.

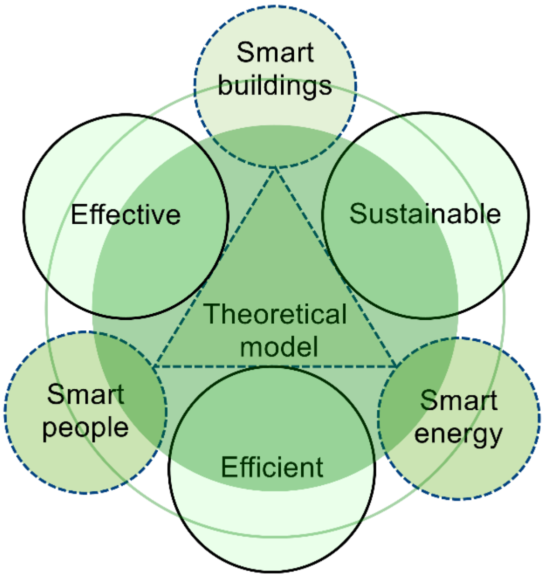


Figure 4.3: Theoretical model of smart city. Source: Author.

The objectives of smart city are not only limited to land conservation and sustainable development, but also include effective transportation systems , efficiency in use of the territory, the preservation of the culture and values of tradition, the promotion of urban telecommunications, and more efficient operations.

4.1.1 Collection of built environment data

The analysis of built environment data is a key factor for adapting smart city systems. It is also one of the most important issues in real-time systems and sensors. In order to enable built environment data collection and enhance its analysis, it is necessary to develop appropriate tools and applications. Understanding the accuracy and precision of the built environment data is a matter of utmost importance. It helps to develop parametric methods to assess smart buildings and cities. The lack of adequate built environment data can result in challenges about the behavior of various systems in terms of diagnostics and decision-making. In this context, Stephens and Ramos [138] pointed out methods to improve built environment data collection. They classified building science measurement into as follows: 1) building characteristics and indoor environmental conditions; 2) HVAC system characterizations and ventilation rate measurements; 3) human occupancy measurements; 4) surface characterizations; and 5) air-sampling and aerosol dynamics.

The collection of built environment data can be helpful for the planning and development of new parametric models in cities. It also can be useful for assessment of energy performance and the improvement of energy efficiency. The development of network nodes such as sensor nodes, smart meters and open source platforms is required today to record and detect specific challenges in smart environments. Information and communication technology (ICT) applications have fundamentally changed the process of data collection and monitoring. Sensor networks (big data) play key roles in collecting required data. They can collect and monitor data in real time and are used for transmitting, processing and storage data within smart cities and smart buildings. Furthermore, cloud platforms can play a constructive role in developing real-time and environmental systems for smart cities. The vision of cloud platforms for smart cities is substantially based on data transmission. Big data and open data platforms provide facilities that can influence sustainable development in different areas. They can turn a vast amount of data into functional information. It is therefore important to focus on developing open platforms and cloud computing to collect and analyze existing data in smart cities. Data warehouse is a powerful application that can provide a statistical foundation to determine regional requirements in terms of energy, transport, security and comfort (Figure 4.4). In order to help a smart city make better use of big data and open data platforms should be taken into account in the process. It is clear that big data and open data platforms will drive the future economy of smart cities and also will provide opportunities to understand building characteristics.

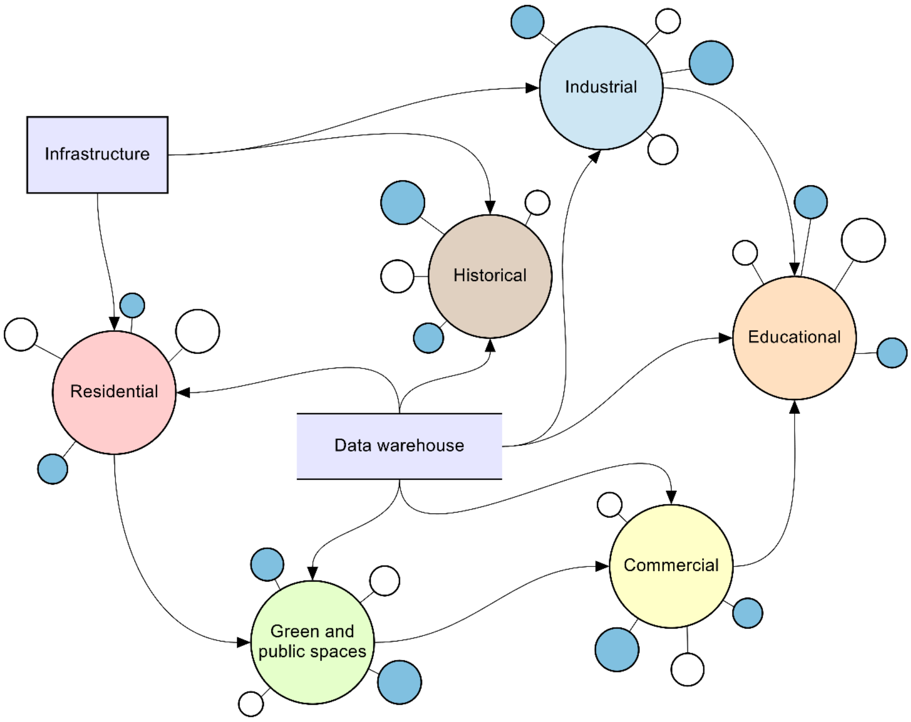


Figure 4.4: An example of smart city infrastructure. Source: Author.

A recent study by Kim et al. [139] shows that it is possible to transfer data such as electricity, heat and gas by using an intelligent power network for demanding areas. They built an energy management system EnerISS (Energy Integrated Urban Planning & Managing Support System) that can combine city information model data from the database, energy consumption data (through a sensor network), and environmental GIS data (Figure 4.5). It builds up its own monitoring database.

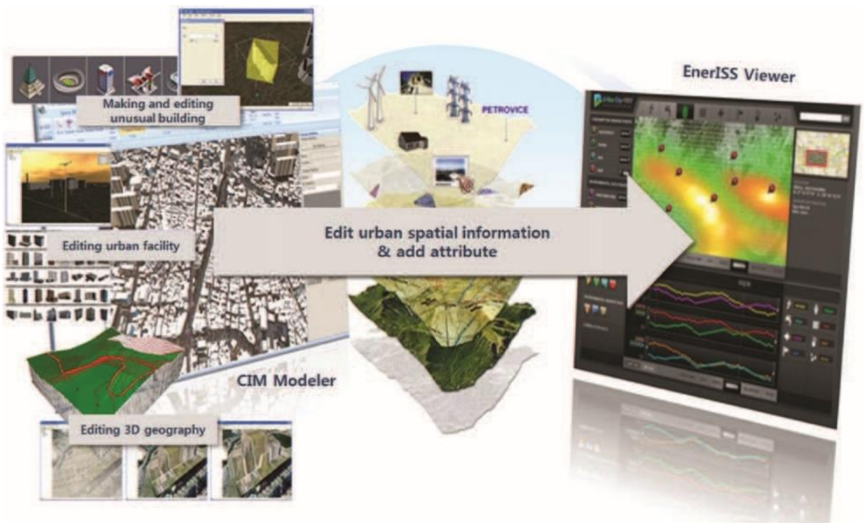


Figure 4.5: Illustration of the EnerISS modeler [139].

EnerISS viewer can help stakeholders predict the energy demand from E-GIS data, enabling in-time planning of energy supply through energy management system (EMS). It allows interactive 3D modeling of urban space, and automatically transfers the model data to the solver, and the solver estimates energy demand of the city by combining the e-GIS data and the geospatial data.

4.1.2 Smart city vision and scenarios

Smart cities are envisioned to achieve both smart growth and sustainable development. The use of efficient scenarios and visions for smart cities, is one of the main methods to provide sustainability-related goals, economic growth, social and cultural facilities. For example, an appropriate vision of energy systems for smart cities can increase energy efficiency. Nowadays, various types of scenario and visions are used to develop smart and sustainable infrastructures. However, it is not easy to implement them correctly into their own surrounding environment.

Considering that ICTs have significant potential for developing smart functions, it is possible to state that smart service applications can facilitate smart information and communication systems in the cities and buildings. As mentioned before, ICTs have certain possibilities in providing real-time information and coordinating access to data in terms of environmental and security. However, they should be assessed based on their performance in detail. In a study by Kramers et al. [140], the opportunities of using ICT as an enabling technology to reduce energy use in cities have been investigated. In this study, a framework was presented for assessing and guiding the implementation of ICT solutions for low-energy cities. Furthermore, energy use was used as an indicator of the contribution of ICT to environmental sustainability. The study showed that ICTs have great potential for highlighting energy use issues. In this regard, Fokaides and Kylili [141] indicated that the smart grids of smart cities employ ICTs to gather and act on information, such as information about the behaviors of generators and consumers, in an automated way for the improvement of the efficiency, reliability, economics, and sustainability of the production and distribution of electricity.

It is clear to all that ICTs have beneficial environmental effects in developing specific scenarios and visions for smart cities. They can be integrated into cities and buildings not only to provide smart opportunities but also to create sustainable principles. Furthermore, they are used to reach specific goals in terms of processing and computing infrastructure.

The development of methods to combine technological innovation and sustainability in smart cities, however, is not only solution to solve the problems related to climate, environment and energy. However, ICT solutions should provide opportunities for smart cities in the areas energy, buildings, mobility, water, security and information. An important aspect within applications of ICTs, is the collaboration between end-users and environments. Figure 4.6 shows some important factors that should be included in the process of switching an existing infrastructure to a smart infrastructure. Although it may be unlikely, ICTs can help to respond to challenges in the process. The role of ICTs should be to establish a connection between data, models, and users. Furthermore, ICTs should make certain typologies methods of their functions, which can be useful to promote smartness in cities.

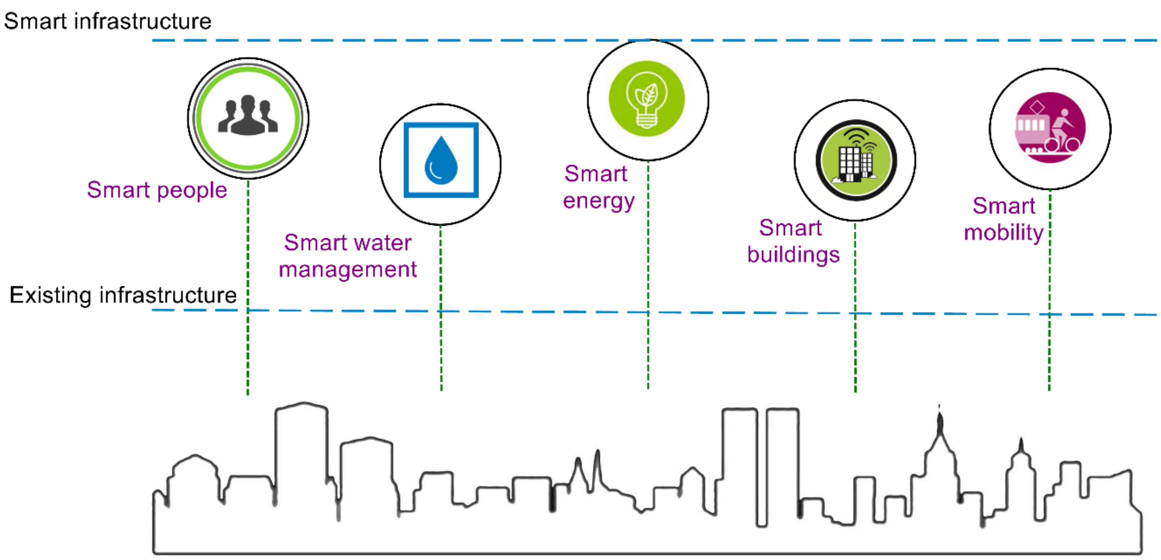


Figure 4.6: The most important factors in the formation of a smart city infrastructure.
Source: Author.

In recent years, smart cities and buildings have contributed enormously to the development of energy savings and environmental management methods. The growing energy problems and environmental concerns have led researchers to speculate on the development of innovative solutions for the urban environment. Although, innovation systems and ICTs technologies have solved several environmental problems, they have not been fully implemented in the control system strategies and smart management systems. Internet of things (IoT) and especially sensor networks are currently used to monitor and manage data in smart cities. They play a key role in collection, transmission, and analysis of data. They are also used to support cultural heritage preservation and energy efficiency targets in historic buildings.

In the context of smart cities, it is essential to determine scenarios and visions that are important in meeting both existing and future needs. They should be designed to support smart cities to deal with climate change. For instance, the use of flood forecasting scenarios can be used to mitigate water management issues. In particular, the proposed scenarios should be based on local conditions and standards.

It is worthwhile to mention that nowadays there is a pressing need for smart energy vision. This is considered as a long-term vision and a long planning horizon. It enables the optimal use of energy resources and improves the quality of energy systems. In this respect, smart grids represent the electrical network models that enable better management of energy flows. Smart grids can facilitate efficient use of renewable energy sources and adjustment to changes in energy supply and demand. In fact, smart grids are the key features of future smart energy visions. They have great potential related to economic and environmental benefits and can significant reduce energy use and costs in the cities. However, existing energy systems need to be adapted to exploit smart grid benefit.

It is evident that a city needs to be both sustainable and smart. It seems that the development of smart sustainable cities leads to benefits that can be expressed as follows:

- ●Providing opportunities for cities to meet their needs along with existing conditions
- ●Improving the environmental quality of spaces through smart networks
- ●Reducing global environmental and climate change challenges
- ●Promoting renewable energy sources and various initiatives
- ●Providing opportunities to create new smart and sustainable vision
- ●Enhancing people contribution to smart and sustainable development
- ●Achieving smart and net-zero energy buildings

According to Höjer and Wangel [142] the concept of smart sustainable cities (SSC) can provide advantages in using ICTs to promote urban sustainability among planners, IT companies and policy maker. They indicated the positive effects of smart sustainable cities (SSC) which can be a common framework or joint vision for developing new framework models and green infrastructures. According to another definition "*A smart sustainable city (SSC) is an innovative city that uses information and communication technologies (ICTs) and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social and environmental aspects"* [143].

The Live Singapore project developed by MIT Senseable City Lab [144], is one example of innovative city projects that focus on achieving goals related to smartness and sustainability (Figure 4.7). It can not only provide access to relevant real-time data but also offer number of applications including weather forecasts to monitor energy consumption.

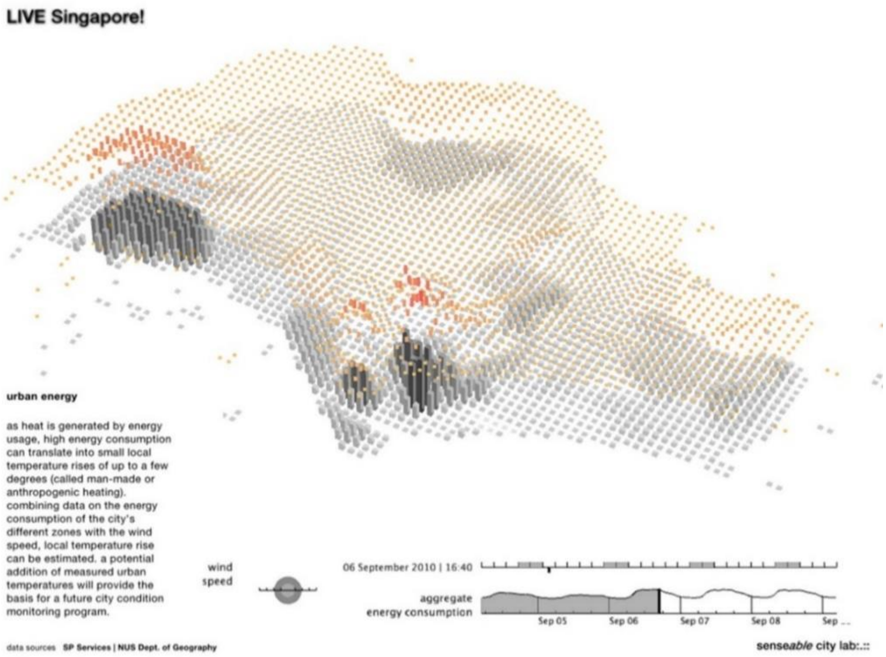


Figure 4.7: One example of urban heat islands (Live Singapore) [144].

4.1.3 Energy harvesting

The imminent depletion of fossil fuels and energy consumption growth have led to the development of renewable energy policies and programs. Renewable energy sources such as wind, solar, hydroelectric and geothermal energies can make significant contribution to energy supply. They can play an increasingly active role in reducing air pollution and maintaining a healthy natural resource. In fact, all renewable energy sources are forms of sustainable energy. According to Renewable Energy and Efficiency Partnership [145] sustainable energy is effectively, the provision of energy in such a way that it meets the needs of the present without compromising the ability of future generations to meet their own needs. Today, renewable energy technologies are mostly used to promote energy sustainability and harvest renewable energies (Table 4.1). They provide the ways to produce and deliver energy. Furthermore, they attempt to fill the gaps between energy sources and energy harvesting process.

According to Evans et al. [146], renewable energy technologies are expected to take the leading role in the forthcoming energy generation portfolio in order to achieve sustainable energy generation. The major constraints for increasing penetration of renewable energy sources is their availability and intermittency which can be addressed through energy storage when available and energy use when needed.

Table 4.1: Energy harvesting sources and systems. Source: Author.

Energy fields	Source	Transducer
Solar	Sun, passive strategies	Photovoltaic (PV) cells, solar panels, batteries
Wind	Wind power, wind farms	Wind turbines
Thermal	Fossil Fuels (natural gas, wood, oil, etc.), temperature gradients	Thermoelectric elements
Artificial lighting	Fluorescent , incandescent, LED, halogen, horticultural , etc.	Photoelectric, light meters
Piezoelectric	Crystals, certain ceramics, etc.	Piezo elements
Mechanical (vibration)	Machines, waste rotations	Electromagnetic
Radiation	Light, solar, electromagnetic radiation	Magnetrons
People	walking , running	Piezoelectric, electrostatic

Today, the use of renewable energy technologies have grown increasingly. For example the development of photovoltaic (PV) systems, due to their lower installation costs and enormous potential for energy production, has significantly increased. Photovoltaic (PV) systems can make a great contribution to supply sustainable energy. In this respect, the Masdar City Centre project developed by Laboratory for Visionary Architecture (LAVA), was one of the first aiming toward zero-carbon and zero-waste city (Figure 4.8). It was designed by sustainable technologies such as photovoltaic (PV) systems and sunflower umbrellas.

Figure 4.8: A view of Masdar City Centre [147].

The use of ‘solar potential maps’ is widespread in many smart cities with the intent of promoting renewable energy generation through photovoltaic (PV) systems. The objective of these maps is to increase the environmental awareness of residents, reduce greenhouse gas emissions and to improve the sustainable image of a city through the expansion of solar energy technology [148].

Segments of smart cities are infused with technologies capable of harvesting energy from the environment power sources (Figure 4.9). For example, it is possible to harvest power from human activity via piezoelectric materials as new concept for alternative energy.

It has become evident that ICTs can provide real-time information about energy supply and consumption and directly control electric power. Indeed, real time data on energy consumption reveals the real usage of the city, which is extremely useful for social and economic policy making, since more accurate design and greater acceptance of policies is likely, based on updated information [149].

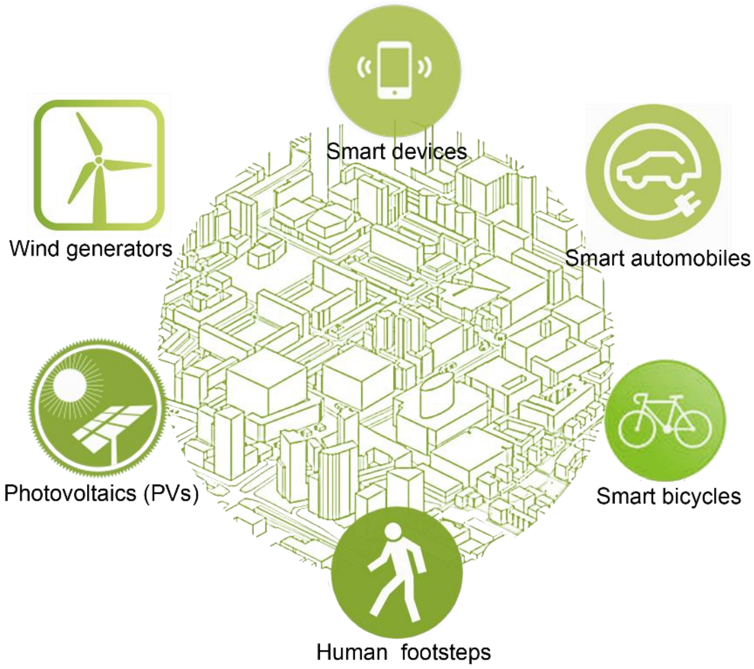


Figure 4.9: The most significant energy harvesting strategies for smart cities. Source: Author.

Recently, European researchers have developed smart energy harvesting sensors that can convert mechanical energy into electricity-generators. This innovation is a key enabler for smart cities, environmental and pollution monitoring and effective disaster management, among many other applications [150].

In the context of smart cities, it is very important to decrease energy consumption of smart devices. Various energy harvesting technologies such as solar, thermal, wireless, and piezoelectric offer new possibilities to harvest energy from the sun, heat or vibrations. As mentioned before, Internet of Things (IoT) can be used to decrease energy consumption of smart devices. In fact, it provides an efficient model of use based on user requirements. The Internet of Things allows users and devices to be connected anytime and anyplace which can help provide the necessary data to adjust the comfort level and to optimize the use of energy in HVAC systems. Moreover, it offers a seamless interconnection between users and devices.

To harvest information from the environment (sensing), visualization is a key requirement for Internet of Things (IoT). It allows interaction of the users with the environment to harvest energy more efficiently. With application of Internet of things, the problems regarding sharing of weather forecast data and information can be resolved during optimization. Another example to illustrate methods of energy harvesting, is Copenhagen Wheel (Figure 4.10) which was developed by MIT Senseable City Lab [151]. The Copenhagen Wheel is an electric bike with regeneration and real-time environmental sensing capabilities. The wheel harvests the energy user input while braking and cycling and stores it for when users need a bit of a boost. At the same time, sensors in the wheel collect information about air and noise pollution, congestion and road conditions.

Figure 4.10: Copenhagen Wheel developed by MIT Senseable City Lab [151].

4.2 Integration of Renewable and Sustainable Energy Sources

Zero-energy is one of the most fundamental goals of sustainable development. The integration of renewable energy sources into power systems has major impact on moving toward zero-energy buildings and cities. It also can play a significant role in reducing CO_2 emissions. Therefore, it is essential to focus on promoting renewable energies in the built environment to achieve net-zero energy goals.

It is clear that renewable energy sources can supply building energy. However, fossil fuels such as coal, oil, gas, etc. are being increasingly used in the build environment and these can cause the environmental problems such as global warming.

According to IEA (2010a) report [152], the current global energy systems are dominated by fossil fuels and renewable energy sources are significantly less likely to contribute to energy supply (Figure 4.11). However, it is important to consider that the use of renewable energy sources such as wind, solar, hydropower, geothermal, etc. can save money and reduce carbon emissions.

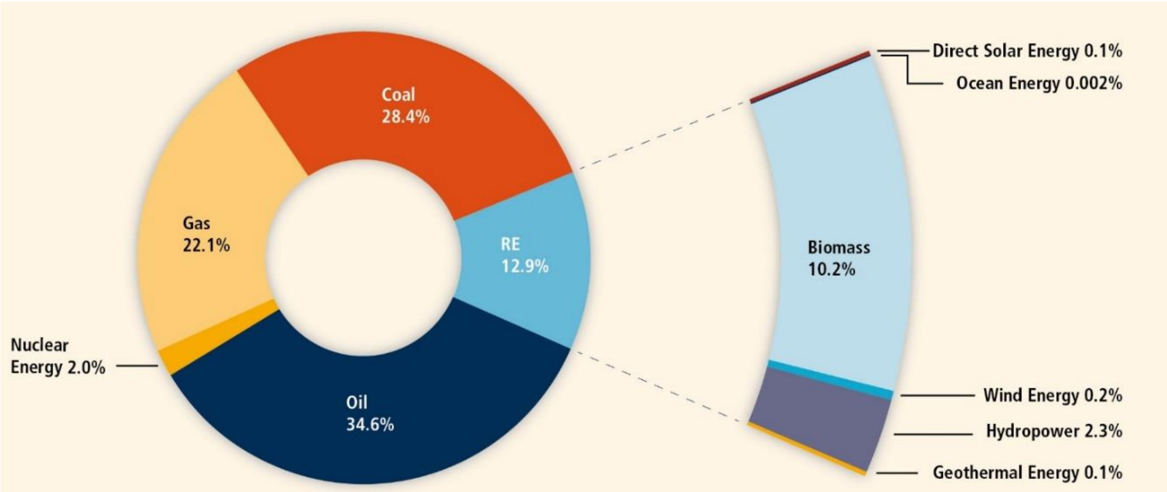


Figure 4.11: Shares of energy sources in total global primary energy supply in 2008 [152].

As mentioned before, renewable energy technologies have made major contributions towards increase environmental and economic benefits. Although, renewable energy technology for a given area or location is typically faced with a range of conflicting environmental, socio-economic and technical criteria [153], it is still significant technology that can offer clean and sustainable energies. Furthermore, renewable energy technologies have greater potential to meet the vast majority of electricity needs. Therefore, they should be taken into consideration in planning and design of built environment infrastructures. For instance, renewable energy technologies such as solar photovoltaic (PV) systems, heat pumps, hydropower systems and wind power generation systems have specific effects on smart sustainable infrastructures (SSI). They can support them to mitigate climate change without applying any other policies and strategies.

It is important to point out that investment in renewable energy is both worthwhile and important. For example, one major path to reduce human impact on global warming is to design buildings and building renovations that have minimal energy demands and meet those demands with renewable energy rather than fossil fuels. According to the International Energy Agency (IEA), renewable energy investments allow efficient buildings to be powered more easily, particularly when these renewables are not grid-connected [155].

4.2.1 Opportunities to develop passive design strategies

Passive systems are strategies that can be integrated into the buildings to perform the functions of heating, cooling and daylighting without using any mechanical systems or additional tools. Passive systems consist of the main principles that can provide the optimum comfort conditions through taking advantage of the natural climate, building form, orientation and building elements. They are also used to improve user requirements by using natural environment possibilities.

A comprehensive review of benefits of solar energy, natural daylighting, ventilation and other environmental factors can help provide a better understanding of passive systems. For instance, the main feature of passive solar systems is to contribute to the achievement of heating and cooling requirements. Passive systems can not only improve indoor environmental conditions but also offer a number of potential benefits for promoting sustainable development and environmental management.

The growth of technology has led to the development of strategies to obtain the maximum benefit of passive systems (Figure 4.12). For example, double skin envelopes are mostly assimilated to improve the indoor environment with passive systems. They allows air to move through the vent systems. In this context, automatically controlled solar shading devices are integrated to maximize use of natural daylight. In addition, embedded wireless sensors and actuators are implemented into louvers to control temperature.

Figure 4.12: A new green complex for Singapore designed by Foster + Partners [156].

The building envelope plays the most important role in developing passive design strategies. Turrin et al. [157] indicated important role of performative skins for passive climatic comfort. The study includes an integrated design approach based on daylight and solar exposure of the covered spaces. They discussed how performance based exploration is accomplished using a tool called ParaGen. The potential of the method is shown in a case study of the SolSt roof which can prevent overheating through designed modular cladding and extract heat through top openings due to the stack effect in the summer conditions (Figure 4.13).

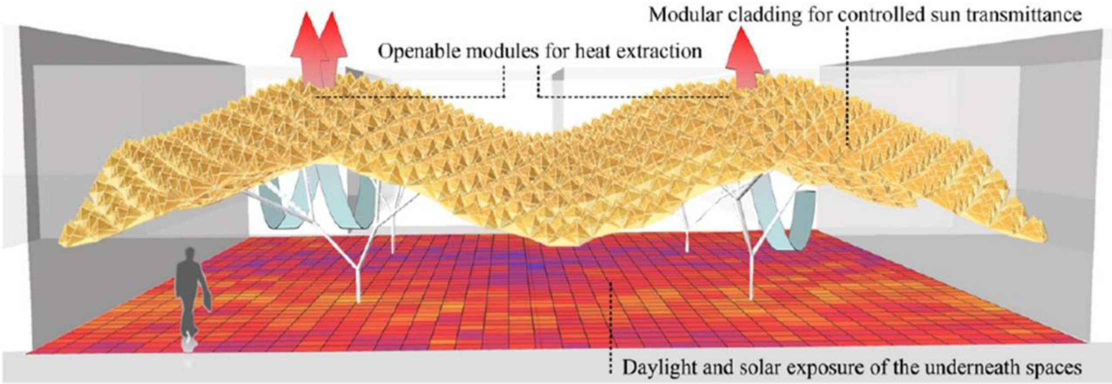


Figure 4.13: Scheme of the concept developed for SolSt [157].

In the context of passive strategies, Nicol and Roaf [158] highlighted that the temperature is not decided by the building engineer, but by building characteristics such as building form, orientation, materials, shading devices, etc.

Passive cooling systems are among the most important design strategies that can provide natural ventilation and influence indoor comfort. They are believed to improve the performance of buildings in terms of energy efficiency and are divided into main categories such as ventilated cooling, radiant cooling, and indirect evaporative cooling. Passive cooling systems are widely used in buildings because of their lower initial and maintenance costs compared to air conditioners. They reduce the energy required for building cooling.

It should be pointed out that smart and mechanical systems are used in order to achieve more efficient and improve passive cooling systems. In this respect, hybrid ventilation and smart passive systems are the most influential strategies for providing substantial energy savings. According to Jagpal [159], hybrid ventilation is a two-mode system that can minimize energy consumption while maintaining acceptable indoor air quality and thermal comfort. The two modes refer to natural and mechanical driving forces. The study [160] indicated that the active mode reflects the external environment and takes maximum advantage of ambient conditions at any point in time. It also pointed out that a hybrid system unlike a conventional system, has an intelligent control system that can switch automatically between natural and mechanical modes in order to minimize energy consumption.

The main hybrid ventilation principles are categorized into three types as follows: a) natural and mechanical ventilation; b) fan-assisted natural ventilation; c) stack and wind-assisted mechanical ventilation (Figure 4.14).

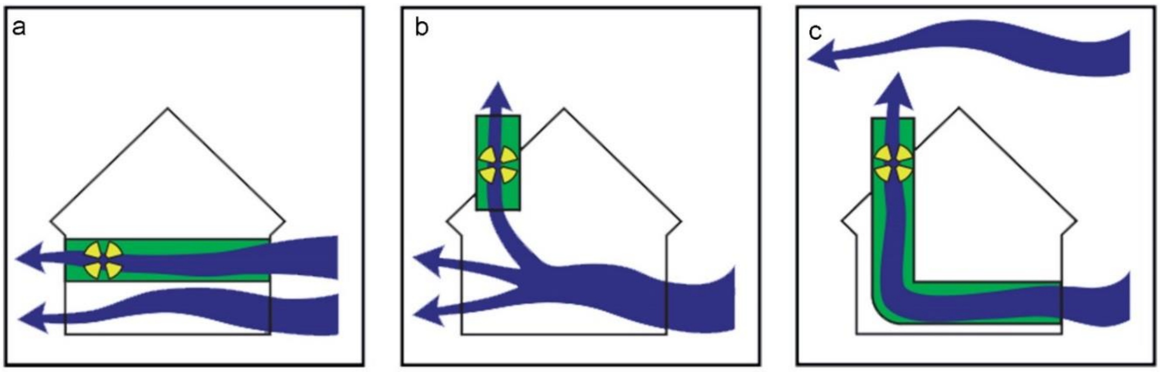


Figure 4.14: The main hybrid ventilation principles [160].

Smart passive systems are new and emerging technologies that help improve conventional ventilation systems. A prototype microcomputer-controlled thermostat was designed and tested by Roche at the University of California Los Angeles (2001, 2002, 2003, 2004) [161]. It can be used to optimize the use of forced ventilation for structure cooling in a building (Figure 4.15). In this experimental system, there is a microprocessor controller that connects to a thermistor and measures temperature. A computer (data logger) can also collect and store experimental data. And a fan and damper are used to adjust cool air. In this regard, Roche et al. [162] have also developed a smart green roof which can produce a cooling effect in the summer and a heating effect in the winter through a series of automatic fans (Figure 4.16).

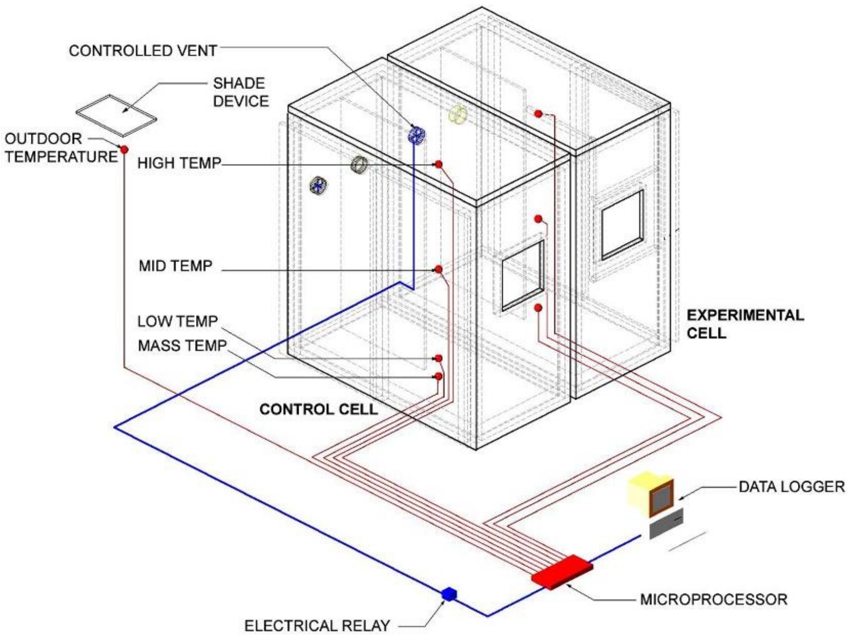


Figure 4.15: Smart ventilation experimental system developed by L. Roche and Milne [161].

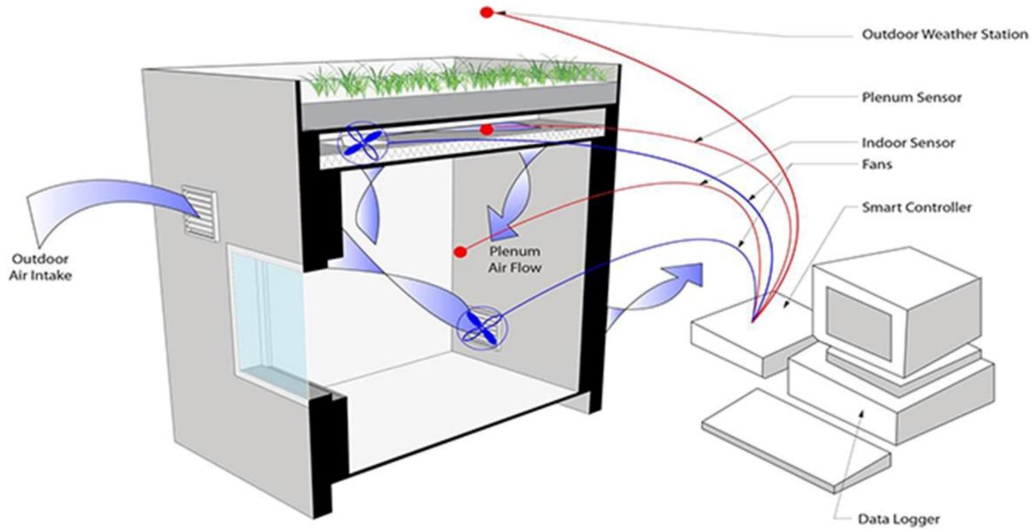


Figure 4.16: Smart green roofs developed by Roche et al. [162].

Generally it can be assumed that natural ventilated and hybrid ventilated buildings are controlled by users, by automated systems or a combination of both [163]. User control has been shown to play an important role in modifying indoor thermal conditions [164]. Roetzel et al. [165] carried out a comprehensive review on investigating effects of user behavior on controlling natural ventilation in buildings. They indicated that user control of natural ventilation depends on a variety of influences and the user's perceived control might not only depend on the presence of openable windows, but also on other parameters like window opening type, window size, shape and placement. Furthermore, Schakib-Ekbatan et al. [166] evaluated the interaction of users with natural ventilation by monitoring of an office and showed that that behavior profiles of window opening give helpful hints regarding the interaction between building and users.

4.2.2 Integration of hybrid renewable energy systems (HRESs)

As mentioned before, renewable energy systems are being used for supplying energy to buildings and cities. It is clear that the combination of renewable energy sources which is called a hybrid renewable energy system can increase dependability and performance of connected systems. The optimum design of hybrid renewable energy systems (HRESs) can significantly reduce emissions and costs. HRESs are cost effective and reliable way to produce renewable energy sources at the same time.

As previous studies have shown, renewable energy sources, especially wind and solar PV have significant environmental advantages and benefits for sustainable development. However, they are faced with challenges regarding weather and climatic conditions. For example, the presence of wind energy is extremely unpredictable and cannot be extracted any time and also because of the unpredictable shadows cast, solar irradiation levels vary throughout the day. So, the combination of wind and solar PV can not only provide a bigger energy supply but also can compensate for load fluctuations when a source is unavailable

(Figure 4.17). According to Nakata et al. [167], renewable power from wind and solar PV is intermittent, therefore, it would be difficult to provide a stable energy supply using only one renewable energy source [168]. In this context, there are several studies in literature that highlight the importance of combining solar PV and wind energy systems instead of single system [169- 173].

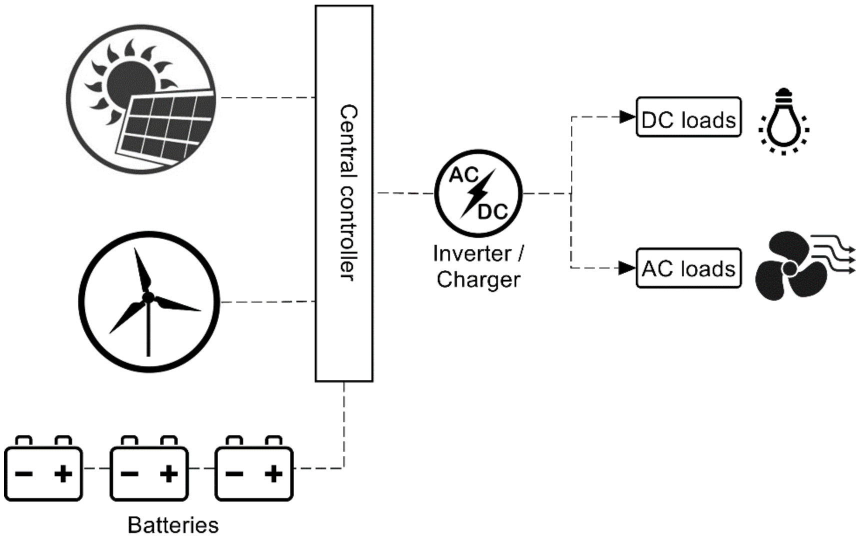


Figure 4.17: Schematic diagram of wind-solar hybrid system. Source: Author.

The main objectives of hybrid renewable energy systems (HRESs) are not limited only to provide electricity, but also includes benefits that can be summarized as follows:

● Reduction of carbon dioxide (CO_2) emissions

● Development of cost-effective energy systems

● Delivering high quality and reliable power

● Ability to be upgraded through grid connections

In addition to the above mentioned techniques, photovoltaic - thermal (PV/T) is a type of hybrid system that can produce electricity and heat at the same time. PV/T systems combine the solar thermal and solar photovoltaic in a single unit (Figure 4.18). They are considered to have the greatest potential for use in solar energy conversion.

A number of studies have examined the potential benefits of PVT systems to convert solar energy into both heat and electricity [174-178]. PV/T systems have environmental and cost savings benefits compared to conventional collectors. They can be classified as PV/T water system and PV/T air system. The main benefits of photovoltaic/thermal (PV/T) can be summarized as follows:

● Complying with environmental and pollution regulations

● Occupying less area compared to conventional power generating systems

● Contributing to a reduction in air pollution and the environmental impacts of energy consumption

● Ensuring quick payback period and high return on investment

● Achieving high efficiency of PV cells by decreasing their temperatures

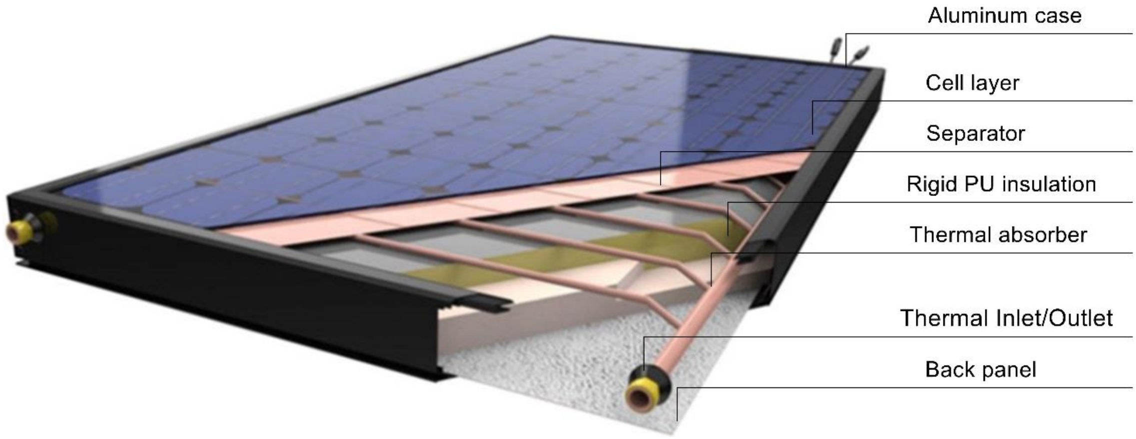


Figure 4.18: Illustration of PV/T system [179].

It is important to emphasize that the performance of a PV/T system depends on a number of factors such as solar irradiance, wind velocity, ambient temperature, inlet fluid temperature and operating temperatures of components. The thermal energy output of the PV/T can be used for several purposes such as production of sanitary hot water, heating or cooling domestic, preheating of ventilation air in offices, etc. It is also worth noting that PV/T systems are able to reduce the PV cell temperature and ambient temperature significantly.

4.2.3 The role of zero-energy buildings

A zero-energy building is known to be capable of balancing its own energy production and consumption close to zero. According to Abel [180], a zero-energy building is "*A building that is used for developing and testing new technologies with focus not only on decreasing energy demand for space heating, but also to decrease the need for electricity".*

In fact, zero-energy building (ZEB) is a building concept that provide its own energy needs (including electricity) through renewable energy-based off-grid systems (Figure 4.19). For example*, "Zero Net Energy Buildings are buildings that over a year are neutral, meaning that they deliver as much energy to the supply grids as they use from the grids. Seen in these terms they do not need any fossil fuel for heating, cooling, lighting or other energy uses although they sometimes draw energy from the grid"* [181].

Nowadays, the development of low-energy buildings and zero-energy buildings (ZEBs) is vital to move towards energy efficient and sustainable buildings. In order to achieve zero or low energy targets in the building, it is essential to use the design process that minimizes the needs for active mechanical systems. In this respect, passive design strategies and user collaboration scenarios can play a key role in achieving the objectives and targets of zero- energy buildings (ZEBs).

It is clear that ZEBs have a leading role within the vision of smart cities or zero-energy cities. They can contribute significantly to reducing energy consumption and carbon dioxide emissions in the smart cities. In addition, they are able to address challenges regarding renewable energy generation, energy management and carbon footprint.

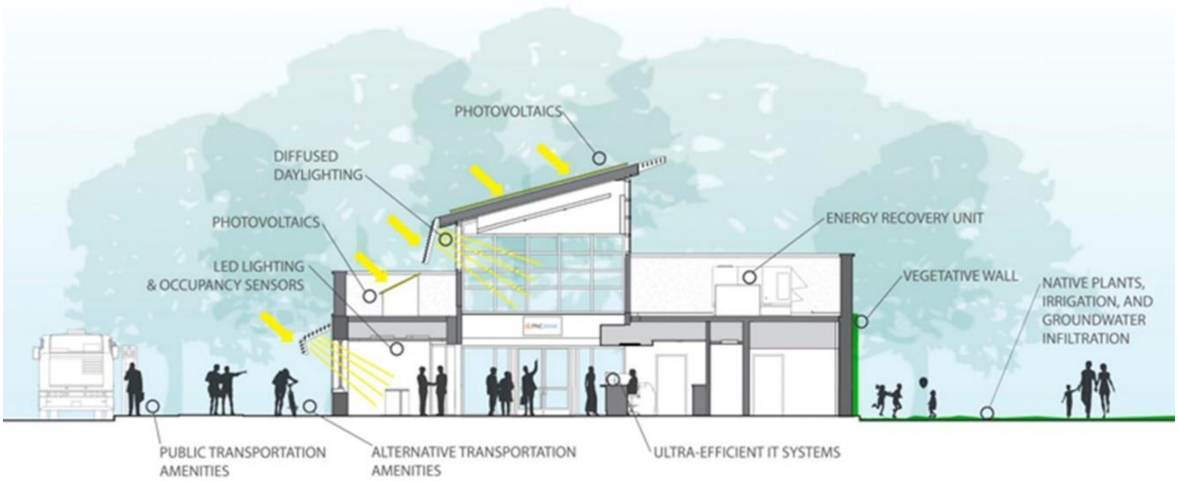


Figure 4.19: An example of a zero net energy building (the PNC Bank, Florida) [182].

As mentioned before, zero-energy building is considered as a self-sufficient building that can provide its own energy needs from renewable sources produced on-site without connecting to energy networks. The vision of zero-energy buildings can contribute to address the sustainability objectives and sustainable value chains in the built environment (Figure 4.20). For example, it is possible to predict the development of sustainable value chains when zero energy has been achieved in the buildings.

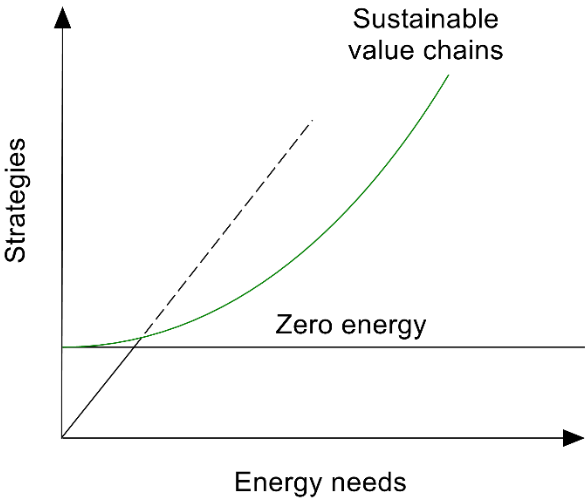


Figure 4.20: Overview of relationship between zero energy and sustainable value chain.
Source: Author.

The development of zero energy buildings (ZEBs) with high indoor environmental quality (IEQ) is one of the key goals of sustainable built environment. To accomplish zero energy goals, users can play a substantial role in maintaining environmental quality. In the field of zero energy buildings with high indoor environmental quality, it is essential to explore the interactions between users and buildings to reach zero energy (Figure 4.21). There is clearly a need to manage environmental factors which can help improve environment possibilities and make energy saving improvements. This may involve exploring methods to enhance naturally ventilation and daylighting.

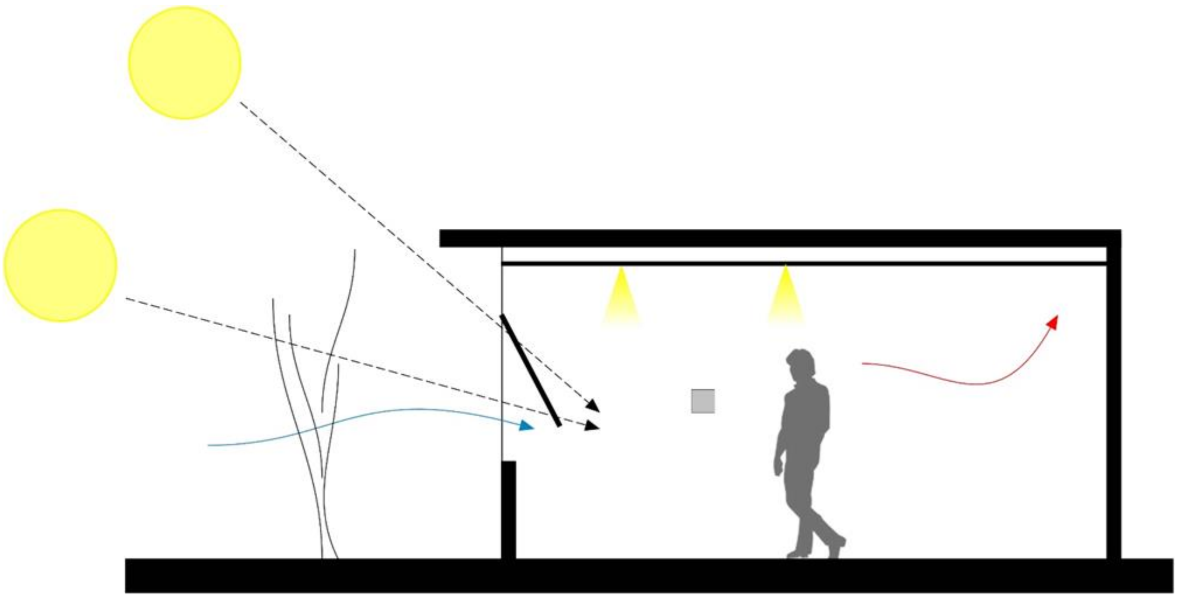


Figure 4.21: Schematic drawing of relationship between user and indoor environment. Source: Author.

It is known that users can manage environmental factors and reduce energy demand in buildings. Determination of the optimum value of environmental factors is one of the most important steps to achieving savings of energy. In order to examine the role of users in improving environmental quality, it is essential to understand environmental factors that affect user comfort in the indoor environment (Figure 4.22).

The possibility of users interacting with the management of the indoor environmental quality may lead to a significantly increase in energy efficiency and improve environmental comfort. Furthermore, it can help buildings achieve zero energy target. Although there are no specific control regulations, users can provide appropriate low energy behaviors for their climate conditions in the buildings.

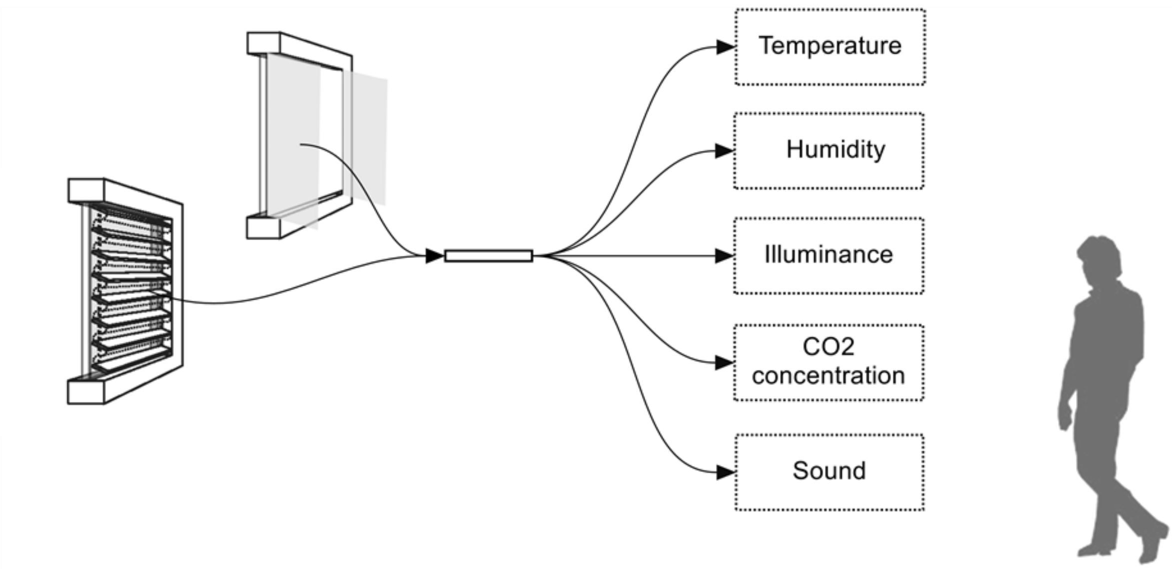


Figure 4.22: The most important environmental factors that affect user comfort. Source: Author.

4.3 Sustainable Development and Refurbishment Strategies

The concept of sustainable development has spread widely in order to meet environmental and energy needs. It has rapidly emerged as an important approach for the conservation of the natural and built environment. Buildings can make significant contributions to sustainable development. Refurbishment of buildings can provide key opportunities to achieve the goals of sustainable development. Refurbishment can be seen as an opportunity not only to modernize a building's appearance but also to enhance its overall technical performance [183]. In this context, sustainable refurbishment has significant environmental benefits to buildings.

4.3.1 Overview of sustainable refurbishment

Sustainable refurbishment promotes development of renewable energy sources (RESs) in buildings. It also helps to enhance indoor environmental quality (IEQ), technical quality, healthy, efficiency, adaptability and usability in buildings (Figure 4.23). Indeed, it is used to refer to methods for upgrading energy, indoor environment and comfort in the existing buildings and can help buildings achieve an optimum indoor environment and optimum energy efficiency. Therefore, it is essential to promote awareness of sustainable refurbishment issues.

Figure 4.23: Impact of sustainable refurbishment on environmental performance. Source: Author.

The sustainable refurbishment of building facades and external walls is among the most efficient ways of improving energy performance and indoor environmental quality (IEQ). It is also a promising approach to sustainability initiatives. Sustainable refurbishment models are considered as key scenarios to reduce energy demand, CO_2 emissions and environmental footprint.

However, architects and designers are not always influenced by attitudes towards sustainable refurbishment or sustainable development. For instance, Prix [184], co-founder of the Coop Himmelb (l) stated that "*sustainability belies signification – and it is therefore not possible to generate 'aesthetics' from the term sustainability. There is no such living aesthetics of sustainability as that of modernist architecture*". It is obvious that Prix's statement does not refer to the general state of sustainable development and practice. Therefore, it cannot be considered. There are several sustainable architectural projects that have certain aesthetic properties. The Arup Building (University of Cambridge) is an example of sustainable refurbishment projects which attempts to demonstrate the highest levels of environmental sustainability and be an exemplar of how to enrich and conserve biodiversity in an urban setting [185] (Figure 4.24). In fact, environmental issues and challenges are solved along with increased attention to the aesthetics in the field of sustainable refurbishment.

Figure 4.24: Sustainable refurbishment of the Arup Building, University of Cambridge [185].

Furthermore, the HPZ central building of the Department of Physics in ETH Zürich is considered as a sustainable renovation project. It involves a net-zero emission strategy as "LowEx" which supplies energy demand through geothermal probes, hybrid collectors and heat pumps (Figure 4.25). Additionally, a decentralized mechanical ventilation unit has been integrated to supply fresh air and appropriate insulation is used to keep temperatures at comfortable level.

Figure 4.25: The renovation and refurbishment of building HPZ [186].

However, in order to improve the sustainability of refurbishment projects, it is necessary to integrate promising innovative tools and information and communications technology (ICT) services. Innovative systems can not only develop efficient solutions but also accelerate the development of optimal comfort conditions. In this context, integrated project delivery (IPD) and building information modeling (BIM) are used as the most significant strategies to assist sustainable design.

According to American Institute of Architects (AIA), integrated project delivery (IPD) is defined as follows "*a project delivery approach that integrates people, systems, business structures, and practices into a process that collaboratively harness the talents and insights of all project participants to optimize project results, increase value to the owner, reduce waste, and maximize* efficiency through all phases of design, fabrication and construction" [187]. The development of IPD approaches can not only provide a detailed understanding of the project but also enable exploration of alternative methods to achieve the project goals. In the context of architectural practice, especially in areas of sustainable design, innovative digital environments and tools can provide useful insights. For example, building information modeling (BIM) has become ubiquitous within the architectural sustainable design for addressing the issues related to a full lifecycle of a target project. BIM can offer an opportunity for extending the life-cycle analysis of buildings. In this respect, it is possible to claim that building information modelling (BIM) is a part of ICT development.

BIM is able to solve complex challenges in refurbishment projects. It can play a role in determining optimization requirements. It is considered as a long-term vision for building renovation. Furthermore, BIM is more cost and time effective to assess the sustainability of refurbishment projects and can contribute to economic growth.

According to Kensek [188], BIM is collaborative, encouraging the sharing of data, knowledge, responsibility, risk and reward. It fosters integrated project delivery (IPD), while still providing benefit to projects under other types of project delivery contracts such as design–bid–build, design–build, or CM (construction manager) at risk. As part of her book she points out that how a relatively small architecture firm can tackle larger projects because of the use of BIM (Figure 4.26). The Claire T. Carney Library is part of one of the most significant experiments in postwar concrete Brutalist architecture that has been renovated by designLAB Architects to meet contemporary needs. It is the first project in the office with a contractual obligation for BIM deliverables.

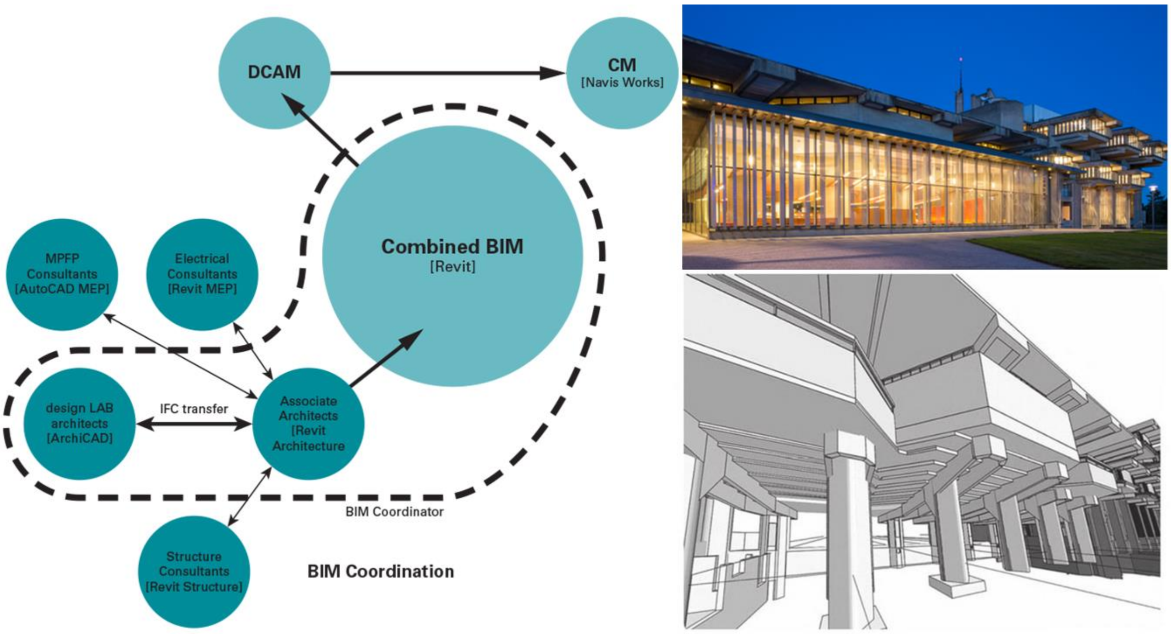


Figure 4.26: BIM implementation plan work flow diagram (left), west façade (top right) and existing conditions building model (bottom right) of Claire T. Carney Library, USA [188].

4.3.2 Technology and sustainable development

Sustainable development is one method to solve issues related to energy supply and the built environment. Furthermore, it seems sustainable development principles can reduce some of the main environmental challenges. In this context, technologies and innovative systems play distinctive roles in balancing strategies according to efficiency and adaptability. The outcomes of the collaboration between technology and the natural environment are expected to meet the principles of sustainable development.

Information and communications technology (ICT) and digital transmission of data have changed sustainable development methods and principles. In a study by Hilty and Ruddy [189] the role of ICT in sustainable development is discussed. Their hypothesis is founded on the “Brundtland definition” this is the definition of sustainable development as that which meets the needs of the present without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development 1987).They point out that the normative implications of the Brundtland definition, if taken seriously, have been underestimated in the discussion of sustainable development during the last two decades and that this underestimation (among other negative consequences) has led to a misconception of the role of information and communication technologies (ICTs) in sustainable development. Furthermore, in their study two points of view techno optimistic and techno pessimistic are discussed. The currently prevailing misconceptions distorting the role of ICTs in sustainable development is a techno optimistic view expressed by the documents produced at the World Summit on the Information Society (WSIS) and a techno pessimistic view expressed by some scholars as an antithesis to the WSIS position. From techno-pessimistic point of view, ICT development could result in pollution and unsustainable structure.

Although ICT applications are still assumed to involve complex arrangement of devices that cannot be easily controlled, they have opened up new possibilities for user interactions with the surrounding environment. Furthermore, they can fruitfully contribute to the move towards more sustainable development and improve spatial and functional qualities of the built environment. For example, ICT based systems play a significant role in energy efficiency and HVAC services [190]. Their study presented control and monitoring strategies to reduce energy consumptions for lighting and air conditioning through both wired and wireless sensor networks.

It is clear that current smart approaches and specific ICT-related applications such as sensors, mobile technologies, networks, big data, etc. can achieve sustainable development goals with physical intervention in the natural environment. A generic description of relevant ICT applications and their impacts on sustainability improvements links together ICT applications, smart objects, and sustainable design objectives (Figure 4.27). ICT applications can provide key contributions to smart and sustainable growth.

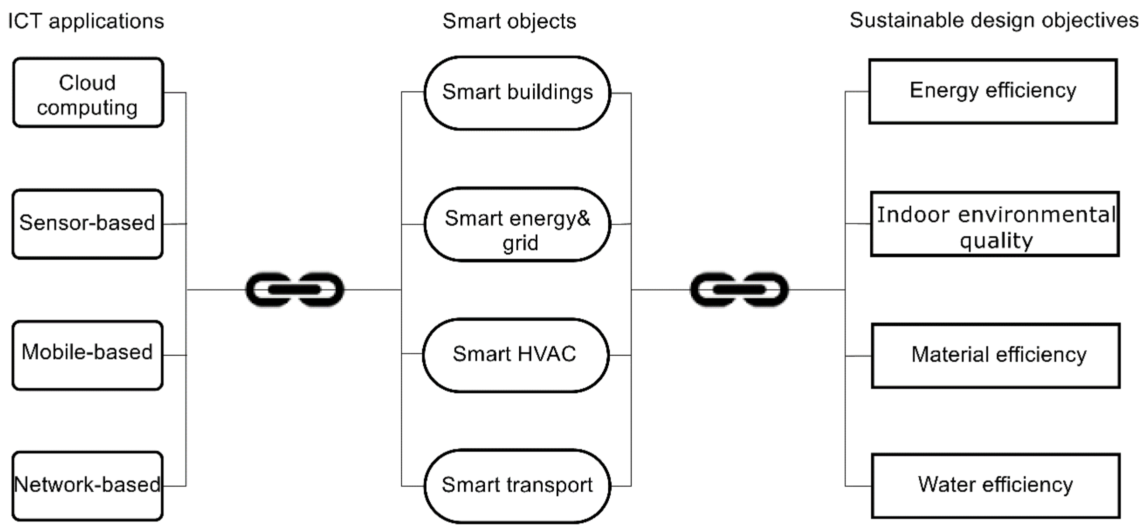


Figure 4.27: Relevant examples of ICT applications and improved results. Source: Author.

There are many initiatives with methods and devices to leverage ICTs for smart sustainable cities and buildings. For example, the eeRegio Wiki is a resource for local, regional and national authorities (cities, municipalities and regions) throughout Europe. The Wiki and forum provide an extensive body of practical advice and examples of good practice in the planning and implementation of energy efficiency initiatives involving ICT [191].

Although ICTs may have side effects associated with energy consumption and incompatible materials, they play significant roles in enabling energy efficiency services in buildings. In order to understand better the impacts of ICTs on sustainable development, it is necessary to compare two main types of direct and indirect effects. As mentioned in the previous sections, ICTs have made major positive impacts to many areas of the built environment including smart buildings, grids, smart transport, etc. Therefore, a life-cycle analysis may be useful to address potential effects of ICT applications on sustainable development and climate change adaptation.

According to SMART 2020 [192], report published by (GeSI), ICT technology can lead to emissions reductions from main sectors such as buildings, transport, industry and power (Figure 4.28). It can be concluded that ICTs should be investigated in depth from climate change mitigation and sustainability goals perspectives.

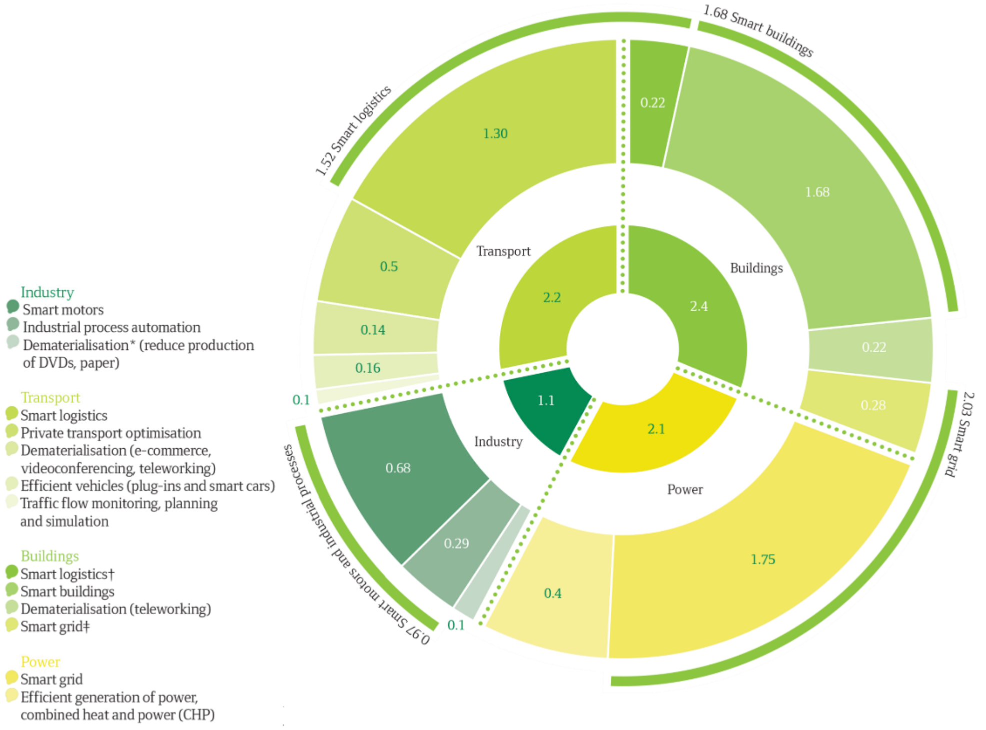


Figure 4.28: The enabling effects of ICTs: Reducing GHG emissions by 2020 [192].

In order to enhance operational efficiency among ICTs, it is necessary to use methods based on key dimensions of sustainable development such as environmental, economic and social. A series of sustainability action plans and targets should be taken into account for the adoption of ICTs and digital technologies prior to launching applications. According to Mitchell [193], there are five main opportunities such as *dematerialization*, *demobilization*, *mass customization*, *intelligent operation* and *soft transformation* for ICTs to make cities and buildings more environmentally sustainable. In the field of intelligent operation, ICTs have potential roles in facilitating energy management in buildings and cities. They can provide pathways to lower energy use through advanced monitoring. Furthermore, the use of ICT applications can help users to better understand and manage energy consumption. It is worth noting that ICTs have a direct impact on user behavior and awareness. The end-user behavior is one of the most important factors for achieving positive systemic outcomes relevant to the use of ICTs in the built environment.

In the context of sustainable development, ICT play an important role in energy savings and comfort conditions. In addition, it can help cities move towards a more sustainable low-carbon. ICT can contribute to the optimization of energy flows and provide more efficient services. The adaptation of sustainability strategies by ICTs can not only generate several development alternatives but also determine the most cost-effective methods. It is important to point out that ICT technologies should be taken into account in advancing sustainable development initiatives.

In addition to the above mentioned interpretations, sustainability program initiatives and innovative sustainable design are considered as the most effective strategies for improving quality of life and the urban environment. For example, Pérez Art Museum and Caixa Forum designed by Herzog & de Meuron, are two examples of innovative projects in sustainable design that have been successful in achieving sustainability goals. In Pérez Art Museum project, hanging garden and tropical landscape are highlighted as sustainability-driven designs and are not only used to create more greenery in the building but also act as natural air purifiers and heat shields. Caixa Forum is a modern art gallery in the center of Madrid and is conceived as an urban magnet. It has been combined with new construction of floors which are encased with oxidized cast-iron. In addition there is a green wall next to the building designed by French botanist Patrick Blanc (Figure 4.29).

Figure 4.29: Two examples of sustainable development projects designed by Herzog & de Meuron, Pérez Art Museum Miami (left) and Caixa Forum, Madrid [194].

4.3.3 Digitalization and visualization of environmental data

Energy efficiency and environmental issues have led to the emergence of digitalization and visualization technologies for analysis of natural and built environments. Geographic information systems (GIS) and building information modelling (BIM) are the most important tools in digitalization and visualization of data regarding natural and built environments. They can provide fundamental adaptation strategies for climate change and sustainable operations. For example, Gong et al. [195] used a 3D GIS-based application to interactively assess the photovoltaic potential in urban areas. They indicated that their framework and its integration with 3D GIS can facilitate the incorporation of multisource geospatial data in analysis and decision making. GIS applications are used for processing, storing, analyzing and displaying data related to locations on the surface of the earth. They include weather-related information like climate, rainfall, and weather activity and they can be used for weather analysis and forecasting. For example, The National Digital Forecast Database (NDFD) is event-driven and covers the contiguous USA, Alaska, Guam, Hawaii and Puerto Rico. It provides a seven-day forecast and contains a seamless mosaic of digital forecasts through GIS applications (Figure 4.30).

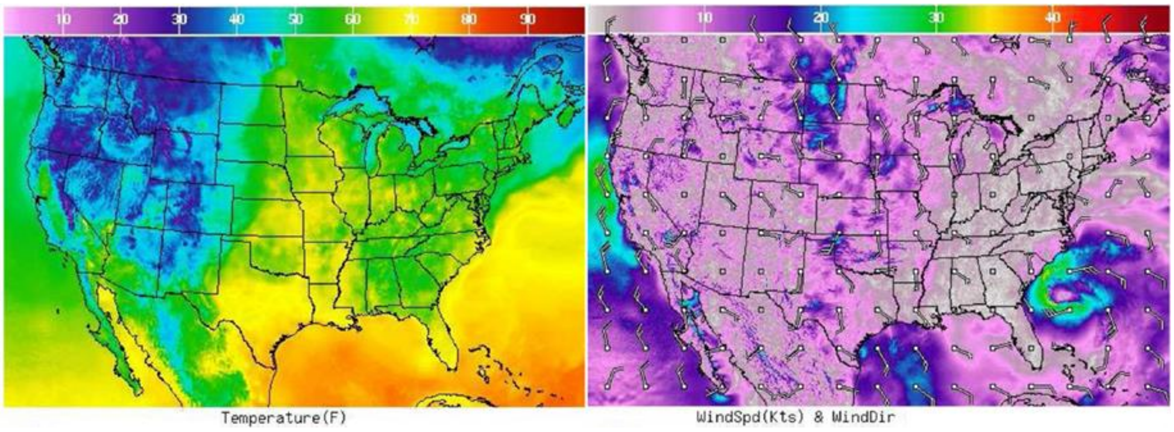


Figure 4.30: Temperature forecast graphic (left) and wind speed and direction (right) [196].

Building information modelling (BIM) is an invaluable tool in the digitalization of the construction industry. It can optimize large-scale projects through digitalization (Figure 4.31). BIM is one of the most promising technologies in the digitalization of city planning and building.

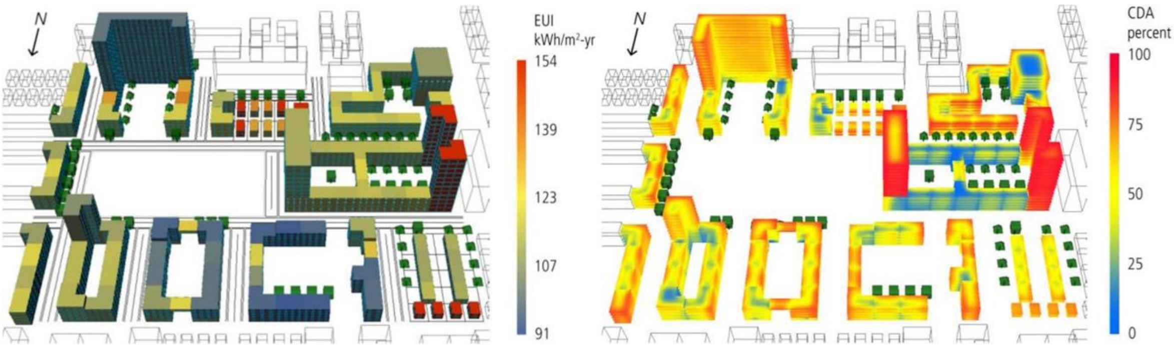


Figure 4.31: Energy and daylighting analysis of a mixed use development in Boston, MA, USA [197].

CHAPTER 5 BUILDING AND CLIMATE CHARACTERISTICS

To improve the environmental performance of built environment, it is necessary to take into account building and climatic characteristics. Building characteristics are determined by a number of factors such as building façade, form, orientation, external, and internal material properties. They are considered as main factors that influence the amount of building energy consumption. Building characteristics should be described in detail and taken into account as the most significant factors for understanding the physical behavior of the building.

The identification of user and building energy use profiles, which are associated with building characteristics, can be considered as the important steps in addressing factors influencing energy expenditure. Understanding building characteristics can be helpful for analysis of energy demand. It also avoids wasting energy through building elements and materials.

The purpose of climatic analysis data in architecture in the form of maps, graphs, diagrams, and tables, is to provide climate and weather forecast models for improving the sustainable design. Analysis of climate characteristics can help to design buildings that meet user needs and reduce negative impacts on ecological systems. From a sustainable design point of view, analysis of climate characteristics is important for evaluating factors involved in dealing with climate change and global warming. Therefore, it is necessary to take into consideration climate characteristics during the early design stage of buildings. The microclimate parameters such as ambient temperature, relative humidity, mean radiant temperature, wind speed can significantly impact on building environmental performance. However, there is still a need to address some of the most important environmental factors for analyzing performance of buildings.

5.1 Application of the Life Cycle Analysis

Life cycle assessment (LCA) is a well-established methodology and a general tool for analysis of the life cycle environmental impacts of resource extraction. It is also used to measure the impact of sustainability and eco-design principles. According to International Standard ISO 14040 [198], LCA is a “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.”
In the context of design of complex systems, LCA can be considered as one of the most important principles and guidelines.

The concept of life cycle thinking what is called the “6 RE philosophy “(Re-think, Re-cycle, Re-pair, Re-place and Re-duce) can be used for creating eco-considerate products and sustainable development (Figure 5.1). It is a basic idea in order to develop efficient methodologies and techniques in the field of built environment. It is also considered to assess the sustainability of a project.

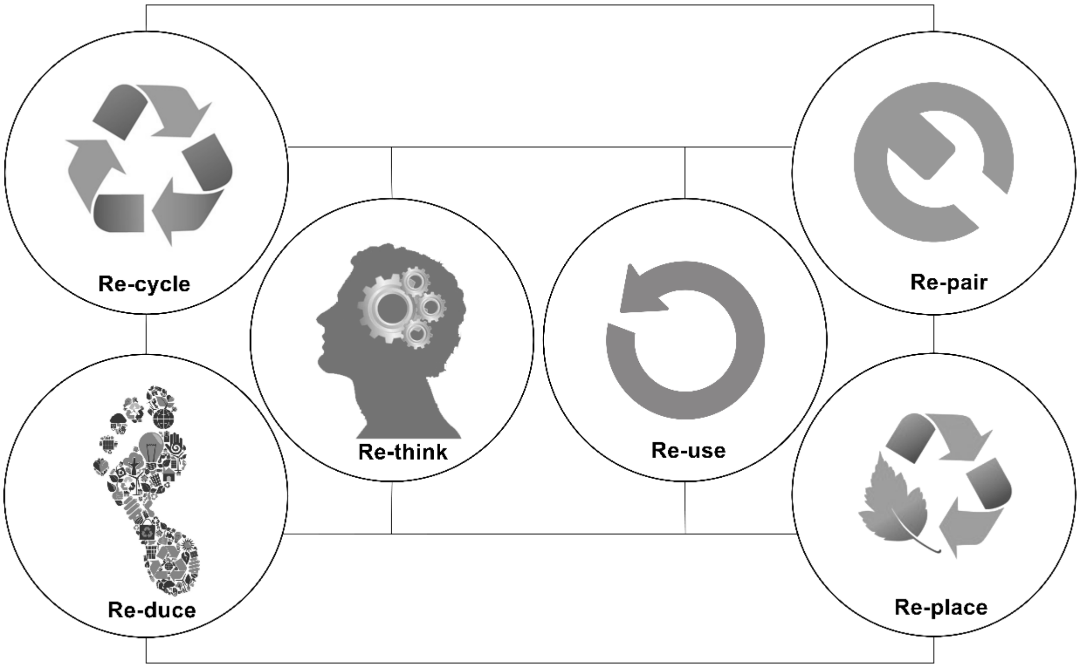


Figure 5.1: The most important contributors to 6 RE philosophy in relation to life cycle assessment. Source: Author.

The main purpose of life cycle assessment (LCA) is to reduce resource consumption and environmental impact of emissions. It is used to describe the positive links between economic and environmental factors. The development of sustainable design with regard to life cycle assessment (LCA), especially during the early phases of building design, can facilitate the decisions of the designer.

LCA can be included in the decision-making process and be involved in solving global environmental problems and concerns. It is the only method that can avoid burden shifting between technologies, territories, life cycle stages, and environmental impact categories [199]. LCA is a systematic approach. It is one of the main contributors to the avoidance of natural resources impacts especially in the building industry.

In order to take advantage of the positive aspects of LCA, the material and energy flows in buildings should be quantified and evaluated individually. LCA is the only tool that is used to determine primary energy consumption for embodied energy of materials. Regardless of limitations of LCA in buildings, LCA is still mentioned as the most appropriate method for a holistic assessment at every stage.

It is important to apply LCA to building design in an accurate and reliable way. For instance, in order to perform an LCA for building materials, different analysis approaches and methods such as material extraction, construction process, manufacturing, use, and end-of-life should be determined.

Life cycle energy analysis (LCEA) is an abbreviated form and important aspect of LCA that measures energy in the life cycle of a building. It is widely used to assess environmental impacts from energy consumption. It also can be considered as a significant tool for calculating the energy demand associated with the manufacture, construction, operation, maintenance and achieving reduction in primary energy use of buildings. LCEA can decrease negative environmental impacts related to energy consumption in the design and development stages. It can help evaluate the areas of energy use, lighting and HVAC systems. In order to promote green and efficient energy strategies, the development of such a LCEA tool can be effective, affordable and appropriate to achieve system design objectives.

According to Ramesh et al. [200], boundary of the building LCEA consists of three phases; production, operation and demolition. LCEA can be considered as a ‘‘streamlining’’ process of life-cycle energy, materials and emissions. It can be used to demonstrate the life cycle benefits of strategies implemented into buildings to optimize energy efficiency at each stage and phase. It is also a significant tool in guiding the development of renewable energy technologies and estimating a system how much energy can produce of a natural flow of energy during its life.

5.1.1 Determination of building energy performance

Energy performance of a building consists of the amount of energy consumed or estimated to meet the different needs associated with a standardized use of the building, which may include, inter alia, heating, hot water heating, cooling, ventilation and lighting [201]. Energy performance is a systematic approach to evaluate the external climatic conditions, indoor conditions and cost factors. It includes criteria to improve the energy in buildings, evaluation of the applicability of renewable energy sources and criteria on how to limit greenhouse gas emissions. Calculation methods for the determination of energy performance are used in conjunction with primary energy consumption.

Simulation and measurement are two important methods to obtain energy use of buildings. The purpose of methods is related to environmental protection and the prevention of energy waste and regulation of the procedures and principles. According to EN ISO DIS 13790 Standard (2007) [202], one of the main standards to determine energy use of buildings, there are two paths for calculating the net energy for heating and cooling as follows: 1) simplified methods based on seasonal, monthly or hourly calculations; 2) comprehensive calculations, typically made with dynamic energy simulation programs.

In the context of building energy performance (BEP), analysis of presence patterns has a significant impact on the reliability of assessments. Therefore, holistic assessment of the energy performance should include key performance indicators based on real-time operational data and user interaction data. Building energy performance (BEP) is a measure of efficiency and comfort. It is widely used to evaluate the performance of energy systems and is expected to determine alternatives expectations in analysis works to meet energy loads with renewable energy. There are several ways of assessing of energy performance in the buildings.

Energy performance certificates are one of the most common methods available that contain information related to primary energy needs (heating, cooling, ventilation, and lighting), insulation properties and information on the efficiency of heating and cooling systems. They show energy efficiency rating of a building based on an "A" to "G rating scale (Figure 5.2).

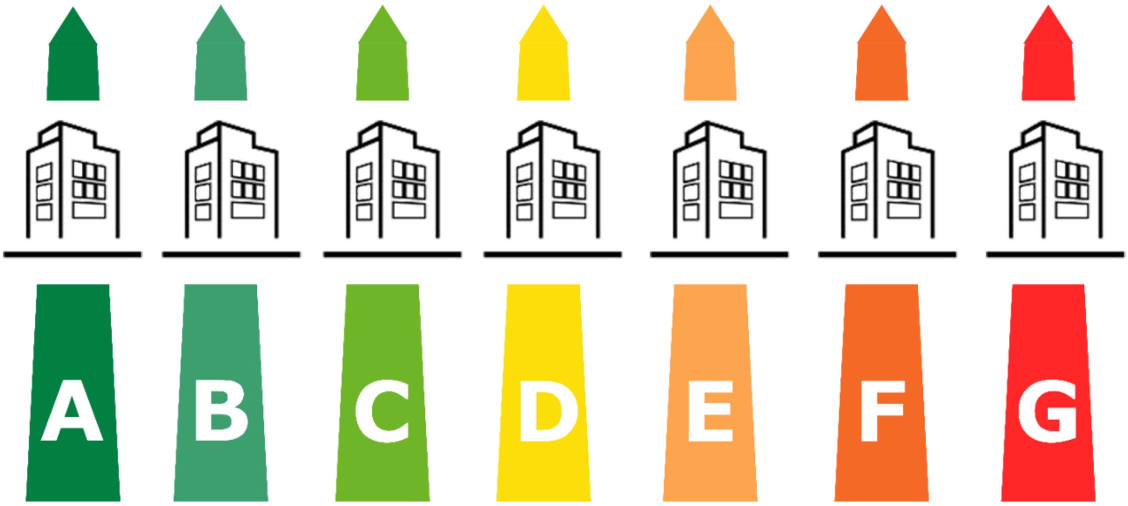


Figure 5.2: An example of an energy performance certificate and rating. Source: Author.

In order to assess the actual energy consumption in buildings, it is essential to collect all data concerning the building envelope, the air-conditioning system, the lighting equipment, etc. In this context, building energy software tools and energy consumption surveys can also be utilized as methods for predicting building energy performance and requirements.

Energy efficiency and environmental awareness in the early design phases may affect whole building performance. Simulation programs play a significant role in decision making, the development of optimization methods, calculating and reporting building energy performance at the early stages of the design process.

Nowadays, building simulation programs are increasingly being used in several studies of energy performance, thermal comfort, lighting, etc. They are commonly classified by their calculation and level methods and are used in order to improve building energy performance or optimize energy consumption.

According to Hensen and Lamberts [203], computational building performance modeling and simulation on the other hand, is multidisciplinary, problem-oriented and wide(r) in scope. It assumes dynamic (and continuous in time) boundary conditions, and is normally based on numerical methods that aim to provide an approximate solution of a realistic model of complexity in the real world.

It should be noted that the primary purpose of energy performance building evaluation, is to develop effectiveness methods for reducing energy consumption and classification of energy consumption patterns.

5.1.2 Definition of the building characteristics

Building characteristics are found to play a significant role in determining the effectiveness of indoor environmental control and condition. There is a lack of understanding about how building characteristics contribute to reducing energy consumption and CO_2 emissions. For instance, the properties of building envelope are the most significant factors that affect energy demand. Buildings gain and lose heat by conduction, convection and radiation through envelopes which varies depending on the building shape and surface area to volume ratio (S/V). Furthermore, window area or window-to-wall ratio (WWR) is one of the major factors affecting energy performance in buildings shows that total energy demand grows when the window-wall ratio also grows (Figure 5.3). It is important to mention that a large amount of energy can be saved though building envelope components.

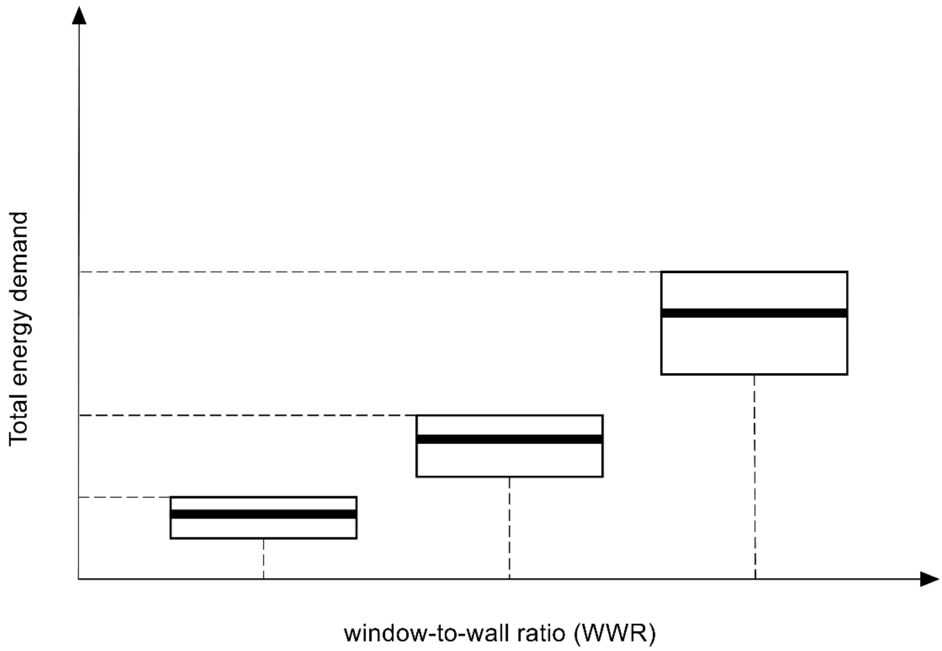


Figure 5.3: The relationship between surface area and volume Source: Author.

To assess the impact of building characteristics on indoor environment and energy consumption, several studies had been conducted among researchers. A study by Santin et al. [204] found that occupant characteristics significantly affect energy use for heating by 4.2%, while building characteristics reduce a large percent of the energy use in a dwelling by 42%.

The information on building characteristics can be gathered by a series of tools and applications. Wireless sensor networks (WSNs) have the ability to determine building characteristics, energy consumption and user behavior in buildings. Furthermore, they can collect and deliver data to corresponding management systems.

Computing the dynamic characteristics of a building is the first and most important step in conducting energy efficiency assessments. An experimental study by Pisello et al. [205] was carried out to investigate the effect of dynamic properties of building envelope on thermal-energy performance in two different envelope typologies (traditional Italian construction technique, and innovative construction) through indoor and outdoor microclimate monitoring equipment (Figure 5.4). The two buildings were designed with different envelope technologies, materials and, therefore, different dynamic properties. The envelopes were found to behave in the same in terms of energy requirement for heating. On the other hand, the thermal-energy dynamics of each test-room presented several observed differences. Study pointed out that observed differences were related to envelope systems and different solar reflectance values of the roofs.

Figure 5.4: View of test-rooms and indoor–outdoor microclimate monitoring equipment [205].

The evaluation of dynamic characteristics and energy performance of buildings can be considered as efficient methods to understand thermal performance of buildings and materials.

5.1.3 Building element analysis

In the context of buildings, envelope elements are increasingly used for the design and evaluation of thermal and energy. Opaque components and transparent components are one of the most important elements of the building envelope. In order to ensure energy savings and comfort in the buildings, building elements need to be fully analyzed before construction process.

The role and importance of elements, especially in the building envelopes, can be categorized according to the environmental performance of materials used. It is necessary to establish a database based on environmental profile of elements which can provide options for renovation projects and energy efficiency schemes. It is also important to analyze the environmental impacts of each of the materials used throughout their life cycle. Performance visualization of building elements can provide a detailed insight into the environmental profile. An example of building element analysis was undertaken by the Harvard Graduate School of Design (GSD) as *"Ceramic Futures"* which was developed for creating an external shading system of unique, high performance, aesthetically pleasing ceramic tile louvers (Figure 5.5). Its performance analysis showed that it has the potential to transform building façade cladding and mitigate energy consumption while improving the quality of life for inhabitants [206].

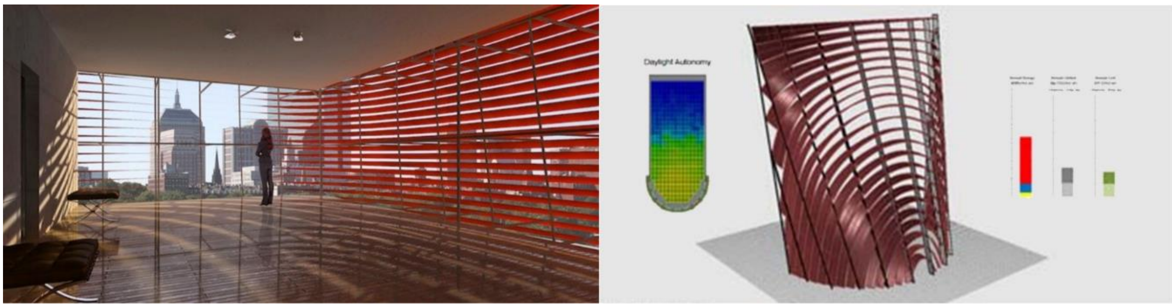


Figure 5.5: Illustration of *Ceramic Futures* developed by Harvard Graduate School of Design [206].

The main goal of building element analysis is to develop optimization scenarios to improve economic and environmental performance. In this context, dynamic building simulation plays a key role in supporting decisions and management process. Building environmental modeling (BEM) is considered as a useful tool for the optimization of environmental models. BEM can help to study the characteristics of building elements and the influence of environmental factors on buildings through computational techniques. For example, Theater spijkenisse designed by UNStudio [207] in collaboration with Arup engineering, is an example project that uses BEM (Figure 5.6). In this regard, Arup engineering helped to manage structural elements, lighting and plant engineering and complex geometry by the use of building environment modeling (BEM).

Figure 5.6: Illustration of the Spijkenisse theatre and its integrated engineering design [207].

In order to develop an efficient building refurbishment, it is necessary to analyze the building elements and material properties. It should be noted that building element analysis can make an important contribution to develop retrofit solutions in terms of energy consumption, comfort and environmental quality. Building elements such as walls, windows, doors, and stairs can play a significant role in determining a building's energy use, thermal comfort and indoor air quality.

5.2 Climate Analysis

Climate is defined as certain conditions of a geographical location based on parameters such as temperature, humidity, wind and solar radiation. Climate condition varies from region to region. It is divided into different types of zones.

The Köppen climate classification system is one of the most widely used tools in determining zones in the world (Figure 5.7). It is classified into five main zones such as tropical, dry, temperate, continental, polar climates according to average monthly temperature and humidity data.

Climate analysis is a method to better understand the spatial and temporal characteristics of climate. It can be useful to advance solutions to sustainable development and climate change. It also be helpful for designing efficient and sustainable buildings. In this respect, climate analysis can be used to create diagrams and graphic presentation of the weather to develop effective and sustainable strategies in the built environment. Climate sensitive approaches are one of the essential requirements for developing adaptation programs. They can address climate risk issues and opportunities. To achieve climate sensitive approaches, it is essential to obtain the understanding of climate conditions and existing environmental conditions. Climate sensitive approaches can play key roles in enhancing microclimatic conditions in urban spaces. The use of a climate sensitive approach can promote the principles of sustainable design in the built environment.

Climate data (weather file) is an important factor for building energy analysis and modeling. In this context, it is important to consider what type of climate data are appropriate for energy models. Furthermore, it is essential to know the exact location of the proposed model in terms of longitude and latitude.

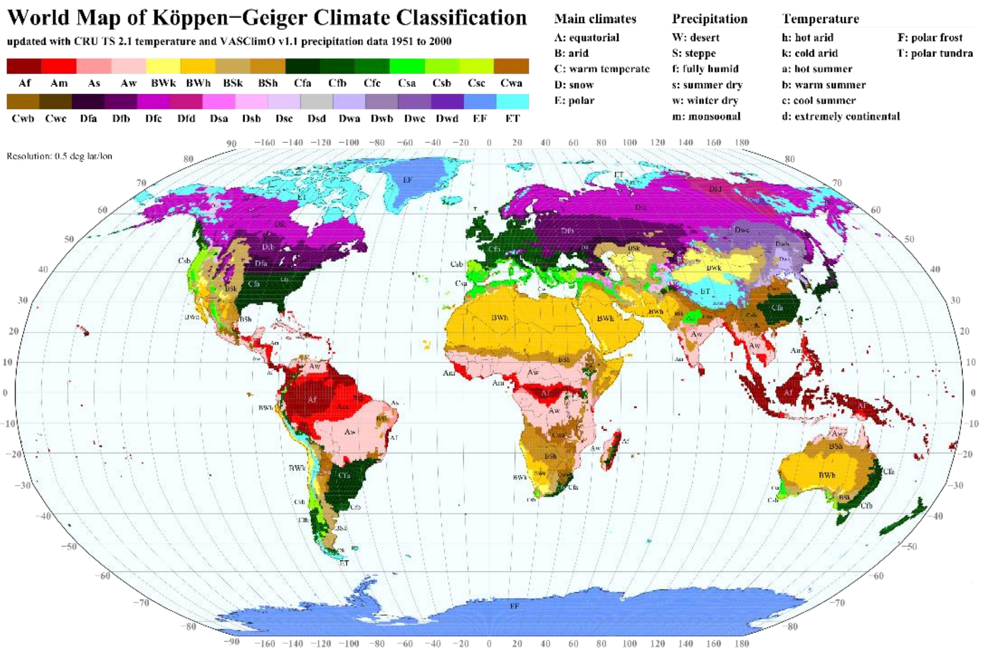


Figure 5.7: Köppen climate classification [208].

5.2.1 Air temperature and humidity

The climate of a location is often influenced by a series of real weather condition segments during a period. It is necessary to determine the essential elements of climate that impact on both natural environment and built environment. Annual temperature, humidity, solar radiation and rainfall profiles are the most important elements of climate. In fact, they can provide more detailed information through diagrams to measure variability in climatic conditions. Each region is frequently represented by the geographic coordinate system which consists of latitude and longitude lines. In order to gain information about actual climate data, it is required to focus mainly on local and annual data profiles. For example, annual temperature profile provides a measure of the seasonal range of temperature. Its value is different from region to region and depends on away from the sun and the sun's rays (Figure 5.8).

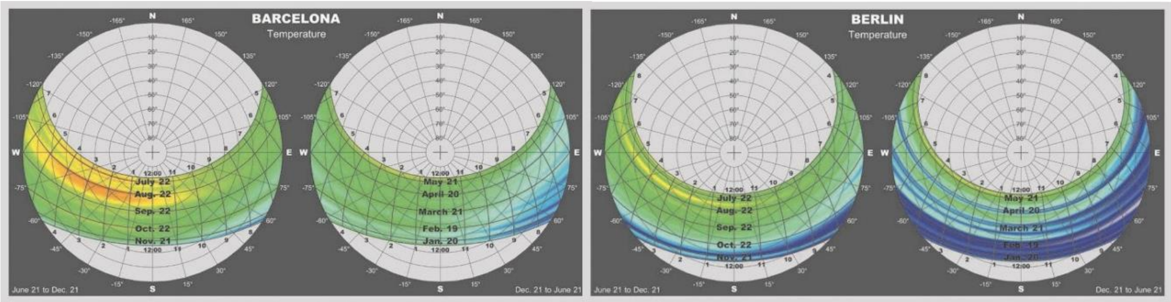


Figure 5.8: Two examples of average temperature profiles (Barcelona and Berlin cities) [209].

The use of annual environmental profiles (e.g. temperature and humidity profiles) can be helpful to predict outdoor thermal comfort conditions. For example outdoor temperatures and weather-related conditions can influence indoor thermal comfort, humidity and indoor air quality. Therefore, it is necessary to carry out a preliminary analysis of outdoor temperature and humidity profiles in order to determine the level of comfort outdoors. To achieve the goal of external environmental comfort level, the values of predicted mean vote (PMV), relative humidity and air temperature should be taken into account.

The analysis of outdoor air temperature and comfort can provide a series of sufficient information for developing effective and efficient design models. A study by Ming et al. [210] developed geometric and mathematical models of wind and thermal comfort to examine the impacts of six strategies such as the border demolition, angle demolition, wedge-shaped demolition, central demolition, interconnected demolition, and scattered demolition on the wind and thermal environment by using user-defined-function (UDF) method (Figure 5.9). Regarding outdoor temperature distributions, they showed that appropriate selection of renewal strategies directly affect outdoor thermal comfort. It can be concluded from the study that urban planning and design strategies can affect outdoor thermal comfort conditions in different types of concepts.

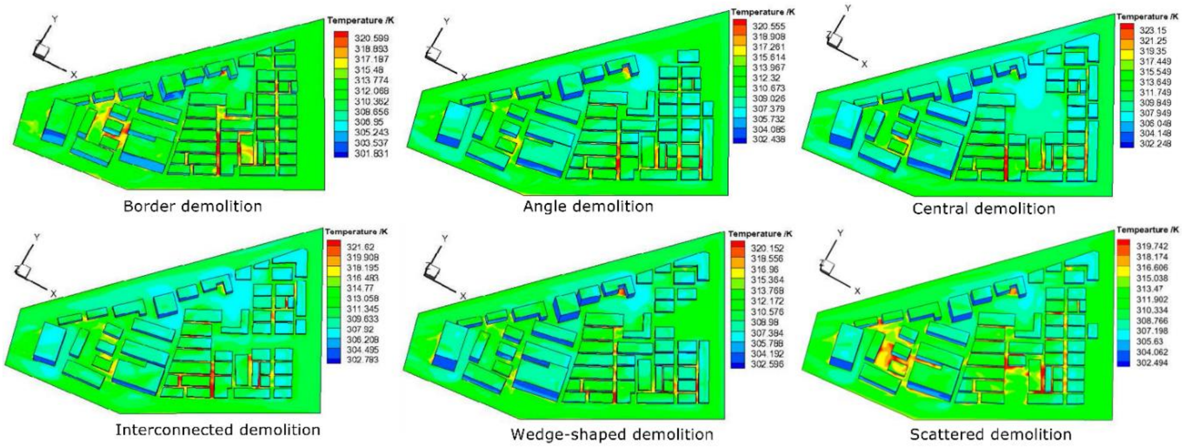


Figure 5.9: Outdoor temperature distributions in the six strategies [210].

In the context of environmental profiles, humidity is another significant factor that affects thermal comfort in both outdoor and indoor environments. It is defined as the amount of water vapor in the air. Therefore, in order to reduce humidity levels in the indoor environments, increasing the ventilation can be considered as an acceptable solution.
Relative humidity has a direct impact on thermal comfort. Furthermore, it is a meaningful parameter in determining thermal urban comfort [211]. It should be considered in planning for adequate environment.

It is well known that outdoor comfort in the urban environment is affected by outdoor temperature and humidity parameters. The determination of outdoor relative humidity can be a useful tool to develop appropriate design strategies that can reduce the intensity of urban heat islands (Figure 5.10). Humidity parameters should be examined more carefully in view of their influence on the built environment.

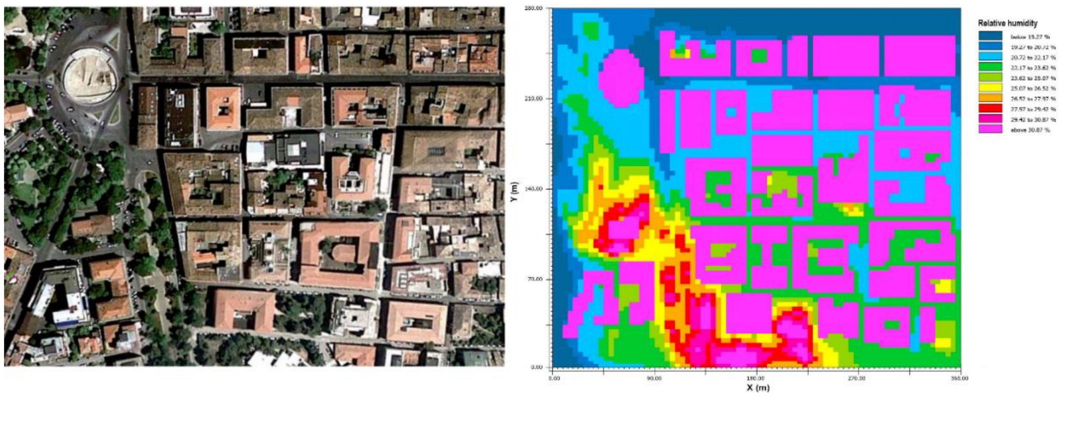


Figure 5.10: One example simulation of outdoor relative humidity [211].

Microclimate variables (radiation, temperature, humidity and air quality) are the key factors that affect both indoor and outdoor environments. It can be noted that analysis of microclimate variables can be useful to predict energy consumption. For example, increases in outdoor air temperature and humidity can often cause excessive energy demand, in particular in electricity demand. Evaluation of microclimate variables can present an opportunity to achieve energy savings.

5.2.2 Solar radiation

The use of solar radiation can be considered as a source of heat energy. The sun is a significant source of renewable energy, it would be worthwhile to explore the possibilities of converting solar radiations into electrical energy and thermal energy. Analysis of incident solar radiation which is based on two primary components such as direct radiation and diffuse radiation, can help to determine the amount of heat gained through building surfaces. It can also be used to calculate the optimum comfort ranges, building energy balance, heat-transfer rates, etc.

According to Causone et al. [212], the analysis of solar radiation effects on the built environment should be separated from the study of other kinds of thermal radiation effects. They examined solar radiation effects on radiant cooling systems and presented an approach that can convert solar radiation to cooling load which is defined as the direct solar load. Solar radiation analysis is a method to assess microclimate aspects and can be useful at the conceptual design stage of a project to find optimal strategies.

The availability solar radiation over a site is a major driver of building form and orientation. Solar radiation can contribute to the reduction of the heating and cooling loads in the buildings. However, solar radiation, in some cases, should be controlled by shading device to achieve significant cooling load reduction (Figure 5.11). In this respect, it is necessary to implement shading devices into transparent surfaces facing south.

In order to understand the impact of solar radiation on building performance, it would be useful to investigate different areas such as passive strategies, daylighting, and renewable energy. Solar radiation plays an important role in the development of some sustainable energy sources.

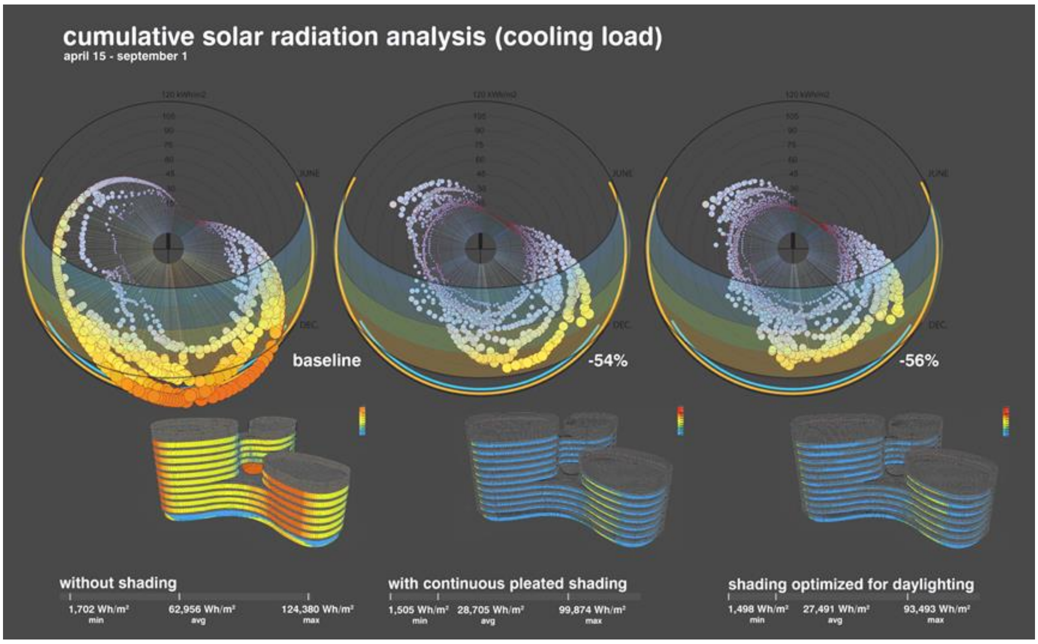


Figure 5.11: A new way of visualizing solar radiation [213].

A detailed investigation of solar radiation amount and variability can be useful in order to optimize solar access of buildings. In fact, studies to analyze solar radiation should focus on establishing appropriate methods for optimizing objectives with regard to local climatic conditions. The contribution of solar radiation for prediction of energy consumption and thermal storage should be considered in the initial part of the design process.

Solar radiation measurements are currently being used to control and optimize solar radiation (Figure 5.12). For example, they are capable of measuring the influence of solar radiation on automatically controlled shading devices and HVAC systems. Solar radiation measurements can be also used for optimization of photovoltaic systems. These applications can collect data of solar radiation to estimate the power output and the efficiency of PV systems.

Figure 5.12: Examples of basic gSKIN solar radiation sensors [214].

In order to determine monthly direct and indirect solar radiation (solar energy potential value) and the amount of accessible solar energy, visualization and analysis tools have been developed and made available (Figure 5.13). These tools can help to understand the solar potential of buildings by sharing solar reports.

Figure 5.13: Urban solar mapping of New York City launched by Mapdwell project [215].

The SIT of the Municipality of Bologna has developed a web application which is based on estimating the amount of solar energy available on the roofs of buildings (Figure 5.14). Assessment of the total amount of direct and indirect solar energy is possible through the use of solar radiation instruments provided with the spatial analyst extension of ArcGIS desktop.

Figure 5.14: Global solar radiation of an area of Bologna city during one year [216].

5.2.3 Wind analysis

It is known that architectural design influences elements of the built environment and outdoor comfort. To achieve sustainability in the built environment, design strategies should attempt to create a consistent and comfortable microclimate. Furthermore, they should provide possibilities for improving energy efficiency and comfort through microclimatic landscape design and planning which make a crucial contribution to improve sustainability of buildings and cities.

A detailed analysis of outdoor parameters can help promote objectives of sustainable design. In addition to the parameters mentioned before, wind is another significant factor for assessing thermal comfort levels in the climate and urban areas. Also, wind is an important driving force for infiltration and ventilation because wind causes variable surface pressures on buildings that change intake and exhaust system flow rates, natural ventilation, infiltration and exfiltration, and interior pressures [217].

Wind is caused by differences in air pressure. It must be analyzed in terms of velocity and direction profiles to understand its impact on the environment. Efficient use and environmental protection of wind have beneficial effects not only on building performance but also on developing sustainable design principles. Accurate wind analysis is critical in estimating the potential of natural ventilation systems which is investigated by using wind tunnel tests and computational fluid dynamics (CFD) calculations. These analysis tools are being increasingly used for the prediction and the assessment of detailed wind environments around buildings (Figure 5.15).

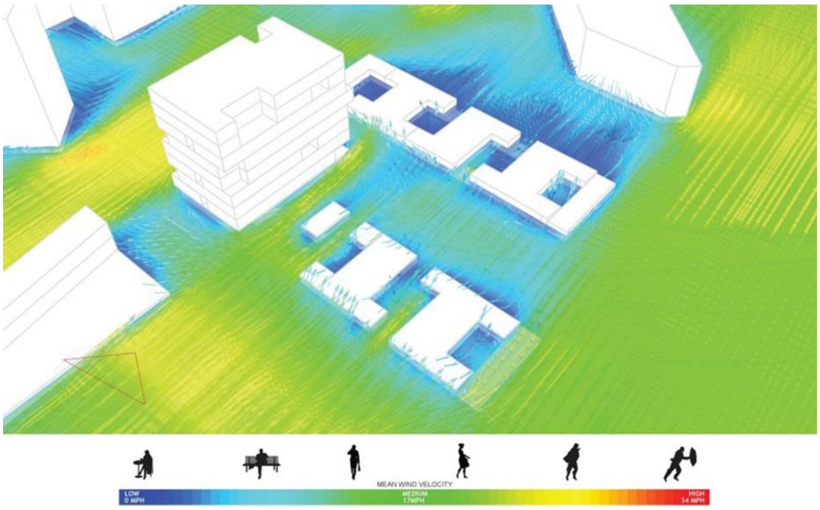


Figure 5.15: An example of wind study (CFD) of Park Merced (San Francisco) [218].

To assess wind conditions in the urban environment in terms of velocity and direction, it is necessary to provide estimates of appropriate directional wind speeds and robust design strategies with regard to local climate conditions. To meet wind design requirements in cold climate zone buildings should be oriented perpendicular to the prevailing wind direction to minimize heat losses while in warmer climates, to take advantage of wind patterns for cooling purposes, they should be oriented in respect of the prevailing wind direction. The essential purpose of a wind analysis is to examine the mean wind profiles for promoting natural ventilation in urban buildings. In order to evaluate wind-driven natural ventilation, the primary vision is to determine the appropriate outdoor airflow rates that are consistent with acceptable indoor air quality levels.

5.3 Sensitivity Analysis Methods

Sensitivity analysis is the study of changes in the parameter values which affect the output of a model. As defined by Baird [219], sensitivity analysis (SA) is the investigation of these potential changes and errors and their impacts on conclusions to be drawn from the model. Also, Fiacco [220] states that: *"A methodology for conducting a (sensitivity) analysis is a well-established requirement of any scientific discipline. A sensitivity and stability analysis should be an integral part of any solution methodology. The status of a solution cannot be understood without such information. This has been well recognized since the inception of scientific inquiry and has been explicitly addressed from the beginning of mathematics".*

Sensitivity analysis methods should be used prior to development and improvement statements. Furthermore, they should be considered to define the key methodological challenges associated with assessment of process. In order to facilitate decision-making, robust solutions and rigorous ways should be developed to bridge the gap between simulation and reality.

Sensitivity analysis in building performance initiatives is one the most important steps for design optimization. It can play a critical role in the development of ways to explore the behavior of complex models. In order to perform the standard sensitivity analysis based on dynamic simulation programs, the key input variables should be identified independently of each other. Also, the relative influence of each analyzed parameter on output should be determined.

It is advantageous to choose an appropriate sensitivity analysis method for building energy simulation. A brief overview of sensitivity analysis methods in building research shows that different approaches are used for building energy models. To identify and categorize sources of uncertainty and error embedded in the simulation results, Lomas and Eppel [221] examined performance of three sensitivity analysis techniques such as differential sensitivity analysis, monte carlo analysis, and stochastic sensitivity analysis. They concluded that differential sensitivity analysis and monte carlo analysis could be applied to a range of thermal simulation tools while stochastic sensitivity analysis was inherently complex. Regarding techniques for uncertainty and sensitivity analysis, Macdonald [222] indicated two different approaches such as internal and external. In the field of building simulation based on internal methods, a deterministic approach can be used to provide a solution to derive the governing equations. In external methods, categorized into global and local methods, input parameters in the application are altered and measured for valuation of output and value added. In this regard, Attia et al. [223] propose the use of differential sensitivity analysis (local method) during the conceptual phase of architectural design which includes prompt investigation of changes in the output along with changes in the input.

5.3.1 Environmental assessment tools

It is important for designers to be able to identify potential environmental impacts and energy performance of buildings. The main purpose of assessment practices in building energy models is to determine the uncertainty of the output parameters and develop sensitivity decomposition methods. Environmental assessment tools can not only help identify areas for continuous improvement and energy key indicators but also can evaluate energy use and environmental performance through simulating and accounting.

The choosing of the correct tools for modeling the energy dynamics of buildings and environmental systems is the most important stage of conducting the assessment. In order to decompose a practice for developing and implementing a dynamic assessment tool, the benchmark determination process can play a crucial role in advancing the state of the art of methodologies (Figure 5.16). The development of a performance assessment system throughout the project could determine some crucial factors that lead to lower environmental performance. It is important to focus on factors that influence decision making process and the development of environmental performance of a project.

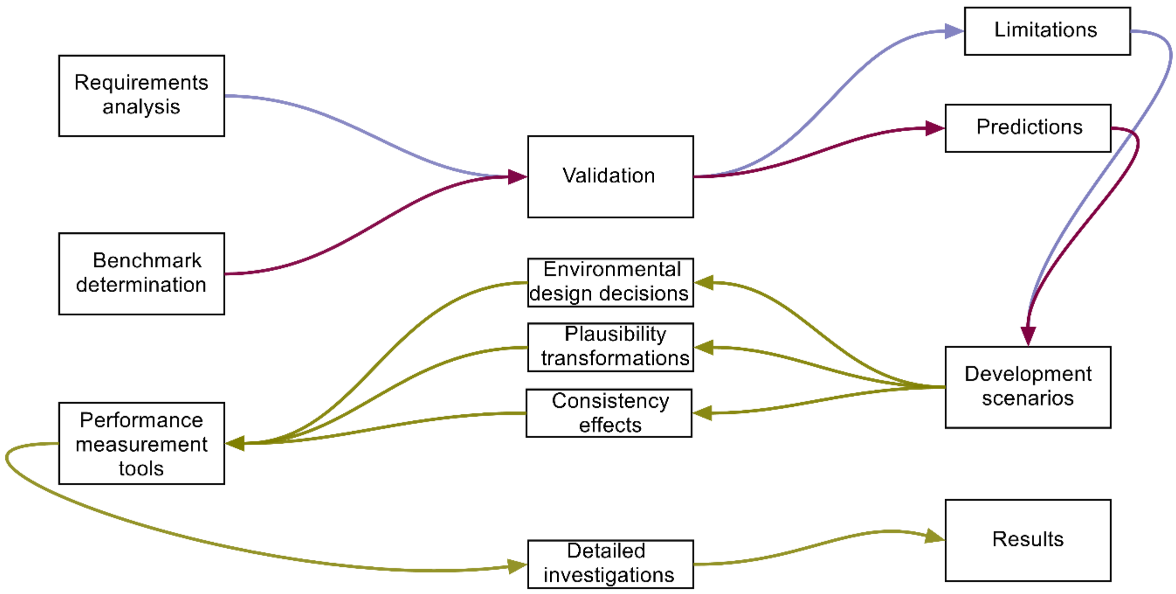


Figure 5.16: Schematic diagram of performance assessment system. Source: Author.

Despite the lack of a decomposition paradigm in some energy and environmental modeling, assessment tools such as Building Research Establishment Environmental Assessment Methodology (BREEAM), Comprehensive Assessment System for Built Environment Efficiency (CASBEE), Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB), Haute Qualité Environnementale (HQE), Leadership in Energy and Environmental Design (LEED) and Protocollo ITACA are being used for benchmarking and improving the environmental performance of a project.

However, the development of a powerful tracking strategy for sophisticated data processing and analysis is important to ensure required assessment performance. The concept of strategy can be decomposed into three phases as follows: data collections, optimization and maintain processing solutions.

To develop a decomposition method for calculating energy and the associated environmental impacts, mathematical programming models and algorithms can be considered in the process. However, they may need to be reconsidered to go beyond the limits of diagnosis in the assessment process.

Evolutionary multi-objective optimization methods and intelligence algorithms can be established to promote assessment approaches. For example, decomposition approaches can be linked with methods known from mathematical programming and some performance improvement formulas. The combination mathematical models and formula into an assessment framework can lead to a new intelligence discipline. To prototype such a strategic intelligence discipline on energy modeling and environmental impacts, there are still a number of issues with the methodology and technology. Although BIM is considered as a rescue solution, it still needs to be amended to maximize its benefits. In addition, it is not still configured to address the full depth of the building information data (Figure 5.17).

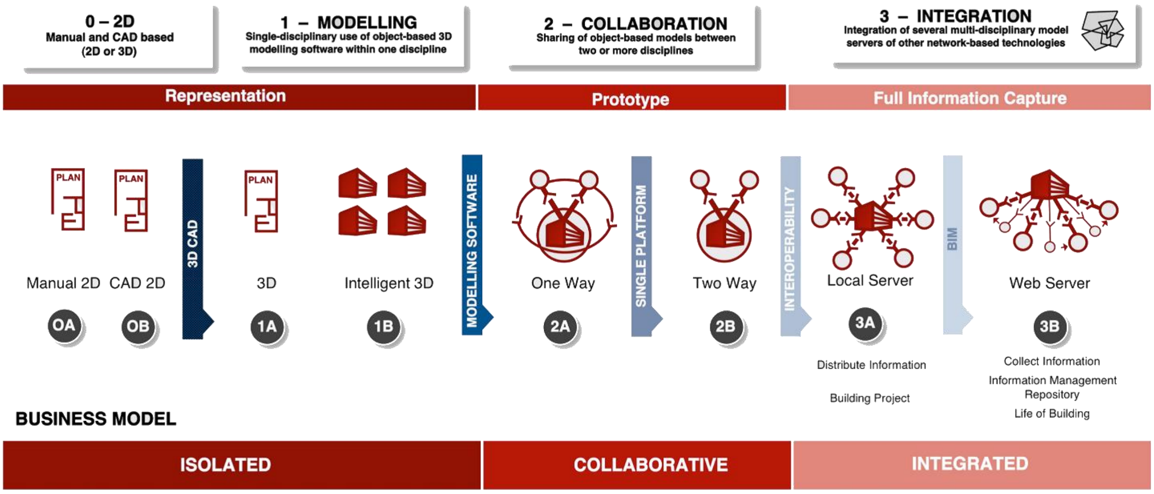


Figure 5.17: A visual representation of BIM concept [224].

However, Eastman et al. [225] pointed out that while building models provide adequate measurements for quantity takeoffs, they are not a replacement for estimating. Also, they pointed out that the process of estimating involves assessing conditions in the project that impact cost, such as unusual wall conditions, unique assemblies, and difficult access conditions. Automatic identification of these conditions by any BIM tool is not yet feasible. According to their study, BIM is only a starting point for estimating and cannot deliver a full estimate automatically from a building model.

It is clear that the field of artificial intelligence (AI) as a decision-oriented tool has recently proven to be a viable alternative approach to resolve these issues. For example, artificial neural networks (ANNs) and support vector machines (SVMs), which are a subset of artificial intelligence, will be widely used to predict energy consumption in buildings. Artificial intelligence is developing systems and technologies of information and control systems rapidly (Figure 5.18). It is also being used to support BIM tools and may convey alternatives in the prediction of actual building performance and energy modeling.

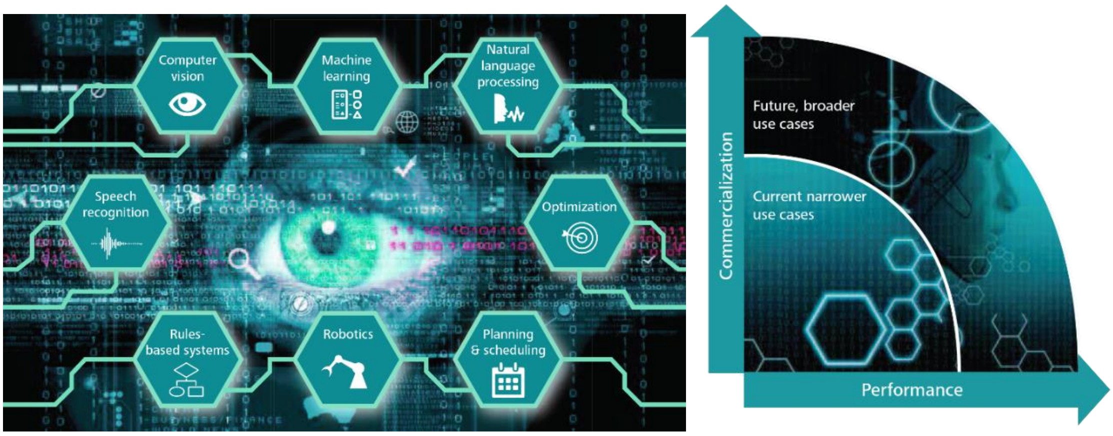


Figure 5.18: Artificial intelligence and commercialization for cognitive technologies [226].

Other key constituents of artificial intelligence (AI) comprise systems for decision support and visualization technologies based on cognitive structures. Depending on the requirements, the inclusion of artificial intelligence (AI) as part of energy control strategies can guarantee interoperability between visualization technologies and control systems without information loss. According to Haymaker [227], artificial intelligence (AI) through optimal use of information technology can certainly contribute to the sustainable building. It can be noted that its contributions in this area may result in increased attention to sustainability in the construction sector. In the field of BIM tools, AI has been recently used to solve the integrated scheduling and planning optimization problems [228, 229, 230]. Although combination of AI with BIM tools enables the creation of an efficient digital information environment, it is still a new trend and needs considerable progress with regard to predictive energy modeling and environmental assessment.

To develop an artificial intelligence approach towards assessing energy and building environmental performance, reduction in data collection costs and accurate prediction of energy consumption should be taken into account in its initial development. Furthermore, in order to evaluate the impact of user behavior on building systems, development of an assessment model based on artificial intelligence can enable acceleration and validation of methods used in the design process. The development of a new concept through artificial intelligence can not only explore potential benefits but also provides ways to achieve an optimum level of efficiency and automation.

5.3.2 Multi-objective optimization

The scope of optimization methods covers a wide range of applications and techniques relevant to the ends desired. The optimization tools typically require a significant number of potential variables for determination of optimal parameters for achieving satisfactory results. Meanwhile, multi-objective optimization methods can effectively optimize queries in data integration systems based on the initial state and find multiple optimal solutions among conflicting objectives (Figure 5.19). Typical multi-objective optimization methods can be formulated [231] as follows:

minimize $F(x)= \{f1(x), f2(x)\ldots\ldots\ldots\ldots\ldots,Fn(x)\}T$

where, $fi(x)=i^{th}$ specifies the objective function to be minimized, n= number of objectives.

subject to $gj(x) \leq 0$, $j = 1, 2, \ldots, J$

$hk(x) = 0$, $k= 1, 2, \ldots, K$

$xi\ (L) \leq xi \leq xi(U)$, $i = 1, 2, \ldots, N$

To develop a multi-objective optimization model for improving building systems and components, combinatorial optimization algorithms play a substantial role in obtaining the optimal solution among alternative sources. In some cases, the algorithms should be robust enough to address challenges in optimization of complex systems and meet desired performance. In order to propose a multi-objective optimization for building energy and comfort systems, it is important to integrate several objective functions for solving multiple problems at the same time.

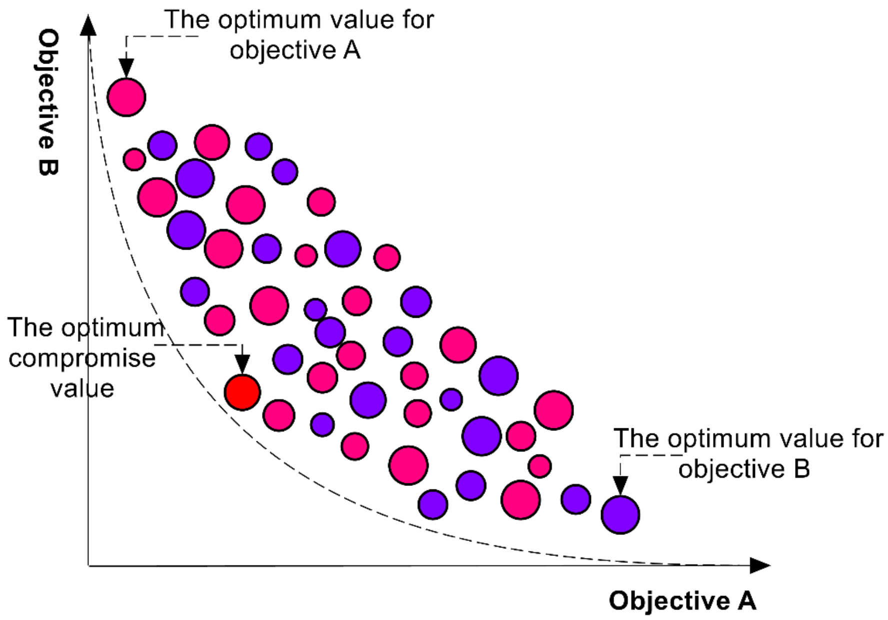


Figure 5.19: Multi-objective optimization process. Source: Author.

A study by Ascione et al. [232] presented a methodology based on multi-objective optimization which combines EnergyPlus and MATLAB interactively for the building performance simulation (BPS) and solving the optimization problem. According to the study's findings, the methodology provides a fundamental set of solutions that optimize both energy performance and thermal comfort. In fact, one of the most challenging problems in the field of multi-objective optimization is resolving conflicting objectives. Although artificial neural network (ANN) and genetic algorithm (GA) have been able to solve these issues, they need to be classified and analyzed through data visualization platforms to compare alternative solutions especially in the early stages of design.

It is clear that the integration of multi-objective optimization with interactive information visualization tools can, not only give the user the possibility to choose an appropriate trade-off solution among conflicting objectives, but also improve management of large solution spaces.

Multi-objective optimization algorithms are divided into two main categories, gradient-based and heuristic algorithms. In the context of building performance and design, gradient-based algorithms are increasingly being used for solving small problems and finding a set of optimal solutions. Gradient-based algorithms use derivatives of variables to find the optimal solution and are able to converge quickly. Furthermore, the gradient-based algorithms describe the curve of a function in optimization problems where positive and negative values represent an increasing and a decreasing function respectively. On the other hand, heuristic algorithms include a variety of methods based on fast and efficient techniques and are used for problems that cannot be simply solved.

However, use of a multi-objective optimization algorithm for improving energy and comfort performance of design models can lead to an effective control system. Not only are multi-objective optimization algorithms to be considered the most important methods for finding optimal solutions, but they are also used to address uncertainties in variables that are more efficient at the same time. In order to derive insight into the algorithms' structure, corresponding performance evaluation can help to select an appropriate algorithm for each design variable.

Although evaluation of algorithms in the design process is not a new concept, it is essential to determine the ability of the algorithmic approach with regard to design requirements. For example, genetic algorithms among other evolutionary methods are widely used in the architecture field in the specific area of computational simulation to address complex design problems and optimize the process parameters. These algorithms use the results from computational simulation tools to further investigate the achieving of energy efficiency and comfort. In this context, genetic algorithms also have the potential to play an effective role in optimizing urban spatial layouts.

In order to use an algorithm as an optimization technique correctly, it is necessary to develop pathway algorithm the formalization of which can lead to the finding of different solutions with different variables. For example, genetic algorithms use techniques inspired by biological evolution, such as inheritance, mutation, selection, and crossover factors which can be transformed into diverse optimization problems and optimal design (Figure 5.20). An algorithmic approach should be aligned with the needs and objectives of the optimization process.

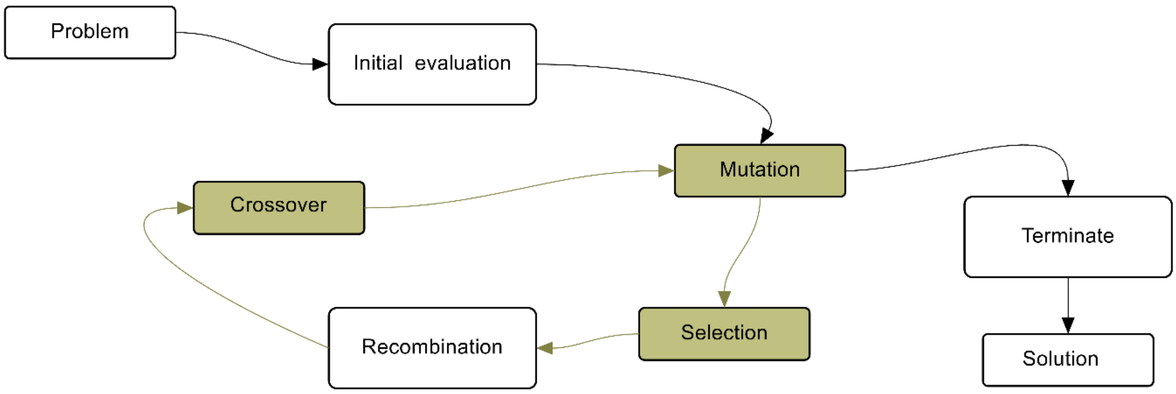


Figure 5.20: Scheme of genetic algorithm. Source: Author.

From the above-mentioned scopes, it can be concluded that the main goal of an optimization concept is to find the optimal solution. In this context, efficient solution algorithms should be implemented into the optimization process for achieving optimality in environmental problems. However, with regard to these processes, some solution algorithms should be expressed in terms of structural optimization and variation techniques.

5.3.3 User-centered analysis and methods

User behavior is an important factor that can affect energy efficiency and comfort in buildings. Therefore, it is fundamental to involve user-centered analysis in the design process. Recently, with the emergence of ICT paradigm, much attention has been paid to individual data visualization tools which are needed for user-centered analysis. Users have different abilities and preferences, therefore, it may be essential to have a deeper understanding of user-building interactions and impacts.

In order to provide adaptive analysis strategy, the inclusion of adaptive visualization and interaction techniques can affect detected estimates of abnormal energy consumption in buildings. To achieve this objective, accurate information data should be addressed by effective visualizations tools to assist users in making informed decisions and behavioral choices. However, it is important to develop a new approach of user-centered adaptive visualization which can result in a better understanding of environmental influences on user behavioral differences.

From a sustainable design point of view, user-centered analysis can indeed enhance opportunities to foster sustainable behaviors. It is clear that the promotion of environmentally sustainable behavior in buildings can be problematic due to the complexity of user behavior and lack of information, but adopting user-centered perspective within visualization tools can engage users toward the above-mentioned goals. Nowadays, user-centered intelligent design has grown increasingly important. Although there are several theoretical frameworks and experiential approaches for designing user-centered systems, there is no single intelligent user interface to individually control indoor environment and energy use.

In order to achieve user-centered design methodology under the paradigm of ambient intelligence, the relationship between technological systems and user needs should be taken as the focal point. Furthermore, they should be taken into account in order to assess the state- the art of adoption of user-centered methods. Involvement of end users in the evaluation process can enable an adaptable, responsive and flexible model for ambient intelligence. They also can contribute to achieving both desirable indoor climate conditions and the enforcement of energy efficiency in buildings. For example, the deployment of an intelligent user-centered HVAC (Heating, Ventilating and Air Conditioner) control system can optimize user comfort and reduce energy consumption during building operations at the same time.

The distribution of user interfaces in ambient intelligent environments can be considered as a step toward addressing user requirements and user-centered information systems. In this respect, the center for building performance and diagnostics (CBPD) at Carnegie Mellon University has revealed a web-based interface which displays real-time and historic data from smart meters and sensors in Navy Yard Building 101 (Carnegie Mellon

University). It also illustrates energy heat and the indoor environmental quality maps which help users identify energy waste during unoccupied hours and understand the environment (Figure 5.21).

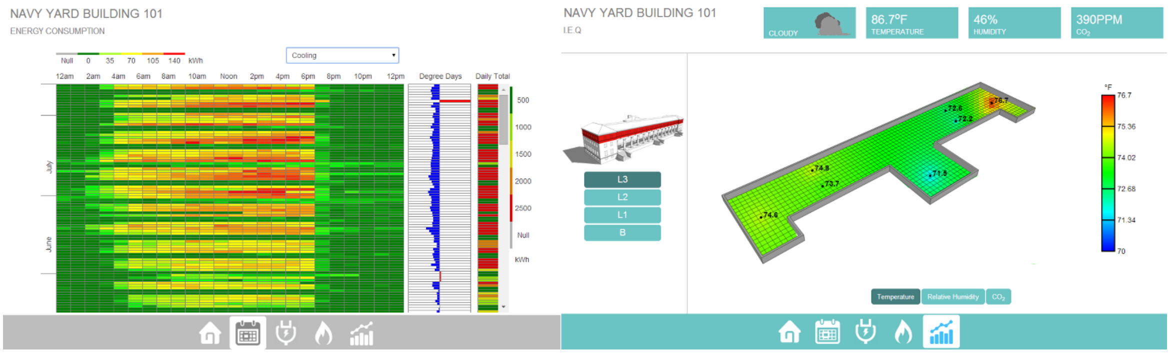


Figure 5.21: Web-based interface of Navy Yard Building (Carnegie Mellon University) [233].

Development of an interface model for information visualization, particularly in office buildings, is on the rise. For this approach, user interaction and satisfaction are two main factors that should be taken into account during formation process of interfaces. It is important to note that interfaces should be designed with responsive, adaptive and flexible principles. However in order to develop user-centered interface, technological systems should support effective practices and optimize user performance through advances in user interaction. The most important aim for user-centered interface is to achieve integration between intelligent management systems and user management. Apart from interfaces, user-centered smart applications and wireless sensor networks are increasingly being used to fulfil user needs in developing ambient intelligence environments. In this context, several smart applications have been developed not only to harvest information relevant to existing infrastructure but also to control environmental factors.

5.3.4 Programming languages and open-source systems

With the increasing multidisciplinary trends in smart buildings and cities, not only will programming languages play a significant role in developing infrastructures but also in operating systems and applications. It is known that different types of programming languages such as BASIC, FORTRAN, COBOL, LISP, LOGO, Java, C++, C, MATLAB, Mathematica, Python, Ruby, Perl, and JavaScript are used to solve optimization problems. Within this context, visual programming languages (VPL) such as Grasshopper and textual programming languages (TPL) such as Rhinoscipt and Python are considered to be the most powerful, versatile and user-friendly programming platforms. In particular, currently, in the field of architecture the use of a visual parametric programming language (Grasshopper) coupled with a 3D design interface (Rhinoceros) is going to be a staple part of the optimization modeling. These programming languages can provide a flexible and efficient computational framework and need to include smart scripts in solving design problems. However, it is important to have proper optimization algorithms as well as programming languages to identify the most important design variables and optimization objective functions. A study by Yang et al. [234], presented a computational design optimization approach through Rhino/Grasshopper and modeFRONTIER platforms (Figure 5.22).

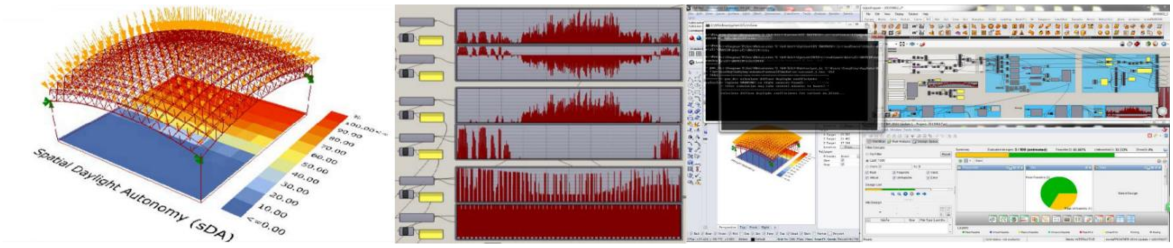


Figure 5.22: One example of visualization performance and optimization process [234].

Grasshopper as a visual programming language in the field of design optimization can not only provide an evolutionary solving function by algorithms but can also play a crucial role in determining optimal designs and desired objectives.

The use of appropriate optimization algorithms in Grasshopper or visual programming language can enable the digitization of traditional methods and generate a number of solution clusters in multi-objective decision problems. From a visual programming language point of view, it is essential to extend the concepts of smart workflow to manage information regarding geometry, user needs, environmental conditions and optimization process. A study by Lobaccaro [235], developed workflow to analyze solar energy potential in existing and new urban areas (Figure 5.23).

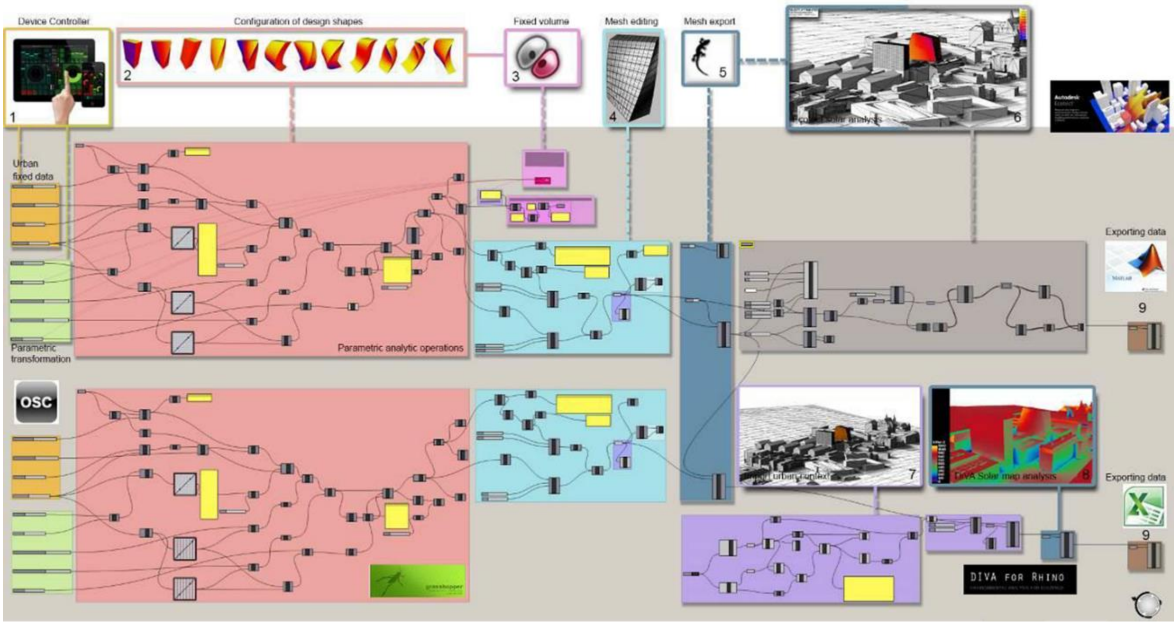


Figure 5.23: One example of the workflow developed for evaluating the solar potential of the buildings. Definition: 1.Urban fixed data (orange) and parametric transformations (green), 2.Analytic operations (red), 3.Fixed volume parameters (magenta), 4.Mesh editing (cyan), 5.Mesh export (clear blue), Solar simulation (6.Ecotect (grey)/8.DiVA (Blue)), 7.Import urban context (violet), 9.Exporting data (brown) [235].

In this respect, it is important to point out that combination of user thinking process with computational creativity can improve theory and practice of artificial intelligence and intelligent behavior in applications. Therefore in order to evaluate the performance of metaheuristic optimization approaches, not only techniques but also the basis of computational thinking should be examined.

In addition to the above-mentioned tools, MATLAB (Matrix Laboratory) is also a well-acknowledged and interactive programming language for numerical computation, process optimization and data visualization. MATLAB is a matrix-based language and all information is stored as a matrix or an array. It provides many proper methods to create various matrices. It also includes features such as matrix operations, plotting data and functions, implementation of algorithms, creation of user interfaces, etc. Today, MATLAB contains a variety of toolboxes, such as signal processing, statistics, neural network, image acquisition, image processing, control systems, filter design, fuzzy logic and genetic algorithms to perform various computation.

According to Xue and Chen [236], MATLAB as a programming language has advantages such as clarity and high efficiency, scientific computation, graphics facilities, comprehensive toolboxes and powerful simulation facilities. They point out that MATLAB language is becoming a widely accepted scientific language, especially in the field of automatic control. Besides, the use of MATLAB solutions to optimize problems with genetic algorithms is very straightforward and consistent.

Nowadays, each operating system has its own programming language. Operating systems include different types of software options such as commercial and open-source. In this context, open-source systems have open access to source code and are freely available for users to use or modification. Furthermore, open-source systems include solutions to various types of problems in nearly every area of technology. For example, open-source building automation system (Open BAS) projects provide affordable solutions and opportunities to specific environmental problems through open-source hardware and software.

Arduino as an open-source hardware and software platform is being increasingly used for multiple objectives (Figure 5.24). Arduino microcontroller boards and their derivatives not only can be used to control electrical devices and appliances but can also be useful for user-friendly smart infrastructures. For example, various sensors and data logger operates can be integrated into Arduino microcontroller to sense the environment. Besides, Arduino microcontroller can provide a satisfactory environment for users by controlling lights, fan coil actuator controls, and other comfort systems.

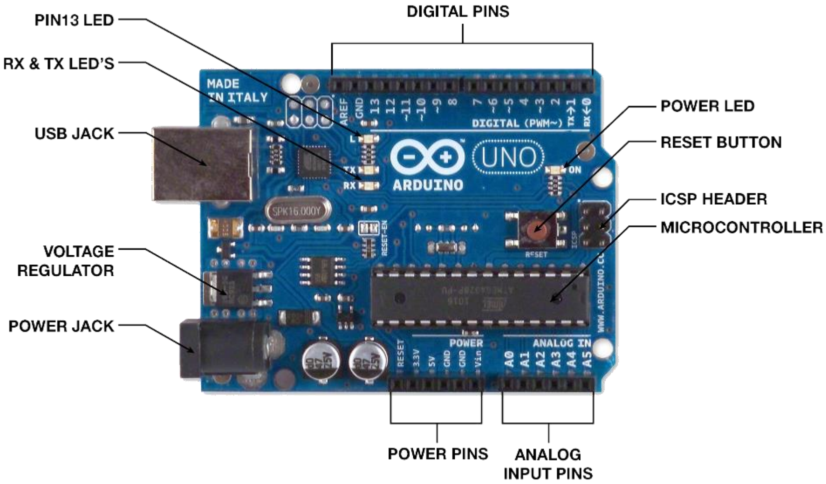


Figure 5.24: An illustration of the Arduino Uno hardware [237].

It is clear that the development control system based on the Arduino platform can lead to a reduction in cost and to increased system functionality in comparison with a typical programmable logic controller (PLC). The Arduino platform can also provide communication with other devices and the internet allowing users to monitor an apparatus, log data and send commands to motors, servos, and relays. In particular, it has great potential for creating a wireless sensor network (WSN) or remote control network.

A variety of sensors and control systems based on the Arduino can decrease complicated mechanical and control systems. The Arduino has several advantages of prototyping interactive user interface based on sensory inputs which can be used to send commands to control systems without advanced electronics skills. In the context of the Arduino software, there are two main parts as follows: integrated development environment (IDE) and a core library. The Arduino development environment is a complete source code editor and is capable of transferring data to the board (Figure 25). Arduino programming language is based on the C and C++ and can interface with MATLAB / Simulink through a serial port which is important for building a control system.

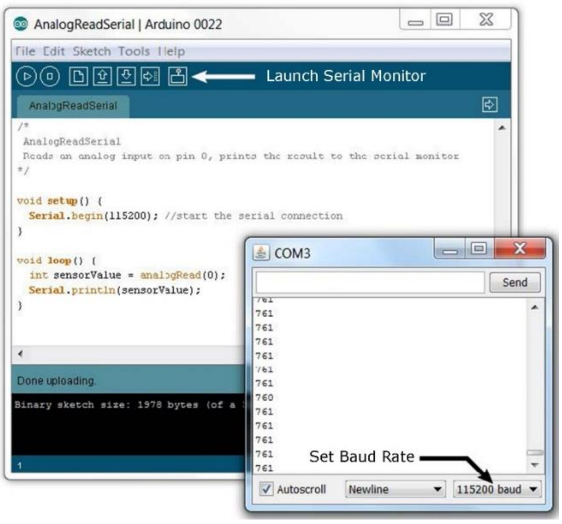


Figure 5.25: A screenshot of the Arduino IDE and serial monitor window [237].

From the above-mentioned literature review, it can be concluded that open-source environmental programs can help designers create new environmentally responsive design concepts. Furthermore, it can be noted that data visualization for indoor and outdoor environments not only helps users identity factors affecting building efficiency but also improves decision making under conditions of uncertainty. Therefore, it is advantageous to integrate emerging parametric design tools and open-source programs into architectural technology and environmental design.

In this respect, open-source architecture (OSArc) is a new collaborative approach to design. According to a research by C. Ratti et al. [238], published in *Domus* magazine, open-source architecture (OSArc) describes an inclusive approach to spatial design, a collaborative use of design software and the transparent operation throughout the course of a building and the life cycle of a city. Open-source architecture can also be employed to rethink environmental sustainable design and energy efficiency in the built environment.

In order to achieve sustainability goals in architecture, different types of façade systems are currently being designed and developed. In particular, there is a growing trend towards designing responsive and adaptive façades. In this context, open-source software and hardware systems have made a major contribution to accomplish objectives. They have emerged as promising technologies to manipulate data and explore design options. Considering these points, it is possible to state that open-source systems have been able to help designers to develop smarter and better environments. For example, the following are a few examples of research projects focused on open-source resources (e.g. Arduino, Dynamo and Grasshopper) that enable interactions with building information software to evaluate the performance of a given number of projects.

-Research project 1

A study by Kensek [239], has shown that a range of simulation and analysis techniques based on virtual prototypes can be the basis for testing the performance of buildings, especially with regard to intelligent façade systems (Figure 5.26). In fact, the study explores the possibility of connecting environmental sensors such as light, moisture, or CO_2 receptors to building information models (BIM). This research attempts to show that building information modeling (BIM) with open-source and visual programming tools such as Arduino, Grasshopper, Rhino, Dynamo and the Revit API (Application Programming Interface) can provide assistance throughout phases of the architectural design process. As part of her research method, she developed eight case studies to show the feasibility of these processes. Within the scope of study, however, she indicated that the interaction time in Dynamo/Revit is much slower than Grasshopper/Rhino.

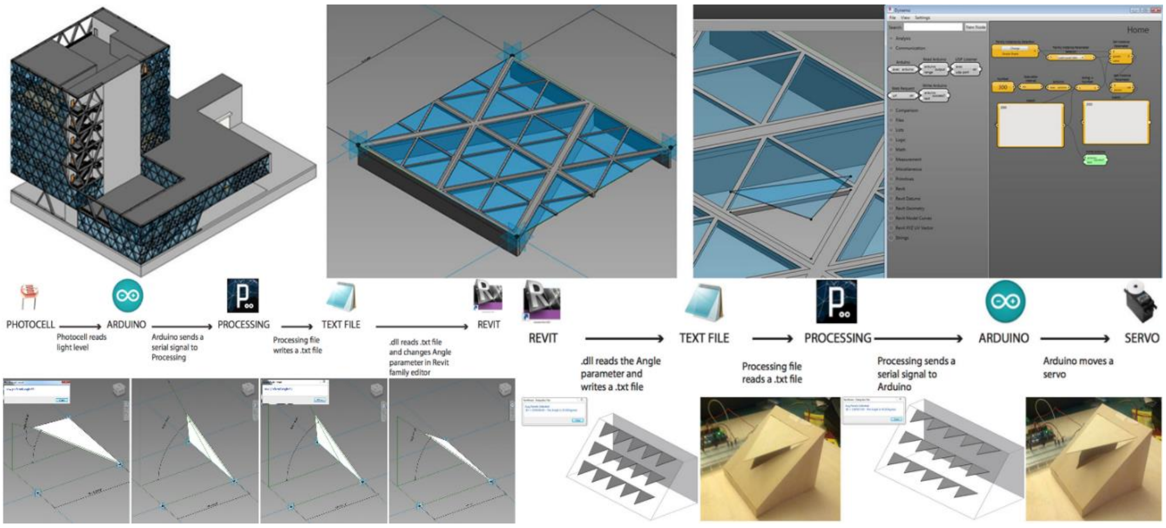


Figure 5.26: A view of the research project 1. 3D model in Revit (top left), façade component in Dynamo (top right), the Revit family editor (bottom left), digital/physical models (bottom right) [239].

-Research project 2

Nowadays, numerous kinetic façade systems have been developed to adapt to varying environmental conditions. For example, the research project conducted by Sharaidin [240], is an example of a conceptual framework that focuses on performances of kinetic façades in the context of indoor environmental performance (Figure 5.27). This research involves significant considerations of using analogue and digital design tools such as Arduino, Raspberry Pi, Firefly, Grasshopper , etc. In fact, the research seeks an action method to determine how kinetic patterns can be explored through alternative tools and platforms . During the design process the structure and a number of physical models have been developed and composed into one kinetic system in order to evaluate its environmental performance. In addition, the folding elements are integrated with many servomotors to modulate the movements of kinetic panels. In order to enable responsive layouts in the project, a series of sensors and actuators are integrated as part of system.

Microcontroller Arduino are used to develop communication between sensors and servomotor. The results from this research show that this project is able to control daylight and thermal heat. From a research perspective, the development of physical prototype during the early design process can be considered as a major determinant of effective decision making. In the context of kinetic façades, the research can be regarded as a future design methodology to environmental conditions. It is evident that kinetic façades have the abilities to respond to environmental conditions and the approach of integrating physical and digital tools during the early design stage can lead to innovation in methods and projects.

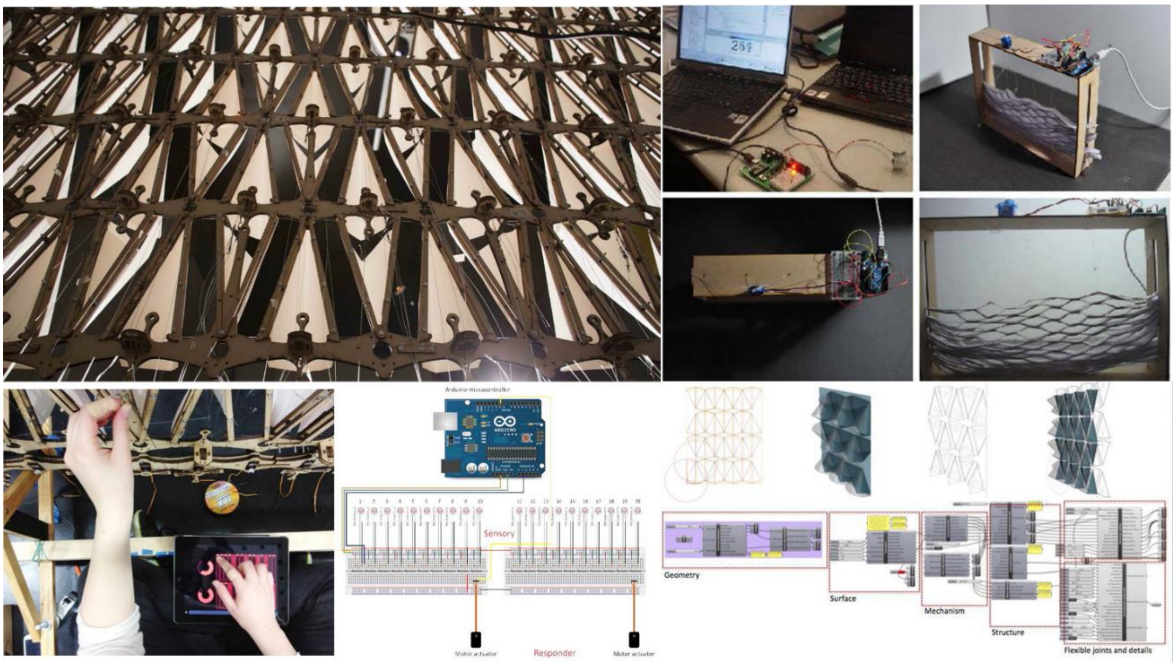


Figure 5.27: A view of the research project 2. The proposed kinetic mechanism and kinetic structure (top left), integration of Arduino and step motor processes (top right), the length of pulley system and Arduino connection between sensors and actuators (bottom left), the algorithms of the kinetic movement and the façades (bottom right) [240].

-Research project 3

To investigate innovative design strategies for morphing architecture, a study by Khoo [241] focused on responsive kinetic material system (RKMS). The research was developed to affect the strategic early stage of designing architectural morphing skins (Figure 5.28). It investigates a new method through the reflective and systematic action process. The research method is configured through four stages of the development process such as skeleton, skin, transformation and responsiveness. In this respect, the sensors in associated with an Arduino microcontroller and Grasshopper program are used to read the process data.

From this research, it is clear that approach attempts to use a range of methods to integrate both responsive materials and innovative computational design tools. Furthermore, the research seeks to create an initial step towards exploiting opportunities to develop new material systems for responsive morphing architecture designs. The research approach is established by design investigations, particularly in the areas of actuation and deformation within the concept of soft kinetics.

It is clear from research findings that the use of different design tools and responsive physical computing devices such as Arduino microcontrollers can provide a viable alternative to conventional techniques.

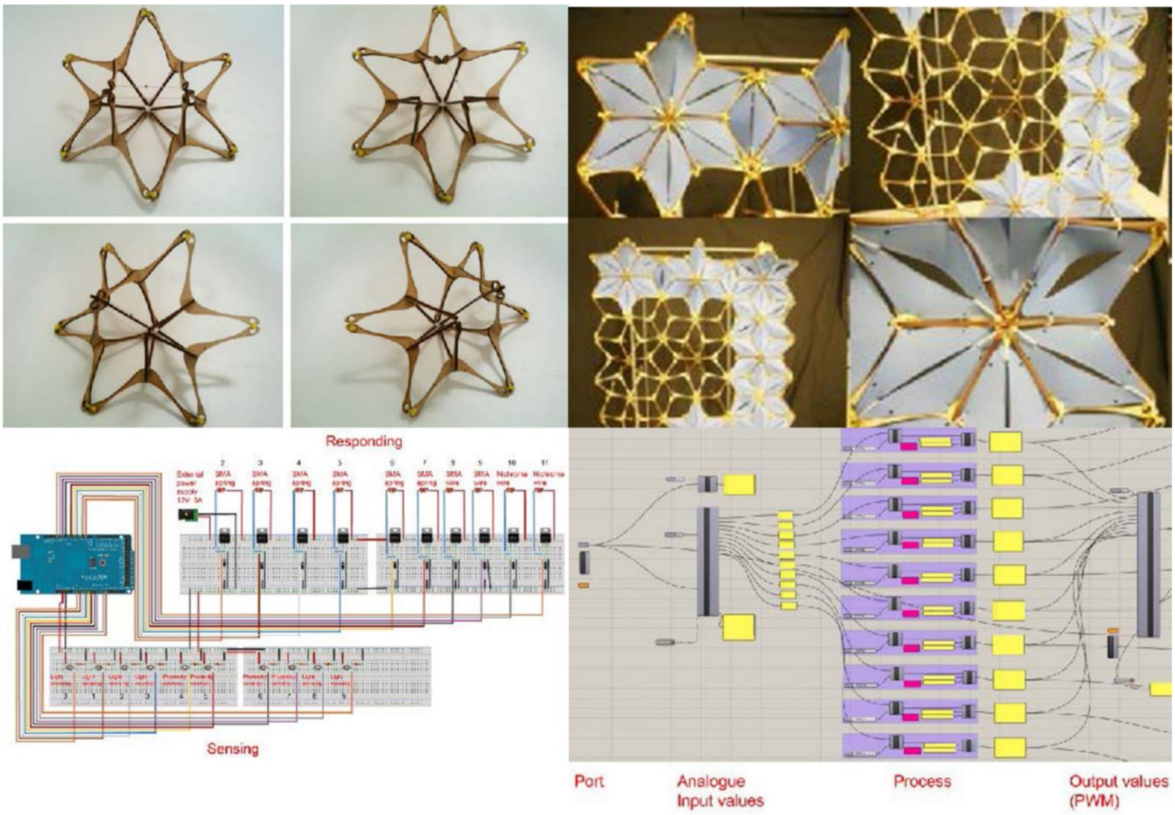


Figure 5.28: A view of the research project 4. Illustration of inverted tetrahedral modules (top left), cluster skeleton with integrated foam skins (top right), an Arduino Mega microcontroller for sensing and responding devices (bottom left), Firefly's schema for sensing and responsive capabilities (bottom right) [241].

-Research project 4

The hybrid parametric wall is another research project based on the concept of open source and low- cost system (Arduino tabs). It was developed by Costerbosa [242] and includes a detailed outline of design approach and parametric modeling tools (Figure 5.29). The research method is based on theory with regard to the kinetic aspect of responsive surface. It provides a flexible framework for the surface to model its own shape according to certain stimuli received from the environment. For example, the photosensitive sensors placed on the surface can cause variations to the module with respect to light. Furthermore, the surface becomes a tool for energy savings and is sensitive to environmental sustainability issues. In this context, it is possible to manage all elements of this project via Grasshopper and the Arduino microcontroller. The new concept of surfaces can also be used to recover energy from solar photovoltaic panels that are installed directly inside the modules. The project was presented at the annual meeting of the Maker Faire Rome 2014, and has attracted the attention of several scientific institutes and private companies.

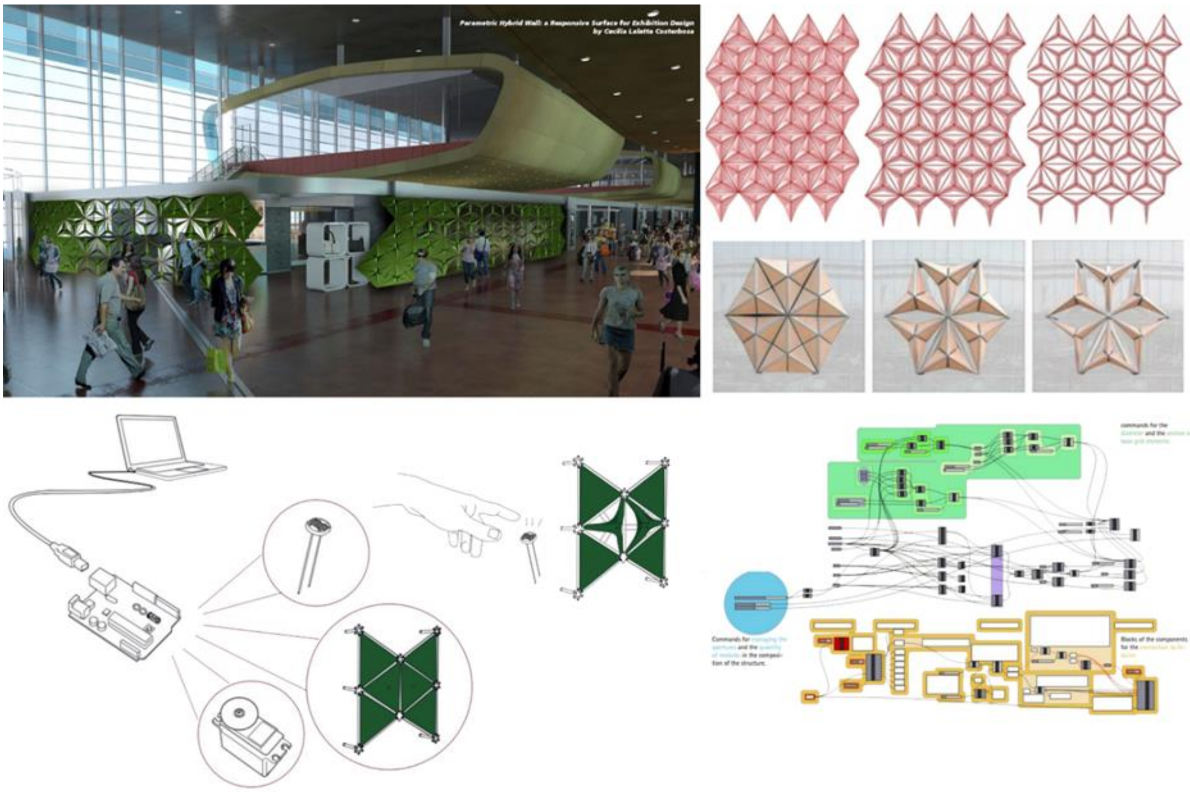


Figure 5.29: A view of the research project 2. Illustration of a Responsive Surface for exhibition design (top left), concepts (top right), diagram of component and operation (bottom left), the generative algorithms within grasshopper in connection with Arduino (bottom right) [242].

CHAPTER 6 COMFORT METRICS

In order to understand the benefits of applying building information modeling (BIM) to improve building performance, energy use and indoor comfort metrics of two case studies were evaluated. A proposed framework was used to explore the performance of two buildings in Ferrara (Italy) and Barcelona (Spain). They are two different types of office buildings in Mediterranean climatic (Table 6.1). The first case study selected one of the building blocks of science and technology center, University of Ferrara-Italy (UNIFE) Department of Physics and Earth Science. The second case study was the laboratory office building of Polytechnic University of Catalonia (UPC), School of Architecture – Barcelona.

Table 6.1: Key features of case studies. Source: Author.

Name	Envelope	Air conditioning system	Structure
Case A (UNIFE)	single-sided	Automatic HVAC system	reinforced concrete
Case B (UPC)	double-sided	Manual radiator system	steel construction

6.1 The Framework of Simulation Process

The first step is to establish a framework to determine building energy and environmental performance of case studies. Building performance simulation (BPS) tools were used to assess them (Figure 6.1). Simulations were performed on two levels: 1) simulation of building energy and indoor environmental quality; 2) simulation of outdoor environmental conditions.

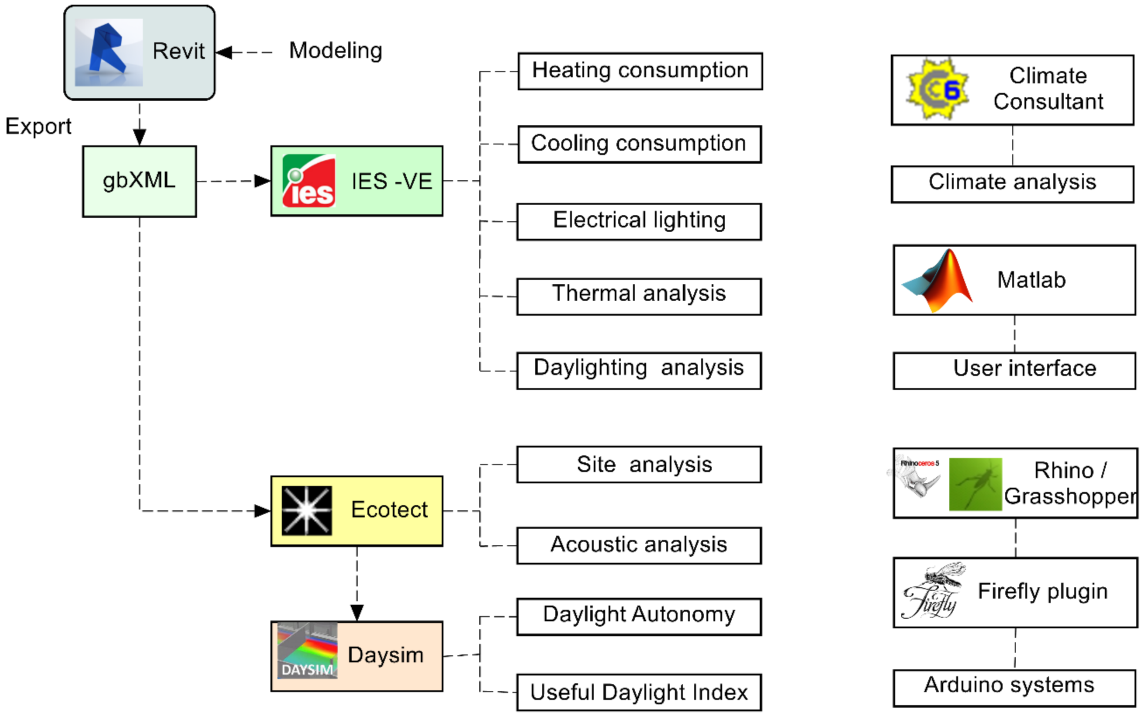


Figure 6.1: Overview of building performance simulation (BPS) tools used for assessing energy and indoor environment. Source: Author.

6.1.1 Buildings information

The first reference building (UNIFE) is based on Department of Physics and Earth Science, the home building of University of Ferrara-Italy in a Mediterranean climate, and is an office building occupied by teachers, researches and students (Figure 6.2). It has 5 floors plus a basement. A detailed simulation analysis and review on case study has been given. ASHRAE 90.1-2007 (climate zone 4, mixed-humid) was used as a reference to simulate the energy consumption of case studies. Before simulating, specific information input requirements for each case study was identified (Tables 6.2, 6.3, 6.4, and 6.5).

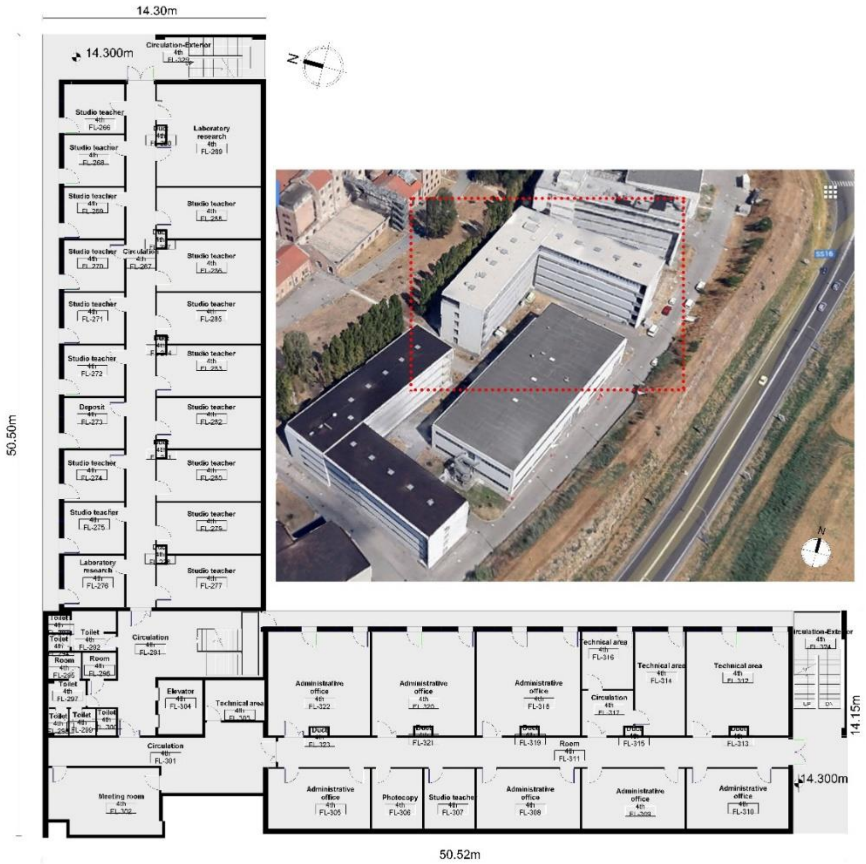


Figure 6.2: 3D view of the reference building and its fifth floor plan (zone evaluated). Source: Author

Table 6.2: The relevant case study A (UNIFE) data. Source: Author

Surface areas of floors	1130.025 m^2
Total south window	164.291 m^2
Total window area	1186.1 m^2
Height/stories	ground floor (3.80 m) & floor-to-floor (3.50 m) / 4 stories
Total surface area	5442.546 m^2

Table 6.3: Thermal properties of materials used in case study A (UNIFE). Source: Author

Construction	Layers	Material	Thickness (mm)	U value (W/m^2k)
External wall	Outermost layer Layer 2 Layer 3 Layer 4 Innermost layer	Plaster Brick Polystyrene foam Block Plaster	20 180 50 120 15	0.35
Internal partition	Outermost layer Layer 2 Innermost layer	Plaster Brick Plaster	10 120 10	1.89
Floor	Outermost layer Layer 2 Layer 3 Layer 4 Innermost layer	Ceramic tiles Cement EPS Concrete Gypsum plaster	10 10 50 300 10	0.53
Roof	Outermost layer Layer 2 Layer 3 Layer 4 Innermost layer	Aluminum Cement Insulation Concrete Gypsum plaster	0.6 120 50 300 10	0.49
Glazing	Double glass aluminum sliding window			1.56

The Sant Cugat campus of Polytechnic University of Catalonia (Barcelona-Spain) was chosen for second case study (Figure 6.3). The building consists of laboratories and offices rooms. The building project is intended for public and professional use.

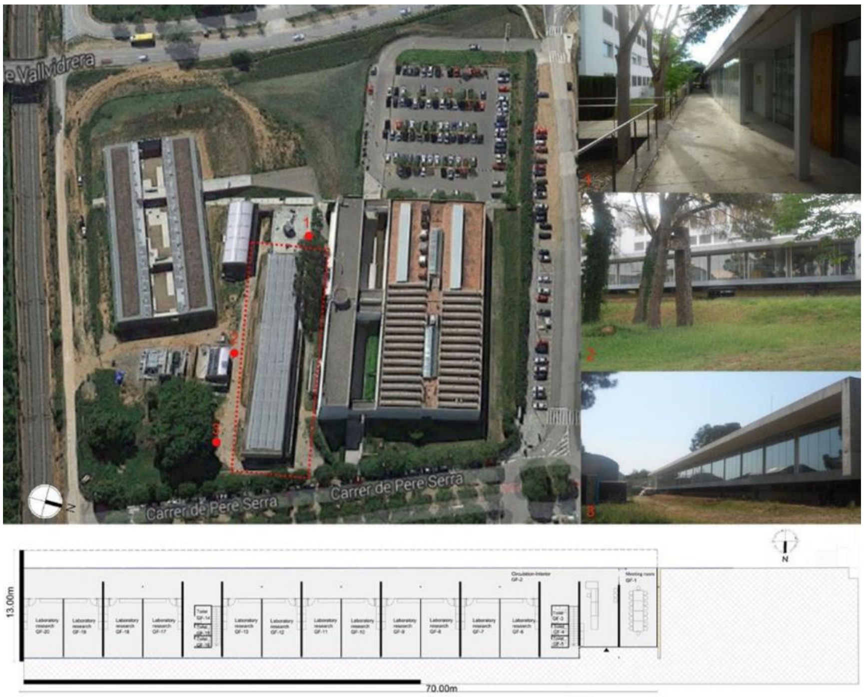


Figure 6.3: Overview of case study B (PUC) and its floor plan. Source: Author

It is located in 41° 18' north latitude in Barcelona in the Mediterranean climate zone and 8 m above sea level. The building is equipped with a manual radiator system for space heating with no mechanical air systems. It utilizes natural ventilation for both ventilation requirements and space cooling and heating is the leading energy consumer in this building.

Table 6.4: The relevant case study B (PUC) data. Source: Author

Surface areas of floors	797.79 m^2
Total south window	209.043 m^2
Total window area	602.600 m^2
Height/stories	ground floor (2.80 m) / 1 story
Total surface Area	797.79 m^2

Table 6.5: Thermal properties of materials used in case study B (PUC). Source: Author

Construction	Layers	Material	Thickness (mm)	U value (W/m^2k)
External wall	Outermost layer Innermost layer	Reinforced concrete Polystyrene foam Reinforced concrete	150 200 150	0.14
Internal partition	Outermost layer Layer 2 Layer 3 Layer 4 Layer 5 Layer 6 Layer 7 Innermost layer	Plywood sheathing Cavity Gypsum plastering Glass wool Cavity Glass wool Gypsum plastering Cavity Plywood sheathing	20 30 15 40 50 40 15 30 20	0.24
Floor	Outermost layer Layer 2 Innermost layer	Polyurethane board Screed Screed Reinforced concrete	30 70 30 300	0.56
Roof	Outermost layer Layer 2 Layer 3 Layer 4 Layer 5 Layer 6 Layer 7 Innermost layer	Galvanized profile Gravel Polystyrene Membrane Laminate P.V.C Membrane Screed Reinforced concrete Plywood sheeting	0.8 10 40 10 1.2 10 10 300 20	0.54
Glazing		Internal glazing External glazing		2.64 1.56

6.1.2 Location and orientation

Position of the sun relative is a major factor in providing daylight and passive design strategies in the buildings. In order to study building orientation in relation to solar radiation and passive solar gains through façades, a detailed solar analysis is performed by Ecotect 2011 for each case study (as shown in the following figures). Furthermore, the analysis was performed to understand which faces or walls receive the maximum solar during a year. Building energy consumption is the amount of energy necessary to meet the requirements of thermal comfort, electric lighting and other equipment. The amount of passive solar can be considered as a natural energy reference to decrease the energy consumption of buildings. Solar access analysis can be used to determine the best building orientation on a site and provide the average daily incident of solar radiation values for all seasons. Also, it provides an indication of the energy absorbed by façades and opaque surfaces which is the main factor in determining the potential and performance of solar PV systems in the buildings.

In this context, a sun path diagram can be used to display the position of the sun which is determined by the solar altitude and solar azimuth. It is a function of site latitude, solar time, and solar declination. It also includes information such as horizontal and vertical sun angles. The sun path diagram can be useful to determine the tilt angle of shading devices which impact indoor cooling loads and air temperature. It visualizes the building's shadow throughout an entire day and the spherical projection of the sun's position on the building. Moreover, diffuse solar exposure is considered to evaluate the total amount of energy received at a specific façade when most exposed. It has a significant effect on thermal comfort and is included in the mean radiant temperature (MRT) calculation.

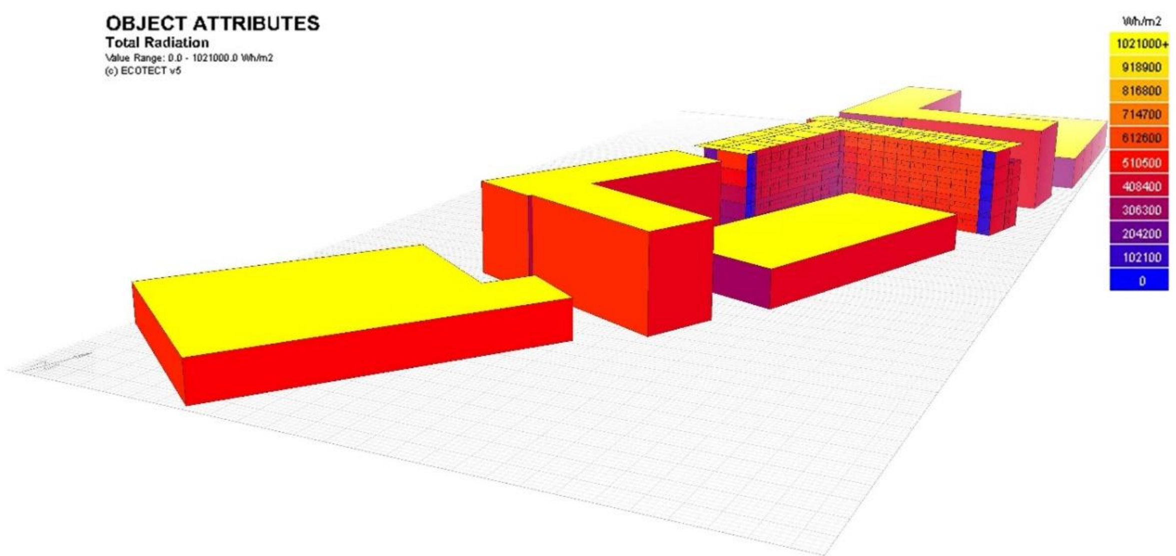


Figure 6.4: Solar analysis of case study A (UNIFE) and its site plan performed by Ecotect 2011. Source: Author

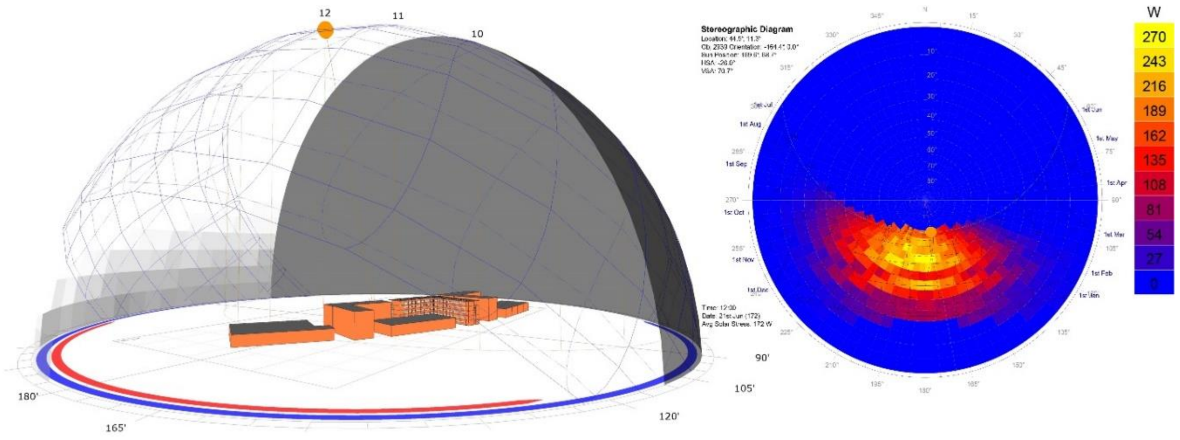


Figure 6.5: Sun path diagram (left) and direct diffuse (right) of south façade of case study A (UNIFE) on 21 June performed by Ecotect 2011. Source: Author.

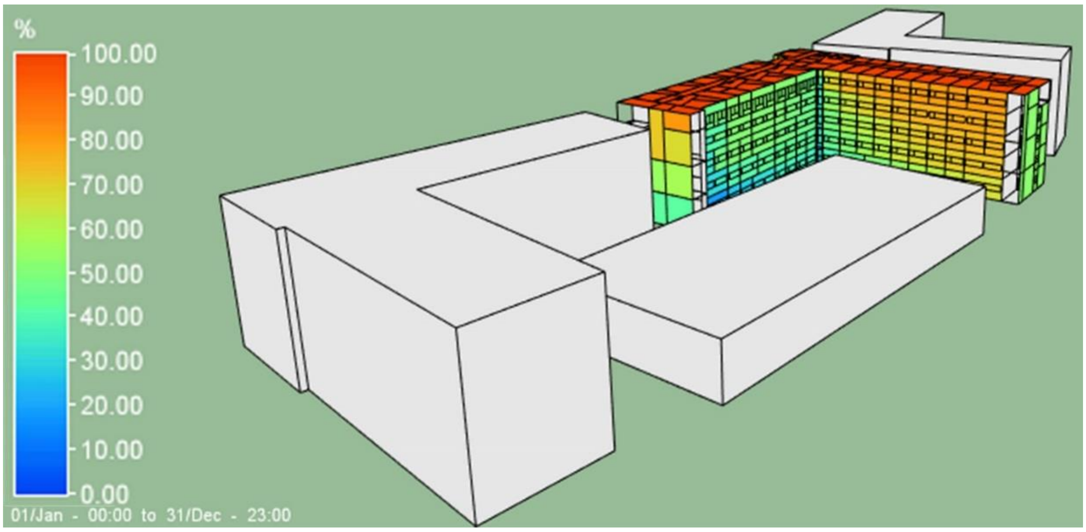


Figure 6.6: Solar exposure of case study A (UNIFE) performed by IES- VE. Source: Author

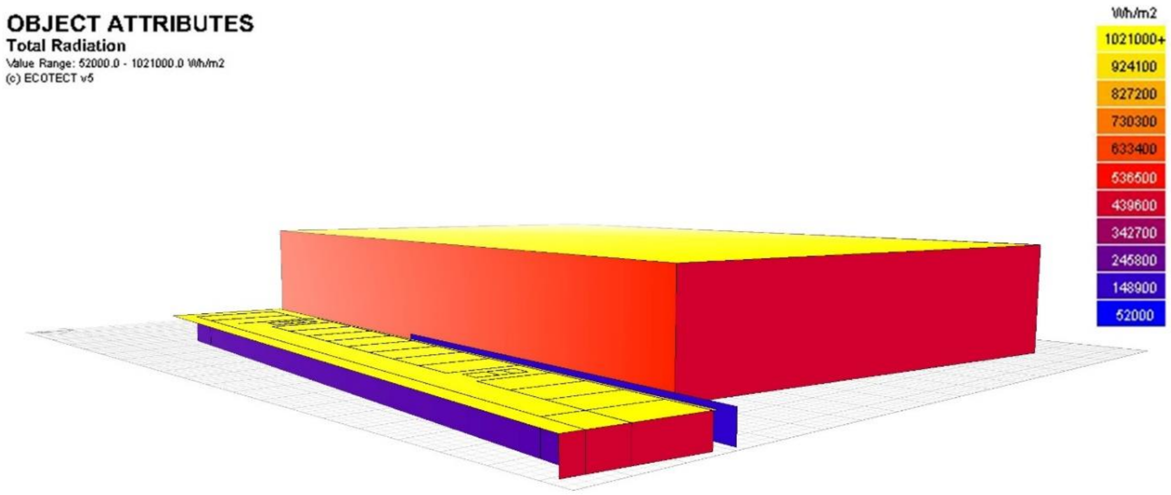


Figure 6.7: Solar analysis of case study B (PUC) and its site plan performed by Ecotect 2011. Source: Author.

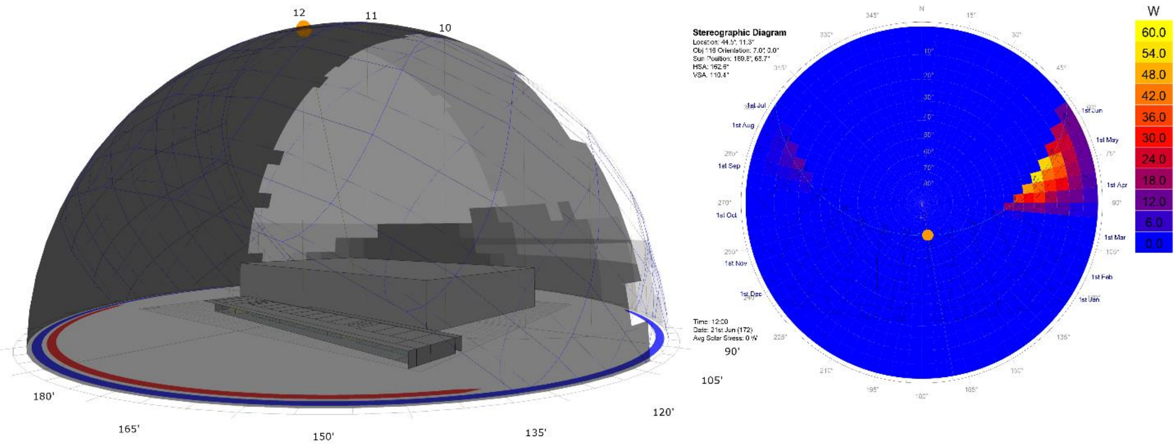


Figure 6.8: Sun path diagram (left) and direct diffuse (right) of south façade of case study B (PUC) on 21 June performed by Ecotect 2011. Source: Author.

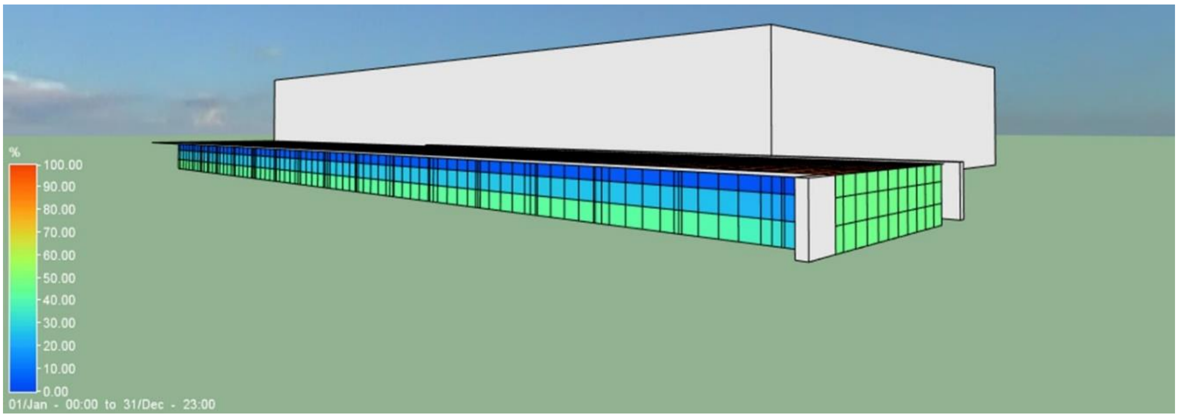


Figure 6.9: Solar exposure analysis of case study B (PUC). Source: Author.

6.1.3 Comfort and weather analysis

It is important to understand outdoor environment condition before being able to develop a climate responsive building. The weather analysis tool is used to identify the outdoor environmental parameters for a particular location. It display different graphic images of various weather attributes. Furthermore, it can used to identify the potential application of passive design strategies. In this context, Climate Consultant 6.0 is used for the analysis and presentation of weather graphics. It reads the local climate data for all 8760 hours per year in EPW (EnergyPlus Weather) format.

Bologna (Ferrara) has a humid subtropical climate whereas Barcelona has a Mediterranean hot climate. According to Climate Consultant 6.0, the temperature charts of Bologna (Ferrara) and Barcelona show that the mean temperature is higher than the comfort zone during four months of the year (June-September). In addition, the climates of the two cities differ greatly in respect to relative humidity (Figures 6.10 and 6.11).

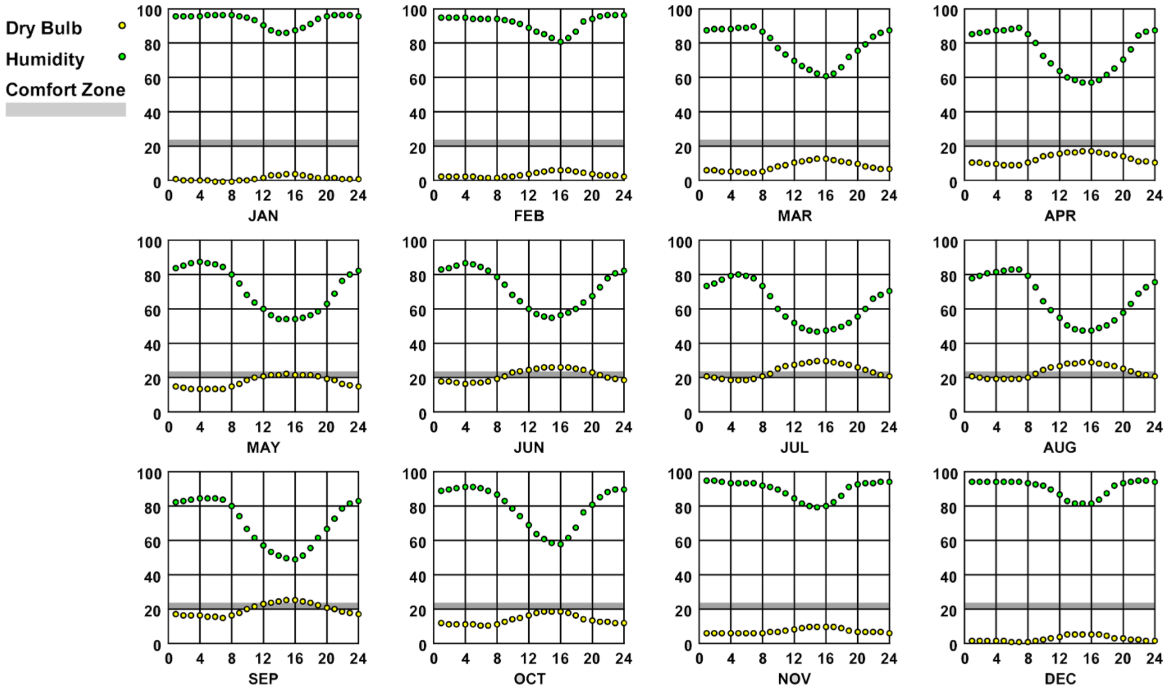


Figure 6.10: Outdoor dry-bulb temperature and humidity data of Bologna (Ferrara).

Source: Climate Consultant 6.

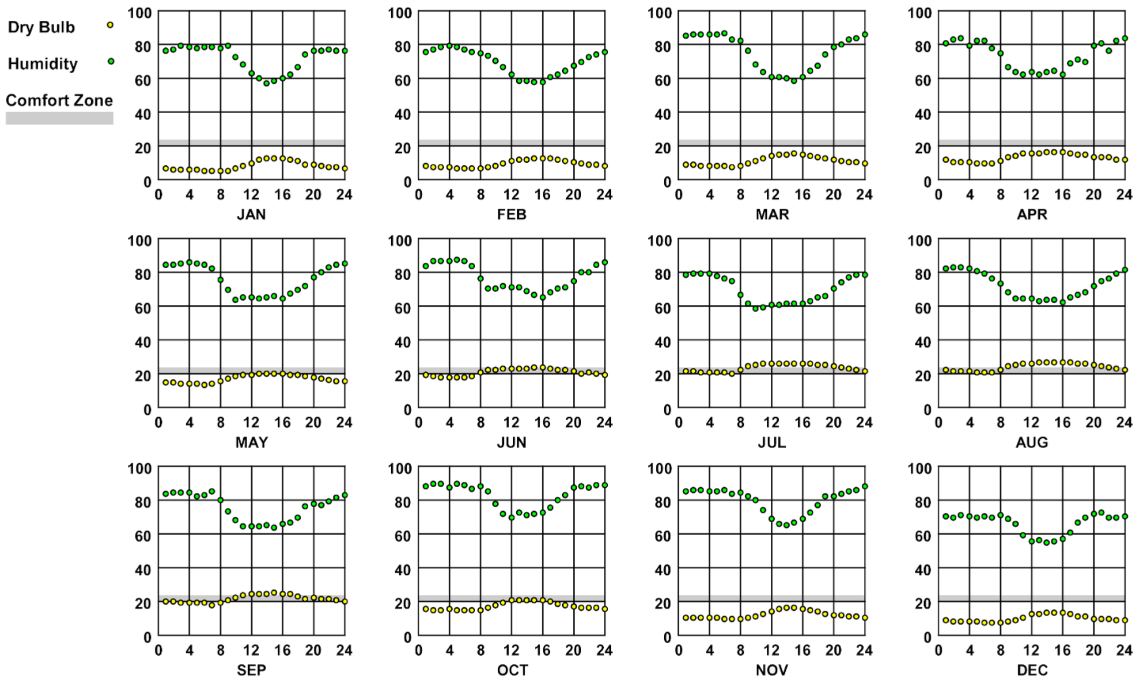


Figure 6.11: Outdoor dry-bulb temperature and humidity data of Barcelona.

Source: Climate Consultant 6.

Psychrometric chart presents physical and thermal properties of temperature and humidity parameters. It presents the relationship between air temperature and humidity in graphical form, and describes thermal comfort conditions for each climate category. It is considered as an important indicator using in climatic analysis. The psychrometric chart contains five physical properties as follows: 1) dry-bulb temperature (vertical lines); 2) wet-bulb temperature (diagonal lines); 3) dew-point temperature (horizontal lines); 4) relative humidity (curved lines); 5) Humidity ratio (horizontal lines). In this chart, the dark blue boxes show the comfort zone. In order to understand the yearly weather fluctuations in Bologna and Barcelona, Climate Consultant 6.0 was used to generate a psychometric chart (Figures 6.12 and 6.13).

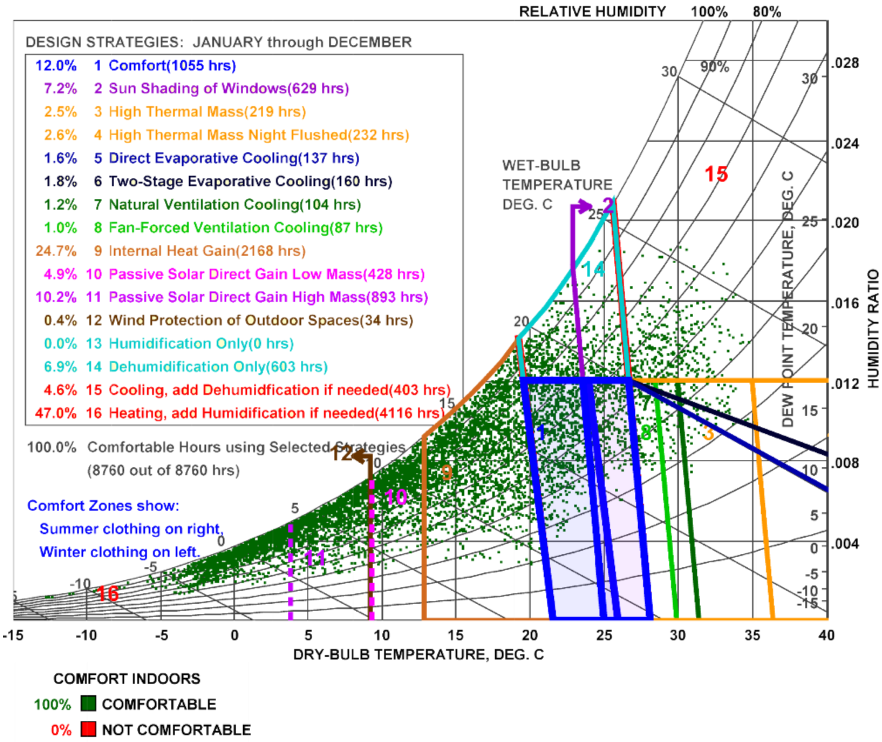


Figure 6.12: Bologna (Ferrara)'s psychometric chart (ASHRAE Standard 55). Source: Climate Consultant 6.

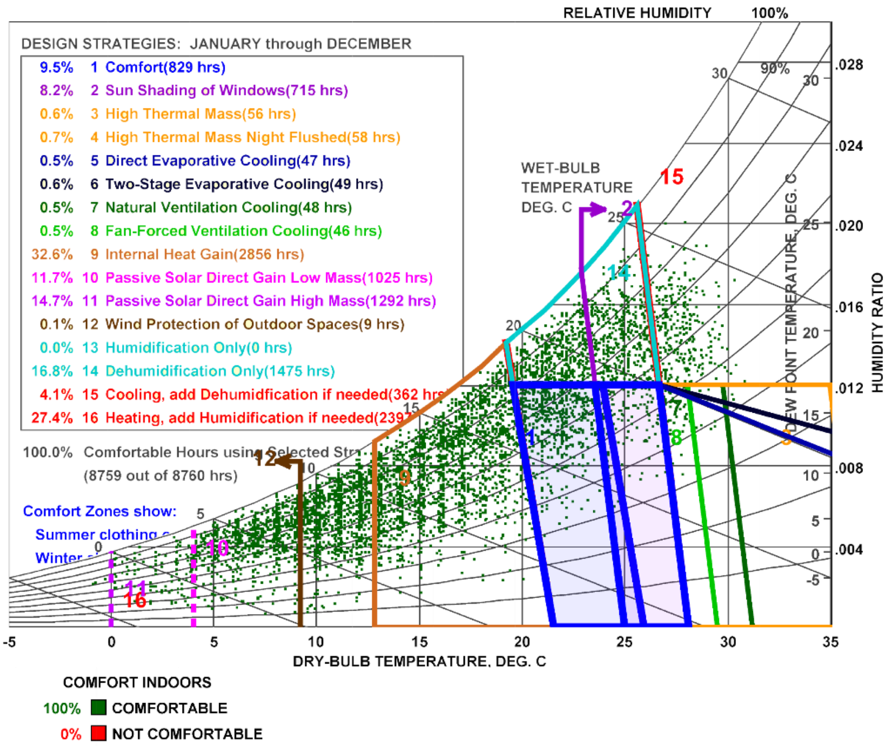


Figure 6.13: Barcelona's psychometric chart (ASHRAE Standard 55). Source: Climate Consultant 6.

To develop a natural ventilation and passive cooling strategy, it is necessary to measure the averages of wind speed and direction. Wind has a significant effect on temperature, humidity, rainfall and degree of air pollution. Its prediction can be useful for planning natural ventilation and forecasting the weather.

The wind rose is a diagram to characterize both the direction and frequency of wind. Annual wind rose for Bologna (Ferrara) and Barcelona, generated by Climate Consultant 6.0 (Figures 6.14 and 6.15). In this diagram, the outermost ring shows the percentage of hours when the wind comes for each direction. Blue bars show the average temperature of the wind coming from that direction (light blue is in the comfort zone and dark blue is cool). Green bars show average humidity (light green is considered comfortable at 30% to 70% while dark green is too humid above 70%).Innermost circle shows the minimum, average, and maximum velocity of the winds from each direction.

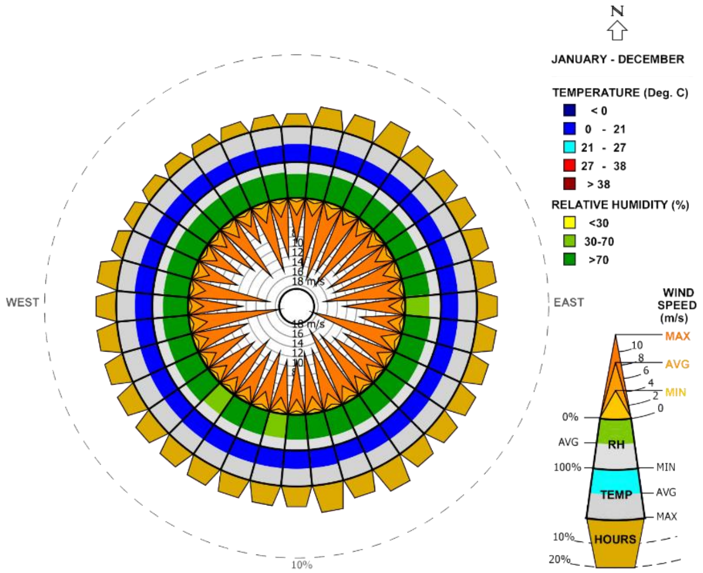


Figure 6.14: Wind wheel of Bologna (Ferrara). Source: Climate Consultant 6.

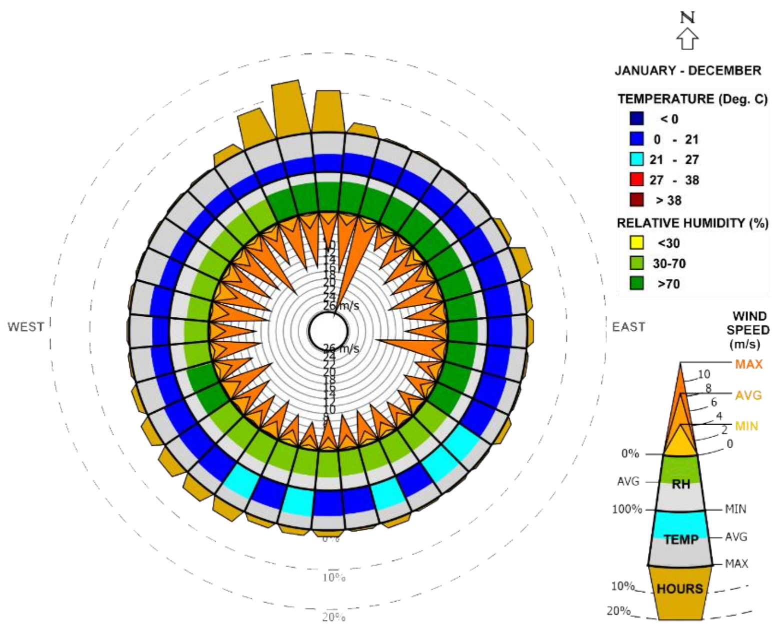


Figure 6.15: Wind wheel of Barcelona. Source: Climate Consultant 6.

In this context, Ecotect and WinAir were used to study the actual airflow around case study projects (Figures 6.16 and 6.17). As can be seen below, airflows are mostly through the cross windows. The maximum air flow in Bologna (Ferrara) and Barcelona is mostly from the north and north-west in summer.

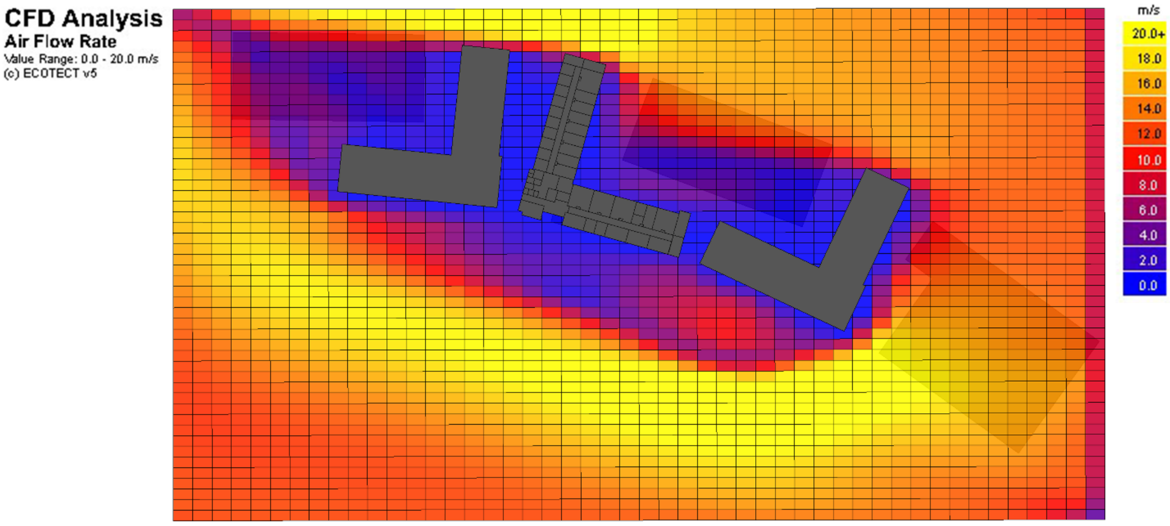


Figure 6.16: Air flow analysis of case study A (UNIFE) and its site in the fifth floor with Ecotect and WinAir4. Source: Author

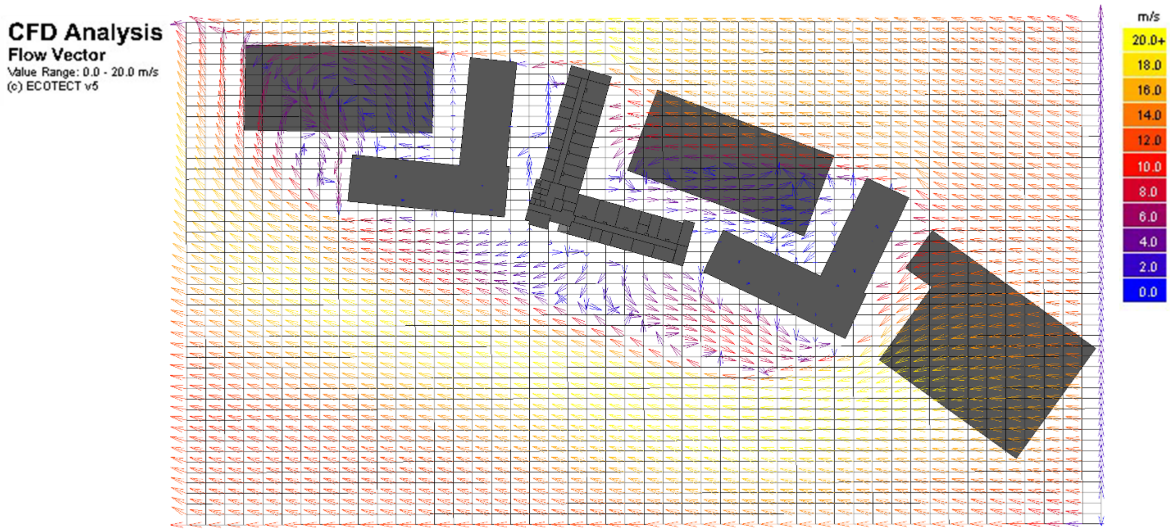


Figure 6.17: Air flow vectors analysis of case study A (UNIFE) and its site in the fifth floor with Ecotect and WinAir4. Source: Author.

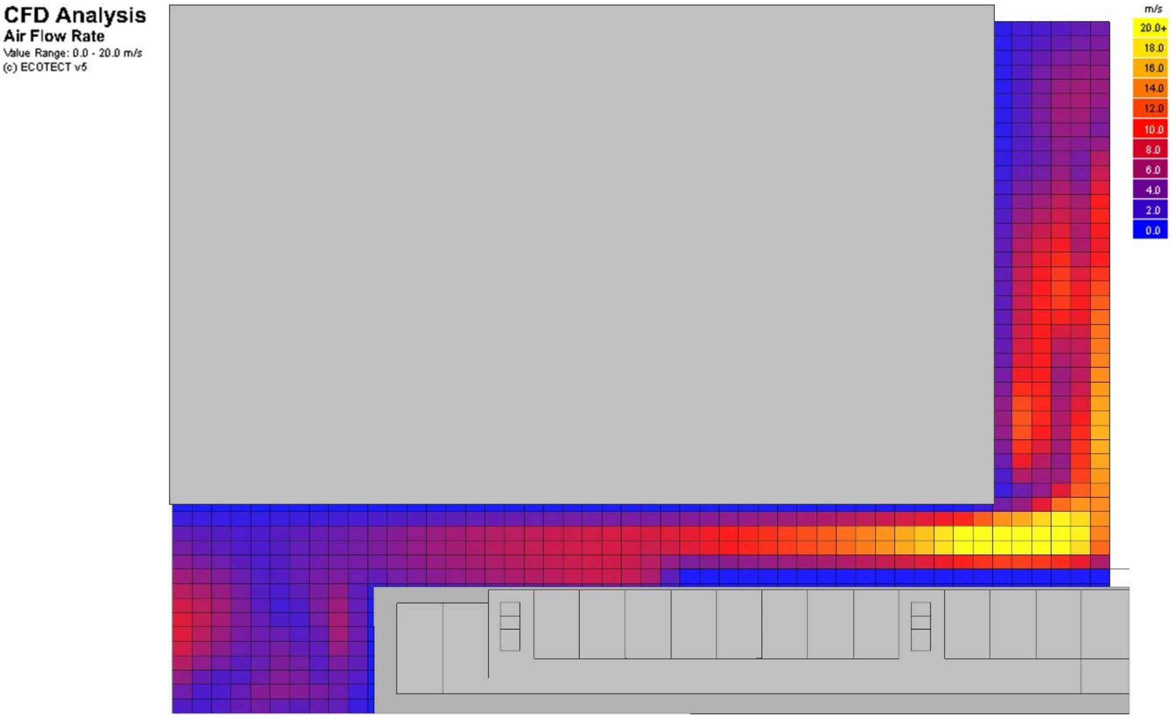


Figure 6.18: Air flow analysis of case study B (PUC) and its site in the ground floor with Ecotect and WinAir4. Source: Author

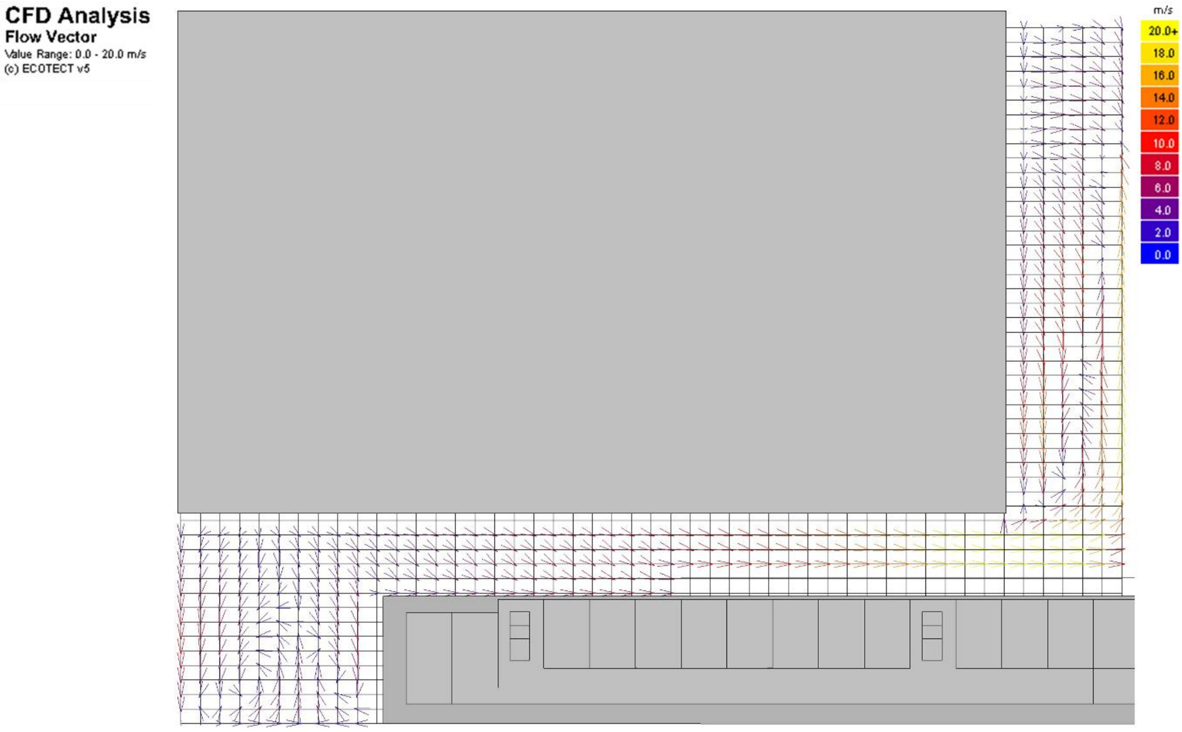


Figure 6.19: Air flow vectors analysis of case study B (PUC) and its site in the ground floor with Ecotect and WinAir4. Source: Author.

6.2 Sensitivity Analysis

Indoor environmental quality (IEQ) is one of the major issues that should be evaluated in the context of building performance prediction. Building indoor environmental quality measurements are often performed in the areas of thermal, lighting, air quality and acoustic. Due to the complexity of analyzing all aspects of environmental factors and the lack of experimental metric, it can be useful to simulate narrow range of indoor environmental conditions. The first step was to define zones that will be integrated into the dynamic simulation. The reference buildings were modeled in Revit and then imported into IES-VE simulation software. Four different types of rooms in the reference buildings were selected to analyze their energy performance and indoor environmental quality (Tables 6.6 and 6.7)

Table 6.6: The reference room zones of case study A (UNIFE). Source: Author.

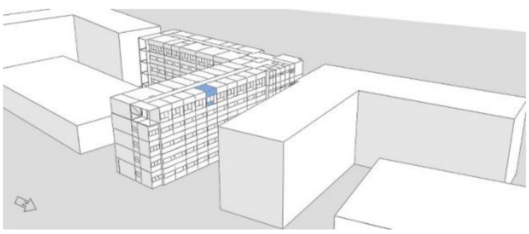
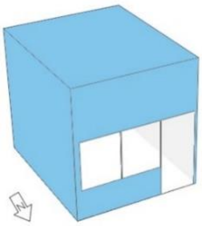
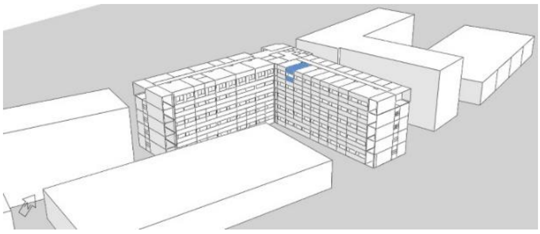
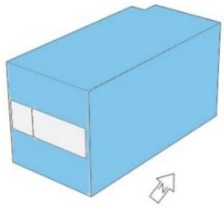
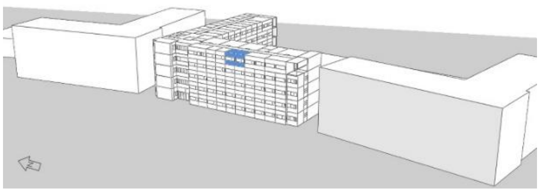
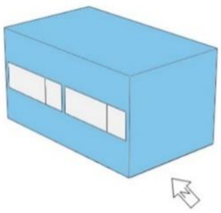
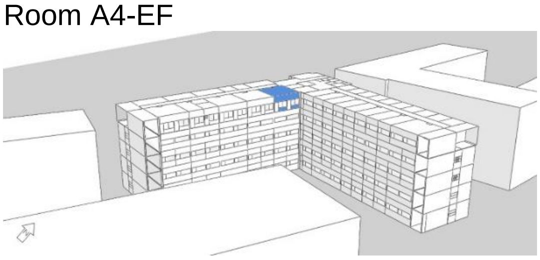
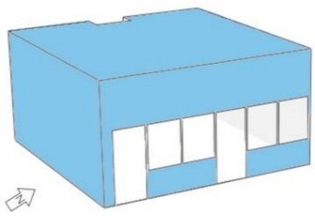
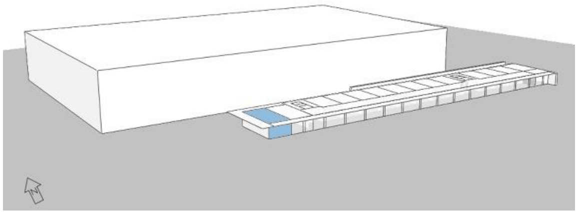
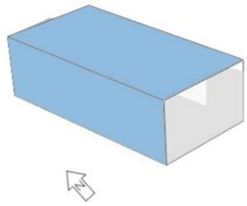
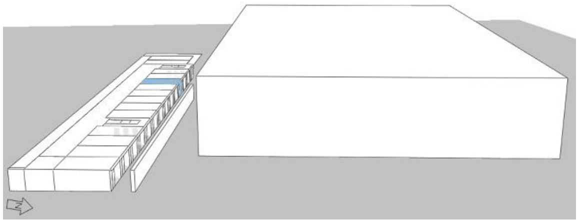
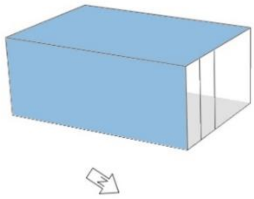
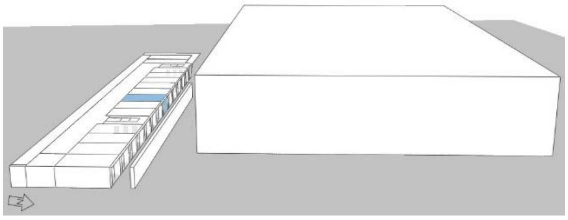
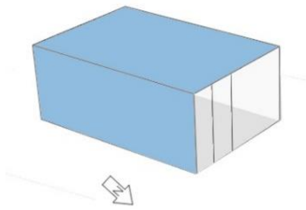
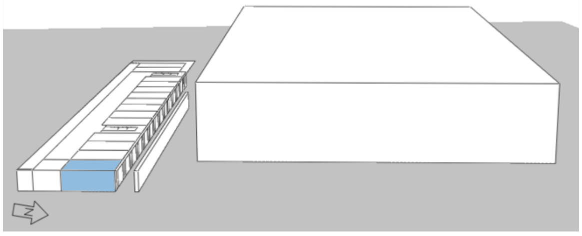
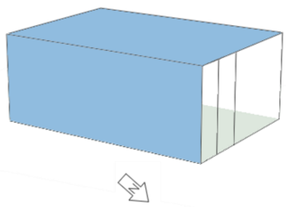
Position of the reference rooms	Façade side	Area m^2	Volume m^3
Room A1-NF 	North 	12.01	42.04
Room A2-SF 	South 	20.37	71.30
Room A3-WF 	West 	24.37	85.28
Room A4-EF 	East 	43.38	151.83

Table 6.7: The reference room zones of case study B (PUC). Source: Author.

Position of the reference rooms	Façade side	Area m^2	Volume m^3
Room B1-SFand NF 	South and north 	43.11	120.72
Room B2-NF 	North 	32.36	90.62
Room B3-NF 	North 	32.37	90.64
Room B4-NF 	North 	34.138	95.58

For a whole building simulation, it is necessary to define thermal zones. In the current work, each room was defined as a thermal zone. For each room, the set point conditions, as well as internal conditions such as the amount of users and their activities, lighting and electric equipment were defined. Furthermore, schedule ventilation for openings (windows-doors), HVAC temperature set points were considered for each thermal zone. Every room was bound by heat transfer surfaces. Openings such as doors or windows were simulated inside the wall surfaces.

6.2.1 Thermal comfort

Thermal comfort is one of the most important factors for improving the quality of the indoor environment. In case of built environment, users always try to achieve a thermally comfortable environment [243]. In this context, standards such as ASHRAE Standard 55 and ISO Standard 7730 are used to obtain appropriate thermal conditions in the buildings. However, parameter values can be variable for people in different climatic zones.

The first thermal comfort models were developed by Fanger and include the combination physical variables in both chart and graph form. Two models commonly used in thermal comfort are known as Fanger's predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD). They are recognized as thermal comfort index. They are also calculated in order to show satisfaction criteria and measure comfort levels at certain thermal environment.

Fanger defined PMV as "the difference between the internal heat production and the heat loss to the actual environment for a man kept at the comfort values for skin temperature and sweat production at the actual activity level". The PMV index is derived for steady state conditions but can be applied with good approximation for minor fluctuations of one or more of the variables [244]. It provides a score that corresponds to the ASHRAE thermal sensation.

The value of the PMV index has a range from -3 to +3 and is a 7-point rating scale (Table 6.8). It represents the average thermal sensation felt by users inside conditioned space. According to ASHRAE, thermal sensation values of –1, 0, and +1 are usually supposed to represent satisfaction. While dissatisfaction is defined as not voting either -1, +1 or 0.

Table 6.8: ASHRAE thermal sensation scale.

Value	Sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

The PMV equation uses the four environmental parameters; air temperature (t_a in ^oC), mean radiant temperature (t_{mrt} in ^oC), air velocity (v in m/s), relative humidity (vapour pressure, p_a in kP_a) and two personal variables (clothing insulation (clo) and metabolic rate (met)). The following equations show relationship between parameters.

$$PMV= \int (t_a, t_{mrt}, v, p_a, I_{cl}, M) \quad (1)$$

PPD is calculated from PMV using the equation:

$$PPD = 100-95 \times \exp(-0.03353 \times PMV^4 - 0.2179 \times PMV^2) \quad (2)$$

PPD predicts the percentage of occupants that are dissatisfied with the given thermal conditions. The PMV and PPD form a U- shaped relationship (Figure 6.20). In this respect, at PMV neutral (0), 5% of the occupants are still dissatisfied.

The calculation of the PMV and the PPD is currently facilitated by simulation programs. The simulation of PMV and PPD can play a significant role in the design and evaluation of the indoor environmental quality.

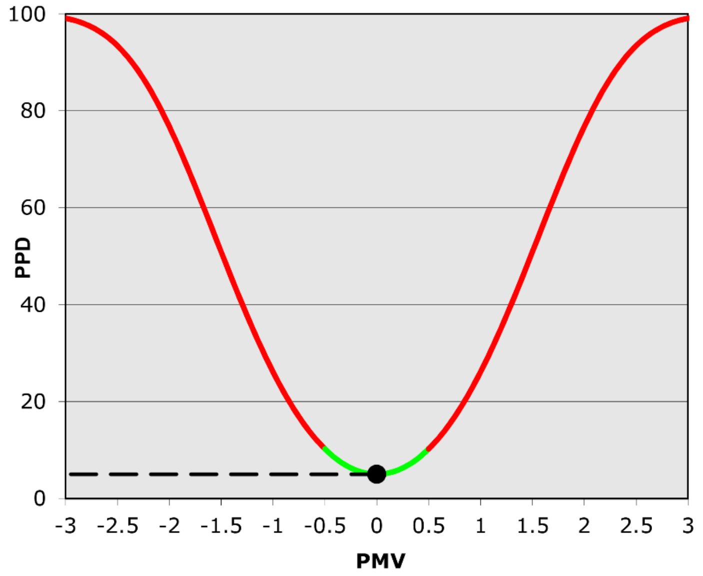


Figure 6.20: Evolution of PPD on the basis of PMV (Fanger, 1970).

In general, the PMV model is used by thermal comfort standards to define acceptable thermal comfort conditions. The recommendations made by ASHRAE Standard 55 are shown in the following table.

Table 6.9: ASHRAE Standard 55 recommendations.

Season	Optimum temperature	Acceptable temperature range	Assumptions for other PMV inputs
Winter	22 º C	20-23.5 º C	Relative humidity: 50% Mean relative velocity: < 0.15 m/s Mean radiant temperature: equal to air temperature Metabolic rate: 1.2 met Clothing insulation: 0.9 clo
Summer	24.5 º C	23-26 º C	Relative humidity: 50% Mean relative velocity: < 0.15 m/s Mean radiant temperature: equal to air temperature Metabolic rate: 1.2 met Clothing insulation: 0.5 clo

According to ASHRAE Standard 55, optimum temperature refers to operative temperature which is defined as the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non uniform environment. In determining thermal comfort, operative temperature (t_o) is roughly the average of the air temperature (t_a) and mean radiant temperature (t_r) weighted by their respective heat transfer coefficients (h_c and h_r):

$$t_o = (h_c\, t_a + h_r\, t_r) / (h_c + h_r) \quad (3)$$

Furthermore, European standard EN 15251 [245] is one of international comfort standards that shows an adaptive comfort model and provides thermal comfort conditions in buildings which are neither heated nor cooled mechanically but people can operate windows and are relatively free to select clothing level [246]. It specifies several different categories of indoor environment which can be selected for a space to be conditioned (Tables 6.10 and 6.11). It also includes criteria for the four indoor environmental factors such as thermal comfort, air quality, lighting, and acoustic.

Table 6.10: Explanation of the applicability of the categories used in EN 15251 [245].

Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons.
II	Normal level of expectation and should be used for new buildings and renovations.
III	An acceptable, moderate level of expectation and may be used for existing buildings.
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year.

Table 6.11: Comfort categories valid for mechanically heated and cooled buildings [245].

	Fanger model		Adaptive model
Category	Predicted Percentage of Dissatisfied (PPD) %	Predicted Mean Vote (PMV)	T_C (°C)
I	< 6	-0.2 < PMV < +0.2	$T_C -2 \le T_{op} \le T_C +2$
II	< 10	-0.5 < PMV < +0.5	$T_C -3 \le T_{op} \le T_C +3$
III	< 15	-0.7 < PMV < +0.7	$T_C -4 \le T_{op} \le T_C +4$
IV	> 15	PMV < - 0.7 or +0.7 < PMV	$T_{op} < T_C -4$ and $T_{op} > T_C+4$

ASHRAE standard 55 and EN 15251 allow the determination of thermal comfort in naturally ventilated spaces and define acceptable ranges of operative temperature. They also have greater influence on the dimensioning and sizing of HVAC systems. According to standard EN15251, ventilation rates that are used for sizing the equipment shall be specified in design.

ASHRAE standard 55 comfort temperature ranges are able to account only for people adaptation. EN 15251 introduces an allowance for air movement and accounts for people's clothing adaptation in naturally conditioned spaces. Adaptive comfort model based on standard EN15251 defines three comfort regions: 1) category I (90%) acceptability; 2) category II (80%) acceptability; 3) category III (65%) acceptability (Figure 6.21).

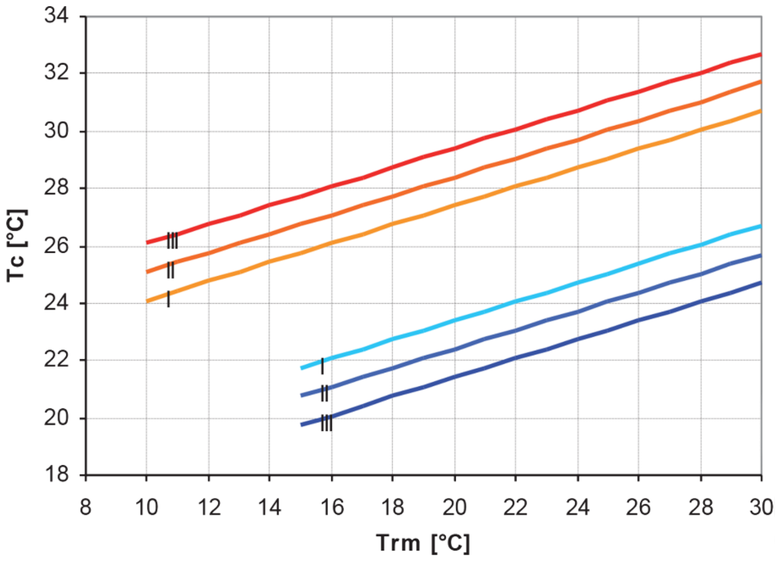


Figure 6.21: Adaptive comfort categories adopted by EN 15251 [245].

The adaptive comfort temperature (T_{comf}) is defined as the optimal operative temperature. It is related to the running mean of the outdoor temperature (T_{rm}) and given by equation 4.

$T_{comf} = 0.33T_{rm}+18.8$ (4)

where $T_{rm} = (1- \alpha).\{ T_{ed -1} + \alpha.\ T_{ed -2} + \alpha^{2}\ T_{ed -3} \ldots.. \}$

and T_{rm} = Running mean temperature for today

T_{ed-1} is the daily mean external temperature for the previous day

$T_{ed -2}$ is the daily mean external temperature for the day before and so on.

α is a constant between 0 and 1. Recommended to use 0, 8.

Upper and lower temperature limits are defined with reference to this adaptive comfort temperature for different categories as mentioned in the standard EN1525. For each of these categories upper and lower limits are set for the operative temperature (T_{op}) by the following equations. The upper limits are applicable for $10 < T_{rm} < 30$ and the lower limits for $15 < T_{rm} < 30$.

Category I: upper limit: $T_{op\ max} = 0,33\ T_{rm} + 18,8 + 2$ (5)

lower limit: $T_{op\ min} = 0,33\ T_{rm} + 18,8 – 2$ (6)

Category II: upper limit: $T_{op\ max} = 0,33\ T_{rm} + 18,8 + 3$ (7)

lower limit: $T_{op\ min} = 0,33\ T_{rm} + 18,8 – 3$ (8)

Category III: upper limit: $T_{op\ max} = 0,33\ T_{rm} + 18,8 + 4$ (9)

lower limit: $T_{op\ min} = 0,33\ T_{rm} + 18,8 – 4$ (10)

where $T_{op\ max\ /\ min}$ = limit value of indoor operative temperature, °C.

●**Simulation of PMV-PPD values (case study A)**

In order to calculate PMV-PPD values of case study A, a full dynamic simulation was carried out in the selected zones (rooms). The simulation period was set from January to December. Bologna (Ferrara) weather data was used in the simulation process. In case study A the zones were considered to be occupied from 7 a.m. to 6 p.m. in weekdays (Figure 6.22).

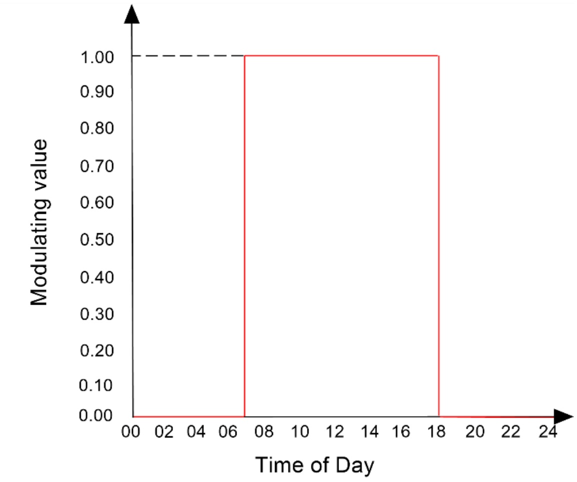


Figure 6.22: Working weekly profile used for case study A. Source: Author.

The internal heat gains were assumed for the occupied and unoccupied period in accordance with ASHRAE 90.1-2004 guideline (Table 6.12).

Table 6.12: Internal gains data for case studies (A and B). Source: Author.

Internal gains	Design level calculation method	Assumed input value
People	m^2 /person	10 m^2 /person
Lighting	Watts / area	10 W/m^2
Electric equipment	Watts /area	15 W/m^2

Fan coil units were used to provide heating, cooling or both in the building. Heating and cooling set points were 20˚C and 25˚C respectively in order to maintain thermal comfort (between 20˚C and 25˚C). Thermal zones used the same operating schedules (lighting, occupancy, and equipment). Public areas such as entryways, corridors, restrooms, stairways and entrances were stimulated by different temperature schedule and set points. In the first step SunCast was used to analyze the effect of sunlight and shadow on thermal behavior of rooms as shown in the following figure. It was performed under solar radiation conditions in the diffuse sky. The next step was to simulate airflows within the building by using MacroFlo component which is used to investigate the effectiveness of natural ventilation (e.g. windows and doors). It is important to note that the simulation results were only considered for the occupied periods of 07.00 am to 18.00 pm (case study A) and 08.00 am to 17.00 pm (case study B).

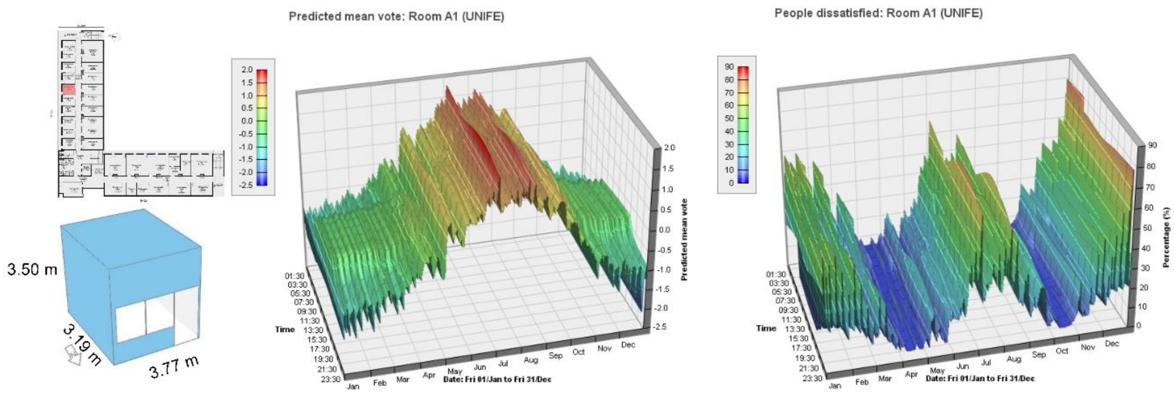


Figure 6.23: PMV-PPD values (linked with solar radiation) for room A1. Source: Author.

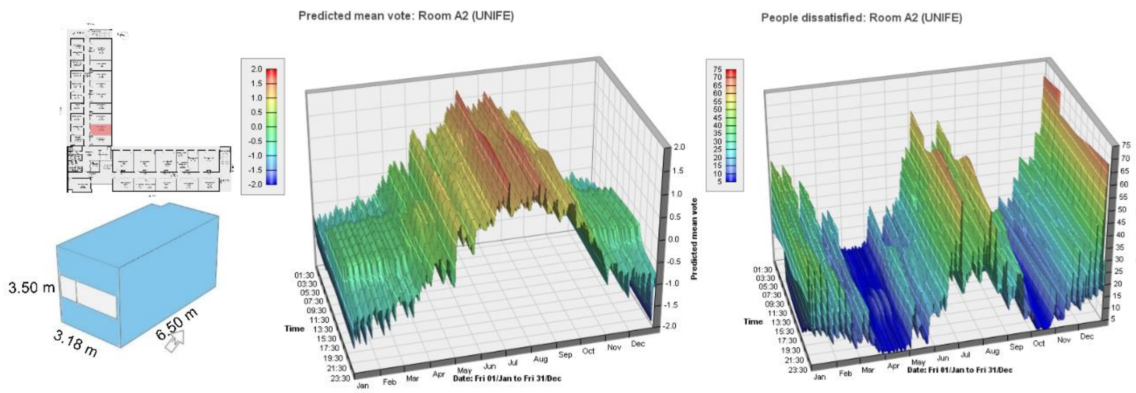


Figure 6.24: PMV-PPD values (linked with solar radiation) for room A2. Source: Author.

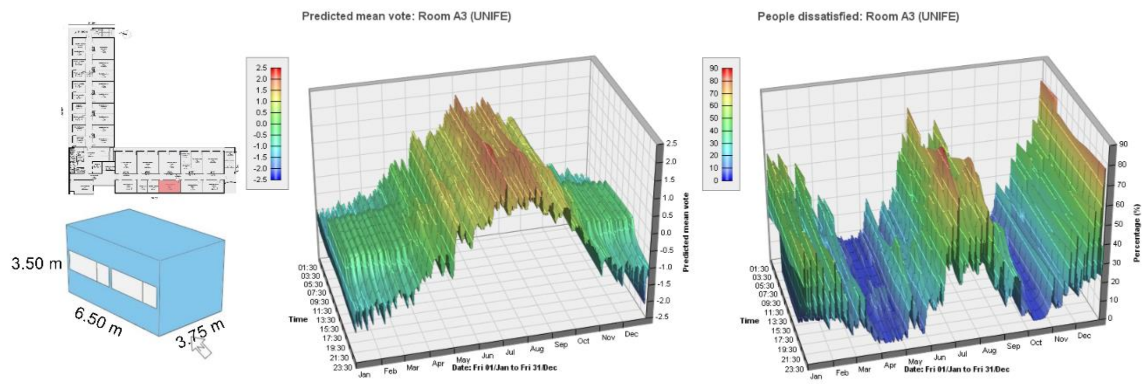


Figure 6.25: PMV-PPD values (linked with solar radiation) for room A3. Source: Author.

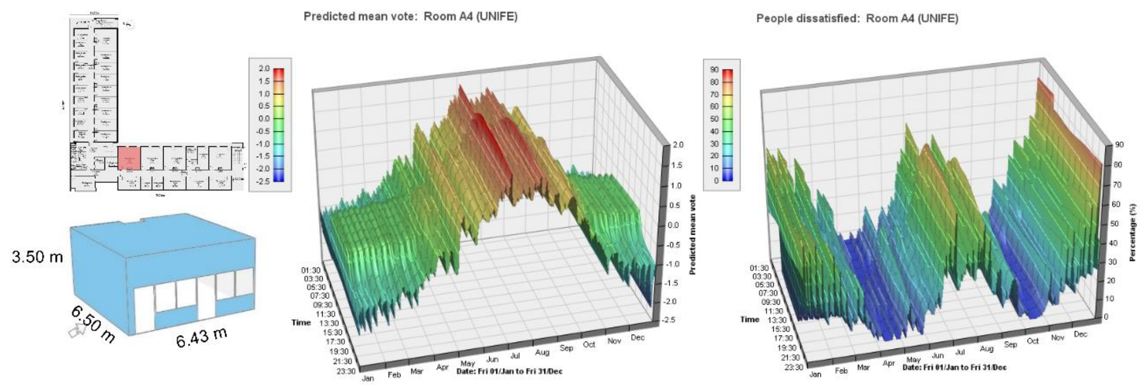


Figure 6.26: PMV-PPD values (linked with solar radiation) for room A4. Source: Author.

It is worth nothing that in the IES-VE software the default comfort settings are 0.69 clo for clothing and 0.9 met for activity (1 met =58 W/m^2; 1 clo = 0.155 m2K/W). In this respect, users are expected to be wearing the same type of clothes across all months and working at the same activity level throughout the year. A summary of simulation results is presented in the following table. A comparison between simulated data and comfort requirements can be used to evaluate indoor thermal comfort conditions.

Table 6.13: Maximum and minimum PMV values for case study A. Source: Author.

Model	PMV values			
	Maximum	Month	Minimum	Month
Room A1	1.67 ~ 1.96	July	-1.96 ~ -2.00	December
Room A2	1.60 ~1.79	July	-1.72 ~ -1.78	December
Room A3	1.80 ~2.19	July	-1.95 ~ -2.00	December
Room A4	1.70 ~1.97	July	-2.00 ~ -2.05	December

The recommended criterion in ASHRAE-55 standard, is to limit the PMV to between –0.5 and 0.5 and a dissatisfaction rate of less than 10 %. The simulation results showed that the values of PMV in the rooms are not always within an acceptable range defined by ASHRAE-55 in the occupied periods (07.00 am to 18.00 pm). According to the simulation results in Table 6.11, room A3 has the maximum PMV values during July compared to other rooms. This is because room A3 receives maximum sunlight as it is situated at the west side of the building. The room A2 has minimum PMV (between -1.72 to -1.78) values during December.

●Simulation of PMV-PPD values (case study B)

A full dynamic simulation was carried out for case study B within SunCast to evaluate the impact of shading and solar penetration on thermal loads. As mentioned before, there is no automatic cooling system in the building's ventilation system. Heating set point temperature was set to 20°C. Occupied hours were defined as Monday-Friday from 08.00 am to 17.00 pm (Figure 6.27). Barcelona weather data was used in the simulation process.

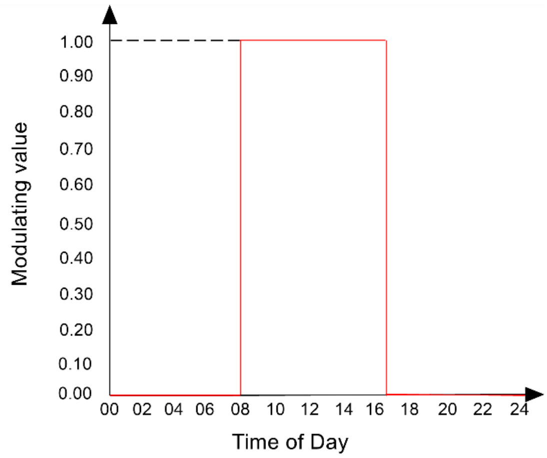


Figure 6.27: Working weekly profile used for case study B. Source: Author.

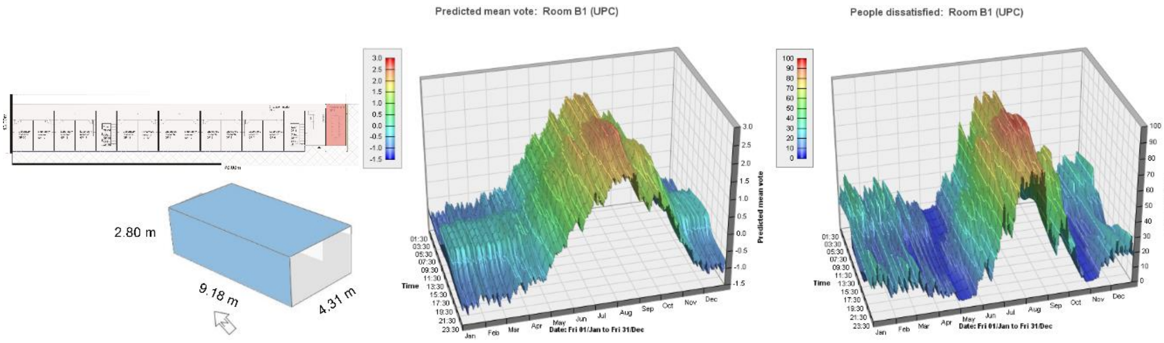


Figure 6.28: PMV-PPD values (linked with solar radiation) for room B1. Source: Author.

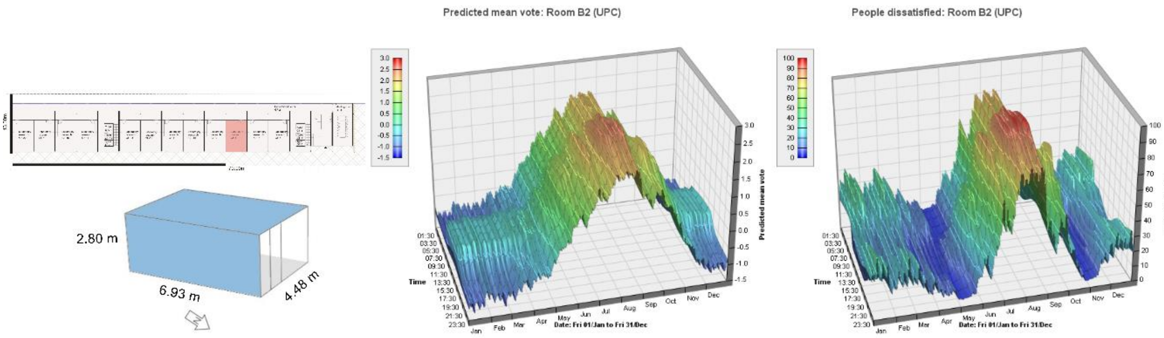


Figure 6.29: PMV-PPD values (linked with solar radiation) for room B2. Source: Author.

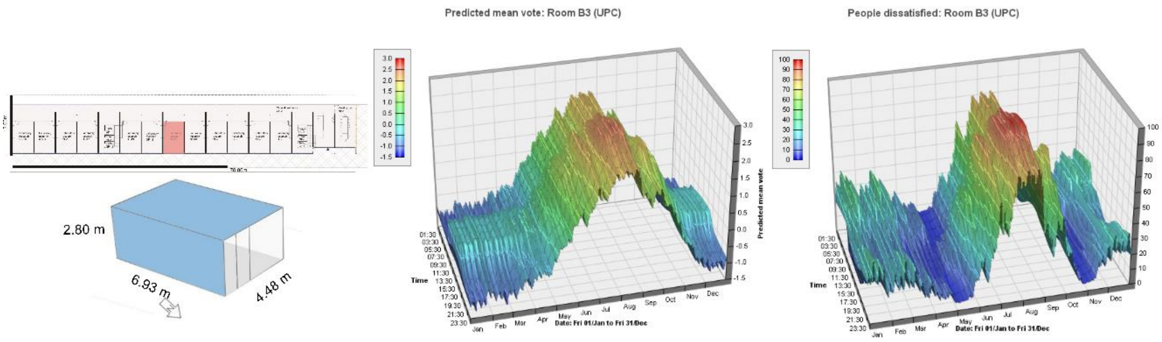


Figure 6.30: PMV-PPD values (linked with solar radiation) for room B3. Source: Author.

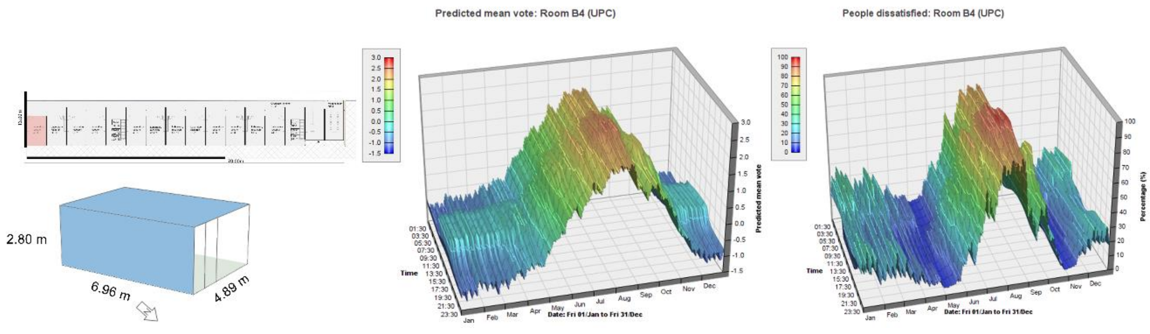


Figure 6.31: PMV-PPD values (linked with solar radiation) for room B4. Source: Author.

It is important to note that thermal comfort can be analyzed for various time periods such as summer (April to September), winter (October to March), and whole year. In this respect, simulations were carried out for a whole year to find critical values of PMVs (minimum and maximum) in the case studies. PMV simulation results of case study B are presented in the following table.

Table 6.14: Maximum and minimum PMV values for case study B. Source: Author.

Model	PMV values			
	Maximum	Month	Minimum	Month
Room B1	2.05 ~ 2.57	Aguste	-1.02 ~ -1.29	January
Room B2	2.07 ~2.67	Aguste	-1.11 ~ -1.34	January
Room B3	2.07 ~2.67	Aguste	-1.11 ~ -1.34	January
Room B4	2.11 ~2.60	Aguste	-1.11 ~ -1.25	January

As shown in Table 6.14, the warmest and coldest months corresponding to maximum and minimum PMV were found during Aguste and January respectively. This could be due to lack of cooling and air ventilation systems, the case study B is mostly hotter compared to the case study A. Furthermore, it can be seen that peak values of PMV (5 Aguste and 10 January) are outside the ASHRAE thermal comfort boundary.

●Natural and hybrid ventilation

Natural ventilation is one of the key environmental factors that plays the significant role in putting forward sustainability principles for buildings. The key purpose of natural ventilation is to provide fresh air and moving heat from indoor environment. Natural ventilation is one of significant methods to achieve the adaptive thermal comfort by users and can improve indoor environmental quality.

A study [247] has stated that mechanical ventilation has been preferred to natural ventilation, as it can provide stable air conditions and resolve airflow problems triggered by inadequacies in design. Nevertheless, heating, ventilation and air conditioning systems (HVAC) are complex and need a large number of components to operate. Furthermore, this kind of technology consumes a great amount of energy, whilst not always managing to deliver the desired indoor climate [248].

Natural ventilation is considered as a sustainable design strategy to reduce cooling energy demand of buildings. It plays an important role in sustaining air flow in the buildings and provides economic and environmental benefits. The main purpose of using natural ventilation into buildings is to provide space cooling. It is important to provide a balance between supply of fresh air and unexpected outdoor air temperature. For example, outside air should remove contaminated indoor air and provide good indoor air quality (IAQ) for users at the same time.

It is clear that users, when the inside temperature is higher than the outside temperature, are willing to open windows. Natural ventilation can be considered as an efficient method to reduce mechanical ventilation consumption. For example, the HVAC system can be shut down in a space when a window is open. In this respect, users have a greater role in opening windows and controlling air conditioners.

The hybrid ventilation (mixed mode) systems combine user controlled natural ventilation with mechanical ventilation systems. They have significant advantages compared to conventional mechanical systems and offer possibilities to improve indoor environmental quality. Hybrid ventilation relies on natural driving forces to provide the desired (design) flow rate. It uses mechanical ventilation when the natural ventilation flow rate is too low [249].

To evaluate the performance of selected rooms with reference to natural ventilation, a detailed analysis of indoor airflow distributions was performed. In this context, the simulations were conducted with the aim of evaluating the benefits of natural ventilation. IES-MarcoFlo (for natural ventilation analysis) was used to determine impacts of natural ventilation on the baseline rooms. In the case study buildings, ventilation occurs through open able windows and doors. Open able area of case study buildings were defined (Figures 6.32 and 6.33).

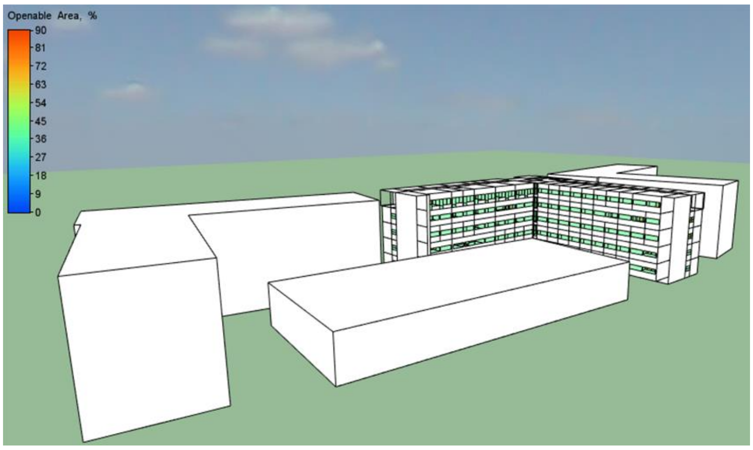


Figure 6.32: Open able area of case study A. Source: Author.

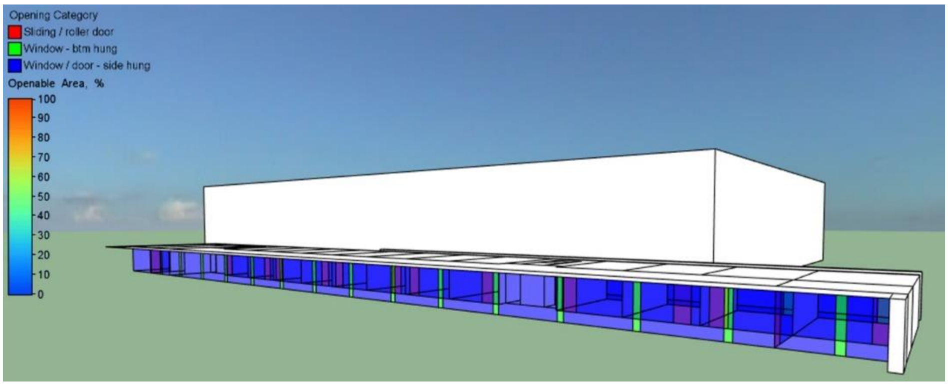


Figure 6.33: Open able area of case study B. Source: Author.

The main aim of analysis was to determine the number of months that natural ventilation can improve indoor environmental conditions within comfort limits (-0.5<PMV<+0.5). In this regard, the simulations were carried out under two conditions (with and without natural ventilation), and the results obtained are shown in the following figures. The waved blue and red lines represent with and without natural ventilation conditions respectively.

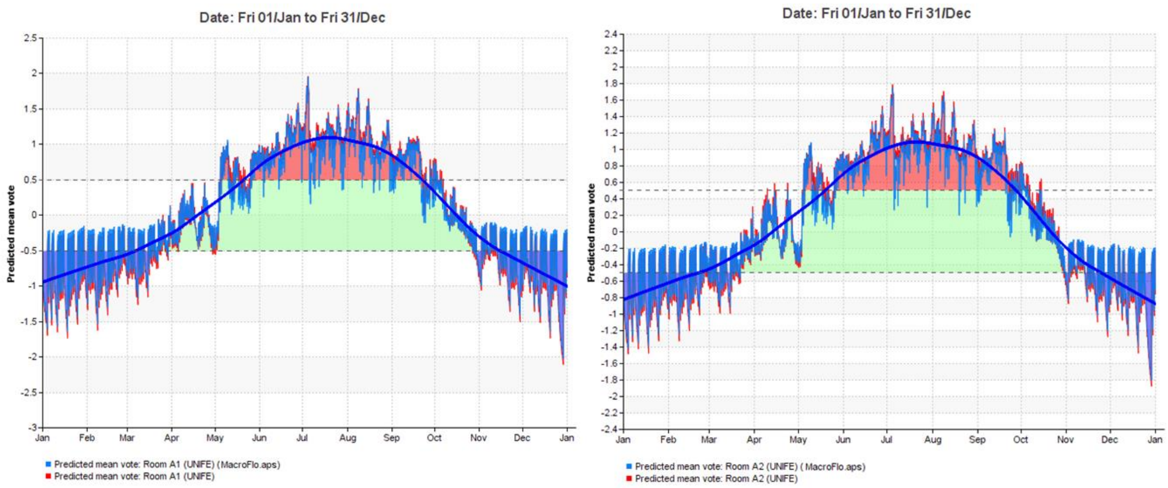


Figure 6.34: PMV values in naturally ventilated: room A1 (left) and room A2 (right).
Source: Author.

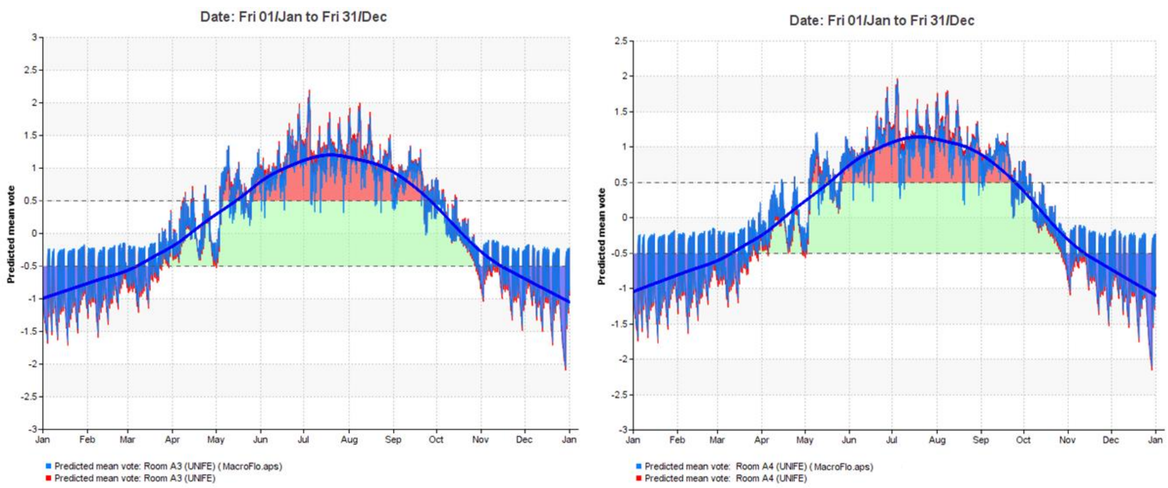


Figure 6.35: PMV values in naturally ventilated: room A3 (left) and room A4 (right).
Source: Author.

It is a fact that there is more natural ventilation in the warmer months. According to the above figures, the desired PMV values were found between May and November. It can also be seen from the figures that natural ventilation can result in the lower PMV values. For example, the maximum PMV values of rooms A1, A2, A3, and A4 have been reduced from 1.96, 1.79, 2.19, and 1.97 to 1.94, 1.74, 2.12, and 1.94 respectively.

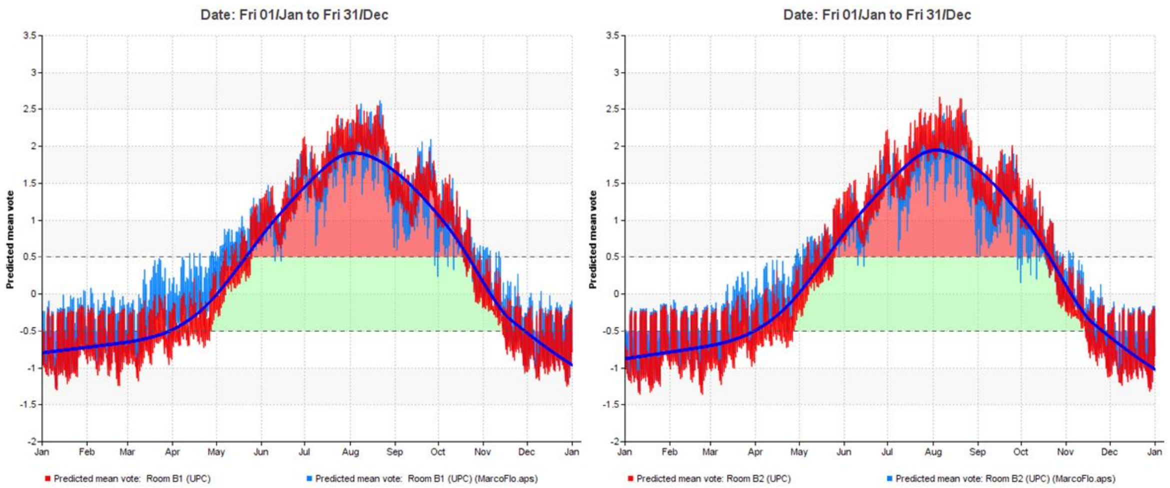


Figure 6.36: PMV values in naturally ventilated: room B1 (left) and room B2 (right).
Source: Author.

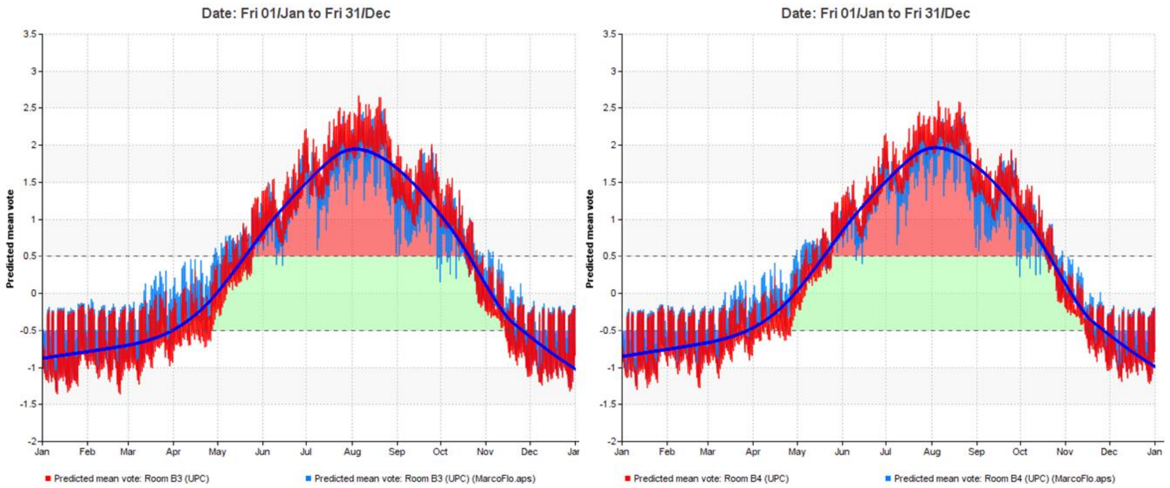


Figure 6.37: PMV values in naturally ventilated: room B3 (left) and room B4 (right).
Source: Author.

As shown in the figures above, natural ventilation can meet requirements of the recommended PMV values between May and November. It is also effective at reducing the maximum PMV values of rooms B1, B2, B3, and B4 from 2.57, 2.67, 2.67, and 2.60 to 2.38, 2.43, 2.43, and 2.39 respectively.

Furthermore, CFD module of IES-VE (Microflo) was used to understand air flow and heat transfer processes occurring within rooms. It was performed in conjunction with the operable bottom hung windows and operable doors in every room. The simulations were conducted at maximum external ventilation of case study A (07 September 14:30) and case study B (02 September 08:30). The results are shown in the following figures.

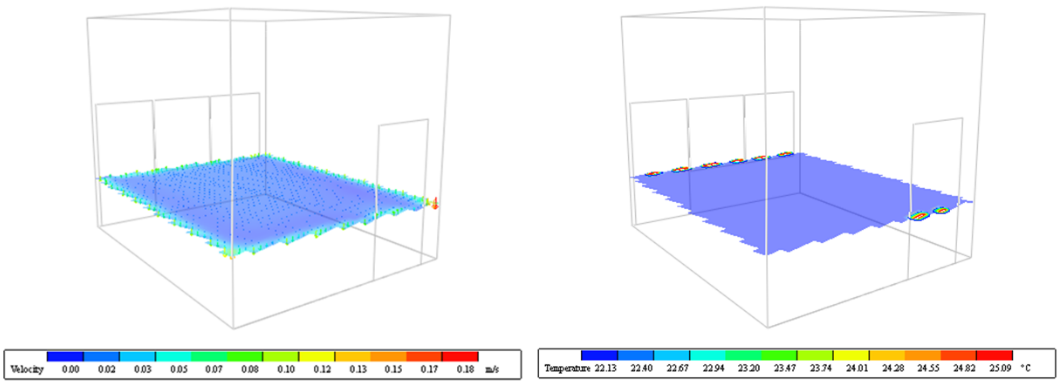


Figure 6.38: Air velocity contour (left) and temperature (right) of room A1. Source: Author

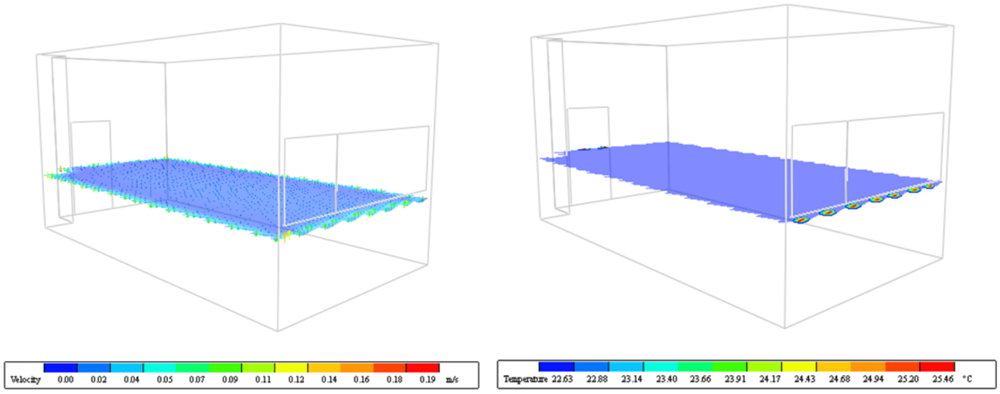


Figure 6.39: Air velocity contour (left) and temperature (right) of room A2. Source: Author

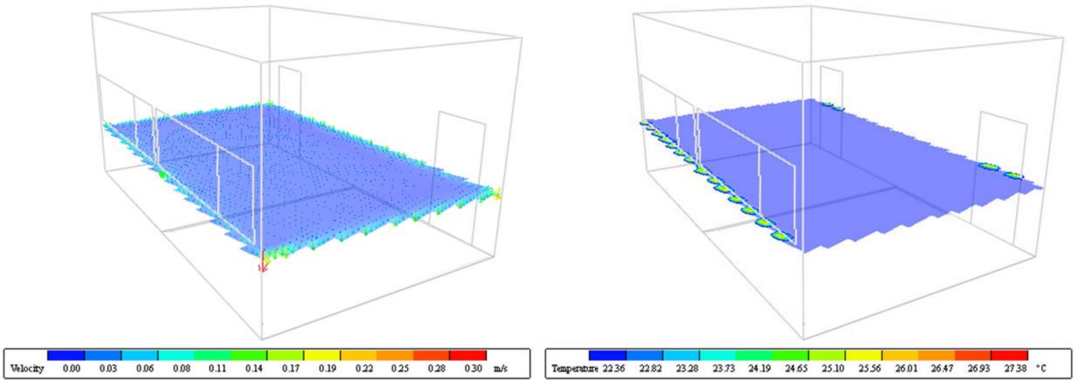


Figure 6.40: Air velocity contour (left) and temperature (right) of room A3. Source: Author

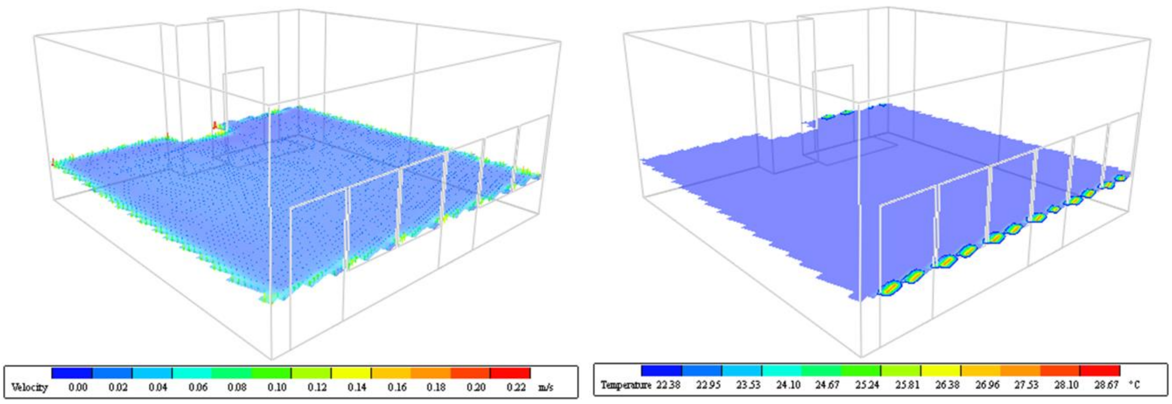


Figure 6.41: Air velocity contour (left) and temperature (right) of room A4. Source: Author

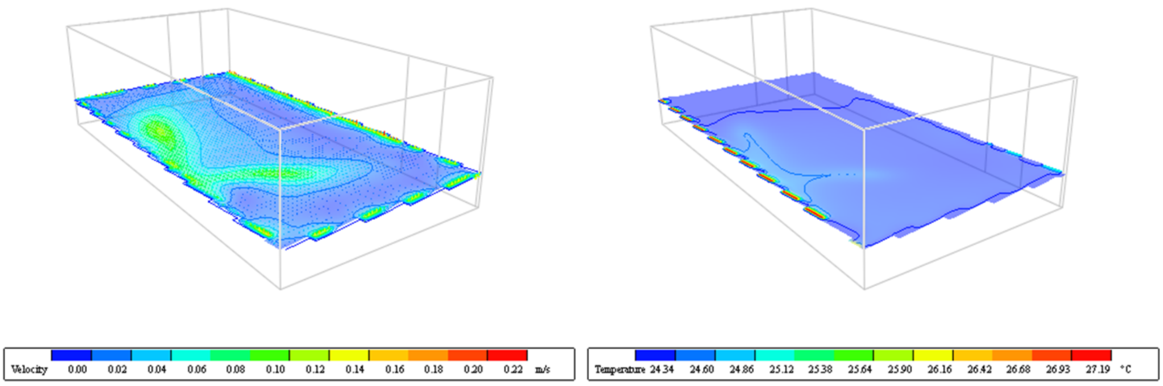


Figure 6.42: Air velocity contour (left) and temperature (right) of room B1. Source: Author

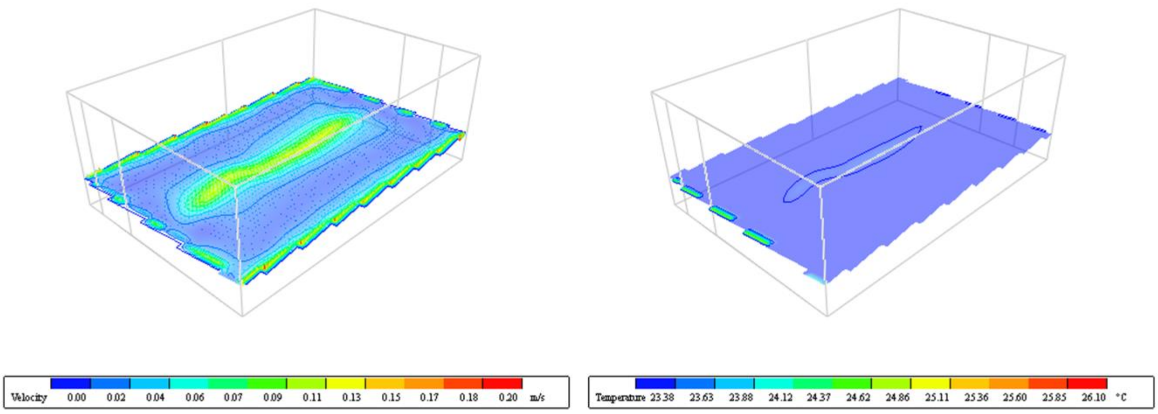


Figure 6.43: Air velocity contour (left) and temperature (right) of room B2. Source: Author

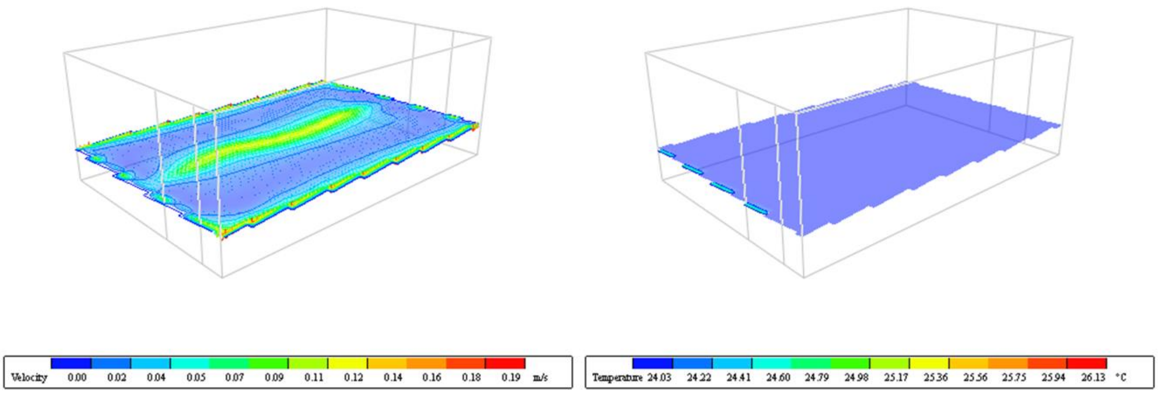


Figure 6.44: Air velocity contour (left) and temperature (right) of room B3. Source: Author

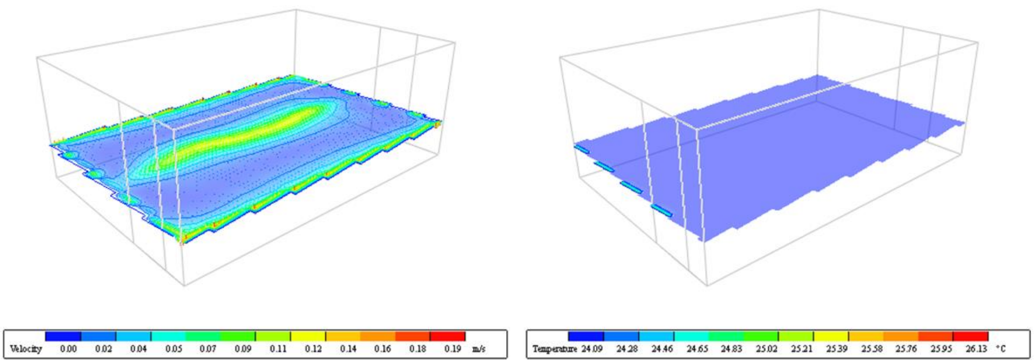


Figure 6.45: Air velocity contour (left) and temperature (right) of room B4. Source: Author

6.2.2 Daylight performance

The use of natural daylight is considered as one of the most important strategies for establishing a comfortable and efficient environment. It can contribute to reduce energy use from artificial lighting in the buildings. It is, therefore, important to gain maximum benefits from natural lighting. Several methods are used to evaluate daylight availability in buildings. Daylight factor (DF) is one of the most commonly applied methods used in evaluating daylight performance. Moreover, useful daylight illuminance (UDI) and daylight autonomy (DA) metrics are considered to provide a more detailed and realistic understanding of the annual daylight availability within indoor climate. The study [250] provided a review of recommended static and dynamic daylight performance metrics (Table 6.15).

Table 6.15: Metrics conducted to assess daylighting performance in the offices in Tropics.

Metric		Criteria	Description
Static	Daylight factor (DF)	<2%	Gloomy appearance with rare daylight. Electric lighting needed during daylight hours.
		2%-5%	Predominant daylight appearance. Some supplementary electric lighting required.
		>5%	Daytime electric lighting rarely needed. Thermal/glare issues may occur along with the high levels of daylight.
Dynamic	Daylight autonomy (DA)	--	The percentage of the occupied period (hours) of the year that the minimum daylight requirement is exceeded through the year.
	Continuous daylight autonomy (DA_{con})	>80%	Excellent daylight designs
		60-80%	Good daylight designs
		40-60%	Adequate daylight designs
	Daylight autonomy max (DA_{max})	>5%	Not acceptable. A high probability that this will lead to a situation with a direct sunlight patch and hence glare.
		<5%	Acceptable
	Useful daylight illuminance (UDI)	<100 lx	Gloomy room with insufficient daylight.
		100-2000 lx	The room is with useful daylight levels for the occupants.
		>2000 lx	The room is too bright and exceeds the upper threshold of the useful range. Higher levels glare or discomfort maybe delivered together with overheating issues.

In order to evaluate the daylighting inside case studies, the simulations were performed with IES-VE, Radiance and Daysim at working planes height of 0.8m from January 1st to December 31st under overcast sky conditions. The minimum illuminance required for a room is 500 lux. Furthermore, simulations were carried out for the solar analysis characteristics days, i.e. the spring equinox (March 21st), the summer and winter solstices (June 21st, December 21st). The reference rooms were considered without dynamic shading device. The results obtained in the simulations are shown in the following figures.

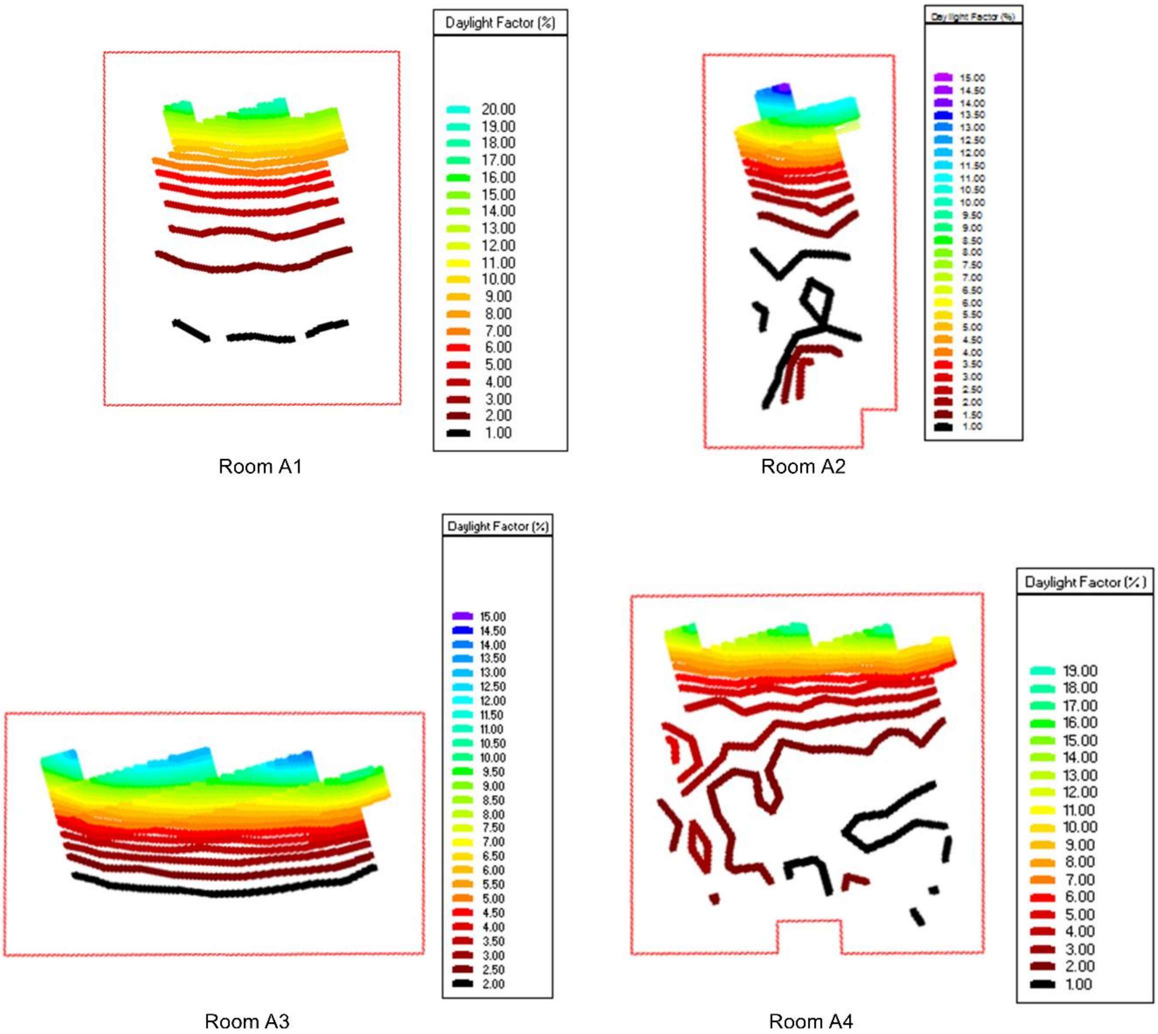


Figure 6.46: Daylight factors in rooms A1, A2, A3, and A4 (performed in IES-VE). Source: Author

The above graphic results show that rooms have different daylight factor distributions. Daylight factor contours in room A2 and A3 show a high uniformity of light distribution compared to other rooms. As mentioned before, rooms with daylight factor between 5% and 10% are considered to be good quality daylight. The simulation results show that floor area of the rooms receive under 2% of daylight factor. It can also be observed that there are high daylight factors near view windows. It is important to note that due to the evaluation of daylight factors under overcast conditions, the measurements are not affected by factors related to time and window orientation (location of room).

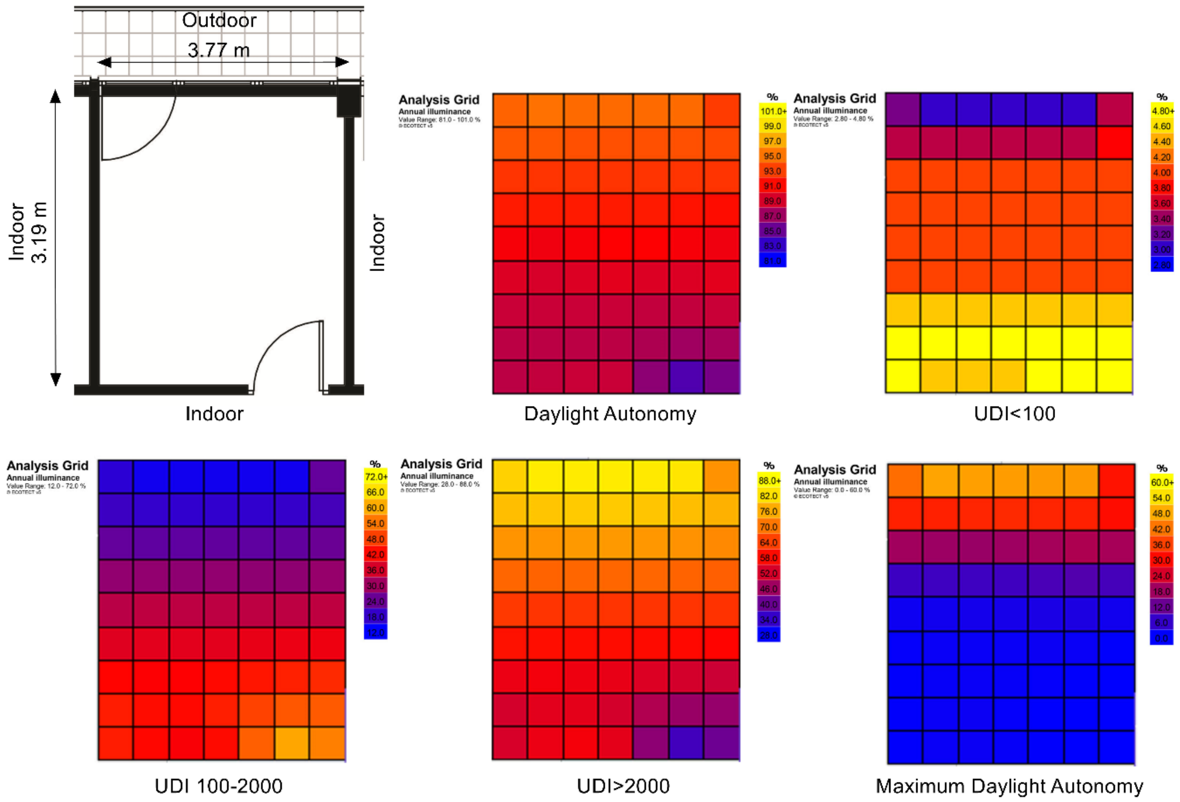


Figure 6.47: Daysim simulation results of room A1: Useful Daylight Index. Source: Author

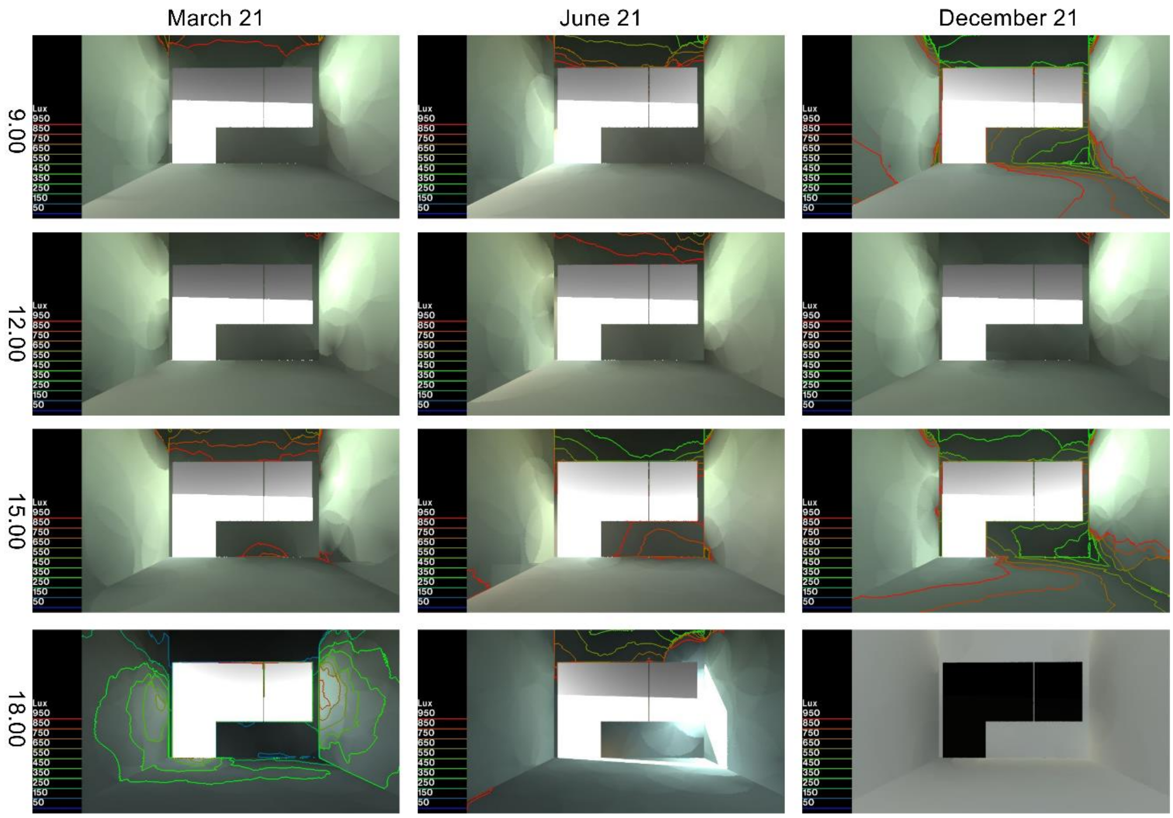


Figure 6.48: Radiance simulation results of room A1: Illuminance. Source: Author

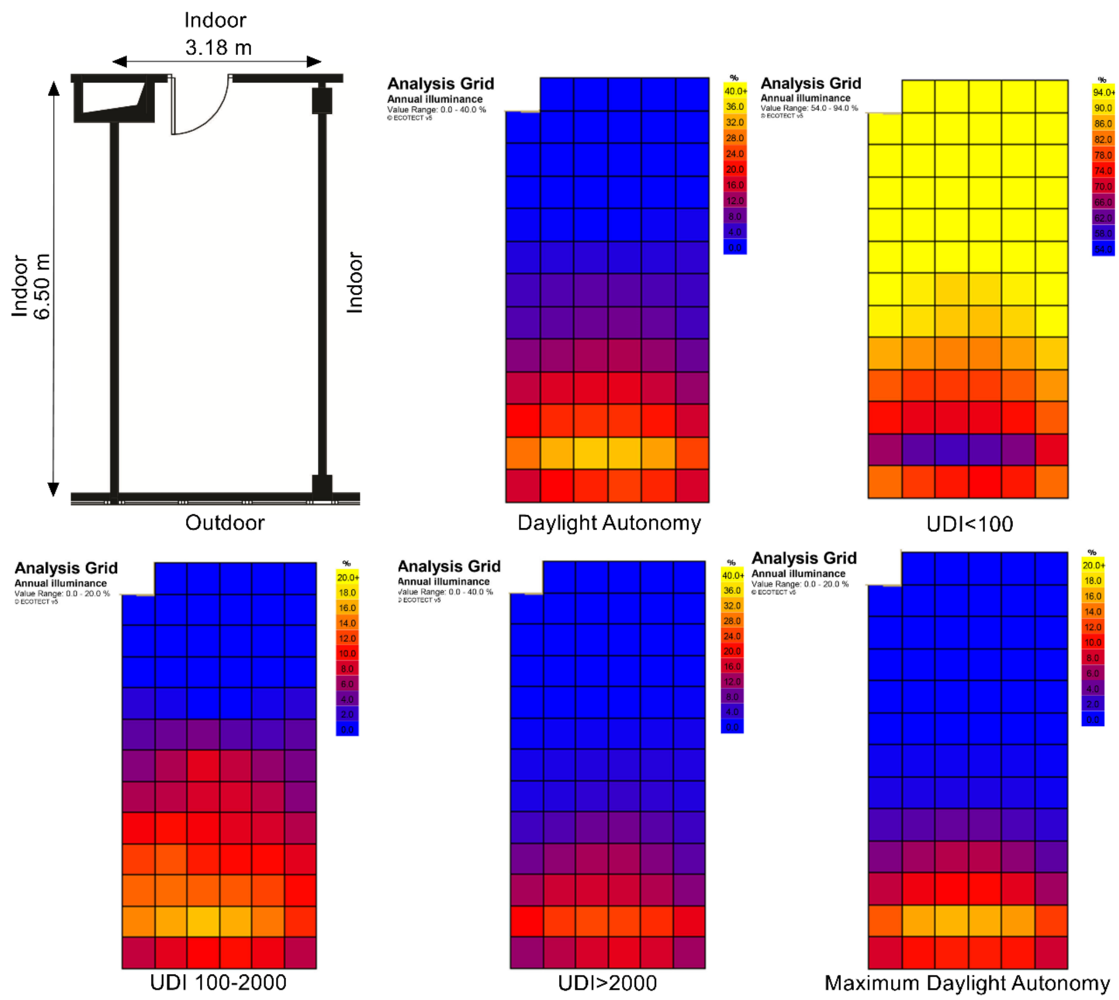


Figure 6.49: Daysim simulation results of room A2: Useful Daylight Index. Source: Author

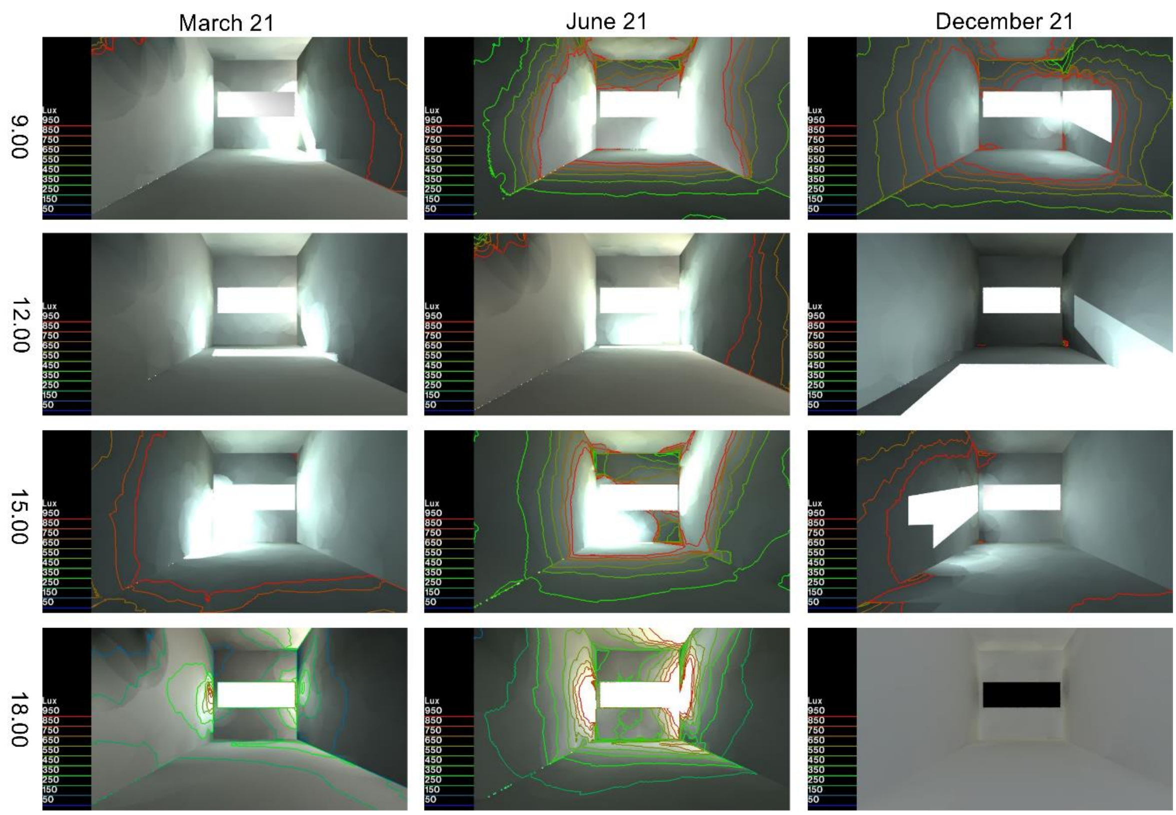


Figure 6.50: Radiance simulation results of room A2: Illuminance. Source: Author

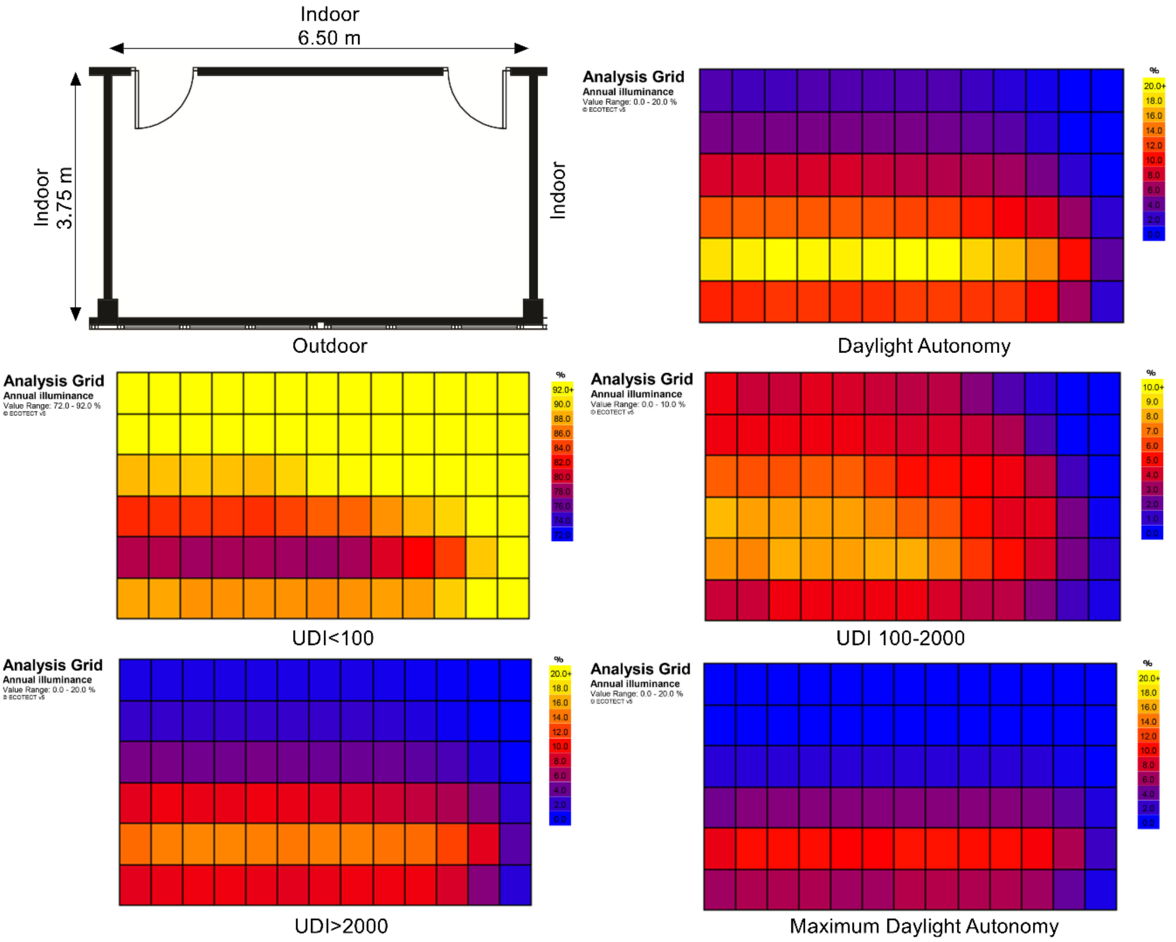


Figure 6.51: Daysim simulation results of room A3: Useful Daylight Index. Source: Author

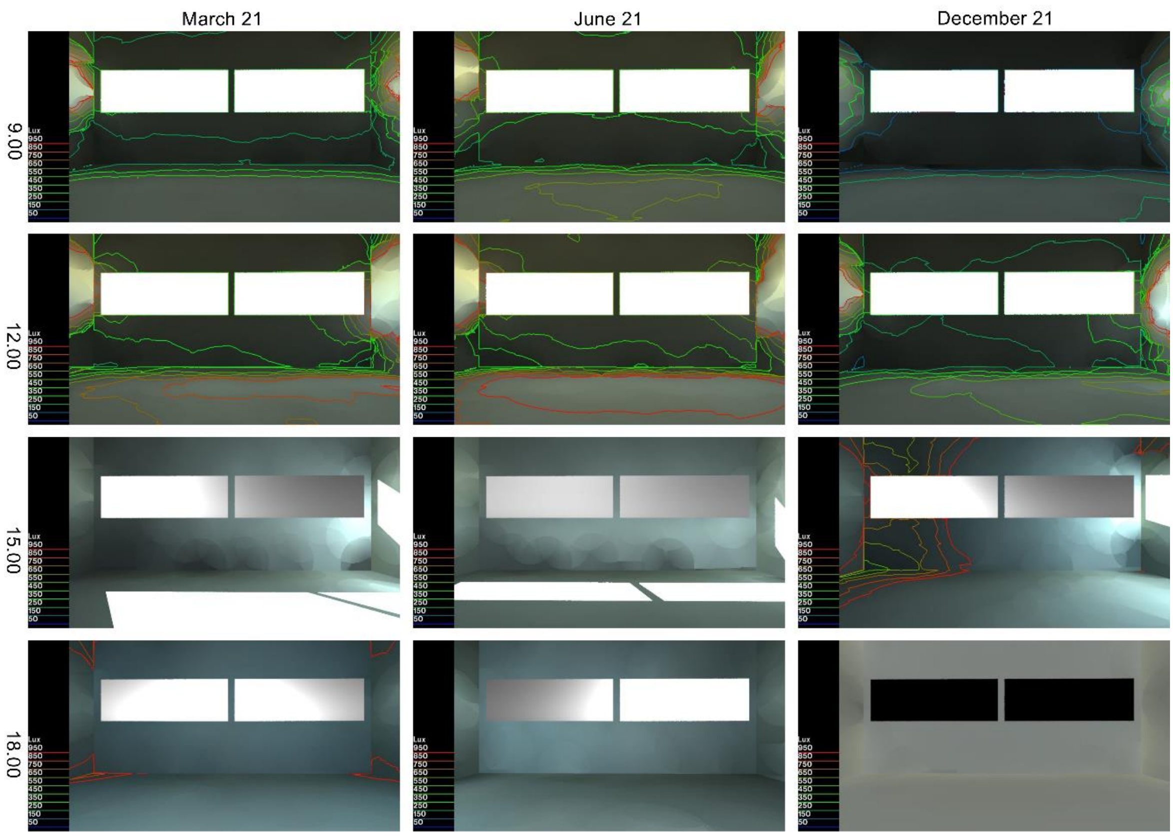


Figure 6.52: Radiance simulation results of room A3: Illuminance. Source: Author

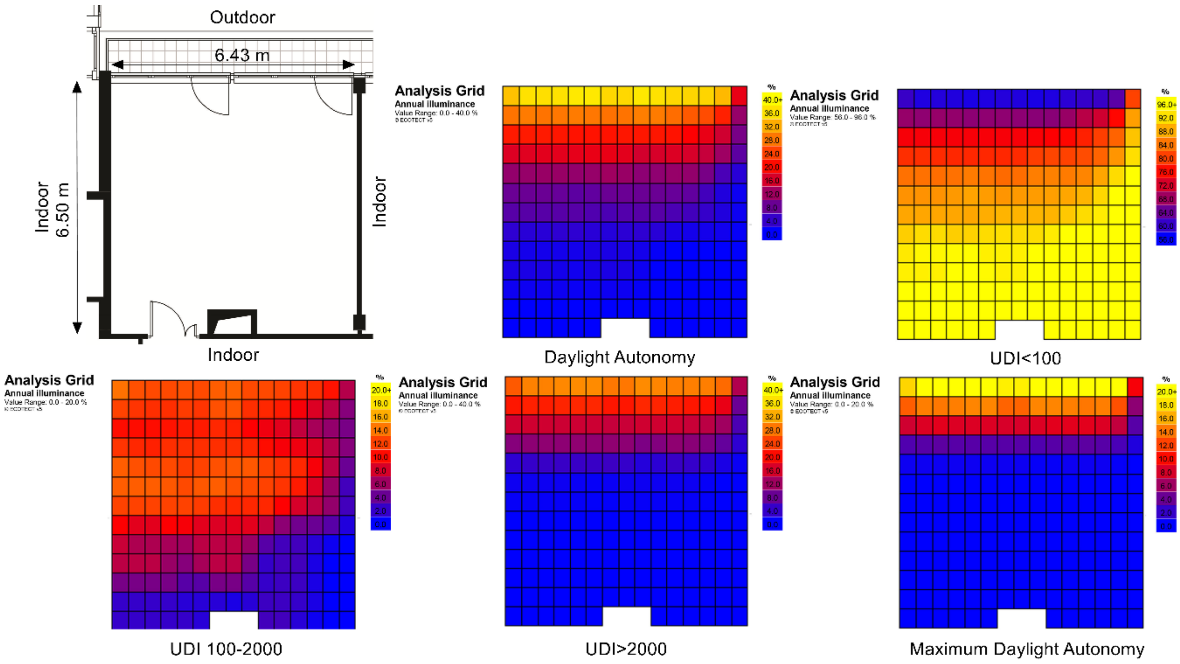


Figure 6.53: Daysim simulation results of room A4: Useful Daylight Index. Source: Author

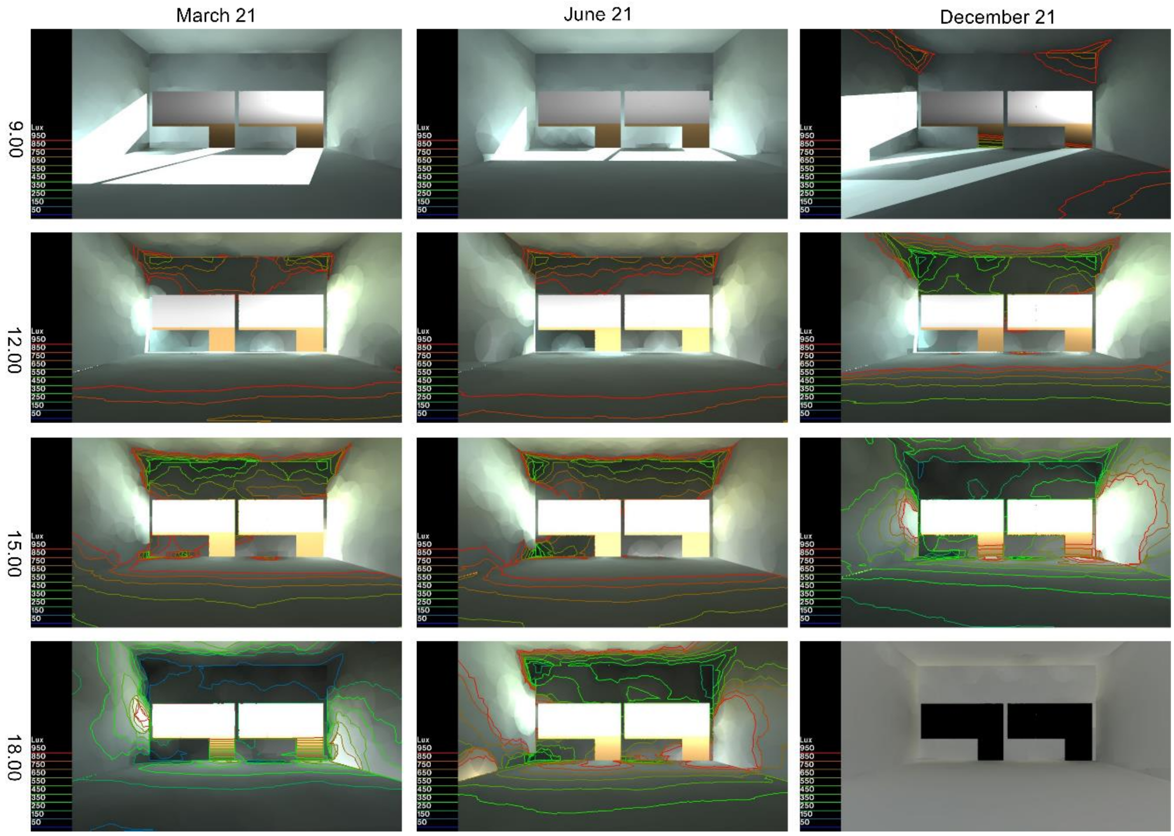


Figure 6.54: Radiance simulation results of room A4: Illuminance. Source: Author

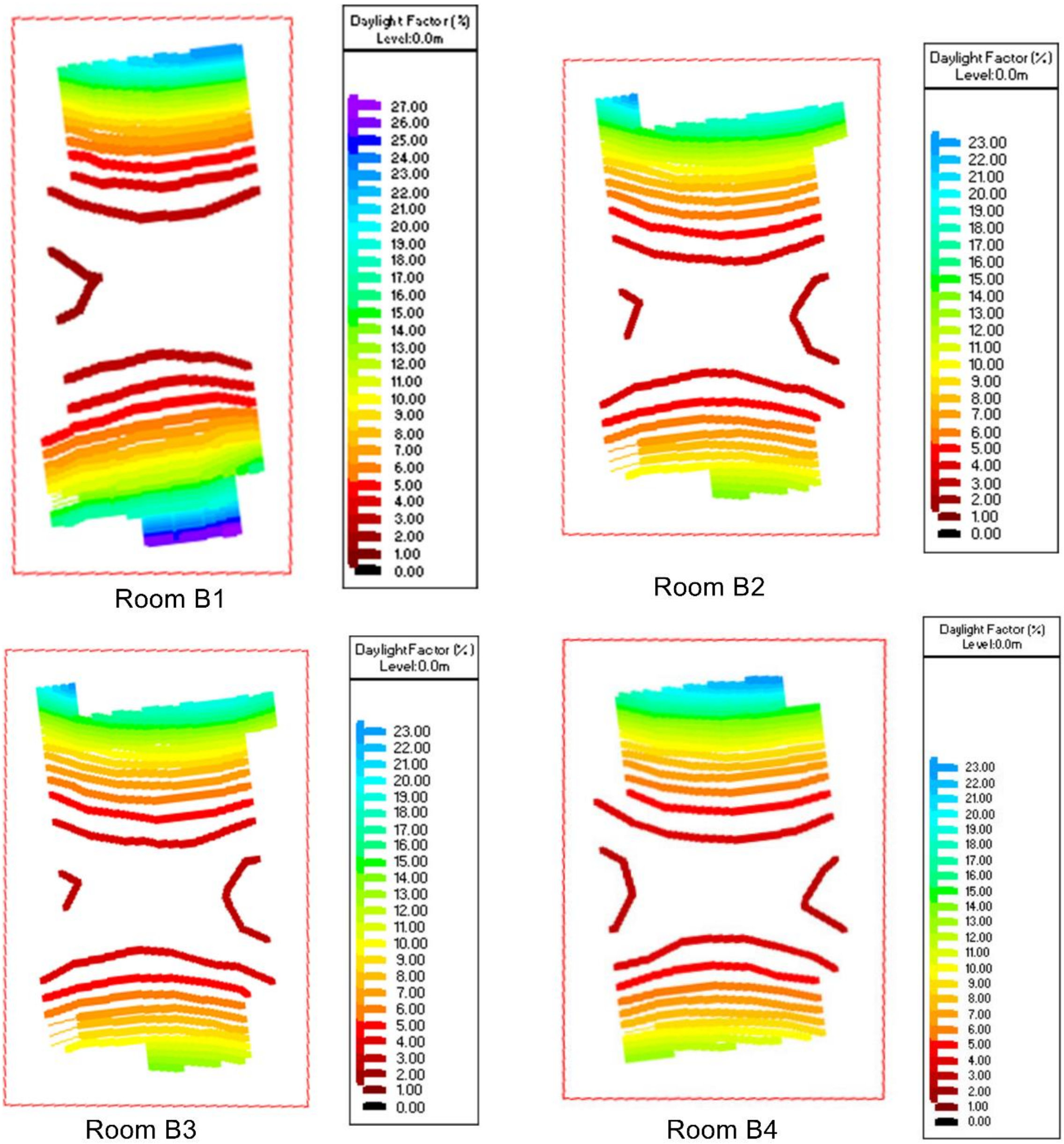


Figure 6.55: Daylight factors in rooms B1, B2, B3, and B4 (performed in IES-VE).

Source: Author

Figure 6.55 shows simulation results of daylight factors in four rooms (case study B). According to results, the daylight factor is equal for both rooms (except room B1). The following figures show Daysim and Radiance simulation results of case study B. It is a fact that daylight factor and illuminance distributions are static daylighting metrics. The dynamic daylighting metrics such as daylight autonomy (DA), useful daylight illuminance (UDI) can be useful to investigate spatial daylight distribution. They are methods for measuring the amount of daylight in the indoor environment. Furthermore, they allow integrating the weather conditions, the different types of skies which can provide a better understanding of the relationship between indoor and outdoor light levels.

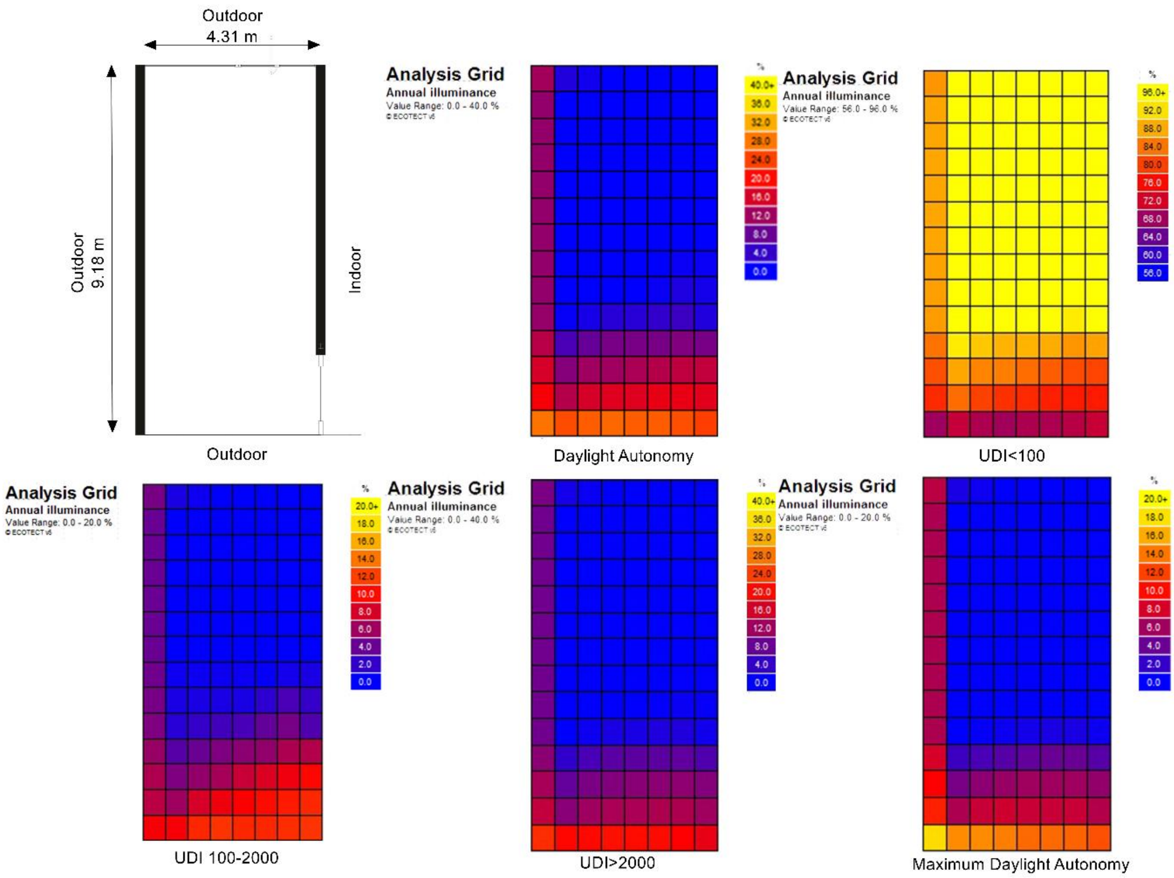


Figure 6.56: Daysim simulation results of room B1: Useful Daylight Index. Source: Author

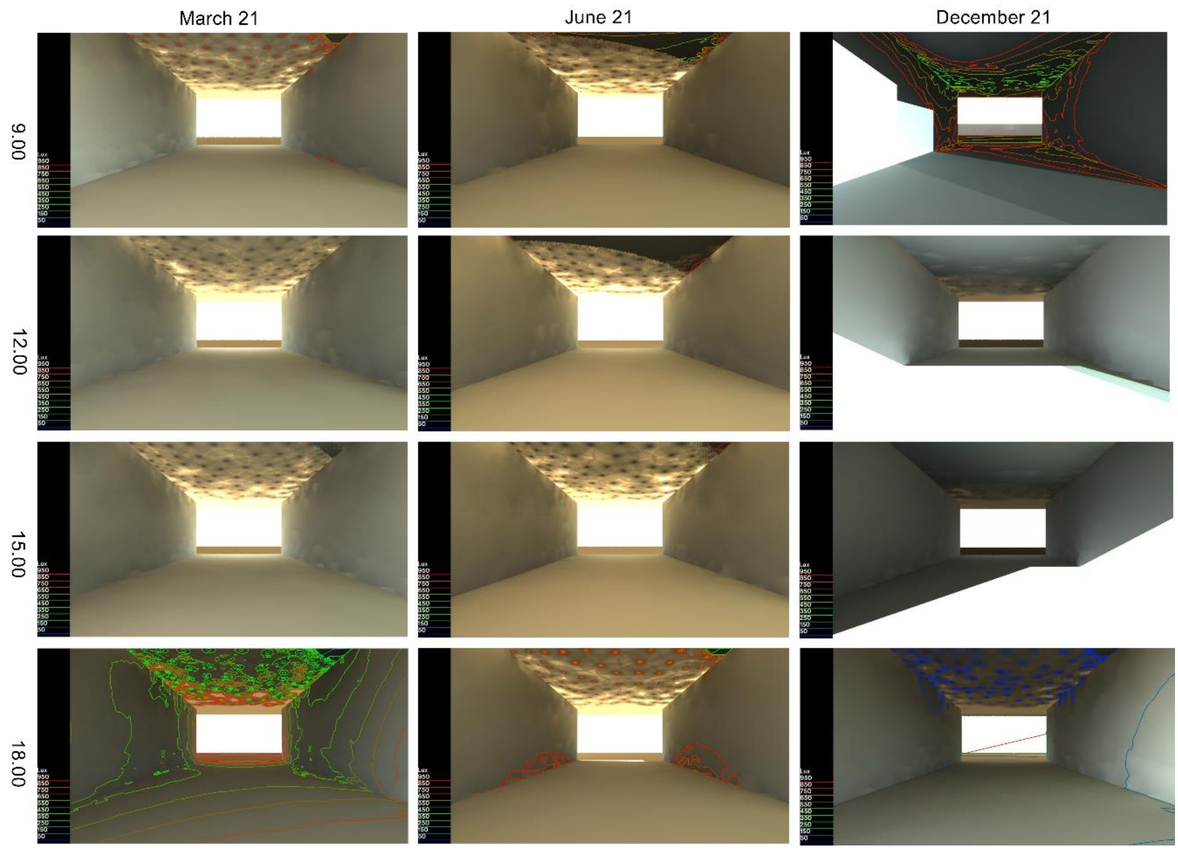


Figure 6.57: Radiance simulation results of room B1: Illuminance. Source: Author

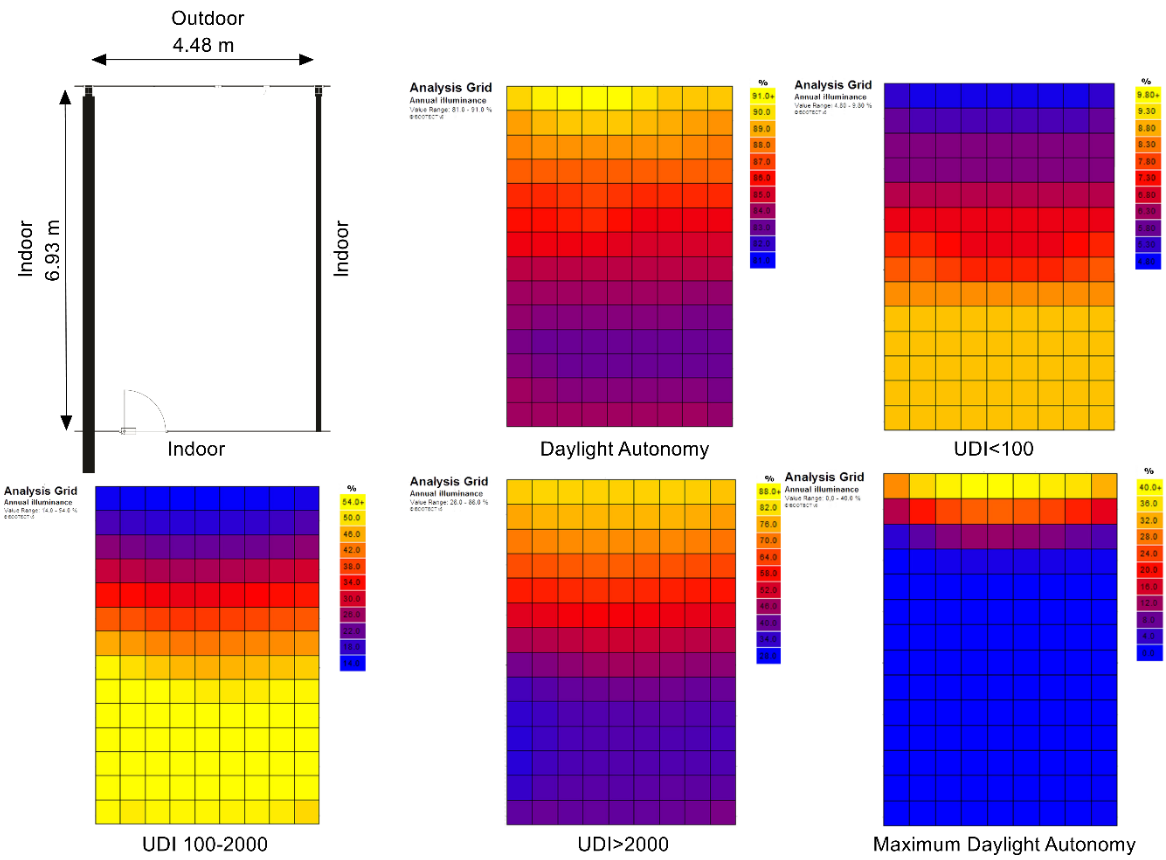


Figure 6.58: Daysim simulation results of room B2: Useful Daylight Index. Source: Author

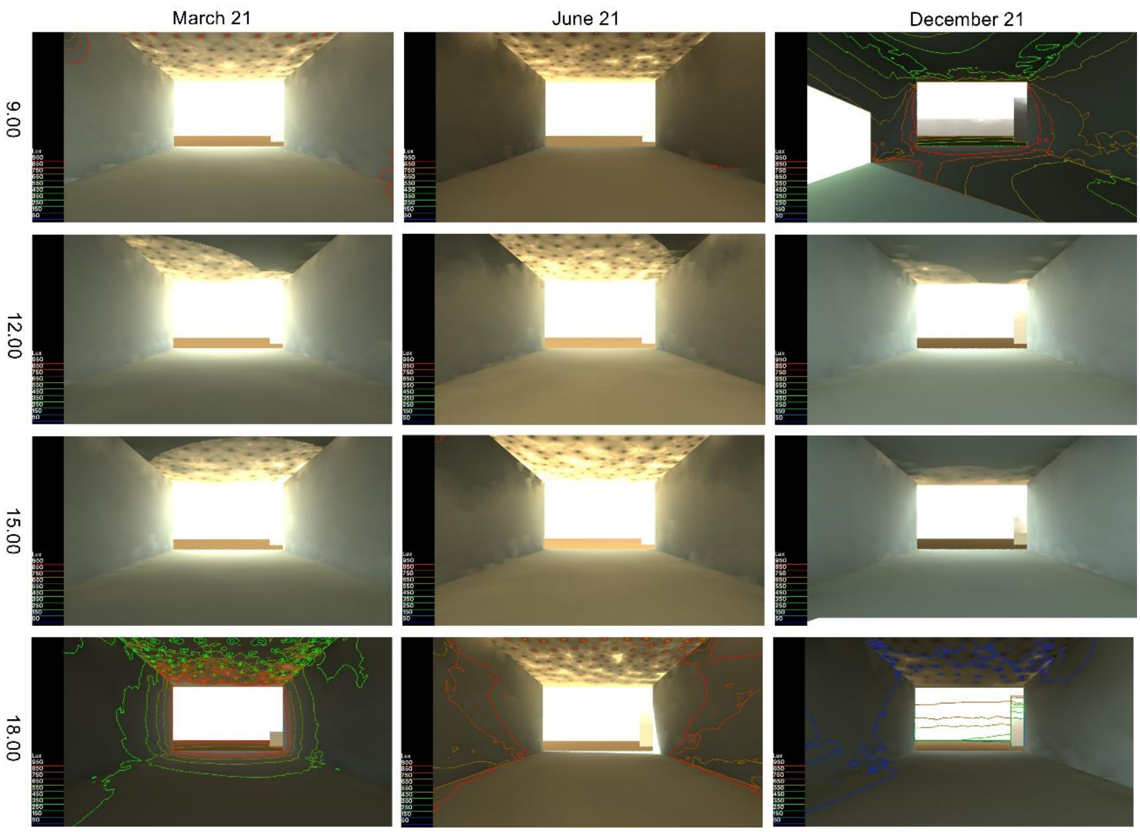


Figure 6.59: Radiance simulation results of room B2: Illuminance. Source: Author

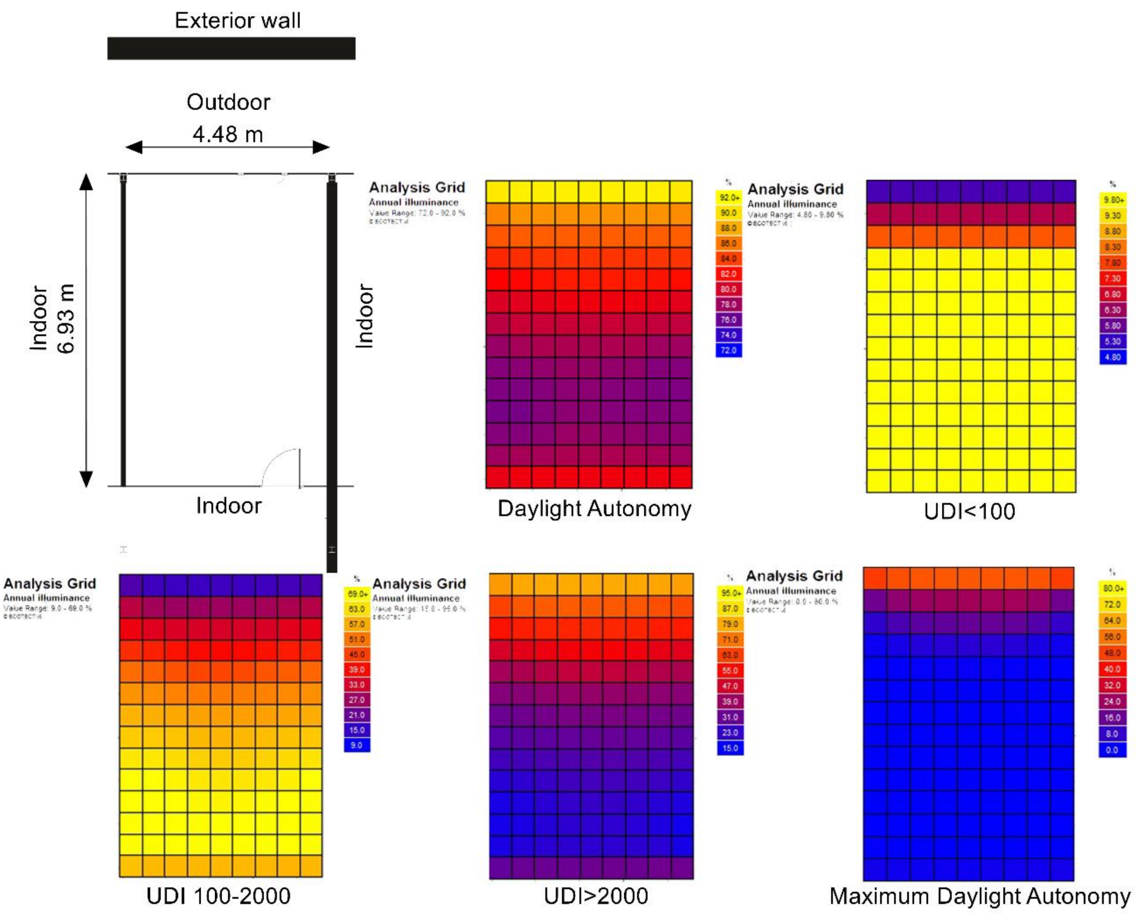


Figure 6.60: Daysim simulation results of room B3: Useful Daylight Index. Source: Author

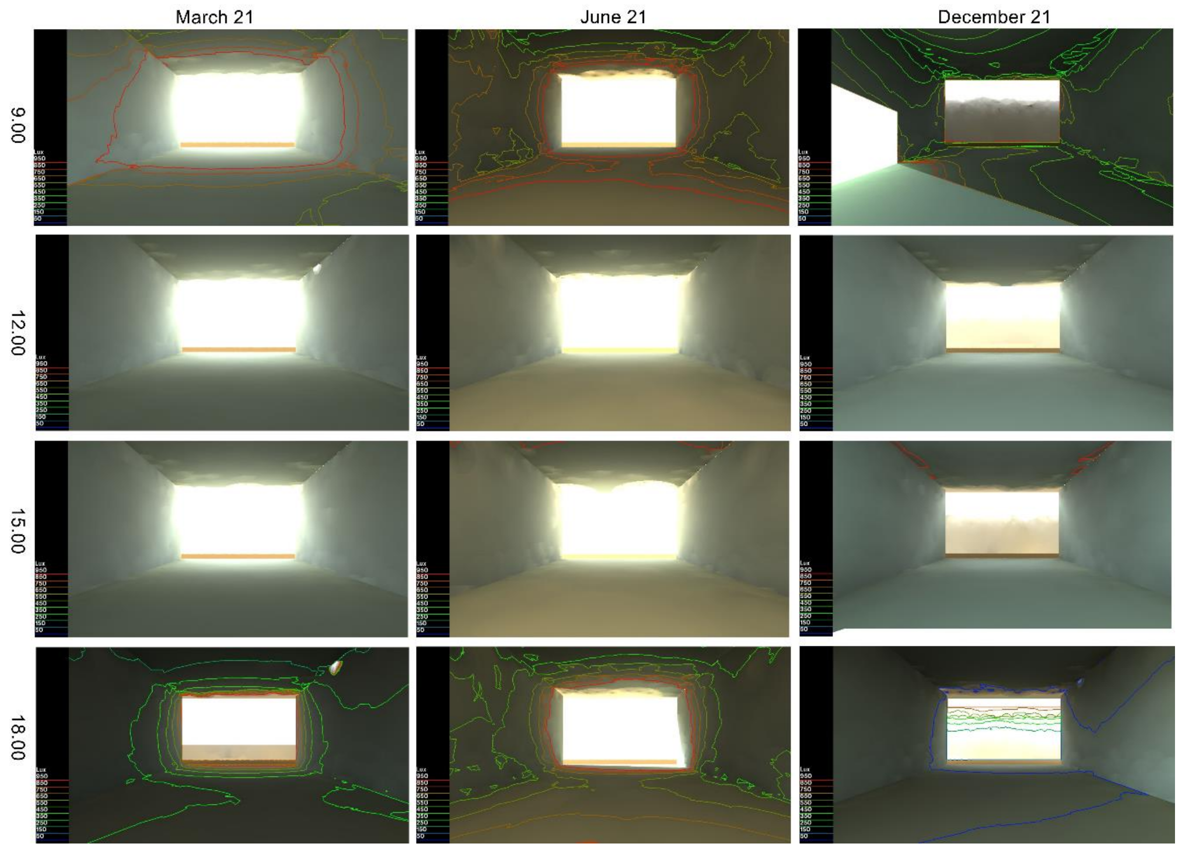


Figure 6.61: Radiance simulation results of room B3: Illuminance. Source: Author

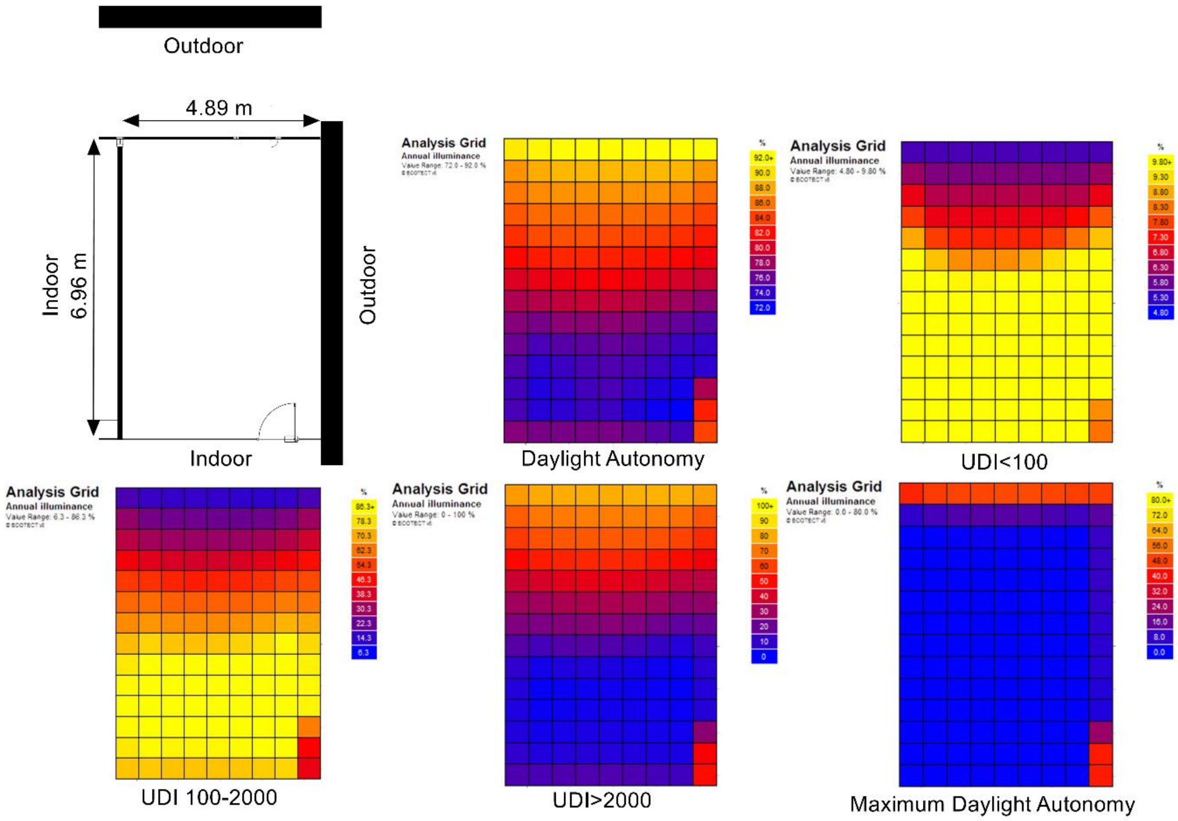


Figure 6.62: Daysim simulation results of room B4: Useful Daylight Index. Source: Author

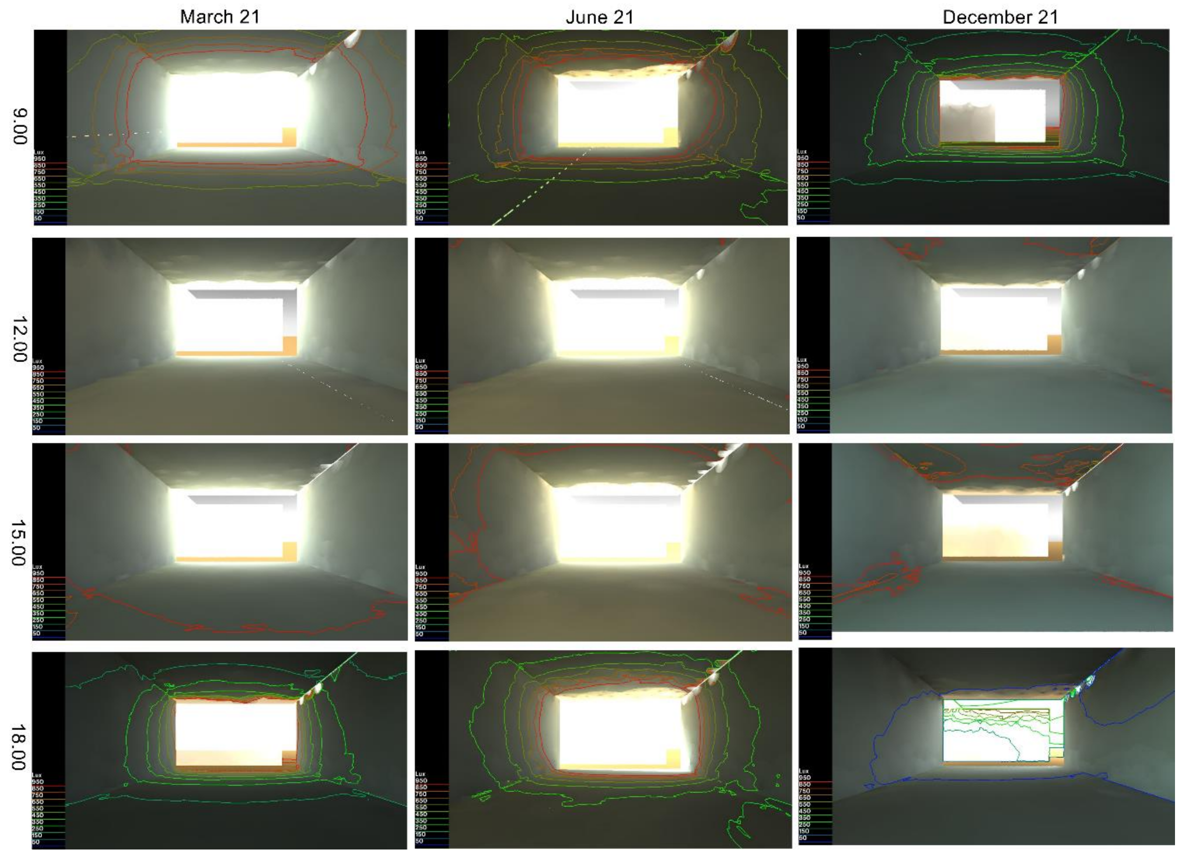


Figure 6.63: Radiance simulation results of room B4: Illuminance. Source: Author

6.2.3 Acoustic performance

Evaluation of acoustic comfort is a necessary step in order to provide a comfortable environment. It can include measurements such as sound insulation, reverberation time, speech intelligibility, etc. In this context, it is important to determine the major factors influencing acoustic performance and the causes of noise in the built environment. Acoustic performances of building elements are the most important criteria in the design and refurbishment of buildings. They should, therefore, be taken into consideration when designing a comfortable environment.

The main sources of noise are air, road and rail traffic, and industrial activities. Road traffic noise is the major contributor to environmental pollution. It is a significant source of noise which affects building user comfort and satisfaction.

●Quality criteria: Reverberation time

The reverberation time (RT) is one of the most significant parameters for evaluating acoustical performance. It has an important impact on speech intelligibility and is controlled by using sound absorption. There are three methods to calculate the reverberation time (RT) in rooms as follows: Sabine, Eyring and Millington-Sette.

According to Sabine's formula, the reverberation time is defined as the time it takes for the SPL (sound pressure level) to decay 60 dB after the sound's source has stopped. The reverberation time (RT) varies depending on enclosure volume and the degree of exposed sound absorbing surfaces. The Sabine reverberation time equation is given by:

Mean sound absorption coefficient $\alpha m <= 0.35$:

$$Ta = 0.16\ V / A \qquad (1)$$

where

Ta = reverberation time (s)

V = room volume (m^3)

A = the sound absorption of the room (m^2 Sabine)

Mean sound absorption coefficient $\alpha m > 0.35$:

$$Ta = 0.16\ V / [(A / \alpha m) \ln (1/ (1-\alpha m))] \qquad (2)$$

Reverberation times is affected by various factors such as materials, building shape and dimensions insulators. It determines the distribution of sound in a space. Although long reverberation time in the concert hall can be excellent, it is less desirable in the workplace. The basis of acoustical comfort in the office buildings is the privacy index (PI). However, proper reverberation time is a very important consideration for each enclosed room. Optimum reverberation time for a room is 0.5 seconds. Recommended reverberation times for private and open plan office are between 0.6 – 0.8 and 0.8 – 1.2 seconds respectively.

In the context of acoustic performance, noise measurement and calculation are usually determined in octave or third-octave band frequency range 100-3150 Hz.

To calculate some simple statistical reverberation times of reference rooms, computational simulations were carried out with Ecotect.

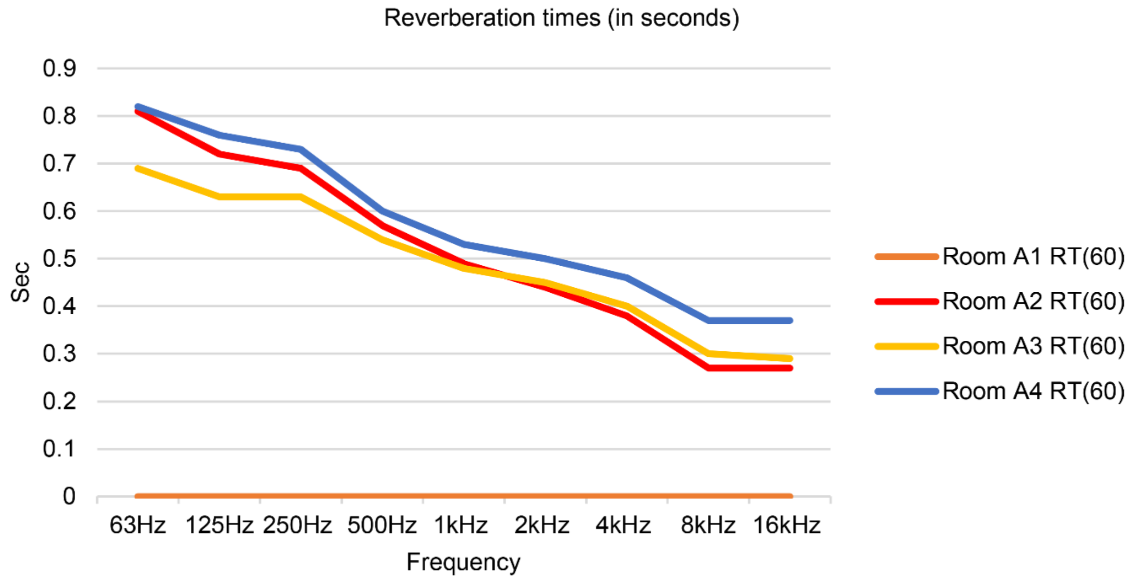


Figure 6.64: The results of reverberation time for A1, A2, A3 and A4 rooms (Ecotect).
Source: Author

Figure 6.64 shows the results of reverberation time for A1, A2, A3 and A4 rooms in 63 Hz to 16000 Hz region. According to the results, only room A1 has zero reverberation time while room A4 has a longer reverberation time. From the results it can clearly be seen that reverberation time is directly proportional to the volume of the room. For example, room A1 has minimum volume (42.04 m^3) and A4 has maximum volume (151.83 m^3).

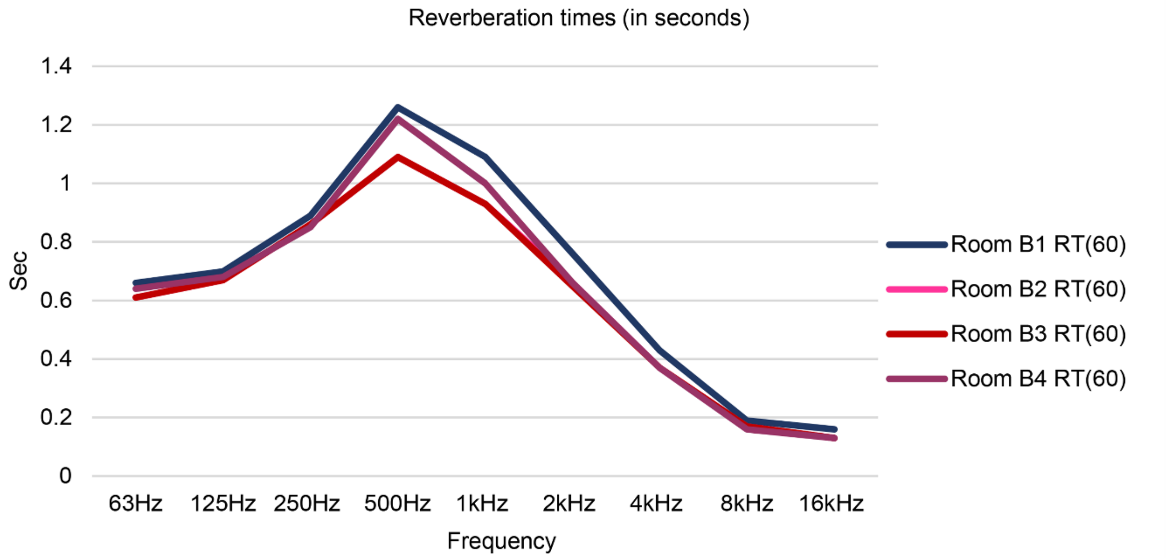


Figure 6.65: The results of reverberation time for B1, B2, B3 and B4 rooms (Ecotect).
Source: Author

Furthermore, Figure 6.65 shows the results of reverberation time for B1, B2, B3 and B4 rooms in 63 Hz to 16000 Hz region. It can be seen that the room B1 has a high reverberation time (with maximum volume 120.72 m^3) among rooms.

6.2.4 Questionnaires and interviews

A user satisfaction questionnaire can provide useful information for evaluating indoor environmental quality. It is important to design appropriate questionnaire for gathering relevant data. Questionnaires and interviews can be used to fill gaps between post occupancy evaluations and actual performance of buildings. Furthermore, they can determine the factors that influence building performance and user satisfaction.

Questionnaires are useful methods to identify and solve problems in the indoor environments. They should be designed to be easily understood. The responses to the questionnaires can reflect user actual feelings. It can be difficult to obtain accurate statistical data about influential factors, but questionnaires may make them easier to evaluate. Questionnaire are often used to assess existing conditions. They can identify factors influencing user attitudes and behaviors. However, questionnaire are required to be correlated with existing conditions. The study [251] provided a questionnaire survey on factors influencing comfort with indoor environmental quality in existing buildings. It indicated that increasing user awareness about the consequences of poor indoor environmental quality on health and the knowledge about how to ensure a good indoor climate would be needed.

A questionnaire (Appendix A) was carried out both for case study A (the fifth floor) and case study B. It was developed with the aim of identifying the end users' requirements and exceptions regarding indoor comfort. It also included questions related to the users' habits and their level of familiarity with smart systems, etc. The questions included in the questionnaire were designed in accordance with research objectives. For example, the users were asked to answer whether smart sensor systems were needed for controlling their own indoor climate. Furthermore, the contents of the questionnaire were focused on the collection of improvement ideas regarding indoor climate. The following figure show the results obtained from the questionnaire.

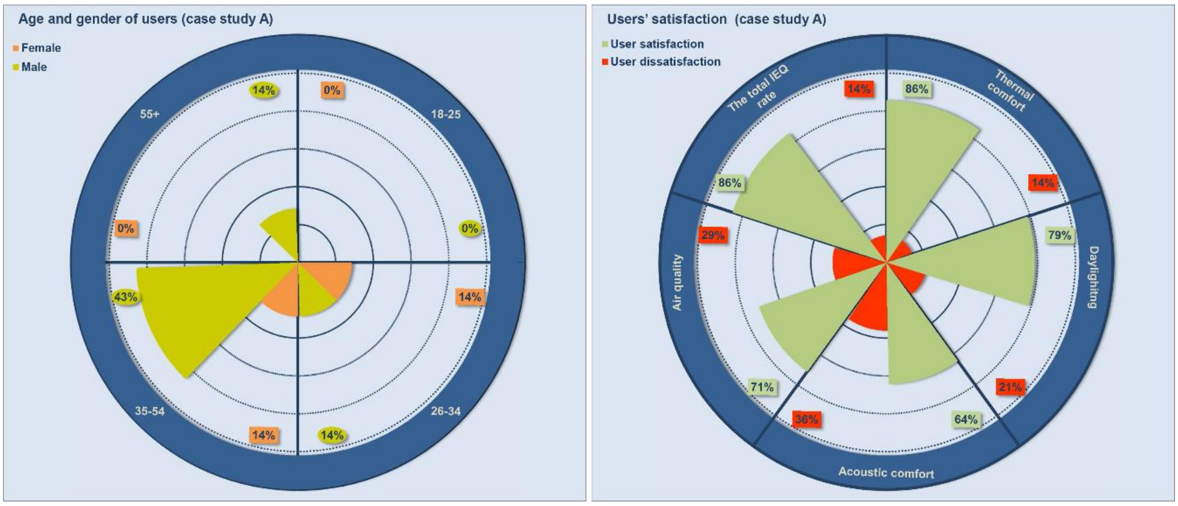


Figure 6.66: The results obtained from age and gender of users (left) and users' satisfaction (right) in case study A. Source: Author

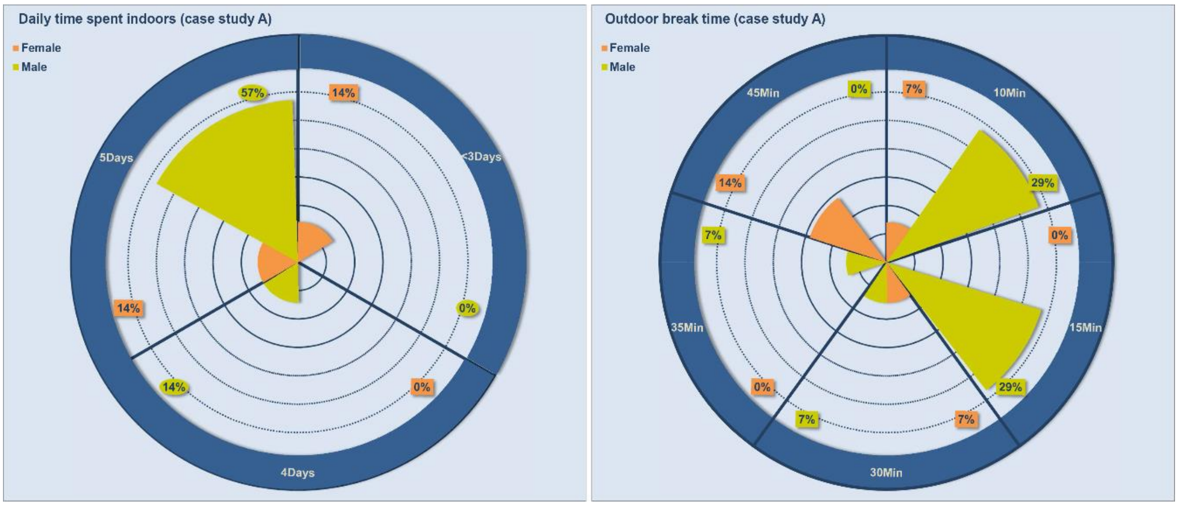


Figure 6.67: The results obtained from daily time spent indoors (left) and outdoor break time (right) in case study A. Source: Author

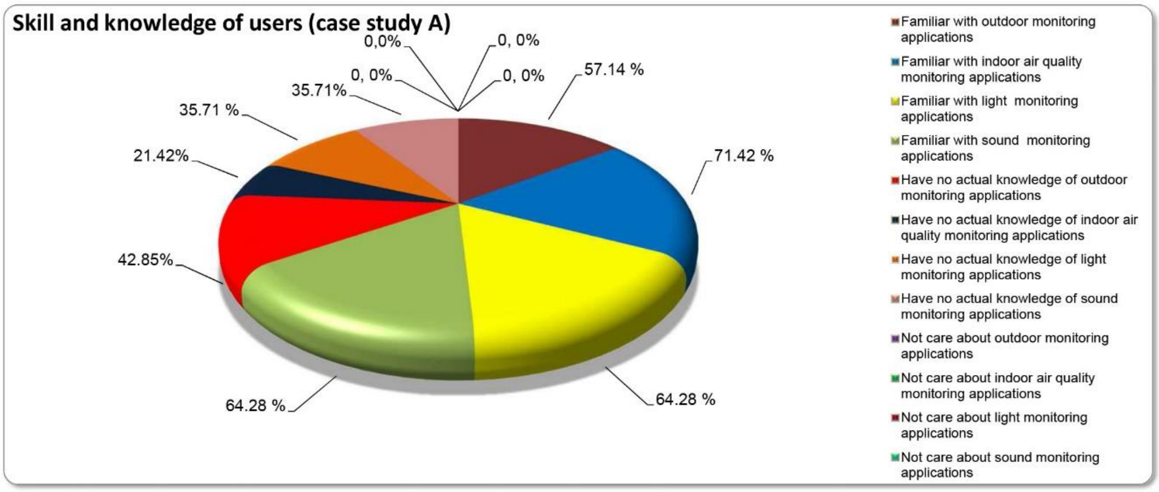


Figure 6.68: The results obtained from skill and knowledge of users in case study A. Source: Author

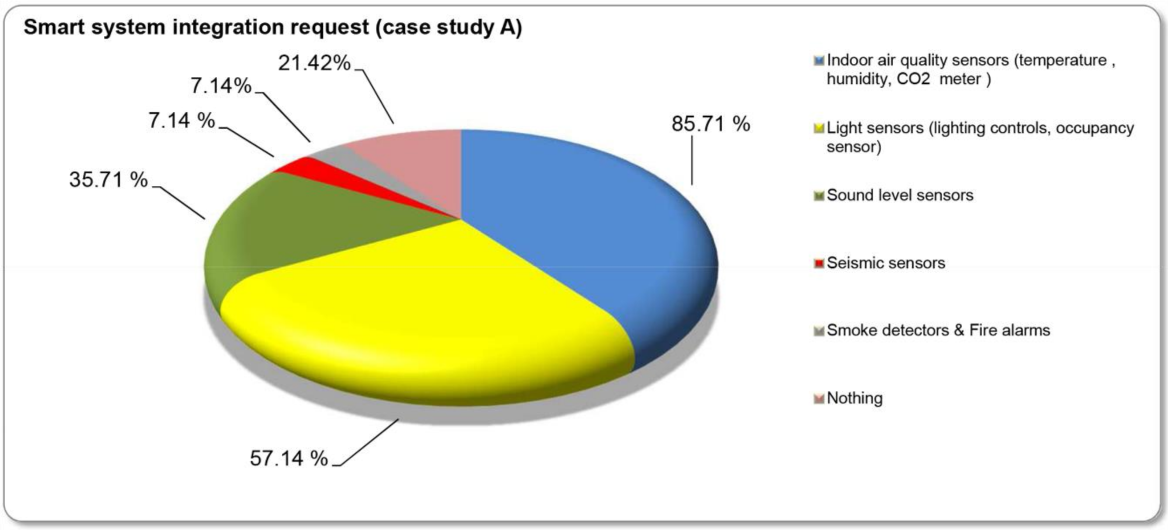


Figure 6.69: The results obtained from smart system integration request in case study A. Source: Author

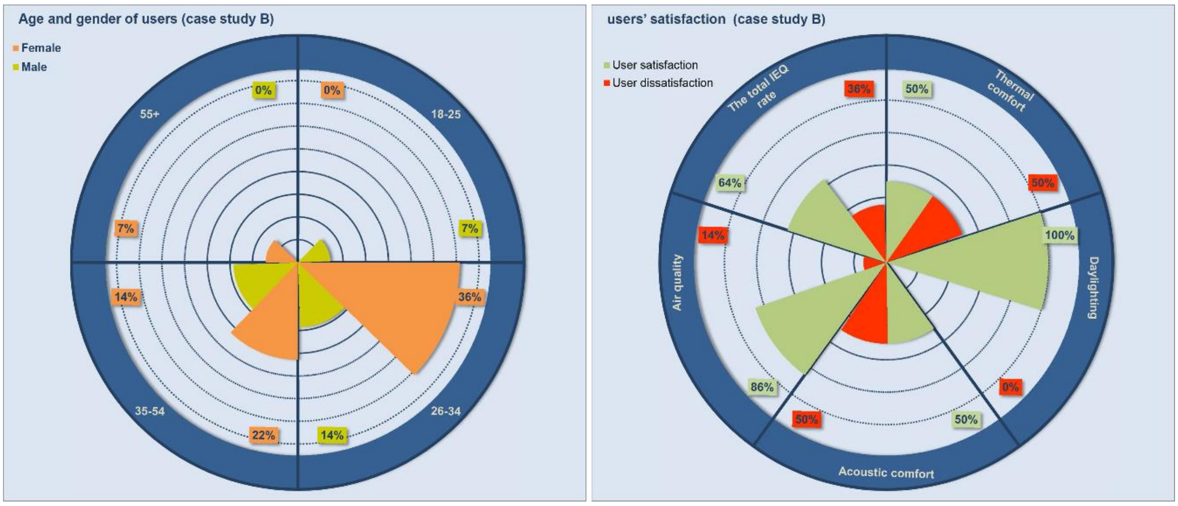


Figure 6.70: The results obtained from age and gender of users (left) and users' satisfaction (right) in case study B. Source: Author

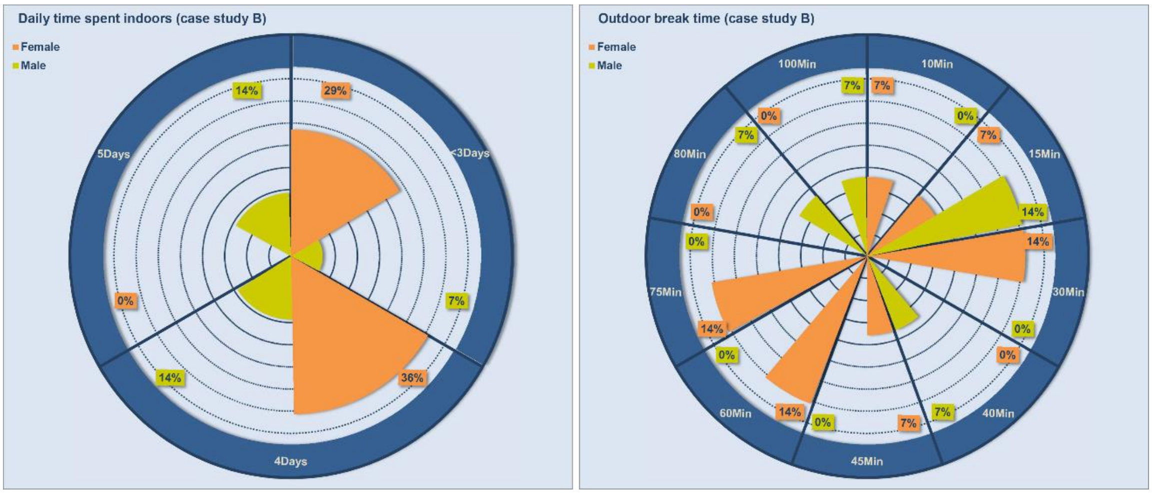


Figure 6.71: The results obtained from daily time spent indoors (left) and outdoor break time (right) in case study B. Source: Author

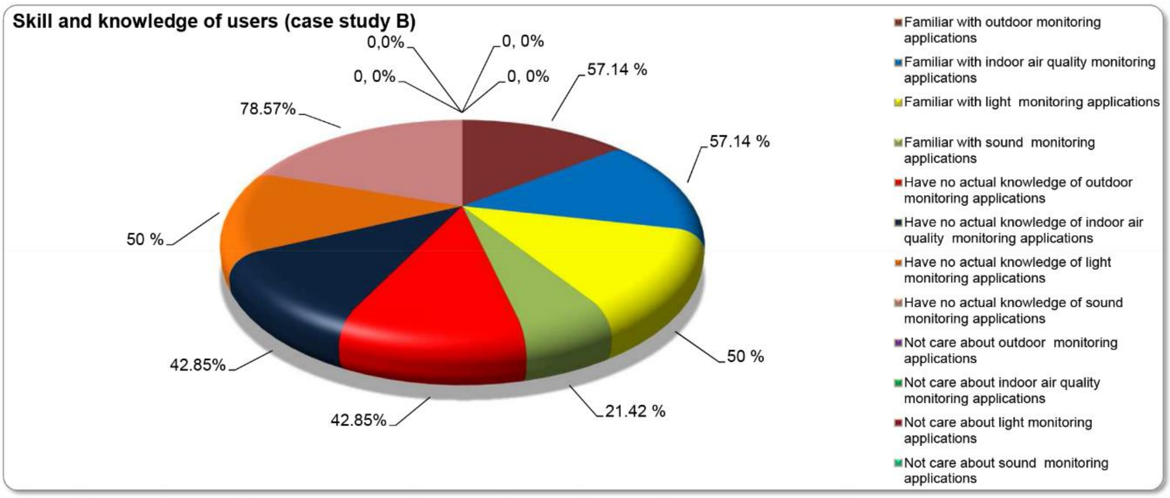


Figure 6.72: The results obtained from skill and knowledge of users in case study B. Source: Author

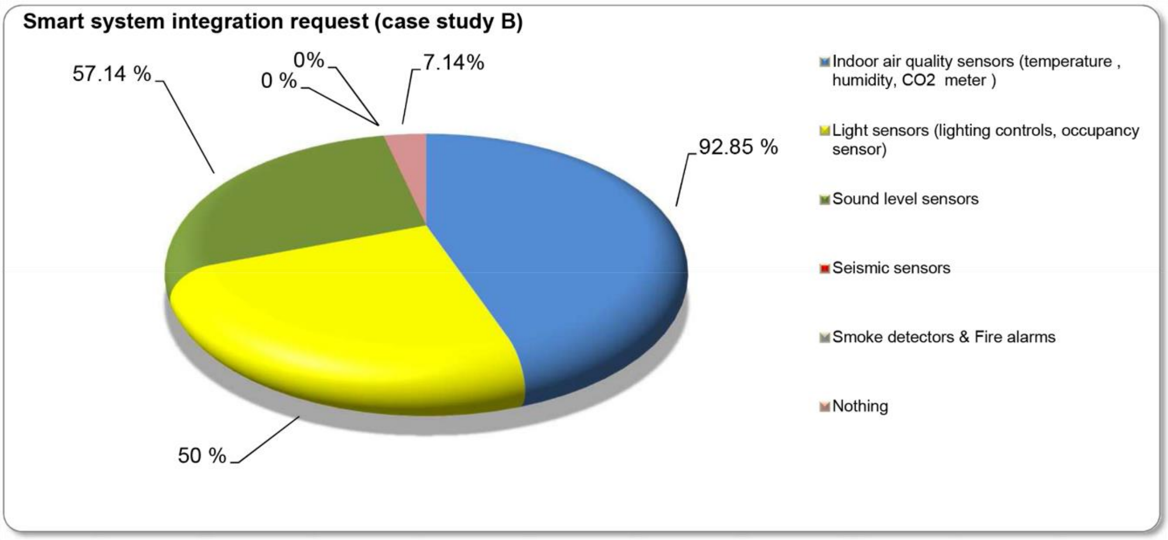


Figure 6.73: The results obtained from smart system integration request in case study B.
Source: Author

The overall results showed that the main indoor environmental parameters (thermal, visual, acoustic and air quality) affect users' comfort and satisfaction. It can be seen that indoor environmental parameters have an important role in the process of evaluating buildings.

Users were more satisfied with thermal comfort in case study A and more satisfied with daylighting in case study B. They were slightly satisfied with indoor environmental quality (IEQ). It was found that users were more familiar with indoor air quality monitoring applications. Smart sensor systems for indoor climate monitoring were requested by majority of users.

CHAPTER 7 FULFILMENT OF HYPOTHESIS

The main objective of energy management system is to reduce energy consumption. To facilitate the implementation of energy management systems in buildings, it is essential to raise awareness of benefits of smart sensor systems and ICT technologies. In this regard, user behavior and its interaction with energy management systems can promote energy efficiency and indoor environmental quality.

Based on these facts, research hypothesis was developed and tested. A prototype system was developed to fulfill the requirements of the hypothesis. It was partitioned into four modules: an indoor quality apparatus, an artificial intelligence algorithm, an intelligence graphical user interface, and a smart material. Building information modeling (BIM) has the potential to play a vital role in facilitating more visibility and interaction in the process of scenario development. It provides enhanced communication and interaction between smart systems and users.

7.1 Smart System Integration

In order to predict the behavior of building systems, it can be useful to create a clearer connection between building information modeling (BIM) and smart sensor systems. The simulation results showed that users can take advantage of natural environment and passive design strategies. In order to fulfill these objectives, users need to monitor and control both outdoor and indoor environmental parameters in real-time.

In order to achieve comfort and energy objectives, a prototype smart system was developed with the focus of attention on ICT systems and sensors. It includes solutions for energy efficiency in the workplace level and methods to examine how user interact with high-performance buildings. The key points in developing the content of prototype system involve a number of processes to read data from sensors (light sensor, sound pressure/mic sensor, temperature and humidity sensor) connected to Arduino boards and an internal shading device limits heat gains resulting from solar radiation. The targeted strategy is to allow users to directly interact with their buildings and improve their comfort at times of crises of discomfort.

With objectives to address issues associated with user behavior, it is required to consider both users who do not have the knowledge to properly manage efficient building systems and users who are familiar with the applications and systems. To encourage users to interact with environmental building performance systems, it is better to implement more efficient and basic applications.

7.1.1 The development of an indoor quality apparatus

In order to measure indoor environmental conditions, a prototype sensor system was developed based on Arduino microcontroller which can obtain and monitor environmental data in real-time. Arduino is an open hardware and software platform based on a microcontroller board. In the current work, it is used to produce an indoor quality apparatus to collect stand-alone environmental parameters such as humidity, temperature, lighting and ambient noise (Figure 7.1).

The goal of the developed apparatus is its use in collecting and then processing data of indoor environmental quality parameters which can lead to understanding environment conditions. The developed apparatus is equipped with different sensors and led lights to carry out monitoring practices in the indoor environments. It also can be used to sense and gather the data from certain places in the built environment. The data are collected in real time from sensors and are visualized within both LCD and interfaces.

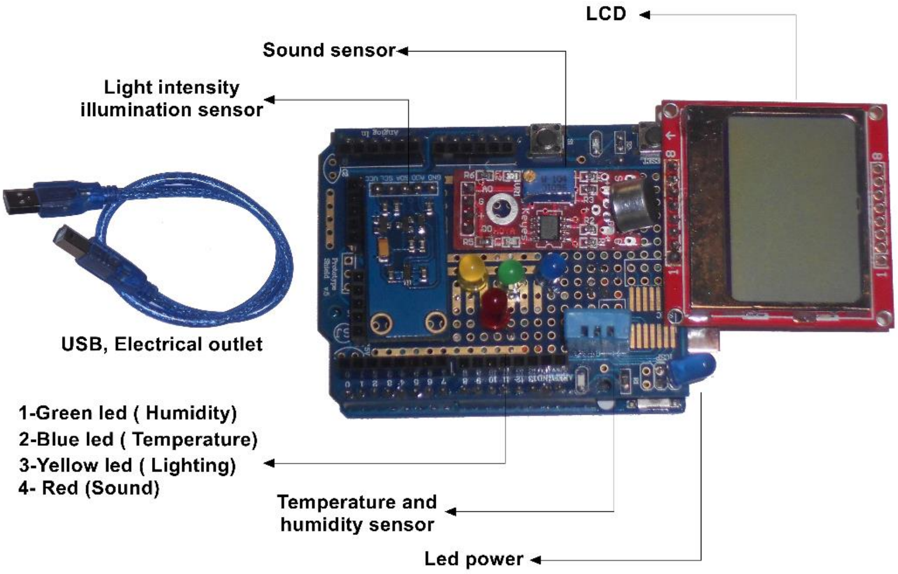


Figure 7.1: Indoor quality apparatus developed by author.

The developed apparatus is programmed to interface with Rhino/Grasshopper and a MATLAB's graphical user interface to visualize real-time environmental data. It can be powered by both electricity and universal serial bus (USB).

The most important function of the developed apparatus is to monitor, visualize and define optimum comfort conditions. The developed apparatus has a light-based alarm that uses lights to alarm user when the temperature, humidity, lighting and sound fall outside the comfort zone. Since Arduino systems are open source software programmable, it is possible to generate the actual program that is required to attain project objectives. Arduino libraries are written in standard C/C++ code. In this respect, a program written in standard C/C++ code and uploaded on the developed apparatus through the Arduino IDE (integrated development environment).

According to the prescriptive requirements of ASHRAE Standard 55, SLL (Society of Light and Lighting) and ASHRAE Handbook (HVAC applications) requirements for office buildings, four comfort zones are defined in the application source code as follows: 1) temperature 21-26 º C; 2) humidity: 40-60 %; 3) Light intensity: 500 Lux; and 4) Sound: 50 dB (Figure 7.2) . As mentioned before, when environmental conditions are outside comfort zone, LEDs will flash while in alarm. A green, blue, yellow, and red LEDs indicate humidity, temperature, lighting and sound levels respectively. In fact, they function as signals that indicates workplace environment is outside or inside the comfort zone.

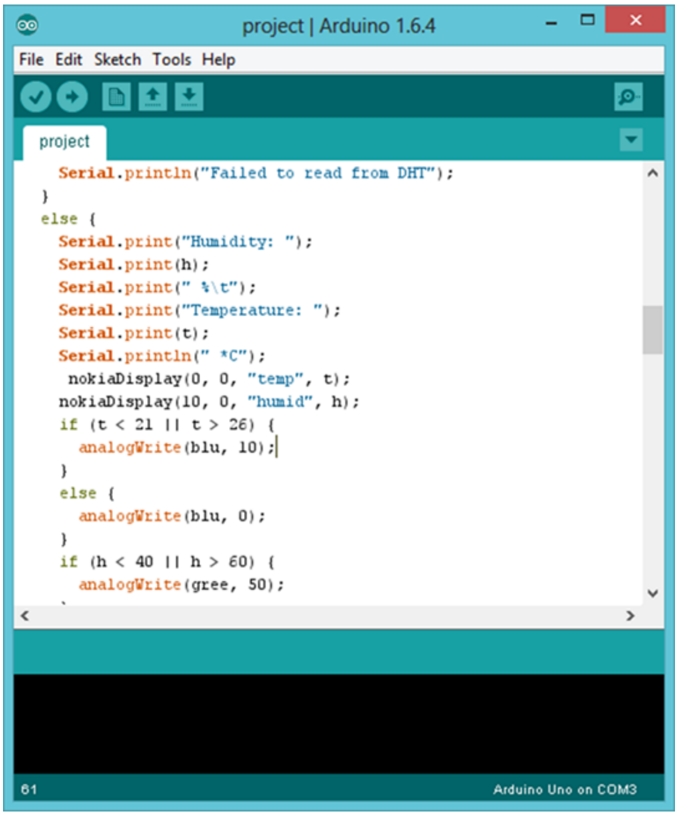


Figure 7.2: A part of Arduino sketch of the developed apparatus. Source: Author.

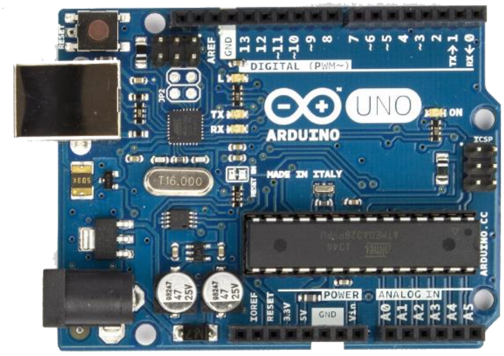
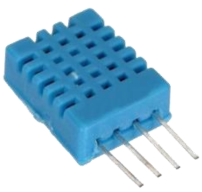
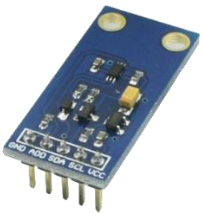
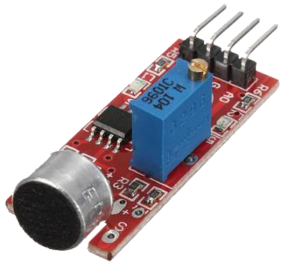
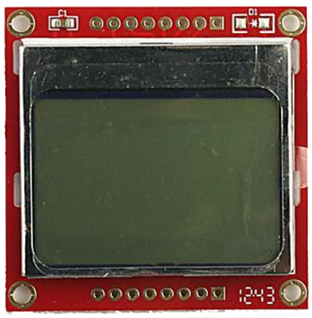
In order to obtain an actual sound pressure level (SPL), it is necessary to pay attention to both the software and the hardware part of apparatus. Furthermore, it is important to convert analog-to-digital (ADC) raw value to dB value. In this context, a script is written in the source code of Arduino sketch (Figure 7.3).

```
}
float LinearToDecibel(float linear)
{
  float db;
  if (linear != 0.0f)
    db = 20.0f * log10(linear);
  else
    db = -144.0f;  // effectively minus infinity
  return db;
}
```

Figure 7.3: A part of Arduino code for the sound sensor. Source: Author.

Monitoring and controlling of an indoor environment requires sensing of physical variables such as mean radiant temperature, indoor temperature, relative humidity, air velocity, CO_2 concentration, light, acoustic, and occupancy. To provide a comfortable workplace environment, temperature, humidity, light, and sound are the most important parameters that need to be considered. For the development of the prototype apparatus, several sensors and components to monitor above mentioned parameters have been integrated into Arduino board (Table 7.1). The measurement of mentioned parameters is processed for transforming data to an intelligent user interface for real-time control of indoor climate.

Table 7.1: The embedded sensors and components of the developed apparatus. Source: Author.

Microcontroller board		
Arduino Uno R3		
Sensors		
1-DHT11(temperature and humidity) 	2- GY-30 (Light intensity Illumination) 	3- Sound sensor 
Alarm LEDs	LCD screen	
 1-Green led (Humidity) 2-Blue (Temperature) 3-Yellow (Lighting) 4- Red (Noise)	 Nokia 5110	
Data storage & Transmission	Stand alone	
Power supply	USB, electronic	

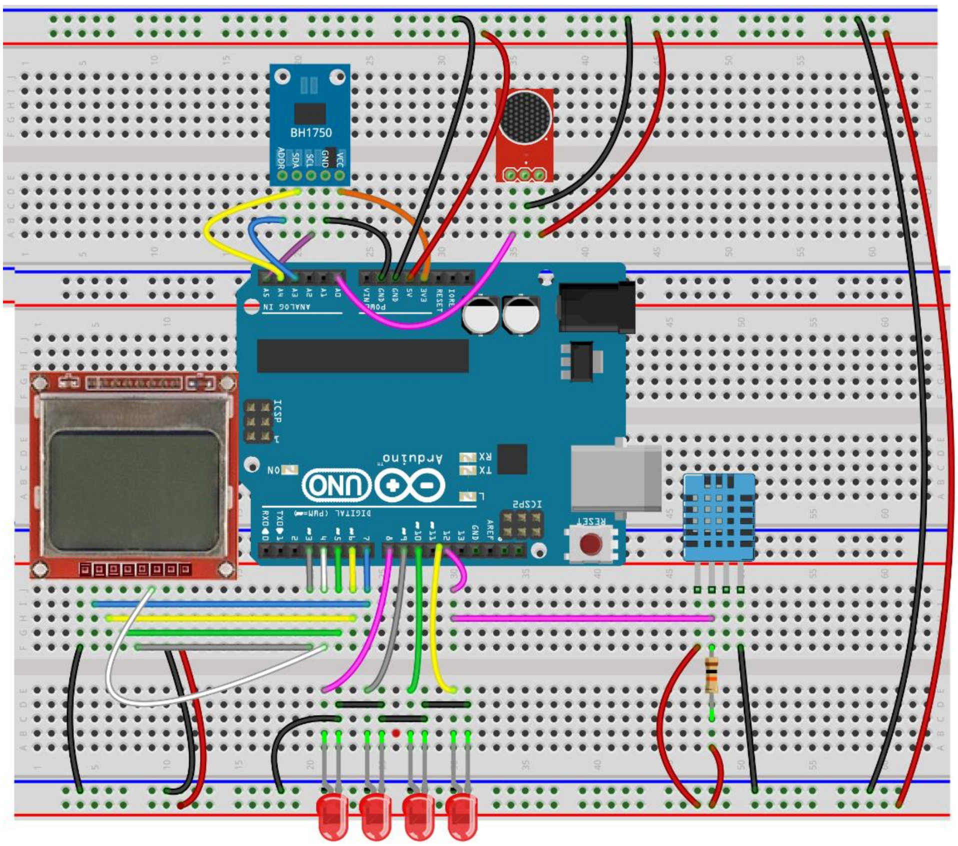


Figure 7.4: Fritzing diagram of the developed apparatus. Source: Author.

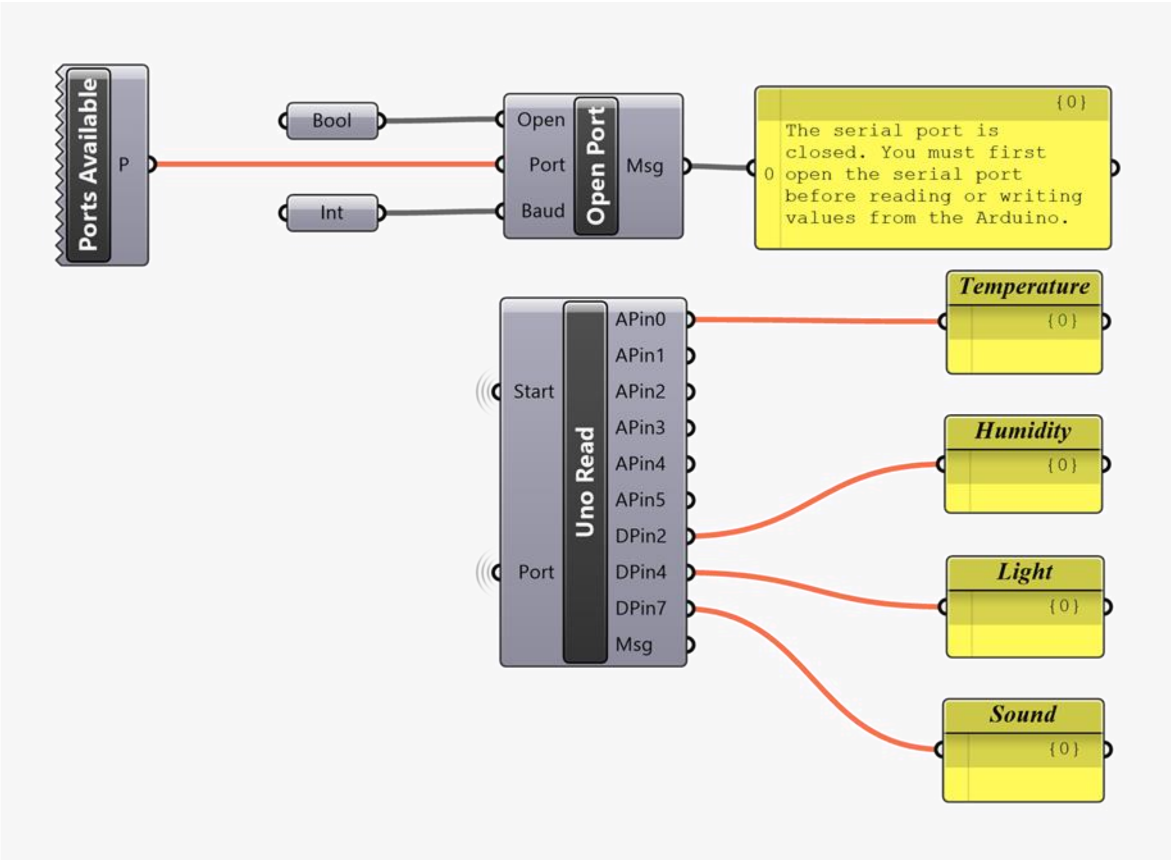


Figure 7.5: Open Port and Uno Read components of the developed apparatus within Firefly plug-in. Source: Author.

Figure 7.4 shows connection of sensors and components of the developed apparatus in Fritzing which is an open-source hardware initiative that makes different sketches for Arduino projects. Figure 7.5 shows Open Port and Uno Read components of the developed apparatus within Firefly plug-in (control Arduino with Grasshopper) which are used to communicate with the Arduino board.

Firefly is a plug-in which bridge the gap between smart sensor systems and the visual scripting tools. It is an interface between Grasshopper and the Arduino microcontroller and can retrieve data from the Arduino board's output pins. Furthermore, it allows components to open a connection to the serial port and read the data into a buffer and spits it out into Grasshopper.

7.1.2 Genetic algorithm

It is desirable to optimize data collected from the temperature/humidity, light, and sound sensors to achieve optimal indoor environmental quality. In order to perform a multi-criteria optimization between the input data of sensors, a genetic algorithm (GA) can be considered. The optimization of the data is made with a genetic algorithm (GA) within Grasshopper (graphical algorithm editor) that is connected with the developed apparatus (Figure 7.6). This process is performed when visualizing and collecting the data in real-time.

The proposed genetic algorithm is based on the scoring algorithm. For example, scores for each of the data collected from the developed apparatus (temperature/humidity, light, and sound sensors) are scaled to values between 0 and 100 according to recommended comfort ranges.

In order to find the most efficient data from sensors, it is useful to initially optimize four parameters under certain indoor environment and send them to a log data which can be used for improving a building control system in order to provide the optimal environmental conditions for users. Since all parameters use a separate algorithm to optimize their objectives, there are no conflicts in determining the optimal data.

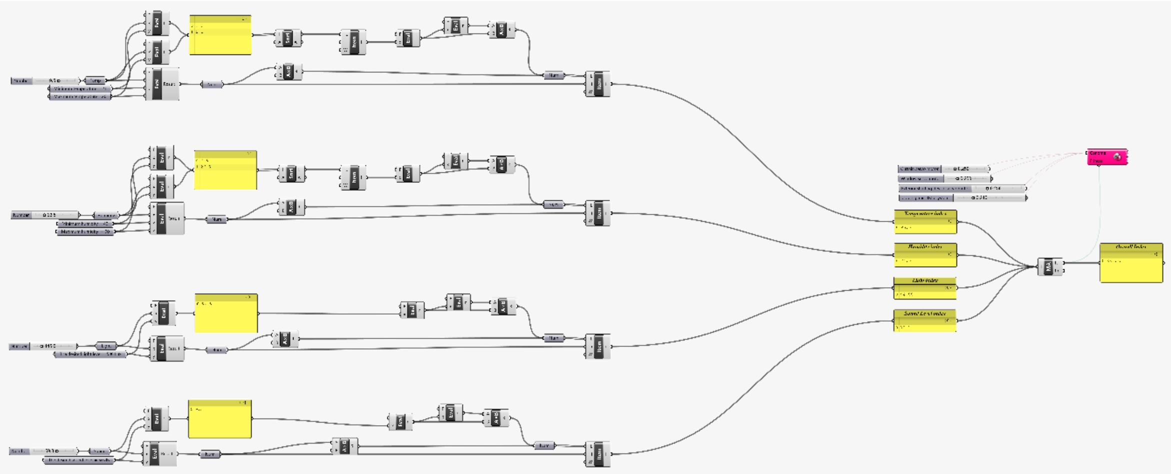


Figure 7.6: The genetic algorithm used for the developed apparatus. Source: Author.

As mentioned above, a comfort range have been defined for each of the four environmental parameters (temperature, humidity, light, and sound). For example, the recommended comfort temperature range is between 20 ° C to 26 ° C. In this respect, if the temperature is between comfort ranges, output value of algorithm will be100. Otherwise output value falls proportionally, according to the distance from comfort ranges. The proposed algorithm is defined in such a way that for each 1°C difference with comfort ranges 10 values will be deducted from output value. For example, temperature 19.5°C has obtained 95 value (Figure 7.7). It should be noted that real-time data from Arduino-based temperature sensor is connected directly to temperature components in the proposed algorithm.

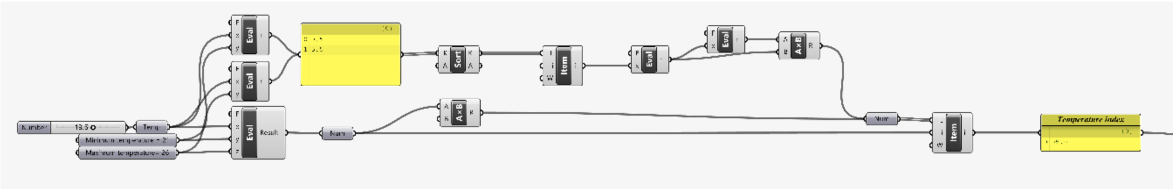


Figure 7.7: The algorithm used in the optimization of temperature level. Source: Author.

The range of 40 % to 60 % is defined as the comfort range for humidity. Therefore, values fall beyond the upper and lower limit of comfort range. In case of the comfort range mentioned, relative humidity obtains 100 values and for every 1 % deviation 4 values fall. The value of 4 is based on maximum acceptable standard deviation. For example, if there is a 25% difference in humidity levels, 100 values will be deducted. The humidity of 33.5% has obtained 74 values (Figure 7.8).

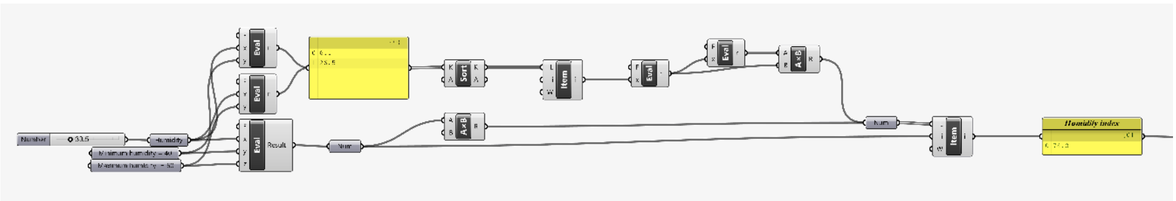


Figure 7.8: The algorithm used in the optimization of humidity level. Source: Author.

The light comfort level should be 500 lux on the workplace. In the proposed algorithm, for every 100 lux below comfort level, 10 values fall. For example, the illuminance of 445.5 lux has obtained 94.55 values (Figure 7.9).

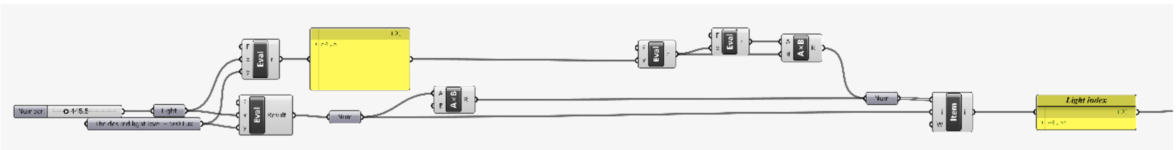


Figure 7.9: The algorithm used in the optimization of light level. Source: Author.

The acceptable sound level is 50 dB at the workplace. Therefore, in the case of below acceptable level, the predicted value is 100. For each 1 dB above of acceptable level 3 values will be deducted. For example, sound pressure level 53.9 dB has obtained 72.1

values (Figure 7.10). The proposed algorithm is designed so that environments with sound level above 84 dB (the threshold loudness level) get 0 value.

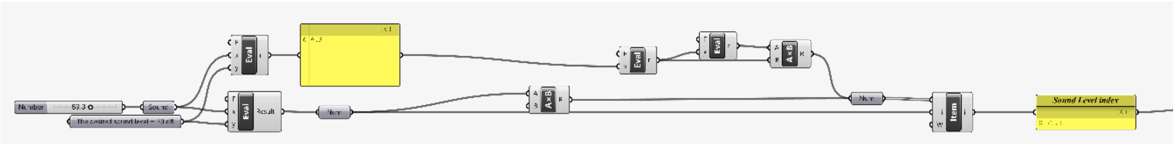


Figure 7.10: The algorithm used in the optimization of sound level. Source: Author.

After data processing and optimization, Galapagos component is used to generate the final solutions (Figure 7.11). In this context, overall index of the four optimized parameters transfer to fitness input in Galapagos component and the inputs for the Genome are used to control systems such as curtain, window, exterior shading device, cooling and building management systems (BMS). All portions of building control systems may not apply to Genome inputs, but using them at the same time can be helpful to find the optimal indoor conditions.

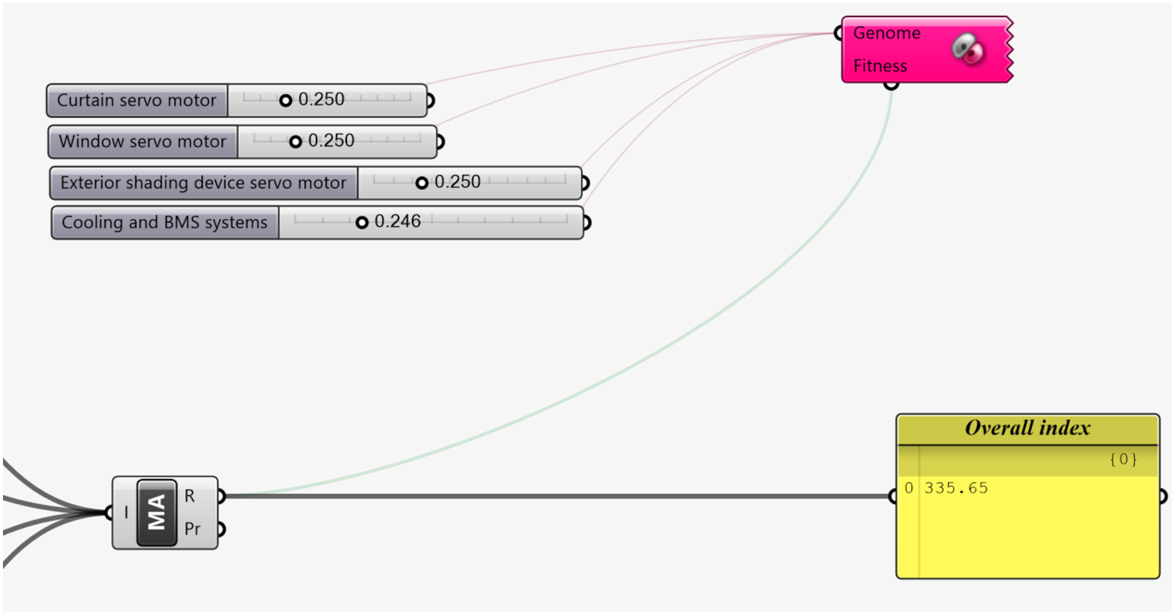


Figure 7.11: The final optimization algorithm with Galapagos component. Source: Author

Galapagos component can provide a generic platform for the application of optimization algorithms. It is a genetic algorithm component that uses and runs based on numeric fitness values. It can maximize the fitness value to achieve multiple objectives.
To run Galapagos component, it is necessary to select the tab Solvers and click Start Solver (Figure 7.12).

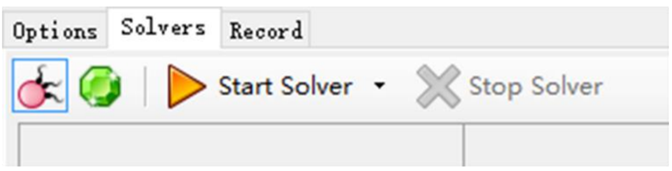


Figure 7.12: Start solver within Galapagos component. Source: Author

7.1.3 Intelligent user interface

A number of intelligent techniques, including fuzzy logic, neural network, neuro-fuzzy, and adaptive-network-based fuzzy inference system (ANFIS) are being widely used today to enhance manufacturing automation. In this context, ANFIS is a fuzzy inference system implemented in the framework of adaptive networks. It consists of five connected network layers such as input, fuzzification, inference, defuzzification, and output (Figure 7.13).

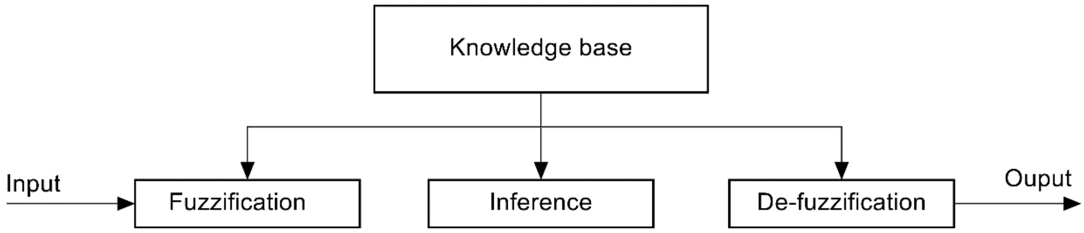


Figure 7.13: ANFIS structure. Source: Author

ANFIS was proposed by [252] based on fuzzy inference system and a neural network. The idea behind neural network and fuzzy inference combination is to design a system that uses a fuzzy system to represent knowledge in an interpretable manner and has the learning ability derived from a neural network that can adjust the membership functions parameters and linguistic rules directly from data in order to enhance the system performance [253].

ANFIS uses a hybrid learning algorithm and combines the gradient rule and the least squares estimate. Because of its flexibility, it can be used for a wide range of control systems. In fact, it is a multi-layer artificial neural network (ANN) with adaptive nodes.

In the field of building control, ANFIS can be used to predict HVAC system [254]. The study used an autoregressive neural network with external inputs to produce indoor temperature forecasts using the outside temperature, relative humidity, wind speed and past forecasts as inputs. Furthermore, the study [255] described a novel methodology for building occupancy detection using a sensor fusion model based on the adaptive neuro-fuzzy inference system (ANFIS) algorithm.

●Development of Simulink model

A Simulink model to control and monitor environmental parameters sensed by the apparatuses (based on Arduino) was developed in MATLAB R2014a (Version 8.3). Together with the ANFIS controller it was developed for configuring and accessing Arduino sensors, actuators and communication interface in both indoor and outdoor environments.

In the context of collecting data, three apparatuses based on Arduino are used. As mentioned before, the developed apparatus sends sensed data from the indoor environment to the target model. Two apparatuses (Arduino-based) are proposed to track data from outdoor environment in a wireless communication system and to send commands from MATLAB Simulink to servo motors (Figures 7.14 and 7.15).

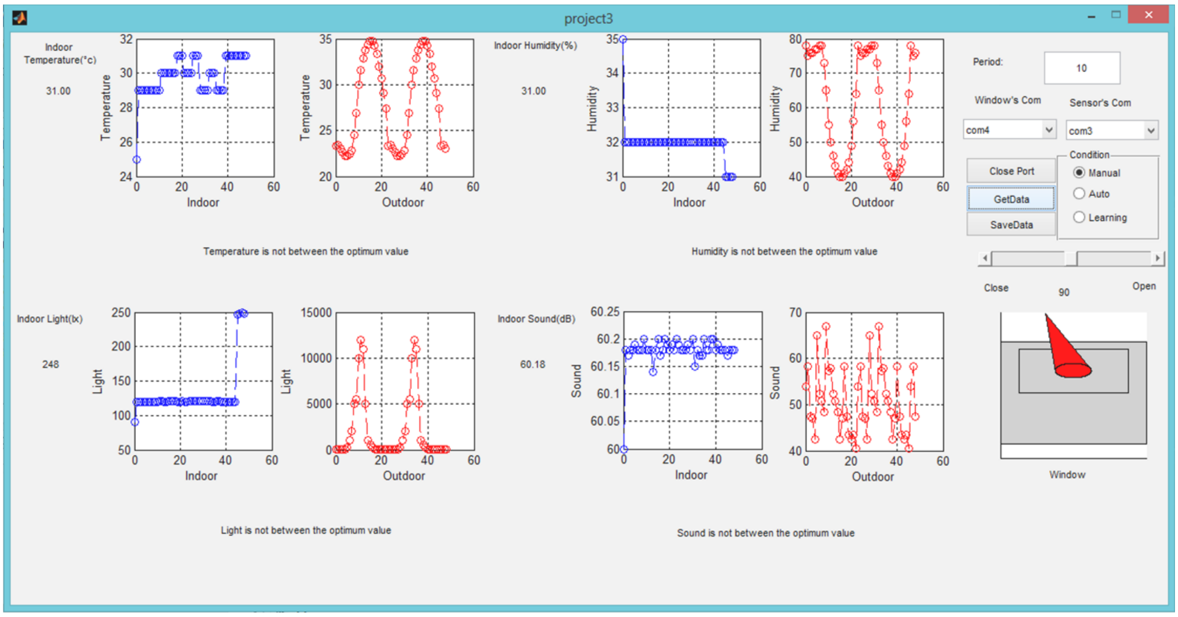


Figure 7.14: Intelligent user interface. Source: Author

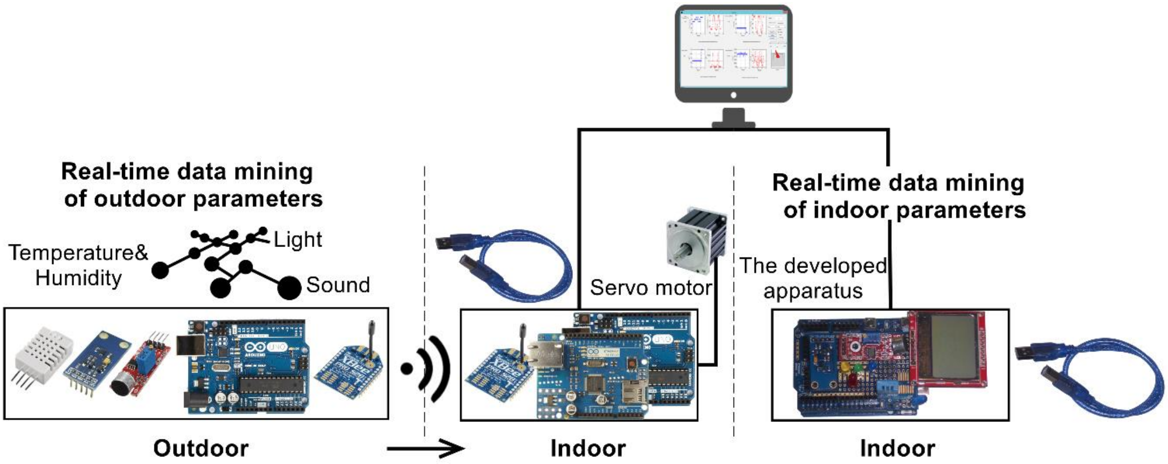


Figure 7.15: A schematic illustration of correlation between intelligent user interface and Arduino based applications. Source: Author

The proposed user interface can collect both outdoor and indoor environmental data. In this context, gathering outdoor sensor data can contribute to achieve the best indoor environmental quality, and to find the appropriate control strategy for a servo motor system. Furthermore, real-time visualization of outdoor and indoor environmental data can be helpful to users to understand their environmental better, and take appropriate actions. Users can obtain real-time data every 10 seconds in the workplace.

The proposed user interface is programmed with comfort zone limits (e.g. temperature 21-26 ^{o} C, humidity: 40-60 %, light: 500 Lux, and sound: 50 dB) and displays the optimum threshold value for each environmental parameter. It uses a genetic algorithm which finds the optimum value of outdoor and indoor environmental. According to this algorithm, performance for each parameters is calculated individually and a framework of ranking-based optimization is used (Figure 7.16).

```
rank1=gbellmf(TT00,[13 20 23]);
rank2=gbellmf(HH00,[15 30 65]);
rank3=sigmf(LL00,[300 400]);
rank4=1-sigmf(SS00,[55 65]);
rank=rank1+rank2+rank3+rank4;


data.TrainInputs=[TT00' HH00' LL00' SS00' bb00'];
data.TrainTargets=rank';

% Generate Basic FIS
%
fis=CreateInitialFIS(data,2);
%
```

Figure 7.16: A view of algorithm optimization of four parameters. Source: Author

The design of the proposed user interface is based on three modes: 1) manual; 2) learning; 3) automatic (Figure 7.17). In manual mode, users can adjust their environment variables by using servo motors (e.g. opening a window, opening shades, turning off artificial lights).

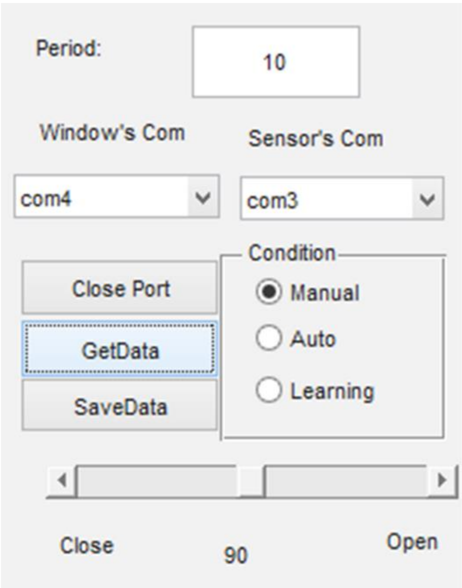


Figure 7.17: Overview of settings in the proposed user interface. Source: Author

In the case of learning mode, users according to their own needs adjust building control systems (e.g. opening windows, adjusting shading device) and along with their actions learning algorithms attempt to learn user behaviors. For example, learning algorithms learn when a window should be opened and then help user achieve the best performance under existing environmental conditions (Figure 7.18). The current learning process is applied to building control systems through the proposed user interface. Furthermore, automatic mode can be used to find the best performance of building control systems without user interaction based on the instructions given. The learning process can be considered a long term adaptation vision and action plan for office building especially in the workplace level. It also can lead to promote indoor environmental quality simultaneously with energy efficiency.

```
function fis=TrainUsingANFIS(fis,data)

 x=data.TrainInputs;
 t=data.TrainTargets;

 train_Epoch=200;
 train_ErrorGoal=0;
 train_InitialStepSize=0.01;
 train_StepSizeDecrease=0.9;
 train_StepSizeIncrease=1.1;
 TrainOptions=[train_Epoch train_ErrorGoal train_InitialStepSize
train_StepSizeDecrease train_StepSizeIncrease];

 display_Info=false;
 display_Error=false;
 display_StepSize=false;
 display_Final=false;
 DisplayOptions=[display_Info display_Error display_StepSize display_Final];

 OptMethod.Hybrid=1;
 OptMethod.Backpropagation=0;

 fis=anfis([x t],fis,TrainOptions,DisplayOptions,[],OptMethod.Hybrid);

end
```

Figure 7.18: A view of learning algorithm used in the proposed user interface. Source: Author

As mentioned before, in the current work methodology user behavior patterns are classified in three types (Figure 7.19). The developed user interface, apparatus, and intelligent algorithms attempt to develop micro scale energy management systems and robust user behavior interpretation. To make buildings more energy efficient, it is essential to develop a few smart systems for individual users to learn their behaviors.

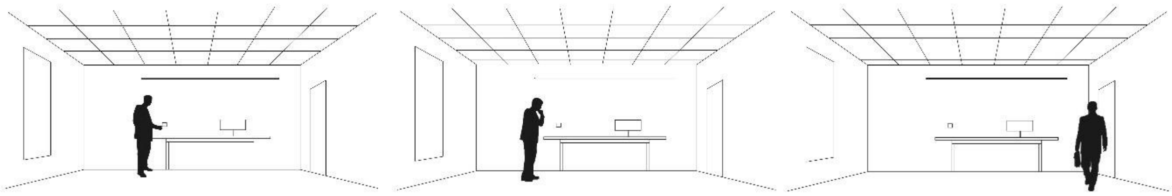


Figure 7.19: User behavior patterns integrated into intelligent user interface: 1) familiar with systems (left); 2) have no actual knowledge (middle); 3) not care about systems (right). Source: Author

7.2 Principles of Validation

It is important to define basic principles for the validation of a method. Process validation can provide documentary evidence that a method is capable of being used for a particular use. It also can be used as a process enforcement tool.

7.2.1 A micro scale energy management system

The development of energy management systems is an attractive and increasingly feasible option for several smart buildings. In this respect, a micro scale energy management system at workplace level is considered as a novel method in the field of smart buildings to improve energy efficiency (Figure 7.20). It can be developed via smart systems and interfaces in the buildings (Figure 7.21).

However, designing highly efficient micro scale energy management systems requires an in-depth understanding of various building systems and user behaviors. An investigation with a focus on interior shading devices is carried out to determine the effect of developed smart systems on building control and management systems.

A recent study by O'Brien and Gunay [256] showed that user are fairly inactive when operating manual roller shades. Furthermore, Reinhart and Voss [257] indicated that users overrode 45% of all automated blind movements and 88% of the times that the blinds were automatically.

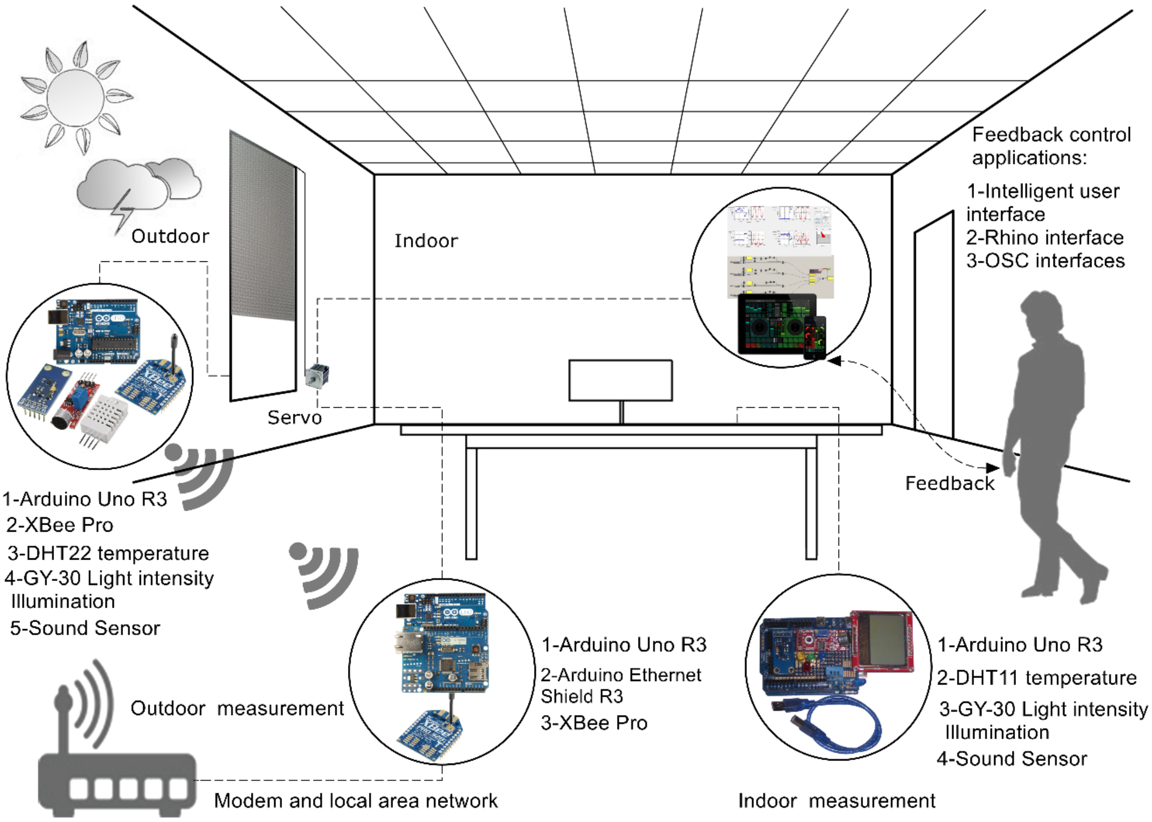


Figure 7.20: A schematic design of a micro scale energy management system. Source: Author

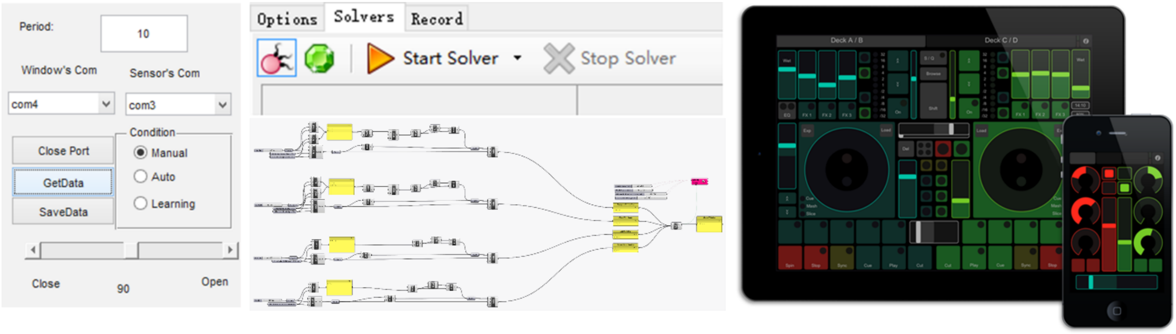


Figure 7.21: Feedback control applications. Intelligent interface (left), Grasshopper (middle), Modular OSC and MIDI control surface (right). Source: Author

In buildings unwanted heat and the loss of heat through windows are the two main issues that directly affect energy efficiency. In-flector is a flexible material designed for use as window insulation and solar shading product (Figure 7.22). It maintains interior comfort in the building by reflecting the transfer of heat back into the room before it can be lost through the window during winter, and reflects the heat back out through the window during the summer (Table 7.2). It also has possibilities for noise reduction (Table 7.3).

In-flector blinds are effectively climate control. They can be installed to either protect from the sun, prevent heat gain from sun rays, or reduce glare massively [258].

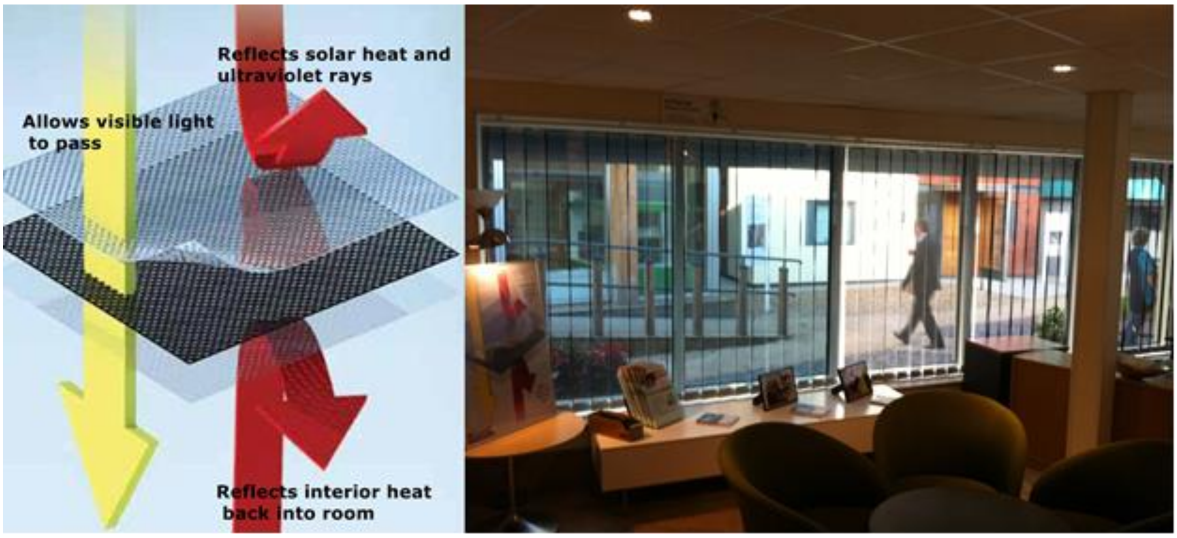


Figure 7.22: Illustration of In-flector insulators in the Building Research Establishment (BRE), Innovation Park Watford, UK [259].

Table 7.2: Thermal and optical factors of In-flector insulator [259].

In-flector	Solar transmittance	Solar reflectance	Solar absorbance	Visible transmittance
Silver side	0.253	0.496	0.251	0.22
Black side	0.253	0.083	0.664	0.22

Table 7.3: Comparison of reverberation times measured by In-flector [259].

Test orientation	Measured reverberation times (sec)				
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz
Existing glazing test area without insulator	0.75	0.91	0.84	0.56	0.53
Existing glazing test area with In-flector insulator	0.61	0.56	0.76	0.54	0.54

7.2.2 Simulation results

To illustrate the impact of In-flector on energy efficiency and indoor environmental, simulations were carried out in the IES-VE software. Four rooms (case study A) were chosen to carry out a heating and cooling load analysis with In-flector insulator (as internal shading device). Furthermore, the peak indoor environmental temperature in each room was analyzed under In-flector insulator. In the following figures a comparison between the results obtained by In-flector insulator and existing condition for each room is presented.

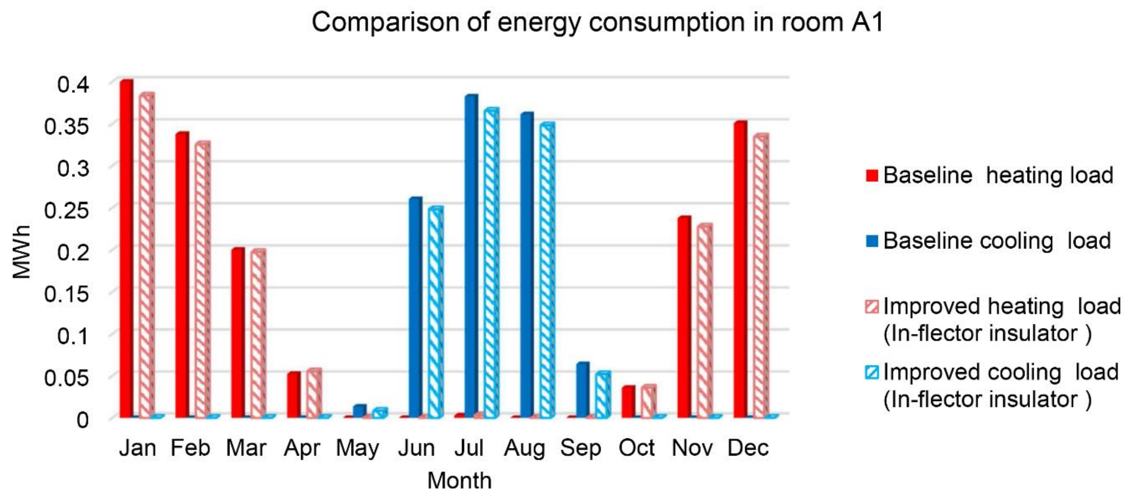


Figure 7.23: Comparison of energy consumption in room A1.Source: Author

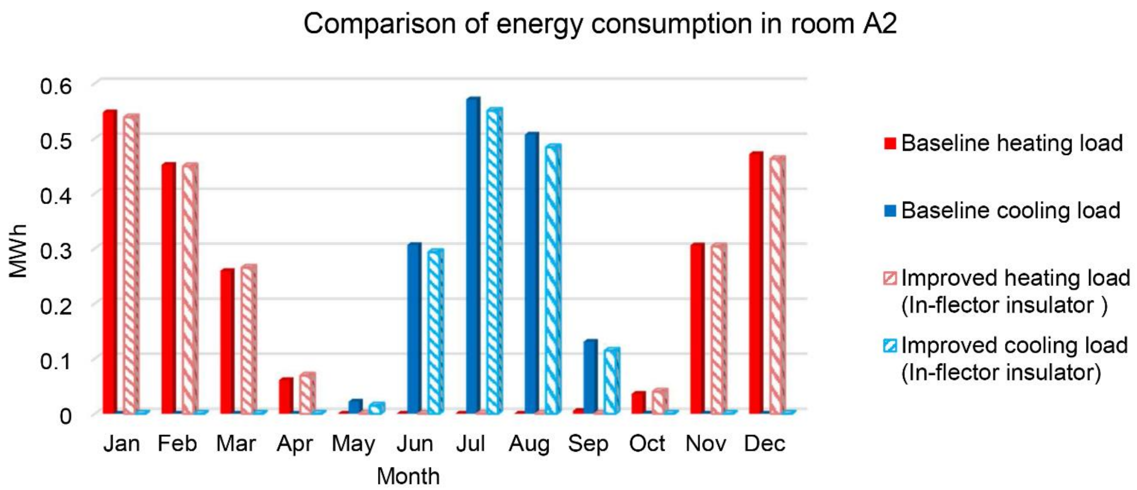


Figure 7.24: Comparison of energy consumption in room A2.Source: Author

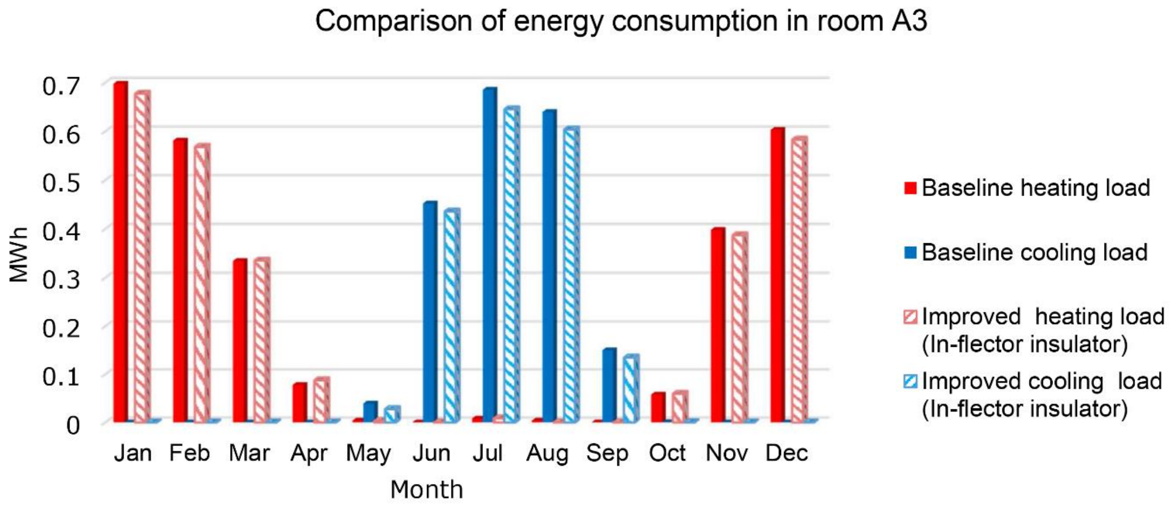


Figure 7.25: Comparison of energy consumption in room A3.Source: Author

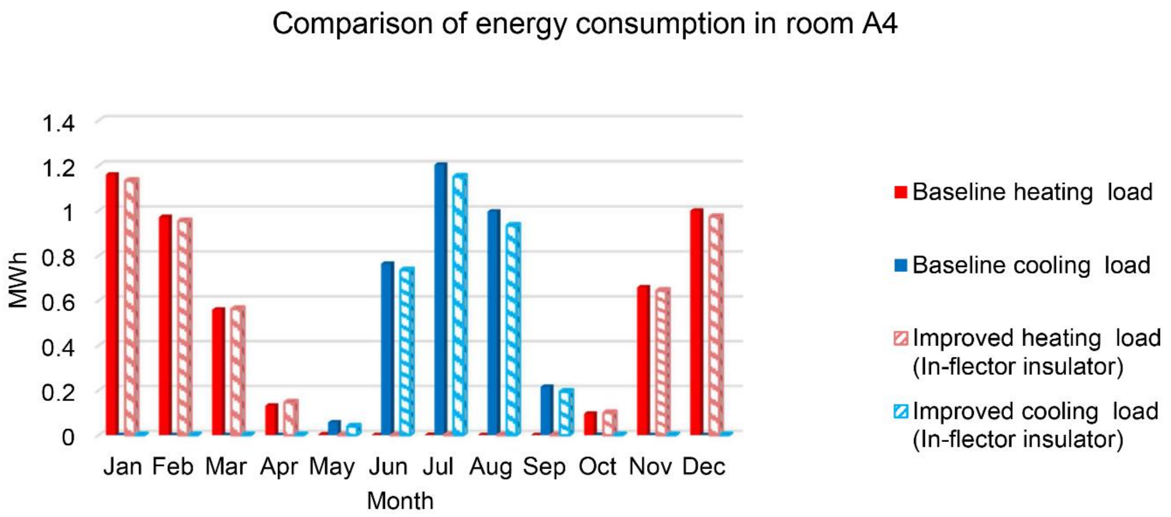


Figure 7.26: Comparison of energy consumption in room A4.Source: Author

Monthly energy consumption for each room obtained by IES-VE. This process can help in understanding the highest demand during each month. From the above figures, it can be seen that there is high demand for heating during winter months and the largest cumulative cooling loads occur in summer months such as Jun, July, and August. Furthermore, a comparison of the performance of In-flector insulator is presented (Table 7.4).

Table 7.4: Comparison of baseline and improved energy consumption. Source: Author

Model	Total baseline heating (MWh)	Total improved heating (MWh)	Reduction (%)	Total baseline cooling (MWh)	Total improved cooling (MWh)	Reduction (%)
Room A1	1.6183	1.5648	~1	1.0821	1.0226	~1
Room A2	2.1385	2.1286	~1	1.5369	1.4561	~1
Room A3	2.7658	2.7088	~1	1.9675	1.8476	~1
Room A4	4.5824	4.5132	~1	3.2365	3.0533	~1

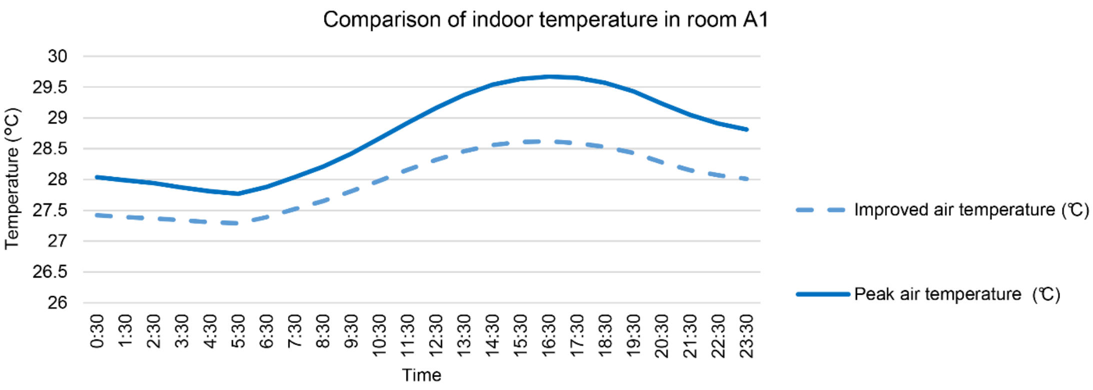


Figure 7.27: Comparison of indoor temperature in room A1 (04 July). Source: Author

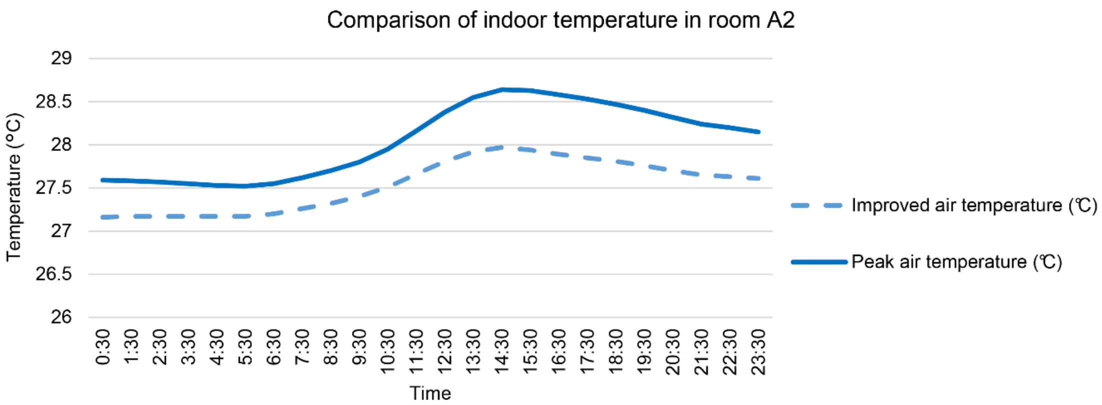


Figure 7.28: Comparison of indoor temperature in room A2 (04 July). Source: Author

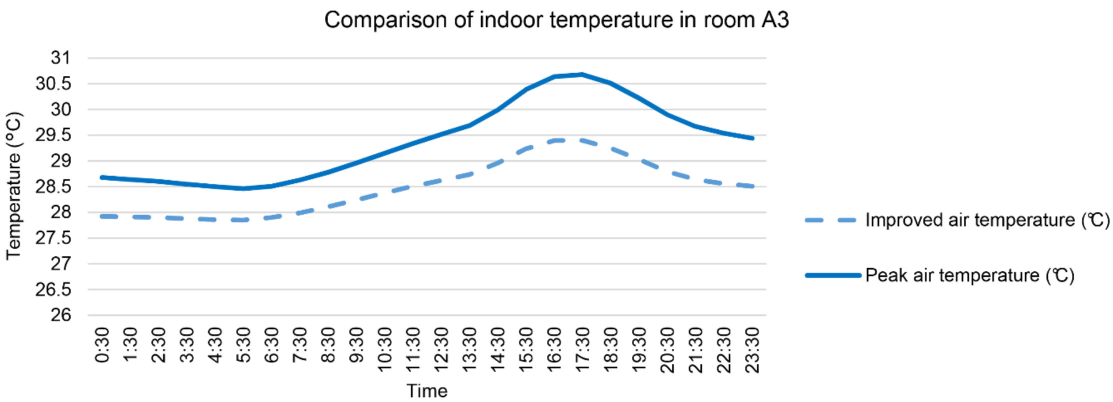


Figure 7.29: Comparison of indoor temperature in room A3 (04 July). Source: Author

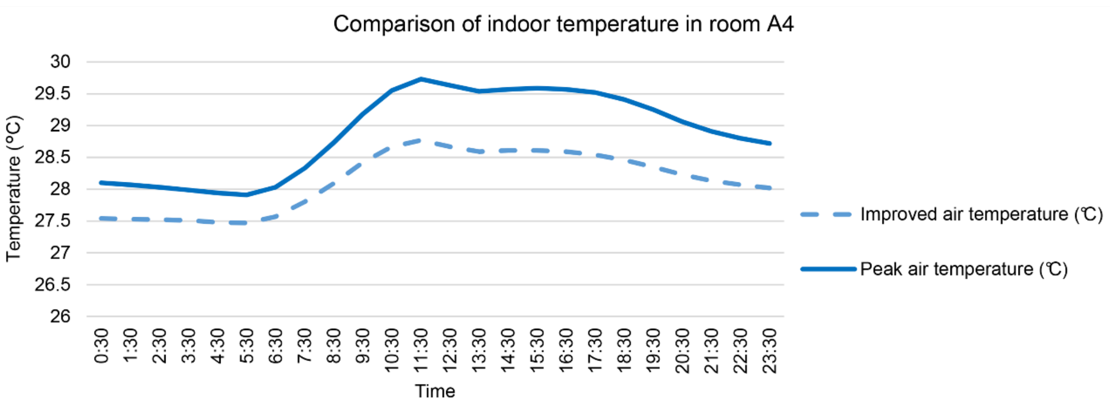


Figure 7.30: Comparison of indoor temperature in room A4 (04 July). Source: Author

As can be seen from the figures above, there are significant difference between peak day time air temperatures and improved air temperature. The following table gives a summary of the results obtained by IES-VE.

Table 7.5: Comparison of indoor temperature in rooms. Source: Author

Model	Peak air temperature (º C)	Improved air temperature (º C)	Temperature reduction(º C)
Room A1	29.67	28.62	~1
Room A2	28.63	27.94	~1
Room A3	30.68	29.4	~1
Room A4	29.73	28.77	~1

7.2.3 Discussion and future work

In-flector insulator proved to be an effective internal shading device. It can be linked with the prototype developed systems (Arduino systems) to provide an acceptable indoor environmental quality. It is important to note that internal shading devices can be part of a comprehensive energy management system. In this context, building users should be considered as the most important determinants of comfort.

To achieve better comfort conditions, it can be useful to gain maximum benefits of outdoor comfort such as natural ventilation and solar gains which can assist in reducing energy consumption in both summer and winter months. The outdoor comfort can be used to improve indoor environment through real-time systems.

Regarding future work, it can be useful to consider optimization algorithm for PMV and PPD in addition to the temperature and humidity ranges. Furthermore, weighting factors should be determined for all of comfort metrics. It is important to set up algorithm so that these weighting factors can be adjusted (within reasonable ranges) by users (or set by the user's actions) so that the optimization is not just one solution set. For example, one user might prefer a higher humidity with higher temperatures whereas another might want a lower humidity for the temperature, both might be considered "comfortable" overall.

CHAPTER 8 CONCLUSION

There is an increasing interest in real-time monitoring of environmental data to reduce energy consumption and to ensure comfortable conditions. User behaviors can play an important and positive role in reducing energy consumption, monitoring and managing systems. It is, therefore, important to understand and determine user behavior in the control systems. Sustainable smart behavior method for sustainable development and smart growth has been developed which encourages users to be involved and mindful of energy efficiency and indoor environmental quality (IEQ).

This current work contributes to an awareness on the part of all stakeholders of the importance of user behavior in improving energy and comfort performance. It highlights the fact that the sustainable built environment can benefit from user behavior in the improvement of efficiency and comfort. In other words, the performance of the built environment and its sustainability is highly dependent on user behavior.

In order to solve challenges from climate change relating to the built environment, it is essential to develop sustainable, smart and user interaction strategies (Figure 7.31). This concept should include the possibility of new perspectives beyond existing systems. For example, collaboration between artificial intelligence and neuroscience can provide an understanding of machine learning. In the field of computer science, machine learning refers to algorithms that learn patterns from data. In fact, machine learning is a branch of artificial intelligence and can adapt itself to information extracted from data.

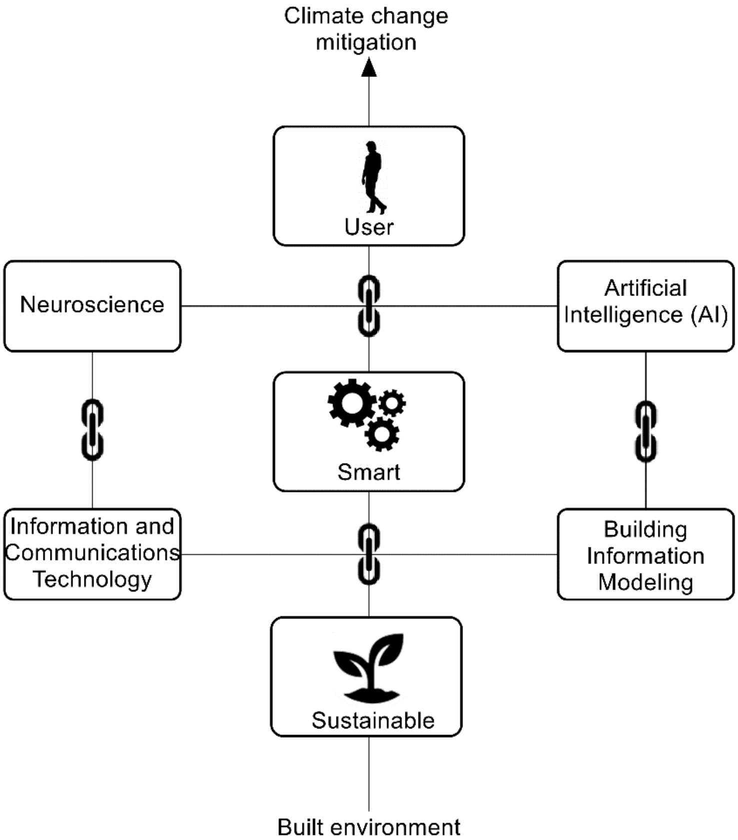


Figure 7.31: A schematic drawing of most factors for mitigating climate change. Source: Author

A machine learning system can be trained to distinguish between comfortable and uncomfortable conditions. After learning, it can be used to provide optimum comfort conditions. It is clear that ambient intelligence requires systems that can learn and adapt. In this respect, machine learning algorithms and applications can be used to predict user behavior patterns and learn user actions.

Intelligent learning algorithms can be used to gain knowledge of environment condition. The work methodology adopted in this study has focused on employing learning algorithms to help users achieve energy efficiency and comfort objectives. It has also investigated the prediction of user behavior from past performance and uses this information to enhance decisions to adapt in the future.

Energy efficiency is a focal point in user-centered applications. In this context, interfaces are used to promote user awareness of energy consumption and comfort conditions. The current work attempted to provide a synergy of feedback and interface tools. An intelligent interface was developed to control and monitor environmental parameters without overwhelming the user with providing sufficient information regarding indoor and outdoor environmental conditions.

To provide an efficient real-time energy use feedback, it is important to develop opportunities for users to interact with control systems. The current work developed an intelligent interface that can assist users in giving both eco-feedback and predictive control. The main contribution of this work is the goal-driven development of an indoor quality apparatus for environmental monitoring data by employing smart sensor systems. It can help users to monitor and control their environment factors and provides functionalities for assessing comfortable ranges.

It is widely believed that the attitudes of stakeholders regarding the potential of research findings can play an influential role in the introduction of products to marketing communications. According to this definition, it is important to develop and produce stakeholder-relevant results. At the same time, awareness of stakeholder needs is an essential step toward a progressive business model. In this respect, the current work shows that cost-effective products and methods have great potential for helping set up viable businesses.

The current work aimed at highlighting the importance of open source software and hardware systems in the field of architectural technology. It has shown that open source technologies can develop new design and technological possibilities within the architectural field. Furthermore, it introduced methods that can adapt and respond to changes in environmental conditions.

Building information modeling (BIM) has been shown to have considerable benefits for a better understanding of existing environmental conditions (e.g. thermal, lighting, and acoustic). Although BIM is unable to simulate actual user behavior in buildings, it is a very effective and efficient process for design evaluation and construction.

User energy behaviors should be considered when designing building energy management systems and be used in the optimization of operations. However, existing research in this field is insufficient.

A micro scale energy management system was developed to highlight the importance of using user behavior in the design of energy-efficient systems and processes. It showed that it is possible to build a smart workplace by employing smart sensor systems, user interaction and smart devices.

It is possible to claim that this PhD study program in architectural technology has proven to be an effective tool for exploring the various challenges facing the built environment. Furthermore, it has provided a detailed outline of architecture from different points of view: user behavior, artificial intelligence (AI) and neuroscience.

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Appendices

Appendix A: Questionnaire

PhD research survey (Arch.Shahryar Habibi University of Ferrara-Italy, Department of Architecture)

Please take a moment to answer this indoor environmental quality survey. Check one answer for each of the following:

Part 1: User's characteristics

1- What is your gender?

Male ◯

Female ◯

2- How old are you?

18-25 ◯

26-34 ◯

35-54 ◯

55 or over ◯

3- What is the highest level of education you have completed?

High School ◯

2-year College Degree ◯

Bachelor's Degree & Master's Degree ◯

Doctoral Degree ◯

4- On average, how often do you come to the office?

3 days or less per week ◯

4 days per week ◯

All days per week ◯

5- On average, how many minutes per day you spend outside of your workplace (coffee, food, smoke, etc.) during working hours? (Please indicate in the elliptic shapes as minutes)

Hours	9	10	11	12	13	14	15	16	17	18
	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

Part 2: Users' satisfaction (energy performance and IEQ evaluation)

6-How would you rate each of the following indoor environmental factors at your workplace?

Indoor Environmental factors	Satisfied	Dissatisfied	Don't know/Not applicable
A. Thermal Comfort (Relative Humidity (RH)& Air Temperature)	⬭	⬭	⬭
B. Daylighting& Lighting	⬭	⬭	⬭
C. Acoustic Quality	⬭	⬭	⬭
D. Air Quality	⬭	⬭	⬭
F. Overall, how would you rate the indoor environmental quality?	⬭	⬭	⬭

Part 3: Skill and knowledge of user in relation to smart systems

7- What is the level of your familiarity with smart systems?

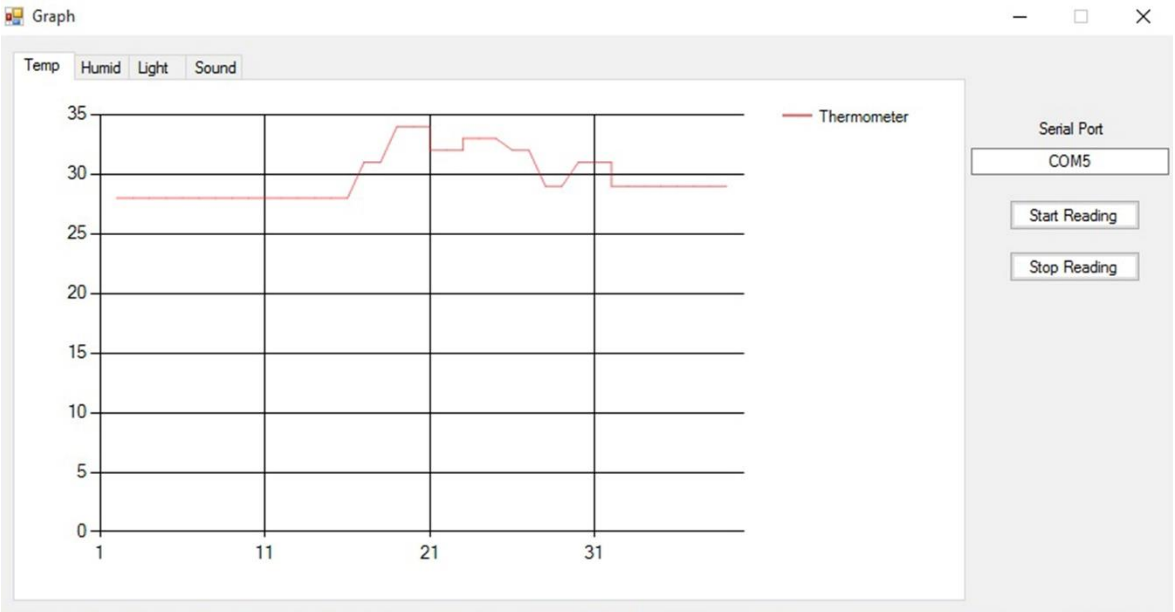
	Familiar with systems	Have no actual knowledge	Not always presence - wasteful & Not care about systems
Outdoor Monitoring Applications	⬭	⬭	⬭
Indoor Air Quality sensors (Temperature , RH meter, CO2 meter)	⬭	⬭	⬭
Light sensors (Lighting controls, occupancy sensor)	⬭	⬭	⬭
Sound Level Sensor	⬭	⬭	⬭

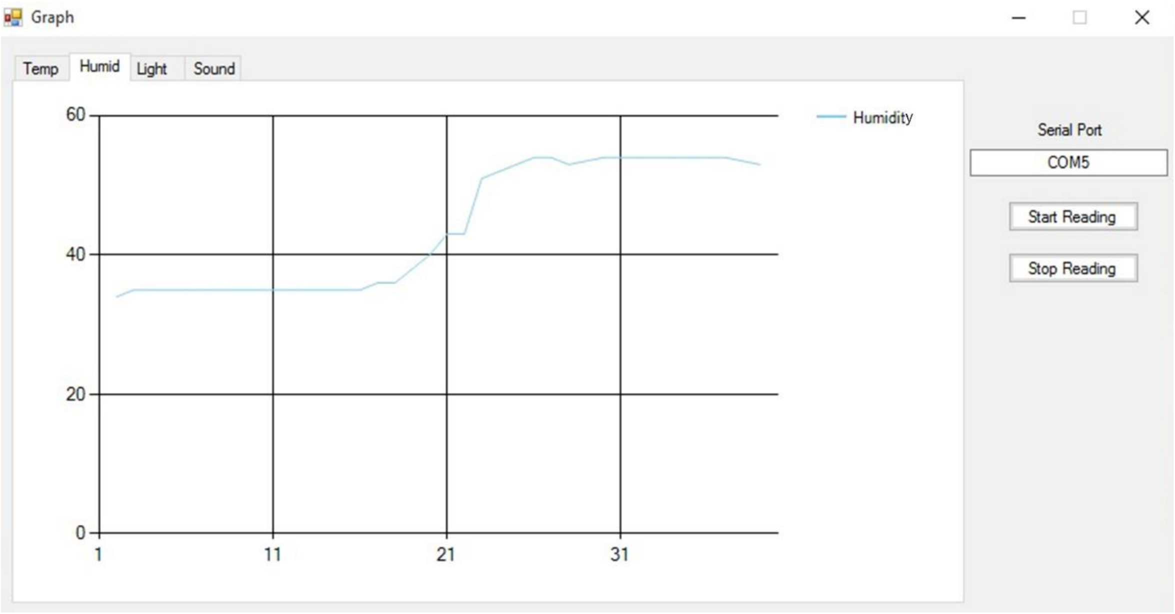
8-In your opinion, which of the systems above (question 7) can be integrated in your office for user satisfaction purpose?

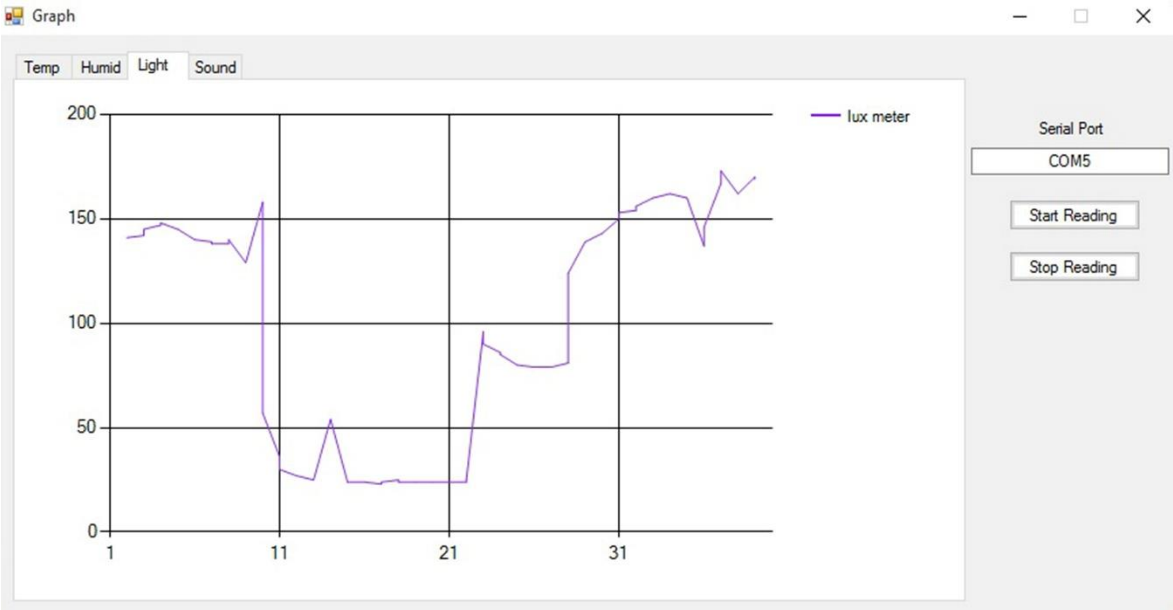
9- In your opinion, which of environmental factors should be considered during improving indoor environmental quality (IEQ) in your office? (Write minimum three factors in order of priority)?

10- Write a sentence or two describing your opinion about using smart systems for the buildings.

Appendix B: A simple user interface for Arduino systems developed by the author






Graph
Temp
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lux meter
Serial Port
COM5
Start Reading
Stop Reading
200
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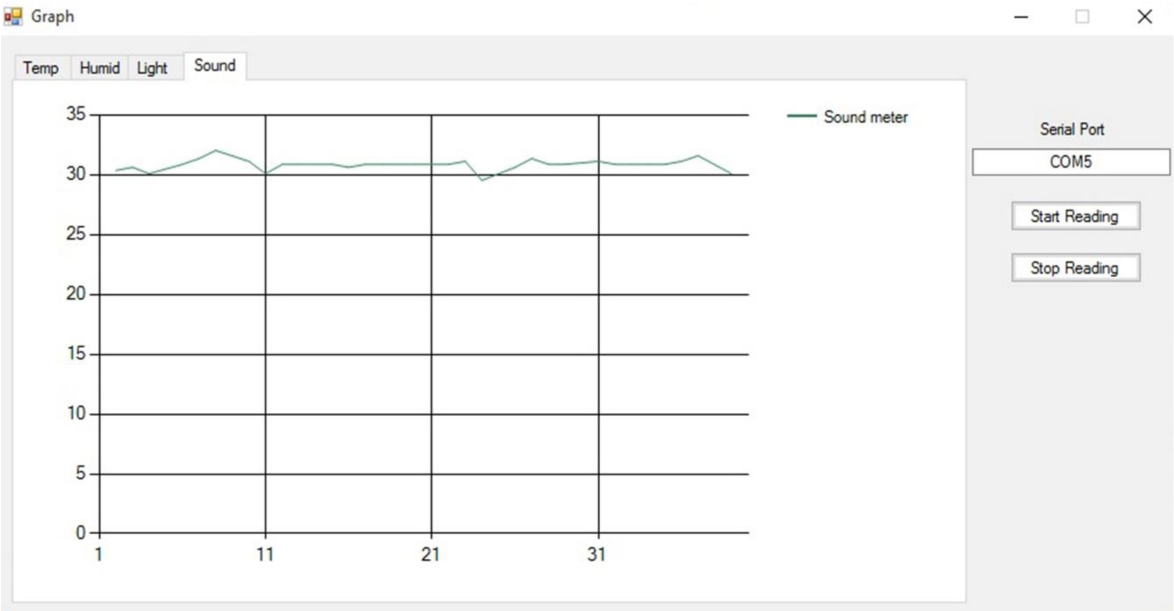
Graph
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Sound meter
Serial Port
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Start Reading
Stop Reading
35
30
25
20
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31

Appendix C: Author publications

S. Habibi, "Energy Efficiency Improvements and Indoor Environmental Quality Through Climate-responsive Architecture," *Proceeding of Healthy Buildings 2015 America*, Boulder Colorado, USA, July 19 –23, 2015.

S. Habibi, "Floating Building Opportunities for Future Sustainable Development and Energy Efficiency Gains," *Journal of Architectural Engineering Technology*, vol.4, 2015. doi:10.4172/2168-9717.1000142.

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S. Habibi, "How Can Smart Systems Affect Energy Consumption and Indoor Environmental Quality? *ASim2014 conference*, IBPSA Japan, Nagoya, Japan, November 28-29, 2014.

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S. Habibi, "Development of Smart Micro-Grid in Energy Efficiency Technologies on Workplace Level," *Proceeding of the Indoor Air 2014*, July 7-12, Hong Kong, ISBN number: 978-962-85138-6-4, 2014.