

Simulation and Analysis of Smart Commercial Building to Evaluate the Effect of Excessive Wireless Control on the Occupant's Health

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Thesis submitted for the fulfilment of the requirements for the degree of
Doctor of Philosophy

Victoria University, Australia

Institute for Sustainable Industries and Liveable Cities

March 2026

Abstract

Smart buildings—or sustainable, energy-efficient, intelligent structures—have garnered considerable global interest in recent decades. This focus arises from their potential to address the energy crisis associated with non-renewable energy use, particularly from conventional buildings, which account for approximately 30–40% of worldwide annual energy consumption and significant CO₂ emissions. The high energy demand not only leads to increased fossil fuel costs but also reduces occupant comfort. However, despite their potential to respond to contemporary problems, smart buildings also face challenges, including diverse sensor networks and inconsistent levels of intelligence.

To address some of these issues, this thesis presents a conceptual model for a sustainable smart building utilising software simulations. The proposed design aims to harness the advantages of modern architecture while minimising CO₂ emissions through reduced reliance on fossil fuels, ensuring optimal comfort for occupants and maintaining material sustainability under natural conditions. The results of the simulation indicate an estimated annual energy reduction of 69.78%, and contribute to the development of methods to mitigate certain identified drawbacks of smart buildings.

The design emphasises maximising the efficiency of renewable energy by integrating photovoltaic (PV) cells and wind turbines. A mathematical model is introduced to facilitate the incorporation of estimated renewable energy figures necessary for specific building requirements. In this framework, PV cell arrays were designed and modelled in conjunction with natural ventilation systems to optimise their generation capabilities. Consequently, significant energy reductions of 85% for newly constructed buildings and 39.84% sun-solar irradiation energy absorption for buildings in the built-in environment are achieved.

In the model, these optimally designed energy solutions are incorporated into indoor loads and into smart grids through wireless transmitting devices and the Internet of Things (IoT), enabling intelligent control applications and efficient operational strategies. The radiating kinetic energy produced from the wireless transmitters is converted into DC power to power low-powered IoT devices. Furthermore, an air quality improvement strategy has also been developed to foster a healthier indoor environment. Finally, an indoor experimental room representing a smart building was developed and equipped

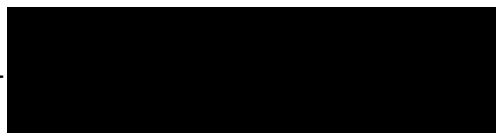
with multiple dense wireless transverse radiating devices; their multipath propagating waves' power density effects were assessed using both sequential and simultaneous simulations to evaluate potential health concerns among occupants. The findings were compared against international non-ionising power density standard guideline limits. From these outcomes, a power density monitoring circuit was developed to provide early warning in cases of high indoor power density levels.

Declaration of Authenticity

I, Berhane Gebreslassie, declare that the PhD thesis entitled ‘Simulation and Analysis of Smart Commercial Building to Evaluate the Effect of Excessive Wireless Control on the Occupant’s Health’ is no more than 80,000 words in length including quotes and exclusive of tables, figures, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

I have conducted my research in alignment with the Australian Code for the Responsible Conduct of Research and Victoria University’s Higher Degree by Research Policy and Procedures.

Signature ---

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Generative Artificial Intelligence (AI)

Acknowledgement

This thesis has been edited for punctuation and grammar using Grammarly. This use complies with VU guidelines on use of editors in HDR theses and overall VU policy on use of AI in research.

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-----Date 6 March 2026

Acknowledgements

I am grateful to my supervisor, Professor Akhtar Kalam, and my associate supervisor, Professor Aladin Zayegh, for their tremendous support during this research. Their support and guidance ensured the timely and successful completion of this thesis. I also wish to thank my family, especially my wife Million Rezene Desta, for their incredible support during this course. Without their support and patience, I may not have been able to complete my course within the time given.

I am also grateful to Elite Editing for assisting me in editing this thesis. Editorial intervention was restricted to Standards D and E of the Australian Standards for Editing Practice.

List of Publications

- [1] Smart Building, Nuisance Electrical Failure, Remote Monitoring and Fault Recovery System: Journal of Electronics and Electrical Engineering; 2024-10-12 | Journal article | Author, Berhane gebreslassie; Akhtar Kalam; Aladin Zayegh; DOI: 10.37256/jeee.3220245043; Part of DOI: 10.37256/jeee.322024; Part of ISSN: 2972-3280
- [2] B. Gebreslassie, Zayegh, A., Kalam, A., 2023, ‘Design of sustainable buildings with renewables’, Chapter 8, Book on “Natural Energy, Lighting, and Ventilation Resources in Sustainable Buildings”, pp.155-190, Springer, USA, ISBN 9783031411472.
- [3] B. Gebreslassie, A. Kalam, and A. Zayegh, "Design, Modeling of a Green Building Energy Optimized Efficient System," ed: IEEE, 2023. 2023 7th International Conference on Green Energy and Applications (ICGEA) Year: 2023 | Conference Paper | Publisher: IEEE
- [4] B. Gebreslassie, A. Kalam, and A. Zayegh, "Converting multiple propagating wave energy to wireless energy transfer to charge low powered cellular devices flat-battery on an emergency situation where charging point is unavailable," ed: IEEE, 2023. 2023 33rd Australasian Universities Power Engineering Conference (AUPEC) Year: 2023 | Conference Paper | Publisher: IEEE
- [5] B. Gebreslassie, A. Kalam, and A. Zayegh: Sustainable building practice, presented at the 47th Australasian Universities Building Education Association (AUBEA2024) conference, submitted to be published in the “Lecture Notes in Civil Engineering.”

Accepted papers

- [6] B. Gebreslassie, A. Kalam, and A. Zayegh: Interconnected wiring systems connect a few electrical devices to many, thereby minimising resource and energy consumption in modern high-rise buildings. (ICSCGE 2025). The 5th international conference on smart city and green energy.

Papers under review

- [7] B. Gebreslassie, A. Kalam, and A. Zayegh: Innovative switched bus-power interconnection wiring systems that connect a few electrical devices to many,

minimising resource use and eliminating unnecessary energy consumption. Elsevier, Energy and Report journals. Manuscript Number: EGYR-D-25-03537.

[8] B. Gebreslassie, A. Kalam, and A. Zayegh: Transition toward Sustainable building design to approach sustainability. Frontiers, Sustainable Design and Construction journal. Manuscript ID: 1778822.

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List of Abbreviations

AI	Artificial intelligence
AQ	Air quality
ASHRAE	American Society of heating and refrigerating and air-conditioning engineers
BACS	Building automation control system
BAS	Building automation system
BIM	Building information modelling
BIoT	Building internet of things
BMS	Building management system
CB	Circuit breaker
CFCM	Component field combining method
CO ₂ -e	Carbon equivalent
CP	Coefficient of performance
CR	Control relay
DC	Direct current
DHI	Diffuse horizontal intensity
DNI	Direct normal intensity
DOA	Direction of arrival
EEB	Energy efficient building
FCC	Federal Communications Commission

FEDMA	Few electrical devices for multiple output-activation
GBCA	Green Building Council of Australia
GBS	Green Buildings Studio
GHI	Global horizontal intensity
GIS	Global information system
GPS	Global positioning system
GWP	Global warming potential
HIoT	Healthcare internet of things
HMI	Human–machine interface
HVAC	Heating ventilation air conditioning
IAQ	Indoor air quality
ICE	International Council of Ethologists
ICF	Insulating concrete forms
ICNIRP	International Commission on Non-Ionising Radiation Protection
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IEQ	Indoor environmental quality
IIoT	Industrial internet of things
IoT	Internet of things
IPD	Incident power density
LCA	Life-cycle assessment

List of Abbreviations

LED	Light emitting device
LEED	Leadership in energy and environmental design
LPD	Lighting power densities
MFCM	Magnitude field combining method
MIMO	Multiple input multiple output
ML	Machine learning
MPPT	Maximum power point tracking
NASA	National Aeronautics and Space Agency
NOCT	Normal operating cell temperature
OLED	Organic light emitting diode
OTC	Optimised torque control
PERC	Perfect electric
PIC	Programmable interface control
PLD	Power loss density
PV	Photovoltaic cell
PWM	Pulse width modulation
RCD	Residual current device
RF	Radiofrequency
RF-EMF	Radiofrequency electromagnetic field
RFID	Radio frequency identification
RMS	Root mean square

List of Abbreviations

RPM	Revolution per minute
SAR	Specific absorption rate
SDR	Semi-definite relation
SDS	Smart data stream
SECMA	Single electrical circuit for multiple-output-activation
SEDMA	Single electrical device for multiple output-activation
SQL	Structural query language
TSR	Tip speed ratio
US	United States
VFD	Variable frequency device
VOC	Volatile organic compounds
VSD	Variable speed drive
WET	Wireless energy transfer
WWR	Window to wall ratio

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Chapter 1

Thesis Overview

1.1 Introduction

Smart buildings play a crucial role in addressing climate change and reducing energy consumption. The concept of smart buildings is rapidly gaining traction alongside practical initiatives; projections indicate an anticipated growth rate in smart buildings of 8.3% over the next decade [1]. Over the next decade, it is anticipated that more intelligent structures will be created, leading to an increase in predicted growth rates. In 2023, the global packaging market for commercial building automation was valued at approximately US\$37.5 billion, with expectations that it would rise to around US\$52.2 billion by 2032 [2]. Forecasts suggest that smart buildings will increasingly cater to the needs of their occupants. Furthermore, by overcoming the limitations associated with conventional buildings, smart structures are positioned as preferable options for both current and future generations. Factors contributing to the swift advancement of smart buildings include technological innovations, heightened demand for energy-efficient designs, lower operational costs and enhanced occupant comfort. However, smart buildings also face various challenges and drawbacks, including diverse sensor networks and inconsistent levels of continuous intelligence.

The aims of thesis were to:

1. Explore and compare the advantages and disadvantages of conventional building design versus sustainable smart building design in terms of structural stability, energy efficiency, the integration of innovative energy sources and the emergence of modern technologies in the indoor environment.
2. Develop methods of mitigating the drawbacks of smart buildings.
3. Explore and assess the potential for wireless energy harvesting, which is alternative source of energy facilitated by excessive indoor wireless devices.
4. Evaluate and develop a mitigation method for an indoor environment to enhance air quality for occupants' health.

5. Examine and evaluate the impact of extensive wireless communication and control of non-ionising radiation on occupant health within smart commercial buildings.

1.2 Definition of Smart Buildings

Sustainable smart buildings are defined as high-efficiency edifices designed with ecological considerations in mind [3]. Further, smart buildings are defined as proportionally aligned with sustainable technological resources while preserving most of the natural environmental substances around the building [4] throughout its lifetime [5].

The definition of sustainable smart building design has evolved through two iterations: an initial version and a more recent one. Initially, a sustainable building was succinctly described as one that ‘satisfies current demands without jeopardising the needs of future generations’ [6]. The latest definition is significantly different from the earlier one because it focuses on practical aspects related to environmental pollution and energy-saving actions. This definition describes sustainable building design as one that harmonises with the natural environment. It takes into account social, environmental and economic factors in decision-making, aims to reduce carbon dioxide (CO₂) emissions through lower energy consumption and focuses on the restoration of natural resources [6, 7]. In the latest definition, social sustainability is significant, ensuring practical action towards a healthy and safer community approach that is connected with economic and environmental endeavours.

Sustainable building design is necessary because buildings are among the highest energy consumers. For example, the United States’ (US’s) buildings consume 40% of the US’s overall annual energy, 75% of the electricity demand [8] and contribute 30% of the total CO₂. This is because most of the current energy used in buildings is still from non-renewable resources, even though the building sector has the highest potential for energy use with renewable energy resources [9]. The latter could be implemented using a comprehensively integrated approach to reduce heating, cooling and lighting demands using passive strategies of a dynamic climate responsive design [10]. Climate-responsive design currently attracts many architects and builders because of its low impact on the natural environment [11].

In this thesis, the concept of designing sustainable buildings with renewables refers directly to building designs that have been energy-sustainable throughout the life-cycle. This requires the implementation of considerable renewable energies. Hence, to meet the definition of a ‘sustainable’ building, the energy produced from the renewables plus the energy reduction obtained from simulation results have to approach equilibrium. This means the building must be designed by considering the amount of energy to be consumed by the building against the amount of energy generated from the renewables. This can be achieved using prior construction energy simulation.

1.2.1 Buildings’ Energy Modelling Information

Building information modelling (BIM) is one of the required criteria for remote interoperability of building systems, with a special focus on energy savings. Using design process modelling, visualisation of tools, material analysis and effective teamwork makes a significant contribution to the design of sustainable smart buildings. In this way, high-performance green buildings can be achieved, which will reduce energy consumption and improve people’s health, lifestyles and general comfort [12]. To achieve this, the most helpful tool currently used by many companies is BIM [13]. Since BIM has become popular, there is an urgent need in the market for green construction simulation and modelling using BIM. However, there is a challenge because the current smart building construction software simulation application has limited services. It requires an updated or new construction software simulation program that will solve the time management difficulties in interoperability with BIM [14]. Thus, building simulation and modelling are necessary prior to making a decision to build, because they are crucial for achieving the desired high energy efficiency. However, the current simulation software available is not sufficiently intelligent [15] to make significant changes.

1.2.2 Performance, Durability and Modelling Design Efficiency of Sustainable Smart Buildings

A review of the research on sustainable building design shows that traditional buildings waste significant amounts of energy and produce considerable CO₂ [16], which negatively affects a building’s performance. This negative effect has encouraged stakeholders to implement sustainable building globally and to define their objectives [17-19]. It has also invited designers, architects, owners, contractors and builders to play a significant role in creating sustainable buildings by planning, designing and selecting

sustainable energy-efficient building materials—for example, through itemisation of insulation levels, shading details, window performance, wall performance, appliance performance and durability of materials. Implementation of these has led to a reduction in the environmental impact of buildings and improved social cohesion; it has ensured the continuation of economic development without severe harm to the surrounding environment [20]. The preliminary designs and architectural orientations play a significant role in implementing sustainable reforms that have contributed to the sustainable performance of buildings. This is because the most important decisions affecting the lifetime performance of buildings are made during these early design stages [20]. A clear understanding of a building's design and lifetime operating methods reduces the operational and maintenance impacts of the building [21] while improving comfort, health and economic aspects.

1.3 Smart Building Energy Rating

Various green star rating systems exist globally and serve as a method of certifying building design, construction and operations. Numerous countries have developed these tools. For instance, the Green Building Council of Australia (GBCA) [22] continually advances its offerings in collaboration with industry stakeholders and government entities. The Green Star is a registered Certification Trademark owned by the GBCA. Projects that undergo evaluation and receive certification from the GBCA can use the Green Star trademark and identify themselves as Green Star projects. The green star has transformed the rating system for newly constructed buildings and for renovations of existing buildings. Its objective is to provide an improved, more user-friendly and pertinent experience that addresses contemporary challenges.

1.4 Advantages of Design-and-Build Construction

The definition of 'design-and-build' is straightforward: the design-build construction delivery method replaces the conventional approach of handling separate contracts for design and construction [23]. In this model, contractors, designers, subcontractors and the owner collaborate as a unified team to deliver a project that aligns with the owner's expectations. Team members emphasise effective communication, collaboration, problem-solving and shared accountability. With this approach, the owner needs only to oversee one contractor, who then assembles a team with the designer and manages all

subcontractors. Together, all work alongside the owner to establish project goals, budget parameters and a construction timeline. The entire design-build team is dedicated to delivering the final product. Involving key contractor members during the design phase enhances their understanding of the project, enabling them to streamline the work process efficiently. This ultimately supports sustainable building design practice.

1.5 Strategic Management and Marketing of Smart Buildings

Both occupants and owners are crucial to the effective implementation of sustainable practices in buildings. By communicating their preferences for sustainable structures to manufacturers, marketers and community stakeholders, they can assist in raising awareness of sustainable design goals [17, 19], driving significant advancements in building design. Manufacturers are tasked with supplying products that align with regulatory standards as well as the preferences driven by consumer demand. Presently, many manufacturers are realising and asserting that they can secure a competitive edge through the successful marketing of sustainable products. This trend is also applicable to designers, builders and developers, as the increasing demand for sustainable building designs has shaped market dynamics, prompting manufacturers, developers and builders to address these evolving market requirements more effectively [24].

1.6 Sustainable Building Construction Materials

Sustainable building materials [25] refer to those that do not contribute to environmental pollution and avoid the use of non-renewable resources. Incorporating sustainable building materials into design [26] can lead to savings in both cost and time. Using timber or concrete reinforced with natural fibres as an alternative to steel—along with engaging energy-efficient certified contractors—exemplifies the approach. Furthermore, buildings can embrace a climate-positive pathway, which consists of specific objectives that align with the recommendations from the Intergovernmental Panel on Climate Change (IPCC) framework. The use of sustainable construction materials is essential to the framework, which is intended to assist in creating a climate-positive structure that operates with less fossil fuels, is enhanced by mainly renewable energy sources, exhibits high efficiency, uses materials with reduced carbon footprints and incorporates nature-based offsets.

1.7 Passive Fire-Protecting Polymeric Materials in Buildings

Another way in which a building can be ‘smart’ is by protecting against fire. A fundamental aspect of adequate passive fire protection involves the use of specialised fire-resistant materials [27]. This study examines key passive fire products, which encompass intumescent paint, vermiculite fire spray, fire-stopping penetrations, fire retardant boards and fire-rated ductwork wrap. This research explores each product in detail and highlights its importance in establishing strong fire safety protocols within structures.

1.8 Modelling an Energy-Efficient Building

Increasing energy efficiency can assist in mitigating economic consequences by decreasing fossil fuel use and reducing CO₂ emissions. Consequently, the principles of energy efficiency in sustainable construction are applied across all aspects of building materials [28]. To promote sustainability regarding energy efficiency, two key areas should be addressed:

1. **Adoption of Energy-Efficient Technologies:** This enhances the quality of energy used and has the potential to reduce both energy consumption and CO₂ emissions significantly. Transitioning to environmentally friendly energy technologies facilitates the transformation of raw sources into usable services like lighting, heating and transportation. A wide array of energy-saving devices and appliances is available, including stoves, air conditioners and refrigerators.
2. **Use of Energy-Efficient Materials:** A diverse selection of energy-efficient building materials is accessible to developers. These include insulating concrete forms, low-emissivity windows and structural insulated panels, along with options such as wood fibre insulation.

1.9 Modelling Smart Buildings with Renewable Energy

Integrating sustainable building design with renewable energy involves various contemporary technologies and energy sources [29]. However, the most effective options currently in use, particularly in intelligent and sustainable structures, are solar panels and wind turbines. Consequently, this study provides a brief examination of these two forms of renewable energy and discusses strategies for maximising their output. Smart,

sustainable building design integrated with renewable energy is necessary because buildings are among the highest energy consumers, and most of the current energy used in buildings is still produced from non-renewable resources. This is despite the building sector having the highest potential for use of renewable energy resources [9]. This potential could be effectively realised using a comprehensively integrated approach to reduce heating, cooling and lighting demands through passive strategies that respond to a dynamic climate [12]. Climate-responsive design currently attracts many architects and builders because of its low impact on the natural environment [30]. The sun provides enough solar energy in just one hour to fulfil global energy demands for an entire year [31]. The sun serves as a potent source of energy, yet humanity has not managed to harness even a small portion of it. However, space limitation has become a significant issue over the past few decades, as the world has witnessed that photovoltaic (PV) cell energy has become the norm in renewable energy, leading to an efficient and feasible transition from fossil oil to a clean energy supply.

Hence, it is more viable for residential than commercial buildings. This is because residential premises have lower electrical loads than commercial or industrial buildings. Further, since the recent decades, commercial buildings and factories have also become beneficiaries [29] of a large PV cell array. On the other hand, the built-in environment has limited space, particularly on rooftops.

In addition, in a built environment, buildings are crowded, and their height and size vary. This makes it challenging to install PV cells in all buildings, as taller buildings can shadow smaller neighbouring ones. This also makes it challenging to use the built environment's roof space for maximum capacity. Therefore, it is essential to reconsider the traditional method of PV cells being mounted on the top of the building roof and the type of PV cells.

Wind energy plays a vital role in economic development. In the US alone, more than 120,000 individuals are employed within the wind energy sector. The US Bureau of Labour Statistics indicates that wind turbine service technicians represent the second fastest-growing occupation in the country for this decade, with career paths available from blade manufacturing to asset management. By the year 2050, the wind industry is projected to create hundreds of thousands of additional jobs. Furthermore, wind energy is a domestic-grown resource that fosters economic advancement in the US. In 2021, wind

turbines across all 50 states contributed over 9% to the nation's total net energy production. Alongside investments in new wind projects, this sector also injects an extra \$20 billion into the American economy.

1.10 Use of Connected Devices in Smart Buildings

The Internet of Things (IoT) refers to a system of tangible objects that are equipped with sensors, software and various technologies, enabling them to connect and share data with other devices and systems via the internet. These objects vary from simple household items to advanced industrial machinery. As of now, there are more than 7 billion Internet of Things (IoT) devices in use. Forecasts indicate this number will exceed 64 billion and could reach 101 billion by 2030. When IoT is explicitly applied to buildings, it is referred to as the Building Internet of Things (BLoT) [32].

Conventional building owners and operators express concern that their buildings are struggling to maintain proper functionality because of declining energy efficiency, increasing operational and maintenance costs, and shrinking budgets. To address these concerns, building owners and operators can consider BLoT [33] to innovate their buildings into smart, sustainable ones. BLoT, sensors and cloud-based building automation demonstrate the capability to minimise energy use and reduce operational and maintenance costs.

1.11 Conceptual Building Simulation Approach

This study aims to create sustainable structures powered by renewable energy sources. This involves the development of a building that not only incorporates advanced features but also aligns with contemporary goals for sustainable architecture. Therefore, this study conducted two types of conceptual building mass [34]. A case study was conducted to model solar radiation energy absorption:

1. On imported conceptual mass, from built environmental using Rhino software, where they were further processed for optimisation using Rhino's plug-in applications.
2. On a newly designed building using 'Autodesk Revit architectural drawing template', where an initial representation of energy modelling was created using randomly selected construction materials. Subsequently, for further exploration

and multiple design iterations, energy use optimisation BIM engineering data (gbXML) files were automatically exported to cloud-based Green Buildings Studio (GBS) and ‘Insight’.

1.12 Enabling Technology in Modern Buildings

‘Enabling technology’ refers to tools or methods that facilitate support. For example, a building management system (BMS) automates energy efficiency and occupant comfort through a unified digital interface. This system oversees and manages electrical and mechanical services, including heating, ventilation and air conditioning (HVAC) and lighting systems. Additionally, it can integrate functions such as security, access control, elevators and safety mechanisms, depending on the particular use and setup of the BMS. A BMS is also recognised as a building automation system (BAS), building management and control system (BMCS) [35], or building energy management system (BEMS). It can be used as a comprehensive solution or as an enhancement for existing systems. Some BMS applications use open communication protocols and are designed for web-based integration with systems from various vendors.

1.12.1 Enabling Technologies When Using Smart Devices and Smart Building Materials

In a smart building, every piece of equipment is considered wise or intelligent according to its application. For example:

1. Building materials react proportionally to the weather of the day using smart algorithms with less interaction from the occupants to minimise energy consumption and maximise the occupants’ comfort.
2. Fridges, cooking ovens and microwaves can synchronise to function accordingly.
3. Fans, indoor temperature sensors and outdoor temperature sensors can synchronise to function accordingly.
4. CCTV cameras, security alarms and internal ceiling lighting can be synchronised to function accordingly.
5. Smart meter, washing machine, dryer and socket outlets can synchronise to function according to the design and user preference programmed algorithm.

6. The bathroom mirror, toilet, bath and eyeglasses can synchronise to function according to the occupant's health daily so that cancer can be detected at an early stage.
7. Wi-Fi, 5G and 6G can create smart local networks with devices that use emerging technologies.

1.13 Enhancing Environmental Quality in Smart Buildings

A sustainable, robust and resilient building can sustain and maintain its functionalities during natural conditions. Resilient building design is the practice of designing buildings that can withstand and quickly recover from various hazards, including natural disasters such as earthquakes, hurricanes and floods, as well as human-made threats such as terrorist attacks and cyberattacks. It involves the use of robust materials, advanced engineering techniques and intelligent design to create structures that can resist damage and maintain functionality even under adverse conditions.

Indoor air quality in sustainable building design is crucial for preventing the release of harmful particles, which can become concentrated because of thermal conditions, humidity and various substances that may adversely affect the indoor environment and the health of occupants. Inadequate ventilation significantly increases indoor pollutant levels by failing to introduce sufficient outdoor air to dilute these emissions [36]. Elevated temperatures and humidity can exacerbate the presence of airborne pollutants within the building. Hence, it is essential to recognise that building regulations address performance-based ventilation standards and establish maximum allowable concentrations for nitrogen dioxide, CO₂ and total volatile organic compounds (VOC) within indoor environments. To enhance indoor air quality (IAQ), it is necessary to implement heating systems designed to reduce particle exposure while ensuring continuous, adequate ventilation through passive stack methods. Optimising the use of extractor fans and windows can help remove indoor air contaminants. Hence, the following mitigation strategies are applied to a healthier building:

1. **Occupants' comfort:** Construction activities can threaten the IAQ of building spaces or rooms. Countermeasures should be implemented to protect the health of construction workers and the occupants of the building. This ensures that airborne particles from construction activities are isolated from the permanently installed

HVAC equipment, flushing out toxins before occupancy, ensuring absorptive materials are kept dry and that the facility is kept free from mould, and using construction materials low in harmful VOC.

2. **Outdoor and indoor air quality system:** Buildings release many harmful pollutants outdoors. Particulate matter is a hazardous pollutant by virtue of its tiny size, and microscopic particles can penetrate deep into the lungs and even the bloodstream. The health impacts of outdoor air pollution are represented in early deaths and costs associated with burning fuels, including gas, oil, biomass and traditional wood burning. Indoor environmental quality (IEQ) refers to the conditions within a building. The definition primarily focuses on air quality, but also encompasses access to daylight, views, pleasant acoustic conditions and occupant control systems for lighting and thermal comfort capabilities.
3. **Definition and performance of healthy buildings:** The World Health Organization (WHO) in its 1948 Constitution defined health as ‘a state of complete physical, mental, social wellbeing and not merely the absence of disease or infirmity’. This definition has been recently expanded to include resilience, which encompasses the ability to cope with health problems and the capacity to return to a state of equilibrium after facing health challenges.
4. **Minimised decarbonisation building:** Carbon emissions are the release of toxins that spread into the atmosphere. CO₂ is the most abundant fuel in terms of the quantity produced through the burning of fossil fuels. CO₂ emissions from human activities are also a major contributor to rising CO₂ levels. CO₂ emissions and other related greenhouse gases [37] are leading causes of climate change and global warming. Research on climate change indicates that over the last decade, average global temperatures have increased by 1.50°C [23] and are expected to continue rising. It is known that different greenhouse gases have different effects on Earth’s atmosphere.

Additionally, when improving the indoor environment, it is crucial to consider various types of effects. For instance, indoor non-ionising frequencies:

1. RF-EMFs (30 kHz to 433 MHz) are used in control system applications.
2. RF-EMF (900–1800 MHz) associated with mobile communication.
3. RF-EMF (2.4–6 GHz) on Wi-Fi connectivity.

Non-ionising frequencies lack sufficient energy to disrupt molecular structures or generate heat in human tissues; however, numerous scientific studies indicate that, despite this limitation, non-ionising frequencies can still cause substantial harm to both human and animal health, potentially resulting in DNA fragmentation. Smart buildings often incorporate a plethora of modern technologies that predominantly use excessive wireless RF signals [38, 39], contributing to their ‘smart’ functionality but also increasing radiation exposure to RF-EMF. This surge in electromagnetic fields results in heightened power density absorption, known as the whole-body average specific absorption rate (WSAR) [38, 40]. Moreover, electromagnetic energy is categorised into high and low energy levels; exposure to low-energy electromagnetic waves induces thermal effects, heating human tissues [40]. Conversely, the implications of exposure to low levels of RF energy remain a topic of ongoing debate.

1.14 Aim of the Research

Sustainable smart buildings increasingly prioritise reducing energy consumption, lowering CO₂ emissions and enhancing occupant comfort. This is achieved through innovative design, the use of energy-efficient materials, the integration of advanced technologies and the implementation of intelligent operational practices. The shift from conventional building designs to sustainable methods has become essential because of concerns over energy scarcity, climate change and the need for comfortable living environments. Consequently, sustainable buildings will likely set the benchmark for residential and commercial properties in the future. However, smart buildings face several challenges in meeting these objectives, including sustaining ongoing ‘green’ efforts, integrating various sensor networks, managing unforeseen expenses and tackling contentious comfort-related issues. This study seeks to address these obstacles by evaluating smart buildings through simulation techniques and analysing associated issues.

1.15 Research Approach

This thesis offers an in-depth exploration of sustainable smart buildings, encompassing the following key points:

1. **Structural stability:** The design of smart buildings must prioritise structural integrity, particularly during natural and man-made disasters. Conceptual simulations are required to verify that sustainability standards are fulfilled.
2. **Environmental sustainability:** Architectural design should emphasise environmental sustainability. Developing and planning smart buildings can effectively minimise energy consumption and limit pollution.
3. **Contextual simulation:** Smart building simulations within the built environment consider the neighbouring structures part of the building context. This contextualisation helps account for actual atmospheric conditions, including the shadowing effect from taller adjacent buildings during solar radiation absorption simulations process.
4. **Standalone simulation methodology:** This type of simulation is employed for newly designed structures without nearby buildings and may not yield precise estimations when compared with case studies. However, it remains a prevalent method used by many researchers focused on solar energy reduction in buildings.
5. **Numerous sustainable solution packages:** Existing energy packages can lead to savings in costs, energy use and time. A fundamental design principle for this project was to create buildings with future considerations in mind. Building services engineers play a crucial role in integrating features into designs that enhance sustainability while improving energy efficiency and minimising CO₂ emissions. Resilient building design consists of practices and strategic methodologies aimed at creating environmentally friendly structures capable of withstanding regional natural disasters. Thus, sustainable building materials are characterised as those that do not contribute directly to environmental pollution or rely on non-renewable resources.
6. **Occupant comfort considerations:** Addressing occupant comfort involves evaluating various sources and areas to meet sustainable building design requirements. Assessments may focus on reducing energy use and promoting circular economic practices through aspects such as electrical control wiring installation, sensor connections and operational methodologies within the building. In traditional methods of construction, electrical components and control wiring are typically routed to a central cabinet, which does not effectively lower installation costs. Alternatively, wireless installation eliminates physical wiring

but raises concerns about exposure to non-ionising RF-EMF radiation—a subject still debated scientifically, with inconclusive evidence regarding its effects.

7. **The incorporation of wireless devices:** Implementing densely populated wireless devices has generated unease among occupants despite the potential for significant energy savings associated with wireless and communication controls in sustainable buildings; these benefits do not alleviate concerns related to residents' health impacts. A core tenet of sustainable building design is ensuring occupant comfort; therefore, if worries persist among residents, genuine comfort and sustainability concerning their wellbeing remain unachieved.

1.16 Vision and Scope of the Research

The vision and the scope of this thesis is to model, simulate and analyse the gaps in our understanding of smart buildings and to develop measures to mitigate their drawbacks. Energy-efficient buildings highlight findings from sustainable building design research indicating that conventional structures consume excessive energy and emit substantial CO₂, adversely affecting overall building performance. This detrimental effect has prompted stakeholders to pursue sustainable construction practices on a global scale and to establish clear objectives for these initiatives.

Additionally, this shift has encouraged architects, designers, property owners, contractors and builders to take on substantial responsibilities in developing sustainable buildings by strategically planning, designing and choosing energy-efficient materials. This includes detailed assessments of components such as insulation levels, shading specifications, window efficiency, wall integrity, appliance functionality and the longevity of materials. Implementing these strategies has contributed to a decrease in environmental impact while fostering social cohesion, thereby supporting ongoing economic growth without inflicting severe damage on the surrounding ecosystem.

1.17 Drawbacks of Smart Buildings, Challenges and Mitigation Methods

Smart buildings have many drawbacks, but the most prominent are the need for constant internet connection, reliable networks and intelligent technology like BIoT sensor network diversity, and interoperability issues. These buildings need a constant power

supply to keep their smartness—lack of those resources maximises the issue. In addition, challenges in smart building include cybersecurity, initial construction or renovation costs, confusion and familiarisation with modern technologies. Cybersecurity has traditionally posed the primary challenge for smart buildings, with concerns revolving around security, privacy, integrity and data availability. The proliferation of internet-connected components escalates the associated risks, perpetually creating hurdles for the industry. The level of trust that occupants of the buildings have in entities handling their data and BIoT services will increasingly impede their willingness to share information. Companies now grapple with heightened physical security risks from merging digital and physical threats. Monitoring open source, deep and dark web activities for early threat detection lags. Corporate governance is facing pressure due to social, economic, and geopolitical upheavals that adversely impact the cybersecurity risks associated with smart buildings [41]. Moreover, sustainable building design suffers from several issues of unsustainability, as follows:

1. It is not easy to meet its objectives [24] and goals regarding clean energy, adequate and continuous uninterrupted supply.
2. Unsustainable design practice and lacks a clear, general governing mathematical model.
3. Rooftop space is limited for an adequate number of renewable energy installations.
4. The renewable energy market is inconsistent with continuous customer demand.

Success depends on consumers' ability to meet their needs through cost-competitive products. The involvement of governments and building regulators is necessary to meet these demands. Thus, government-responsible authorities and agents are encouraged to contribute significantly by implementing sustainable building objectives and strengthening their reforms. There is a need to obtain adequate support from the community to approach sustainable building reforms, which could be achieved by raising awareness among the community and providing solutions to the questions raised by community members [42].

In recent decades, sustainable building design has attracted rapid growth. However, there are a few challenges in sustainable building designs:

1. Resistance to rapid change from conventional building practice.
2. Recently designed smart, sustainable buildings still suffer from sensor network diversity [43].
3. The green/smart building accreditation organization such as GBCA has not provided clear guides or regulations defining the classification of smart, sustainable building levels.
4. Although sustainable designs are continuously updated with new technology, they still lose part of their sustainability and ‘smartness’ during full or partial occurrences of internal electrical faults.

1.18 Research Methodology

The thesis begins by conducting a review of the literature on both conventional and sustainable building construction practices, aiming to identify gaps. The thesis employs various methods to thoroughly examine conceptual mass buildings for efficient energy modelling, using prototyping as an initial method. A crucial aspect of this process involves understanding environmental characteristics and potential building locations; therefore, two case study approaches are used. The first approach entailed a ‘built-in environment’, in which a built-in segment of Melbourne, specifically an area spanning less than one kilometre, was imported into simulation software using CadMapper. Subsequently, current meteorological data from the nearest weather station in Melbourne were loaded into the simulation software to ensure an accurate ambient temperature, pressure, humidity and wind speeds. These played an optimised role during the simulation phase. The second case study method focused on standalone building simulations that considered new constructions without contextual influences, disregarding factors such as solar radiation and shading from surrounding structures. Energy modelling for buildings was developed from these case studies. Additionally, renewable energy sources like solar panels and wind turbines were simulated utilising several types of software. Moreover, theoretically, the interoperability-enabling technologies within smart buildings were examined in detail. Innovative algorithm technologies aimed at mitigating drawbacks associated with smart buildings were also formulated using mathematical methods. Furthermore, IAQ, as well as wall and floor conditions, were simulated with IAQ software to assess carbon deposition levels and ensure the provision of clean, fresh air.

An indoor experimental room representing a commercial office was set up to address RF-DC energy harvesting and to evaluate occupants' health concerns from RF-EMF radiation power density exposure. This office was designed to meet actual specifications while incorporating cutting-edge technology available today. The office structure underwent simulations where power density and electric field data were gathered through a spectrum analyser and RF field meter. The resulting data were analysed against established standards. Using this analysis, a power density monitoring circuit was developed.

1.19 Contribution to Knowledge

This thesis offers several distinctive insights and contributes to the literature on sustainable smart buildings as follows:

1. The simulation of solar radiation for energy modelling in smart buildings has been conducted over recent decades with the goal of optimising building performance. However, these simulations often focus on individual buildings without accounting for the solar radiation and shading effects from neighbouring structures. This oversight represents a gap identified in the current research literature. To achieve accurate estimations of annual solar energy for buildings, this study conceptually optimises energy-efficient designs through two case studies. The first case study employs 'built-in environment conceptual buildings' that are integrated into simulation software, enabling simultaneous simulations of conceptual mass building contexts alongside actual buildings where solar irradiation assessments occur. Conversely, the second case study examines a new building isolated from contextual influences, disregarding surrounding solar radiation and shading impacts.
2. Smart buildings maintain their intelligent functionality only with a continuous electricity supply; they lose this capability when power is interrupted or partly supplied because of issues like Residual RCD trips caused by nuisance or legitimate earth faults. This thesis highlights the challenges faced by smart buildings during RCD trips, and proposes solutions. A circuit was modelled to remotely monitor, diagnose and rectify nuisance failures, which minimised downtime and prevented further loss of products. This previously constituted a gap in the literature concerning smart buildings, which the thesis now resolves.

3. The goals of smart buildings include resource minimisation and enhanced energy efficiency; this study attempts to address these objectives within selected cases by modifying traditional bulk wiring methods. This approach represents one of the few strategies available for improving economic efficiency related to electrical devices in construction or innovation projects.
4. Smart buildings integrate smart BIoT devices along with wireless communication and control systems to enhance intelligence beyond mere energy-efficient design or material reduction. These technologies provide occupants with rapid access to high-bandwidth services that foster comfortable living conditions. Additionally, indoor wireless signal propagation is converted into RF-DC for wireless energy transfer (WET) harvesting purposes. Numerous researchers have explored WET concepts over the past decades for applications such as wireless charging and powering low-energy BIoT devices; however, most investigations rely on transmitter-receiver coils for WET. In contrast, this study developed a passive circuit that effectively harnesses indoor radiating RF energy. The resulting power density estimates are transformed into practical applications, leading to an emergency charging solution suitable for environments abundant in RF devices. This research thus adds value to the discourse surrounding indoor energy harvesting.
5. A key aim of sustainable building design is to ensure an environmentally friendly space conducive to occupant health, allowing individuals who live or work within these structures maximum comfort levels. Striving towards this objective presents various challenges, leading some occupants to experience discomfort. Some of these issues lie beyond the scope of this research. However, the study seeks to tackle several concerns through proposed theoretical contributions and practical solutions. Conventional construction materials like gas heating systems, paints and adhesive polymers emit VOCs, creating unpleasant conditions that may pose health risks for occupants—a concern already noted in existing literature but further examined here with additional proposals aimed at addressing VOC issues comprehensively through exploration of environmental IAQ. Furthermore, discomfort among smart building occupants may also stem from non-ionising radiation produced by indoor wireless power density—a topic still under debate despite considerable investigation; this further underscores another gap in the existing literature reviews. To investigate indoor wireless power radiation patterns

more thoroughly, multiple antennas were designed using specialised software applications incorporating both sequential and simultaneous methodologies during simulations involving distance, phase shifts and amplitude variations as input parameters. Results indicated that simultaneous simulations yielded higher metrics than sequential ones, largely because data derived from multiple transmissions were not averaged out across single transmitting devices; additionally, an indoor monitoring device was developed capable of displaying cumulative indoor power density readings.

In brief, smart buildings are designed not only for reduced energy consumption but also to lower ongoing operational costs while efficiently catering to occupant preferences with minimal human intervention, thereby enhancing overall intelligence across all aspects associated with smart architecture.

1.20 Summary of Research Contribution

Many studies over recent decades has focused on simulations of solar radiation energy absorption for smart buildings, aiming to develop energy-efficient and optimised structures. However, these simulations often focus on individual buildings, failing to account for solar radiation and shading effect from neighbouring structures. This limitation reveals a significant gap, which is highlighted in the literature review. To accurately assess solar radiation for modelling a building's energy consumption during simulations, it is essential to factor in the solar radiation and shading impacts from adjacent buildings, because these elements significantly influence the simulation outcomes. In light of this, this thesis conducted a solar radiation simulation encompassing two case studies. The first case study involved simulating solar radiation for a building while taking into account its 'built-in environment', which includes surrounding structures. Conversely, the second case study examined a new building without contextual influences, disregarding the solar irradiation and shading effects from its surroundings. A comparative analysis of both studies revealed that findings from the first case study indicated lower values because of contextual influences.

The design of smart buildings is driven by specific objectives, where this thesis attempted the achievement of several key aims:

1. **Reduction of annual energy consumption:** The primary objective is to minimise annual energy use and thereby lessen the ecological footprint associated with buildings.
2. **Enhancement of operational efficiency:** The exploration of reduced ongoing operational costs seeks to improve productivity and ensure occupant comfort.
3. **Sustainability through resource minimisation:** Utilising recyclable materials aims to decrease resource consumption, ensuring sufficient resources remain available for future generations.
4. **Integration of conventional practices with smart design:** A detailed discussion on adapting traditional building practices, particularly regarding electrical wiring, to align with smart building design principles is presented alongside developed mitigation methods.
5. **Energy harvesting potential from RF-DC:** An analysis of the potential for harvesting energy from RF-DC includes modelling a passive circuit designed to reuse indoor radiating RF energy.
6. **Addressing IAQ concerns:** Traditional construction materials such as gas heating systems, paints and polymer adhesives release VOCs that can negatively affect occupants' health. This study investigates environmental IAQ impacts and proposes solutions for managing indoor VOC levels.
7. **Assessment of indoor wireless power radiation:** This thesis evaluates indoor wireless power radiation propagation through conceptual designs of multiple antennas using software applications. Two methodologies—sequential and simultaneous simulations—were employed in this process. Results indicate that exposure levels remained within RF-EMF guide limits when simulated at a distance; however, adding a cellular antenna near human proximity resulted in exceeding these limits. Additionally, an indoor power density monitoring meter circuit was developed.

To sum, this thesis strives to contrast conventional and sustainable building design practices while aiming to enhance both energy efficiency and occupant comfort.

1.21 Thesis Structure

Chapter 2 provides a comprehensive literature review comparing conventional buildings with sustainable smart buildings. It briefly discusses the origins and evolution of smart

buildings, including how they acquired their designated name. Additionally, it explores the benefits of utilising various types of simulation software for building's solar energy modelling. The chapter also delves into the interoperability of BIM engineering data in detail. Furthermore, it touches upon the various methods and configurations used in building automation and building automation control systems (BACS). Consequently, the subjects addressed in this chapter serve as a foundation for constructing this thesis project.

Chapter 3 outlines the methodological framework of the thesis in its initial sections, subsequently shifting focus to an evaluation of the benefits of smart buildings compared with traditional architectural designs. It discusses the increasing necessity of smart buildings and their rapid global proliferation in response to escalating market demands. The chapter also examines the limitations associated with smart buildings and proposes several solutions:

1. The first case study presented that models conceptually optimised energy-efficient buildings. In this initial case study, a conceptual mass of a built-in environment, less than 1 km², is imported into simulation software. The contexts of these conceptual mass buildings are simulated concurrently with an actual building, incorporating solar radiation simulations to accurately reflect real ambient conditions. This approach ensures that the simulation process aligns with the atmospheric characteristics of surrounding structures, thereby affecting solar radiation on the modelled building. The simulation yields a minimised annual energy intensity optimum of 8,687.2 kWh/m² at a 70° orientation.
2. The second case study aims to explore the concept of achieving energy self-sufficiency and decarbonisation. This involves conceptually designing and modelling a building using alternative energy-efficient materials.
3. The third case study presents energy-efficient materials that are selected for simulation purposes, which occurs in two phases: a 'base run' and an 'alternative design run'. The outcomes from both phases are compared to determine which approach results in lower annual energy consumption. Notably, the alternative design demonstrates significant reductions in fuel use while showing a slight increase in electric energy consumption, indicating a transition towards greater reliance on electric energy sources. As a consequence, an overall reduction of 68.9% was achieved.

In **Chapter 4**, seven renewable energy software applications are evaluated through five case study methodologies. The objective is to determine the optimal renewable energy capacity necessary for the annual energy consumption of commercial buildings. The outcomes from each software simulation are analysed according to their functionalities and purposes. For example:

1. **Autodesk Revit:** Used to estimate and enhance the generation of PV cells.
2. **SCAPS1D:** Employed to model the layer thickness and energy bandgap of PV cells.
3. **DesignBuilder:** Used to assess the contribution percentage of a new building's PV cells to its annual energy consumption.
4. **Rhino, Grasshopper and Ladybug:** Implemented for simulating detailed hourly energy generation from PV cells over a year within a built environment.
5. **PVsys7:** Applied to analyse the shading impacts on PV cells.
6. **Setfos:** Focuses on measuring the absorptance, transmittance and reflectance characteristics of PV cell layers.
7. **Ashes:** Used for wind turbine arrays to estimate optimised power output while also managing cooling beneath the PV cell array.

Furthermore, a mathematical model has been developed to calculate the required amount of renewable energy installations for various buildings, thereby minimising reliance on estimations that could lead to inefficient expenditure. The numerical value findings from the chosen case studies are summarised as follows:

1. **Case 1:** This analysis provided a conceptual estimation of annual energy production. With 36 PV cells in one panel receiving an average of 8 hours of sunlight daily, it was projected that a single panel would generate approximately 7,895.096 kWh annually.
2. **Case 2:** If 12 panels were installed on the roof, this would total approximately 9,474.152 kWh, contributing around 7.01% of the building's overall annual energy use.
3. **Case 3:** Demonstrated that newly constructed buildings benefit significantly from solar energy; one PV cell accounts for about 1.3% of total annual energy needs, while 63 panels together provide around 85%.

4. **Case 4:** Estimated significant hourly energy production using assumptions that 63 PV cells receive sunlight for roughly 8 hours daily, leading to an estimated total average output of about 81,855.9 kWh.
5. **Case 5:** Involved simulating wind turbine maximum power point tracking (MPPT) using Coefficient of Performance (CP), Turbine Rated Capacity (TSR) and Overall Turbine Rating (OTR). The estimated annual power contribution from the wind turbine was approximately 1,639.65 kW.

Chapter 5 examines the application of contemporary technology in smart buildings. The integration of emerging wireless smart devices and artificial intelligence (AI) enhances building intelligence. Various types of facilities, including educational institutions, commercial spaces, manufacturing plants and healthcare establishments, use IoT and AI technologies to perform tasks more swiftly, reliably and securely. Buildings equipped with IoT and AI systems have a positive impact on the lives of their occupants through their sensory and responsive capabilities.

The chapter discusses a significant issue in smart buildings: the inability to maintain power supply during a Residual Current Device (RCD) trip caused by nuisance or genuine faults. A solution is presented involving a model that can be remotely monitored, diagnose issues and recover from nuisance failures. This approach effectively reduces the duration of nuisance trips, thereby minimising downtime.

In addition, this study's attempt to achieve the objectives of resource minimisation and energy maximisation within smart buildings involves analysing selected case studies. This section modifies traditional bulk wiring methods to meet these goals. The modifications represent one of the few strategies aimed at enhancing the economic efficiency of electrical installations in buildings. Beyond its immediate economic advantages and energy-saving potential, this method also serves as an initiative for preserving construction materials for future generations.

In **Chapter 6**, the progress of indoor wireless technology, power density regulation and the concept of radiofrequency radiation energy harvesting are discussed and analysed. Smart buildings' indoor wireless technologies are among the fastest-growing technologies today. Buildings are equipped with sensor networks, including BIoTs, and wireless controls. In addition, newer technologies are practically experienced in

renovated buildings in the built environment. Furthermore, the chapter emphasises the importance of the current indoor wireless technology being replaced by short-wave, higher energy. This enables more efficient communication with building AI, healthcare facilities and emergency services. Moreover, this study assesses the indoor power density generated by various wireless devices. To achieve a precise estimation, power density regulations from various standards are considered, and wireless energy is measured at six locations at Victoria University. In parallel, multiple indoor antennas are conceptually designed and modelled. Then, the energy from numerous indoor RF propagating waves is simulated using sequential and simultaneous methods. The estimated power density result is converted into meaningful, practical action DC energy. As a result, a passive charging circuit has been developed for use as an emergency charger in areas with dense RF device populations.

Chapter 7 presents the concept that sustainable smart buildings are necessary to comply with the principles of protection against indoor environment pollution and those of standard guide limits set by a regulatory body. Environmentally enhanced buildings offer their occupants comfort and a healthier lifestyle. This can be achieved by first providing clean air quality (AQ)—for instance, IAQ. A building with good IAQ benefits from low toxins and pollutants. IAQ ensures that absorptive materials are kept dry and that the building is free from mould, using construction materials with low levels of harmful VOC. Furthermore, smart buildings are connected and operated with numerous wireless devices, communications and controls, which increases the indoor electromagnetic field radiation that may cause occupants to raise concerns because of feelings of discomfort. To alleviate the occupants' concerns, this study conducts sequential and simultaneous software simulations by designing and modelling multiple antennas. The incident power density (IPD) results obtained from both simulations and measured values are analysed. Using the results, an indoor IPD monitoring circuit is developed and modelled.

Chapter 8 presents the key conclusions from the research. It outlines the development of smart buildings. This chapter summarises the primary components of the study, including the methodologies employed, the process of simulating solar energy in buildings, the integration of renewable energy sources, and the strategies implemented to enhance building efficiency and performance. Furthermore, it highlights various theoretical, conceptual and measurement approaches aimed at improving IEQ. The discussion also

encompasses occupant comfort and the building automation control methods applied in this context.

Chapter 2

Literature Review

2.1 Introduction

Smart buildings, often known as ‘sustainably designed building structures’, introduce involvement and integration of advanced electrical, electronic and electromechanical systems. These intelligent devices can detect and assist occupant activities and minimise excessive, unnecessary energy consumption. Additionally, these smart devices play a crucial role in monitoring the building’s security against both physical threats and cyber risks [44]. Moreover, smart building practice expands and complements classical building design by addressing issues related to economy, utility, durability and comfort. Hence, newer technologies are constantly being developed to complement current practices in creating greener structures [45]. The common objective is to ensure that the smart building is designed to minimise the overall impact of the building’s environment on human health and the natural environment by efficiently utilising all available energy resources. In addition, the goal is to protect occupants’ health and satisfy their comfort, which in turn leads to improved productivity, increases the reduction of waste and pollution and prevents environmental degradation [46], considering future generations’ resource use while meeting present needs. This chapter presents a comprehensive literature review of modern buildings in comparison with traditional building practices and materials, which are essential to sustainable building design.

2.2 Research Objectives

The purpose and goals of sustainable smart buildings are centred on reducing overall energy consumption, thereby minimising CO₂ emissions while maximising occupant comfort. This can be achieved through innovative or new building designs, the use of energy-efficient materials, the integration of advanced technologies and enhanced operational practices. Consequently, smart buildings are rapidly evolving alongside emerging technologies such as 5G, 6G and AI, making it essential to maintain continuous

intelligence. A significant challenge lies in effectively utilising these emerging technologies within smart buildings without compromising their consistent performance.

Therefore, this study identifies the study of ‘enabling technologies’ that can seamlessly integrate into smart buildings as one of its primary aims and objectives. Initially, the study aims to explore the objectives of smart buildings—specifically, what these objectives entail and how they are implemented during the design and innovation phases. Additionally, it will assess which goals have been achieved and which remain unmet. In the second phase, the study aims to identify research gaps and shortcomings by analysing and evaluating the objectives that remain to be fulfilled. In the final phase, it will examine these unfulfilled objectives more closely and employ simulation techniques, measurements and equations to address selected deficiencies.

2.2.1 Research Gaps and Scope

Sustainable smart buildings are currently considered the future of building for the next generation. Research on smart building is an ongoing project. Today’s smart buildings may not remain ‘smart’ in a few decades. For instance, today a building can reduce its annual energy consumption by 30% [47], but further research is required to achieve a reduction of 30% to 70% and beyond; additionally, improvements in performance and comfort are continually necessary. The World’s 2030 energy reduction expectation prescribed that countries should reduce fuel energy use by 50%. However, this could take longer than the forecasted years to achieve for residential buildings and maybe decade for commercial buildings. Hence, a more effective or alternative approach is necessary to achieve the recommended energy reduction.

The absorption of solar radiation in energy modelling of smart buildings has been continuously simulated over the last few decades to achieve more accurate energy reduction estimates [46]. However, these simulations are carried out with reference to a single building or a standalone building, without considering or giving much attention to the surrounding buildings’ solar reradiating and shadowing effects. This study identified this as a gap in the research. To obtain a precise estimation of annual solar radiation energy absorption on a mass of buildings’, it is crucial to consider the influence of surrounding building contexts.

The objective of sustainable building design is to incorporate recyclable materials that reduce current resource consumption, ensuring sufficient resources remain for future generations. To achieve this goal, smart buildings should differ from traditionally constructed buildings, particularly regarding their electrical systems and the number of devices installed during construction. Yet although the devices used in smart buildings are advanced, their quantity and wiring methods mirror those employed in traditional devices. Consequently, this research identifies a gap in the literature review database concerning the design practices of smart buildings, which still rely on traditional methods.

To comply with the name ‘smart’ it is essential that buildings use and implement the available sources optimally. Thus, smart buildings are increasingly equipped with wireless devices, presenting a significant opportunity for WET harvesting. Many researchers have studied and analysed the concept of WET and its practical application. For example, wireless charging can be used to power low-powered IoT devices [48]. However, many existing studies and practical applications rely on transmitter and receiver induction coils for WET, and most of them fail to capture the simultaneously radiating waves from multiple sources. Furthermore, the expense associated with building a transmitter surpasses that of using cables. This approach does not contribute to energy savings since the active components consume power. Consequently, this research highlights a gap in the literature on WET. It should be noted that excessively transmitted signals can be efficiently captured through a particular band-pass array design for each of the receiving devices. Hence, this study advocates for harnessing the free energy that propagates through the air for meaningful applications.

Furthermore, the smart building’s indoor data communication and automation control wiring is increasingly being installed through wireless means, allowing electrical components to feature a point of access that facilitates both control and monitoring wirelessly. However, this approach leads to increased exposure to indoor non-ionising radiofrequency electromagnetic fields (RF-EMF). The scientific research and discussion surrounding RF-EMF remains contentious and there is a need for more definitive proof regarding its effects. Considerable concern exists among occupants regarding contemporary structures equipped with wireless technologies, such as smart meters and various smart devices. Although sustainable buildings utilising wireless controls can achieve notable energy savings, overlooking or not attempting to mitigate the problems

associated with these effects can lead to occupant discomfort. A fundamental aspect of sustainable building design is ensuring occupant comfort; therefore, if concerns persist, true comfort cannot be achieved, and nor can the health-related sustainability objectives be fulfilled. This study identifies a gap in the literature on the comfort of occupants of smart buildings. Accordingly, this study conceptually simulates a sustainable building that addresses the outlined gaps, seeking especially to optimise energy reduction, occupants' comfort and resource mining practices.

2.2.2 Smart Buildings and Sustainable Development

Sustainable buildings, also known as 'environmentally friendly high-efficiency structures' [49], are fundamentally designed to integrate sustainable technological resources while aiming to preserve the surrounding natural environment [7] throughout their life-cycle [50]. The term 'intelligent building' emerged during the oil crisis of 1973–1974 [51], when both government bodies and private enterprises began exploring alternative methods of energy use to reduce unnecessary consumption. This situation prompted energy researchers to investigate ways to lower energy use in buildings. A review of the literature on sustainable building design reveals that conventional buildings waste significant amounts of energy and emit substantial amounts of CO₂, thereby adversely affecting overall performance [16]. These adverse outcomes have motivated stakeholders worldwide to adopt sustainable construction practices and set clear objectives for such initiatives. In this context, designers, architects, property owners, contractors and builders are encouraged to actively contribute to the development of sustainable structures by carefully planning, designing and selecting eco-friendly and energy-efficient materials [17, 19]. Specific factors to take into account involve evaluating insulation standards, shading techniques, window performance, wall efficiency, appliance functionality, and material longevity. The aim is to reduce environmental effects while promoting social unity that encourages sustained economic development without significantly damaging the eco-friendly environment.

Prioritising early-stage design decisions is crucial, because these choices significantly influence a building's long-term operational performance. Understanding a building's design alongside its operational methodologies can mitigate maintenance challenges while enhancing comfort, health standards and economic viability [52]. Moreover, occupants and owners play a crucial role in promoting sustainability by raising awareness

about sustainable design goals and communicating their preferences to manufacturers and communities, thereby driving influential changes in construction practices. Indeed, manufacturers are responding to regulatory requirements and customer-driven demands with products that align with sustainable principles. Many are recognising a competitive advantage through effective marketing of their eco-friendly offerings [53]. This trend also applies to designers, builders and developers whose practices have adapted in response to market demand for sustainable solutions. However, several sustainability challenges within building designs warrant attention in this study:

1. Difficulty in achieving clean energy objectives because of an inadequate supply of renewable energies.
2. Absence of a comprehensive governing mathematical model for sustainability practices.
3. Limited rooftop space available for sufficient renewable energy installations.
4. Discrepancy between the dynamics of the renewable energy market and consumer demand; success hinges upon affordability.
5. Resistance from traditional construction methods despite the recent rapid growth in sustainable architecture.
6. New smart buildings often grapple with variations in sensor networks.
7. Insufficient government guidelines defining classifications for smart, sustainable building standards.
8. Smart buildings' technological advancements—such as monitoring, controlling and information retrieval continuity—may not be sustained during electrical failures.

To address these issues effectively requires active involvement from government entities and regulatory bodies that focus on promoting sustainable building objectives through community engagement initiatives aimed at raising awareness and addressing local concerns. Fostering a collaborative approach among all stakeholders is crucial for advancing sustainable building practices effectively.

2.2.3 Sustainable Building Design

Energy efficiency and sustainable designs have emerged as primary concerns for both new and existing structures. These aspects have been at the forefront of priorities for

contemporary building developers and researchers since the 1970s [46]. The analysis of the correlation between BIM data and a data mining technology management system is essential for streamlining the workflow of smart building designers. This approach aims to enhance energy efficiency and promote the creation of sustainable buildings [54]. Hence, sustainable design principles in construction are poised to improve building performance, boost energy efficiency, lower operational expenses and consequently attract investors focused on the green economy [55]. Any aspect of building sustainability presents a significant global challenge, particularly for designers of smart buildings and urban planners, as well as policymakers [13]. Sustainable construction extends beyond the way a structure is built and its resilience against environmental factors; it also encompasses reducing energy consumption within the buildings themselves. This approach aims to reduce or eliminate excessive energy use in buildings worldwide. Hence, sustainable building design covers and addresses a range of objectives. One recently published paper outlined environmental, economic, social, and cultural benefits in addition to buildings' technological, institutional, policy, health and safety benefits [56]. However, the author of this paper overlooked the crucial fact that energy conservation for future generations is a key element of sustainable building design.

2.3 Building Information Interoperability

BIM is essential for intelligent structures, as it requires a strong integration of building systems, particularly aimed at energy efficiency. Employing design process modelling, visualisation tools, material assessments and collaborative teamwork all play a crucial role in creating sustainable, smart buildings. In this way, it is possible to develop high-performing smart structures that reduce energy use while enhancing individuals' health, quality of life and overall comfort [14].

To achieve the goal of sustainable building design, one of the most valuable tools widely adopted by architects is the interoperable capabilities of BIM [13]. As BIM gains traction, there is a pressing demand in the industry for simulating and modelling smart construction utilising BIM technology. However, existing software simulation applications for smart building construction offer specified functionalities, and lack the necessary intelligence [15] to make significant changes. This necessitates the enhancement or development of new construction simulation programs to effectively address the time management challenges associated with BIM interoperability [14]. Facility engineers, managers and

building designers are growing increasingly apprehensive about the time and labour demands associated with modelling and simulating the energy efficient building (EEB) process. For this reason, there is a growing focus on enhancing the energy efficiency modelling procedure to create cost-effective digital twin software tools [14, 17] that lead to practical solutions. This proves that conducting simulations, modelling and analysis before deciding to construct the project is essential for attaining the optimal goal of energy efficiency. A recently published paper presented an architectural design of a villa using a case study in which the architectural design BIM was interoperably modelled among experts by transferring and sharing engineering data [58]. The author of this paper describes BIM as an efficient tool that limits the ‘distinct inefficiency of the traditional methods’. However, the author also outlined the lack of BIM interoperability between different pieces of software.

2.4 Smart Buildings and Structural Design Stability

Building stability serves as a fundamental guideline applicable to all types of structures, ranging from traditional buildings to smart constructions; its relevance extends across various sizes. The construction of smart buildings is required to adhere to the National Building Code (NBC). For instance, in Australia, the Building Code Australia (BCA) systematically governs building standards, with a strong focus on structural stability. The concept of building stability is defined with reference to the forces exerted on a structure from multiple directions, which can be categorised as lateral, spire and vertical forces [57]. The extent to which a building withstands external forces is determined by its response to those influences. Stability is an aspect that applies broadly, not just to smart buildings; however, these structures need to maintain both energy efficiency and structural integrity. This study serves as a preliminary exploration of building stability, aimed at illustrating its significance in the design and modelling of smart buildings.

2.5 Strategic Management in the Construction of Smart Buildings

Strategic management in building construction refers to a methodical approach that addresses the significant [58] and growing duty of general management in positioning construction companies within their environment to ensure enduring success and reduce the risk of unexpected challenges. This facet of management focuses on selecting a

strategy and outlining how it will be executed. It can be divided into three primary components:

1. **Strategic analysis:** This involves assessing the company's current strategic position.
2. **Strategic planning:** This element centres on formulating how the chosen strategy will be enacted.
3. **Strategic implementation:** This is related to organising or managing the execution of the selected strategy.

In addition, there are recurring themes in defining strategy that pertain to the methods employed to achieve specific outcomes, emphasising goal attainment. Strategic management serves as a framework for guiding decisions regarding project-related behaviours.

2.6 Passive Building Materials

Passive design refers to an approach that aligns with the local climate to ensure a comfortable indoor temperature [59]. Effective passive design can minimise or even eliminate the need for supplementary heating or cooling, depending on the geographic area, and often requires active participation from occupants to function optimally. Buildings designed with passive principles can provide long-term thermal comfort [60], lower energy costs and decreased greenhouse gas emissions.

Elements of passive design—such as building orientation, thermal mass and insulation—work in tandem to use natural heating and cooling sources while mitigating unnecessary heat gain or loss. Implementing passive design strategies is crucial when constructing a new building or enhancing an existing structure for higher efficiency. Passively designed and modelled buildings adhere to a set of design principles established by climate specialists. These principles focus on maximising thermal comfort for occupants while enhancing energy efficiency. This approach incorporates elements such as insulation, artificial lighting, window and door configurations, and systems for recovering heat through ventilation.

2.7 Fire and Smoke Protection

Fire and smoke protection are critical elements in the design of buildings intended for specific purposes. Ensuring fire and smoke safety is vital for the protection of life and property [61]. A minor fire can escalate rapidly, potentially engulfing adjacent areas of a building within seconds and leading to severe repercussions such as property damage, injuries or even fatalities. Structures that incorporate fire and smoke detection systems can significantly mitigate damage to both the building itself and its contents during a fire event. These systems also enhance the chances of occupants safely exiting without harm during emergencies.

Fire protection measures encompass a range of systems, including fire suppression mechanisms, smoke detectors and flame-retardant materials. Emergency warning intercom systems (EWIS) and fire sprinkler systems have been developed to meet safety requirements. In Australia, the installation of fire and smoke detection devices should adhere to current Australian standards, with independent certifiers overseeing their commissioning upon completion. Furthermore, passive fire-protecting polymeric materials protection involves using fire-rated materials installed to reduce the flammability of building components in the event of a fire incident. This category includes elements such as fire doors, emergency exits, fire shutters and flame-resistant windows.

In addition, active fire protection and emergency evacuation protection involves components within a building that respond when a fire is detected. Examples include sprinkler systems and other suppression technologies designed to combat fires actively. Advanced active devices for detecting smoke and flames can identify early warning signs, triggering alarms and activation mechanisms; these technologies aim to minimise damage caused by fires within buildings.

2.8 Virtual Energy Simulation of Smart Buildings

Simulations of buildings' energy use, particularly regarding smart building technology, were initiated by the US Department of Energy (DOE) in collaboration with various industries and academic institutions following the onset of the oil crisis in 1973–1974. This crisis led to an energy deficit in the US, resulting in substantial adverse impacts on

the national economy. However, the simulations conducted during this period primarily focused on managing room temperature rather than broader energy concerns. After 1990, there was a swift evolution of PC-based simulation software applications, which advanced to include graphical user interfaces that greatly enhanced the efficiency and speed of simulations compared with traditional methods [62].

‘Energy sustainability’ refers to the ability to fulfil the energy needs of current generations while ensuring that future generations can also meet their own needs. However, specific smart construction initiatives do not focus on retrofitting existing structures. While the principles of smart construction can be effectively applied to both retrofit projects and new builds. Smart buildings demonstrate considerable advantages over traditional buildings; a 2009 report from the US General Services Administration indicated that sustainably designed buildings had lower operational costs and superior energy performance. Occupants also expressed greater satisfaction with these buildings than those in typical conventional commercial structures. In summary, traditional buildings are responsible for excessive energy waste and substantial CO₂ emissions, which negatively affect occupants’ quality of life and lead to increased expenses [63]. Hence, it is crucial to transition from conventional designs to modern ones.

2.9 Trends in Buildings’ Energy Consumption

The US building sector accounts for 30–40% of annual energy use [66]. As shown in Figure 2-1, heating space alone accounts for 32% of this. It is necessary to mitigate high energy use by utilising energy-efficient construction materials. For instance, constructing the outer walls of smart buildings with steel studs while utilising energy-efficient techniques that adhere to international building standards can result in a 27% improvement in energy efficiency.

Other energy savings can be realised through the implementation of a thermal wall insulation system that evaluates R-values; a higher R-value indicates reduced heat flow, whereas a lower R-value suggests more effective continuous thermal insulation [64]. The implementation of steel exterior studs has resulted in significant improvements in temperature regulation and energy efficiency in buildings. By reducing thermal bridging through these studs, the effectiveness of insulation is enhanced, resulting in moderated

temperatures within the wall cavity. This also contributes to a reduction in condensation inside the wall and decreases the demand for heating and cooling [64].

The efficiency of smart buildings increases if the initial design model aligns with the objectives of an eco-charrette [65]. An eco-charrette, often referred to as ‘the kick-off meeting’, is a collaborative brainstorming and team-building session focused on establishing sustainability objectives for a smart building. This gathering includes participants occupying various roles, such as the design team members, owner, architect, civil engineer, mechanical engineer, landscape designer, general contractor, maintenance personnel, tenants, neighbouring residents and relevant officials. The primary goal is to share insights and suggestions that will enhance the building’s design and functionality [65], which leads to an effective, high-performance building.

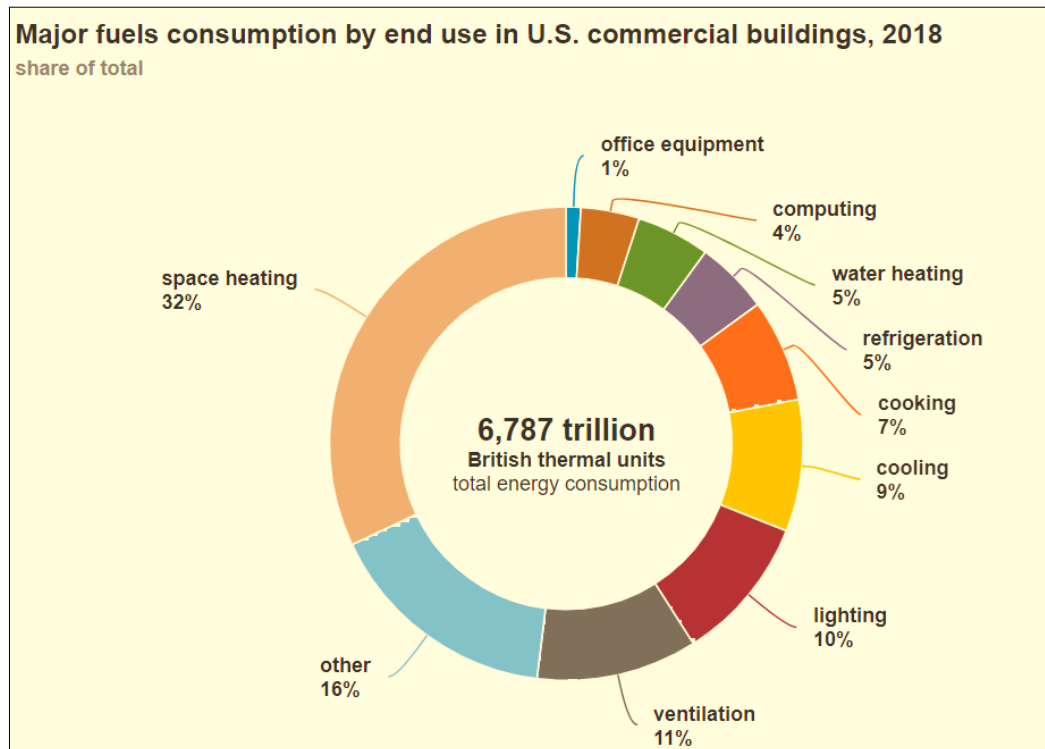


Figure 2-1. US Energy Information Administration infographic released in 2018

Source: <https://www.eia.gov/energyexplained/use-of-energy/commercial-buildings.php>

2.10 Energy Optimisation Trends in Buildings

Conceptual simulation packages, such as that of the American Society of Heating, Refrigerating and Airconditioning Engineers (ASHRAE), demonstrate a significant energy reduction, particularly in the building’s solar radiation energy simulation, in fuel

electricity and life span energy consumption. A recent study shows that the use of optimisation reduced energy by approximately 30–60% [66-68]. Furthermore, efficiently optimised wind turbines and solar panels have also shown a significant increase in clean energy. A research paper focused on wind turbine energy optimisation achieves a considerable boost. The optimisation was attempted using mathematical equations and conceptual simulations. The basic potential energy of the wind turbine was mathematically optimised by considering the three main proven techniques: power coefficient (C_p), tip speed ratio (TSR), and optimum torque control (OTC) [69, 70]. Similarly, the basic efficiency of solar panel cells was optimised using the conceptual sunlight intensity tracking method, where the sun's altitude and azimuth angle direction are constantly tracked to obtain maximum intensity [73] throughout the day. Additionally, the integration of IoT and smart grids contributes significantly to energy reductions.

2.10.1 Building Modelling and Integrating with Renewables

Renewable energy sources contribute to sustainable energy efficiency in buildings. They help to address the major global issue of CO₂ emissions, which have increased by 25–30% over the last century. This increase has led climate specialists to express significant concern regarding both the volume and pace of CO₂ changes in the atmosphere and, consequently, the carbon content found in biomass [71]. The existing literature on green energy, which considers post-occupancy energy consumption, has yet to reach a consensus on the efficiency of green energy. Discussions about research findings related to dry and cool simulations continue to take place. There is persistent contention over the acceptance of specific geographic and atmospheric concentrations for hot and dry climates. For instance, the outcomes from the Leadership in Energy and Environmental Design (LEED)-based smart building simulation carried out in Arizona have proven to be unsatisfactory [72]. However, modelling almost the entire building structure for optimal energy efficiency and developing the ideal EEB necessitates using a robust computer-aided simulation approach to green energy. Hence, the process involves several methodological approaches, including accounting for solar thermal mass for economic daylight savings, utilising various renewable energy sources and implementing natural ventilation techniques.

2.10.1.1 Solar Skin Buildings in Melbourne, Australia

Perovskites encompass a diverse range of crystalline materials with the chemical structure $A_2 + B_4 + X_{2-3}$. A few of these materials are semiconductors that exhibit significant light absorption within the visible spectrum, rendering them particularly appealing for use in the harvesting of solar energy. In contrast to silicon solar cells, the perovskite active layer in solar cell devices can be produced using solution-phase chemical techniques, which substantially lowers both the energy requirements and costs associated with manufacturing the devices. Over the past 10 years, device efficiencies have advanced swiftly, achieving 25.2% for single-junction solar cells and 29.1% for perovskite-silicon tandem cells. Figure 2-2 shows Australia's first office solar skin building, which is expected to be constructed soon. The entire building will be covered with 1,182 Perovskite solar panels, known as 'solar skin'. On completion, the building will produce 50% more than the basic solar panel installed in residential areas and will eliminate 70% of building's carbon emissions a year. Moreover, it is expected to generate more than its annual consumed capacity and approach carbon neutrality. Similarly, Australian property investor and developer Cbus Property has announced its intention to cover a \$1 billion commercial office tower currently under construction in Melbourne's central business district with a 'solar skin'. The design, which is created by the architectural firm Bates Smart, features around 60,000 square metres of office space spread across 48 floors. The exterior window will be adorned with translucent vertical glass PV panels. This solar skin technology is modelled to facilitate the generation of 20% of the power required for the building's core operations.



Figure 2-2. A modern building's entire exterior covered with solar panel skin

Source: <https://www.theguardian.com/environment/2022/jun/05/tower-of-power-new-office-building-to-be-fully-clad-in-solar-panels-in-australian-first>.

2.10.2 Grid Integration with Renewable Energies

A smart grid is an electricity network that integrates sophisticated digital, analogue and other modern technologies to effectively monitor, control, secure and intelligently manage the distribution of electricity. The infrastructure of a smart grid encompasses various associated technologies, including smart meters, energy storage systems, human-machine interfaces (HMI) and dynamic demand management systems.

Renewable energy is produced from buildings that connect with a smart grid through advanced HMI and computer-controlled software systems, enabling energy consumption to be effectively and efficiently managed. The smart grid plays a significant role, especially in dynamic load response, load prioritising, peak load demand configuration and economic market integration with renewable energy suppliers [73]. However, higher penetration of renewable energy into the grid must be considered, because it can cause a power imbalance in the entire grid connection network. A recently published research paper shows that more than 30% of renewable energy penetration can cause severe disturbances, resulting in shutdowns. Effective mitigation has therefore been developed by many researchers in parallel. For example, a journal paper published in 2022 developed a method that uses several inertial variations [74].

2.11 Smart Devices Connected to Modern Buildings

Devices that are connected to buildings, also known as BIoT, are implemented to enhance building functionality, improving occupants' activities, productivity, energy reduction and comfort. Modern, freshly constructed and innovative buildings that are connected with BIoTs have shown significant performance improvements over conventional buildings. On the contrary, building owners and operators are concerned that it is difficult for buildings to maintain their proper functionality because of increasing energy consumption, rising operational and maintenance costs, and shrinking budgets.

To address these concerns, building owners and operators can consider the BIoT's [33] role in innovating their buildings into smart and sustainable buildings. The integration of BIoT, sensors and cloud-based building automation has demonstrated the potential to decrease energy consumption while also lowering operational and maintenance expenses. For example, the building's security system network (BSSN) is one of the leading BIoT

networks that effectively contributes to the smart building's goals. In addition, the implementation of BIoT networks not only physically secures the buildings using surveillance cameras and motion detector sensors, but also significantly assists in securing them against various cyberattacks [75].

Figure 2-3 illustrates a 15 year comparison between IoT and non-IoT devices, showing that connected IoT devices have been significantly increasing, while non-connected devices have remained relatively constant over the entire 13-year range.

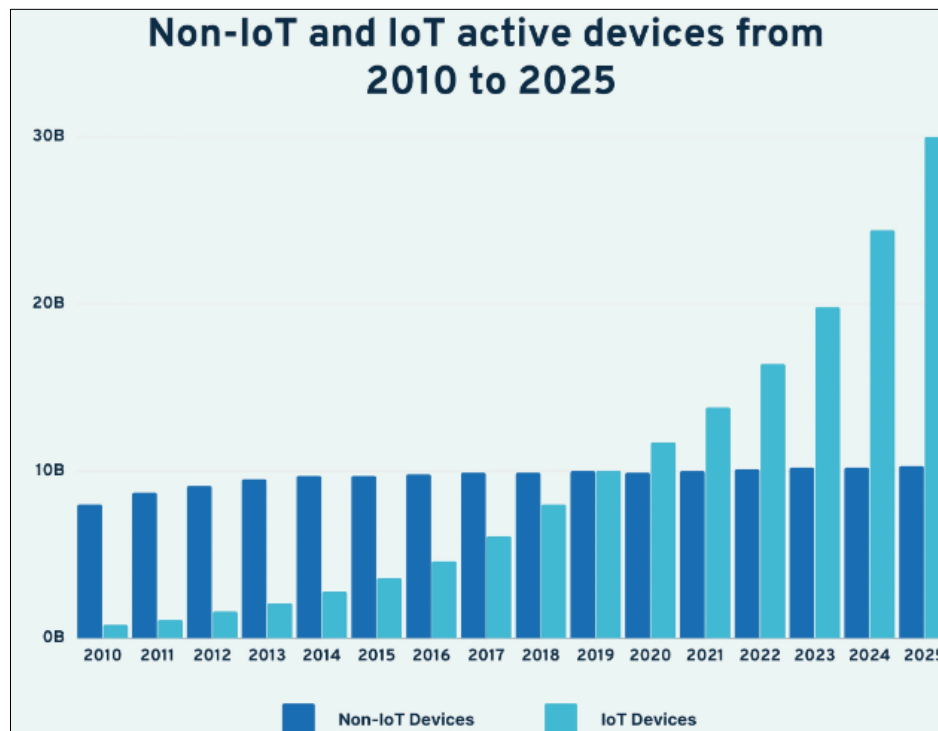


Figure 2-3. Growth in connected IoT devices versus non-connected devices globally

Source: https://www.researchgate.net/figure/Total-number-of-active-device-IoT-and-Non-IoT-connections-worldwide_fig3_351932619.

2.11.1 Smart Building Contribution to Circular Economy

The circular economy is a framework designed to perpetually reuse materials, thus minimising waste through recycling and avoiding disposals. This concept is termed 'circular' because it reflects the natural regenerative processes found in nature. Achieving this system involves maintaining products and materials in circulation through various methods, including maintenance, reuse, refurbishment, remanufacturing, recycling and composting. The circular economy addresses critical issues such as climate change,

biodiversity loss, waste management and pollution by separating economic activities from reliance on finite resources. Moreover, the circular economy addresses nonlinear economic integrity, and it is a shifting process to emerge from linear economic activities [76]. A recent paper describes the contribution of the circular economy to building sustainability as ‘increasing waste minimisation by keeping materials and resources in a closed loop’ [77] to approach substantial economic growth.

2.12 Smart Building Rating Accreditation

To mitigate the environmental impact associated with construction, it is essential to assess and quantify building performance while also investigating and comparing various alternative resources. Globally, a diverse array of rating systems exists (as illustrated in Figure 2-4), which categorises implementations of these schemes using building energy rating values. Sustainable design practices are evaluated to ensure alignment with the energy rating credit systems established by the relevant accrediting bodies or government authorities in each country. As a result, the codes governing credit rating systems vary according to the regulations of each nation’s credentialing authority. For example, the Australian Green Building Council (AGBC) employs a design-as-built star rating system. In contrast, LEED uses a LEED Accredited Professional framework [78]. The most commonly used accreditation is the LEED, which is widely implemented across North America. This is because LEED’s energy packages have been shown to reduce the amount of energy consumed.

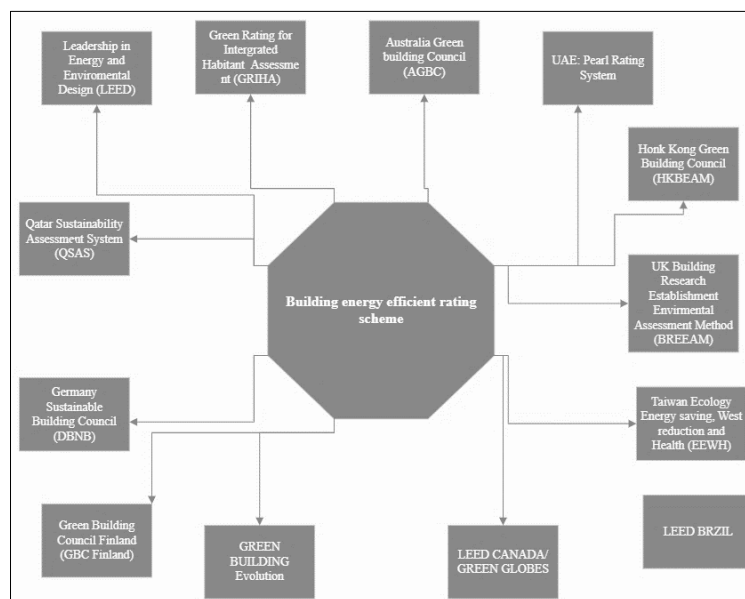


Figure 2-4. Individual countries’ / organisations’ accreditation rating systems

2.13 Enabling Multiple Smart Technology Networks

This study examined the benefits of intelligent networks, particularly IoT sensors, and more devices are anticipated soon. It is expected that IoT networks will soon supplant human expertise, with decisions and analyses being entirely conducted by IoT machines. For instance, sensor-based data will be derived from healthcare systems and will dictate necessary activities and treatments. This shift occurs as Health IoT (HIoT) devices collect all essential information from their environments. Currently, human health treatment relies heavily on medical professionals, but it is projected that in the future, human life will increasingly depend on HIoT technologies and artificial devices [79]. Moreover, IoT networks and various advanced networks function within contemporary buildings. The building multimedia entertainment system (BMES) is an example of intelligent technology that enhances smart buildings by wirelessly transmitting audio and video streaming data both inside and outside of the structure, ensuring that occupants receive quick and independent information [80]. Thus, the role of contemporary technological networks leads to the designation of buildings as ‘smart buildings’.

Despite their rapid growth and widespread acceptance, smart buildings continue to evolve, facing many challenges. For example, there are no definitive standard specifications regarding the regulatory framework for smart buildings. Which criteria must be met for a building to qualify as a ‘smart building’? Recent studies indicate that various smart technology network protocols are used in the construction of smart buildings. The authors of this research argue that the building that is equipped with extensive data derived from diverse sensor networks encounters specific interfacing challenges [81]. This is primarily because of the lack of compatibility among varying protocols. For instance, interoperability in smart buildings arises from sensor networks such as IoT systems. These IoT networks can connect with healthcare biometric data, while another IoT network may engage with machine learning data [82, 83]. In both scenarios, data gathering is conducted by IoT sensor networks, and these networks’ operating protocols are different because they are fabricated by various manufacturers. Thus, even though the sensors and the network are intelligent, they employ incompatible protocols. Facilitating direct communication between these distinct protocols becomes a significant concern and a challenge to the BAS.

Figure 2-5 depicts a variety of indoor wireless networks that function on separate protocols, which presently lack direct or indirect interconnectivity. The Boos automation network is unable to establish communication with the ADT alarm system, smart meter and local area network (LAN). To facilitate interaction among these systems, the involvement of a third party or intermediary is essential. Incorporating such third-party or agent software will result in initial, operational and maintenance expenses. This represents a significant drawback in the design practices of smart buildings.

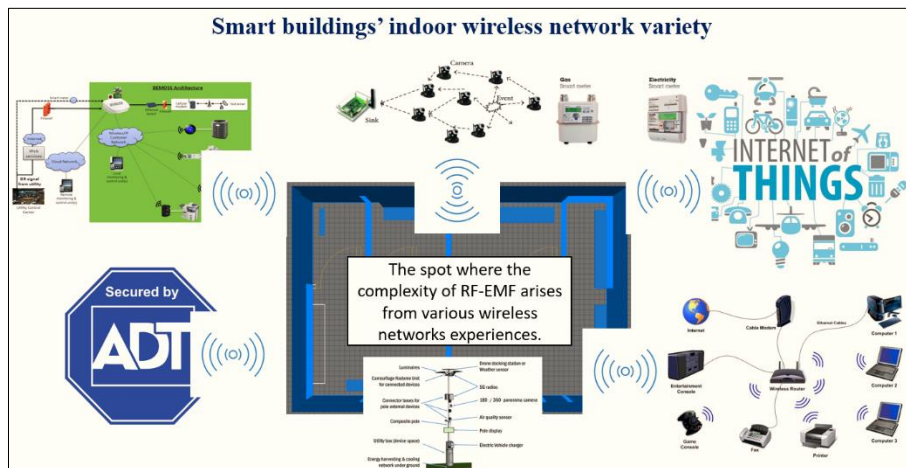


Figure 2-5. Various types of wireless networks are implemented in intelligent buildings

2.13.1 Wireless Communication and Its Latest Generation

The interest in adopting emerging technologies and preparing for the next generation stems from the benefits that earlier versions could not provide. However, the exact performance of the newer version, such as the sixth generation (6G), will become clear only once its development and application are thoroughly executed, evaluated and tested for a reasonable time. Experts and researchers in wireless technology anticipate distinct outcomes as part of the historical progress of this field. The evolution of wireless technology, particularly cellular communication systems, represents a significant milestone in research and development, fostering innovative and advanced technologies. However, in the public's perspective, it is not anticipated that the latest version will differ markedly from earlier models, as a result of reduced signal penetration. Despite, the public, the newer version 6G marked a significant transformation, enabling a diverse range of applications [84]. Thus, 6G remains on the distant horizon, and many individuals are already investigating potential applications for this new technology. The use of 6G is likely to continue evolving as its release approaches, and there is widespread anticipation

that it will profoundly affect various sectors as it progresses. Although the fifth generation (5G) transitioned from the fourth generation (4G) in 2020, it currently offers reliable and high-speed data transmission, which is expected to connect about 30 billion devices [85]. Figure 2-6 illustrates the existing configuration of a 6G outdoor wireless network. This network uses millimetre wave (mmWave) technology and operates at a distance of several metres from indoor devices within the premises. As depicted in Figure 2-6, the network can extend its coverage to a minimum range for indoor reception and a maximum range for satellite communication. Consequently, the power consumption for signal transmission may fluctuate according to an algorithm, or it may be maintained consistently at a high level, meaning that the transmitter uses the same amount of power to reach both ranges. Thus, 6G networks are characterised by their density and elevated energy levels, resulting in increased power density.



Figure 2-6. mmWave generation

Source: <https://www.lightwaveonline.com/5g-mobile/blog/14285180/6g-what-it-means-for-the-access-network>.

2.13.2 Smart Building Automation Control and Communication Using Different Network Protocols

For smart building designs, the initial phases of development typically involve the use of basic BACS or BMS. These systems manage the operation of electrical and electronic components, as well as pneumatic and hydraulic machinery, allowing actuators to activate or deactivate on demand and at the correct time. Such control systems have achieved a significant decrease in energy consumption, resulting in substantial savings measured in

kilowatt-hours (kWh). Furthermore, by incorporating off-peak use schedules into the programming, energy savings can be enhanced by approximately 30–35%. Currently, a variety of tools are available to reduce building energy consumption. For instance, an automated control system that employs ‘predicted mean votes’ has achieved an energy use reduction of about 30% [86]. In contemporary times, algorithms driven by AI are becoming increasingly prevalent, representing a key aspect of future technological advancements. The implementation of AI holds the potential for substantial reductions in both energy use and time efficiency. A prime example of this is the BAS, which serves as a crucial component in managing energy consumption within buildings through network technology. The interoperability of BAS networks with BIM further enhances this integration [87], enabling data to monitor the building’s energy and to allow it to consume wisely [88]. Currently, excessive wireless network communications and controls operate within a range that encompasses BIoTs, modems and AI to enhance the functionality of components.

Currently, buildings using modern technology have gone beyond the scope of BAS, with the help of the BIoT and ancillary services offered by the power supply of the grid. There is a current focus on an occupant density-centred approach to develop smart cities [89]. The widespread acceptance of intelligent buildings and their rapid growth has exceeded expectations. The term ‘smart building’ emerged from conventional building in the early 1980s [90, 91]. Further, smart buildings appear to be related to saving energy and reducing greenhouse gas emissions, which is also known as sustainable smart buildings [17]. An opportunity exists to design and model smart buildings using economically cost-effective, modern, reliable, industry-proven technologies, such as the ‘Profibus network protocol’, which is now used by many industries to reduce the costs of electrical devices and their installation. Migrating this type of technology to the building sector will enhance the energy consumption of buildings and align with the scope and objectives of smart buildings.

2.13.2.1 Excessive Use of Wireless Technology Indoors Increases Electromagnetic Field Radiation

Wired systems continue to be the prevailing choice in building automation. As an alternative, wireless technology can be employed for the electrical and electronic components within a building’s automation control wiring and indoor communications.

This approach allows these components to connect through a point that enables remote management and monitoring. Higher energy wireless technology possesses higher bandwidth and offers faster transmission, which facilitates global communication and the control of industry automation systems. In addition, recent research demonstrates that the total power transmitted from multiple input multiple output (MIMO) antennas approaches non-ionising maximum power density guideline limits. This approach was obtained from 5G mmWave bands, which range from 2.4 to 86 GHz frequencies, and produce maximum power density when evaluating the MIMO antenna's total power density. The research uses the eigenvalue decomposition (ESD) and the semi-definite relation (SDR) program methods [92].

Other recently published research attempts to solve the maximum RF-EMF power density produced from multiple antennas by summing the electric field magnitude vectors using the magnitude field combining method (MFCM), component field combining method (CFCM), ESD and SDR. The researcher demonstrates their results using two case studies. The first case study seeks to determine specific absorption rate (SAR) exposure at 2 GHz operating frequency for the User Equipment (UE) [92]. The result obtained from this first case study indicates that the scalar E-field combining method overestimated the results. The second case study operates at the upper bound of the 5G UE frequency (28 GHz). In this second case study, the scalar E-field combining method proved suitable for measuring the maximum exposure limits. Hence, these different methods indicate that RF-EMF's power density limit depends on the compliance boundaries [93]. Furthermore, from the study's results, the researcher suggests that ESD is the most accurate method for evaluating optimised RF-EMF power density limits.

Similarly, another recently published paper demonstrates that RF-EMF's power density effect on health is at the alerting stage. This is from temperature rise on the skin tissues caused by continuous-wave below 6 GHz for a six-minute duration. This paper computed the temperature rise duration for brief single and numerous pulse durations drawing on the computational bio-heat SAR effect, operating below the International Commission on Non-Ionising Radiation Protection (ICNIRP)'s guide exposure limit of six minutes. Contrary to the above research findings, another similar study of the 5G band operating at a higher frequency demonstrates that the maximum simulation result shows that 5G massive MIMO with smart antennas and beamforming technology is safe. According to

the researcher, the 5G is significantly efficient and minimises the effect of the building's power density level [94]. Thus, 5G wireless communication is probably safer than the other higher wireless indoor communication frequency bands.

2.13.2.1.1 Comfort of Smart Building Occupants and Controversy over Health Concerns

The objective of the smart building is to satisfy occupants' desire to live or work in a building that fulfils the need for comfort. However, people who live or work in buildings that are fitted with dense wireless communication have raised concerns over various types of RF-EMF power density levels [38, 95, 96]. In the last decade, several studies have warned that the occupants of smart buildings could be exposed to RF-EMF power densities [39]. This is because of the increasing implementation of wireless BIoT devices in smart buildings [81], especially when multiple BIoT devices are grouped to form a population of devices. Hence, it is one of the causes that non-ionising RF-EMF exposure levels [97] have raised public concern controversy [96, 98]. Public concern is raised not only because of the increase in modern and emerging technologies of multiple wireless frequencies, but also because of the higher energy frequency bands involved [99, 100].

2.13.2.2 RF-EMF Radiating Waves: Strong vs Weak Characteristics Analysis

Several researchers have conducted studies in medical science that indicate RF-EMF power density can cause significant health effects. These run contrary to studies by engineering researchers, which conclude that the RF-EMF power density simulation does not show adequate evidence to claim that there is a significant health effect. As a result, the topic remains controversial [101]. However, these wireless devices, when implemented excessively, can cause indoor RF-EMF radiation when their multiple waves are formed constructively. Advanced research and debates are ongoing within the scientific community concerning the ongoing RF-EMF and the lack of conclusive analytical evidence regarding its impacts. The number of wireless devices, including smart meters and various technologies in contemporary indoor buildings, has generated genuine concern among the residents of smart buildings. On the other hand, sustainable smart buildings that feature wireless controls can yield considerable energy savings and show positive economic benefits. Currently, the research question is how to mitigate the

concerns of occupants while achieving energy and financial savings. A key element of sustainable building design goals is ensuring the comfort of those who reside within; therefore, if concerns persist, genuine comfort is undermined, preventing the fulfilment of health-related sustainability objectives for residents.

Indoor wireless communication that operates at higher frequencies involves a complicated propagation process characterised by multipath diversity channels [102]. In such a multipath environment, multiple signal replicas traverse various paths, each experiencing distinct propagation delays [103]. At any given location, whether arbitrary or at the receiver, it is possible to observe different phases shifts and signal strengths. These waves can interfere with one another either constructively or destructively, leading to swift variations in the channel's characteristics [104, 105]. A multipath channel can be conceptualised as a linear time-variant system where its parameters fluctuate randomly over time [106].

Additionally, indoor wireless signals exhibit inherent time-varying properties; their parameters change not only over time but also according to the objects they encounter. Consequently, these wireless channels are considered to have more challenging characteristics than wired alternatives [107]. The response of the channel is represented as a multidimensional random variable influenced by both time and space, functioning through instantaneous random complex propagation delays characterised by multiple parameters [108].

Moreover, the indoor wireless multipath propagating waves can be described as a convolution response resulting from several complex channels [109]. Analysing radiating signals in proximity to the field presents complexities because of antenna coupling effects observed in the near-field region [110]. In recent decades, several researchers have concluded their studies with findings indicating that occupants in smart buildings may be exposed to higher levels of RF-EMF [111]. This situation arises from the integration of BIoT, which involves numerous interconnected devices, alongside the development of various wireless communication technologies within contemporary buildings [112]. This has resulted in heightened exposure to non-ionising RF-EMF [113], leading to health implications that have sparked widespread public concern [114]. Despite a growing number of studies suggesting notable effects and highlighting occupants' worries, the subject remains a topic of debate [115]. However, most past and recent studies in this

field have employed single-device sequential simulation analysis, and have been reluctant to consider simultaneous simulation combined effect analysis. Thus, this study evaluates the effects in terms of power density, E-field, H-field and SAR by considering sequential and simultaneous simulation exposure analysis.

2.13.2.3 Smart Building Opportunity for Wireless Energy Harvesting

The idea of wireless power transmission was first introduced by Nikola Tesla, a Serbian-American electrical engineer and inventor, in 1883. Tesla's practical vision involved using distributed towers to transmit both electricity and information wirelessly across the globe. However, his grand ambitions faced limitations in practical implementation. In 2007, a team of experts from the Massachusetts Institute of Technology (MIT) successfully achieved power transfer over a distance of two metres using magnetic resonance techniques, wirelessly delivering 40% to 60% of the required energy to illuminate a 60 W light bulb.

Similarly, recent research has focused on multiband wireless frequency energy harvesting ranging from 2.4 GHz to 5.8 GHz. The research outcome indicates significant advancements in RF energy to direct current (DC) energy conversion efficiency, reaching up to 66.5% at a frequency of 2.35 GHz and under a power density of 66 $\mu\text{W}/\text{m}^2$.

Other studies have explored the potential for WET utilising intelligent, reflective materials, which enhance both the efficiency of energy propagation and communication signals for short-distance applications. The harvested energy has been used to power low-latency communication devices in BIoT systems.

Moreover, rapid algorithms enable efficient WET to various BIoT devices, effectively reducing charging times. A research team has also developed hardware capable of charging underwater devices through tri-axis induction coils, claiming reliable performance for both energy and data transfer [116]. A 2021 study [117] reported notable success in transferring energy via audio signals combined with inductive magnetic coils. This method relies on mutual inductance principles among coils used for WET; however, it does not adequately consider power-saving measures, as highlighted in related works [117].

2.14 The Digital Twin Concept and Modern Buildings

A digital twin is a virtual model that functions as the real-time digital equivalent of a physical entity. It acts as a blueprint for an asset. The creation of a digital twin aligns with an operational asset, ensuring that all parties involved have access to the same continuously updated information. Digital twins help minimise mistakes and enhance collaboration, leading to greater transparency in projects and increased engineering efficiency.

The National Aeronautics and Space Agency (NASA) initially developed the digital twin concept in 2010 [118]. Its main aim was to track the status of flying aircraft in real-time situations remotely. NASA defined the digital twin as ‘an integrated multi-physics, multi-scale probabilistic simulation of a vehicle or system that uses the best available physical models’. Since then, the concept has gained more attention and become the most attractive topic among all stakeholders, especially researchers in this field. For instance, according to a recent paper, a digital twin comprises three main elements—accuracy, performance and stability [119]—and its structure can be developed using two steps, ‘geometric and physical’. The author of the paper conducted his study on ‘micro-target assembly’, in which the accuracy of the virtual presentation model versus the physical presentation model was forecasted to be more than 90%. Hence, the increase in technological advances [120] helps the sustainable building construction sector gain widespread acceptance and awareness.

2.15 Smart Building Features and Development with Artificial Intelligence (AI)

The terminology of AI, ‘can machine thinking’, or ‘can machine design’, was developed after 1950 and defined as machine intellectual activities [121]. Smart building uses rule-based frameworks, statistical models and reactive automation. In contrast, intelligent buildings incorporate automation powered by AI, which significantly enhances data analysis through advanced machine learning techniques. The integration of AI offers numerous benefits and improvements, particularly in domains like energy efficiency and predicting in keeping up with personalised user-oriented interactive design experiences [121]. Nowadays, AI is being used in many sectors and is emerging as the most suitable solution to ease tasks, offering the best accuracy, performance and stability. For instance,

a recently published article uses AI algorithm tools to optimise the properties of composite construction materials by implementing the ‘Multiple Object Genetic Algorithm’ method, thereby decreasing environmental impacts. The author of the article demonstrates an improvement of 15% in CO₂ emissions, 20% in tensile strength, and a decrease of 12% in energy consumption [122].

2.16 Enhancement of Smart Buildings’ Indoor Environment Quality

Modern structures are designed to support individuals participating in activities that promote environmental well-being. Buildings need to ensure comfort, efficiency, health and safety for individuals as they carry out their activities. The concept of smart design aims to develop structures that enhance occupant comfort while reducing adverse environmental impacts. Smart buildings prioritise occupant comfort by offering a range of services tailored to their needs [123]. However, as mentioned previously, a smart building that is equipped with the latest advanced technologies, including wireless systems, may inadvertently diminish occupant comfort or lead occupants to perceive that their comfort is not fully optimised. This situation arises from the adverse effects associated with high wireless power density. The health concerns stem from the use of elevated radio frequencies in these wireless technologies [124]. When designing a smart building, the energy reduction and the comfort it offers should be unencumbered by concerns. Indeed, comfort that stems from the enhancement of environmental quality and is not undermined by concerns leads to sustainable productivity.

2.16.1 Environmental Sustainability

Factors pertaining to building sustainability should be prioritised before considering other associated elements. It is essential to conduct thorough analyses of the building to verify compliance with sustainability standards. Environmental sustainability aims to preserve natural resources, create alternative energy sources and minimise pollution and ecological damage. The future state of environmental sustainability is commonly evaluated over periods of 50, 100 and 1,000 years. This approach serves as a foundational principle for assessing environmental stability [125]. Many initiatives focused on environmental sustainability aim to restore forests, safeguard wetlands and protect natural habitats from resource extraction. However, a significant criticism of these sustainability efforts is that their goals may conflict with the demands of an expanding industrial society. Sustainable

development refers to the approach of land use and construction that minimises environmental impact while fostering energy-efficient and self-sufficient models. This can include the installation of solar panels or wind turbines at manufacturing sites, employing geothermal heating methods or engaging in cap-and-trade systems.

The most significant criticism argues that sustainable development falls short in its immediate conservation efforts and relies on the notion that environmental degradation in one region can be offset by protective measures taken elsewhere [126]. In an offset environment, the counter-balancing approach slows the overall speed of the predicted sustainable development missions. On the contrary, a parallel or simultaneous approach can speed up the desired sustainability. Hence, global understanding and collaboration from the building infrastructure side are essential to avoid non-counterbalanced solutions.

CO₂ emissions and other related greenhouse gases are leading causes of climate change and global warming. Over the last decade, average global temperatures have risen by 1.5°C [37] and are predicted to continue growing. Further, research has revealed that different gases have different effects on the Earth's atmosphere. For example, a ton of methane in the atmosphere is more climate-potent than a ton of CO₂, but it lasts approximately 12 to 15 years in the atmosphere. CO₂, however, can last in the atmosphere for 300 to 1,000 years. This indicates that current CO₂ emissions can contribute to rising temperatures in future centuries. In addition, 'greenhouse gases' refer to gases that, when released, trap heat in the atmosphere, which leads to an increase in the global temperature. This phenomenon is known as the 'greenhouse effect'. Greenhouse gases mainly consist of CO₂, methane and NO_x. CO₂ accounts for most of the greenhouse gases. This indicates that the CO₂ and carbon equivalent (CO₂-e) [40] quantities are contributing to climate change. CO₂-e emissions are equivalent quantities of non-CO₂ gases that could contribute to the greenhouse effect, causing the same effect as CO₂.

A recent study in this area examines how global warming potential (GWP) factors can be applied to quantify the emissions of non-CO₂ greenhouse gases. The research highlights that GWPs are a subject of ongoing scientific inquiry, and the precise equivalency for non-CO₂ gases remains unverified. For example, results of the initial simulation from a recent investigation indicated that the GWP for methane was calculated at 21 tons; however, further simulations revealed an increase in methane's contribution to 28 tons. If this additional evaluation is accurate, then one ton of methane would have the same

warming impact as 28 tons of CO₂. While each greenhouse gas possesses its unique GWP, sulphur hexafluoride (SF₆) stands out as having the highest GWP among non-CO₂ greenhouse gas contributors.

2.16.2 Indoor and Outdoor Air Quality (IOAQ) Improvement Strategy

The strategies of using extractor fans and open windows can effectively help in eliminating indoor air pollutants. Outdoor air circulates in and out of buildings via infiltration, natural ventilation and mechanical means, which are also helpful. Infiltration occurs when outdoor air enters through gaps in walls, floors, ceilings, windows and doors. Appropriate measures to seal the openings are advisable to maintain proper AQ mitigation. ‘Natural ventilation’ refers to the movement of air through open windows and doors. The airflow resulting from both infiltration and natural ventilation is influenced by temperature differences between the interior and exterior environments as well as wind conditions. The term ‘air exchange rate’ describes how quickly outdoor air replaces indoor air; inadequate infiltration or limited natural or mechanical ventilation can lead to a low exchange rate, resulting in heightened pollutant levels [127].

Economically beneficial commercial structures prioritise the enhancement of natural sustainability, the prudent use of resources and the advancement of alternative energy solutions while reducing pollution and avoiding significant environmental harm. Sustainable buildings consider both indoor and outdoor air quality as it pertains to the build-up of harmful particles resulting from indoor pollutants influenced by temperature, humidity and various materials such as VOCs. Inadequate ventilation worsens indoor pollutant concentrations through insufficient fresh air circulation. One primary objective of sustainable building practices is to reduce these emissions.

2.17 Smart Building Drawbacks and Mitigation Countermeasures

The most critical challenges to sustainable building designs are:

1. Resistance to fully changing from conventional building design practice, even though sustainable building design has attracted rapid growth in recent decades.
2. Even the most recently designed smart, sustainable buildings still suffer from sensor network diversity [43]. This is because of the presence of different non-interfaceable brands operating on the premises and the various companies using

different sensors and brands to build their unique network systems. To differentiate the connected sensors, a number of companies use the ‘K-means clustering technique’ [128] to save them from using manual identifications.

3. Lack of clear guidelines or regulations from the government side to define the classification of smart, sustainable building levels.
4. Smart building names are mostly monopolised and operated by different competitive commercial private companies or private organisations using various names and concepts, such as digitised/intelligent building, green building and BlueIoT Buildings. In addition, organisations such as LEED [78], GBCA and others have developed energy rating and certification systems for equipment to define the energy consumed, particularly for green building achievements. While adopting these names and certifications has made a significant contribution to reducing energy and greenhouse gas emissions, the criteria for naming and certification system has been left to individual organisations.
5. Smart buildings fail to be continuously smart and sustainable during occurrences of full or partial internal electrical faults. In smart buildings, the failure to continue supplying power during an RCD trip, whether because of a nuisance or real fault, has been identified, and a solution has been proposed. For example, various researchers have expressed interest in developing solutions aimed at enhancing the characteristics of RCDs that lead to nuisance tripping because of high-frequency transient currents. These devices exhibit sensitivity to elevated frequencies but fail to activate when exposed to pure-tone high-frequency signals. This finding was highlighted in a recent study [129] that conducted measurements on different RCD models within a frequency range of 4 to 40 kHz using mapping methods focused on spectrum uncertainties tied to residual current at non-fundamental frequencies. The study’s results indicated that the range of frequency shows less effect instead, the combination of transient current magnitude and its duration had a more significant influence.

Frequent nuisance trips often stem from inrush currents generated when electrical loads are turned on after being off for some time; these currents tend to exceed normal steady-state levels caused by low impedance or cold conditions of de-energised equipment. Efforts are underway to enhance the new RCD designs against these sudden current surges. Several studies [129-131] have investigated various mitigation strategies to reduce nuisance tripping incidents. For example,

a recent research project investigated a three-phase non-isolating transformer electric vehicle charger utilising an AC/DC configuration, along with a current source rectifier (CSR) circuit employing pulse width modulation (PWM). The PWM technique incorporates third harmonic injection methods, which produce low-frequency common mode currents via parasitic capacitance within the DC output circuit—currents that may surpass RCD thresholds. To counteract low-frequency common-mode effects, this study designed a virtual control circuit intended to ground these currents before their interaction with the RCD circuitry. Another relevant study [132] focusing on limiting DC output parameters was introduced as an approach for filtering out average leakage currents—this method effectively enhances RCD trip rates. An additional investigation that focused on transients from lightning strikes led to the development of an auto-reclosing RCD, specifically designed to recover from nuisance tripping events. However, it did not address significant real earth leakage issues.

6. The smart building's objectives are to use minimal resources and maximise energy reductions, which are attempted in this study for selected cases only. In this section, the conventional bulk wiring method is modified to satisfy the objectives. This is one of the few methods to improve the construction or innovation of the building's economic efficiency in terms of electrical devices.

2.18 Achievements of Smart Buildings

This research project demonstrates that comprehensive savings of green buildings are obtained from four different sources:

1. Reductions in fuel and electricity energy use, mainly from the building fuel energy simulation, related to HVAC annual consumption.
2. Optimised implementation of renewable energies, especially PV cells.
3. Building water use. The highest savings occur when the smart building is fitted with efficient facilities that reduce the amount of water required for cooling and heating and minimise the energy needed to perform these tasks, which in turn reduces costs; several studies show that up to 20% of a commercial building's energy consumption is attributable to the heating of water [133].
4. Enhanced device control system. This is the method used for controlling building facilities, electrical/electronic devices and plug-in appliances. This type of energy

saving is achieved by controlling and monitoring the activities of these devices so that they function only during demand periods.

2.19 Conclusion

In its first few sections, this chapter presented a comprehensive review of the literature on conventional building practices and modern buildings. It discussed the history of traditional buildings versus smart buildings, focusing on the derivation of smart buildings from conventional buildings. This chapter has also provided an in-depth exploration of the simulation of the absorption of building solar radiation aiming at a reduction in annual energy use. The chapter examined the capability of commercial buildings to be energy-efficient, structurally stable and to ensure occupants' comfort, including health and safety. It introduced the enabling smart device. Finally, it explored and assessed the opportunity to use the harvesting of indoor energy produced by multiple wireless devices in meaningful applications.

Chapter 3

Modelling Smart Buildings, Methodology and Conceptual Simulation of Solar Energy Radiation Absorption

3.1 Introduction

Smart buildings and smart cities are major contributors to smart environmental living. However, there are no precise standard specifications that smart buildings should include or exclude. To be called a ‘smart building’, which criteria have to be satisfied? Several recent research papers prove that smart buildings are implemented with various innovative technology network protocols. Researchers of these papers have uncovered that smart buildings that are equipped especially with extensive data from multiple networks experience interfacing drawbacks and issues [43]. This is because the diversity of the protocols is not easily compatible. For instance, a particular IoT network can interface with healthcare bio-data, and another IoT network can interface with machine learning data [87, 134]. In both networks, data collection and distribution is performed by the IoT sensors. Assuming both network devices use different manufacturers that have incompatible protocols, there is the issue of how to communicate directly between these other protocols. Consequently, current smart buildings face the following drawbacks:

1. Even the most recently built smart buildings suffer from sensor diversity [20]. Non-interoperability in modern technology remains a significant issue.
2. The lack of clear government standards or guides for classifying smart buildings.
3. The smart building suffers from having to be continuously smart; during the occurrence of full or partial internal faults, it loses its smartness. The building is smart as long as a continuous power supply is present. However, when, for example, a nuisance failure occurs in the part of the electrical wiring installation and the protection devices trips in the main switchboard, the smart equipment connected to that part of the line loses its smartness and remote access points lose functionality, resulting in no information being transmitted or retrieved.

4. Smart buildings do not adequately meet their stated objectives and goals. These include utilising minimal resources, implementing cost-reduction strategies, employing smart techniques, and devising effective device interconnection methods and a smart strategy for seamless device integration.

This study is designed to rectify and mitigate some of the drawbacks listed in the previous paragraphs. It evaluates and analyses the mitigation using case studies. The study provides an overview of the implemented method, followed by a brief discussion of the smart building objectives, highlighting the criteria that have been met and those that remain to be met. As the central part of the study, this chapter presents an in-depth analysis of the building's absorption of the sun's solar irradiation energy, using a conceptual simulation to estimate annual energy and water consumption.

3.2 Applied Methodology for Modelling Sustainable Smart Buildings

Figure 3-1 presents a methodological flowchart illustrating the conceptual modelling of sustainable smart commercial buildings through simulation software. This approach addresses the requirements of the present generation of technology while incorporating essential measures for future generations. The initial stage in modelling the building involved conducting a literature review that compared traditional buildings with smart buildings. This comparison was extensively investigated, revealing various gaps and shortcomings in the literature. From the identified issues, specific objectives were established. The aims of the Sustainable Smart Building initiative were thoroughly examined, leading to a clear identification and classification of its goals.

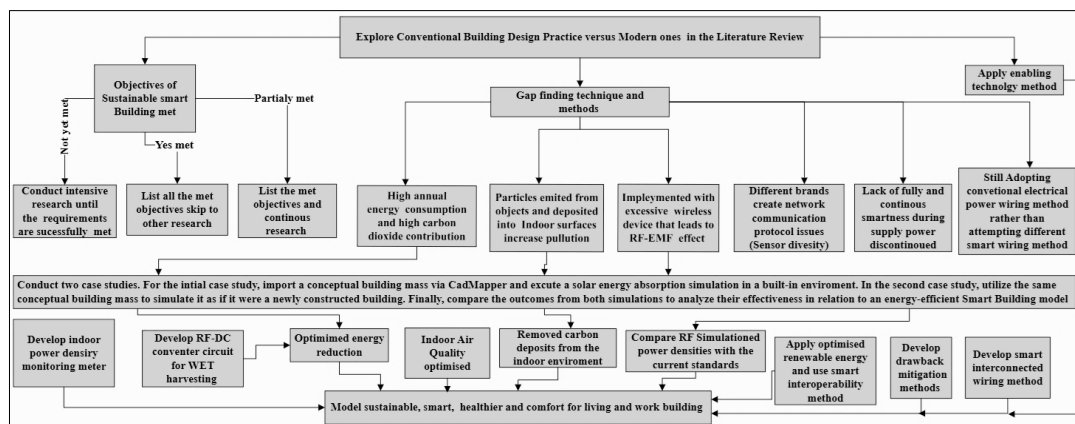


Figure 3-1. Applied methodological flow chart

3.3 Design and Modelling of Smart Buildings, with Minimum Criteria

Smart buildings shall be designed and modelled considering the minimum threshold objective criteria shown in Figure 3-2, aiming to use natural resources up to the minimum point at the time of construction as well as during continuous operations. This can be achieved by approaching the resource use efficiency of reducing, reusing and recycling [135], known as ‘R’. It can also be achieved by maximising the use of efficient construction materials and innovative practices in the following ways:

1. Boosting the use of natural sources and sinks in the building’s surroundings.
2. Minimizing the energy consumption of the building so that it can operate autonomously based on the renewable energy it produces.
3. Applying highly proficient equipment for the indoor area and using highly proficient methods for water and waste management while reducing negative impact on the environment by the construction and operation of a building. This shall include the external environment at the building location, the internal area for the occupants of the building, and the areas not close to the building [136] should also be preserved.

It is important to ensure the development of sustainable smart buildings by considering the concept of minimum requirements:

1. Reducing the amount of energy that is consumed by the building.
2. Increasing the use of energy sources that do not produce any greenhouse gases and are renewable in nature.
3. Emphasises natural lighting concepts—such as temperature control and efficient design—to further reduce the carbon footprint, as well as reduce the cost of operation of the building [137].
4. Emphasises the concept of improving the design of the products and reusing and recycling materials. This results in significant waste reduction and also helps to reduce the environmental impact of the building [138].
5. Improving health and productivity by ensuring hygiene in the building helps boost human productivity.
6. Use of optimised intelligent control, communication and monitoring systems.

7. Comply with the country's building standard, building regulation and code of practice.

Thus, the smart building concept provides clean and neat living conditions for the building's occupants and others. In addition, secure and intelligent control, communication and monitoring systems are implemented as minimum criteria.

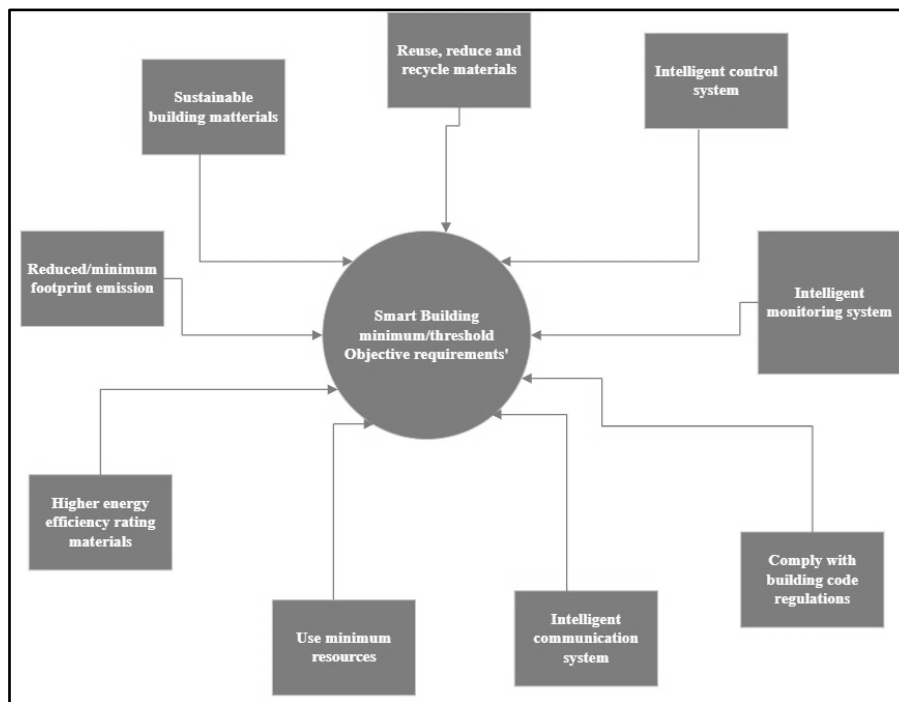


Figure 3-2. Smart building minimum/threshold requirement criteria

3.3.1 Simulation of Solar Irradiation Absorption: Case Study 1

This part of this chapter deals with the conceptual building of solar energy modelling and simulation. The main objective of this conceptual building simulation was to estimate the overall annual and lifetime energy use. The conceptual building was first designed and modelled to suit and obtain the optimised direction of sunlight intensity. For a conceptual case study, the location of the energy modelling of the smart, sustainable building was chosen to be Melbourne city, Victoria, Australia. The actual design, construction modelling and documentation of the buildings were primarily conducted through teams. Team members were responsible for creating models and documentation that could be leveraged across planning, designing, remediation, visualisation and asset management using architectural software applications. It is usual practice that when the actual virtual construction design is completed, the building is simulated for energy solar radiation

analysis by loading the particular weather file for that location. However, this type of solar energy simulation practice did not achieve the optimised estimation results. This was because the surrounding building context was not included in the simulation. To obtain the correct estimation, the simulation should run as a ‘built environment’. Thus, in this chapter, a built environment consisting of conceptual mass buildings is imported using CadMapper [139] into Rhino architectural software, as shown in Figure 3-3. The imported conceptual mass buildings are simulated using Rhino’s plug-in software (Grasshopper and Ladybug) and by loading weather files from the nearest weather station. Further, the conceptual building contexts are simulated simultaneously to reflect reality, while only one mass conceptual building is simulated, as shown in Figure 3-4. This is because the simulation process accurately replicates the actual weather conditions of the simulated building within the built environment. The surrounding buildings and the natural environmental conditions influence solar radiation into the building. This is to cover the direct, reflected solar radiation intensities and shading-affected intensity during seasonal variations. However, the simulation of solar radiation energy intensities maximises the quantity of solar energy captured by the building components during a non-cloudy day.

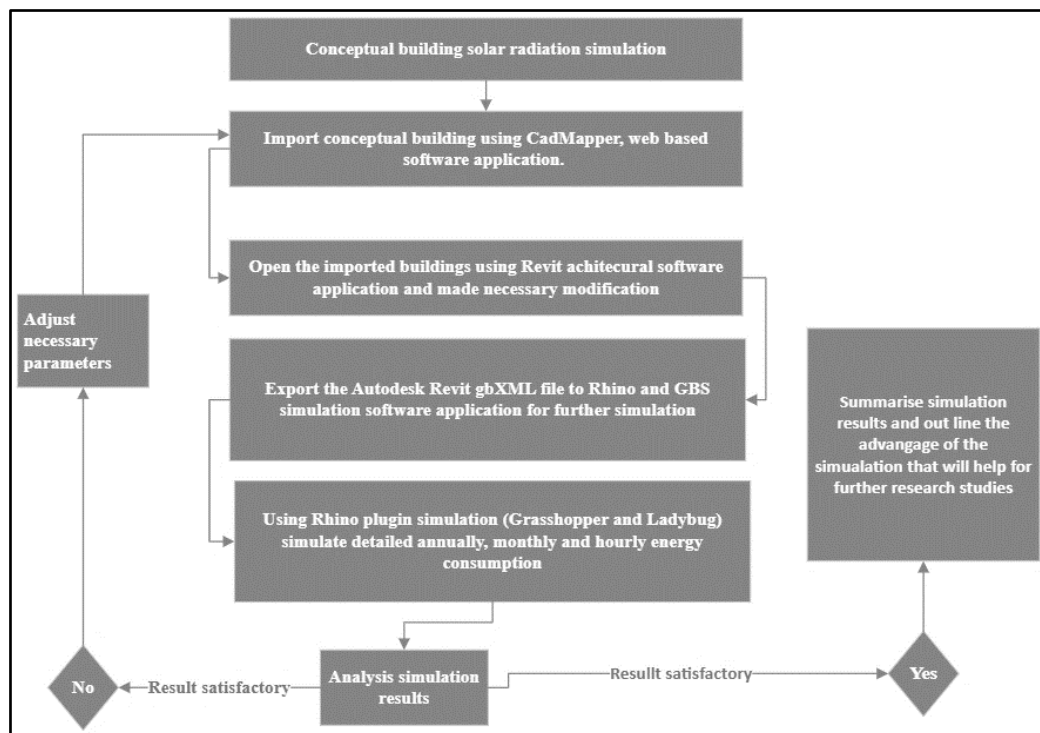


Figure 3-3. Procedure for designing the conceptual building energy simulation

Various techniques can be employed to simulate solar radiation for buildings, with the choice largely influenced by the designer's proficiency in selecting suitable energy-efficient components and tools. For instance:

1. **Building orientation techniques:** This refers to how a structure is positioned in relation to the sun's trajectory. The intensity of solar radiation fluctuates according to this path throughout different seasons. Thus, optimising building orientation can enhance energy efficiency, contributing to increased occupant comfort and reduced operational costs.
2. **Daylight modelling:** This technique is used by designers, architects and engineers to assess the levels of natural light within a structure. By examining how daylight interacts with its environment, this method supports informed decision-making regarding energy consumption and architectural features. It enables professionals to accurately predict sunlight patterns, facilitating the design of spaces that maximise daylight use while minimising energy expenditure. Additionally, daylight modelling plays a crucial role in optimising window sizes, orientations and external shading strategies to improve access to natural light while limiting heat loss or gain. Ultimately, this leads to reduced dependence on artificial lighting and HVAC systems, resulting in significant energy savings. As illustrated in Figure 3-4, the results of the annual solar radiation simulation are presented in terms of kilowatt power density, showing values ranging from a maximum of 971.18 kWh/m² to a minimum of 97.12 kWh/m², with a total accumulation of 6,212.54 kWh/m².

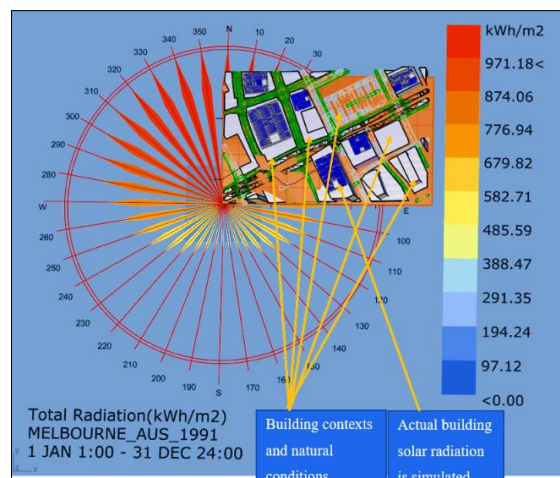


Figure 3-4. Total solar radiation simulation for conceptual building: Annual results per kWh/m²

3.3.2 Initial Analysis of Building's Solar Radiation Energy

The input parameters from the weather file that are incorporated into the simulated building have a significant influence on the built environment. The interaction between adjacent structures and environmental conditions contributes to the impact of solar radiation energy on the simulated building. This interaction is crucial for generating accurate energy estimations during the simulation process, which are vital for engineers and property owners in modelling the annual energy consumption of a building. Moreover, these preliminary outcomes signify an effort towards environmental sustainability by evaluating various factors such as building performance, projected yearly energy consumption, life-cycle energy use, required renewable energy potentials, CO₂ emissions, total annual energy costs, fuel energy use per year, electric energy consumption per year and heating and cooling load requirements annually, along with peak demand figures.

Additionally, specific parameters from the weather file—like annual wind speed frequency distribution, average diurnal temperatures over a year, and average yearly humidity—play a critical role in simulations of solar energy absorption for the modelling of a building's energy estimation [140]. Overall, weather information is essential for accurately estimating a building's annual energy consumption by assessing its volume, and to generate corresponding detailed output results. For this study, the Melbourne weather station has been selected as the specific regional weather source, as indicated in the 'Location Weather' and 'Site dialog of Melbourne'. This station provides accurate and current forecasted weather data for the area. During simulations, both maximum and minimum temperatures specific to the building's location were used.

Surrounding buildings were also considered in the analysis to account for their impact on external ambient temperature, which affected the context of the primary building model. Internal gains from sources such as occupants, lighting, equipment and building envelopes influence the heating and cooling requirements of the building. This highlights that HVAC loads are directly related to weather data, while light loads are contingent upon conditions within the conditioned indoor spaces.

3.3.2.1 Solar Irradiation Approach and Absorption Directions Analysis

The total solar radiation that reaches the Earth's surface is approximately 950 Watts/m². It approaches the Earth's surface in three directions [141], which are the global horizontal intensity (GHI), diffuse horizontal intensity (DHI) and direct normal intensity (DNI). These, together with infrared radiations, are shown in the software simulations recorded in Figures 3-5-3-8. The atmospheric medium plays a significant role in distorting solar radiation, dividing it into portions, where some is reflected straight away from the medium, some is refracted horizontally, and the greater portion travels through the medium and reaches the Earth's surface. The incident ray that reaches the ground is composed of two main radiations, the DHI and the DNI, which are equal to GHI.

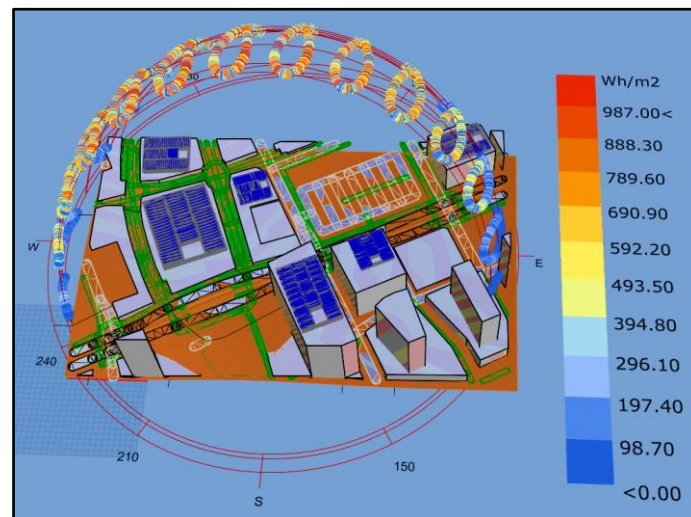


Figure 3-5. Direct normal radiation approach to the surface of the Earth

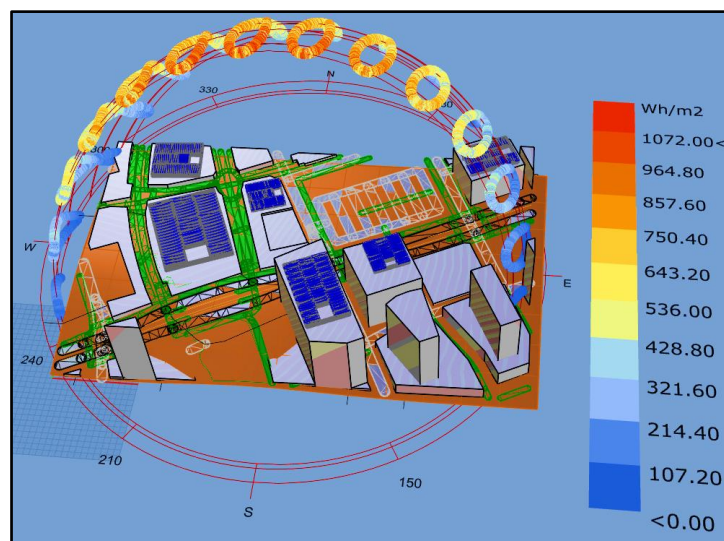


Figure 3-6. Horizontal radiation approach to the surface of the Earth

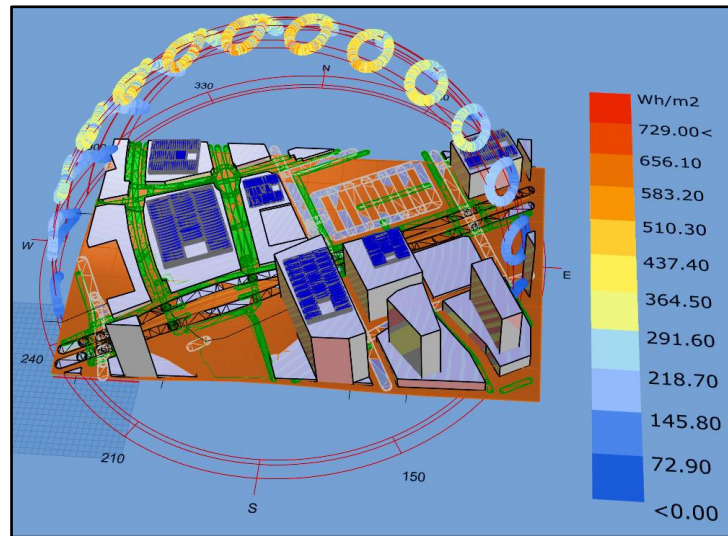


Figure 3-7. Diffuse radiation approach to the surface of the Earth

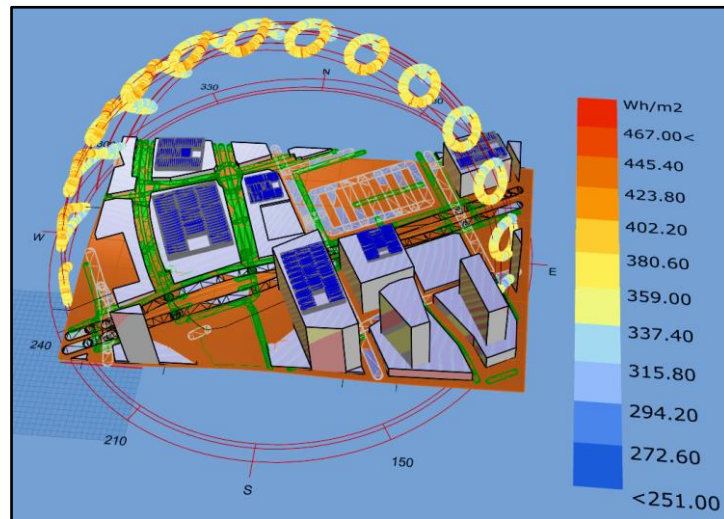


Figure 3-8. Infrared radiation approach to the surface of the Earth

3.3.3 Simulation of Barometric Pressure, Wind Speed and Temperature Variations

The Earth's atmosphere comprises layers of gases known as 'air' that exert pressure generated by the weight of the air above a specific altitude. This pressure at the Earth's surface is referred to as 'surface pressure', which is directly correlated with the mass of air present in that area. The pressure gradient drives air movement from areas of high pressure to low pressure, causing wind flow [142]. The rapid movement of wind carries kinetic energy, which is then transformed into stationary barometric or atmospheric pressure. Elevated wind velocity correlates with decreased air pressure, determined by

the discrepancy in pressure between two points. Extreme low pressure in a specific area can result in exceptionally high wind speeds, potentially leading to severe storms.

The Earth's rotation influences the direction of wind as it travels across regions. In the northern hemisphere, winds veer to the right because of the Earth's rotation, whereas in the southern hemisphere, they curve leftward and circulate counter-clockwise around areas of high pressure—a phenomenon known as the Coriolis Effect [143].

High-velocity winds carry significant energy, leading to abnormal weather patterns caused by climate change. These conditions can give rise to severe events that endanger lives and property, such as the formation of cyclones. Thus, for smart building, the local weather simulations, as shown in Figures 3-9, 3-10, 3-11 and 3-12, are crucial for understanding the consequences of these dynamics and protecting occupants' lives, as well as preventing property damage.

Ensuring the structural stability of the building is a crucial safety consideration that must be addressed before undertaking energy modelling practices. A thorough evaluation that incorporates relevant factors is necessary to meet the requirements of sustainable building design and maintain structural integrity. Consequently, this study emphasises the simulations of wind speed characteristics and their influential effects, such as dry and wet bulb temperature and average annual humidity, which vary across Melbourne. Analysing the sun-path, the average yearly humidity varies from east to West. In the east, the average moisture starts at 100%, and as the sun moves and approaches the middle path, the average humidity decreases.

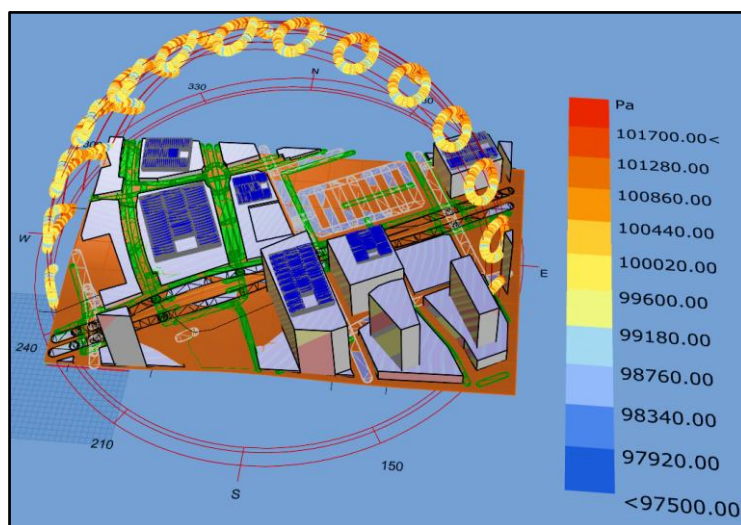


Figure 3-9. Barometric pressure approach to the surface of the Earth

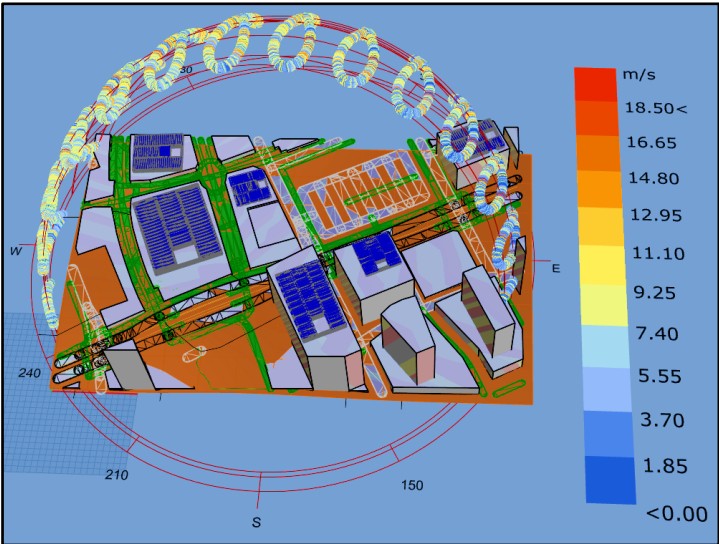


Figure 3-10. Wind speed approaches the surface of the Earth

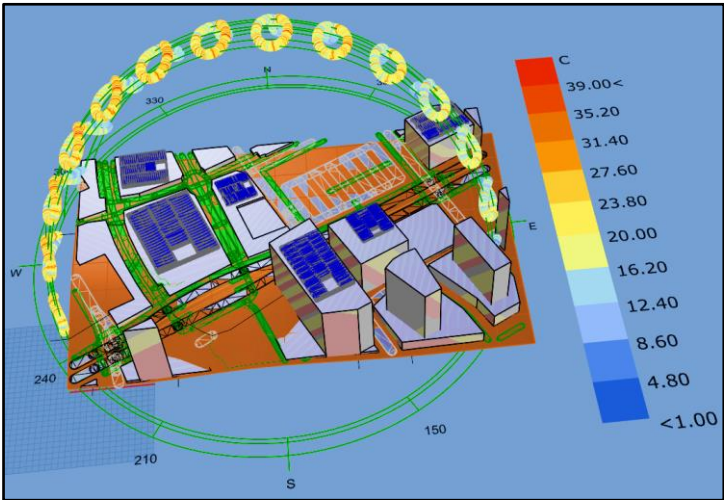


Figure 3-11. Dry and wet bulb temperature approach to the surface of the building

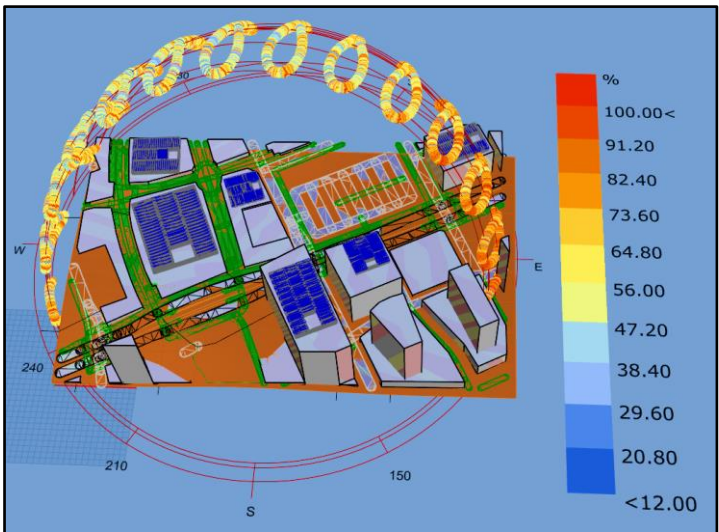


Figure 3-12. The temperature and humidity approach the surface of the building

3.3.4 Orienting Buildings to Use Natural Energy Efficiently

Building orientation [144] is defined as the positioning of a building considering seasonal variations in the sun's path because the intensity of solar radiation varies correspondingly. Optimum building orientation can help increase the energy efficiency of buildings, offering maximum comfort for occupants to live or work in the building and making the building's operations less expensive. For successful building orientation, understanding the principles of orientation along with the local climate is crucial. Indeed, the orientation and the local climates are the most critical factors to consider when determining the region's environment. Furthermore, it is also significantly important to consider the true north and the azimuth angles of the sun, which aid the optimum absorption of solar radiation energy. Choosing the optimum orientation for a particular climate in a region where a building is located maximises the building's potential for solar radiation, passive heating and cooling, which complies with the principles of building orientations. A building oriented with true north [145] helps to maximise natural solar energy.

For these reasons, in this study, building orientations are simulated using software applications. This is done to estimate the minimised energy consumption and optimise energy efficiency before the building commences. Orientation simulations are conducted as shown in Figure 3-13. To investigate the optimised orientation angle, 36 insertion simulation angles are conducted throughout 360°C for the length of a one-year cycle of the sun-path from 1 January to 31 December. Thirty-six insertion lists results are analysed, of which 32 are shown in Figure 3-14. Each insertion step simulation result corresponds to its orientation angle. The optimised angle is found at 70°C, and the corresponding result is also shown next to it. Thus, to use the proposed orientation, the building needs to rotate to 70°C.

Building orientation can also help to withstand disaster. Sustainable building can survive natural and artificial dangers such as earthquakes. Sustainable building, designed with concrete slabs, allows the building to twist and bend but correct itself and self-centre [146] after an earthquake ends. This type of sustainable design absorbs energy from earthquakes to deform, reshape and restore its original form.

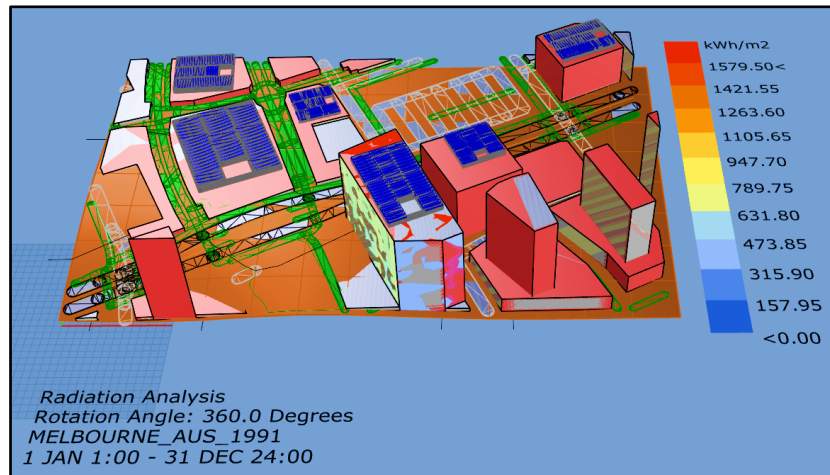


Figure 3-13. Total building solar radiation analysis absorbed by the building for one year cycle

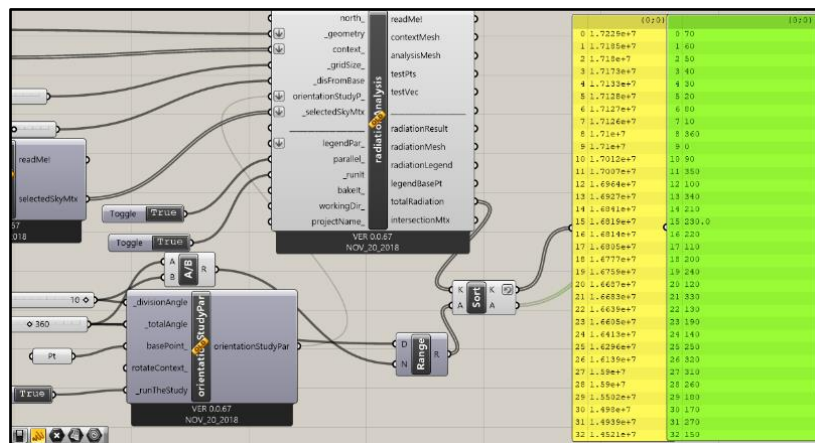


Figure 3-14. A list of 36 items aimed at examining the energy-efficient orientation of the building

Optimal orientation of a building can optimise natural energy use. The optimised building's natural energy use follows the following steps:

1. Specify efficient HVAC and lighting load conditions.
2. Implement renewable energy sources such as solar heating for hot water, geothermal space heating and groundwater cooling.
3. Optimise building performance by employing an energy-modelling package during design and building orientation.
4. Optimise system control strategies by considering occupancy and CO₂ sensors during operation.
5. Monitor project performance using commissioning, metering, annual reporting and periodic re-commissioning.

6. Integrate water-saving technologies to reduce energy consumption.
7. Use daylight energy saving in buildings.

3.3.5 Automating Building Elements to React According to Sensor Network Inputs

Sensors that measure the intensity of the sun's radiation can send a proportional signal strength to the building automation algorithm program, allowing for proportional solar energy to be directed to the building during different weather conditions and climate seasons. This enables shades, windows and curtain walls to react accordingly to the sun's intensity. Automating the use of operating systems in sustainable building is beneficial not only for energy reduction purposes but also for occupants' comfort. Therefore, wise building operation management is important for sustainable building design and modelling. Wise building operations can encompass various methods, but the most valuable, when implemented, can lead to reduced energy consumption and enhanced occupant comfort. These methods relate to:

1. Automated building operating hours per day.
2. Enhanced control and monitoring technology.
3. Wise use of operation techniques pertaining to space occupancy.

3.4 Building Solar Radiation Simulation Using an Alternative: Case Study 2

In the preceding case study, the conceptual mass building was imported into the Rhino architectural software via CadMapper. This imported mass served as a virtual representation of the built environment's content. The simulation of solar energy absorption from sunlight accounted for the potential impact of surrounding buildings on the simulated model. Conversely, in this second case study, the same size of conceptual mass building was first designed using Autodesk Revit, followed by the creation of an energy model. This energy model incorporated fundamental building components, although demonstrating their energy efficiency ratings was not deemed necessary and materials were selected at random. The initial phase involved conducting a primary simulation of solar radiation energy and generating a BIM green building Extensible Text

Markup Language (gbXML) file for export, facilitating subsequent advanced simulation analysis.

3.4.1 Capability of Building's Engineering Data to be Exporting and Importing to Third-Party Energy Simulation

For additional examination, the solar radiation data of the building, primarily generated through specific simulation software, can be transferred to various compatible software platforms. In this case study, the gbXML file containing the BIM data for the green building was exported from Autodesk Revit's conceptual mass simulation into the cloud-based database known as Green Building Studio (GBS) [147]. GBS automatically integrates and configures various energy-simulating input packages through alternative energy-efficient package lists. For example, among the energy package lists used by GBS are Window-to-Wall Ratio (WWR) energy packages, high-performance material energy packages, ASHRAE energy packages, building orientation energy packages, lighting efficiency energy packages and scheduled operational hours energy packages, as shown in Figure 3-15. These types of energy packages are added to the GBS database via insertion techniques. Consequently, while GBS resembles the primary simulation run, it incorporates more sophisticated alternative energy-efficient packages and design options that allow users to choose between automatic or manual selection methods. In the manual selection process, contractors, owners and engineers are required to identify suitable energy-efficient materials. These approaches facilitate simulations that assess a building's solar energy through various alternative insertion runs, utilising what is referred to as EEB elements.

The software executes the simulations in sequence, using regularly updated actual regional weather data to ensure that the simulation process and estimations accurately reflect current environmental conditions [140, 148]. Furthermore, the localised threshold actions of weather files, as illustrated in Tables 3-1 and 3-2, facilitate a more detailed demonstration of annual energy consumption for the alternative design, resulting in significantly lower figures. Notably, several key simulation outcomes include the annual electricity use intensity measured in kWh/m²/year, the annual fuel use intensity expressed in MJ/m²/year, the total yearly energy use intensity (EUI) also in MJ/m²/year, as well as average life-cycle estimates for electricity use in kWh and fuel use in MJ, alongside average life-cycle costs presented in Australian dollars. Moreover, the GBS energy

simulation involved processing 254 different insertions of alternative package lists. This provides the owner or builder of the sustainable structure with options to select the most effective reduction package from these 254 alternatives.

In this context, The HVACTYPES_ASHRAE_Package Terminal Heat Pump emerged as the most favourable choice because it exhibits the lowest annual fuel energy consumption at 156,292.00 MJ and a corresponding electrical use of 1,305,415 kWh, as depicted in Figure 3-16. During manual selection, various energy-efficient building materials were evaluated along with lighting power densities (LPD) that could reach up to 400%. This was aimed at identifying the optimal energy package. The potential for solar energy harnessed by buildings represents a significant yet largely untapped resource for global energy production. On-site generation has the potential to enable buildings to eliminate their carbon footprint when implemented and operated effectively with solar systems designed to mitigate heating needs during winter months, cooling demands during summer and overall lighting energy consumption throughout the year [149].

The main criterion to achieve is the smart selection of the interchangeable building elements—for instance, WWR, window shading, window shading height, window glass type, building orientation, wall insulation type, roof insulation type, infiltration, lighting efficiency, daylight control, occupancy energy control, plug-load efficiency and LPD. These materials and package lists are important in evaluating the energy end-use of sustainable building design. The alternative best run detailed annual energy end-use consists of two primary energies: the annual electricity energy end-use and annual fuel energy end-use, as shown in Figure 3-17. This figure indicates that 6.0% of the electricity end-use is supplied to space heating, 8.4% to fans (ventilation), 9.4% to pumps, 14.6% to space cooling, 1.1% to exterior loads, 34.6% to miscellaneous equipment and 26.4% to lighting. On the other hand, the fuel energy accounts for 97.4% of the HVAC loads, and 2.6% of the total is used for hot water.

Hence, the results of end-use loads demonstrate a shift towards electrical use. The fuel is connected only for heating, which minimises the use of fuel. This is because the use of fuel contributes to greenhouse emissions and is not as safe for occupants' health as electricity.

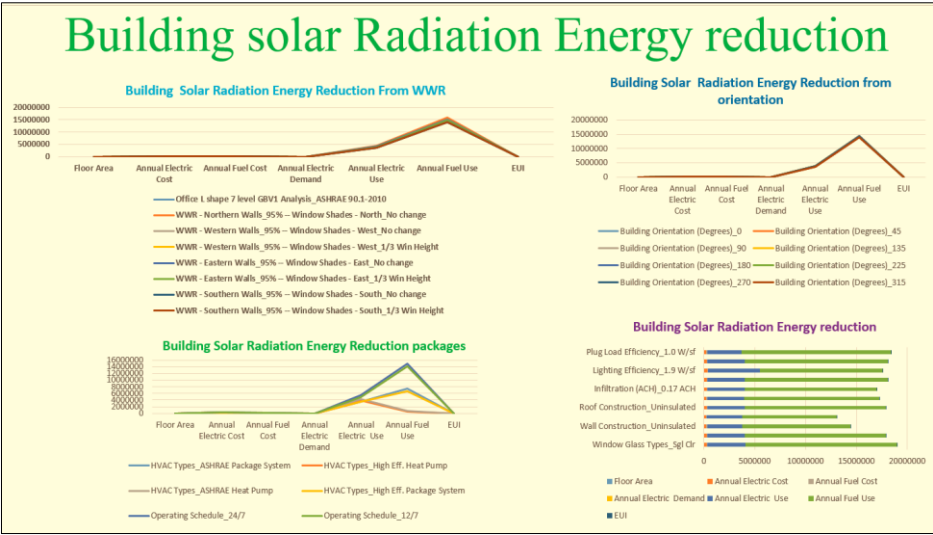


Figure 3-15. Energy reduction in simulations of building solar radiation using different packages and building orientations

Table 3-1. Basic annual cooling and heating temperature per day

Cooling Degree Day		Heating Degree Day	
Threshold	Value	Threshold	Value
65 °F	318	65 °F	4303
70 °F	95	60 °F	2978
75 °F	10	55 °F	1808
80 °F	0	50 °F	1093

Table 3-2. Primary run annual design data weather conditions

Threshold	Cooling		Heating	
	Dry Bulb (°F)	MCWB (°F)	Dry Bulb (°F)	MCWB (°F)
0.1 %	88.3	69.0	28.4	29.9
0.2 %	87.6	67.4	29.1	27.7
0.4 %	86.2	66.8	29.7	27.9
0.5 %	85.5	67.0	30.0	28.4
1 %	83.1	65.5	31.3	29.0
2 %	80.1	64.9	32.9	30.9
2.5 %	78.6	64.0	33.4	31.2
5 %	74.1	61.9	35.2	33.4

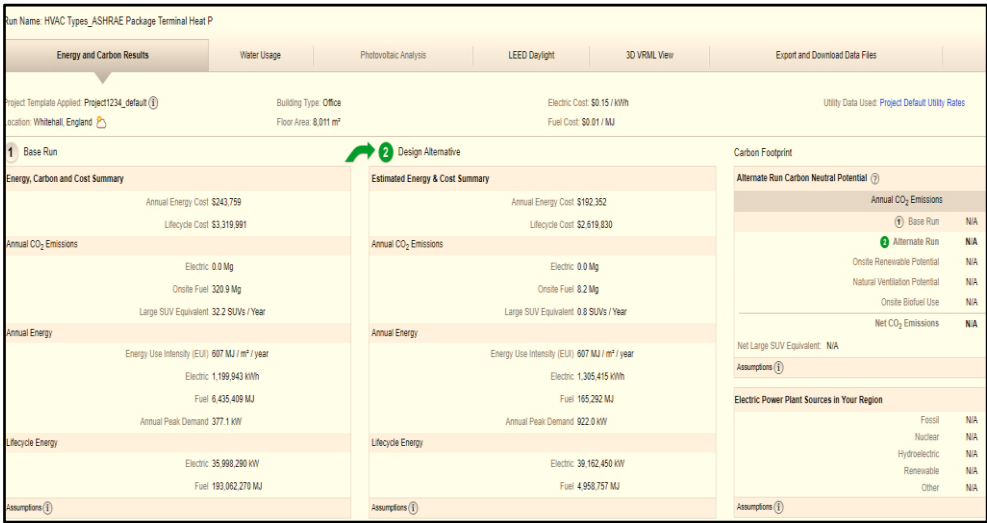


Figure 3-16. Simulation results comprising primary, alternative and footprints for best methods to design significantly less energy annual consumption

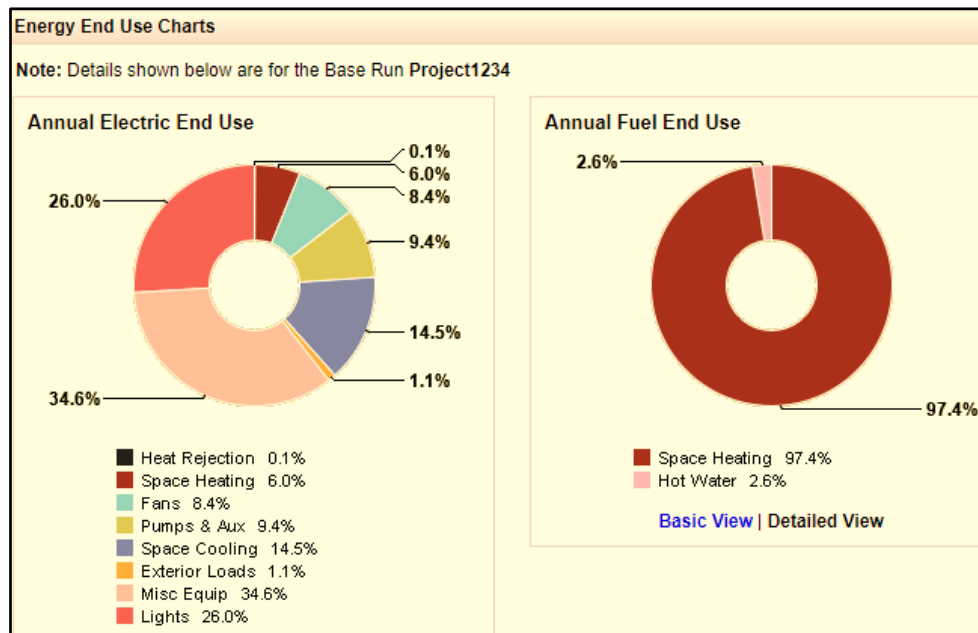


Figure 3-17. Annual end-use loads connected to every item of indoor and outdoor equipment

3.4.2 Building Information System

Implementing a new information system represents a significant strategic transformation within an organisation, extending beyond merely incorporating modern technological elements. Information technology can facilitate various degrees of organisational change, ranging from minor improvements to extensive transformations. The key phases in the development of a system include systems analysis, design, programming, testing, conversion, deployment and maintenance. There are two main strategies for designing and developing information systems: structured methodologies and object-oriented development methodologies.

Hence, a continuous approach and use of technological information systems from the time the construction commences is a system of digital information that is a life-cycle model [150]. The approach requires a linear advancement through established developmental stages.

3.5 Geo-Enabling with Technologically Advanced Interoperability

Geo-enabling initiatives encompass a range of technologies, including global positioning system (GPS), global information system (GIS), remote sensing and data sharing [151], and geospatial analytics. These tools enable building designers to gather, store and

analyse location-based information, which can subsequently be used for monitoring and overseeing various activities. For instance, devices equipped with GPS can track vehicles and manage the delivery of goods. At the same time, GIS facilitates the creation of maps and data analysis to uncover patterns and trends. A significant advantage of geo-enabling initiatives is their capacity to deliver real-time information, empowering organisations to make swift and informed decisions. For example, in emergency response scenarios, timely data aids in effectively deploying resources and enhances the likelihood of favourable outcomes. These initiatives provide organisations with a clearer understanding of on-the-ground situations, enabling more accurate and efficient decision-making.

Another benefit is the ability to perform remote monitoring and supervision, which diminishes the necessity for physical presence at locations. This capability proves especially valuable in instances where having personnel on-site may not be practical or safe, such as in conflict zones or hazardous environments.

Furthermore, remote monitoring contributes to cost savings and boosts efficiency by minimising travel needs and other resource expenditures. Geo-enabling initiatives are reshaping how organisations monitor activities and make decisions by enhancing both accuracy and efficiency. Investing in geo-enabling technologies within smart buildings significantly improves operational management capabilities, leading to better outcomes and fostering long-term success.

For a smart building to qualify as geo-enabled, it should incorporate at least one cutting-edge technology along with a minimum number of intelligent elements, as illustrated in the conceptually assembled commercial office building depicted in Figure 3-18. Its contents are controlled using a decentralised method of smart, sustainable buildings integrated with various sensor-based smart networks and control network systems, utilising an innovative and straightforward technique for energy-saving electrical wiring and communication network protocols. This is an example of geospatially enabled implementation, whereby the building's automation can be configured, controlled and monitored through the global internet, GPS and GIS.

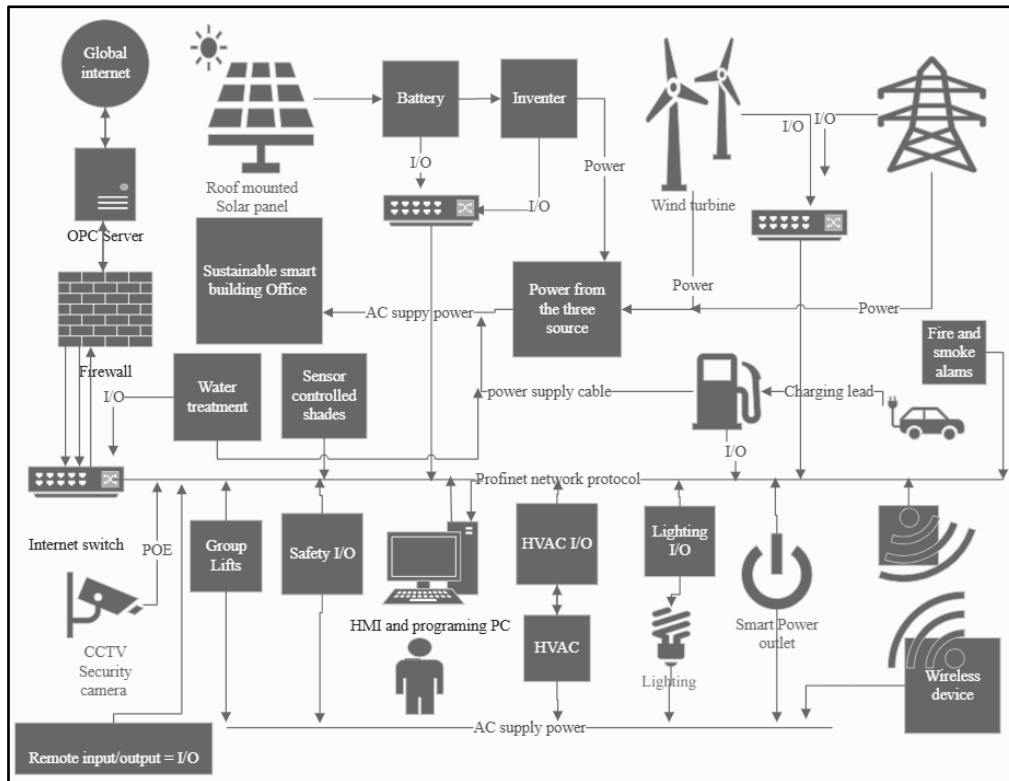


Figure 3-18. Smart, sustainable buildings integrated with sensor smart networks

3.5.1 Measurements and Quantities Over the Life-Cycle of Projects

Running a construction project without proper measurements is akin to navigating a vehicle in the dark without a navigation tool. This approach significantly increases the chances of waste, accidents and catastrophic failures. Measurement plays a crucial role in enabling project managers to identify issues and implement necessary adjustments.

Currently, numerous construction firms use metrics through the minimum viable approach (MVA) [152] tools that facilitate continuous measurement and analysis while collecting data. To model sustainable buildings effectively, it is vital to employ at least a foundational set of measurements. Two types of measures are critical for modern sustainable building projects:

1. Building contractors and engineers must establish specific financial metrics as mandatory measures. However, accurate measurement data are essential, and this requires support from building owners. Delays in decision-making related to this support can result in lagging indicators.

2. The second type of measurement holds greater significance than the first, because it leads to positive indicators that can enhance predictive capabilities regarding the project's short-term, medium-term and long-term outcomes.

Additionally, smart building measurements throughout the project life-cycle should encompass at least four primary assessments, as illustrated in Figure 3-19. These evaluations are crucial for ensuring that the building complies with environmental safety standards.

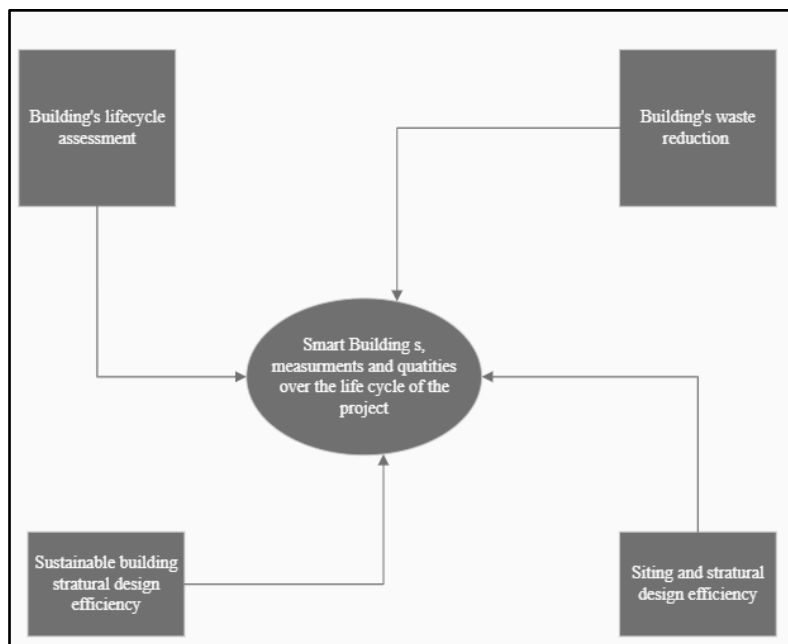


Figure 3-19. Smart building measurement for the project life-cycle

3.5.2 Life-Cycle Assessment

Life-Cycle Assessment (LCA) [153] serves as a valuable tool for professionals in the building industry to understand the energy use and environmental impacts associated with a building's entire life-cycle. This process encompasses an examination of the ecological impacts associated with the various stages of products and materials throughout their life-cycles, focusing on environmental factors and possible negative consequences. The assessment involves documenting energy consumption, material inputs and emissions to identify potential environmental impacts. The findings aim to inform decision-making that considers both human health and wellbeing, as well as the environmental impacts of products, processes and activities. Typically, software applications are used in this

evaluative process to assess a product's comprehensive environmental footprint accurately.

3.5.3 Buildings and Waste Reduction

LCA entails a thorough evaluation of the various stages involved in a product's life, including its production, use and disposal. This assessment encompasses aspects such as material transport, packaging and waste management. Adherence to established international LCA standards is imperative.

Environmental designers should recognise the significant impact that even minor mistakes in production and construction can have on the environment. Gaining insight into these specific impacts is fundamental to sustainable design practices. Educating building operators on LCA techniques empowers them to adopt effective waste management strategies, thereby fostering an environment that minimises pollution through building management.

Additionally, smart building modelling employs sophisticated methodologies to avert improper waste disposal. As a result, builders, contractors and engineers apply LCA methodologies to illustrate how the use of eco-friendly building materials can yield energy savings throughout their entire life-cycle. This strategy enables building owners to recognise that sustainable products and enhanced operational systems can significantly lessen environmental impacts over time.

3.6 Structural Design Efficiency in Sustainable Building

Buildings of the future can be constructed using a sustainable simulation and practical processing approach. Buildings designed for the future use real-time data and interoperable technologies to create sustainable, resilient, efficient and user-centred environments that align with occupants' needs. These structures leverage advanced automation, IoT data analytics and highly efficient renewable energy sources. As a result, they optimise energy use, enhance occupant comfort, improve safety and security, and mitigate environmental instability. Achieving these outcomes involves implementing intelligent lighting systems, sophisticated HVAC solutions, smart meters, occupancy sensor networks and energy management systems. This interconnected approach significantly contributes to minimising energy consumption, lowering CO₂ emissions and

ensuring a seamless user experience. Future buildings hold out several benefits; for example, organisations can implement sustainable net-zero strategies that eliminate unnecessary energy waste, mitigate carbon emissions and reduce energy costs.

Modern energy management systems paired with microgrids also enhance resilience by safeguarding building assets and ensuring continuous operational capabilities. By employing AI-driven data aggregation and machine learning (ML) technologies, operational efficiency is enhanced through real-time data access, task automation, improved decision-making processes and reduced operating expenses. This not only optimises occupant experiences through integrated data management but also fosters increased attraction and retention in smart buildings. Moreover, these buildings are equipped to withstand both natural disasters and human-made emergencies. These buildings' features allow for flexibility, enabling structures to twist or bend during seismic events while returning to their original form post-disaster. Such sustainable designs absorb seismic energy, deforming temporarily before reverting to their initial state. When developing new architectural plans, engineers must carefully consider design alternatives in conjunction with the ecological impacts of construction materials. According to estimates from the California Integrated Waste Management Board, approximately 40–50% of greenhouse gas emissions originate from construction activities. Thus, evaluating design efficiency is essential in creating resilient structures that not only minimise energy consumption but also protect the environment from both natural occurrences and human-induced effects.

3.7 Siting and Structural Design Efficiency

The guidelines for site selection and design aimed at enhancing the efficiency of structural buildings are tailored to the specific locality in which the construction takes place. These site guidelines detail optimal practices for the design and modelling of structures on-site. These recommendations serve as a resource for both individuals and organisations engaged in planning initiatives focused on sustainable development. The principles of design efficiency consider the challenges posed by climate change and population growth, ensuring the preservation of local resources so that residents can continue to use and appreciate their environment.

3.8 Smart Construction Materials

Creating a smart building entails employing strategies designed to reduce its adverse impacts on both the environment and its occupants. This methodology prioritises improving efficiency, reducing the use of construction materials and decreasing long-term operational costs. It emphasises the optimisation of resources while promoting healthier living and working environments. Innovative building materials are classified as eco-friendly resources that contribute to sustainable architecture. These materials possess the following characteristics:

1. Durability.
2. Reusability through recycling processes.
3. Composition of green building materials should be sourced locally and use various techniques.

3.8.1 Smart Building Construction Walls

Massive concrete walls are primarily used for commercial building purposes. This is because the enormous amount of concrete functions as a building envelope. In addition to their primary functions, massive concrete walls play a significant role in regulating heating and cooling zones because of their natural thermal mass characteristics, which enable them to absorb, store and release heat [154-156]. These materials exhibit natural behaviour by absorbing energy slowly and retaining it for much longer periods. This delayed response reduces the heat transfer through the thermal mass and shifts the energy demand to an off-peak time. Energy is saved when a reversal in the heat flow occurs within the walls. In addition, mass and heat flow play significant roles in balancing temperature fluctuations. For example, WWR [157] plays an important role. In winter, the WWR allows excess light into the building, and it allows significant heat to be lost during the opposite season. However, the construction of the building materials, such as cement manufacturing, contributes to substantial environmental degradation and has a significant impact on high energy consumption, natural resource depletion and CO₂ emissions. Hence, it is necessary to minimise the impact and emissions. The amount of cement used in concrete must be reduced by a ‘portion of the cement with coal fly ash or Ground Granulated Blast Furnace (GGBF) slag’ [158]. This is because the level of fly ash in concrete typically ranges from 15 to 35% of the total cementitious material, but

can reach 70% in massive walls. Furthermore, epoxy polyester concrete has the potential to contribute to energy efficiency by providing thermal mass to the building envelope, which slows heat transfer.

3.8.2 Smart Building Construction Windows

Windows play a vital role in building energy efficiency. Windows influence thermal performance by regulating the amount of natural light that enters, which can subsequently decrease the demand for electric lighting. The placement of windows and doors, as well as the choice of construction materials, significantly affect energy consumption. Windows form an integral part of a building's envelope, contributing to a notable reduction in heating and cooling energy needs. An optimal window design enhances daylighting advantages while reducing overall energy use.

In recent decades, innovative and sustainable building designs have successfully addressed up to 80% of indoor lighting requirements by integrating natural light, providing adequate ventilation and appropriately sized windows. Double and triple-glazed smart windows have gained popularity for their demonstrated energy efficiency during this timeframe. As illustrated in Figure 3-20, triple-glazed windows positively influence a building's thermal performance by facilitating a dynamic flow of natural daylight, which helps lower reliance on artificial lighting.

It is essential to consider the orientation of these triple or double-glazed windows in terms of building shape, construction materials and wall alignment to optimise energy efficiency. For example, placing double glazing on a north-facing wall may be more effective than triple glazing because this wall receives more sunlight than others. Therefore, strategically installing glazing according to its prospective benefits could enhance energy savings.

Similarly, when installing double or triple-glazed windows, it is essential to evaluate how external shading affects window performance. Although such shading might not significantly alter window functionality, it could lead to increased energy demands for heating and cooling from HVAC systems. An effective window model maximises natural daylight benefits while minimising reliance on artificial energy sources.

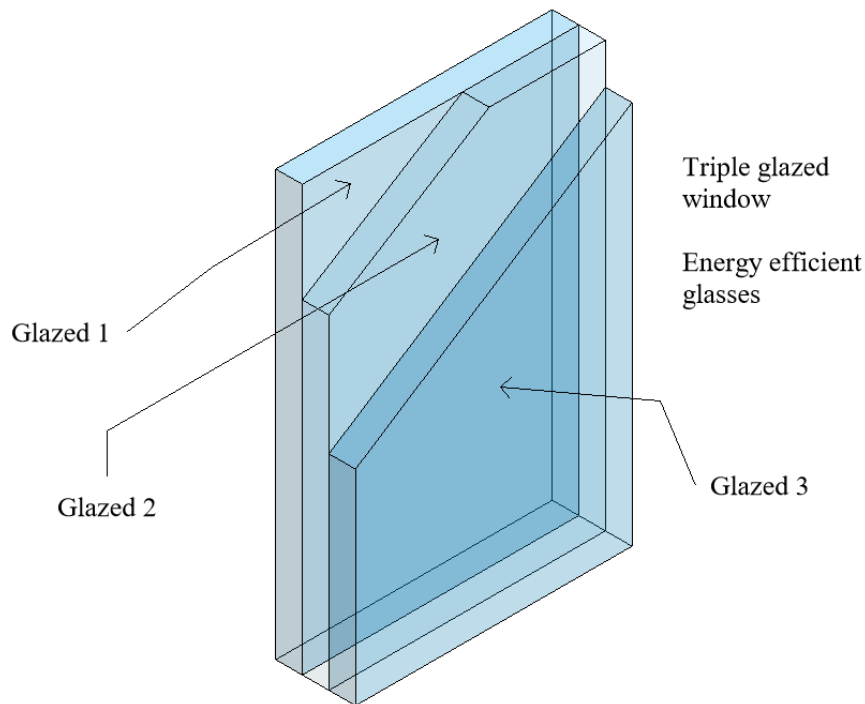


Figure 3-20. Triple-glazed window that responds to sunlight intensity

3.8.3 Building Insulation Materials

Contemporary structures are equipped with unique layers of concrete foam materials to reduce energy use. This construction technique is gaining popularity because it merges the durability of reinforced concrete with the insulating capabilities of foam. The approach presents numerous advantages, positioning it as an optimal and appealing insulation option for builders. This energy-efficient concrete is produced using cast-in-place Insulating Concrete Forms (ICF) [159]. The concrete, reinforcement steel bars, and foam-supporter furring strips are squeezed between two layers of polystyrene foam walls, as shown in Figure 3-21. The elevated thermal efficiency of ICF construction stems from the insulating properties of the foam material, the temperature stability afforded by the concrete's thermal mass and reduced air leakage.

Typically, ICF walls have an R-value of around R-15. Incorporation of recycled materials is possible in both the foam and concrete insulation elements used in ICF constructions. The likelihood of toxic emissions from ICF walls is minimal because the materials are tested before being installed in the building. Expanded polystyrene is the predominant insulation medium employed in ICF construction, which generally does not release harmful emissions. The expenses associated with ICF construction are roughly comparable to those of poured concrete or concrete block methods. While ICF

construction tends to be slightly more expensive than wood or steel-frame options, the energy savings achieved through this method can lead to a lower overall life-cycle cost compared with traditional techniques of wall construction:

1. **Advantages of ICF:** In addition to its notable benefits in construction, ICF exhibits exceptional energy efficiency. The insulating foam panels incorporated into ICF walls establish a continuous thermal barrier that significantly curtails energy consumption for heating and cooling purposes.
2. Furthermore, the substantial thermal resistance of ICF walls aids in maintaining a comfortable indoor climate.
3. **Superior insulation:** ICF walls provide enhanced insulation compared with conventional building practices. The foam panels, usually manufactured from expanded polystyrene system (EPS) or extruded polystyrene system (XPS), demonstrate remarkable resistance to heat transfer. This results in diminished air infiltration, reducing drafts while ensuring stable indoor temperatures.
4. **Sound insulation:** ICF construction stands out for its sound insulation capabilities, contributing to a more tranquil living environment. The synergy between concrete and foam results in excellent sound absorption qualities, thereby lowering airborne noise transmission between rooms and from external sources.
5. **Strength and durability:** Known for their strength and resilience, ICF walls combine reinforced concrete with structurally robust foams to create a strong building envelope. These walls exhibit superior resistance to fire, wind and impacts, making them suitable for regions susceptible to extreme weather conditions or seismic activity. Additionally, they are resistant to decay and pest damage, leading to a longer life span when compared with traditional wood frame structures.
6. **Design flexibility:** ICF construction allows for significant design flexibility, facilitating various architectural styles. Foam panels can be easily cut and shaped for custom wall designs, curved surfaces and intricate architectural features. This adaptability enables builders and architects to realise unique aesthetic visions while benefiting from the advantages offered by ICF construction.

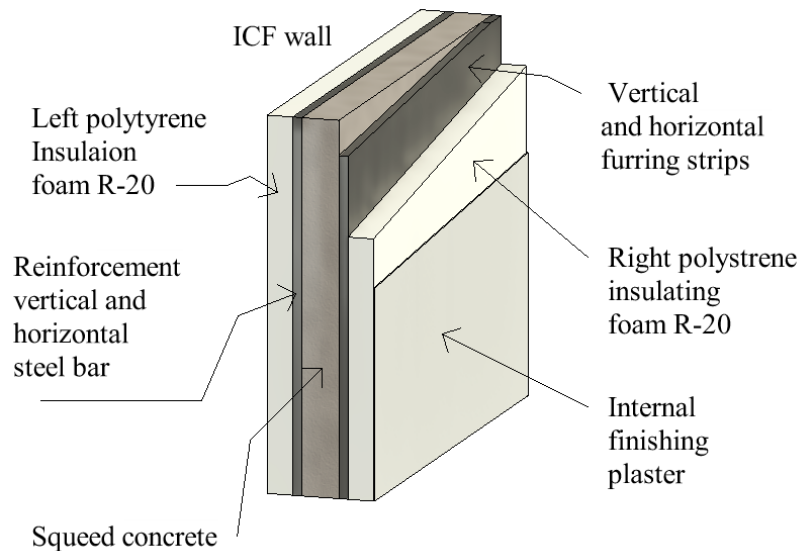


Figure 3-21. ICF element, gap filled with reinforced steel

3.8.4 Energy-Efficient Exterior Finishing in Building Design

Exterior coatings serve to hinder the penetration of water and air [160]. The outer surface serves as a protective barrier against moisture, safeguarding internal components such as wood and steel and insulation from damage caused by water. Contemporary manufactured sidings are crafted to require less maintenance than traditional exteriors. Exterior shades located above windows and doors automatically adjust to sunlight intensity, either bending or straightening as necessary to reduce reliance on artificial lighting. Using materials with recycled content can be an effective and efficient choice for ensuring durability against the effects of sunlight and severe weather conditions.

Additionally, it is essential to consider a design's resistance to external weather factors to achieve optimal performance. For example, exterior insulation finishing systems (EIFS) [161] refer to a specific category of exterior finishes that reduce air infiltration and energy consumption.

3.8.4.1 Smart Building Green Roofs

Dark, non-reflective roof surfaces [162] create heating effects by absorbing energy from the sun and radiating it as dissipated heat. This effect causes ambient temperatures to rise, which increases the cooling requirements in the opposite season. This leads to the use of larger HVAC equipment, resulting in increased building energy consumption. However, a roof system with light colours can reflect heat instead of absorbing it. This helps reduce

the requirements for HVAC equipment, energy use, solar reflectance and thermal emissivity. Hence, it is essential to advise manufacturers of roof products to comply with these requirements.

3.9 Passive Fire-Protecting Polymeric Materials

Fire safety is an important consideration for reinforced concrete structures worldwide. Although concrete is often regarded as fire-resistant, it can still suffer damage from elevated temperatures during a fire, resulting in spalling and compromising the structure's integrity. This situation presents considerable threat to the safety of inhabitants and the financial stability of buildings.

Over the last decade, various fire protection strategies have been developed to address these issues and enhance the thermal properties of materials cost-effectively. Inorganic polymeric materials [163] have emerged as a viable option, offering a combination of physical, chemical, mechanical and thermal properties that provide significant environmental benefits.

3.10 Building Construction Analytics

Smart construction analytics solutions yield various outcomes, as illustrated in Figure 3-22. These analytical tools are generally integrated into a dashboard that displays real-time key performance indicators at the project, program and portfolio levels. Initially, construction data—often gathered through manual methods and involving paper-based processes—shift towards automated processing as the quality of the source data improves. A database platform is employed to organise, analyse and synchronise incoming data, ensuring consistency across diverse sources. These data are then entered into a visualisation dashboard that provides consistent and relevant information for presentation. The visualisation tool enables efficient reporting on critical performance metrics at customisable levels.

Construction analytics solutions evaluate real-time data against established performance benchmarks, analyse trends over time and translate insights into the dashboard format. This process ultimately enhances decision-making capabilities and optimises overall project delivery.

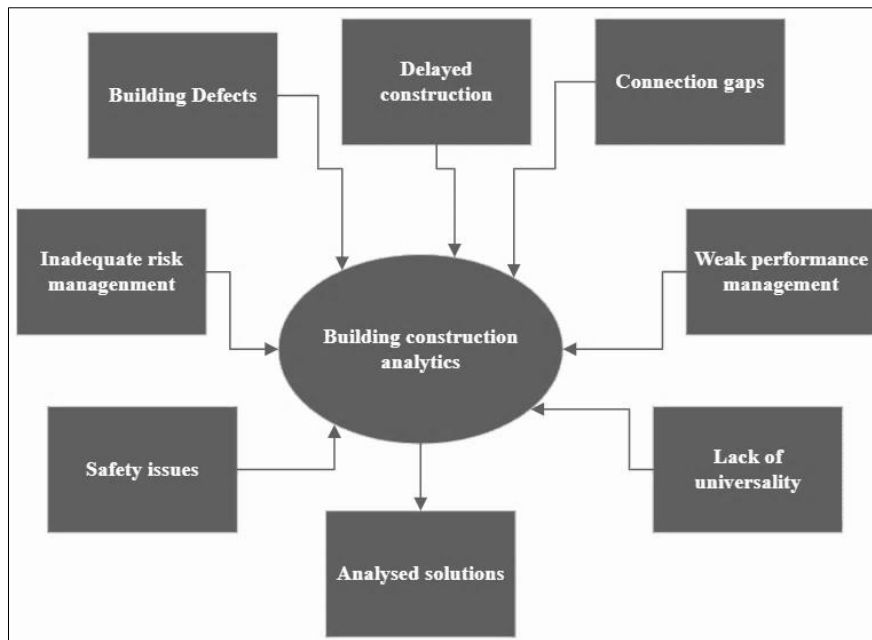


Figure 3-22. Defective elements of building construction and their analysed solutions

3.10.1 Analysis of Defects in Building Design

Although construction projects are typically long-term endeavours, the industry frequently lacks a forward-thinking outlook. This tendency often leads to decreased productivity, higher expenses and the acceptance of significant flaws and persistent problems within construction processes. Labour productivity fails to keep pace with broader economic productivity, resulting in delays in the completion of building projects. Moreover, issues in the design of constructions and failure to comply with standard quality guidelines [164] lead to substantial defects, which delay overall construction.

3.10.2 Delayed Construction Leads to Overspending

Traditional construction techniques tend to be costly and often lack efficiency. In particular, during extensive projects, contractors commonly face challenges in adhering to schedules, managing budgets and following established guidelines. In one survey, some 98% of construction initiatives indicated that they experienced cost overruns exceeding 30%, with a completion delay of 40%. Large-scale construction endeavours typically require around 20% more time than budgeted to finalise, resulting in approximately 80% of projects exceeding budget estimates. The construction industry must embrace innovative, smart methods to mitigate these delays.

3.10.3 Weak Performance Management

Performance management systems that are inadequately designed and executed can lead to substantial negative consequences for any project. Therefore, it is prudent to dedicate significant time and resources towards developing a strong and intelligent performance management strategy. Ongoing performance management is significantly efficient in terms of both time and cost, yielding better results by enabling the prompt detection and resolution of issues. It is essential to avoid disruptions stemming from mid-project changes, ineffective communication and insufficient accountability, which leave problems unresolved.

3.10.4 Lack of Universal Information

In construction, it is crucial for team members to effectively transition their work, whether collaborating with the same colleagues or new ones. Clear communication among team members is vital for executing tasks. Such effective dialogue not only aids in preventing errors but also reduces safety risks on site. If problems arise from earlier phases of the construction process, it may indicate that the project manager lacked sufficient information or was not adequately informed. This situation often results from a gradual erosion of crucial details through poor communication and management practices. Ineffective information management hinders the manager's ability to grasp the nuances of issues and makes it challenging to identify solutions.

The procurement team oversees complex contracts, which can lead to misunderstandings for construction project management (CPM) [165] when challenges emerge during the building phase. To mitigate against potential errors, smart building projects are initially modelled using software simulation technologies such as digital twins before commencing actual construction.

3.10.5 Connection Gaps

In the domain of construction design planning, multiple factors are involved, including meticulous preparation and ongoing tasks. When there is a discrepancy between day-to-day functions and the main goals set for that day, it is essential to notify schedulers; however, this action is often neglected. As a result, delays arise because of the absence of timely modifications to task priorities. Within the sphere of smart building

development, collaboration gaps are greatly minimised by promoting an integrated strategy among contractors, engineers and owners, ensuring that communication flows effectively and consistently.

3.10.6 Water-Damaged Buildings

Various types of water-related structural damage can affect buildings, with erosion, flooding and moisture being the primary offenders. Structures that are poorly constructed may suffer from water intrusion arising from insufficient drainage systems or defective downspouts, which can result in overflow problems. Flooding has the potential to undermine the foundation of inadequately designed properties, possibly leading to structural failure. Moisture issues, frequently arising from high humidity levels in enclosed spaces, can cause significant complications such as dry and wet rot or the growth of black mould. These issues can be overcome using biological wastewater treatment, known as a ‘living machine’ [166], typically installed at the bottom of the building, which enhances ecological sewage technology and mitigates against water damage.

3.10.7 Inadequate Risk Management

Construction managers, engineers and contractors often assess potential long-term risks associated with planning, design, construction, operations and maintenance. However, they frequently neglect to address immediate risks related to the work itself. These minor construction challenges can significantly disrupt decision-making processes and result in considerable delays to the project schedule. To mitigate this issue, smart building implements a comprehensive risk management matrix designed to prevent cascading delays.

3.10.8 Building Work Practices and Safety Issues

Safety management practices represent a critical factor in the context of smart buildings. Workplace injuries can delay projects, resulting in budget overruns because of the need to address these setbacks. By investing in effective safety management programs, organisations can significantly lower the incidence of workplace injuries, leading to fewer disruptions and enhanced productivity that helps keep budgets on track. Robust safety management not only boosts project return on investment [166] but also enhances the company’s reputation.

3.10.9 Analysed Solutions

Enhancing core project management capabilities emerges as a practical approach to addressing construction challenges and improving overall efficiency. By emphasising transparency and real-time collaboration, a fluid workflow is created, which supports an environment that allows for swift resolution of issues. With the implementation of efficient tracking systems and preparedness for unexpected developments, construction teams can respond proactively to minor changes, ensuring both adaptability and flexibility.

The use of transparency, real-time data and comprehensive tracking methods helps streamline change-order procedures, thus minimising delays caused by disputes in construction projects. This strategy results in reduced downtime, presenting a valuable opportunity for boosting productivity at construction sites. Although the integration of technology plays a crucial role in enhancing productivity within the project, it is essential to acknowledge that its effective deployment in project management presents considerable challenges. Improvements in performance and productivity often lead to better financial results; however, the overarching goal is to cultivate a sustainable and flourishing construction sector that serves the interests of global stakeholders.

3.11 Strategic Management

Smart building strategies focus on energy management, safety, security and the ongoing pursuit of environmental sustainability. To attain effective energy management that enables accurate tracking of energy consumption and expenditures in designated areas, buildings should adopt comprehensive energy management plans. These plans should include detailed monitoring, verification processes and predictive analytics conducted at a granular level with increased frequency. This methodology supports continuous automated energy evaluations using predictive information regarding indoor temperatures, occupancy rates and operational hours. In this way, it becomes possible to gather data on greenhouse gas emissions, generate energy use reports and enhance occupant accountability.

As illustrated in Figure 3-23, the strategic management of smart buildings encompasses various branches that function as distinct components, each with specific responsibilities.

Therefore, tailored strategies are necessary for effectively and intelligently managing these tasks. The ongoing strategic oversight of smart buildings contributes to enhanced overall performance across the building facility.

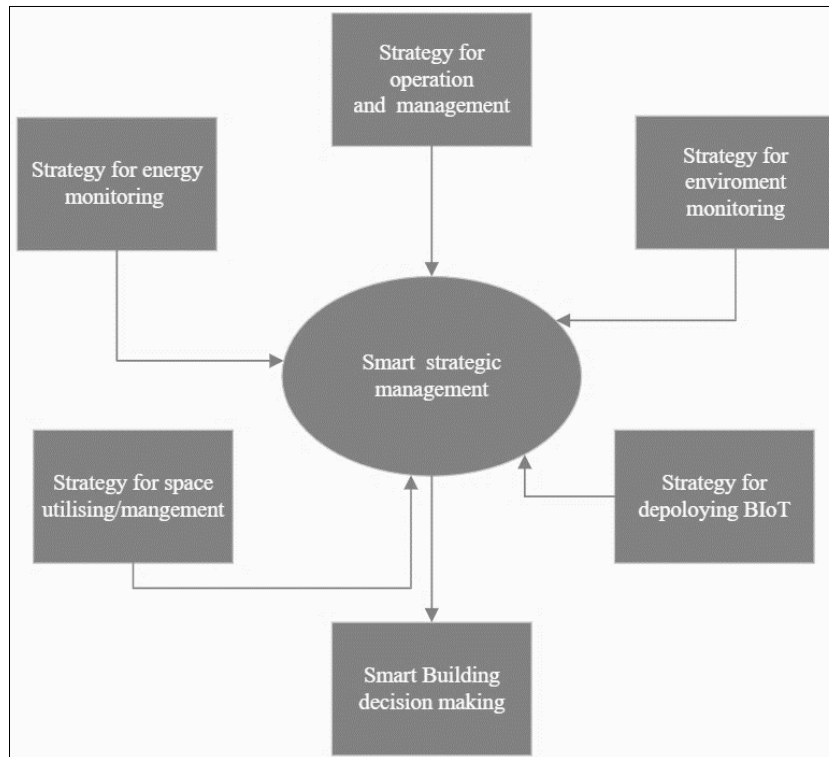


Figure 3-23. Smart strategy for smart managing of the building during design and operation

3.11.1 Strategy for Monitoring-Based Commissioning of Energy

Efficient energy management can be significantly enhanced through the adoption of monitoring-based commissioning. This methodology provides building technicians and operators with essential tools to track and manage the performance of HVAC systems, identify and address equipment issues proactively, and prioritise maintenance tasks aimed at prevention. Monitoring HVAC performance plays a vital role in effectively managing energy use, peak demand and off-peak consumption. Ensuring both indoor and outdoor air quality is crucial for safeguarding environmental standards in high-performance building management.

3.11.2 Strategy for Space Management

To improve the understanding of space use among building developers, operators and occupants, it is essential to recognise the specific users of various spaces. This can be accomplished by implementing occupancy sensors with a spatial resolution that does not exceed 500 square feet per sensor in buildings. Additionally, it is advisable to install anonymous people-counting systems in individual rooms. The use of RFID tags [167] and digital access control systems for shared or maintainable areas is vital for effective management of smart building spaces. A deeper insight into building energy consumption can be achieved by examining space use, shifting focus from energy per unit area intensity (EUAI) to occupancy-based energy metrics. This transition can facilitate initiatives aimed at improving both energy and spatial efficiency within environments.

3.11.3 Strategy for Deploying Building BIoT Systems

Most smart building BIoT systems typically consist of multiple elements, beginning with BIoT sensors that collect data from within the building. These sensors connect to a gateway, which facilitates communication between the network elements. BIoT may also link to the building's server to consolidate information from all gateways.

A cloud-based server synchronises with the gateways or an on-site server dedicated to data storage and data analysis. It is therefore essential to collaborate with information technology (IT) departments to identify and mitigate any potential security risks. In some cases, strategic BIoT solutions can provide integration options for protocols such as BACnet and Modbus, as well as other similar systems, through their networks.

3.11.4 Operation and Management.

Wise building operation strategy is essential in sustainable building design. The strategy can include many types of operation methods, but the most valuable methods are:

1. Building operating hours per day method.
2. A control and monitoring system method.
3. Space occupancy operation technical method.

The practical implementation of these methods provides reduced energy use.

3.11.5 Decision-Making Strategy

The foundation of strategic decision-making in smart buildings relies on the integration of interconnected technologies. These buildings use a network of sensors, devices and systems to collect and analyse vast amounts of data, allowing them to adjust in response to fluctuating conditions. Automated lighting systems adjust brightness levels according to natural light availability, thereby contributing to sustainability by reducing energy consumption. HVAC systems react instantaneously to enhance comfort while reducing energy wastage. This level of adaptability not only enhances occupant comfort but also significantly reduces resource consumption and greenhouse gas emissions, thereby promoting environmental sustainability.

Interconnected technology also boosts productivity within smart buildings by promoting integrated communication systems that facilitate seamless collaboration among employees, irrespective of their physical locations. For instance, state-of-the-art audio-visual features in smart meeting rooms allow for more effective presentations and discussions. Additionally, facilities management teams can remotely monitor and control various building operations, optimising maintenance schedules and minimising disruptions. By harnessing interconnected technology, smart buildings cultivate an environment that enhances productivity and operational efficiency.

3.12 Water Efficiency Management

Nowadays, contemporary buildings are equipped with networks of BIoT flow sensors that facilitate proportional control systems. When used judiciously, water-efficient appliances and fixtures can significantly reduce water use and help preserve sustainable water resources. Washing machines, toilets, showers and gardening applications rank among the highest-consuming uses of water. As a result, smart buildings implement various strategies to curtail water consumption. One practical approach is the recycling of wastewater through advanced filtration and treatment methods. Additionally, harnessing rainwater is crucial because it helps decrease the overall wastewater produced by the building.

3.12.1 Building Solar Radiation Simulations for Water Reduction

The aim of building a solar radiation energy simulation is to achieve significant savings in annual water use for sustainable building design, which enables increased water efficiency and reduced corresponding energy costs. Studies in this field have shown that up to 30% of commercial buildings' energy use reduction is from the water heating sector [51]. Implementing highly efficient hot water use and considering alternative methods, such as 'geothermal heating' (subject to availability), could lead to improved energy reduction and minimise the amount of pollution related to energy consumption.

For this study, a simulation of a building's absorption of solar radiation is conducted to estimate the annual energy use. Solar radiation directly influences a building's water efficiency because of the intensity of radiating energy, which allows water to evaporate quickly and wet materials to dry rapidly. For instance, a particular building may use evaporative water-cooling systems that lose significant quantities of water through evaporation. Hence, water simulation is crucial for the effective use of smart buildings and achieving water efficiency.

Here, two cases have been configured to obtain the correct estimated simulation reduction: primary configuration and alternative configuration. In the primary configuration, no change is made. All the water sources are configured as standard use, as shown in Figure 3-24; no significant measures are taken to reduce water use. In the alternative configuration, considerable measures are taken to reduce water use, as shown in Figure 3-25. All other parameters are configured as water-saving, excluding the number of occupants. For instance, water efficiency is configured as 'standard' in the primary configuration method, whereas water efficiency is configured as 'low flow' in the alternative configuration. As a result, a notable decrease in water use is observed when these two scenarios are analysed within the alternative configuration simulation. The net annual savings result is estimated at 197,491 L/year. In addition, the alternation NetZero-saving is estimated at 3, 138, 36 L/year.

LEED® Water Efficiency

Water Usage and Costs

Total: 5,637,788 L / yr \$8,082 / yr

Indoor: 4,564,403 L / yr \$7,348 / yr

Outdoor: 1,073,385 L / yr \$734 / yr

Net Utility: 5,637,788 L / yr \$8,082 / yr

General Information

Project Title: Project 224

Run Title: WAC_Types_224WAC_Package_Terminal_Heat_P

Building Type: Office

Floor Area: 0.011 m²

Water Usage Estimator

Change building type or project to adjust water usage and costs

Estimate Save Reset

Indoor Water Factors

Number of People: 265

Percent of Time Occupied (%): 25

Unit Water Prices

Water: 0.68 \$ / m³

Sewer: 0.92 \$ / m³

Outdoor Water Factors

Irrigated Area (m²): 1000

Timed Sprinklers: 100 %

Pool: 100 %

Other Equipment/Fixtures: 100 %

Usage: 25 L / day

Building Summary

	Total	Male	Female	Employee Only	Efficiency	Percent of Indoor Usage (%)	Gallons per Year	Annual Cost Savings (\$)
Toilets	11	10	10	3	Standard	0	0	0
Urinals	5	5	5	3	Standard	0	0	0
Sinks	4	10	10	2	Standard	0	0	0
Showers	5	5	5	5	Standard	0	0	0
Clothes Washers	5	5	5	5	Standard	0	0	0
Dishwashers	5	5	5	5	Standard	0	0	0
Cooling Towers	0	0	0	0	Standard	0	0	0
Total Efficiency Savings:					0%	0	0	0

Net-Zero Measures

Annual Rainfall (mm): 612

Catchment Area (m²): 1144

Surface Type: Grass/Turf

Net-Zero Savings

	Annual Rainfall (mm)	Catchment Area (m ²)	Surface Type	Liters per Year	Annual Cost Savings (\$)
Rainwater Harvesting	Yes	612	Grass/Turf	0	0
Native Vegetation Landscaping	Yes	612	Grass/Turf	0	0
Greywater Reclamation	Yes	612	Grass/Turf	0	0
Site Pervious Water Sources	Yes	612	Grass/Turf	0	0
Total Net-Zero Savings:					0

Figure 3-24. Standard water configuration where no saving is attempted

LEED® Water Efficiency

Water Usage and Costs

Total: 4,980,241 L / yr \$6,296 / yr

Indoor: 3,772,404 L / yr \$4,961 / yr

Outdoor: 1,207,837 L / yr \$1,535 / yr

Net Utility: 3,648,207 L / yr \$4,763 / yr

General Information

Project Title: Project 224

Run Title: WAC_Types_224WAC_Package_Terminal_Heat_P

Building Type: Office

Floor Area: 0.011 m²

Water Usage Estimator

Change building type or project to adjust water usage and costs

Estimate Save Reset

Indoor Water Factors

Number of People: 265

Percent of Time Occupied (%): 25

Unit Water Prices

Water: 0.68 \$ / m³

Sewer: 0.92 \$ / m³

Outdoor Water Factors

Irrigated Area (m²): 1000

Timed Sprinklers: 100 %

Pool: 100 %

Other Equipment/Fixtures: 100 %

Usage: 25 L / day

Building Summary

	Total	Male	Female	Employee Only	Efficiency	Percent of Indoor Usage (%)	Gallons per Year	Annual Cost Savings (\$)
Toilets	11	10	10	3	Low-Flow	11.8	538,171	888
Urinals	5	5	5	3	Low-Flow	3.5	155,340	257
Sinks	4	10	10	2	Low-Flow	1.2	57,811	92
Showers	5	5	5	5	Low-Flow	0.8	35,471	57
Clothes Washers	5	5	5	5	High-Efficient	0	0	0
Dishwashers	5	5	5	5	Efficient	0	1,807	2
Cooling Towers	0	0	0	0	Optimize	0	0	0
Total Efficiency Savings:					17.4%	791,969	\$1,275	

Net-Zero Measures

Annual Rainfall (mm): 612

Catchment Area (m²): 1144

Surface Type: Grass/Turf

Net-Zero Savings

	Annual Rainfall (mm)	Catchment Area (m ²)	Surface Type	Liters per Year	Annual Cost Savings (\$)	
Rainwater Harvesting	Yes	612	Grass/Turf	960,832	386	
Native Vegetation Landscaping	Yes	612	Grass/Turf	1,804,464	1,246	
Greywater Reclamation	Yes	612	Grass/Turf	753,543	1,213	
Site Pervious Water Sources	Yes	612	Grass/Turf	15,259	13	
Total Net-Zero Savings:					3,136,369	\$2,858

Figure 3-25. Configured for high-standard water savings

3.13 Reusing Construction Materials for the Circular Economy and Sustainable Development

Recovering and reusing products, components and materials by applying recycling encourages sustainable practices and reduces dependence on limited natural resources. The circular economy model focuses on the reuse of materials to meet sustainability objectives while minimising environmental impact. Moreover, shifting from a linear to a circular economic framework can help protect the planet and its resources for future generations, thereby supporting sustainable development initiatives.

Figure 3-26 illustrates the sustainable economic circulatory system of the building, which can be realised through threshold objectives derived from the building's characteristics.

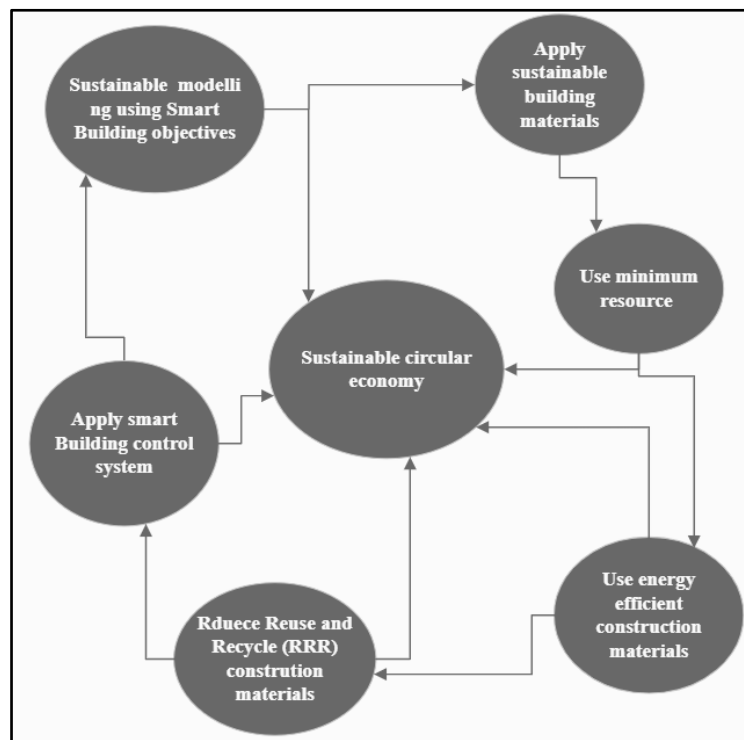


Figure 3-26. Circular economy of the sustainable building model

3.14 Analytical Approach to a Sustainable Smart Building Model with Energy Optimised

The results of the energy-efficient package simulation for the final alternative design, as presented in Table 3-3, indicate a considerable decrease in annual fuel energy consumption, achieving a reduction of 97.43% in fuel energy when compared with the baseline results. In contrast, yearly electricity use showed an increase of 8.78%. However, the substantial decline in fuel energy far outweighs the minor rise in electrical consumption.

The purpose of this energy simulation is to realise and estimate an overall reduction in annual energy use, which totals 88.65% of the baseline. These reductions are based solely on the simulation of the building's solar radiation and do not account for potential savings from the BACS energy control system, BIoT integration and smart grid efficiencies. In addition, the current literature on BACS suggests that an average energy saving of 15–30% is possible [44, 68, 168-170].

Hence, calculating the 15% Base run energy reduction is:

$$\sum \left[Fuel + Electric = \frac{4435409}{3.6} + 1199943 \right] \times \frac{15}{100} = 448133.49 \text{ kWh}$$

Total energy reduction is:

$$\sum \left[Fuel - electric + BACS = \frac{6270117}{3.6} - 105475 + 448133.49 \right. \\ \left. = 2084357.17 \text{ kWh} \right]$$

Hence, the total energy reduction as a percentage is:

$$\Sigma \left(\frac{2084357.16}{2987556.6} \right) \times 100 = 69.78 \%$$

In this case, the optimum energy reduction is approximately 69.78%.

The decrease in rest energy is expected to be achieved through the generation of renewable energy sources. This allows the building to be approximately self-sustaining in terms of annual energy consumption and zero carbon footprint emissions.

Table 3-3. Energy simulation results of sustainable building design

Primary run annual use simulation results		Alternative design run energy simulation result	
Annual electricity use	1,199,943 kWh	Annual electricity energy	1,305,415 kWh
Annual electric cost (\$0.15/kWh)	\$179,991.45	Annual electricity cost (\$0.15/kWh)	\$195,812.25
Annual fuel energy	6,435,409 MJ	Annual fuel energy	165,292 MJ
Annual fuel cost (\$0.01/MJ)	\$64354.09	Annual fuel cost (\$0.01/MJ)	\$860.95
Life-cycle electric energy	35,998,290 kW	Life-cycle electric energy	39,162,450 kW
Life-cycle fuel energy	193,062,270 MJ	Life-cycle fuel energy	4,958,757 MJ
Annual CO ₂ emissions (on-site electric)	0.00 Mg	Annual CO ₂ emissions (on-site electric)	0.00 Mg
Annual CO ₂ emissions (on-site fuel)	320.9 Mg	Annual CO ₂ emissions (on-site fuel)	8.2 Mg

3.15 Conclusion

The aims of achieving comprehensive energy efficiency in commercial smart buildings remain complex, with numerous critical challenges yet to be addressed. Recently, there has been a notable increase in research aimed at tackling these challenges. This chapter has primarily examined the methodologies employed in these studies, transitioning into the central theme of conceptual energy simulation.

Two distinct solar radiation simulation software programs were analysed alongside their outcomes to determine optimal strategies for reducing energy consumption. The two solar conceptual simulations were:

1. Building a simulation of sun intensity irradiation in a built-in environment, where the surrounding building influences the simulated building using imported conceptual mass. Total annual intensity of 6,212.54 kWh/m² is absorbed at a randomly built structure, and when orientation is conducted, 8,687.2 kWh/m² is obtained. There is a 39.84% increase in energy absorption, which is beneficial in cold climates, allowing for a significant reduction in heating consumption and making it suitable for the northern hemisphere.
2. The solar energy from the solar radiation was carried on a newly constructed conceptual mass without considering the influence of surrounding buildings, and an estimated 69.78% annual energy saving was achieved.

Furthermore, detailed discussions in this chapter encompassed aspects such as building orientation, water efficiency, structural defects and smart management techniques. The findings from both software indicate a substantial decrease in energy use, resulting in reduced annual energy costs and minimised carbon emissions.

Chapter 4

Modelling a Building's Energy with Renewables for Sustainable Development

4.1 Introduction

In this chapter, the idea of creating smart, sustainable buildings that use renewable energy directly pertains to a model of construction designed to be energy-efficient throughout its entire life-cycle. Achieving this necessitates the incorporation of substantial renewable energy sources. Fulfilling the criteria and objectives associated with sustainable buildings aligns closely with the reductions in energy consumption predicted through solar radiation simulations. The designer of the building should evaluate the relationship between the energy consumed by the structure and the energy produced from renewable sources before beginning construction. This simulation of energy consumption should aim to match actual use levels closely. By doing so, reliance on non-renewable energy sources can be minimised, promoting environmental sustainability within the construction sector. Therefore, this chapter presents five conceptual case studies using various software tools to meet the basic requirements for achieving smart building objectives through renewable resources.

4.2 Sustainable Building Design and Modelling with Renewals

Integrating sustainable building designs with renewable energy covers several new modern energy sources [29]. However, the most effective devices currently available, particularly in innovative, sustainable buildings, are PV cells and wind turbines. These renewable energy sources offer significant economic advantages. This chapter provides a brief overview of their integration with smart grids and the IoT to achieve optimised performance.

Renewable energy integration with a smart grid refers to an electricity network that employs a combination of digital, analogue and other sophisticated technologies within an integrated system for the intelligent control and secure management of electricity

distribution. The infrastructure of a smart grid encompasses various related technologies, including smart metering, advanced energy storage solutions, HMI and dynamic response technology management. The renewable energy generated by buildings interfaces with a smart grid through the use of HMI and PC-based software systems.

4.2.1 Mathematical Modelling of Renewable Energy

The term ‘design of sustainable building with renewables’ refers to creating buildings that are energy-efficient and environmentally sustainable. ‘Renewable energy’ refers to an energy source that can provide a continuous supply of clean energy, although its availability may vary under certain conditions [171]. Hence, the structure should strive for self-sufficiency to ensure a sustainable supply of clean energy. This approach will aid in reducing the ecological footprint and meeting the criteria for an ‘environmentally friendly building’, which is a key goal of sustainability. Effective and sustainable building designs must incorporate enough renewable energy devices or adequate renewable resources to generate energy that matches the building’s annual energy consumption. Hence, to calculate the estimated yearly energy consumption, it is essential to use simulations of absorption of solar radiation energy and implement a smart building automation control system algorithm. To achieve this, the following procedures should be undertaken:

1. Run the building’s solar radiation absorption and obtain primary run simulation results.
2. Run an alternative design using the energy package provided by the simulation software application.
3. Estimate the annual energy reduction obtained from the smart building automation control system.
4. Estimate the maximum available space for renewable energy installation for both rooftop and side mounting spaces, then formulate a conceptual equation that will allow the building to be sustainable in terms of energy supply. However, in practice, the equation may not be beneficial, and achieving the desired outcome may be difficult because the number of renewable sources does not match the building’s available rooftop and side spaces. Additional spaces or high-efficiency PV cells must be considered to use the renewable energy potential.

The formulation of a mathematical model for the sustainable building design's expression of consumed energy is presented in Equations (4-1) and (4-2). Equation (4-1) is for single-renewable devices and Equation (4-2) is for multiple. In Equation (4-1), A_c and E_g are fixed values, but alternative run values range from 1 to 254 simulation energy results. The range increases the likelihood of finding the best energy reduction among the 254 alternative lists. Hence, in Equation (4-2), A_{run} and E_g are not fixed values. Therefore, there are significant opportunities to select the best energy reduction from the 254 lists and to add the number of renewable energies to satisfy Equation (4-2).

$$E_c = B_{run} - \left(\sum_{N=1}^{N_m=254} A_{run} + A_c + E_g \right) \quad (4-1)$$

$$E_c = B_{run} - \left[A_c + \left(\sum_{N=1}^{N_m=254} A_{run} + \sum_{S=1}^{S_m} E_g \right) \right] \quad (4-2)$$

Where,

E_c is the annual estimated energy consumed by the building.

B_{run} is the primary run annual energy potential obtained from the first simulation result.

A_{run} is an annual alternative design energy reduction selected from the alternative design results.

A_c is estimated to have energy reductions obtained from control systems, IoT and daylight savings.

E_g is the calculated or simulated annual energy generated from renewables.

N_m is the maximum number of alternative design energy package lists.

N is the selected number of energy packages.

S_m is the maximum number of available spaces for renewable energy installation.

S is the number of renewable energy installations.

PV cells and wind turbines, as well as rooftop space limitations, create alternative solutions. Wall-mounted solar and wind turbine energies have significant advantages over their rooftop counterparts, especially for future designs, as building land decreases. High-

rise premises are becoming preferable for residential living and business hubs. However, PV cells and wind turbines mounted on the side of the wall require more mounting materials than their rooftop counterparts. This adds cost, which will reduce the overall efficiency. The conceptual and practical performance of wall/façade-mounted PV cells [164] is lower than that of rooftop-mounted. This is because of building shape, where most buildings are rectangular, circular or L-shaped. For instance, when PV cells are mounted on each side of the walls, the following effects will likely occur:

1. In the morning, only the PV cells facing east will have access to the sun; other PV cells facing north, south and west will produce almost zero energy.
2. Similarly, during the afternoon, only PV cells facing west will have access to the sun. Hence, it is necessary to consider the total hours that the PV cell receives adequate sunlight intensity on average cloudy days. This estimation will help to determine which side of the wall is feasible for installing PV cell panels.

It is known that PV cells produce the highest output at noon. PV cells mounted on the wall are unlikely to obtain optimum sun intensity even then. In the case of vertical/horizontal axis wind, the turbine [172] mounted on the side of the building wall exhibits a phenomenon similar to that of PV cells. A wind turbine mounted on the side of a building wall will experience wind speed (wind drag and lift forces) only when the wind direction is in favour of its side. It is also unlikely to change the blades in the direction of the wind. In contrast, rooftop wind turbine blades can be adjusted according to the direction of the wind. PV cells and wind turbines mounted on the side of the building wall will experience limited hours of sunlight and variable wind directions. Increasing the number of PV cells and wind turbine devices will compensate for them, but will also reduce overall efficiency.

In addition, well-planned and designed sustainable buildings have the advantage of minimising energy use and contribution to pollution. This creates a resilient impact on environmental stability, resulting in long-term, environmentally friendly benefits within the building. To implement this, there is a need to consider several sustainably designed solution packages:

1. Methods to save money, energy and time.
2. Consider building design to construct buildings with future lifetimes.

3. Use cooperative work methods that all responsible bodies incorporate into the design to make it truly sustainable, which will contribute to energy efficiency and reduce CO₂ emissions.
4. Model environmentally capable buildings that are resilient to the region's natural disasters and fulfil the sustainable building design objectives.

4.2.2 Optimising PV Cell Arrays Using Autodesk Revit Software: Case Study 1

Over the past few decades, advancements in solar energy technology have led to substantial improvements in efficiency. With the integration of solar battery storage systems, solar energy has become a highly effective source of renewable power.

Light consists of electromagnetic waves that include particles known as photons; when these photons strike a flat semiconductor surface, they can be reflected off from the top layer, absorbed by the semiconductor material itself or transmitted through the material, missing these two chances (reflection and absorption). Lights that are reflected or transmitted are often regarded as inefficient since the photons fail to capture electrons for energy generation. When the light-sensitive semiconductor material absorbs photons, electrons can be excited instantaneously from the valence band to the conduction band. Energy generation occurs when photons possess sufficient energy to dislodge electrons from the valence band into the conduction band; this happens when a photon's energy meets or exceeds the material's bandgap energy. Moreover, materials characterised by a higher absorption coefficient ($\alpha = 4\pi K/\lambda$) are more likely to absorb photons effectively [173]. The absorption coefficient indicates the depth to which light of a specific wavelength can penetrate a material before being absorbed. This coefficient varies depending on both the type of material and the wavelength of the light. For optimal energy generation from PV cells, it is essential that the material effectively absorbs enough short-wavelength photons and has a high absorption coefficient.

To enhance energy production from PV cells, it is beneficial to implement a system that tracks sunlight intensity. The energy output from solar panel cells is contingent upon sunlight intensity, which is maximised when sunlight strikes the panel at a right angle. Consequently, these cells generate the highest amount of energy around midday when they receive peak sunlight intensity. However, several factors can influence the energy-

generating capability of solar panel cells. These include the sun's position in relation to azimuth angles during morning and evening hours, seasonal variations caused by the Earth's tilt (declination angle) and the sun's elevation in relation to zenith angles. All these elements play a crucial role in determining the intensity of sunlight. In response to these challenges, researchers over the past decade have explored various alternative methods aimed at enhancing the fundamental performance and efficiency of solar panel cells. These innovations are designed to mitigate energy losses caused by influencing factors and strive for maximum output throughout daylight hours. Different techniques and approaches have been employed in this pursuit; one notable method involved is 'servo motor sunlight tracking' [174], where the servomotor is employed to rotate and tilt the solar panels. Alternative methods operate on a similar straightforward principle: when the solar cell panel is obscured by an 'adaptive curtain wall component or material', it tilts slightly to align itself with the sun's position. This adaptive element can detect sunlight intensity and adjust according to the sun's orientation. A conceptual simulation enables the adjustment of solar cell panels to a flexible tilting angle that aligns with the sun's trajectory in the sky, thereby optimising light reception at a nearly constant angle of incidence. The concept has been validated through software simulations using 'vector point algorithm codes' directed towards both the sun and solar cell panels.

Figure 4-1 illustrates how the solar panel performance varies at different times of day, considering three specific sun positions. Position 1 occurs in the morning (7:12 AM), depicted in Figures 4-2 and 4-3; Position 2 takes place post-noon (1:46 PM), as shown in Figures 4-4 and 4-5; Position 3 is during the evening hours (6:12 PM), represented in Figures 4-6 and 4-7. At Position 1, the sun has minimal impact as it rises above the horizon, resulting in negligible effects on the solar cell panel. At Position 2, as the sun ascends further, its azimuth angle nears 90° , exerting maximum influence on power generation from the solar cell panel. In contrast, at Position 3, sunlight efficiency mirrors that of Position 1, yielding minimal impact. The efficacy of the PV cell rises along with increased output power, which correlates with an elevation in current levels. As previously noted, the current variation in the PV cell is proportional to changes in sunlight intensity. Thus, besides the initial current, potential difference, efficiency and thickness, other parameters fluctuate with sunlight radiation intensity as indicated in Figures 4-2 to 4-7. Such variations occur as sunlight transitions between positions while a conceptual software script manages Autodesk Revit parameters and modifies their values according

to solar position. As light intensity increases, optimal power generation for the PV cell can exceed expectations—ideally reaching above 8 Amps—and could approach up to 10 Amps if each panel contains 36 cells ($10 \times 36 = 360$ Amps). During morning hours when incident angles are zero, currents also remain low; however, as daylight advances and angles approach 90° , both performance metrics for current and efficiency reach their peak potential points. Tracking the maximum capability of solar panel cells is viable also through various contemporary techniques.

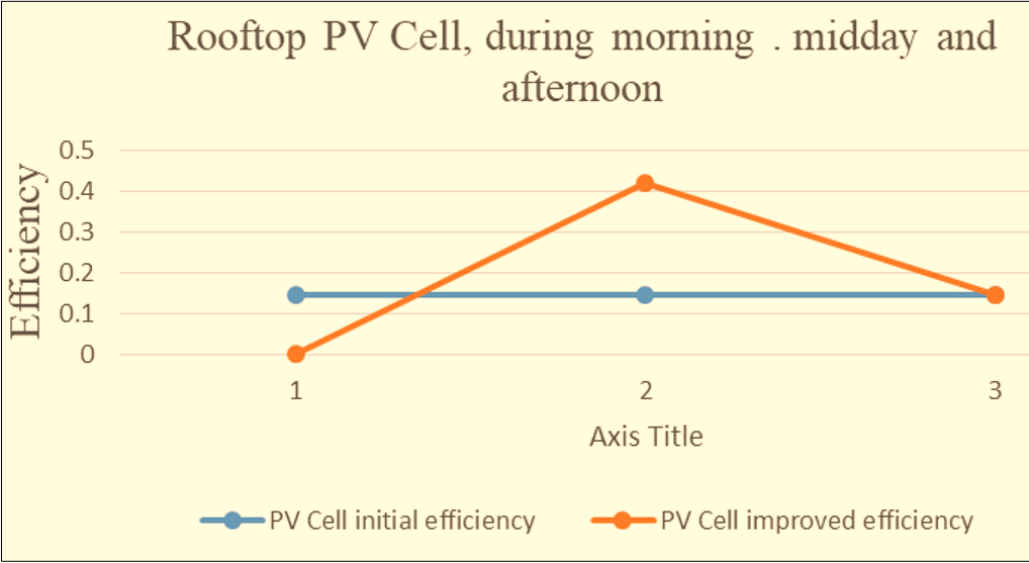


Figure 4-1. Variations in sunlight intensity throughout the day vary PV cell energy generation

Parameter	Value	Formula	Lock
Construction			
Construction Type		=	
Materials and Finishes			
Finish		=	
Solar_Panel_Colour	<By Category>	=	
Electrical Engineering			
PV Cell Maximum Current	360.00 A	= 10 A * 36	
PV Cell Improved current (default)	0.00 A	= sin(Rotate_Middle) * PV Cell Maximum Current	
PV Cell Inial Current	124.56 A	= 3.46 A * 36	
PV Cell Potential Difference	21.96 V	= 0.61 V * 36	
Electrical - Loads			
PV Cell Improved Output Power (default)	0.00 W	= (PV Cell Potential Difference) * PV Cell Improved current	
PV Cell Inial Output Power	2735.34 W	= (PV Cell Inial Current) * PV Cell Potential Difference	
Dimensions			
Area of Solar Panel	18.581 m ²	= (3.048 m * 6.096)	
L (report)	3048.0	=	
Rotate_Middle (default)	0.000°	=	
Rotation_Bottom (default)	0.000°	=	
Rotation_Top (default)	0.000°	=	
Thickness	76.2	=	
Energy Analysis			
PV Cell Improved Efficiency (default)	0.000000	= (PV Cell Improved Output Power) / PV Cell Input Energy Capacity	
PV Cell Initial Efficiency	0.147219	= (PV Cell Inial Output Power) / PV Cell Input Energy Capacity	
PV Cell Input Energy Capacity	18580.00 W	= (18.58 W) * 1000	
Analytical Properties			
Analytic Construction		=	
Visual Light Transmittance		=	
Solar Heat Gain Coefficient		=	
Thermal Resistance (R)		=	
Heat Transfer Coefficient (U)		=	

Figure 4-2. Simulation parameters for solar panel cell and its performance during morning hours

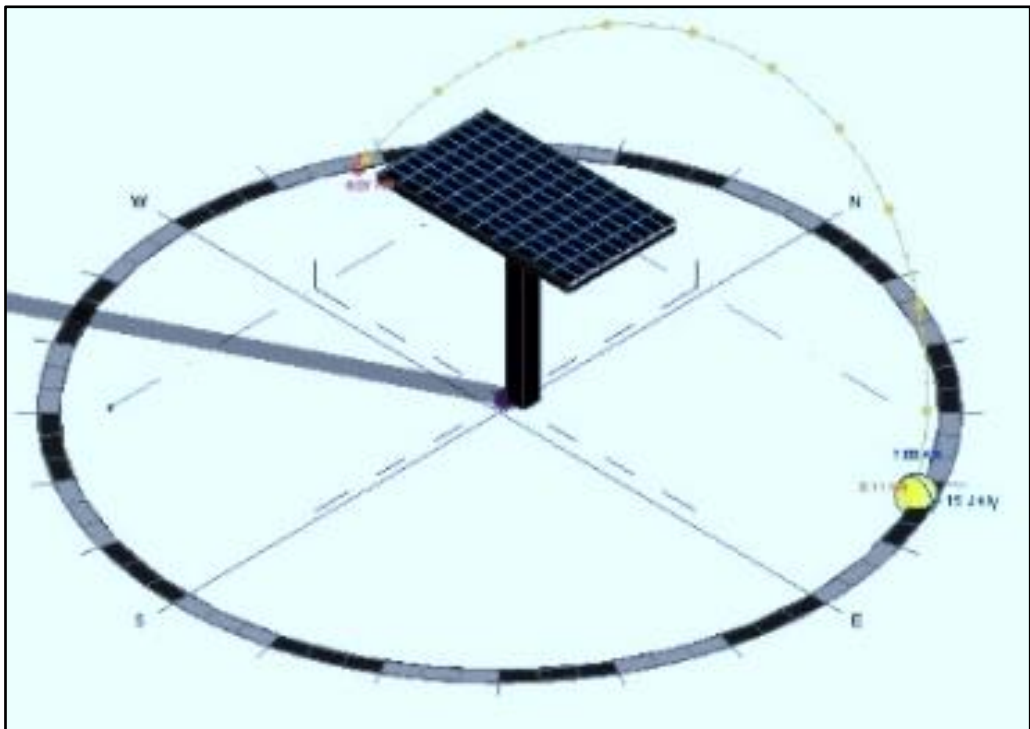


Figure 4-3. Solar panel cell and simulation of sunlight intensity optimisation during morning hours

Family Types

Name:

Parameter	Value	Formula	Lock
Construction			
Construction Type		=	
Materials and Finishes			
Finish			
Solar_Panel_Colour	<By Category>		
Electrical Engineering			
PV Cell Maximum Current	360.00 A	= 10 A * 36	
PV Cell Improved current (default)	355.32 A	= sin(Rotate_Middle) * PV Cell Maximum Current	
PV Cell Inial Current	124.56 A	= 3.46 A * 36	
PV Cell Potential Difference	21.96 V	= 0.61 V * 36	
Electrical - Loads			
PV Cell Improved Output Power (default)	7802.89 W	= (PV Cell Potential Difference) * PV Cell Improved current	
PV Cell Initial Output Power	2735.34 W	= (PV Cell Inial Current) * PV Cell Potential Difference	
Dimensions			
Area of Solar Panel	18.581 m ²	= (3.048 m * 6.096)	
L (report)	3048.0		
Rotate_Middle (default)	80.754°		
Rotation_Bottom (default)	80.754°		
Rotation_Top (default)	80.754°		
Thickness	76.2		
Energy Analysis			
PV Cell Improved Efficiency (default)	0.419962	= (PV Cell Improved Output Power) / PV Cell Input_Energy Cap	
PV Cell Initial Efficiency	0.147219	= (PV Cell Initial Output Power) / PV Cell Input_Energy Capacity	
PV Cell Input_Energy Capacity	18580.00 W	= (18.58 W) * 1000	
Analytical Properties			
Analytic Construction			
Visual Light Transmittance			
Solar Heat Gain Coefficient			
Thermal Resistance (R)			
Heat Transfer Coefficient (U)			
Identity Data			

Family Types

New...

Rename...

Delete

Parameters

Add...

Modify...

Remove

Move Up

Move Down

Sorting Order

Ascending

Descending

Lookup Tables

Manage...

OK Cancel Apply Help

Figure 4-4. Simulation parameters for solar panel cell and its performance during midday hours

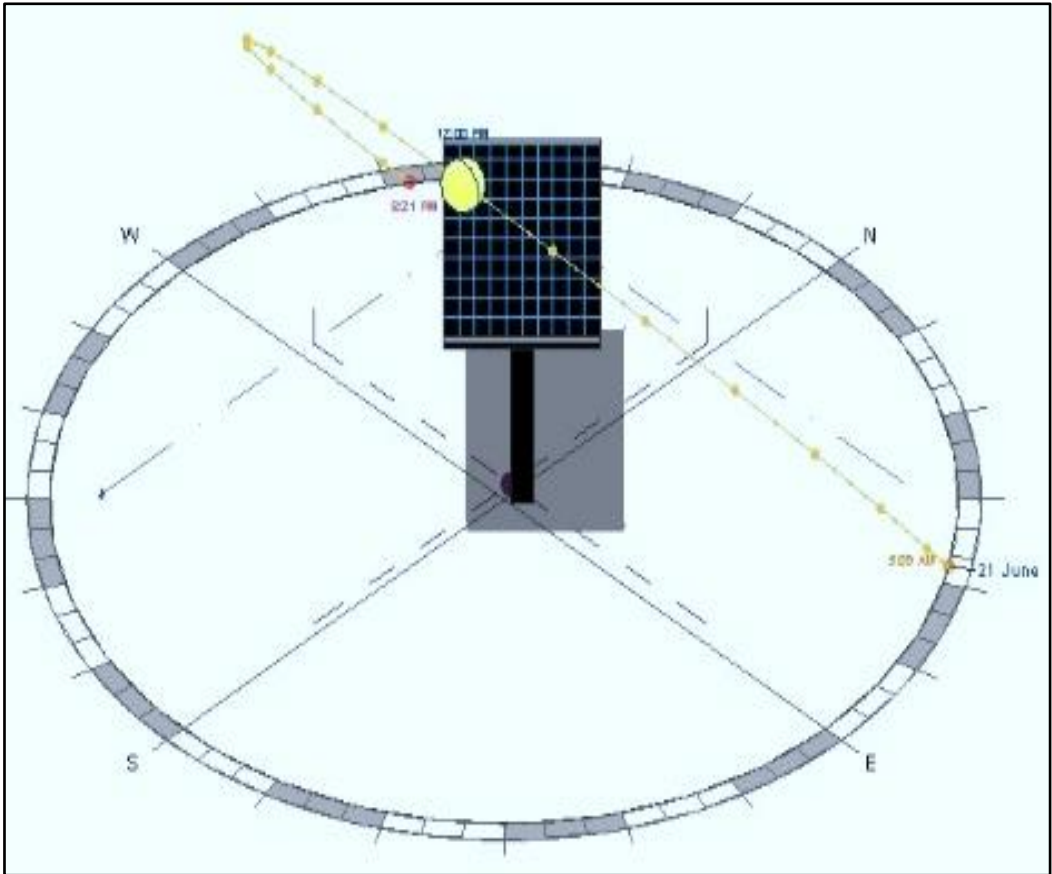


Figure 4-5. Solar panel cell and simulation of sunlight intensity optimisation during midday hours

Parameter	Value	Formula	Lock
Construction			
Construction Type		=	
Materials and Finishes			
Finish		=	
Solar_Panel_Colour	<By Category>	=	
Electrical Engineering			
PV Cell Maximum Current	360.00 A	= 10 A * 36	
PV Cell Improved current (default)	123.13 A	= sin(Rotate_Middle) * PV Cell Maximum Current	
PV Cell Inial Current	124.56 A	= 3.46 A * 36	
PV Cell Potential Difference	21.96 V	= 0.61 V * 36	
Electrical - Loads			
PV Cell Improved Output Power (default)	2703.87 W	= (PV Cell Potential Difference) * PV Cell Improved current	
PV Cell Initial Output Power	2735.34 W	= (PV Cell Inial Current) * PV Cell Potential Difference	
Dimensions			
Area of Solar Panel	18.581 m ²	= (3.048 m * 6.096)	
L (report)	3048.0	=	
Rotate_Middle (default)	20.000°	=	☐
Rotation_Botom (default)	20.000°	=	☐
Rotion_Top (default)	20.000°	=	☐
Thicknes	76.2	=	☐
Energy Analysis			
PV Cell Improved Efficiency (default)	0.145526	= (PV Cell Improved Output Power) / PV Cell Input_Energy Capacity	
PV Cell Initial Efficiency	0.147219	= (PV Cell Initial Output Power) / PV Cell Input_Energy Capacity	
PV Cell Input_Energy Capacity	18580.00 W	= (18.58 W) * 1000	
Analytical Properties			
Analytic Construction		=	
Visual Light Transmittance		=	
Solar Heat Gain Coefficient		=	
Thermal Resistance (R)		=	
Heat Transfer Coefficient (U)		=	

Figure 4-6. Simulation parameters for solar panel cell and its performance during evening hours

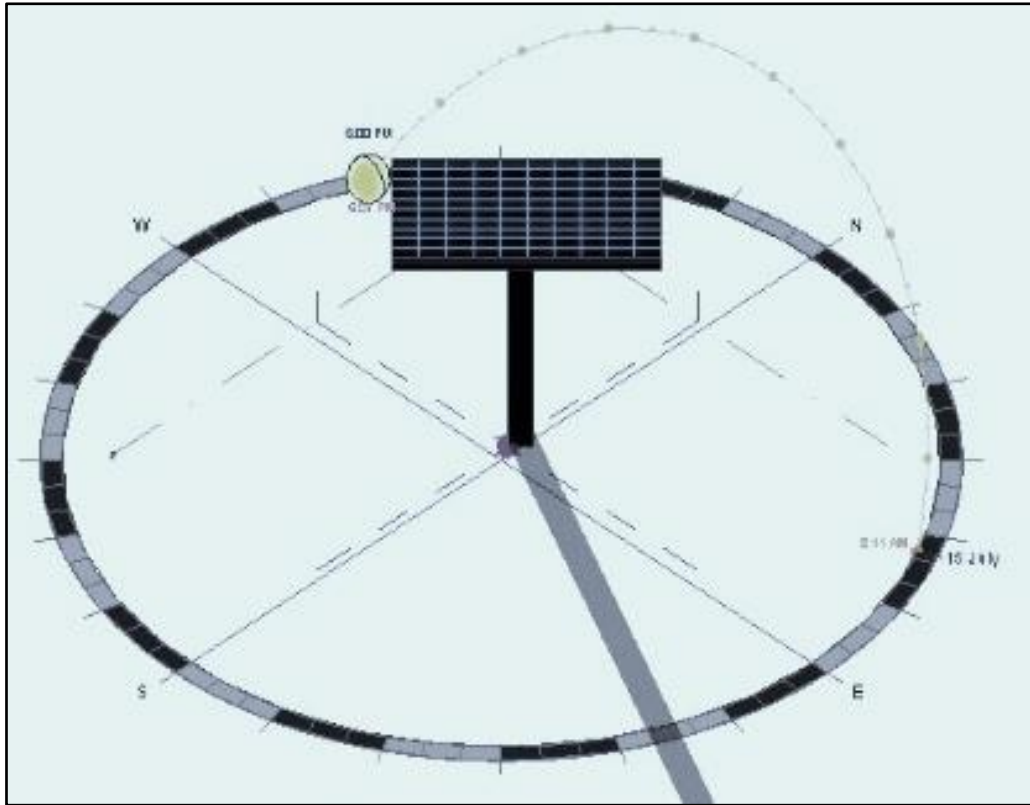


Figure 4-7. Solar panel cell and simulation of sunlight intensity optimisation during evening hours

4.2.3 Optimising PV Cell Arrays Using SCAPS and DesignBuilder Software in a Built Environment: Case Study 2

This research method focuses on PV cell simulation in a built environment. A few software applications were considered, as shown in the flow chart in Figure 4-8.

To obtain the PV cells' best efficiency, various layer thicknesses were simulated using SCAPS1D software [175]. SCAPS1D is a PV cell software application for optimising efficiency and performance. It is known that the efficiency of a PV cell varies with the layer thickness [176] and with its bandgap energies. To ensure the optimal thickness that maximises efficiency, several different thicknesses were simulated, as shown in Figure 4-9 and Table 4-1. In addition, the cell's left and right dopant composition was changed to achieve enhanced performance.

Furthermore, a conceptual PV cell panel's support frame were modelled using DesignBuilder [180] software to minimise thermal losses. DesignBuilder is an architectural building design and energy simulation software. An initial energy simulation

was conducted before the model was exported to Rhino [177] and its plug-in software (Grasshopper and Ladybug). Rhino is parametric architectural building design software that can interface with various plugins. Grasshopper runs under Rhino software, and Ladybug runs under Grasshopper software [177].

Grasshopper and Ladybug use or incorporate EnergyPlus's [178] weather files to simulate solar radiation intensity and building absorption. EnergyPlus is a thorough energy simulation tool used by engineers, architects and researchers to analyse energy use related to heating, cooling, ventilation and lighting, as well as plug and process loads along with water consumption in buildings.

The main aims of the simulation were as follows:

1. Solve the space limitation for rooftop PV cell panels.
2. Solve the temperature rise associated with inadequate air ventilation on the back of the solar panels.
3. Improve the PV cell's bandgap to increase the chance of absorbing more photons.

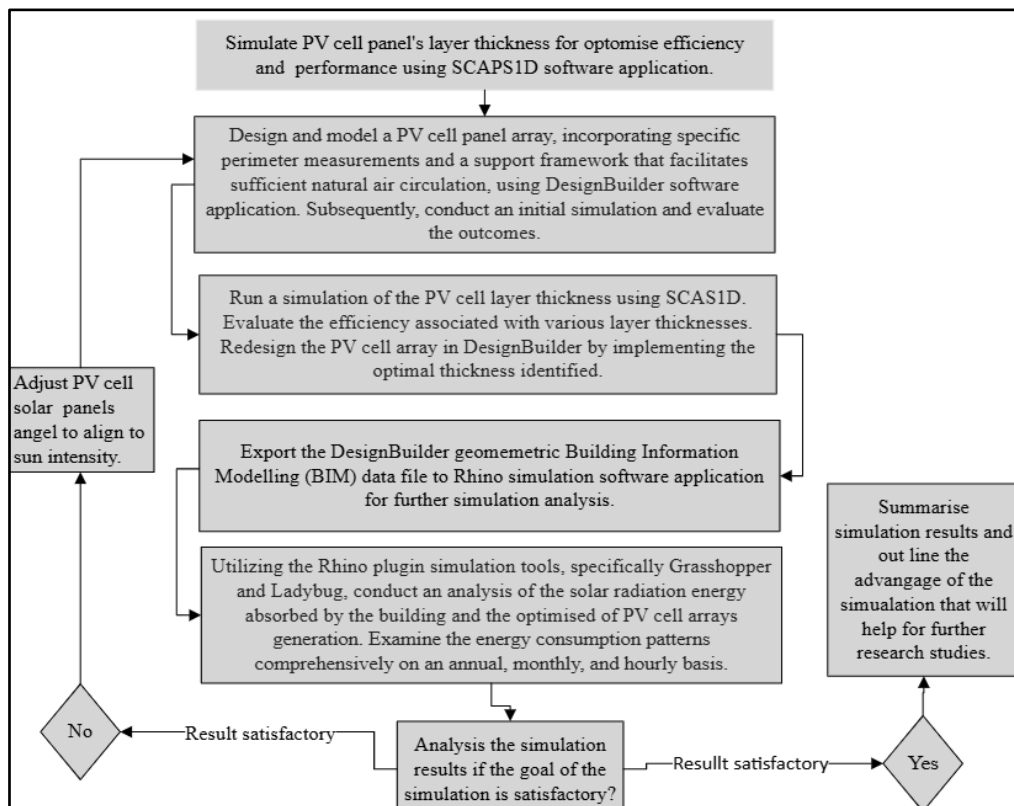


Figure 4-8. Cell simulation using SCAPS, Rhino and Rhino plug-in software applications

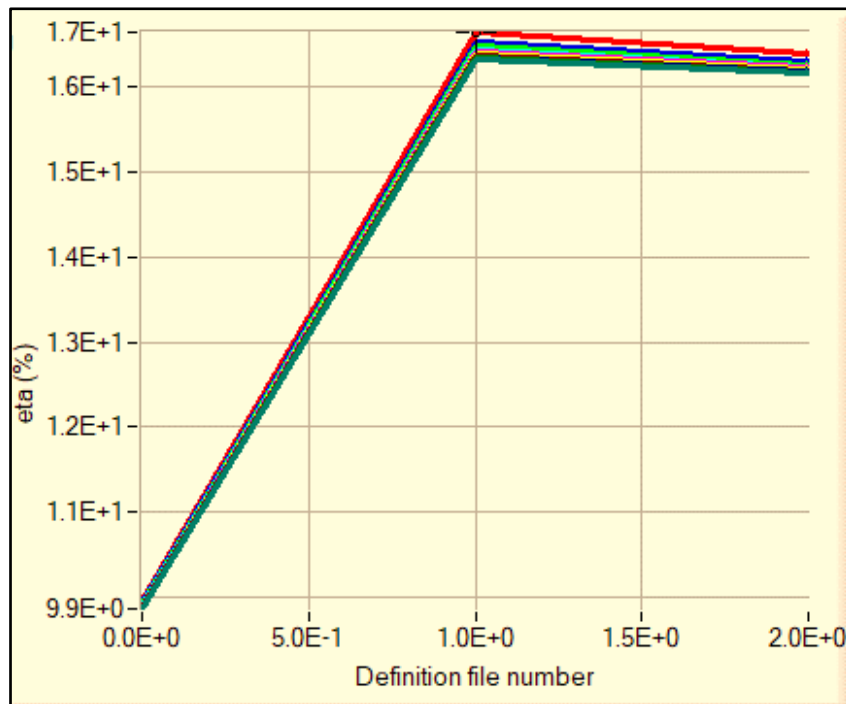


Figure 4-9. PV cell layer thickness variation for optimised efficiency

Table 4-1. PV cell layer thickness variation for optimised efficiency extracted from
Figure 4-9

Sequential insertion number	Layer thickness	Corresponding efficiency (%)
1	0.1	16.3945019
2	0.2	16.3051635
3	0.3	16.2697226
4	0.4	16.2476399
5	0.5	16.2301801
6	0.6	16.2151033
7	0.7	16.2015899
8	0.8	16.1892958
9	0.9	16.1779994
10	1	16.1675507

4.3 PV Cell Feasibilities in the Built Environment

Several decades ago, the world witnessed the emergence of PV cell energy as a natural renewable energy source, paving the way for an efficient and feasible transition from

fossil fuels to a clean energy supply. It became particularly viable for residential buildings because residential premises have lower electrical loads than commercial or industrial premises. This notwithstanding, in recent decades, commercial buildings and factories have become beneficiaries of large PV cell arrays [179]. However, in a built environment, space is limited, especially on the building's rooftop. Buildings are often crowded, and their height and size vary randomly. This makes it challenging to install PV cells in all buildings; the shadows of the taller buildings affect neighbouring smaller buildings.

This also makes it challenging to use the built environment building's roof space for maximum capacity. Therefore, it is crucial to reconsider traditional methods of PV cell's installation. Thus, this research study aims to address two of the three problems listed in section 4.2.3. The limitation of rooftop space is beyond the scope of this research study. The temperature rise and energy bandgap are approached to minimise their effects. The temperature is mitigated by re-modelling the support frame, as shown in Figure 4-10. The support frame is designed with a wide opening at an adequate height of 175 cm, about the average height of a man, and mounted 159.76 cm higher than the traditional mounting practice of 6 inches. This is to allow excessive air ventilation underneath the PV cell panels.

For this research, thin-film crystalline silicon (c-Si) PERC was considered. PERC can reflect the long wavelength known as useless photons from the front surface and the short wavelength from the rear of the PV cell so that short-wavelength photons have multiple chances to be absorbed [180]. In addition, the PV cells were simulated for optimum energy output using the Ladybug renewable energy performance software 'PVSurface', as shown in the graphical script in Figure 4-11. This was conducted by loading Melbourne weather file data input parameters, as shown in Figure 4-12. The parameter data consisted of temperature, wind speed, wind directions, pressure and solar radiation intensities.

DesignBuilder uses EnergyPlus simulation packages to estimate the PV cell's array optimised output. To test elevation influences, three PV cell panels are selected from the tallest and shortest buildings, presenting 63 PV cell panel arrays on each building. One PV cell panel consists of five cells (2 m x 1.1 m) in size, contributing to a total area of 11 m². Each panel receives 0.21 kWh/m² radiation intensity during the hottest month and 0.0 kWh/m² during the coldest month, as shown in Figure 4-13. Consequently, the DC

power is 0.42 kWh during the hottest month and 0.0 kWh during the coldest month, as shown in Figure 4-14.

According to the simulation result, there are three seasons in the duration of 10 months in which the PV cells are able to generate energy. Examining these three sessions' generating capacities:

1. During the hottest months of the hottest season, the PV cell is able to generate 26.46 kWh.
2. During the transition months of the season, the PV cell is able to generate 15.75 kWh.
3. During the coldest months of the coldest season, the PV cell is able to generate 2.52 kWh.

The generated capacity was estimated on an hourly basis for a single PV cell panel.

Using the multiplication formula, the total generation was calculated for each panel as:

1. During the hottest month ($63 \times 0.42 \times 5 = 132.3$ kWh).
2. During transition month ($63 \times 0.25 \times 5 = 78.75$ kWh).
3. During the coldest month ($63 \times 0.04 \times 5 = 12.60$ kWh).

For buildings in the built environment, PV cell arrays are added after the buildings are built, creating limitations in performing the simulation of the whole building solar radiation and complicating efforts to estimate the total energy consumption of the building. However, the main purpose of this research is not to focus on the amount of generated power; it is to focus on the performance of the PV cell, ensuring that the PV cells are not overheated to the extent of minimising generation.

As shown in Figure 4-15, the simulation results for the operating temperature of the PV cells indicate a peak of 45.88°C in Melbourne's hottest month [181]. The excessive cooling system assists in lowering the temperature; otherwise, the PV cell's operating temperature could be over the range of 50–60°C [182]. Considering this evidence and comparing it with the ambient temperature, 45.88°C is reasonable.

In addition, the input weather file data temperature parameter prior to simulation was under 20°C, as shown in Figure 4-16. After the simulation was conducted, the PV cell

output air temperature was close to 25°C. There was an increase of approximately 5°C, meaning that the PV cells heated up 5°C over the ambient temperature. This ensures that the performance of the PV cell over the entire hottest period is relatively steady, with a fluctuation of 5°C.

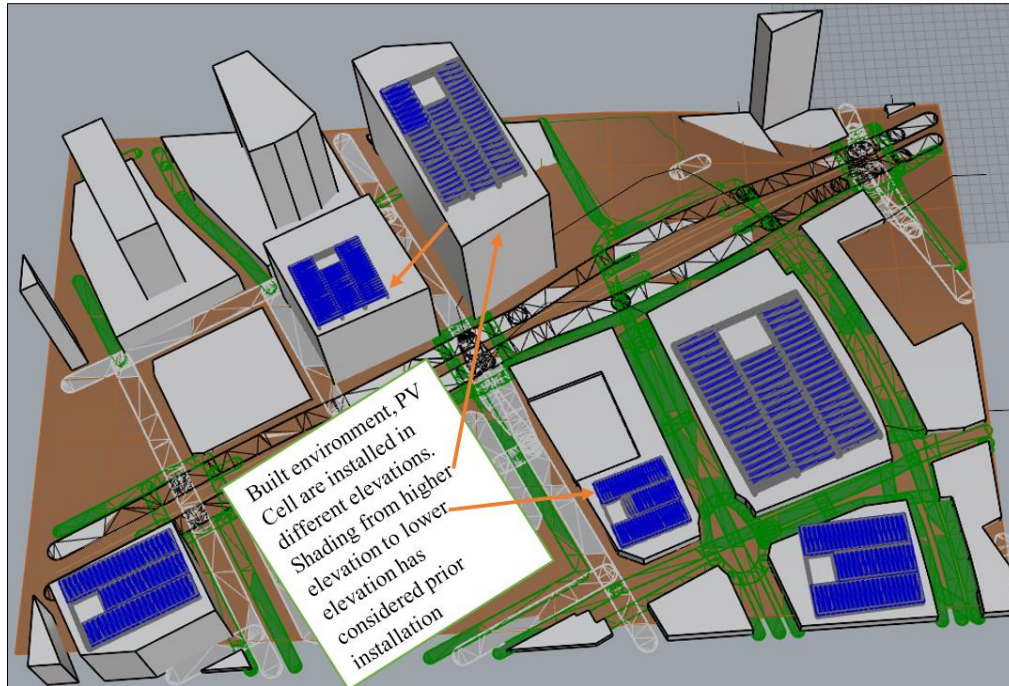


Figure 4-10. Modelling PV cells in a built environment

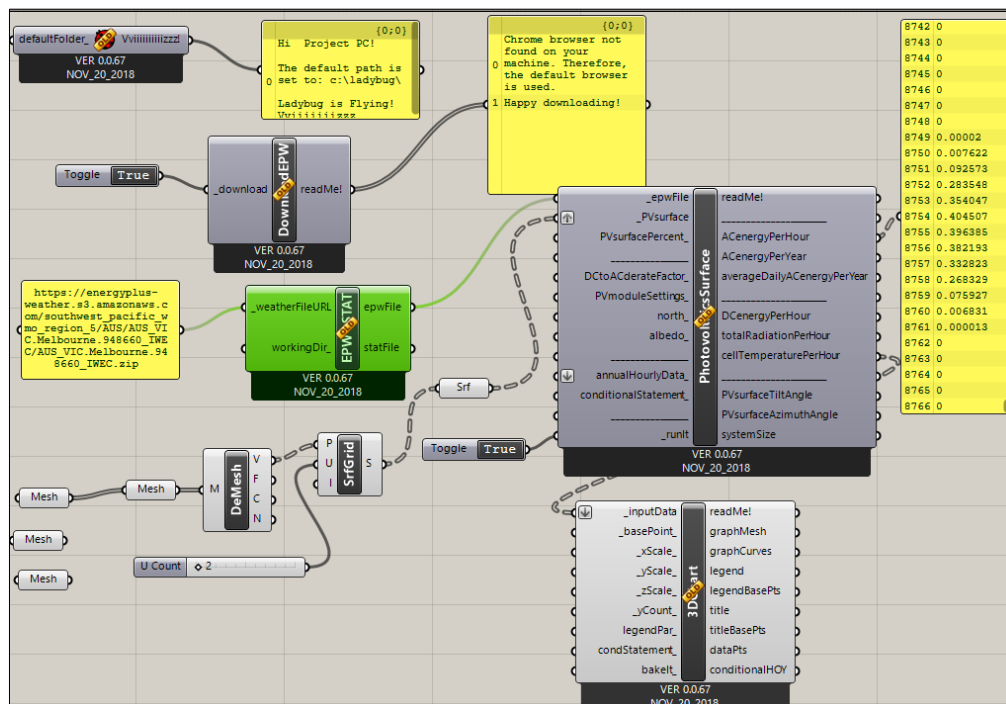


Figure 4-11. Graphical script programming to manipulate the simulation parameters

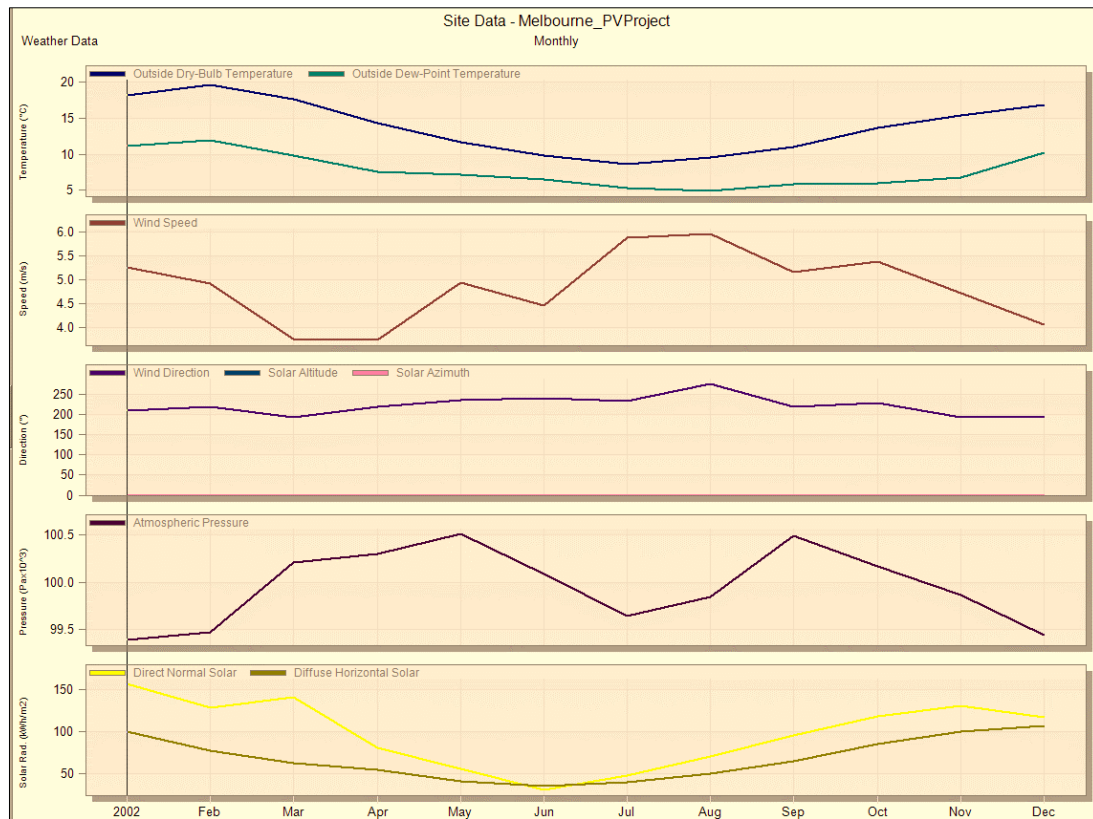


Figure 4-12. The weather file consists of input parameters

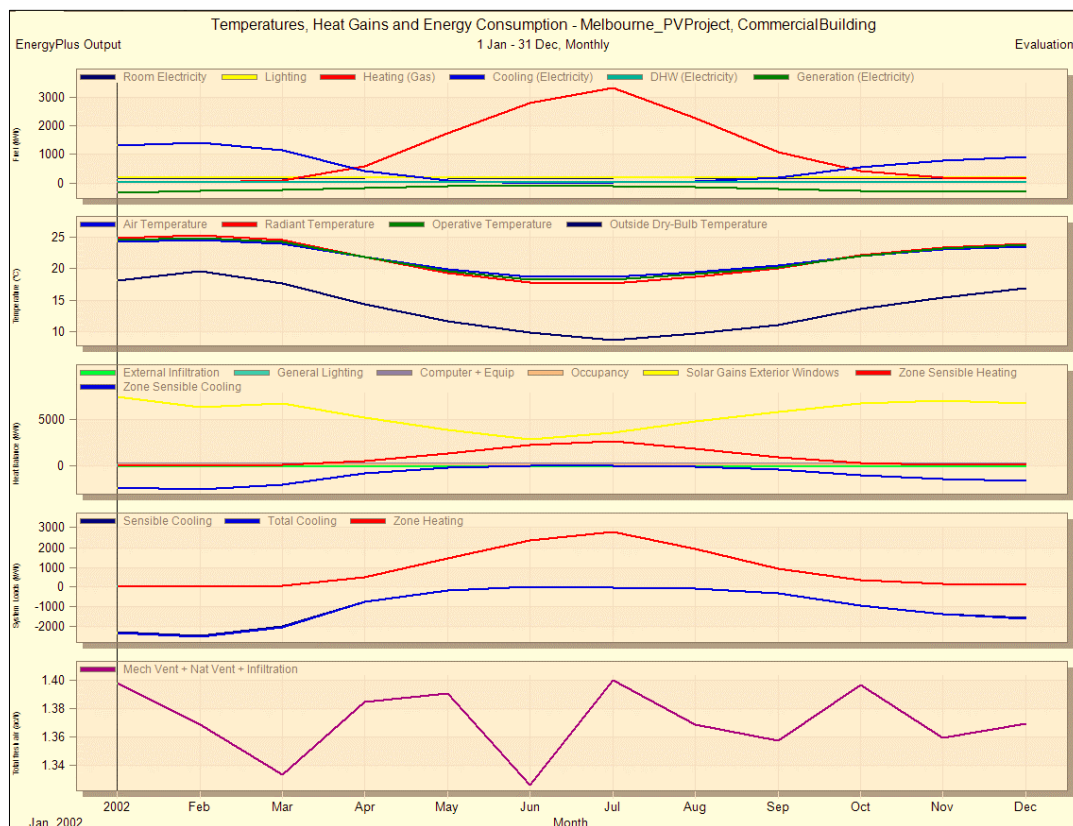


Figure 4-13. Simulation results regarding variations in operating temperature

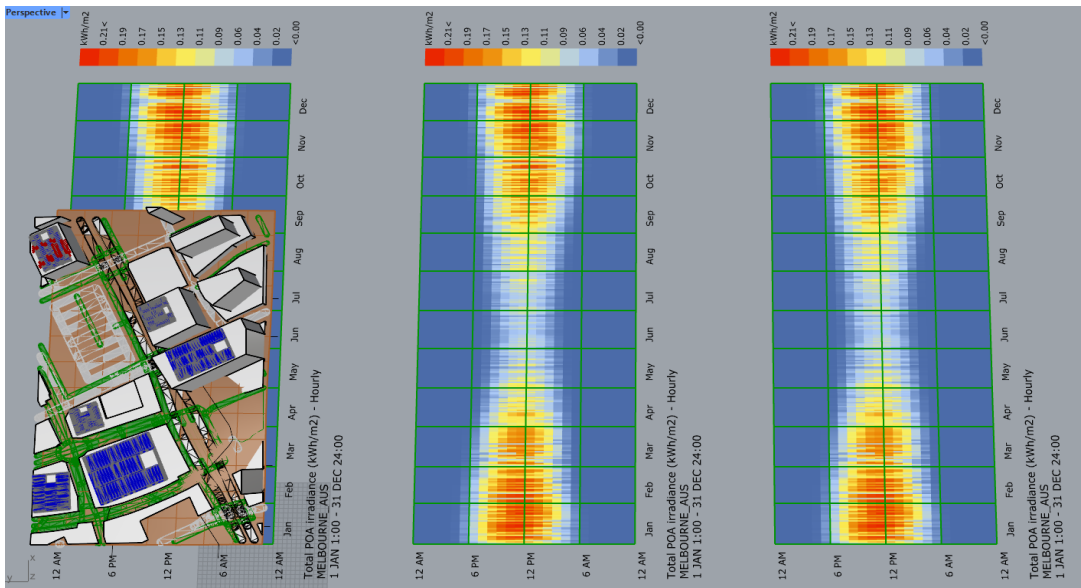


Figure 4-14. Annual-hourly sun-solar irradiation falling into the building as per the weather files for Melbourne

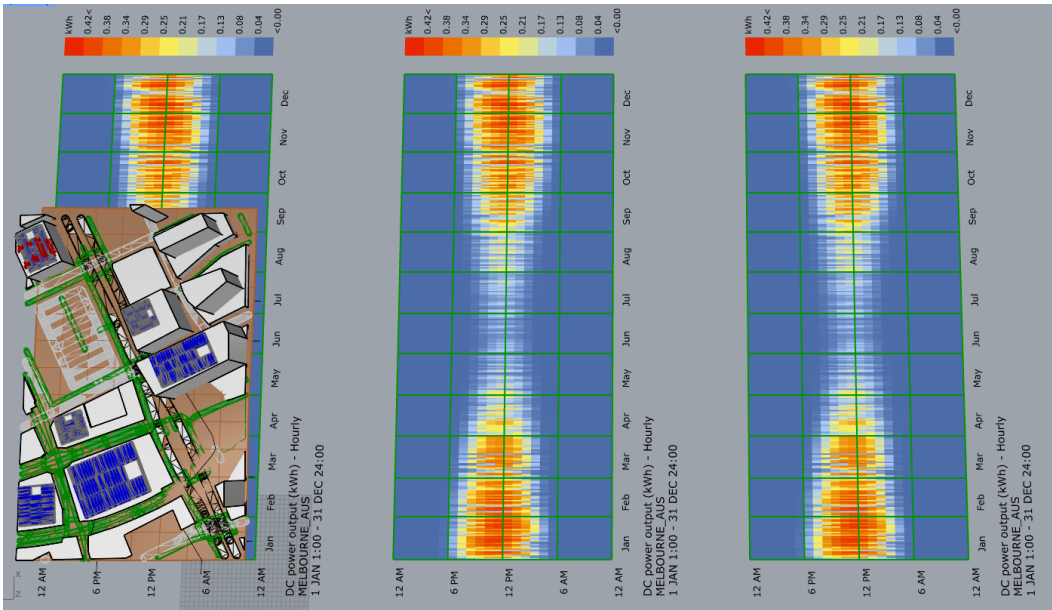


Figure 4-15. Annual-hourly simulation result for DC power output using Melbourne weather files

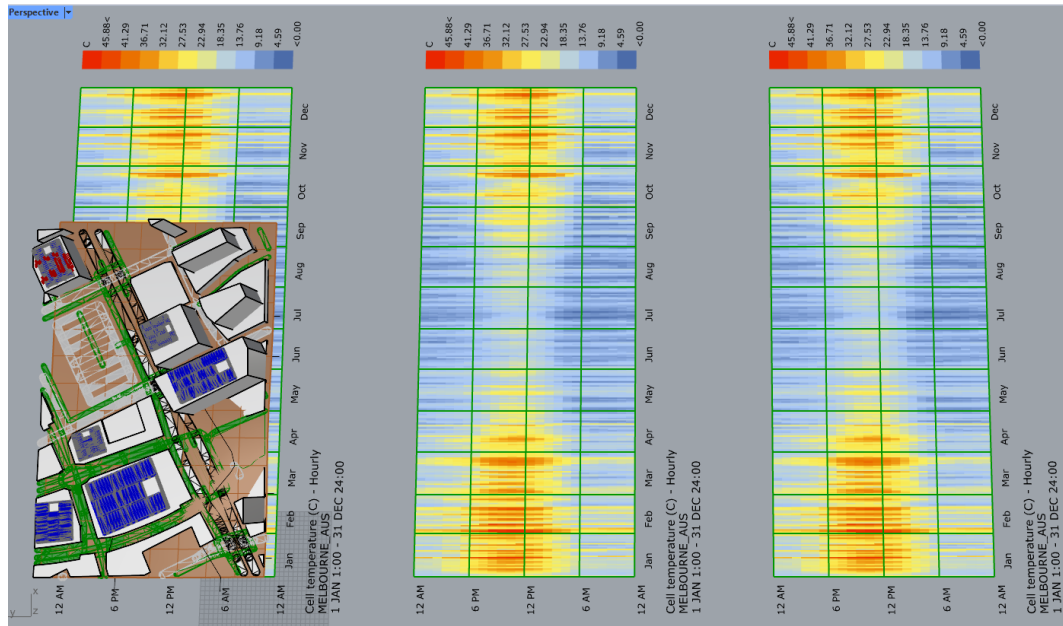


Figure 4-16. Annual-hourly simulation result for AC-power output using Melbourne weather files

4.3.1.1 PV Cell Array Performance in Built Environment

PV cells installed in a built environment contribute less performance than the same PV cells installed on a farm or at sea. PV cell performance is affected by a wide range of external and internal factors. For instance, PV cell performance can be affected by degradation [183] rates, shades [184] and mounting orientation angles [185]. In addition to these physical factors, PV cell performance is also entirely dependent on the normal operating temperature [186-188] and its bandgap energy [189]. The normal operating cell temperature (NOCT) [190] is the temperature reached during the open circuit voltage test under the condition of 25°C, 1,000 W/m² irradiance and 1 m/s wind velocity. Furthermore, it is defined as the operating temperature of equilibrium between the heat generated by the PV cell and the heat loss to the surrounding environment through conduction, convection and radiation. Hence, the best NOCT is 33°C, the typical operating temperature is 48°C and the worst operating temperature is 58°C [187]. The expression to calculate the PV cell temperature is:

$$T_{cell} = T_{Air} + \frac{NOCT - 20}{80} S \quad (4 - 3)$$

where S = insolation in mW/cm², T_{cell} is Cell Temperature, and T_{Air} is ambient air temperature.

Therefore, the operating cell temperature can be mathematically approached using Equation 4-3. Hence, the maximum simulated temperature shown in Figure 4-17 is 45.88°C, and the hourly irradiance is $0.21 \text{ kWh/m}^2 = 21 \text{ mW/cm}^2$. The PV cell NOCT is 33°C. Assume Melbourne's estimated hottest day ambient temperature in January (T_{Air}) is 42°C. Insert these parameters into Equation (4-3). The result is 45.413°C, which is close to 45.88°C.

The efficiency of the PV cell varies with the width of its bandgap energy, as shown in Figures 4-17 and 4-18. Correspondingly, the PV cell's efficiency also varies with temperature increase and decrease, as shown in Figures 4-19 to 4-20. For example, at 200K, the simulation result of the cell's open voltage (V_o) is 0.9930 V, the short current of the Cell $J_{sc}(\text{mA/cm}^2)$ is 24.1927 and the efficiency of the cell is 18.99 %. At 400K V_{oc} , it is 0.6284, $J_{sc}\text{mA/cm}^2$ is 24.1688 and the efficiency of the cell η is 10.4%. The simulation result shows that the open voltage drops sharply beyond 200K, but the short circuit drops slowly up to 400K and increases beyond. Similarly, the efficiency drops sharply over 200K. Hence, to function properly at optimum performance and efficiency, the PV cell's operating temperature is recommended to be at 300K or under.

The temperature coefficient of a PV cell's material is also important in determining the maximum power. This is because for each 1°C over STC (25°C), the maximum power of the PV cell decreases by the amount of temperature coefficient value. In addition, the PV cell bandgap is also important for determining the efficiency. However, it is much affected by temperature fluctuations [191], causing the majority carrier lifetime to decrease with temperature rises. The rise in temperature further causes a minor increase in short currents.

The dark saturation current (I_s), which is dependent on the temperature of a single diode, varies as Equation (4-4).

$$I_s \propto \exp\left(\frac{-E_g}{kT}\right) \quad (4 - 4)$$

While the open voltage (V_o) varies as Equation (4-5).

$$V_o \propto \frac{kT}{q} \ln\left(\frac{I_{ph}}{I_s} + 1\right) \quad (4 - 5)$$

Where

E.g. is the bandgap, T is the absolute temperature, k is Boltzmann's constant, I_{ph} is the generated current, and q is the electric charge.

Equation (4-4) shows that the cell's saturation current varies exponentially with the bandgap energy. This causes the bandgap of the PV cells to shrink or widen with temperature changes and affects their efficiency.

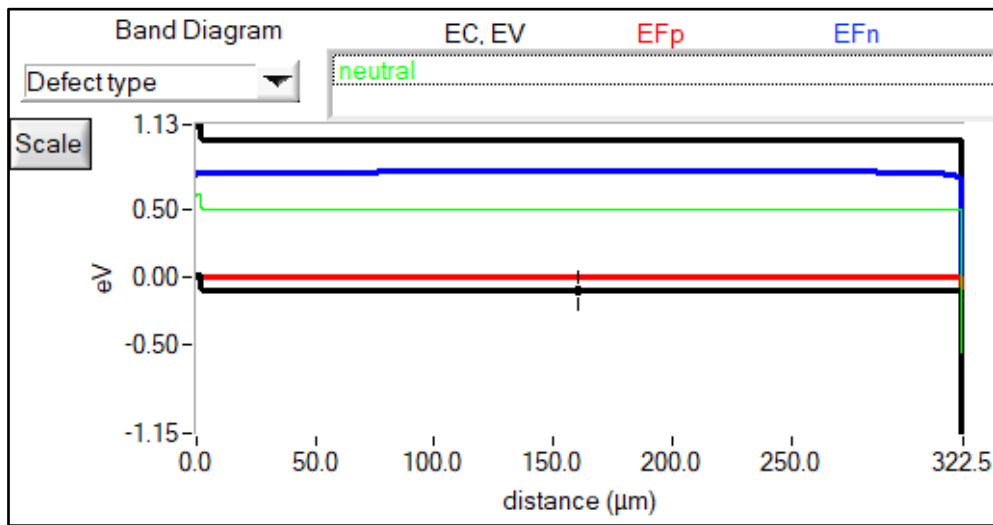


Figure 4-17. PV cell efficiency varies with energy bandgap width. The bandgap width varies proportionally with material composition and increases as temperature decreases.

For example, 1.13 bandgap width is resulted from 200K

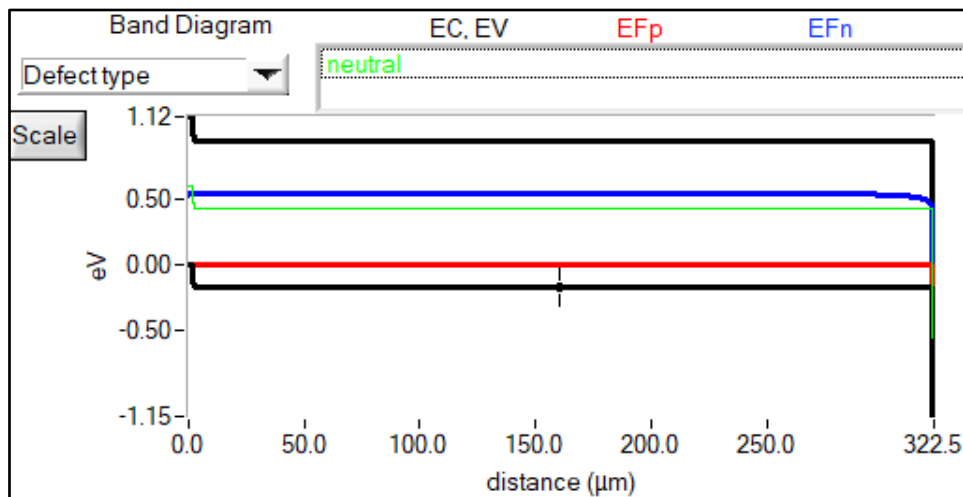


Figure 4-18. PV cell efficiency varies with energy bandgap width. The bandgap width varies proportionally with material composition and decreases as temperature increases.

For example, 1.12 bandgap width is resulted from 400K

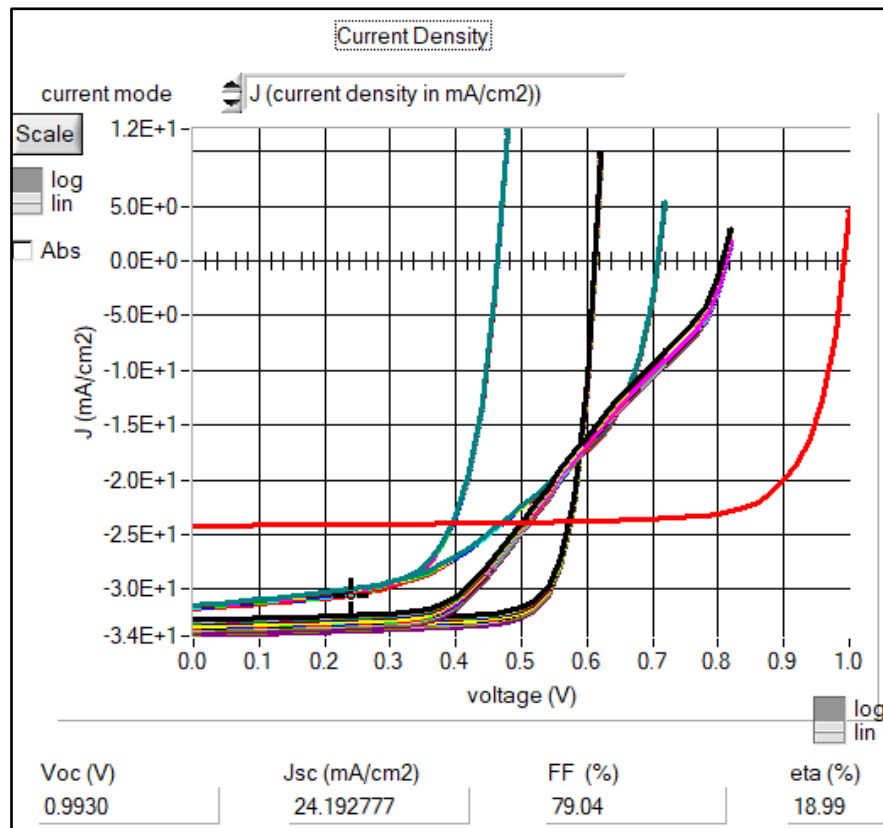


Figure 4-19. PV cell current density and efficiency using SCAPS

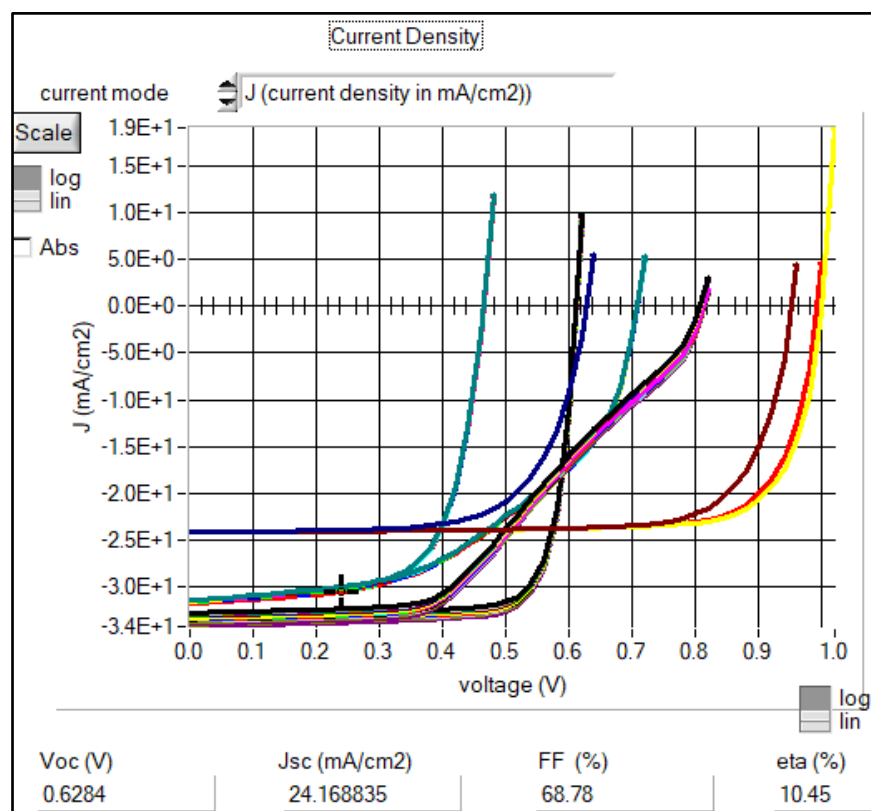


Figure 4-20. PV cell current density and efficiency using SCAPS1D

4.4 Simulation of Performance of PV Cell Array in a Newly Built Building

Figure 4-21 depicts a newly built three-level office building. Like the built environment buildings, 63 panels are installed on the top of the roof. However, because of the trial software capability, only one PV cell panel was simulated.

The total site energy was estimated at 325,088.71 kWh, and the net site energy was estimated at 32, 2841.73 kWh, as shown in Table 4-2. The difference between these two energies is 2,246.981 kWh, which is from the one-panel PV cell and accounts for 1.36% of the building's total energy consumption in one hour, as shown in Table 4-3. Hence, there are 63 panels, i.e. $63 \times 1.36\% = 85.68\%$. Indeed, this is a significant contribution.

Furthermore, PV cell panels installed in the built environment encounter temperature fluctuations [192] to align with their surroundings. The support frame features a broad opening mounted at an optimal height of 175 cm, which approximates the average height of an adult male, and is elevated by 159.76 cm compared to the conventional 15.24 cm height. This design facilitates the escape of excess air from beneath and/or behind the PV cell panels. The panels are arranged with sufficient spacing to promote airflow for cooling purposes. Additionally, the side windows of the supporting frame can be adjusted to meet ventilation needs and to maximise the corresponding energy generation.

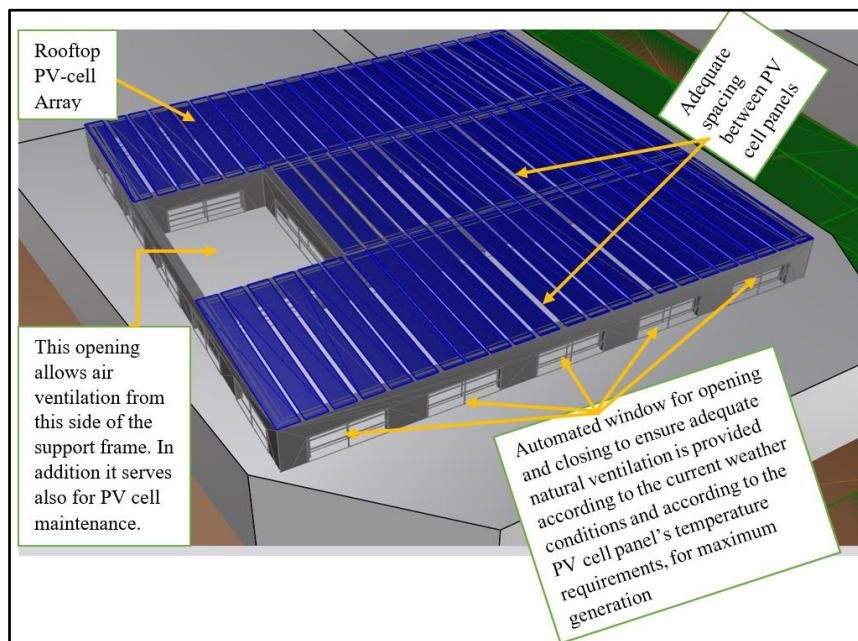


Figure 4-21. PV cell annual generated energy estimation for newly designed buildings

Table 4-2. PV cell simulation using DesignBuilder software and site information data for newly built buildings

Site and Source Energy			
	Total Energy [kWh]	Energy Per Total Building Area [kWh/m ²]	Energy Per Conditioned Building Area [kWh/m ²]
Total Site Energy	325088.71	170.02	170.02
Net Site Energy	322841.73	168.84	168.84
Total Source Energy	787425.87	411.81	411.81
Net Source Energy	780309.68	408.09	408.09

Table 4-3. PV cell simulation annual energy estimation using DesignBuilder for newly designed building

Electric Loads Satisfied		
	Electricity [kWh]	Percent Electricity [%]
Fuel-Fired Power Generation	0.000	0.00
High Temperature Geothermal*	0.000	0.00
Photovoltaic Power	2340.605	1.36
Wind Power	0.000	0.00
Power Conversion	-93.62	-0.1
Net Decrease in On-Site Storage	0.000	0.00
Total On-Site Electric Sources	2246.981	1.30
Electricity Coming From Utility	170469.687	98.70
Surplus Electricity Going To Utility	9.298	0.01
Net Electricity From Utility	170460.389	98.70
Total On-Site and Utility Electric Sources	172707.370	100.00
Total Electricity End Uses	172707.370	100.00

4.5 Optimising PV Cell Array Using PVsys 7 Software in a Built Environment: Case Study 3

PVsys is a software program intended for architects, engineers and researchers to use [193]. PVsys serves as an educational tool with a comprehensive contextual help feature that clarifies the methods and models used, providing user-friendly guidance for project development. PVsys provides a range of analysis tools to help users understand and optimise the efficiency of their system. It generates analytical graphs that depict energy production, efficiency and performance to provide users with insight. Moreover, PVsys is hailed for its flexibility, accuracy and end-user friendliness. In addition, PVsys software has four key advantages of connection methods:

1. **Standalone:** The standalone approach is most suitable for small, self-contained PV cell energy systems that operate independently from the grid. It is ideal for remote cabins, boats or off-grid homes, offering significant energy production and self-reliance.
2. **Grid-connected:** Techniques are optimal for energy systems linked to the grid and capable of selling surplus energy. This method is well-suited for residential or commercial buildings, providing advantages in maximising energy output and cost-effectiveness.
3. **Hybrid connection:** Strategies are best suited for energy systems that integrate various technologies, such as PV cell panels, solar water heaters and energy storage systems. They are particularly beneficial for businesses aiming to enhance energy efficiency and reduce carbon emissions.
4. **Thermal:** A thermally connected PV cell approach is used in systems that use solar power to generate heat, such as solar water heaters or solar thermal power plants.

This system is commonly used in industrial hot water setups and large-scale power generation applications, considering factors such as temperature, flow rate and efficiency to optimise its performance. However, this research employs PVsys to model the effect of shading from nearby buildings on PV cell panels within the built-in environment, as illustrated in Figures 4-22 to 4-27. In this section, two cases are analysed by varying the distance to assess how shading from adjacent structures affects the performance of PV cells installed nearby.

Figure 4-22 depicts a PV cell panel situated in an urban setting before initiating the shading effect simulation. In this first case, the distance between the neighbouring building and the PV cell rooftop structure is recorded at 11.730 meters, as demonstrated in Figure 4-23. The outcome of the average shading effect simulation reveals a 31.7% reduction, as depicted in Figure 4-24. In contrast, for the second case, the distance is randomly increased to 71.108 meters, as shown in Figure 4-25. Consequently, the shading effect diminishes to just 3.7%, as illustrated in Figure 4-26. Therefore, it can be concluded that the influence of neighbouring buildings' shading of the PV cell array is directly related to their proximity; greater distances yield minimal shading effects.

A comprehensive simulation of overall shading effects is presented in Figure 4-27. The findings indicate that shading can reduce a PV cell's energy generation by anywhere from 1% to as much as 40%. This represents a significant loss; thus, it is crucial to evaluate potential shading impacts on PV cells before their installation within urban environments.

Hence, the maximum shading effect occurs at closer distances. Overall, there is a proportional relationship between the proximity of neighbouring buildings and their impact on the performance of installed PV cells.

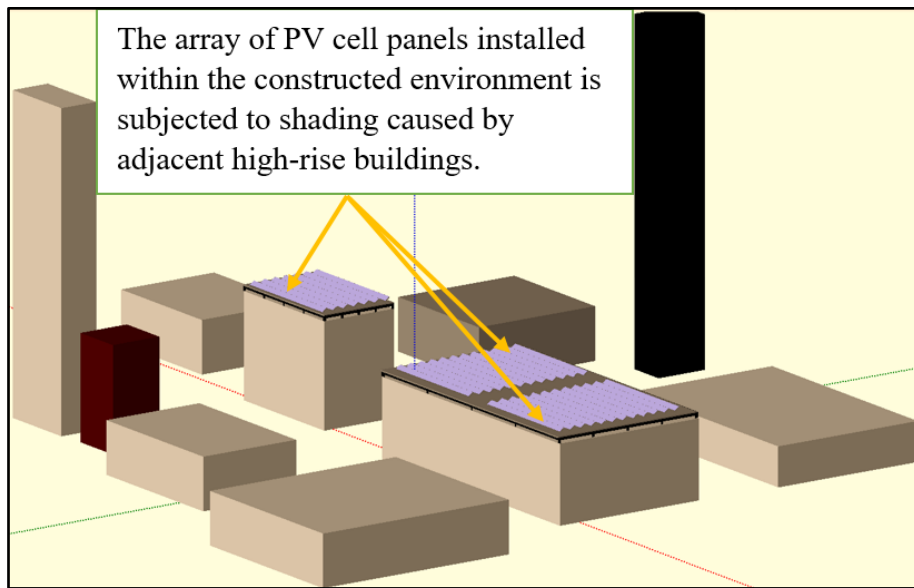


Figure 4-22. PV cell array simulation using PVsys software to estimate the PV cell's shading in a built environment

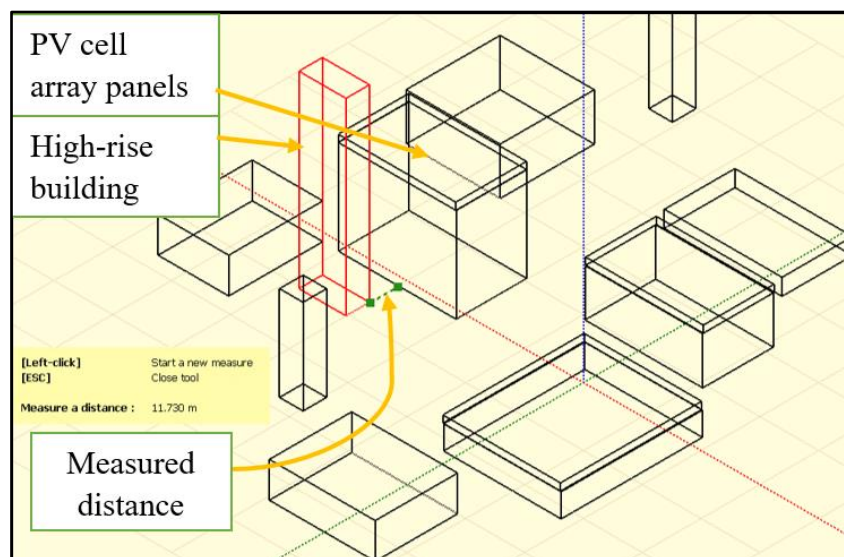


Figure 4-23. PV cell array simulation using PVsys software to estimate the PV cell's shading in a built environment

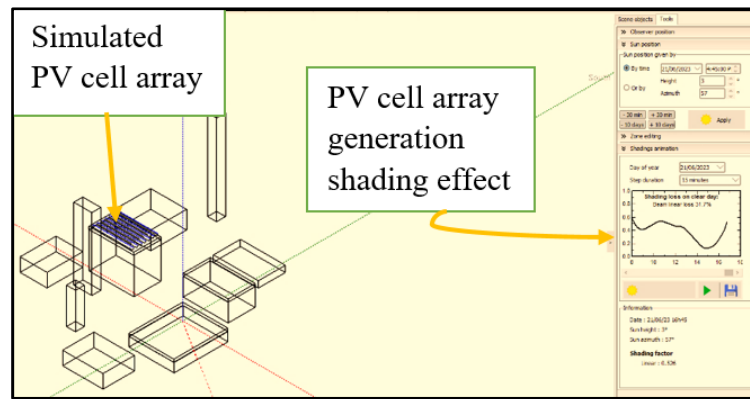


Figure 4-24. PV cell array simulation using PVsys software to estimate the PV cell's shading in a built environment

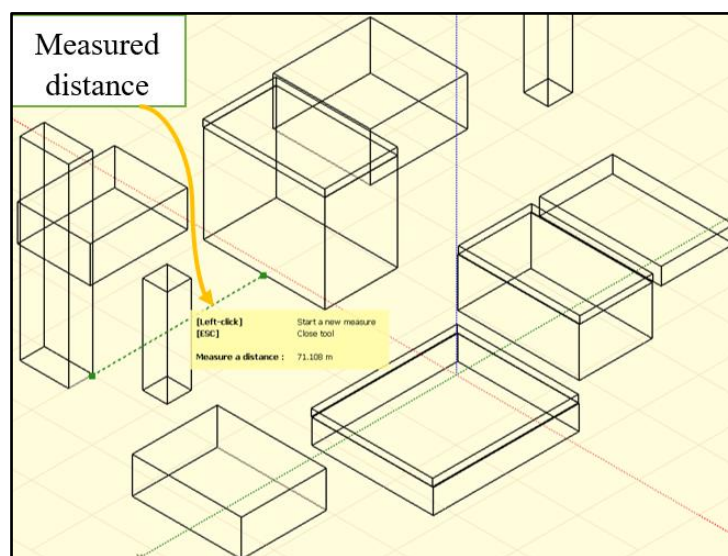


Figure 4-25. PV cell array simulation results show the PV cell's shading effect in a built environment

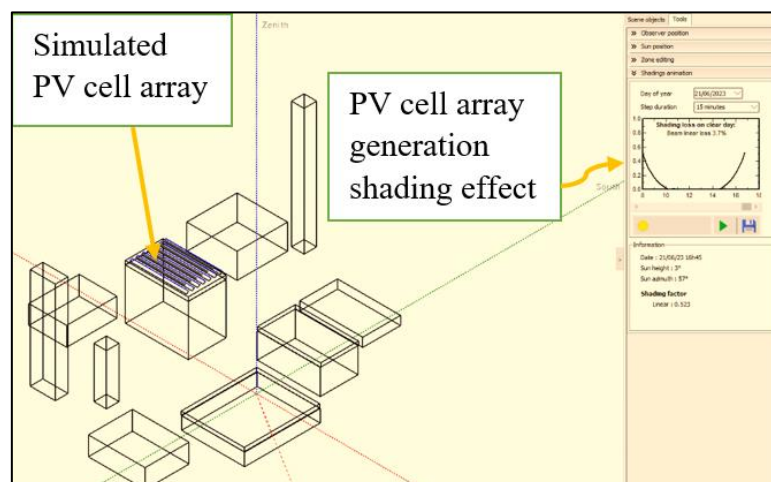


Figure 4-26. PV cell array simulation using PVsys software to estimate the PV cell's shading in a built environment

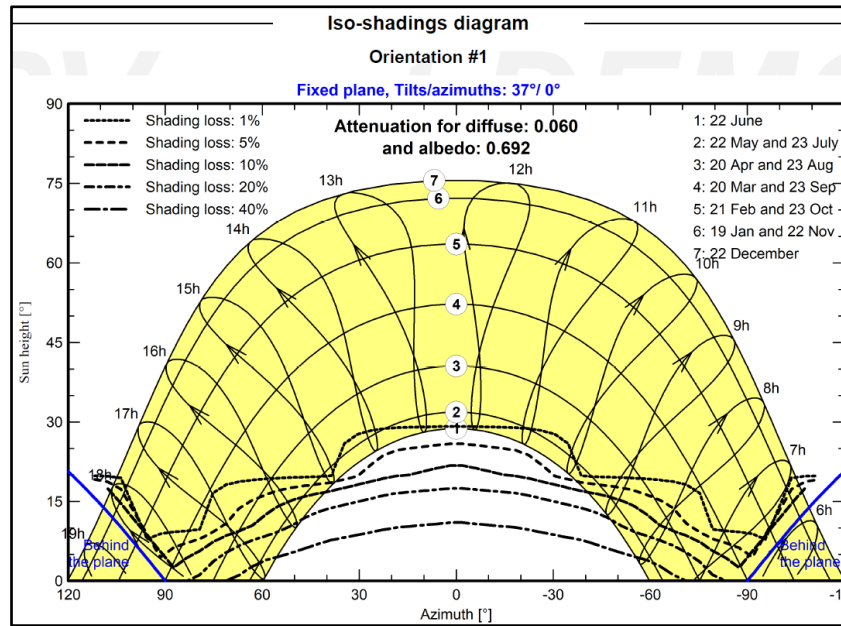


Figure 4-27. Simulation results from PVsyst software for PV cell's overall shading effect

4.6 Optimising PV Cell Array Using Setfos Software: Case Study 4

Setfos software is a powerful simulation tool for the optical and electrical modelling of semiconductor devices [194]. The software has been developed especially for PV cells, tandem thin-film and other semiconductor materials, such as OLED (organic light emitting diode) display devices using organic semiconductors. Thin-film solar cells consist of a minimal layer, between 1–3 μm , of PV cell material applied to a substrate, which can be flexible plastic or lightweight metal. By layering two thin-film materials with adequately distinct band gaps on a single surface, energy conversion efficiency can be enhanced without sacrificing flexibility or weight. Moreover, thin-film tandem cells present a more sustainable alternative for future solar energy generation. Additionally, the manufacturing process for thin-film tandem solar cells demands less energy and fewer raw materials than conventional silicon panels.

Hence, in this study, several different modules can be simulated using Setfos software—for instance, light emissions, absorption, transmittance, reflectance, scattering and charge transport. However, for this research, modules related to PV cell generation are simulated.

4.6.1 PV Cell Absorption Analysis

Figure 4-28 shows the estimated simulation result for absorption as a function of the wavelength of light. The absorption rate starts at 200 nm and sharply reaches its

maximum point at about 310 nm. After a slight sharp decrease, it reaches its maximum point again at 475 nm. Beyond 500 nm, the absorption rate gradually decreases up to 750 nm and then sharply falls to 900 nm. Hence, this type of absorption characteristic proves that only specific wavelengths can be used to generate useful energy. In addition, Figure 4-29 shows a particular layer's thickness absorption rate versus the red, green and blue light photon energy.

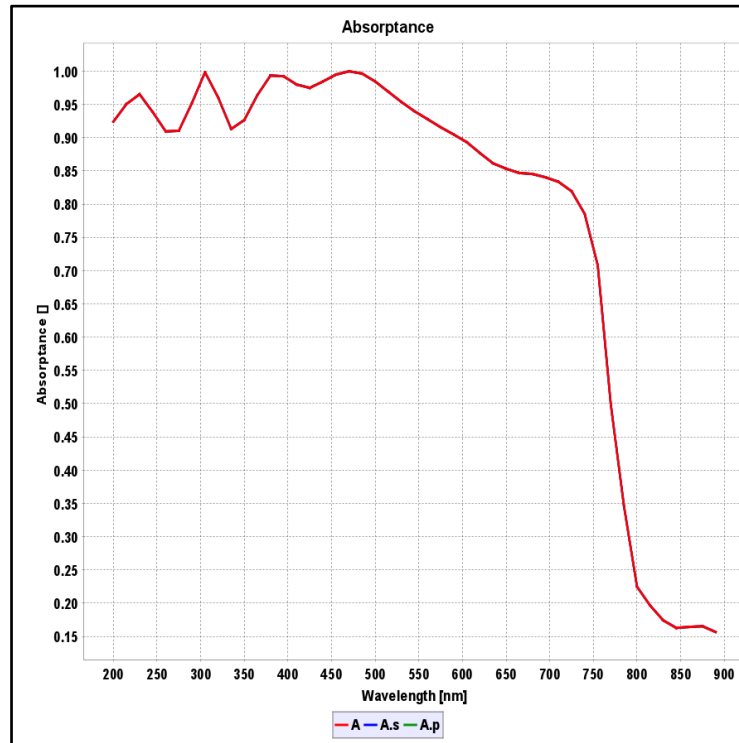


Figure 4-28. PV cell absorptance varies with wavelengths

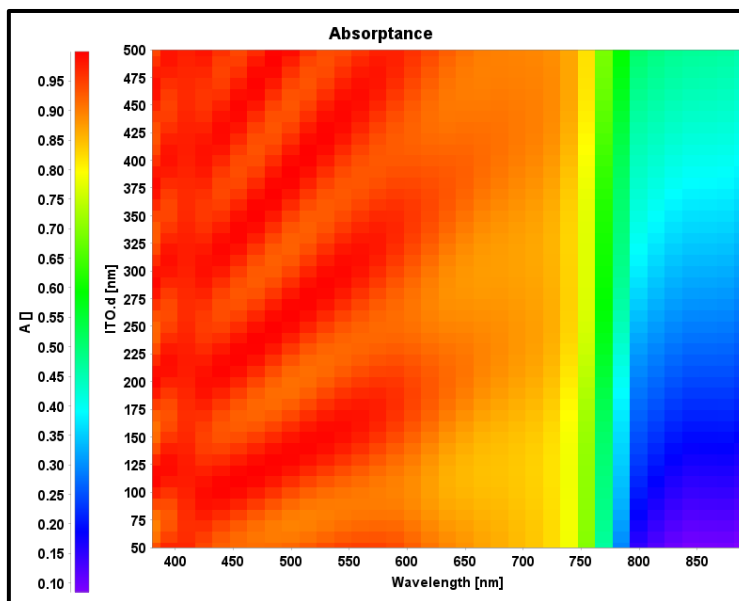


Figure 4-29. PV cell layer coloured absorptance varies with wavelengths

4.6.1.1 PV Cell's Multiple Layer Absorption Analysis

For devices with multiple structures, such as tandem solar cells, each material layer exhibits varying absorption efficiencies for specific wavelength ranges. Consequently, accurate spectral adjustment is essential to ensure that each layer captures light energy within its optimal absorption spectrum, thereby optimising conversion efficiency. This can be achieved by stacking PV cell layers with the lower material, such as tandem cells, to capitalise on the distinct absorption capabilities of the different materials.

The upper layer primarily captures high-energy photons, while crystalline silicon or alternative materials absorb lower-energy photons. This arrangement not only broadens the cell's ability to harness a broader range of the solar spectrum but also diminishes energy losses associated with excess or inadequate photon energies that are typical in single-material cells. As a result, tandem PV cells make more effective use of solar radiation through the innovative combination.

Furthermore, tandem PV cells advance solar energy conversion efficiency and open new avenues for the development of PV cell technology.

In this study, to investigate the optimum efficiency, various PV cell layers at different material layer thicknesses are simulated, as shown in Figure 4-30. Among these materials, the 'A-unpol' is shown to be the highest absorber of almost the entire wavelength range, followed by 'Perosvkte-A'. The absorption rates of individual material layers are estimated, which helps to identify and choose the most appropriate material for a particular application.

The absorption rates of individual material layers are also simulated by varying the voltage versus the wavelengths of the different colours of light, as shown in Figure 4-31. The most widely absorbed colour is red, which corresponds to the infrared light ranging from 450–625 nm spectrum.

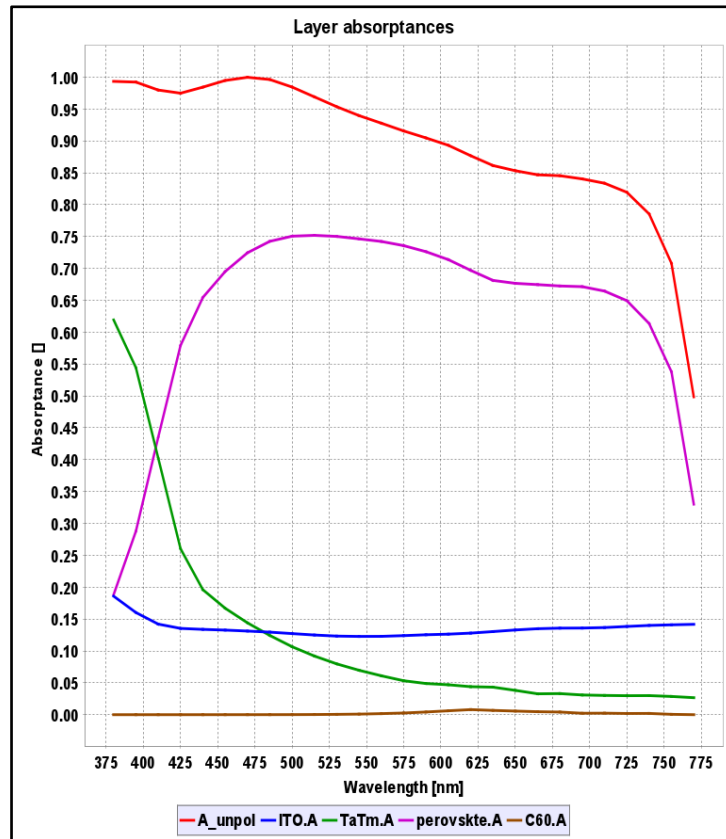


Figure 4-30. PV cell's multiple layer absorptance varies with wavelengths

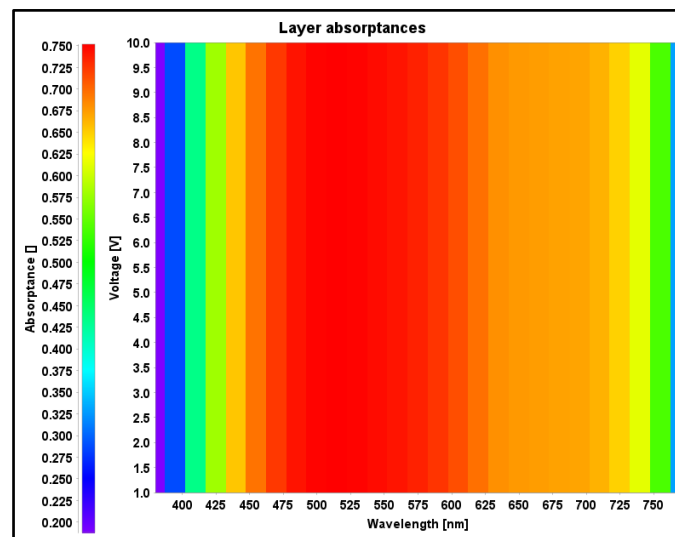


Figure 4-31. PV cell coloured absorptance varies with wavelengths

4.6.2 PV Cell Layers Transmittance Analysis

Figure 4-32 shows the PV cell layer transmittance characteristics versus the wavelength of light. Transmittance reduces the efficiency of the PV cell. To maximise efficiency, a lower or negligible transmittance is desired. However, the transmittance of a particular

material layer depends on how the material absorbs and reflects light related to its wavelengths. In this case, beyond the 75 nm spectrum, the transmittance of the particular material increased sharply. Transmittance also varies with supply voltage, as shown in Figure 4-33, where the higher frequency spectrum, primarily the blue and purple, is transmitted.

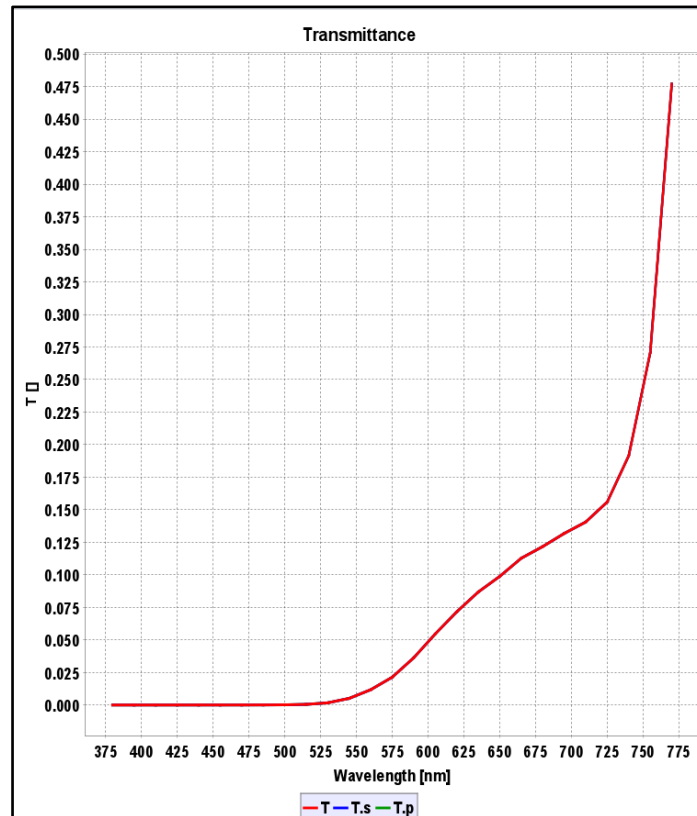


Figure 4-32. PV cell layers transmittance analysis

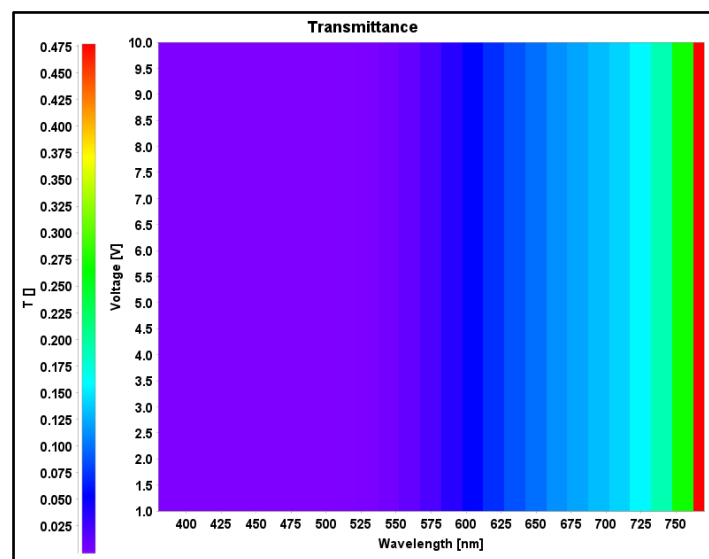


Figure 4-33. PV cell coloured layers transmittance analysis

4.6.3 PV Cell Layers Reflectance Analysis

The efficiency of PV cells depends on the reflectance, transmittance and absorption characteristics of the material layer, as mentioned previously. Figure 4-34 shows the reflectance of the PV cell layer versus the wavelength of incident light. Reflectance is undesired when it is reflected from the top of the layer, but it is desired when it is reflected from the bottom of the layer. This is because it gives photons a chance to be absorbed. In the simulation result, the sharp maximum reflection occurs at about 260 nm. Reflectance also varies with supply voltage, as shown in Figure 4-35. Most of the higher frequencies, which are the green colours, are reflected.

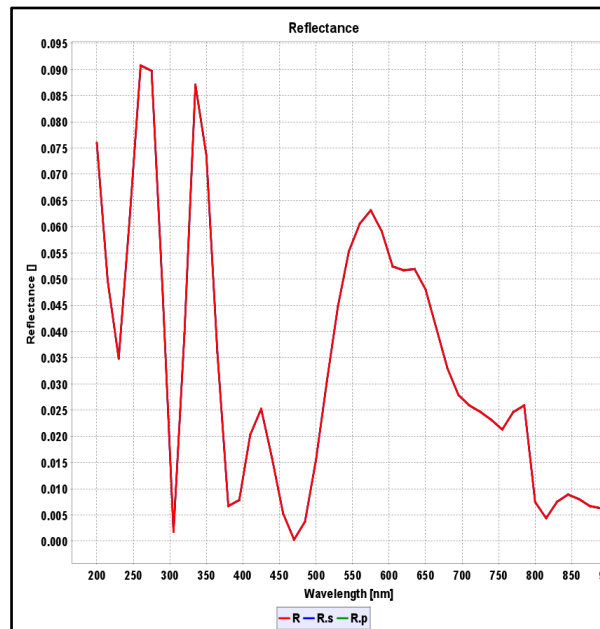


Figure 4-34. PV cell layers reflectance analysis

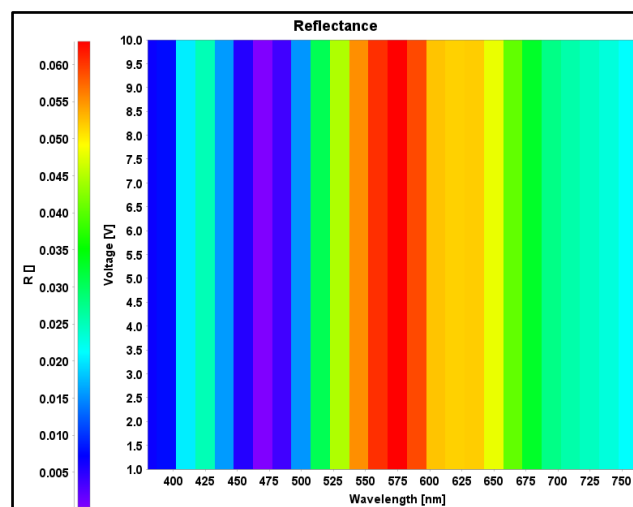


Figure 4-35. PV cell coloured layers reflectance analysis

4.7 Wind Turbine Integration Using Ashes Software: Case Study 5

The concept of a wind turbine or wind power refers to the mechanical process of generating electricity through the use of aerodynamic kinetic energy. Aerodynamics plays a crucial role in designing an efficient wind turbine; however, size is also a significant factor. Specifically, longer turbine blades result in a larger rotor diameter, which enhances the amount of energy a turbine can harness from the wind, thereby increasing its electricity generation capability. Typically, when the rotor diameter is doubled, the energy output increases four times [195, 196]. In certain situations, improved performance can be achieved with a smaller rotor diameter in areas of lower wind speeds. A rotor with a smaller diameter can generate more wind energy than its larger counterpart, because it requires less wind power to rotate the smaller generator. Consequently, the turbine can operate consistently at full capacity. Furthermore, the height of the tower plays a significant role in determining production capability; as turbine height increases, so does its potential for energy capture. This is because wind speeds rise in proportion to elevation, with an approximate 12% increase in wind speed for every doubling of height [195]. The wind turbine designs that are most effectively used are either horizontal-axis or vertical-axis types. Among these, the horizontal-axis turbine with a three-blade setup, illustrated in Figure 4-36, is extensively adopted worldwide for its efficiency and stability in aerodynamic turbulence. For this study, smaller-scale versions are chosen and conceptually simulated to meet the cooling specification requirement for the roof-mounted PV cell panels. An array of scaled triple-blade wind turbines is installed under the PV cell panels to provide cooling service while generating power.

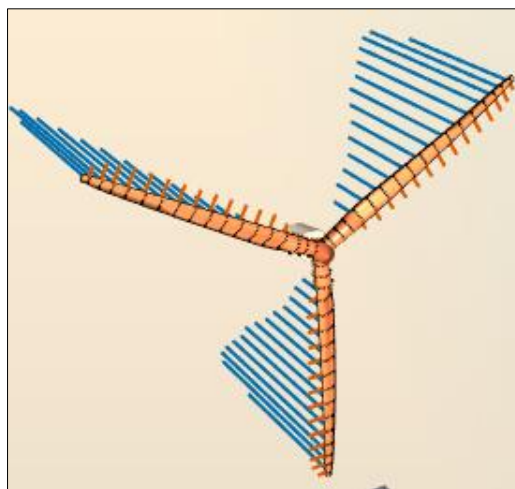


Figure 4-36. Horizontal-axis triple-blade wind turbine

4.7.1 Roof Side Small Wind Turbine Array

Wind farm turbines are now economically comparable to gas, geothermal, coal and nuclear power facilities. However, these massive alternative wind energy sources cannot be integrated into buildings like the building-mounted turbine, a small-scale version of a wind turbine that has a minimal impact on the building's structural stability. Figure 4-37 illustrates a basic conceptual model of a wind turbine array installed on the roof frame structure that also supports solar cell panels within the built environment. This arrangement not only generates electricity but also enhances the cooling efficiency of the solar cell panels. The airflow produced by the wind turbine circulates beneath the solar cell panels to help ensure consistent, continuous operation, which will optimise the performance and minimise fluctuations in generation caused by the inconsistent temperature of the solar panels.

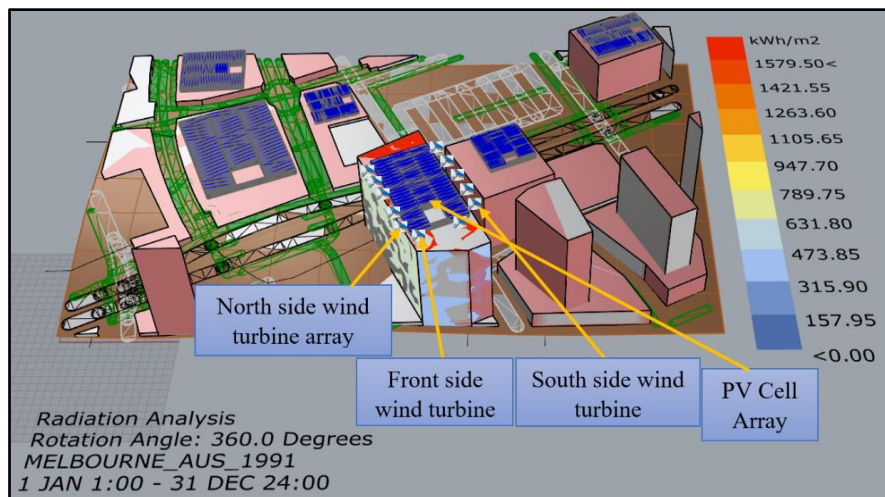


Figure 4-37. Wind turbine design using software

4.7.2 Optimising Wind Turbine Power

The conceptual design and modelling of wind turbines aim to achieve the highest level of optimisation. As a result, the design of aerodynamic blades and the diameter of the rotor are crucial for enhancing output. However, a recent investigation into maximising power extraction from wind turbines indicates that this process encompasses numerous intricate challenges [197, 198]. The research identifies three primary established techniques for optimising the output power of wind turbines:

1. Wind turbine power coefficient (C_p).
2. Tip speed ratio (TSR).

3. Optimum torque control (OTC).

For the purposes of the present research, ‘Ashes’ simulation software is used to optimise generation and to track the optimum output power.

4.7.3 Wind Turbine Optimisation Using C_p

The power coefficient Equation (4-6) quantifies the efficiency of a wind turbine.

$$(C_p) = \frac{\text{wind turbine actual produced power}}{\text{wind power provided in to the turbine}} \quad (4 - 6)$$

It is defined as the ratio of the actual electrical power generated by a wind turbine to the total wind energy that flows into the turbine blades at a given wind speed. This coefficient reflects the overall efficiency of different components within the wind power system. Manufacturers calculate the C_p for specific turbines, providing data across various wind speeds that can fluctuate according to operational factors such as wind velocity, blade angle and rotation speed. An optimised power coefficient indicates that as more wind energy approaches the turbine blades, there is a corresponding increase in the amount of electrical power extracted [199].

Figure 4-38 illustrates the tracking of the C_p through a rotor sensor system, averaging at 48.83%.

Figure 4-39 depicts the monitoring of the wind turbine’s thrust coefficient. While both the thrust coefficient and C_p display similar tracking graphs, the graphs are represented by distinct coefficient values.

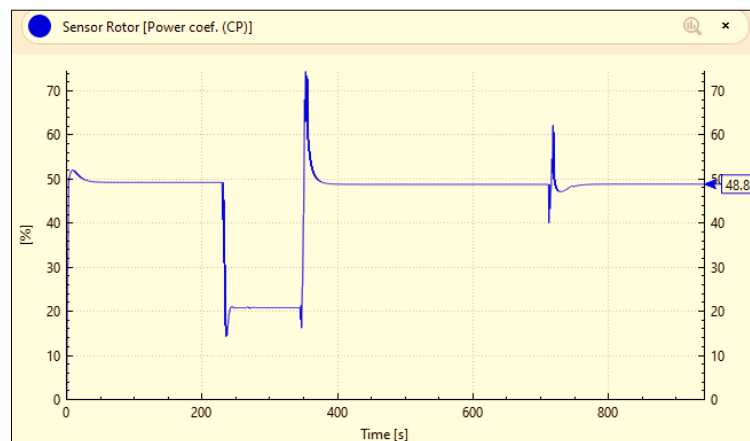


Figure 4-38. Wind turbine optimisation using C_p

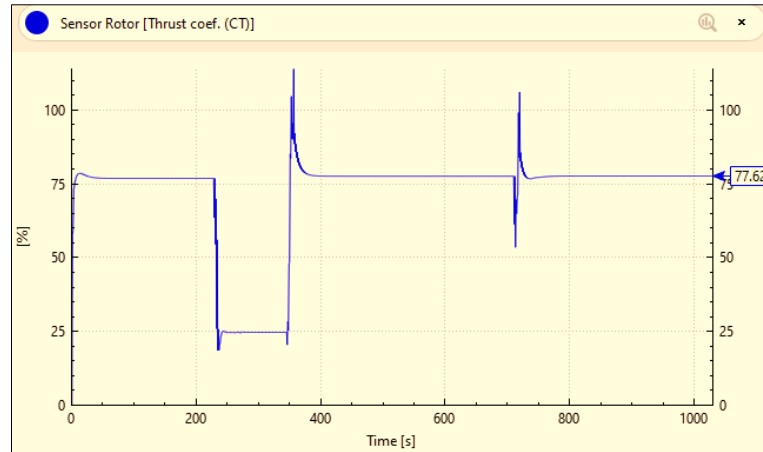


Figure 4-39. Wind turbine rotor thrust coefficient

4.7.4 Optimising Wind Turbine Power Using TSR

The purpose of utilising TSR Equation (4-7) is to enhance performance for individual generators at designated sites.

$$(\text{TSR}) = \frac{\text{wind actual tipping speed of the blade}}{\text{current speed of the wind}} \quad (4 - 7)$$

The purpose of utilising TSR is to enhance performance for individual generators at designated sites. The optimal TSR is influenced by factors such as the shape of the aerofoil blades, the number of blades and the specific model of the wind turbine. A three-blade wind turbine that functions within a TSR range of 6 to 8 is ideal for maximising power output [131] and demonstrates greater efficiency than those operating below 6 or above 8. Figure 4-40 illustrates the TSR tracking system implemented with a sensor rotor.

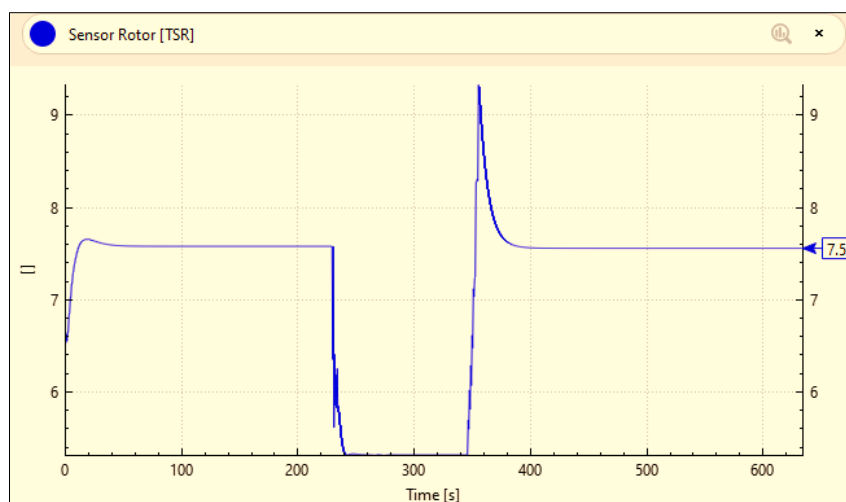


Figure 4-40. Wind turbine optimisation using TSR

4.7.5 Optimising Wind Turbine Output Power Using OTC

The OTC expression is given in Equation (4-8) and depends on the torque equation.

$$(P_m) = T_m \omega \quad (4 - 8)$$

Where:

T_m represents the peak torque, while ω denotes the angular velocity of the wind.

The OTC technique is employed to extract MPPT. Because of the slow response characteristics of wind turbines with significant inertia, enhancements were made to the traditional OTC method by dynamically adjusting the generator torque in relation to rotor speed, thereby increasing turbine efficiency.

For an optimised OTC approach, it is advantageous to establish an effective tracking range (ETR) that aligns with the local wind speed intervals and has a concentrated distribution of wind energy [200].

Furthermore, the revolution per minute (RPM) is monitored by the sensor, as illustrated in Figure 4-41, contributing to sustaining the optimised OTC displayed in Figure 4-42. Consequently, the output power is derived from the CP optimum MTPP Equation (4-9).

$$P = [(0.5C_p)\rho\pi R^2 V^3] = 136.637 \text{ kW} \quad (4 - 9)$$

Where:

ρ is Melbourne's average or standard air density 1.125 kg/m³.

V is Melbourne's average wind speed taken from Melbourne's specific location weather file data, which is 11.7 m/sec.

R is the wind turbine blade (1.5 m).

The C_p (48.83%) is taken from the simulation result shown in Figure 4-38.

The wind turbine array is multiplied by 12 to estimate the total power extracted. This is because 12 wind turbine arrays are installed, as shown in Figure 4-37.

Hence, the total power (P) = $136.637 \times 12 = 1,639.65 \text{ kW}$ is estimated.

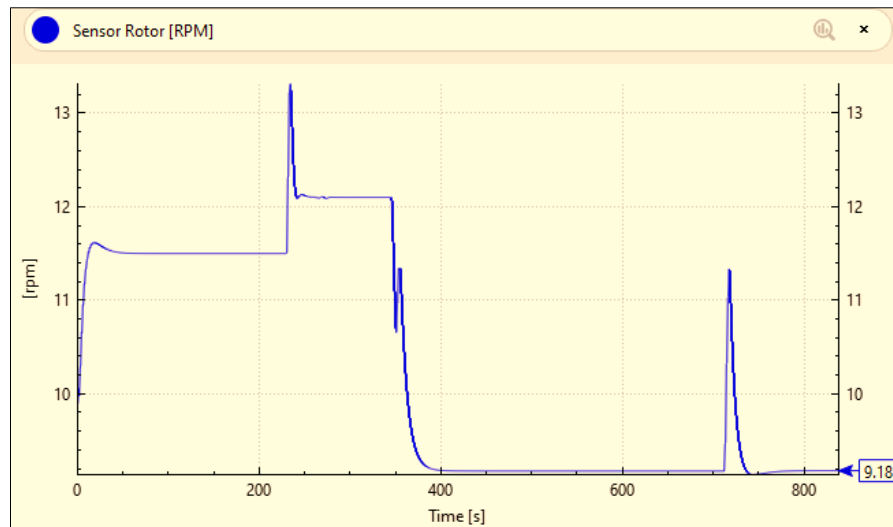


Figure 4-41. Wind turbine RPM

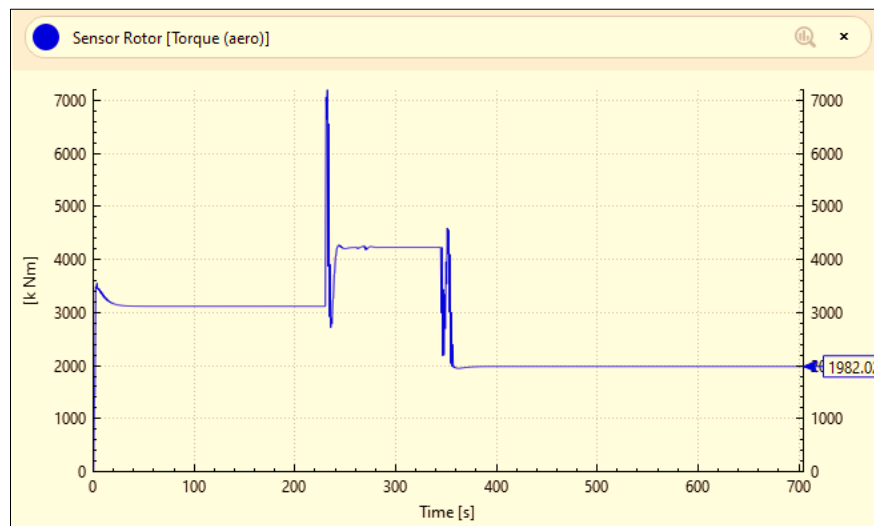


Figure 4-42. Wind turbine torque

4.8 Renewable Energy Connected Grid Penetration Effect

Incorporating large amounts of variable and somewhat predictable energy sources, such as renewable energy, can significantly disrupt the stability of the power grid. The rise of renewable energy sources not connected to the grid has presented challenges for maintaining secure operations within the electrical grid, affecting both transmission and distribution system operators. These renewable sources are primarily integrated into the distribution network at medium and low voltage levels, which have historically operated as radial systems with power flowing from transmission networks to loads connected to distribution networks. The considerable increase in intermittent distributed renewable energy sources has led to a bidirectional flow of electricity, requiring new operational

strategies and control mechanisms, including protective algorithms, to ensure a reliable electricity supply and adequate power quality for consumers. For this reason, this study theoretically evaluates the concept of power stability and the effects of penetration levels.

4.9 Conclusion

Designing and modelling a smart building equipped with renewable energy systems is recognised as a sophisticated undertaking. In practice, this endeavour involves a multifaceted process that necessitates the collaboration of various engineering specialists, experts in intelligent energy solutions and contributions from construction contractors. This research evaluates seven software applications for renewable energy through five distinct case study methodologies. The outcomes of each software simulation are analysed in relation to its specific uses and goals. For instance:

1. Autodesk Revit aims to enhance the optimal generation capacity of photovoltaic PV cells.
2. SCAPS1D is used to model the thickness of PV cell layers and assess their material energy bandgap. The bandgap of the cell determines the generation of optimised power. Hence, this case study focused on the efficient thickness of the cell.
3. DesignBuilder simulates the percentage contribution of the new building's PV cells to annual energy consumption. In this case study, the rooftop is fully covered by the PV cell, and the estimated amount generated is 85.6%.
4. Rhino, along with Grasshopper and Ladybug, provides detailed simulations of hourly PV cell energy generation throughout the year within built environments.
5. PVsys7 assesses the shading effects on PV cells.
6. Setfos analyses the PV cells' layer characteristics of absorptance, transmittance and reflectance. In this case study, a simulation is carried out to optimise the absorption.
7. Ashes software optimises wind turbine power generation while tracking the output performance. In this case study, the wind turbine is designed, modelled and simulated to suit the rooftop PV cell supporter frame to allow adequate cooling underneath the PV cell panels.

Additionally, a mathematical model has been created to accurately estimate the required amount of renewable energy installations, thereby minimising estimation errors.

Chapter 5

Enabling Technology in Smart Buildings and Mitigating its Drawbacks

5.1 Introduction

Enabling technology in smart buildings refers to the tools and approaches that, whether used independently or in conjunction with other technologies, assist occupants or workers in achieving greater autonomy within their environments. When these technologies are applied with a focus on the needs of the occupants, the technologies can significantly enhance long-term services and supports (LTSS), particularly for individuals learning specific tasks related to intellectual development skills.

The aim is to foster independence, facilitate personal growth and create more opportunities. Thus, today's buildings are outfitted with advanced technology designed to support their inhabitants. These modern structures are regularly updated with the latest innovations to conserve natural resources and foster an environment that significantly reduces energy consumption. As illustrated in Figure 5-1, future buildings will incorporate enhanced technology that positions them as part of the solution to environmental challenges rather than contributing factors to global pollution.

This chapter aims to facilitate the interoperability of intelligent and emerging devices with contemporary buildings by applying innovative concepts and smart strategies. The initial section focuses on a theoretical examination of technologies relevant to building systems, subsequently addressing the alleviation of shortcomings through simulation. It also emphasises the theatrical and practical application of smart thinking principles by utilising case studies for feasibility analysis.

The feasibility case studies use:

1. Mitigation of specific challenges and drawbacks associated with smart building, and

2. The concept of optimising resource use while enhancing energy efficiency in smart buildings.

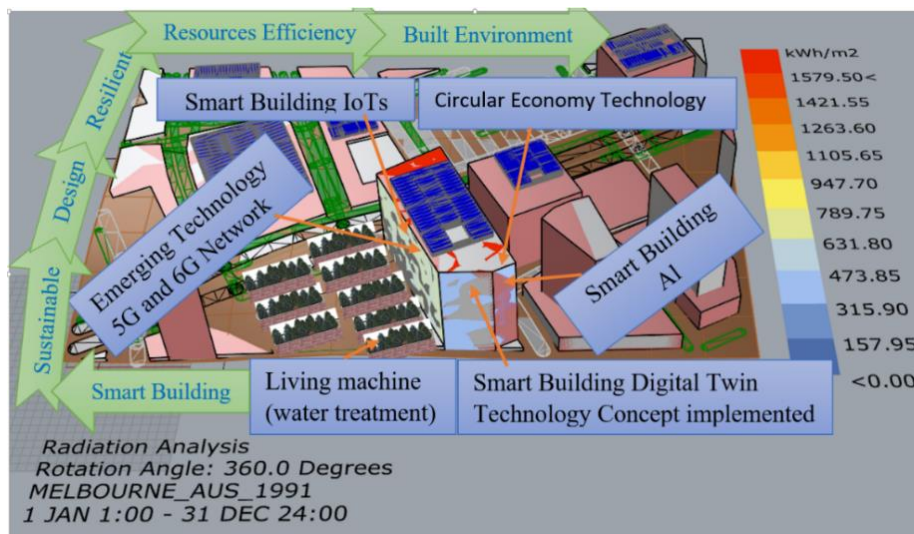


Figure 5-1. Technologically enabled smart building model in the built environment

5.1.1 Enabling Outdoor and Indoor Wireless Technology

The advancement of wireless technology, particularly in cellular communication, represents a notable achievement in research and development, fostering innovative and cutting-edge technologies. Researchers and experts view 6G as not especially distinct from its predecessors. However, it is essential to note that certain foundational technologies are absent in 6G. Hence, the commercial introduction of 6G marks a significant revolution that will facilitate the emergence of numerous cases that benefit the end-user. As 6G approaches the market, many are already investigating its potential applications. The uses of 6G technology are expected to develop further as its release date nears; there is widespread anticipation regarding its substantial influence on the following areas:

1. Comprehensive sensory digital perception for augmented reality applications.
2. Incorporating of artificial intelligence both at the network's edge and through its infrastructure.
3. Industrial internet applications for manufacturing automation and smart factories.
4. Tactile or haptic internet for conveying touch experiences.
5. Operation of autonomous vehicles.
6. Virtual healthcare solutions.

5.1.1.1 Current 6G Promises to Offer Key Advantages Over 5G

The 6G wireless technology signifies a significant advancement beyond 5G, and is aimed at enhancing connectivity and user experiences through cutting-edge infrastructure and solutions. The primary goal of 6G is to enhance the reliability of mobile broadband and communication networks. This network is expected to serve as a driving force for the development of emerging applications, including AI and IoT, while also facilitating further innovations in the field of telecommunications. Thus, with its sophisticated features, 6G is poised to exceed the capabilities of 5G technology. This forthcoming generation of technology is projected to unveil a new range of applications and improve user experiences by broadening network connectivity options, including:

1. Increased capacity at least within the terahertz (THz) spectrum range.
2. Enhanced coverage and reliability through an expanded spectrum.
3. Peak speeds of up to 1 Terabit per second (Tbps).
4. Reduced latency, with microsecond latency, multiple-fold increase in spectral efficiency up to 100 bps and enhanced mobility support accommodating speeds up to 1,000 km/h or 600 mph.

On the other hand, there are challenges associated with the construction of architectural engineering and related objects. The emergence of 6G technology is expected to significantly improve data transmission rates across networks, which consequently expands the potential for cyber vulnerabilities. The integration of AI, IoT devices and complex network infrastructures in the context of 6G introduces challenges in protecting these interconnected systems from breaches and cyberattacks. Although 6G networks provide accelerated data transfer capabilities, maintaining the confidentiality and integrity of this information becomes a pressing concern. The risk posed by unauthorised individuals intercepting and altering data represents a significant threat to user privacy and data security. Additionally, the use of higher communication frequencies, such as 100 GHz or 1 THz, will require innovative RF designs and new semiconductor materials. To handle speeds that exceed Tbps, it is essential to adopt faster processing technologies, such as optical processing or quantum computing. Power efficiency is evaluated according to the number of data bits transmitted per kilowatt consumed. While 5G networks demonstrate greater efficiency than their 4G predecessors, the predicted increase in network density and traffic anticipated with 6G may negate these

improvements, leading to energy consumption for 5G that could be four to five times greater than that of 4G. Consequently, 6G networks are expected to be denser and faster than those of 5G, and a significant rise in power consumption is likely to be the main issue.

5.2 Smart Buildings Connected to Advanced Technology Devices

The IoT is an umbrella name; in reality, IoT is categorised according to the place name of its application. BIoT, healthcare internet of things (HIoT) and industrial internet of things (IIoT) are a few examples of IoT; this study contributes extra focus to the concept of BIoT:

1. BIoT is a network of equipment, sensors and devices that communicate with each other directly, wired or wirelessly, to gather information, analyse the collected information and activate an actuator. BIoT's data include information from key building equipment such as HVAC, security and lighting systems. As technology matures and intelligent systems become a vital part of new construction and retrofits, newer, alternative best practices in technology are emerging.
2. IIoT refers to the application of IoT technology in industrial sectors, especially with respect to instrumentation and control of sensors and devices that engage cloud technologies. Recently, industries have used machine-to-machine communication (M2M) to achieve wireless automation and control. With the emergence of allied technologies, such as analytics and ML, industries are currently undergoing a new level of automation that creates new revenue streams and business models, marking the fourth wave of the industrial revolution.
3. HIoT asset monitoring provides multiple benefits to the healthcare industry. Doctors, nurses and orderlies often need to know the exact location of patient-assistance assets such as wheelchairs. Hence, in modern hospitals, healthcare and medical centre wheelchairs or other patient-related assets are equipped with IoT sensors; the assets are tagged with trackable IoT tags from the asset-monitoring application so that the IoT contributes to timely managed site operating facilities in return, enabling technology to achieve optimised efficiency.

5.2.1 IoT Comprises a Minimum of Seven Elements

Each connected IoT consists of several key components, as illustrated in Figure 5-2. These seven components embody the essential functions of the IoT system. An IoT device is equipped with various resources and includes a database for data storage. This database features web services that enable user communication via the internet. Moreover, each IoT is designed for specific applications, which include a controller device or program to manage the flow of data. At the same time, analytical components are tasked with processing the gathered information. For instance, BIoTs, such as those used for monitoring temperature, humidity and energy, require a thorough analysis of the data collected.

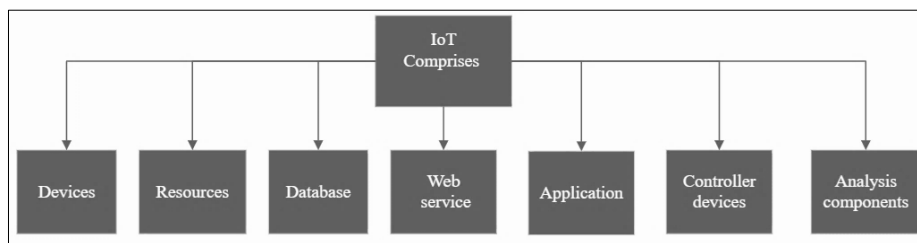


Figure 5-2. IoT-connected devices comprise seven different types of applications

1. **Connected Devices:** The networking, communication and connectivity protocols used with internet-enabled devices are primarily determined by the specific IoT application in use. Given the multitude of IoT applications available, there are also various options for connectivity and communication. This includes connections among a building's IoT devices for information exchange, links between IoT devices and services, and connections between IoT devices and users, such as mobile phones and other personal gadgets.
2. **Resources:** The IoT refers to a network of physical objects equipped with sensors, software and other technological elements to facilitate data connection and exchange over the internet. These objects can range from everyday household items to advanced industrial equipment.
3. **Database:** Data generated by IoT systems primarily constitute a time series flow, necessitating an appropriate IoT database. Such databases record data in real-time while efficiently compressing and storing it. There is a variety of IoT database types; notably, relational databases like PostgreSQL and NoSQL databases such as Cassandra and ScyllaDB offer lower latencies than traditional relational

database management systems (RDBMS). The selection of the optimal database for managing IoT data ultimately depends on user requirements. While structural query language (SQL) databases tend to be stable and well-supported, SQL may not be adept at handling large volumes of data efficiently. SQL can manage smaller applications but may falter under the demands of high-performance IoT systems. For IoT applications in smart buildings, moderate data storage solutions, such as NoSQL databases, are often more suitable.

4. **Web Services:** Trends in web services, along with advancements in IoT technology for smart buildings, facilitate remote connectivity that allows service contractors and facility teams to monitor and troubleshoot systems without being physically present near the equipment. As the IoT landscape expands, there is an increasing need for coordinated efforts with service providers to establish secure network connectivity and user authentication strategies that ensure safe integration with building systems.
5. **Application:** IoT devices find applications across various sectors, including health care, commercial buildings and consumer markets; notably, consumers account for approximately 60% of all connected IoT devices. For instance, specific IoT devices are designed to detect human presence—when occupants arrive at their premises, their vehicle communicates with the garage door opener. Once inside the building, features like thermostats automatically adjust to preset temperatures while lighting adapts to reduced intensity or colour settings. Other examples include irrigation systems that modify watering schedules according to weather forecasts or robotic vacuum cleaners that learn which areas require frequent cleaning. Additionally, the escalating demand for widespread connectivity, alongside storage capabilities, has spurred growth in diverse IoT applications. These include weather monitoring systems that provide updates on indoor/outdoor climate conditions, as well as building automation controls that feed signals into central processing units. Security-focused IoTs monitor suspicious activities within premises by reporting anomalies while managing entry-exit movements—unknown individuals may be denied access. At the same time, images are sent for further analysis before permission is granted using verified details.
6. **Controller Services:** An IoT controller facilitates communication between various connected devices—from sensors to facility machinery—and operates as

a bridge linking these devices to cloud-based servers or other remote platforms. Controllers serve as centralised control points, allowing efficient management of device performance optimisation. There are two primary types of controllers: hardware-based, which are compact, low-power units that connect via wireless protocols such as Wi-Fi or Zigbee, and software-based controllers, which operate through cloud deployment using application programming interfaces (APIs) for device interaction.

7. **Analysis Components:** Implementing intelligent analytics in smart buildings can significantly enhance operational management and efficiency improvements. Modern iterations of the IoT generate vast datasets requiring robust analytical tools for meaningful interpretation. As more components become interconnected through diverse sensor networks within buildings, enhanced visibility into long-term operational efficiencies emerges. However, the actual value of the IoT lies not merely in raw data collection but rather in converting that data into insightful information—a critical aspect underpinning many leading trends in smart building technology that relies heavily on analytics capabilities. Intelligent analytics play an essential role in organising information systematically while highlighting specific details regarding building conditions, along with potential improvement opportunities. Key advantages gained from integrating analytics encompass enabling strategic preventive maintenance instead of unnecessary routine servicing; correlating environmental metrics with equipment performance, facilitating fault detection; generating actionable insights aimed at optimising efficiency while minimising energy use; fostering increased automation, reducing dependence on manual processes; and ultimately enhancing client experiences through tailored reports alongside intuitive dashboards.

5.3 AI Augment for Virtual Reality

Utilising AI technologies, smart buildings can enhance their environments to encourage sustainable practices. Intelligent analytics are vital in organising this data and extracting specific insights about building conditions and areas for improvement. The advancement of AI in contemporary buildings is rapidly accelerating; currently, AI is taking over numerous tasks requiring analytical processes—such as in health care, marketing and engineering data. Similarly, AI assistance to optimise energy management is aimed at

reducing consumption on an hourly, daily and annual basis. As a result, efforts are being made to minimise carbon emissions while creating spaces that offer early warning alerts for issues, as well as fostering enjoyable living or working environments. These buildings promote high productivity and enhance the wellbeing of occupants. Practical data analysis is critical for the advancement of smart buildings that continuously manage substantial amounts of information related to various factors such as temperature, pressure, humidity, VOCs and IAQ. These data are fed into the system to play an essential role in ensuring optimal building functionality. This is because AI is crucial in efficiently processing these data quickly, as human capabilities fall short of delivering timely results.

Furthermore, AI continuously analyses data to pinpoint potential problems or opportunities for improvement. For instance, in a modern building, a room might maintain an optimal temperature with no complaints reported. However, AI-driven data analysis can reveal inconsistencies in the hot and cold water flow, signalling an issue that might have otherwise remained unnoticed. This scenario illustrates an energy inefficiency that human observation may miss but is quickly identified through AI's constant data monitoring. As a result, AI generates alerts or initiates work orders to encourage maintenance personnel to investigate and resolve the detected issue. This proactive approach to fault detection and diagnostics aims to minimise unexpected downtime.

5.3.1 AI Machine Learning Related to Buildings

A comprehensive building optimisation system encompasses all aspects of managing buildings and facilities. Examples of ML are:

1. ***Classic application of ML:*** Classical ML solutions are essential for enabling faster and more informed decision-making. Nevertheless, efficiently and affordably building, training and deploying these systems can be challenging. By utilising a strategic combination of hardware and software technologies, companies can boost productivity, maximise value and protect privacy and data integrity. To maintain competitiveness, numerous contemporary commercial buildings are incorporating classical ML—a branch of artificial intelligence—into their operations. Classical ML employs models or algorithms to autonomously analyse large datasets, identify patterns and predict outcomes. This capability allows companies to make timely, intelligent decisions that enhance operational

efficiency, improve security measures and foster the development of innovative data-driven products tailored to consumer behaviours. Moreover, various classical ML models—including linear and logistic regression, support vector machines, nearest neighbour searches and decision trees—are employed for these objectives. In contrast to deep learning neural networks, classical ML models typically require less computational power and depend significantly on the quality of input data for their learning processes. These AI are categorised as explainable machines. This characteristic offers decision-makers and data scientists clear insights into how algorithms produce specific results. Such transparency is vital for recognising potential biases within the system and understanding how different variables affect outcomes, an essential consideration in regulated industries like finance and government.

2. **Facial recognition:** Facial recognition technology aims to identify individuals from images or videos. Although this technology has existed for some time, its recent widespread adoption has brought it to the forefront across various sectors such as personal photo applications and mobile device authentication processes. Grasping the underlying principles of facial recognition is crucial to understanding its advancing capabilities. Facial analysis features enable users to detect faces, along with attributes such as eye state, mood expressions and hair colour details. These attributes are beneficial for tasks such as quickly sorting or searching extensive image databases using metadata. Facial recognition is applied in diverse fields ranging from identification in news media coverage to secondary authentication methods in mobile apps and automated indexing of media files by entertainment companies. Face-matching systems use ML algorithms in conjunction with computer vision technologies through several steps:
 - a. Identify the facial region within an input image.
 - b. Extract this facial region while ensuring proper alignment.
 - c. Convert each cropped face image into a face vector; note that search queries consist of sets of face vectors rather than full-face images.
 - d. Compare source and target face vectors to generate a similarity score reflecting likeness between faces; higher scores indicate a greater likelihood of identical identities.

- e. The application of a similarity threshold is critical in determining the accuracy of search results—the higher this threshold, e.g. 99.99% accuracy, the fewer misidentifications occur, known as ‘false positives’.
3. **AI training data:** AI and ML are among the technologies experiencing rapid development in contemporary society. Many companies worldwide are dedicated to creating applications that use AI functionalities to optimise various operations and enhance overall efficiency. The core process of AI training entails collecting data and inputting it into ML algorithms for analysis and educational purposes. This process includes functions such as detecting relationships, deriving insights, making informed decisions and evaluating results with reference to the supplied training data. The performance and effectiveness of these algorithms are significantly influenced by both the quality and quantity of the training data employed. Typically organised in a tabular format, AI datasets contain observations represented through text, images and videos. Furthermore, training data refers to the initial dataset used for developing an ML model, from which the model formulates and refines its operational protocols. The quality of this foundational dataset plays a crucial role in shaping subsequent stages of model development, establishing an essential framework for all future applications that rely on this same dataset. Therefore, it is vital to ensure that algorithms receive high-quality datasets to achieve success. This requires seamless integration of human resources, ML specialists and labelling tools. Tackling issues related to cleaning and filtering training data, collaborating effectively with teams and employing labelling tools to produce large volumes of high-quality data are essential tasks within this field. By identifying patterns in labelled data during training sessions, algorithms can apply these learned patterns when faced with unlabelled datasets.

5.3.2 Generative AI

Generative AI technology enables users to efficiently create new content by analysing a range of inputs. These sophisticated models leverage neural networks to identify patterns and structures in existing data, allowing for the production of innovative content across various formats, including text, images, audio, animations and 3D models. A significant advancement in generative AI is its ability to use different learning approaches, such as

unsupervised or semi-supervised learning, during the training phase. This adaptability enables organisations to leverage unlabelled data quickly and effectively, thereby developing foundational application models such as GPT-3 and Stable Diffusion, which enhance language processing capabilities. These applications demonstrate the capabilities by allowing users to create essays based on brief text prompts effortlessly. It is essential to maintain high-quality outputs for applications that interact directly with users since clarity is crucial for understanding. Visual outputs from image generation should also closely mimic natural images to achieve optimal results. Thus, generative AI incorporates several key elements:

1. **Diversity:** Effective generative models can accurately capture less frequent data distribution patterns without sacrificing quality, thereby mitigating biases inherent in learned models.
2. **Speed:** Numerous interactive features require rapid content generation; for instance, real-time image manipulation is vital for efficient content creation processes. In addition to these aspects, generative AI presents several notable advantages.
3. The ability of generative AI algorithms to produce genuine content—whether images, videos or text—that is nearly indistinguishable from human-created material benefits sectors such as entertainment, advertising and creative industries.
4. These algorithms improve the efficiency and accuracy of existing AI systems, like natural language processing and computer vision, by generating synthetic data valuable for training and evaluating other algorithms.
5. Generative AI empowers businesses and researchers to investigate complex datasets creatively, uncovering hidden patterns and trends that may not be readily visible through raw data alone.
6. Generative AI algorithms enhance the automation and acceleration of various tasks, resulting in significant time and resource savings for companies.
7. Overall, generative AI's potential impact extends across multiple industries and applications, marking it as a crucial focus within the field of AI research and development.

5.3.2.1 AI is Revolutionising Smart Building for the Next Generation

The incorporation of AI into the daily experiences of building occupants is reshaping the landscape of living and working. This transformation involves the automation of mundane tasks to enhance workplace collaboration and facilitate data-informed decision-making, effectively integrating AI into smart living environments.

Figure 5-3 shows the revolutionary collective contribution of building AI that demonstrates that embedding AI within future smart buildings is crucial and its importance cannot be overstated. Indeed, AI-enhanced smart buildings offer tangible advantages to residents. This represents a particularly thrilling phase in the evolution of smart buildings. Because of recent developments, personalising workspaces according to individual preferences has become feasible. AI is fundamentally transforming smart buildings by enabling tailored learning according to specific building attributes, facilitating swift data-driven choices, customising occupant experiences, ensuring intelligent safety and security measures, improving forecasting capabilities and enabling ongoing enhancements simultaneously.

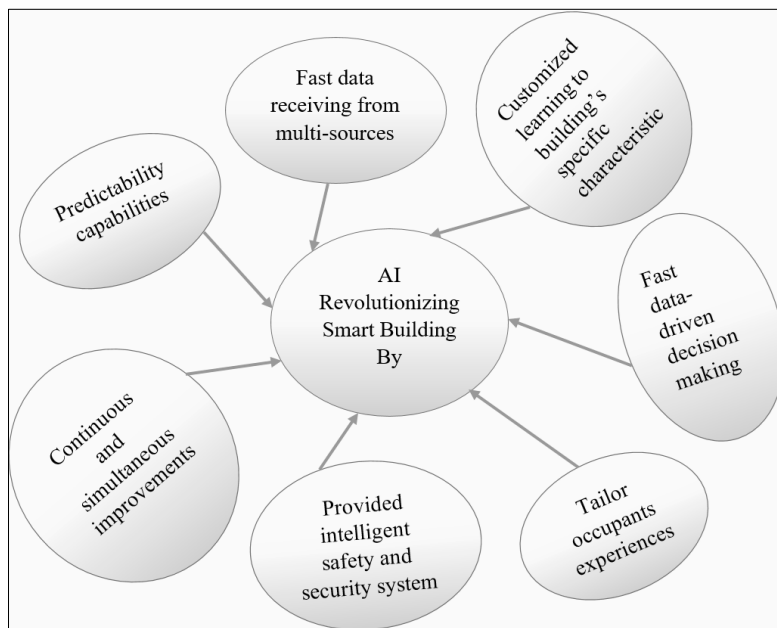


Figure 5-3. AI is revolutionising smart building for future generations

5.3.3 Technological Issues and Challenges for AI

Understanding information privacy depends significantly on individuals' capacity to make informed choices regarding the data shared with AI systems. The intricate nature

of AI operations can cloud the understanding of how personal information is used, which complicates the process of achieving genuine informed consent. For instance, elucidating the reasoning behind decisions derived from deep learning methodologies can be difficult, even for the creators of these algorithms. Companies and individuals encounter challenges in ensuring transparency within AI practices related to obtaining consent. This situation has prompted considerable investigation into the ‘privacy paradox’, a phenomenon in which individuals express concerns about their privacy yet readily disclose their information through various technologies and systems. The paradox implies that even when aware, individuals frequently feel pressured to accept terms that permit data use, believing there are no real alternatives but to comply. As technology ecosystems and data acquisition methods grow increasingly complex, relying solely on a binary yes/no consent model at the start of interactions becomes less relevant. Privacy legislation advocates for oversight mechanisms to mitigate power disparities between citizens and government bodies by guaranteeing the appropriate management of personal data. In future discussion of AI and privacy, attention may shift from merely collecting data to prioritising the ethical and responsible management of data following its acquisition. Efforts to limit or regulate data collection will likely encounter heightened obstacles because of the omnipresence of data-gathering technologies. Consequently, it is suggested that ethical stewardship of data post-collection should be emphasised by encouraging transparency, accountability and robust governance practices as fundamental elements in this initiative.

5.3.4 The Concept of the Digital Twin

In the current fast-paced technological environment, the concept of digital twins has emerged as a transformative idea with the potential to alter the built environment significantly. A digital twin serves as a virtual model of a physical entity, system or process, facilitating simulation, integration, testing, monitoring and maintenance activities. The study of digital twins will examine the revolutionary capabilities of digital twins and their effects on the architecture, engineering, construction and operations (AECO) sector. By examining practical examples and drawing comparisons with industries such as the automotive and aerospace industries, the concept aims to reveal the substantial benefits that digital twins can offer, while providing companies with practical strategies for leveraging this technology. A digital twin acts as a digital likeness of a

tangible object, process, service or environment that mimics its real-world counterpart in both appearance and behaviour. For instance, it could represent wind farms or more extensive structures, such as buildings or entire cities. Alternatively, this technology may be employed to replicate processes or conduct simulations to gather data for predicting performance outcomes.

Figure 5-4 shows the elements that contribute to the concept of the digital twin. Digital twin technology refers to a software application that uses real-world data to generate simulations, aiming to predict the performance of products or processes. These simulations rely on both the asset's current state and historical information. In addition, these applications can also incorporate elements from IoT, industry artificial intelligence and software analytics to optimise results. IoT sensors facilitate the transmission of real-world data, enabling the creation of virtual representations within a digital environment. With advancements in ML and the influence of big data, these virtual models have become essential in contemporary engineering, fostering innovation and enhancing performance.

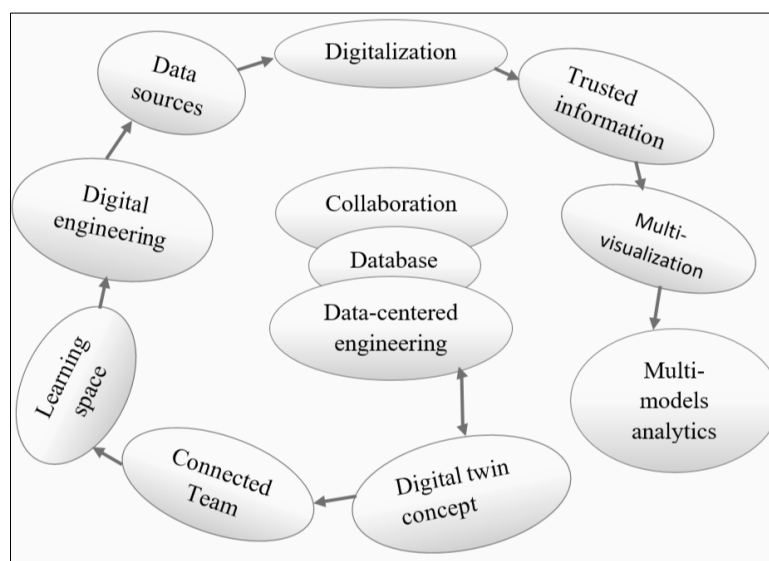


Figure 5-4. The concept of the digital twin in engineering of smart buildings

5.3.5 Smart Building Innovation Information System

Intelligent connectivity within a building represents the pinnacle of independence from conventional building practices, and innovates the building by implementing integrated modern concepts. These integrated technologies enhance comfort seamlessly, intuitively and effectively. In addition, recent innovative digitalisation expansion systems offer

extensive alternatives for managing, controlling and adapting operations to various needs in the modern building industry. For instance:

1. **Information access in a smart building:** Information access refers to the capability to locate, obtain and use information proficiently. It plays a crucial role in fostering social, political and economic progress. Historically, information has been shared through numerous formats that were generally accessible, frequently via public libraries. Many people still depend on interpersonal networks and media sources for their information needs, even though advancements in computer technology have transformed how information is accessed, enabling extensive collections of data related to business, education, health and entertainment to be available online. This technological evolution has significantly influenced both the volume and accessibility of digital content.
2. **Smart Data Stream (SDS) in a smart building:** The SDS processing service facilitates the forwarding of incoming messages to Service Access Point (SAP) and Blockchain Transmission Protocol (BTP's) streaming analytics. This service enables the development of applications capable of processing real-time streams of event data, allowing for the collection and response to incoming information. These services use the streaming web service interface provided by SDS to relay messages to the streaming real engine.
Additionally, it channels all messages of a designated type to their respective SDS input stream. Consequently, the schemas for both the message type and input stream must possess identical properties. The correspondence between message-type fields and input stream fields closely mirrors how the SQL processing service correlates message-type fields with table columns.

5.4 Mitigating Smart Buildings' Drawbacks Through Enabling Technology

As outlined in the introductory chapter, smart buildings encounter various challenges. This research aimed to identify the most significant issues and propose solutions for some of them. While several strategies for addressing these challenges exist, this study focuses on two specific drawbacks, presented through case studies:

1. **Electrical supply nuisance tripping devices:** The main switch regulates the entire electrical system of the building and may be influenced by faults arising from appliances. Its key function is to disconnect the power supply, particularly during maintenance activities. Individual sub-circuit breakers are affected primarily by short circuits or over currents, which are uncommon unless caused by overloads or improper wiring in the circuit. The most frequent issue encountered is with the RCD. This device can be temporarily or permanently affected by nuisance spikes or genuine earth leakage currents [201]. Designed for safety, it requires manual resetting rather than automatic resetting, making it ineffective for addressing temporary or intermediate fault spikes. Downtime caused by faults could lead to considerable production losses. Thus, a redesign of the RCD is essential.
2. **Asset and energy saving:** Conventional wiring methods consume considerable electrical power, which adds to undesired initial and running costs. These initial and running maintenance costs decrease energy efficiency. To reduce costs and minimise energy deficiency, this research study proposes an alternative use of the single electrical device for multiple output-activation (SEDMA) and few electrical devices for multiple output-activation (FEDMA) wiring methods. Using these methods, machine initialisation, running costs and energy use can be saved. This research method begins with a group of Lifter variable speed drives (VSDs), commercial laundry machines and ceiling lighting; however, the concept can be expanded to industries such as manufacturing, where multiple sequential conveyors, robots and computer numerical control (CNC) machines are in operation. Hence, intelligent sequential and simultaneous operations can be experienced with much-minimised devices by implementing intelligent demultiplexing algorithms with real-time definite precisions.

5.4.1 Remote Mitigating Method for RCD Nuisance Fault Recovery and Monitoring System

Modern building switchboards are equipped with a primary switch known as the ‘main switch circuit breaker’ along with one or more RCD breakers, which vary according to the installation size. Multiple sub-circuit overcurrent protection circuit breakers are also included, with each component serving distinct functions.

The main switch oversees the entire building's electrical system and may not be influenced by faults arising from appliances within the structure. Its fundamental role is to disconnect the power supply, particularly during maintenance work. The individual sub-circuit protection circuit breakers respond primarily to dead shorts or overcurrents in their respective circuits. Faults occur when there is an overload or improper wiring. RCDs are notably susceptible to faults; nuisance spikes or actual earth leakage currents can either temporarily or permanently affect them. Because they are designed for safety, RCDs do not automatically reset and require manual intervention. The design poses challenges in managing temporary spikes and intermediate faults, which can lead to significant production losses during downtime.

To mitigate these issues, it is essential to redesign the RCD along with Wi-Fi-controlled socket outlets and lighting switches to ensure that the RCD functions together effectively when failures occur in sub-circuit zones. This is illustrated in Figure 5-5, where the 5 V Direct Current (DC) is injected at the RCD terminal, and the arrows indicate the type of device used. Figure 5-6 presents a flowchart detailing the design process as well as steps for monitoring and fault resolution.

For continuous and constant monitoring, a remote application tracks the status of the building's electrical system. A practical test was conducted to satisfy the theoretical concept. For this study, a 10 A, 2,400 W heating appliance was selected for continuous monitoring of operational current. Variations in load consumption are categorised into the full load, partial load and no load conditions, as illustrated in Figure 5-7; any readings outside these classifications may indicate abnormal current activity, and the no-load threshold is close to zero.

The ACS712 current sensor continuously tracks the primary circuit current. This device is used in both industrial and commercial building settings for measuring electrical currents [202]. Moreover, electronic current sensors are commonly used not only in industrial and commercial buildings but also in various types of machines.

For this study, the sensor was installed at the RCD infeed terminal, measuring the maximum current flowing into the building. Current which was higher than the normal rating was recorded. The 10 A, 2,400 W heating appliance was used. The method can also function with higher currents; however, the sensor must be positioned at the main supply

point to monitor the total current flowing throughout the building. In the event of a fault occurring at any socket outlet, changes in current may occur owing to the tripping of either the RCD or circuit breaker. The last recorded current before tripping can assist in determining the nature of the fault, as indicated in Equation 5-1.

As illustrated in Figure 5-6, if no signals are detected for an extended duration, the applications perform self-diagnoses regarding internet connectivity. Upon receiving a notification of a current that deviates from specified limits or indicates a failure, the application investigates potential RCD malfunctions. The remote monitoring application verifies whether the RCD failure is confirmed.

Hence, it is essential to assess both the short circuit and overcurrent values against the ratings and tripping characteristics of the circuit breaker. After resetting the RCD, the application checks for further faults. When a nuisance fault occurs, it should be resolved. If issues persist, additional troubleshooting steps should be undertaken. The following parameters must be entered into the remote application when installing the components:

Primary supply voltage $\leftarrow 230 \text{ V}$

Monitor the main supply current $\leftarrow 10 \text{ Amps}$

Sub-division line impedance (Z) $\leftarrow$

Monitor no load threshold current $\leftarrow 0.5 \text{ Amp}$

If (Monitor no load threshold current is $< 0.5 \text{ Amp}$ or connection not established for greater than 10 seconds), then the application or the Wi-Fi fails. Check for the application's correct operation, Wi-Fi connection and resume monitoring. If a failure notification message is received, execute Equation (5-1) and analyse the last recorded fault current.

$$\text{Monitored Fault Current (X)} = \frac{V}{Z} \quad (5 - 1)$$

Where

V is the RCD rated Volts.

Z is the impedance of the line cable connected to the RCD and the socket outlets.

Current monitoring 10A node = $\begin{cases} X \geq 10A \text{ is earth leakage} \\ X < 11A \text{ is over current} \\ X < 15A \text{ is short current} \end{cases}$

Current monitoring 15A node = $\begin{cases} X \geq 15A \text{ is earth leakage} \\ X < 16A \text{ is over current} \\ X < 19A \text{ is short current} \end{cases}$

Current monitoring 20A node = $\begin{cases} X \geq 20A \text{ is earth leakage} \\ X < 21A \text{ is over current} \\ X < 25A \text{ is short current} \end{cases}$

If the RCD fails, the linear actuator is set to 'true' for $t = 10$ seconds, and then the actuator is set to 'false'. Then, wait for the response for two minutes. If the response is positive, the nuisance fault is cleared, and monitoring is resumed. If the response is negative, then the 5 VDC is set to 'true'. Read socket outlet node voltages and set them to 'true'. If the failure type is not identified, repeat the process; otherwise, if the read lowest voltage cannot be identified and node voltages are similar, set the neutral loop wire to 'false', then read the node voltage individually. If the lowest voltage is identified and the fault type is identified, then isolate the faulty node, set it to 'true', and resume power.

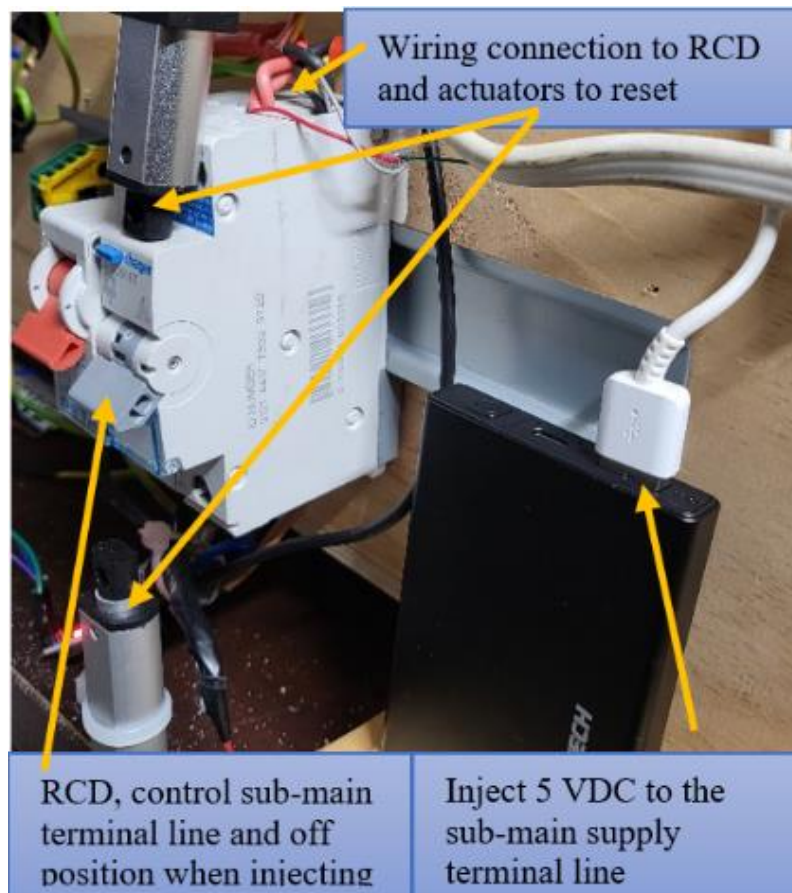


Figure 5-5. Socket outlet, node voltage fault identification testing components

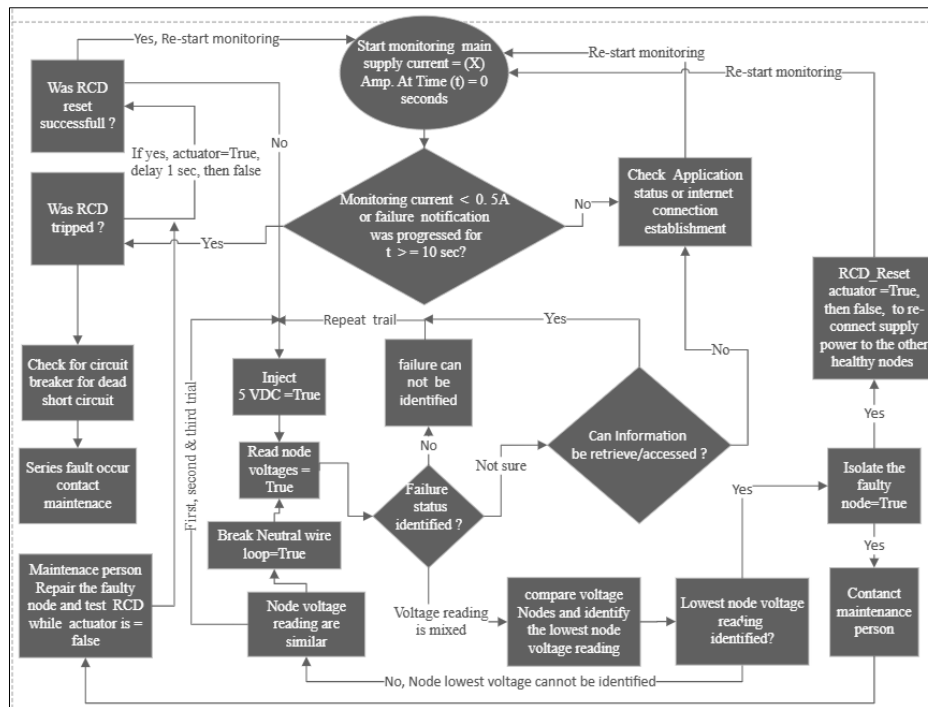


Figure 5-6. Remote monitoring and fault rectification design flow chart

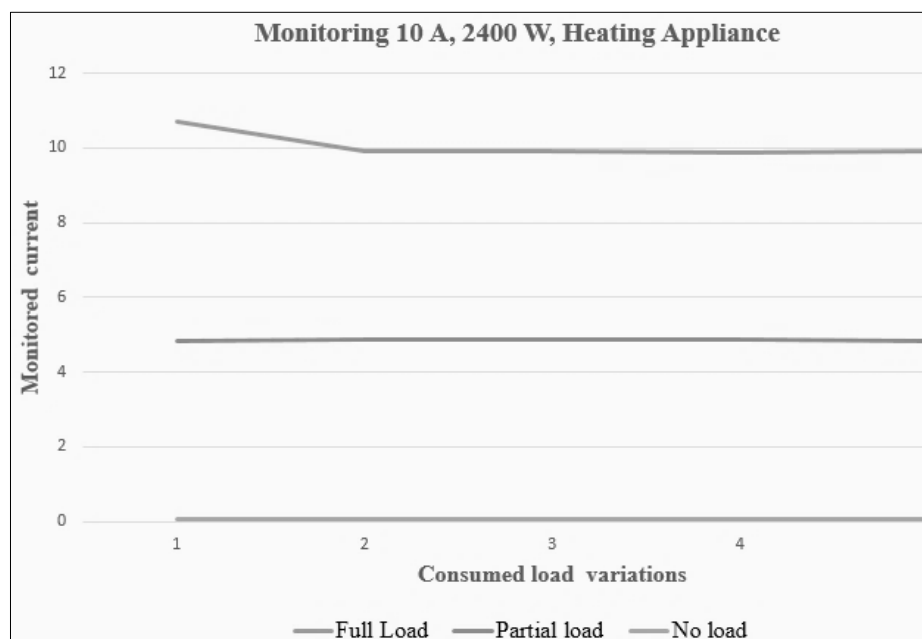


Figure 5-7. Remote current monitoring test for 10-Amp 2,400-Watt heating appliance

5.4.2 RCD Operating Principle and Occurrence of a Nuisance Fault in a Power System

RCD is an electromechanical safety apparatus designed to safeguard against electrocution and electrical fires by automatically interrupting the flow of electricity when it detects a current leak in the circuit. The operation of an RCD is based on the principle that the

incoming current should equal the outgoing current. It includes a core balance transformer (CT) with primary and secondary windings, along with a sensitive relay for immediate fault signal detection [131, 203]. The primary winding of the RCD is arranged in series with both the supply mains and the load, while the secondary winding connects to a highly sensitive relay. Under normal conditions, the magnetising currents flowing through the conductors counterbalance each other, resulting in no residual magnetic field capable of inducing voltage in the secondary coil. However, when leakage current flows, it creates an imbalance within the circuit that generates leakage flux in the secondary coil. This flux produces an electrical signal detected by the relay, which then triggers a mechanism to disconnect the supply voltage. The tripping mechanism operates at a residual current level between 60% and 80% of its specified leakage current [204].

Currently, RCDs are mandatory for monitoring electrical circuit safety on both residential and commercial properties. RCDs manage multiple line circuits within an electrical switchboard on residential and commercial buildings and serve to prevent electric shocks and save lives from potential electrocution. However, these safety devices can face both genuine and non-genuine faults, especially when low-impedance heating devices are connected or during periods of higher harmonic distortion and temporary transients within the circuit [131, 203]. In such instances, the RCD may isolate circuits without determining the specific cause of failure.

Moreover, given that RCDs control numerous sub-division terminals, identifying which terminal has experienced a fault can be challenging. In some cases, locating these faults can take considerable time, even for skilled tradespeople or electrical engineers, resulting in unnecessary operational costs for owners and operators of commercial buildings. The RCD, nuisance tripping and response to the steepness of the rise of the distorted current depend on Equation (5-2) [205].

$$\frac{di_1}{di_2} = \frac{2\sqrt{2\pi I_1 f_1}}{\sqrt{\sum_{k=1}^n h_k^2}} \sum_{k=1}^n (h_k k \cos(\phi_k)) \quad (5 - 2)$$

Where I_1 = the effective value of the primary current distorted by harmonics with a share of $h_k = \frac{I_{mk}}{I_{m1}}$,

ϕ_k = the angle of the k^{th} harmonic

k = the number of next harmonic

f = frequency

$\frac{di_1}{dt}$ = The actual rate of change of the currents with respect to time is time-variant. This can be defined as the actual speed of the current in the circuit.

Circuits that include capacitance and inductance exhibit one or multiple resonant frequencies. If these resonant frequencies align with the harmonic frequency generated by nonlinear loads, it can lead to harmonic resonance [206]. Furthermore, voltage and current during the resonant frequency can be highly distorted. This distortion can cause nuisance failure in an electrical power system.

Additionally, nuisance failure may occur because transient ground current exceeds the RCD threshold, leading to RCD malfunction. The transient or harmonic frequencies, while short-lived, can lead to the tripping of the RCD through their combined magnitude and duration, resulting in power disconnection from the circuit. The tripping behaviour of the RCD is altered in a circuit where the residual current is distorted. The mathematical representation of how RCD relays a trip because of harmonics is based on the residual current's time function, its amplitude and the presence of harmonics, frequencies and phase angles [207].

The distorted residual current can be expressed by Equation (5-3).

$$i_{\Delta} = I_{\Delta amp} [\sin(\omega t + \varphi_1) + C_3 \sin(3\omega t + \varphi_3) + C_5 \sin(5\omega t + \varphi_5) + \dots + C_h \sin(h\omega t + \varphi_h)] \quad (5 - 3)$$

Where

i_{Δ} , residual current as a function of time.

$I_{\Delta amp}$, the amplitude of the residual current

$C_3, C_5 \dots C_h$ are the content of the amplitude to fundamental frequency due to the 3rd, 5th... hth harmonics, while $\varphi_3, \varphi_5, \dots$, are the phase angles of the corresponding harmonic 3rd, 5th... hth harmonics.

5.4.3 Designing a Circuit that Interfaces with the Safety RCD and the Wireless Wi-Fi-Controlled Terminal Socket Outlets

This study explores the limitations of RCD and proposes a voltage-sensing circuit that is integrated into each terminal of smart socket outlets, as well as current sensors located within the main circuit RCD, as illustrated in Figure 5-8. In the event of a failure, this circuit transmits a remote alert signal to the designated individual via a Wi-Fi web application. The circuit then assesses the status of the fault currents to ascertain whether the RCD is encountering genuine earth leakage.

To safeguard against electrical hazards, the RCD disconnects the circuit; during this period, the responsible person can remotely analyse the type of fault to determine its authenticity through several steps:

Step 1: *Retrieve the last recorded fault current from the main circuit controller, reset the RCD and attempt to ascertain the failure status. If this initial assessment is inconclusive, proceed to further steps.*

Step 2: *Apply 5 VDC into the circuit while keeping the RCD switched off and check the condition of the terminal socket outlets. The 5 VDC is supplied at both active and earth wires connected to RCD terminals; thus, if an actual earth leakage current exists, it will flow from the active wire into devices/appliances and return via the earth wire.*

Step 3: *Compare and identify which terminal has failed by measuring the returning voltage from all terminal nodes after injecting 5 VDC.*

Step 4: *If all terminal nodes display similar voltages, disconnect the neutral loop wire and individually supply injected voltage to each node for readings.*

Step 5: *If identified as a nuisance failure, reset the RCD.*

Step 6: *If deemed an absolute failure, isolate only that specific faulty terminal while resetting the RCD to restore power to other functional terminals in that sub-division. Then, await further status feedback.*

Step 7: *Once a fault has been identified, power can be restored to other operational, healthy terminal nodes, and the sensors of these terminals should indicate similar*

voltage readings. If no failures are detected in any other terminals, the control circuit will send a notification.

Step 8: When multiple terminals experience failures, repeat these procedural steps for each affected terminal.

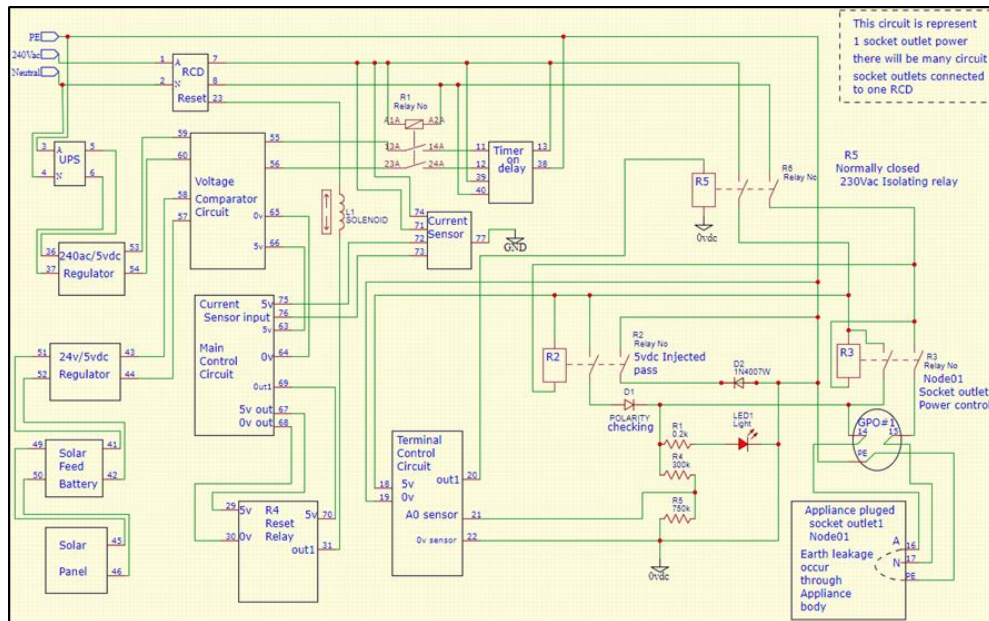


Figure 5-8. Remote monitoring and automatic reset for the nuisance fault recovery circuit

5.4.3.1 Current and Voltage-Sensing Devices

Assume the RCD controls 12 socket outlets, as shown in Figure 5-9. According to AS/NZS3000 standard wiring rules, the minimum cable size is 0.0025 m^2 , and the maximum circuit breaker current capacity rating that is allowed to be installed to protect the cable is 20 A. Correspondingly, the socket outlet's current capacity rating that can be connected to a 0.0025 m^2 cable is either 10 A, 15 A or 20 A. Then, any current greater than 20 A passing through the circuit is automatically examined as an overcurrent/short circuit current. The short current value depends on three parameters:

1. On the impedance of the circuit.
2. On the base current of the circuit breaker.
3. On the tripping characteristics of the circuit breaker.

These parameters can be calculated using Ohm's law. During the short circuit fault, the impedance goes near zero; assume it will be 1Ω or less than 1Ω . This ensures that the

short circuit fault current will be greater than its base current, meaning over the circuit breaker rating, which controls the circuit. In this case, the 20 A circuit breaker tripping current will be over 20 A. Hence, it can be treated as an overcurrent. This is also true for 15 and 10 A circuit breakers. Thus, any current outside of these parameters can be assumed to be a nuisance or earth leakage current. These parameters can be programmed into the smart circuit controller device during the installation process. Additionally, this configuration is monitored remotely, allowing a decision on remote response to proceed accordingly. Identifying real and nuisance faults remotely assists in making correct decisions.

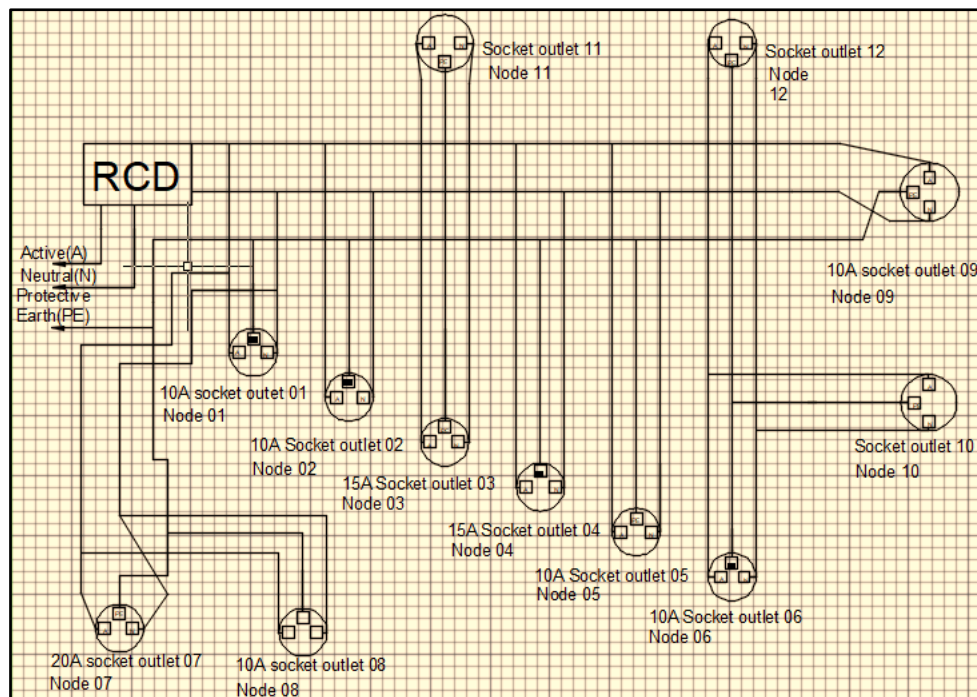


Figure 5-9. RCD sub-division socket outlet network nodes

The 5 VDC is injected to identify the terminal voltage, which is donated as a terminal node. Injected voltage is measured during the fault occurrence and is present using analogue voltage detector devices. The sensor can detect up to 25 VDC [208], but for this study, 5 VDC is used. This is to comply with the smart Wi-Fi-controlled socket outlet. The sensor is connected to the ESP32 analogue input. Complying with AS/NZS3000 wiring rules, the cable size that connects the main circuit breaker where the injected voltage is applied to the socket outlet node is 2.5 mm², and its length is approximately 0.5 meters.

$$\text{The resistance of the cable is } (R_c) = \frac{\rho L}{A} \quad (5 - 4)$$

Where

R_C is the resistance of the cable, ρ is the resistivity of the cable, and A is the cable cross-sectional area. The resistivity of copper wire at standard temperature is $1.77 \times 10^{-8} \Omega/\text{meter}$. The cross-sectional area of 0.0025 m^2 converted into square meters is:

$$(0.0025)^2 \times \frac{1}{1} = (0.0025)^{-2}$$

$$R = \frac{1.77 \times 10^{-8}}{0.0025^{-2}} \times 0.5 = 0.000354 \Omega \quad (5 - 5)$$

The injection circuit cable resistance is in series with the sensor voltage divider resistor ($R_1 = 300\text{k}$ and $R_2 = 75\text{k}$), as shown in Figure 5-10. The voltage drop with the 0.5 meter is $V_d = 0.0000472 \text{ V}$. Hence, the drop voltage is not significant; it has been assumed to be a lossless circuit. However, for non-research projects, it is necessary to consider that the length of the cables increases by a factor of 20 or 30. Remote fault identification was conducted with respect to time (t), as shown in Table 5-1. At $t \leq 30$ seconds, 5 VDC is injected into active and earth wires, and then the reading from the sensor is examined. At $t < 60$ seconds, the signal is sent to break the neutral wire loop. Then, the readings from the sensors are reviewed again to identify the fault node.

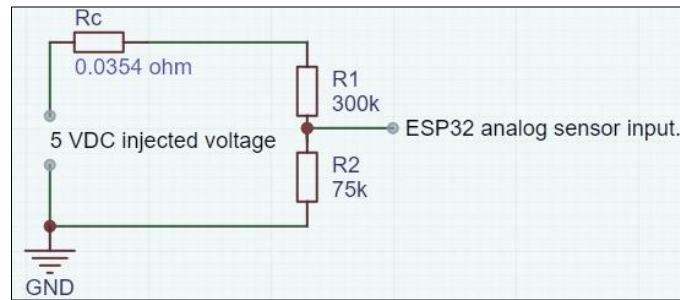


Figure 5-10. Ejected voltage-sensing resistance circuit

Table 5-1. Socket outlet node fault identification method, where t is the testing time

First trial			
Node number	At $t = 0$	At $t = 30 \text{ sec}$	Fault status
1	5 V	5 V	Fault exists
Activate the push button to disconnect the neutral wire loop at $t < 60 \text{ sec}$.			
2	5.16 V	0.16 V	No fault

3	5.15 V	0.16 V	No fault
Second trial			
1	5 V	5 V	Fault exists
Activate the push button to disconnect the neutral wire loop at $t < 90$ sec.			
2	5.16 V	0.16 V	No fault
3	5.16 V	0.16 V	No fault
Third trial			
1	5.16 V	5.16 V	Fault exists
Press the button to disconnect the wire loop at $t < 120$ sec			
2	5.16 V	0.14 V	No fault
3	5.16 V	0.16 V	No fault

Furthermore, revising the design of safety mechanisms, RCDs and wireless Wi-Fi-controlled socket outlets can significantly decrease the duration of failures in settings such as pharmaceutical manufacturing plants, food processing industries, hotels and restaurants. In these environments, prolonged failure times for RCDs can result in considerable reductions in production efficiency owing to the potential impact on cold storage equipment. Machines that maintain high operational availability contribute to increased production levels by remaining functional during active production phases, while unexpected equipment malfunctions can disrupt their operational capacity. The overall effectiveness of a machine is primarily assessed by combining its scores for availability, quality and performance.

A machine that achieves a high effectiveness score operates with minimal or negligible defects. The introduction of redesigned RCDs and smart socket outlet circuits controlled via Wi-Fi will address some challenges associated with assessing electrical device performance in smart buildings. Further exploration and analysis of nuisance tripping issues related to RCDs are important. Hence, for research purposes, a pharmaceutical cold storage facility is considered, in which five machines share power through a single line connected to an individual RCD via five socket outlets. Conceptually, each machine stores products requiring specific temperature tolerances; deviations outside this range are unacceptable.

In this analysis, two conceptual scenarios are examined, and each machine maintains different temperature settings according to product requirements. In the first scenario, all five machines experience nuisance failures overnight, with no technicians available on-site for resetting purposes. Suppose advanced technology alerts responsible personnel about this issue; by the time the technician arrives at the site after receiving notifications, internal temperatures have risen by 5°C beyond acceptable limits, as shown in Figure 5-11. This leads to total product losses because the machines experience nuisance failure, causing the temperature of the product to rise by 5°C until reset manually. The temperature rise exceeds the upper limit tolerance in all machines.

In contrast, the second scenario, in which technicians remotely reset the RCD's fault condition, results in only a 1°C increase in temperature across all machines except one, which has the lowest upper-temperature tolerance, as depicted in Figure 5-12. This scenario ensures product integrity within allowed limits except for one machine. All machines experience nuisance failure, which causes them to rise by 1°C until being reset remotely. The temperature rise exceeds the upper limit tolerance in Machine 3, and all other machines are resting within the tolerance limit. Production loss is incurred only in one machine, and 80% of the product is saved.

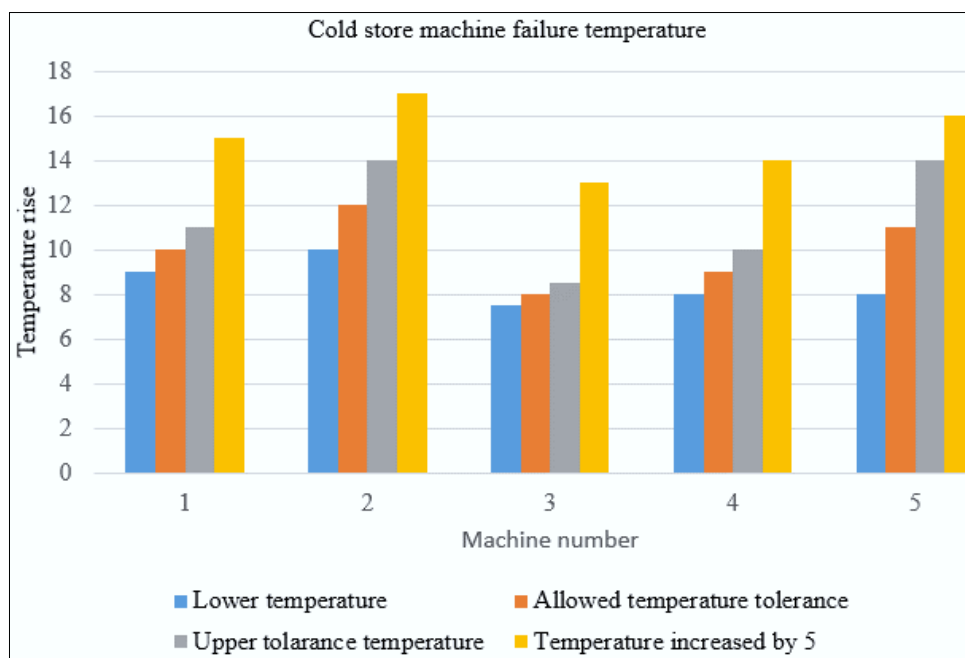


Figure 5-11. Unattended nuisance fault in pharmaceutical cold store machines

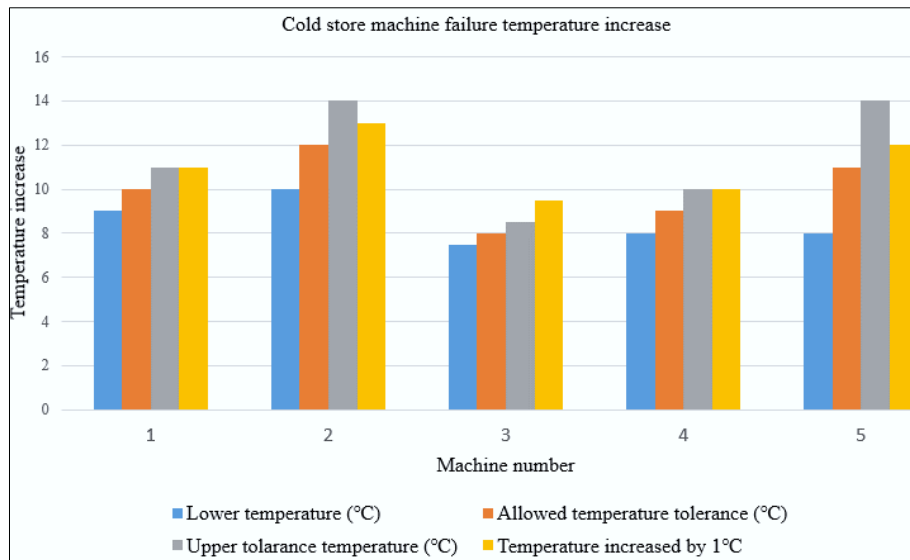


Figure 5-12. Attended nuisance fault in pharmaceutical cold store machines

5.5 Smart Buildings, Resource Minimisation and Energy Reduction for Economic Benefit

Enabling smart technology and innovative thinking to use minimised building's electrical devices, such as the Variable Frequency Devices (VFDs) [209]. The study aims to achieve one of the objectives of smart buildings: minimising resource use and maximising energy efficiency. To align with this objective, it is necessary to modify the conventional wiring technique, as proposed in this study, offering a viable strategy for enhancing the economic efficiency of the building through electrical devices [210]. This methodology supports current cost savings and energy conservation measures, as it helps in securing construction materials for future generations.

These significant changes can be achieved by introducing intelligent technological techniques and a fast demultiplexing system of algorithms. This approach represents a unique strategy to advance the effectiveness of construction and innovation in building design. In addition to its immediate economic and energy-saving benefits, this strategy can be viewed as a means of preserving construction materials for future generations.

Smart buildings are expected to differ significantly from traditional structures in terms of the types and quantities of construction materials and devices employed, particularly electrical systems. Smart buildings should address many limitations associated with conventional buildings. However, despite its designation, the concept of smart building

often lacks adequate attention to its foundational goals during design and construction. In practice, many standard appliances and equipment commonly found in traditional buildings use similar methodologies.

Building equipment and devices rarely function simultaneously; for example, in a smart building, not all lights in every office will illuminate at once because of occupancy-based lighting systems. Similar to traditional lighting setups, each fixture is equipped with its own transformer, ballast or LED (light emitting device) driver, depending on the type of lighting used.

This conventional approach has transitioned from traditional buildings and lacks a resource-efficient methodology. However, a smart building should optimise resources. For instance:

1. **Consider an office with 30 ceiling lights.** Rather than installing 30 individual transformers or ballasts, one could install just 10 or fewer and use advanced demultiplexing algorithms to control the transformers according to the necessary illumination for the space.
2. **Consider Melbourne's central business district,** where commercial skyscrapers employ groups of smart elevators that communicate among themselves regarding passenger movement—upward or downward—as well as safety measures, energy efficiency and security concerns. However, like traditional elevators, each unit still operates on its own identical circuit. This wiring configuration is economically inefficient and fails to align with the smart building objectives, which aim to minimise resource use.

This research further explores and presents the principle of minimising resource use through feasibility case studies. A single or a few VFDs that currently individually manage electrical machines can be altered to operate multiple elevator motors. This method leverages demultiplexing techniques within a dynamic demand response system, which organises elevators into queues and assigns tasks using a First Operate Last in Queue (FOLQ) procedural technique.

The approach will significantly assist in sustainable, intelligent building design [211] or innovation [212] in existing conventional buildings. The approach is needed to achieve optimised energy consumption and to conserve the non-polluting global environment. It

is also one of the alternative methods to tackle the rising price of fuel oils [213] and to transition from traditional designs to advanced, modern ones. Moreover, the method offers flexible opportunities for operation and maintenance. For example, adapting this method, urgent replacement of a faulty device is no longer required, as any device can operate any actuator or motor within the group.

5.5.1 Enabling Technology to Implement a Single Electrical Device for Multiple Output-Activation (SEDMA) Feasibility: Case Study 1

The demultiplexing technique is crucial in SEDMA methods. Rapid demultiplexing algorithms can activate or deactivate output terminals according to task requirements. This approach effectively reduces waiting times for subsequent tasks. This method is particularly applicable to a group of devices within commercial buildings that feature various high-rise and space-occupied ceiling lighting systems. Figure 5-13 illustrates two VFDs operating on a single circuit board. In this setup, both the converter circuit and DC-Link circuit share one board, while the control circuit remains separate. This presents the conceptual simulation circuit diagram for four three-phase VFDs sharing a common converter and bus DC-line for two inverter controller circuits that supply motors M1 and M2. The circuit has four main sections: the converter, the DC-bus line and two inverters. The inverter section includes the control, the switch and the motors. This arrangement reduces by 50% the number of components required to install two converters and DC-Link circuit boards.

It is essential to consider widening the size of the signal of the trace before attempting the practical task. The technique can be employed across multiple applications located at the same site. Moreover, as part of this study, a simulation application has been used to validate its feasibility. Figure 5-14 represents the simulation analysis. The VDC1 is the DC-bus line supply and is shared by all the individual circuit boards. G1 to G3 are the phase-sequential configured inverter Printed Circuit Board (PCB) layer 1. Similarly, G4 to G24 is configured for the other consecutive PCBs. The results from this simulation are depicted in Figures 5-14 and 5-15, showcasing current and voltage readings. The voltage V1 is the inverter PCB layer 1. Similarly, V2 and V4 are the voltage nodes at PCB layers 3 and 4. The analysis of current voltages aims to evaluate the collective impact on the electromagnetic field of the circuit board. Results indicate that conducting four

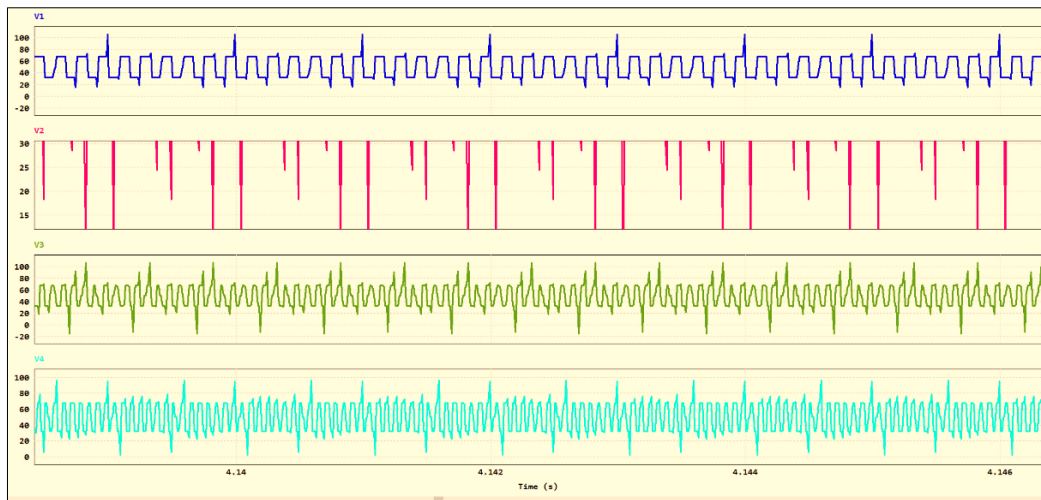


Figure 5-15. A single circuit board for multiple motors controls the load voltage

5.5.1.1 Enabling Technology to Implement Single Electrical Circuit for Multiple-Output-Activation (SECMA) Feasibility: Case Study 2

This feasibility case study explores a single electrical circuit designed to serve multiple end-use machines. While it shares similarities with the first case study, it presents different content. The study demonstrates that the SECMA method is versatile and not limited to specific machines; it can be applied in scenarios where machines do not operate simultaneously. However, a key requirement must be adhered to by all machines linked to the circuit—they should function sequentially if only one circuit is available for multiple outputs, such as motors or actuators.

This approach effectively demonstrates the reuse of a single circuit for various machines. Hence, by employing this method, significant opportunities exist to minimise the number of circuits required in commercial markets, such as laundries. In the current commercial laundry environment, each washing machine and dryer typically requires its own dedicated circuit. Let us consider a laundry station that uses one washing machine and one dryer, as illustrated in Figure 5-16, where circuit breaker (CB1) manages the primary circuit while an overcurrent device safeguards against excessive currents.

VFD1 regulates the speed of the laundry motors, and the control system orchestrates the activation and deactivation of CB1 and Contactor Relay (CR1 and CR2). The control system algorithm switches either CR1 or CR2, depending on the customer's preference. Customers have the option to either wash or dry their clothes at any given moment; however, the usual standard practice prioritises using a washing machine first before

proceeding to use the dryer. Occasionally, customers may arrive with already-washed clothes and opt to use only the dryer. In both scenarios, operations occur sequentially, as it is impractical for one customer to use both a washer and a dryer simultaneously.

Implementing this methodology in practice can lead to a 50% reduction in initial installation costs and materials required. Operational and maintenance expenses can also decrease by 50%.

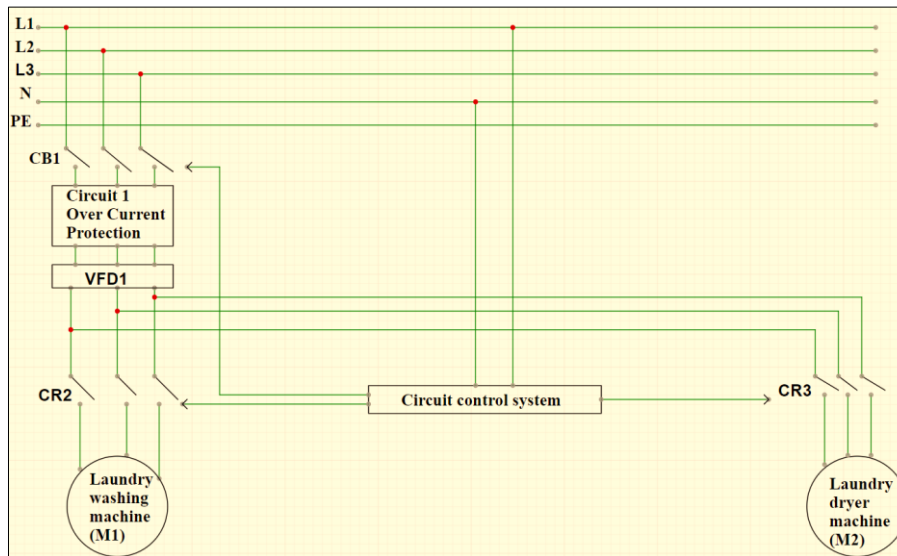


Figure 5-16. A single circuit board for multiple motor control methods, circuit diagram

5.5.2 Enabling Technology to Implement Fewer Electrical Circuits for Multiple-Output-Activation (FEDMA) Feasibility: Case Study 3

This case study highlights the potential for implementing fewer circuits across multiple machines in an automated sequential process. The research introduces a combined demultiplexing technique as a viable alternative aimed at minimising both initial and operational costs, which encompass maintenance expenses. It examines various distinct methods and demonstrates their relative advantages when compared with traditional wiring approaches. This methodology is conceptually demonstrated through a feasibility analysis focused on a group of machines within a large-scale commercial laundry setting. The premise is that there are opportunities to decrease the number of circuits and VFDs required for commercial washing machines, as illustrated in Figure 5-17, where one of two circuits can control any motor from M1 to M5. In this examination, the demultiplexing algorithms manage the operation of VFDs, relays CR1 through CR10, and circuit breakers CB1 and CB2.

In commercial laundry environments, numerous circuits and VFDs are typically present alongside several washing machines and dryers. Assuming there are ‘X’ washing machines and ‘Y’ dryers interconnected with the main circuit, the quantity of each type should be balanced. At time t_0 —denoting the start of operations—customers might initiate one or several machines in the morning.

Let us define ‘N’ as the number of active machines at that moment, where $0 < N \leq X$; however, it is improbable that all dryers will commence their cycles simultaneously with the washers at t_0 . If we consider that the circuit sizes designated for both washers and dryers are equivalent, there is an opportunity to employ fewer circuits while accommodating a larger number of machines. The more substantial the machine count, the greater the potential to use only 50% of the required circuits.

It is imperative to evaluate a feasibility study before initiating practical installation efforts. Assume there are seven washing machines labelled $X = [X_1, X_2, X_3, X_4, X_5, X_6, X_7]$ and similarly seven dryers denoted $Y = [Y_1, Y_2, Y_3, Y_4, Y_5, Y_6, Y_7]$ during peak operation days for sampling purposes. If we consider that each washing cycle begins at t_0 and lasts 24 minutes—and we allow an additional 4 minutes for loading/unloading plus a 2-minute gap—the total duration for each cycle amounts to 30 minutes (T_1). Over an average span of 8 hours (yielding $T = 8$), this results in 16 operational intervals (from T_1 through T_{16}). To conduct a one-day feasibility analysis within this 8-hour timeframe, both duty intervals and skipped (S) intervals are part of the evaluation process. The mathematical modelling pertinent to this feasibility study will proceed as follows:

$$X_1 = \sum_{T_1}^{T_{16}} \frac{(N - S)}{T} \quad (5 - 6)$$

Where:

$$N = (T_1 + T_2 + T_3 + \dots + T_{16}) \text{ and } S = (S_1 + S_2 + S_3 + \dots + S_{16})$$

Feasibility study case 1, if $X_1 = 1$, i.e. 100%, is not feasible.

Feasibility study case 2: if $X_1 = 0.875$, i.e. 87.5% is not feasible.

Feasibility study case 3, if $X_1 = 0.75$, i.e. 75%, is not feasible.

Feasibility study case 4, if $X_1 = 0.625$, i.e. 62.5% is not feasible

Feasibility study case 5, if $X_1 = 0.5$, i.e. 50% feasible.

Feasibility study case 6, if $X_1 = 0.625$, i.e. 62.5% feasible.

Feasibility study case 7, if $X_1 = 0.75$, i.e. 75% feasible.

Feasibility study case 8, if $X_1 = 0.875$, i.e. 87.5% feasible.

Feasibility study case 9, if $X_1 = 1$, i.e. 100% feasible.

Examining the number of circuit breaker (CB) interlock switches (SW) and Control Relay (CR), it is essential to note that the addition of SW is necessary for creating an interconnected wiring system. This necessity arises because CBs and CRs are already integral components of traditional wiring systems and should not be considered as new elements. The quantity of SW required is determined by the number of load devices present. For example, in this case, there are five motors ($M = 5$), and the total number of SW (N) can be calculated as follows:

$N = M - 1$, resulting in $N = 5 - 1 = 4$. The expense associated with these interlock switches is significantly higher than that of a single LED or VFD. Furthermore, the advantages that these switches offer to the building automation sector elevate their status as notable advancements in smart technology.

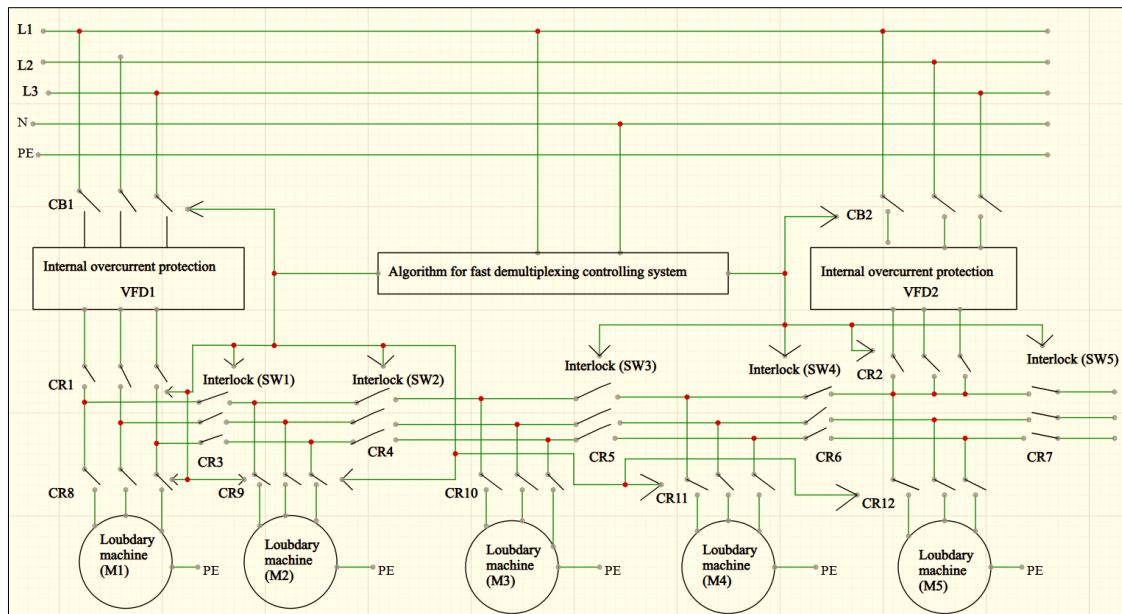


Figure 5-17. Innovative combined demultiplexing interlocked wiring method

5.5.2.1 Feasibility of Techniques for Reusing Group of Elevators' VFDs: Case Study 4

This feasibility case is a continuation of the previous case study. The necessity of this case study is to prove that the proposed method can be applied not only to specific machines but also to other machines as long as the feasibility criteria are met. For instance, assume a particular high-rise building wants to install five lifts that will operate at different heights in the building complex. For this study's purposes, all lifts should operate at the same height but at different locations. The specifications of the average lift parameters are:

1. Speed of the lifts (v) = m/s²
2. Distance to travel to the final destination (d) = metres (m).
3. The time taken to travel to the final destination (t) seconds.
4. The time taken to unload and load passengers at each level
[$2 \times (t_1 + t_2 + t_3 + t_4 + t_5) = t_{Lt}$] seconds.
5. These algorithms receive instructions from a smart HMI, which assigns tasks and estimates the time needed for their completion. When a new task is assigned, the algorithm can expedite the previous task and quickly transition to the next machine, prioritising safety throughout the process.

Assume the lifts stop at all levels and load and unload passengers within the specified time. The maximum time taken to reach the destination and return to the origin is

$$T_{travel} = \frac{d}{v} + t_{Lt} = T_m \quad (5 - 7)$$

Taking a one-hour random variable sample, where [$X = (X_1 + X_2 + X_3 + X_4 + X_5)$] represents the lifts variable carrying passengers/or not carrying passengers status within the T_m timeframe. The digit '1' represents the status of carrying passengers, and the digit '0' represents the status of not carrying passengers within the T_m time limit, which is about a 2-minute time limit in this model. Accordingly, there are 30 intervals in 1 hour and a range of T_{m1} to T_{m30} , as shown in Table 5-2. Then, Table 5-2 is filled with random variables. Take a sample of these five lifts and their characteristics, such as how busy the lifts are at this specified timeframe.

1. First step, at $T_m = 0$, all five lifts are ready to accept passengers.

2. At $T_m = 0$, start timing and record how many of the five lifts start carrying passengers.
3. Stop the timer at $T_{m1} = 2$ minutes, record and start over. Then continue this process until $T_{m30} = 30$ intervals.
4. The random variable status sum of '0' and '1' is shown in Figure 5-20, the graph of the five-time trials, where the sum of different trials is shown in different colours.

The probability of elevators carrying passengers for every definite T_m continuously for 60 minutes, where one interval is 2 minutes, is examined for feasibility using Equation 5-2. The feasibility case study result uses the percentile assumption. For instance, using the data recorded in Table 5-2, the probability that all elevators are carried simultaneously in the definite period is less than 50%.

Hence, the assumptions are:

1. If the probability of feasibility is 90–100%, this method is not worth installing because it is inefficient.
2. If the probability of feasibility is 75–90%, it is less significant.
3. If the probability of feasibility is 60–75%, it is significant.
4. If the probability of feasibility is less than or between 45% and 60%, it is significantly essential and efficient.

Hence, it is recommended that interested companies or individuals perform a feasibility study by collecting sample data and examining the feasible probability of the collected data before commencing practical work. This will determine not only the feasibility status but also the ratio of VSDs versus elevators.

Assuming the method is feasible, instructions similar to Figure 5-19 are required. These respond dynamically during emergency situations and when the number of loaded lifts is approaching the number of waiting task lifts within the T_m .

$$P(X = 30) = \left[\frac{\binom{20+19+18+16+15}{30}}{5} \right] = 0.47 = 47\% \quad (5 - 8)$$

$$P(X) = \begin{cases} 100\% & 0 < X = 30, \text{not feasible} \\ 75\% & 0 < X < 25, \text{feasible} \\ 25\% & 0 < X < 10 \text{ significantly feasible} \end{cases} \quad (5-9)$$

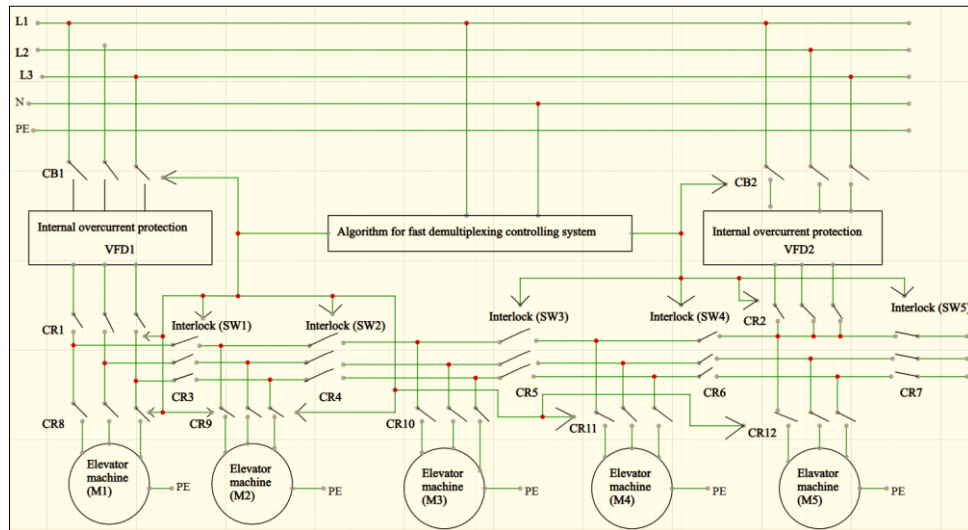


Figure 5-18. Operating procedures are for normal and non-normal operating periods

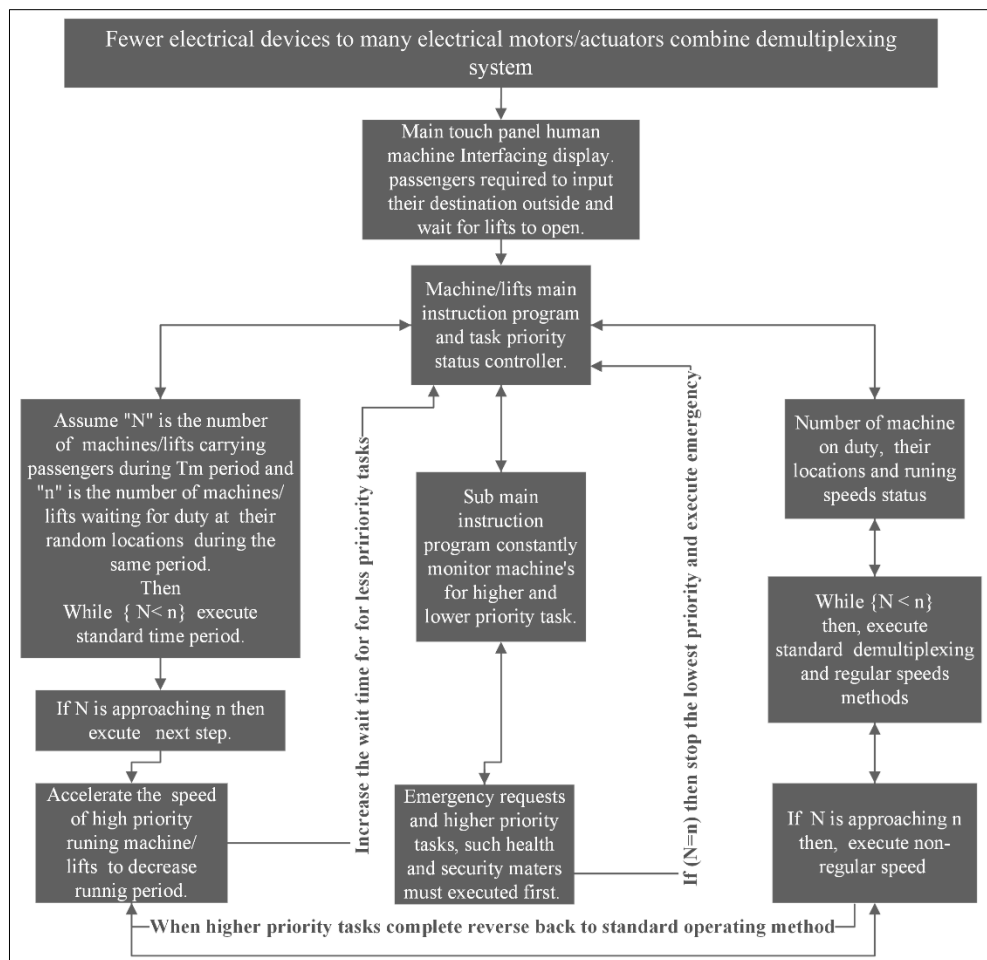


Figure 5-19. The smart combined demultiplexing interconnected wiring method

Table 5-2. Sample data collected for an hour

T_m	X_1	X_2	X_3	X_4	X_5
T_{m1}	1	1	0	1	0
T_{m2}	0	0	1	1	1
T_{m3}	1	1	0	1	0
T_{m4}	0	0	1	0	1
T_{m5}	1	1	0	1	0
T_{m6}	1	1	0	1	0
T_{m7}	1	0	1	1	0
T_{m8}	0	1	0	0	1
T_{m9}	1	0	0	0	1
T_{m10}	1	1	1	1	0
T_{m11}	1	1	1	0	1
T_{m12}	0	1	0	1	1
T_{m13}	1	0	1	1	0
T_{m14}	0	1	0	1	1
T_{m15}	1	0	0	0	0
T_{m16}	1	1	0	1	1
T_{m17}	0	1	1	0	0
T_{m18}	0	1	1	1	1
T_{m19}	1	1	0	0	0
T_{m20}	0	0	1	1	1
T_{m21}	1	1	0	0	1
T_{m22}	1	1	1	1	0
T_{m23}	1	0	1	1	1
T_{m24}	1	1	0	0	1
T_{m25}	0	1	1	0	0
T_{m26}	0	0	1	0	0
T_{m27}	1	1	0	1	1
T_{m28}	1	0	0	1	1
T_{m29}	1	1	1	1	0
T_{m30}	0	1	1	0	1
Sum	19	20	15	18	16

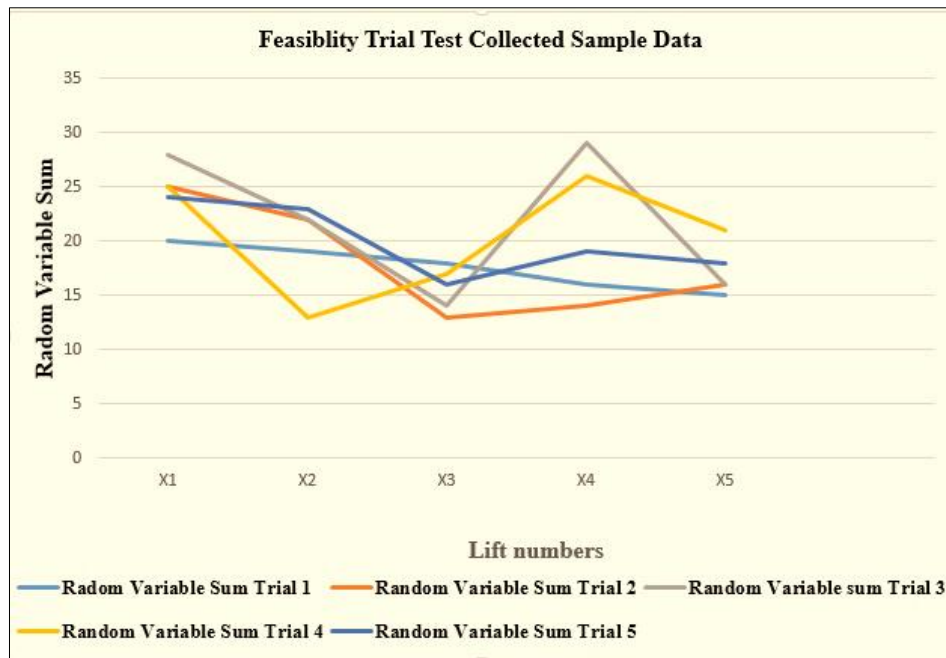


Figure 5-20. Feasibility study chart

5.5.2.2 Practical Feasibility of Technique for Reusing Lighting Transformer and LED Light Driver: Case Study 5

Strategies aimed at enhancing space use, optimising room configurations and adjusting lighting arrangements offer more efficient avenues for energy conservation in buildings. Although this approach helps reduce energy consumption, it does not lower the upfront costs, because each light fixture requires its own LED drivers.

There are scenarios in which all lights in a particular office area might be turned on simultaneously, while there could also be prolonged periods, ranging from days to months, before some lights are activated or turned on. As a result, traditional wiring methods often maintain significant assets that are underused on a daily or weekly basis, which increases the initial, operational and maintenance costs.

This case study seeks to address the issue of high initial costs by employing strategic thinking and utilising advanced algorithms to minimise the number of LED drivers needed for multiple fixtures. This is illustrated in Figures 5-21 and 5-22, which apply the feasibility study Equation 5-1 alongside practical applications. Figure 5-21 shows the interconnected wiring schematic diagram, and Figure 5-22 shows the practical wiring that can operate with two LED drivers for five LED lights.

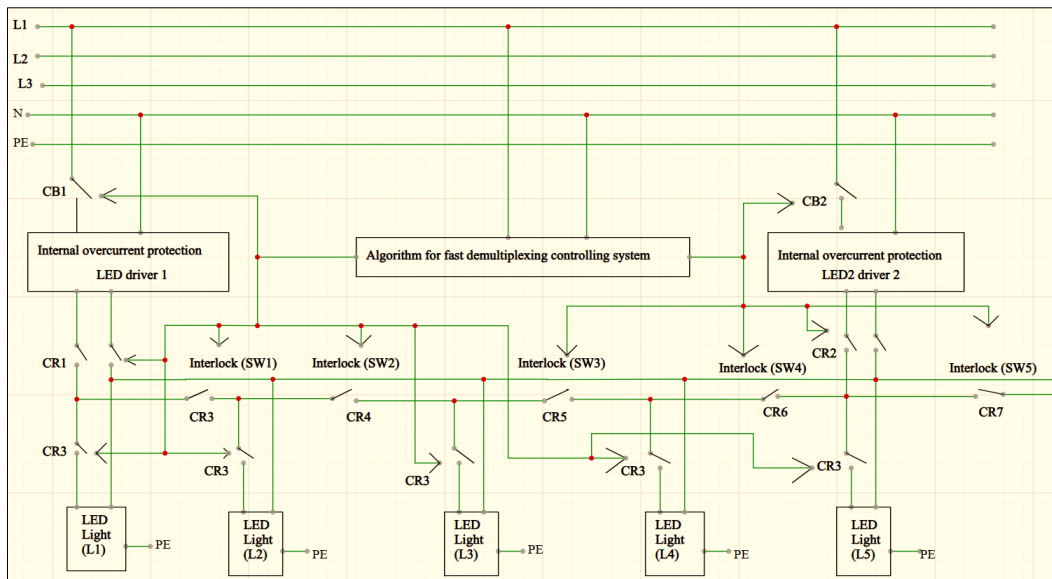


Figure 5-21. Interconnected wiring configuration of LED lights

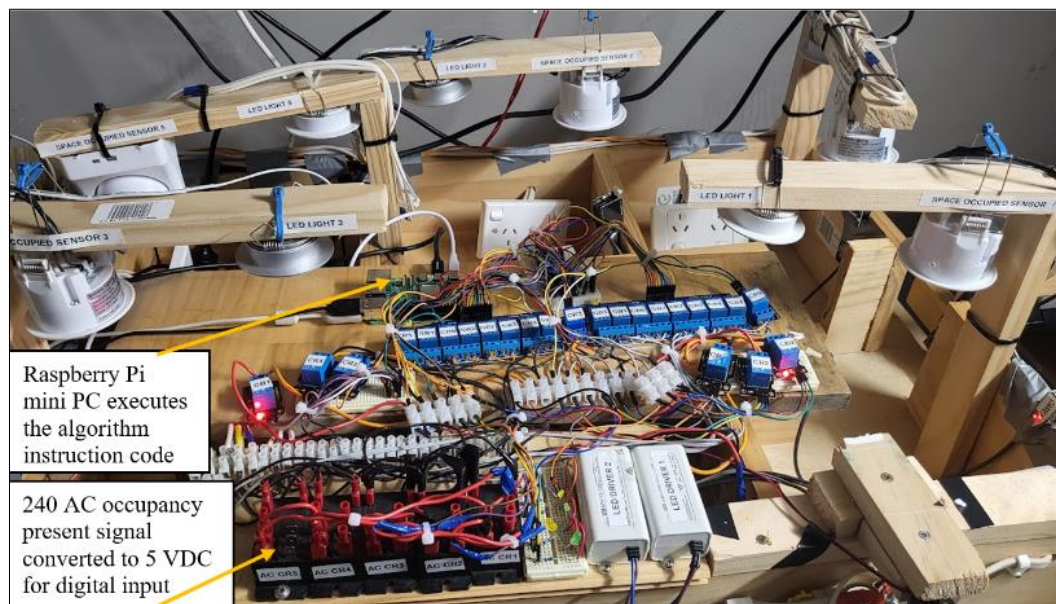


Figure 5-22. Interconnected wiring method: A practical case study of two LED drivers for five LEDs

5.5.3 Conventional Wiring Method Versus Interconnected Smart Wiring Method

The conventional wiring method is the current dominant method in all building types, including industrial and manufacturing. Perhaps it will prevail until a proven better method is developed. The conventional and smart building wiring methods are largely the same, except for the control, safety and security wiring. On the contrary, in this

proposed concept, electrical machines are connected in an interlockable and interconnected method to operate machine motors, actuators and lighting within their branch with fewer supply devices.

5.6 Conclusion

This chapter has discussed the current and anticipated technological innovations that are either in use or expected to be adopted in sustainable smart buildings over the coming decades. The research has examined existing technologies relevant to indoor environments, highlighting advancements such as wireless devices up to 6G, BIoT, digital twin technology and AI.

To achieve one of the goals associated with smart buildings, an innovative approach to conventional wiring techniques has been explored, which enhances the cost-effectiveness of electrical systems, including circuits, VFDs and ceiling lights. The feasibility study presented here aims to lower the initial costs of these devices by around 20–30%. This reduction not only supports economic advantages but also facilitates operational processes driven by timely and dynamic decision-making. Beyond its immediate financial and energy-saving advantages, this strategy also promotes sustainable practices by conserving construction materials for future use. Finally, it provides flexible maintenance options that eliminate the urgency of replacing a malfunctioning device during peak periods.

The present chapter has also investigated the nuisance failure characteristics of residual RCDs affected by high frequencies, distorted harmonics and transients, particularly in relation to incidents of nuisance tripping. These failures represent significant challenges within smart building technology. To mitigate against this issue, a strategy is proposed that combines safety features with RCDs and Wi-Fi-controlled socket outlets. This framework enables the remote detection and resetting of faults originating from either genuine problems or nuisance triggers. The developed circuit is particularly beneficial for use in pharmaceutical cold storage facilities, the food industry, restaurants and hotels, where prolonged outages in cold storage systems can result in substantial production losses.

Chapter 6

Wireless Technology, Power Density Regulations and Harvesting of Radiofrequency (RF) Propagating Wave Energy

6.1 Introduction

The idea of smart building is garnering significant interest from investors because of the numerous advantages it provides over traditional structures. These contemporary building designs incorporate advanced technologies, particularly the widespread application of wireless signals, which enhance the building's performance in terms of occupant comfort, energy efficiency and cybersecurity. The denser number of newer RF [214, 215] technologies increases correspondingly with the presence of indoor electromagnetic field (EMF) propagating waves. The waves are further divided by indoor architectural engineering and objects, which cause multipath propagation and spread delay. The spread delay can have a significant constructive magnitude that can lead to higher energy at the random spot [216], which is commonly known as 'power density' (PD) [217, 218]. This creates an opportunity for free indoor energy harvesting where the propagating wave energy can be converted to beneficial reuse, known as Wireless Energy Transfer (WET).

In this chapter, the regulations regarding power density exposure established by different organisations are examined to provide an introductory understanding of power density from the perspective of standard regulations. This knowledge is also instrumental in calculating WET. The formula related to power density potential is used to estimate wireless energy harvesting. This chapter also provides a brief overview of RF propagation both indoors and outdoors, along with simulations aimed at demonstrating energy harvesting through the design of conceptual antennas. Furthermore, the converted direct current (DC) power results generated from these simulations help in developing a low-powered charging circuit.

6.2 Globally Accepted Standards for Wireless Energy Transmission

Standards limiting power density, electric field (E-field) and magnetic field (H-field) strength differ across countries, with most nations distinguishing between occupational and general public exposures [219, 220]. This study focuses exclusively on open unrestricted general public area exposures. The standards present variations in scalar values but maintain consistency in measurement units. There are three widely accepted standards for RF-EMF exposure radiation power density globally:

(A) The Federal Communications Commission (FCC).

(B) International Electrotechnical Commission/Institute of Electrical and Electronics Engineers (IEC/IEEE).

(C) International Commission on Non-ionising Radiation Protection (ICNIRP). While some aspects of these guidelines are similar, there are notable differences in the exposure limits specified by each standard.

For this research project, only those power density exposure guidelines pertinent to the study were selected for comparison against the results derived from software simulations and measurements taken from public open areas and enclosed indoor areas. To effectively manage the radiating power density in these regions, it is crucial first to investigate the diverse global standard guidelines and limits.

6.2.1 FCC Standard

The FCC's guidelines are defined in terms of power density (mW/cm^2), electric field strength (V/m), and magnetic field strength (A/m). In the distant region of a transmitting antenna, the free space allows for the electric field vector (E), the magnetic field vector (H), and the direction of wave propagation to be regarded as mutually perpendicular, thus fulfilling the criteria of the plane-wave equations. For example, Equation (6-1) satisfies the far-field conditions of power density:

$$S = \frac{E^2}{377} = 37.7H^2 \quad (6-1)$$

Where:

S = power density (mW/cm^2), E = electric field strength (V/m) and H = magnetic field strength (A/m).

Equation (6-2) determines the far-field power density in terms of distance desparation.

$$S = \frac{PG}{4\pi R^2} \quad (6 - 2)$$

Where:

S = power density (in appropriate units, e.g. mW/cm^2); P = Input power to the antenna (mW); G = power gain of the antenna in the direction of interest relative to an isotropic radiator (dBi), and the formula gives the antenna's gain: $G = 10^{dB/10}$; R = distance to the centre of radiation of the antenna (cm).

FCC, standard for simultaneous multiple frequency transmitting antennas are governed by summing methods. The summing method for fixed number of multiple transmitters can be determined by Equation (6-3):

$$\sum_{i=1}^a \frac{P_i}{P_{th,i}} + \sum_{j=1}^b \frac{ERP_j}{ERP_{th,j}} + \sum_{k=1}^c \frac{Evaluated_k}{Exposure Limit_k} \leq 1 \quad (6 - 3)$$

Where:

‘ a = number of fixed, portable RF sources; b = number of fixed, portable RF sources; c = number of existing fixed, portable RF sources; P_i = the available maximum time-averaged power; $P_{th,i}$ = the exemption threshold power for fixed, portable RF source i ; ERP_j = the available maximum time-averaged power, of fixed portable RF source j ; $ERP_{th,j}$ = exemption threshold ERP for fixed portable RF source j ; $Evaluated_k$ = the maximum reported SAR of fixed portable RF source k and $exposure limit_k$ = uncontrolled maximum permissible exposure’.

6.2.2 ICNIRP and Australian Standards

The standards cover a frequency range from 100 kHz to 300 GHz. It is recognised that members of the public are typically unaware of their exposure levels, may experience ongoing exposure and cannot be reasonably expected to take measures to reduce or avoid such exposures. This context emphasises the need for stricter guidelines regarding power

density exposure limits. The standards address both whole-body and localised exposures. The present research concentrates on local or spatial exposures, excluding whole-body exposure simulations from its scope.

The new release of the ICNIRP standard for simultaneous multiple-frequency field states: ‘It is important to determine whether, in situations of simultaneous exposure to fields of different frequencies, these exposures are additive in their effects.’ Hence, Equation (6-4) has been used to properly evaluate this research exposure in terms of energy density and power density. The additive multiple frequency of SAR and power density values should be added according to Equation (6-4).

$$\sum_{i=100\text{KHz}}^{6\text{GHz}} \frac{SAR_i}{SAR_{BR}} + \sum_{i>6\text{GHz}}^{30\text{GHz}} \frac{S_{ab,4\text{cm},i}}{S_{ab,4\text{cm},BR}} \leq 1 \quad (6-4)$$

Where:

‘SAR_i and SAR_{BR} are the local SAR level at frequency i and the local SAR basic restriction given in Table 2’ (ICNIRP standard document updated 2020), respectively; ‘S_{ab,4 cm,i} and S_{ab,4 cm,BR} are the 4-cm² absorbed power density level at frequency i and the 4-cm² absorbed power density basic restriction given in Table 2’ (ICNIRP standard document updated 2020).

6.2.3 The IEC/IEEE Standard

The latest version of the IEC/IEEE RF-EMF standard addresses exposures related to IoT devices and outlines the criteria for assessing exposure. It notes that the criteria provided are not comprehensive for every type of IoT device. There are existing gaps in exposure assessment standards and regulations that could result in deficiencies in the exclusion criteria, which the relevant regulatory authorities should evaluate. Consequently, given factors such as time-averaged radiated power, pulsed EMF energy and deployment scenarios, some devices may not require an exposure assessment. Therefore, this new release prioritises the transmitting power of IoT devices as a fundamental criterion for evaluation.

$$P = \frac{1}{T_{ep}} \sum_{m=1}^M \times \sum_{n=1}^N \times \int_0^{T_{ep}} P_{n,m}(t) dt \quad (6-5)$$

Where:

‘P is the averaged power in W. $P_{n,m}(t)$ is the time-dependent power radiated by the n^{th} radio device of the m^{th} IoT device in W. T_{exp} is the exposure evaluation period in seconds, as an example, 360 seconds for 6 min exposure time. N is the number of radio devices inside the same IoT device. M is the number of devices’.

$$E_{\text{limit}} \geq E = \sqrt{\frac{\eta}{4\pi T_{\text{exp}}}} \sum_{n=1}^N \times \int_0^{T_{\text{exp}}} \frac{P_n(t) G_n(\vartheta\varphi)}{R_n^2} dt \quad (6-6)$$

The simultaneous multiple frequency exposure considered by the ICE/IEEE standard raises significant concerns about how multiple IoT devices installed in a building can increase power density.

The standard states that ‘Multiple IoT devices are grouped to form a population of devices’. The limits can be considered to estimate the maximum number of devices that can be included over a closed surface while radiating simultaneously.

Hence, the power density exposure from multiple sources complies with the exposure reference level (ERL) if the sum of the ratios is less than unity as per Equation (6-7), along with Equations (6-8) to (6-10).

$$\sum_{i=1}^a \frac{P_i}{P_{th,i}} + \sum_{j=1}^b \frac{P_j}{P_{th,j}} + \sum_{k=1}^c \frac{Evaluated_k}{Exposure Limit_k} \leq 1 \quad (6-7)$$

$$P_{th}(mW) = \begin{cases} ERP_{20cm} \left(\frac{d}{20cm} \right)^x & d \leq 20cm \\ ERP_{20cm} & 20cm < d \leq 40cm \end{cases} \quad (6-8)$$

$$x = -\log_{10} \left(\frac{60}{ERP_{20cm} \sqrt{f}} \right) \quad (6-9)$$

$$ERP_{20cm}(mW) = \begin{cases} 2040f & 0.3 GHz \leq f < 1.5 GHz \\ 3060 & 1.5 GHz \leq f \leq 6 GHz \end{cases} \quad (6-10)$$

6.3 Common Indoor Wireless Propagating Bands

It is widely recognised that most wirelessly transmitted indoor RF signals have shorter wavelengths and higher energy levels. Currently, these signals are extensively used as

New Radio (NR), especially in modern buildings. Therefore, this study focuses on these particular frequency ranges:

1. 433 MHz controls.
2. 900 MHz communication.
3. 2.4–5 GHz for Wi-Fi communication.
4. 700 MHz–2.7 GHz for 4G communication.
5. 6–15 GHz for 5G communication.

Most indoor RF devices operate by transmitting and receiving data according to demand and dynamic probabilities. The chances of simultaneous and continuous transmission can differ among values such as 0, $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$ and 1. Each device has a unique operating duty cycle. Power density varies directly with the duty cycle while inversely relating to distance. In contrast, wireless CCTV cameras typically have a duty cycle of nearly 100%, because they continuously transmit to capture events.

Transmission occurs from various sources, where non-orthogonal transmission significantly increases the likelihood of constructive interference patterns. For instance, the power density from an individual device is determined using the following Equation (6-11).

$$P_d = \frac{(EIRP) \times (DC)}{4\pi r^2} \quad (6 - 11)$$

Where:

P_d is power density, EIRP is effective isotropic radiation power (mW), DC is the duty cycle and $4\pi r^2$ is the area of the sphere.

This research has thoroughly examined and analysed both direct and indirect indoor wireless communication and control systems, as depicted in Figure 6-1. The direct connections primarily involve smart appliances linked to Wi-Fi, while the indirect devices interface through the building automation network. The power density at any given indoor location is inherently complex; likewise, the amalgamated radiating energy is intricate and necessitates an RF-DC conversion process.

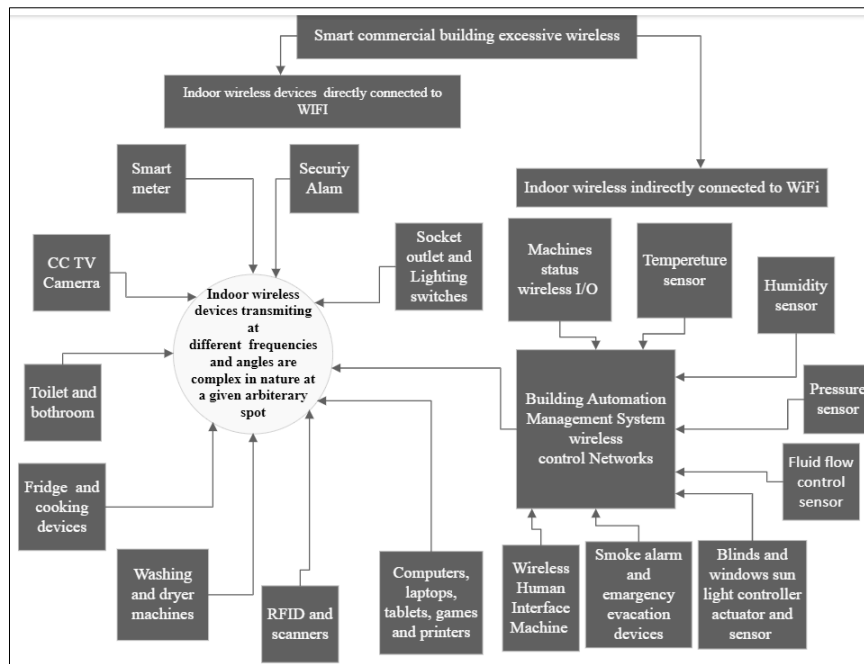


Figure 6-1. A smart commercial building fitted with excessive wireless devices

6.3.1 Evaluating RF Power Density in Public Indoor and Outdoor Spaces at Victoria University: Case Studies

Wireless communication propagating outside of any enclosed area is referred to as ‘outdoor’ or ‘open-area’ RF propagation [214], while ‘indoor’ indicates coverage by sides and a ceiling. Closed areas at Victoria University include classrooms, offices, the library and hallways, whereas the open spaces include areas such as cafes, courtyards, and the corridors located between the buildings.

Cellular (GSM 900 MHz) and Wi-Fi bands are the dominant signals in Victoria University's indoor areas. Their transmitted RF-EMF radiation waves are likely to form constructive or destructive interference.

Signals radiate from both the university Wi-Fi, staffs and students’ cellular devices. Staff and students walk and talk in different directions, hence these signals are likely to form a Doppler frequency shift rather than constructive or destructive interference.

The intensity of wireless communication is evaluated in terms of its magnitude, and an analysis of the risk to general public in closed and open areas is conducted according to these signal strength values. In outdoor environments, electromagnetic waves are less likely to undergo reflection, refraction or scattering; as a result, multipath propagation

may be minimal. However, signals from various sources can interfere with one another, creating either constructive or destructive interference depending on the direction of propagation and time delays that result in phase shifts.

6.3.2 Areas in the University Compound: Case Study 1

Measurements were obtained from several spots in the university compound, mainly in closed locations, using a spectrum analyser and an RF field meter. These designated locations were used as case studies aimed at assessing the extremes of power density. A total of six case studies were performed, collecting data related to power density and E-field measurements across different frequency bands. Measurements were taken at random points throughout the area without knowledge of the distance to the transmitting devices. Examples of a screenshot graph of the recorded data for power density and E-field from cellular networks are given in Figures 6-2 and 6-3, respectively. Similarly, the data for 2.4 GHz Wi-Fi are shown in Figures 6-4 and 6-5. The graphs within these Figures use five distinct colours to represent:

- a. The combined value, indicated by green;
- b. The maximum value, shown in red;
- c. The dynamic maximum hold value, depicted in orange;
- d. The average value, represented by yellow;
- e. The minimum hold value, illustrated in pink.

A summary of the six-spot measured values is presented in Table 6-1, indicating that the highest recorded value came from Wi-Fi operating at 2.4 GHz. These measured values are compared against various safety standards to determine whether the power density and E-field exceed the specified limits.

The RF data reading was performed in each of the selected spots during the afternoon. This is because most lectures cease in the afternoon, giving students opportunity to access their wireless devices. The peak recorded values were $15.69 \mu\text{W}/\text{m}^2$ and $0.2381 \text{ mV}/\text{m}$, respectively.



Figure 6-2. Victoria University café, power density from cellular devices

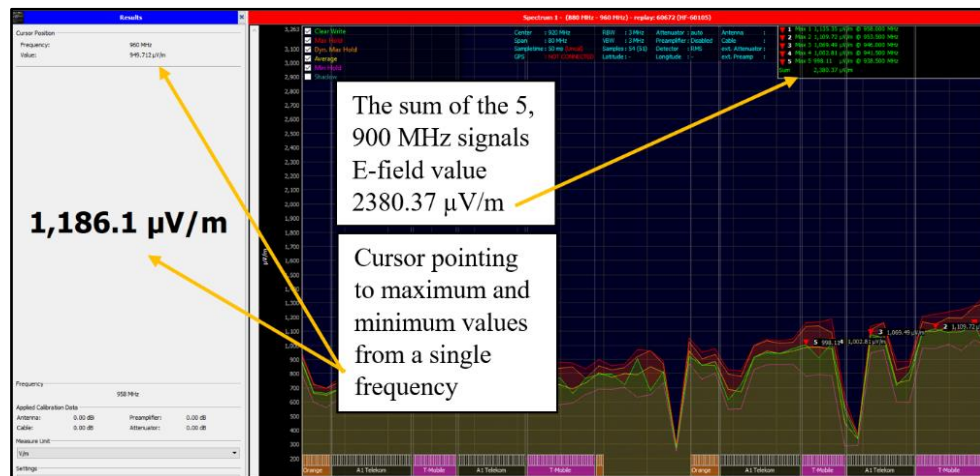


Figure 6-3. Victoria University café, E-field from cellular devices

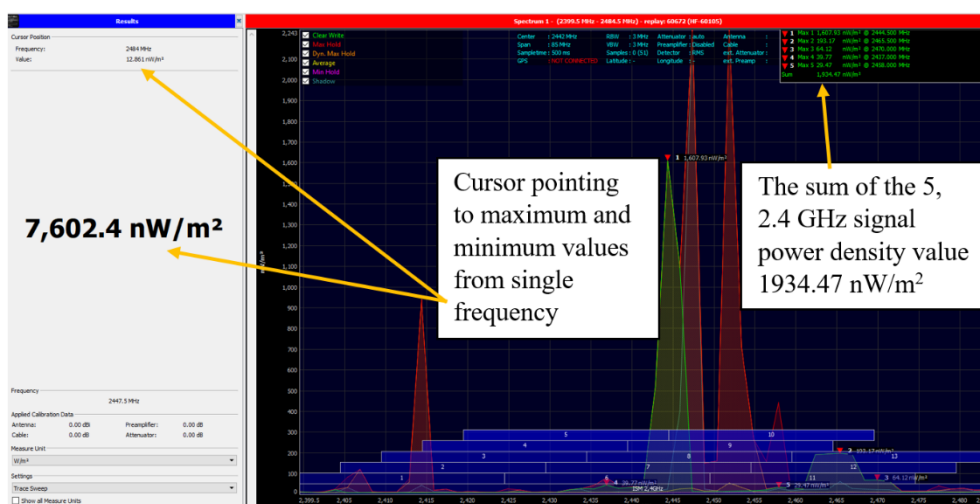


Figure 6-4. Victoria University library ground floor, power density from 2.4 GHz devices

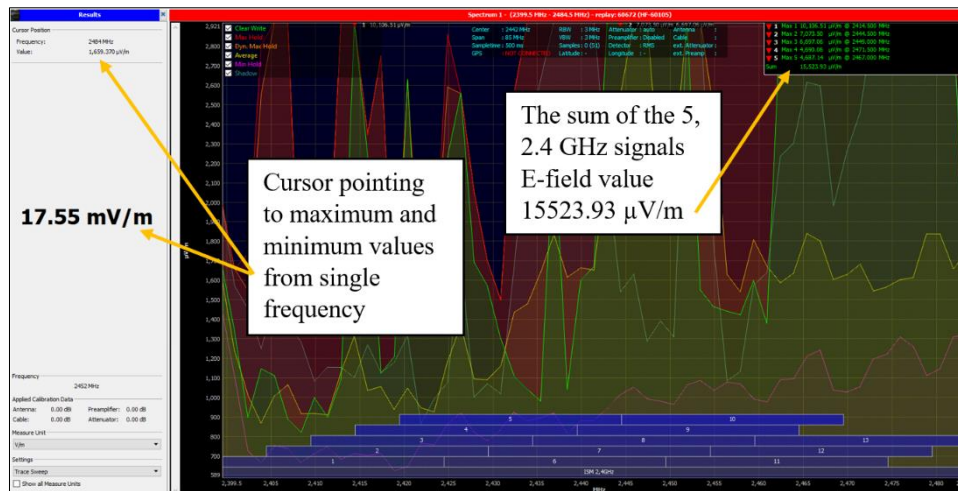


Figure 6-5. Victoria University library ground floor, E-field from 2.4 GHz devices

Table 6-1. Power density and E-field summed values for public unrestricted areas

Case study areas	Summed, measured values of power density and E-field	
University café	0.0168 $\mu\text{W}/\text{m}^2$	0.002381 V/m
Building D corridor	4.27615 $\mu\text{W}/\text{m}^2$	0.0414 V/m
Building M student service centre	4.16980 $\mu\text{W}/\text{m}^2$	0.03967 V/m.
Library, ground floor	1.9345 $\mu\text{W}/\text{m}^2$	0.01552 V/m
Library, Level 1	0.12641 $\mu\text{W}/\text{m}^2$	1.963 V/m
Building C outdoor	0.12641 $\mu\text{W}/\text{m}^2$	0.004642 V/m

6.3.2.1 Analysis of Measured E-field Values from General Unrestricted Areas, Using RF Field Meter

The RF 3-axis RF field strength meter (TM-196) was used to measure the strength of the E-field, in addition to the measurements obtained using a spectrum analyser. In these case studies, the E-field readings were measured and recorded. The recorded RF data were analysed and compared to determine which area experienced the highest E-field exposure.

The summary graph in Figure 6-6 shows that the student service centre (Building M) registered the highest reading of 4.4 V/m. As previously noted, these measurements were conducted without knowledge of the distance from the transmitting devices, which may have been quite far, potentially 20 metres. For this analysis, a distance of 20 metres was

considered a reasonable estimate, allowing for calculations of reverse power attenuation to ascertain the power density at closer distances to the transmitters.

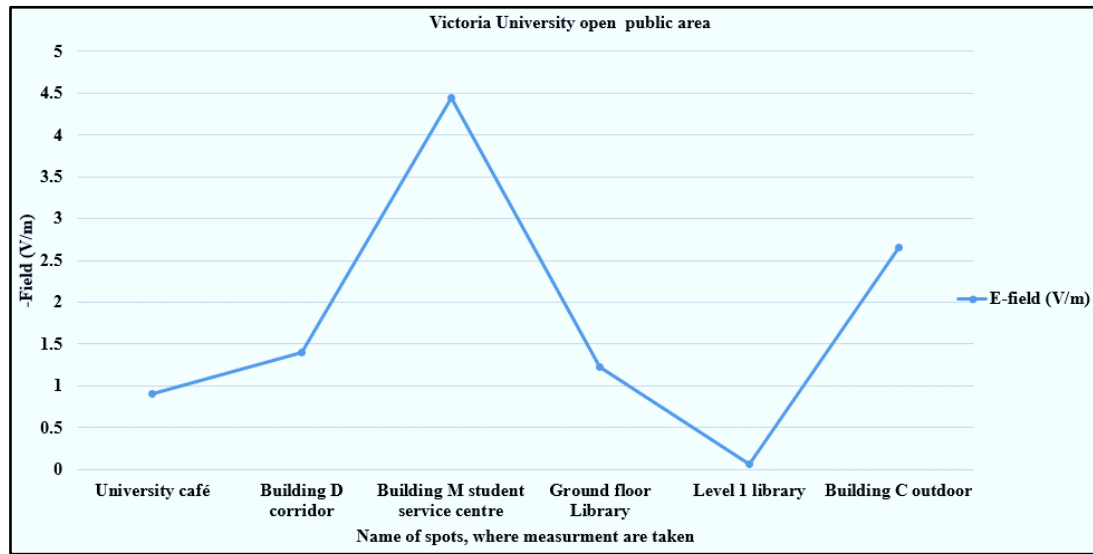


Figure 6-6. E-field values for public spaces, taken using a 3-axis RF field strength meter (TM-196)

6.3.3 Power Density and E-field Evaluation from Various Bands in Closed Experimental Room Using Spectrum Analyser: Case Study 2

An experimental room of dimensions $6 \times 5.5 \times 2.74$ m was used for measuring RF power density and E-field magnitudes from various indoor wireless devices, especially, from 2.4 GHz. The data collected were gathered using a spectrum analyser, as illustrated in Figures 6-7 and 6-8. For this data collection effort, three Wi-Fi transmitters were deployed and configured to transmit continuously to three laptops for video streaming purposes. Four video cameras were set up to provide live streaming data. In addition, IoT devices such as pressure, temperature and humidity sensors transmitted data at specified duty cycle rates.

Two hours were designated to obtain the maximum magnitude of these measurements. It was observed that an increase in the number of transverse devices corresponded with a rise in power density, culminating in a peak measurement of 1.9 mW/m^2 from a single device. To observe the summed energies, the power density and E-field from five devices were aggregated as depicted in the top corner of Figures 6-7 and 6-8, respectively.

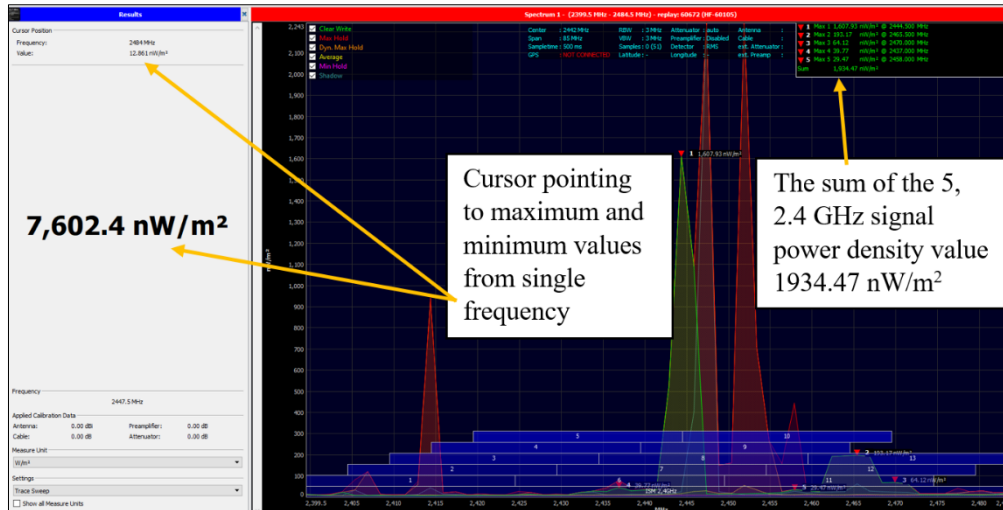


Figure 6-7. Experimental room 2.4 GHz multipath signal propagation power density



Figure 6-8. Experimental room 2.4 GHz multipath signal propagation E-field

6.3.3.1 Analysis of E-field Measured Magnitude Values from the Experimental Room, Using Tri-axis RF E-Feld Strength Meter (TM-196)

Parallel to the power density measurement, the E-field measurement was also conducted by sequentially turning on the 2.4 GHz Wi-Fi devices. It was observed that the E-field magnitude is gradually increased with the increase of transmitting devices, as shown in Figure 6-9, graph.

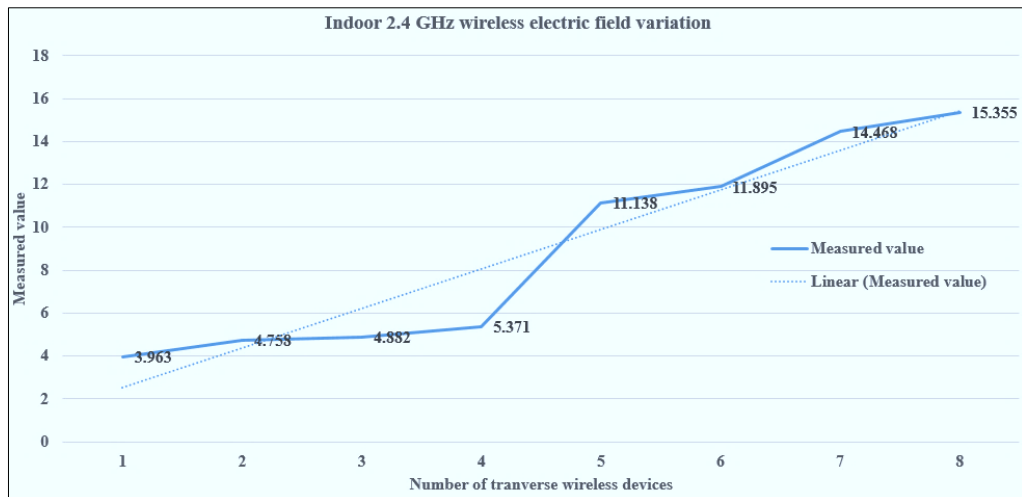


Figure 6-9. Experimental room, 2.4 GHz wireless propagation measured E-field result

6.4 Multiple Radiofrequency Multipath Propagation Characteristics

Wireless communication systems that operate indoors are commonly referred to as ‘indoor communication frameworks’. Modern buildings often incorporate a range of wireless communication technologies, including Wi-Fi networks, sensor arrays and components related to the IoT. The RF signals produced by these devices experience different types of fading caused by effects like reflection, refraction and scattering. This leads to the re-radiation of RF signals, resulting in multiple propagation paths. Consequently, the intensity of the RF signal can vary—either increasing or decreasing—at different locations within a structure. To evaluate power density at particular points, it is essential to comprehend the integer multiples of the re-radiated RF properties. This study aims to simulate and examine how various RF characteristics influence power density by modelling several antennas that represent both transmitted and re-radiated multipath signals across different spatial locations.

6.4.1 Constructive and Destructive Signal Formation for Multiple Frequency, Multipath Propagation

Indoor high-frequency wireless communication is a complex propagation of multipath diversity channels [102]. In a multipath channel, multiple copies of signals travel along different paths with different propagation delays [221]. At any arbitrary spot or at a receiver spot, different phases and strengths can be examined. These propagating waves are added constructively or destructively, resulting in rapid fluctuations in the channel

magnitude [104, 222]. Further, a multipath channel can be viewed as a linear time-variant system in which the parameters change randomly with respect to time [223, 224]. The channel response is a multidimensional random variable of time and space, which leads to a function of multi-parameter instantaneous random complex propagation delays [225]. Moreover, the propagation of indoor wireless signals can be represented as a convolution of multiple complex channels, especially in the near-field region. Hence, analysing the characteristics of radiated signals in the near-field is challenging. This is because of the effects of antenna coupling in that rear radiating region. Accurate analysis of signal features is feasible only for far-field radiation.

A highly effective method for assessing indoor wireless communication is the ray-tracing technique. In this approach, transmitted rays are reflected and traced, potentially undergoing multiple bounces. The vector fields are adjusted according to the properties of the reflecting surfaces. Each time a reflected ray interacts with a surface, it bounces again. It progresses through subsequent bounces until it either exits the area without affecting another surface or reaches a predetermined maximum number of bounces [226]. When a ray encounters a surface that permits penetration, it produces both a reflected and transmitted ray. Wireless channels display time-delaying characteristics, with parameters changing randomly over time and in accordance with nearby objects. This changing parameter strength value proves that wireless channels possess more complex features than wired channels [226]. Thus, it is essential to understand the indoor properties of wireless channels, particularly their physical propagation.

Finally, the multipath propagating signals have two chances at the far end of the transmitters [215]: (1) to diminish their magnitude by reflection, refraction, absorption and scattering [109]. (2) Form constructive or destructive magnitude. The formation depends on the geometrical dimensions, boundaries, dielectric properties and objects present inside the building, such as walls, floors, ceilings and furniture [110]. Constructive signals occur when two constructive signals are out of phase by a zero-degree or 2π -degree shift. In contrast, destructive signals occur when two signals are out of phase by a π -degree shift.

A phase shift can happen to any degree, but the most meaningful phases are multiple integers of $(2\pi, 4\pi \dots)$, $(\pi, 3\pi \dots)$, $\pi/2$ and $\pi/4$. However, constructive signals are mainly considered for this study.

6.4.1.1 RF Signal Propagation Reaction From Stationary Transverse Antennas Over Free-Space Distances

When the RF signals were away from the near-field radiating source, the electric and magnetic fields were perpendicular and proportional to each other in the direction of propagation, and both fields possessed equal energy [227]. Hence, to examine the propagation characteristics, it is sufficient to know only one of the sinusoidal waveform characteristics. Starting with the free-space transmitted RF signal, the electric field in free space can be expressed as $\cos(2\pi ft)$. This can be further described with time variation propagation:

$$E(f, t, (r, \theta, \varphi)) = \frac{\alpha_s(\theta, \varphi, f) \cos 2\pi f \left(t - \frac{r}{c}\right)}{r} \quad (6 - 12)$$

Where:

r is the distance from the transmitter to the point where the electric field is measured. θ, φ = the vertical and horizontal angles from the transmitter antenna to the point where the electric field are measured, and α_s is a scaling factor.

c = speed of light.

f = radiating frequency of the transmitter.

Another consideration of the RF propagation characteristics is when a spot of location is not a fixed space but is moving, or the receiving antenna is moving away from the transmitter or towards the transmitter. The characteristics of propagating RF wave signals can be mathematically formulated at any arbitrary moving location.

$L(t) = (r(t), \theta, \varphi)$ with $r(t) = r_{in} + vt$. This equation is satisfied when moving away from the transmitting antenna. On the other hand, when moving towards to the transmitting antenna, it is expressed as $L(t) = (r(t), \theta, \varphi)$ with $r(t) = r_{in} - vt$.

L is the point of the moving location and r_{in} = the initial position. Adding the moving away equation into Equation (6-12) gives the arbitrary moving away from the transmitter measuring location as illustrated in equation (6-13).

$$E(f, t, (r + vt, \theta, \varphi)) = \frac{\alpha_s(\theta, \varphi, f) \cos 2\pi f \left(t - \frac{r_{in}}{c} - \frac{vt}{c} \right)}{r_{in} + vt} \quad (6 - 13)$$

In Equation 6-13, the Doppler shift frequency is observed. Hence, the propagation of this equation occurs outdoors. The moving speed and its direction determine whether the Doppler frequency increases or decreases.

6.4.1.2 RF Propagation on Non-Free Space

As mentioned in the previous sections, the transmitted RF signal and its replicas are either reflected, refracted or scattered from the building's geometrical interior constructions, such as walls, ceilings, floors and objects placed inside the building, as shown in Figure 6-10. These signals can be observed when approaching the arbitrary receiving spot; the signals experience either constructive or destructive interference, as illustrated in Equation (6-14). This equation neglects the Doppler Effect because the contribution of the Doppler Effect to indoor signal propagation is minimal.

$$E_r(f, t) = \frac{\cos 2\pi f(t - r)/c}{r} - \frac{\cos 2\pi f \left(t - \frac{(2d - 2)}{c} \right)}{2d - r} \quad (6 - 14)$$

Where:

d is the distance from the transmitter to the other sidewall. The received signal is a composite of the superposition of two or more propagating waves; however, for the sake of simplicity in this study, only two superposition waves are considered. These superpositioned waves have the same frequency but may not have the same phase and amplitude. This is because the length of the multipath distance travelled delayed the propagation. The phase difference between two randomly meeting signals is illustrated in Equation (6-15).

$$\Delta\theta = \left(\frac{2\pi f(2d - r)}{c} + \pi \right) - \left(\frac{2\pi fr}{c} \right) = \left(\frac{4\pi f}{c} \right) (d - r) + \pi \quad (6 - 15)$$

Where:

$\Delta\theta$ is the E-field strength that determines the integer multiple phase angle differences, and when the phase difference is 2π , the waves are added constructively [228]. The

constructively added signal is strong in magnitude. On the other hand, when the phase difference is shifted by an integer multiple of π , the waves are added destructively, and the combined signal strength is weak.

Moreover, two superposition waves have a phase difference of $\pi/2$, which can occur when the integer multiple frequency phase is shifted by $\pi/2$. In this scenario, there is a possibility that the two-superposition progressive wave correlated circumstance forms elliptical or circular wave motion [224], which leads to circular polarised superposition RF wave characteristics. The formation of elliptical or circular motion depends on the amplitude sizes, and equal magnitudes form circular motion.

In Figure 6-10, the receiving location is subject to a combination of varying amplitudes and delayed signals arriving from multiple directions. This fluctuating amplitude originates solely from a Wi-Fi router. Commercial buildings typically contain several Wi-Fi routers. The wave signals emitted by these numerous routers create intricate variations in amplitude and phase at any given point. As a result, the energy radiated from this complex amplitude can be either strong or weak.

Furthermore, the signals are weakened when partly reflected or refracted by indoor architectural designs and the dielectric properties of materials used within the building interior design.

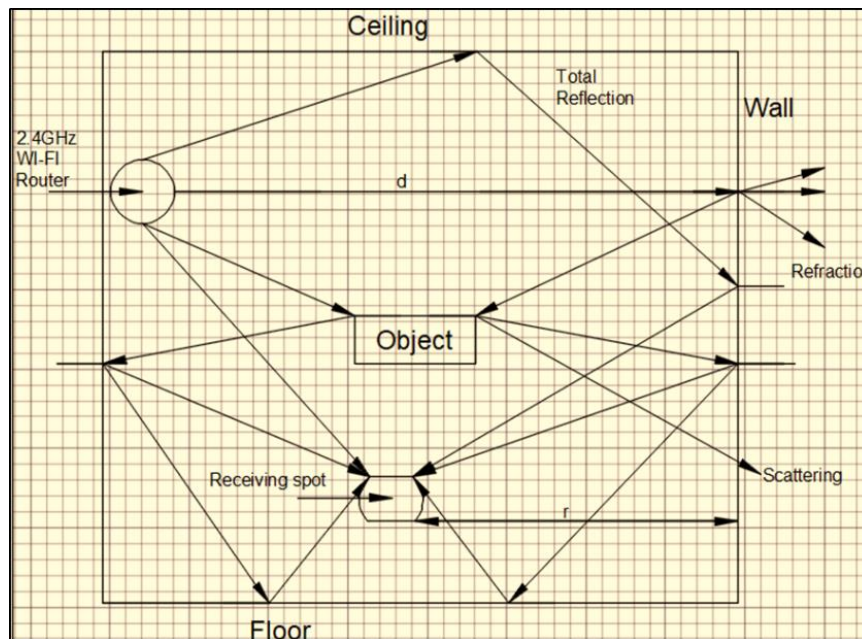


Figure 6-10. Characteristics of indoor wireless multipath wave propagation

An intriguing aspect lies in the combined magnitude, which consistently reaches its peak and can be analysed through a developed combined method. It is presumed that the fields are completely gathered at all evaluation points of the MFCM, as depicted in Figure 6-11. The resulting progressive vectors align with the propagation plane, adhering to Maxwell's equations. For instance, the circularly polarised electromagnetic wave E_1 travels in the $-y$ direction within the x - z plane. Consequently, the electric field fluctuates over time across the z - and x -planes. If another re-radiated electromagnetic wave E_2 reflects off a wall with a $\pi/2$ phase shift relative to E_1 , then at any given point in space, two components will propagate in circular and orthogonal manners. As a result, their corresponding electric and magnetic field vectors remain at their maximum values, as demonstrated in vector Equations (6-16) to (6-17).

$$E(y, t) = E_{12}[\cos(\omega t + kx)z^{\wedge} + \sin(\omega t + kx)x^{\wedge}] \quad (6 - 16)$$

The combined magnitude is:

$$|E| = \sqrt{E_1^2 + E_2^2} = E_{12} = \sqrt{[\cos^2(kx + \omega t) + \sin^2(kx + \omega t)]} \quad (6 - 17)$$

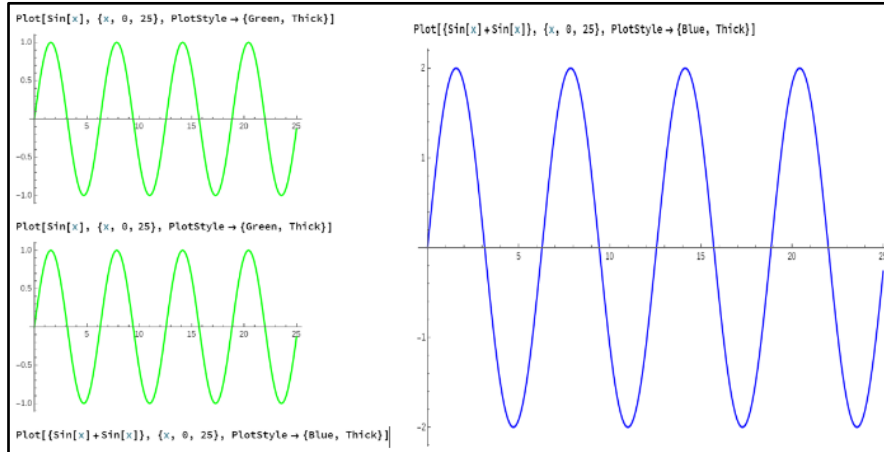


Figure 6-11. Two propagating waves with a 2π phase shift, having an E-field maximum travelling in opposite directions

6.5 Indoor Multiband Propagation and Multipath Propagation Loss

RF propagation barriers can be categorised as hard partitions when they are part of the building's physical or structural components. In contrast, obstacles formed by office furniture and either fixed or movable structures that do not extend to the ceiling are designated as soft partitions. The behaviour of radio signals as they pass through these

various types of barriers is frequently unpredictable. Analysing signal propagation inside a building reveals that RF path loss follows an inverse square relationship with distance. Additionally, in indoor wireless environments, transmitted and re-radiated signals experience both combined and individual multipath losses. Presently, numerous wireless devices within a single building operate randomly, either sequentially or concurrently. To examine the cumulative propagation at a specific location, data on the cycle time and radiance of standard indoor bands are collected and presented as shown in Figure 6-12. It is assumed that most frequency bands are transmitting simultaneously in the same direction. At any given location, the resulting combined propagating waves are intricate and necessitate sophisticated simulation tools as well as techniques for analysing multipath propagation loss and effects of exposure to power density radiation. This study begins with a straightforward approach aimed at integrating the multipath propagation losses at 2.4 GHz along with its radiation exposure impacts. The original transmitted wave energies and their re-radiated counterparts converge towards the exposed object. The receiver is subjected to radiation energy from multiple directions; for simplicity's sake, the multiple directions are reduced to two analysed directions:

1. Direct transmission from the transmitters.
2. An indirect signal initially reflected off the ceiling, then further reflected off a side wall and another signal reflected from the back wall.

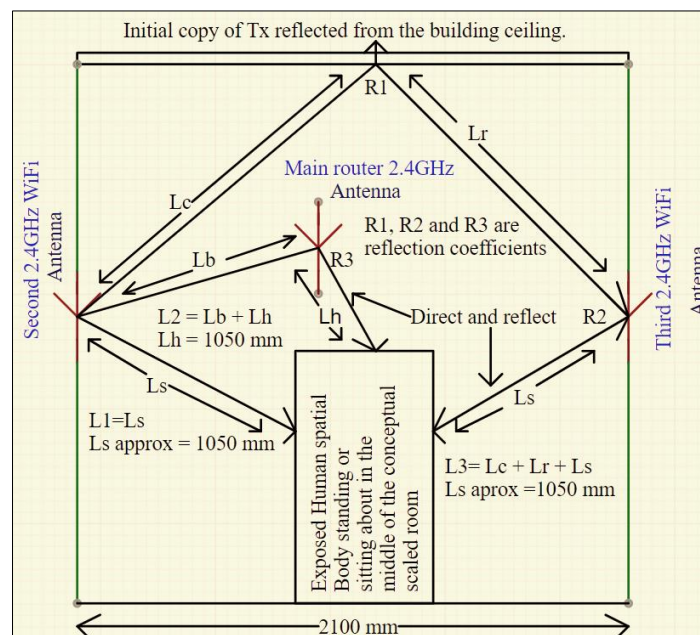


Figure 6-12. Three indoor RF antennas transmit and reflect copies of the original signal, and the power densities sum at the selected point

The maximum signal magnitude E-field strength can be assessed to convert to power density using the CFCM and MFCM [229]. To examine these characteristics of indoor wireless RF propagations, multiple antennas matching the various copies of re-radiated signals are designed using the CST Studio Suite simulation software application, and the results of the simulation are analysed.

The associated real power density approaching the spatial spot through path loss are, the direct approach: $F_{D1} = G_t \frac{P_t}{L_1^2}$ (6 – 18)

The indirect approach from the side wall: $F_{D2} = R_2 G_t \frac{P_t}{L_2^2}$ (6 – 19)

The indirect approach from the back wall: $F_{D3} = R_3 G_t \frac{P_t}{L_3^2}$ (6 – 20)

$$F_D = \sum_{N=3}^N F_{D1} + \sum_{N=2}^N F_{D2} \pm \sum_{N=2}^N F_{D3} \quad (6 – 21)$$

Where:

G_t is the transmitter's gain, and P_t is the transmitted power. L_1 , L_2 and L_3 are the lengths to the receiving spot. F_D is the total received flux density. N is the number of multipath propagations. The spatial rectangular spot area receives the radiation from the three directions. Let us say A_1 , A_2 and A_3 . Then, the combined receiving power is:

$$P_D = \sum_{N=3}^N F_{D1} A_1 + \sum_{N=2}^N F_{D2} A_2 \pm \sum_{N=2}^N F_{D3} \quad (6 – 22)$$

6.6 Design and Modelling of Multiple Antennas

For this study, several instances of 2.4 GHz patch antennas were designed according to the parameter configuration of a rectangular patch antenna for 2.4 GHz Wi-Fi, utilising CST Studio Suite software. The antennas were positioned in various orientations to accommodate the phase shifts associated with indoor multipath transmission and re-radiation of electromagnetic waves. Consequently, to achieve optimal radiation efficiency:

$$W = \frac{1}{2 f_r \sqrt{\mu_0 \epsilon_0}} \sqrt{\frac{2}{\epsilon_{r+1}}} \quad (6 – 23)$$

$$L = \frac{1}{2f_r\sqrt{\epsilon_{reff}}\sqrt{\mu_0\epsilon_0}} - 2\Delta L \quad (6-24)$$

$$\epsilon_{reff} = \frac{\epsilon_{r+1}}{2} + \frac{\epsilon_r + 1}{2} \left[\frac{1}{\sqrt{1 + 12\left(\frac{H}{W}\right)}} \right] \left\{ \frac{W}{H} \geq 1 \right. \quad (6-25)$$

$$\Delta L = (H \times 0.412) \frac{(\epsilon_{reff} + 3) \left[\frac{W}{H} + 0.264 \right]}{\epsilon_{reff} - 0.258 \left[\frac{W}{H} + 0.8 \right]} \quad (6-26)$$

Where:

W is the width of the planar patch antenna, and L is its length. ϵ_r is the relative electric permittivity of the material, and ϵ_0 and μ_0 are the free-space electric permittivity and magnetic permeability, respectively. f_r denotes the resonant frequency. ϵ_{reff} is the effective dielectric constant of the material. The input resistance of the rectangular patch antenna is:

$$R_{in} = \frac{\pi}{2} \times \frac{(\epsilon_r)^2}{\epsilon_r - 1} \left(\frac{L}{W} \right) \quad (6-27)$$

The impedance matching technique, which is the microstrip line length, is:

$$Y_0 = \cos^{-1} \left(\sqrt{\frac{Z_{in}}{R_{in}}} \right) \quad (6-28)$$

Where:

Z_{in} is the desired impedance, which is usually 50 Ω .

Then, the 2.4 GHz patch antenna wavelength is:

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{2.4 \times 10^9} = 1.25 \text{ cm} \quad (6-29)$$

6.6.1 Criteria for Selecting 2.4 GHz Rectangular Planar Patch Antenna

With the rapid expansion of modern wireless communication systems [230], devices with multiband and ultra-wideband (UWB) [231] capabilities are broadly required in wireless communication systems to meet the rising system complexity. Hence, a rectangular planar patch antenna with a microstrip feeding type parameter was chosen because:

1. Planer patch antennas have a low physical profile and cost, and are easy to fabricate [232, 233].
2. Planar patch antennas perform well at 2.4 GHz and are currently widely used in indoor Wi-Fi router applications [234].

Three antennas are configured to accommodate multiple indoor RF transmissions and re-radiations from walls and other objects, as illustrated in Figure 6-13. Table 6-2 provides the complete design specifications of these antennas. It is assumed that two antennas are positioned directly opposite each other at an angle of 180 degrees, while the third antenna is oriented at a phase difference of 90 degrees.

A fourth additional antenna is situated near the specimen's head to simulate cellular devices. The test materials, representing a human spatial body, are placed at the centre of the three antennas. For simulation purposes, the dielectric properties of the specimen materials are represented by modelling two rectangular layers that correspond to human shoulder muscle and skin; these layers are designated as left and right skin, respectively. Above these shoulder layers, a neck muscle layer is introduced to represent the human neck, also defined into left and right sections. Similarly, a semicircular layer representing the head and face is modelled above the neck layer. All layers are strategically positioned to accurately reflect human anatomy and effectively absorb radiation from various antenna orientations with different dielectric properties, as depicted in Figure 6-13.

Table 6-3 outlines the material properties of tissues, including density (kg/m^3), human skin characteristics, muscle attributes, thickness of head bone (in mm), dielectric properties [235] and tangential loss of the homogenous medium. The homogenous medium dielectric and tangential loss properties are complex and frequency-dependent, absorbing and dissipating energy according to the dielectric property strength and applied frequencies.

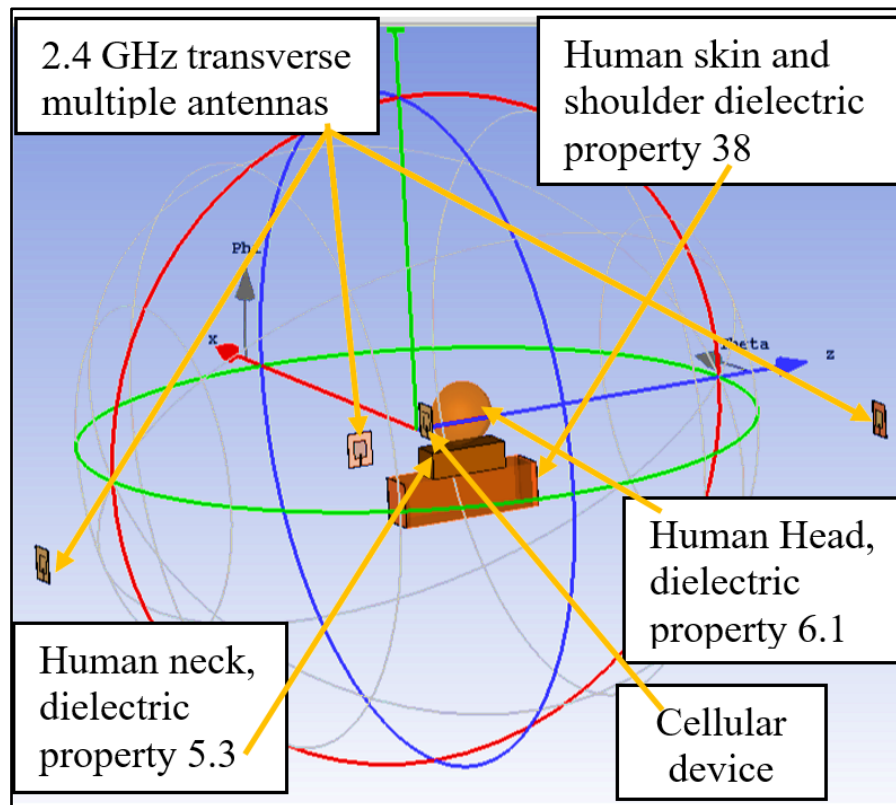


Figure 6-13. Distance orientations of multiple antennas relative to the specimen

Table 6-2. Design specifications of antenna parameters

Antenna layers	Length (L) mm	Width (W) mm	Thickness (H) mm
Ground	58.86	76.02	0.035
Substrate	58.86	76.02	1.588
Rectangular patch	29.43	38.01	0.035
Microtrap (feeding)	14.72	2.86	0.035
Strip length	8.4	0.74	0.035

Table 6-3. Simulation material property specifications

Material name	Density (kg/m ³)	Thickness (mm)	Dielectric property	Tangent constant
Skin	1,090	1.45	38	0.93
Neck	1,050	120	5.3	0.16
Head	1,200		6.1	0.93
Shoulder	1,050	10	38	0.16

6.6.2 Sequential and Simultaneous Simulation Analysis

The CST Studio Suite simulation software offers optional selectable antenna ports, allowing for concurrent excitation of individual or multiple ports. These simulation methods enable the simulator to select appropriate techniques tailored to specific applications.

For this study, simultaneous simulation was favoured over sequential simulation. This preference arose because sequential simulation excites the ports one at a time, while simultaneous simulation evaluates all ports collectively and provides combined results referred to as ‘F-parameters’, in contrast to S-parameters that result from single-port simulations. The importance of simultaneous simulation lies in its ability to accurately represent duplicated and re-radiated indoor signal copies.

Additionally, it provides the flexibility to define specific groups of port selections known as modes for time-domain solver excitations. Users can excite either selected groups or all modes at once. A particularly valuable feature of simultaneous simulation is its capacity to manipulate various amplitudes, phase shifts and frequencies. The corresponding software simulation results shown in Figures 6-14 and 6-15 represent instantaneous antenna port simultaneous excitation. The ports are excited by varying the phases, distances and amplitudes to match the indoor electromagnetic wave multipath propagation.

In Figure 6-15, ports i1 to i4 have a 2π or zero, meaning no phase difference was made. The ports are excited at 2,100 mm and 1,050 mm distances from the centre of the specimen material, respectively, and powered by 0.5 W of 1 V amplitude.

Similarly, the graphs in Figure 6-16 are excited at the same distance, but the ports i4 and i3 phase changed to $-\pi/2$ and $-\pi/3$, and show a slightly different pattern representation than the graph in Figure 6-15. In Figure 6-15, none of the three ports show identical pattern representation, but in Figure 6-16, the pink and green colours show a slight shift from overlapping each other. This is a result of the $-\pi/2$ phase shift effect, which forms a circularly polarised resultant travelling wave. The resultant E-field magnitude remains at its maximum continuous propagation at all times, regardless of time and space variations.

This occurs when two ports radiate simultaneously at the maximum amplitude at opposite phases and travelling directions.

Hence, the signals form a superposition resultant circular E-field. The combined superposition of the E-field contributes to the power density. This approach ensures optimal antenna performance to achieve accurate power density simulation outcomes.

The directivity graphs presented in Figures 6-17 and 6-18 illustrate the performance of the antenna under varying phase shifts, distances and orientations. The results from these directivity simulations indicate that slight changes in the simulated frequencies can lead to notable differences in the main lobes of directivity of an isotropic antenna, as detailed in Table 6-4. Consequently, a rise in directivity is significantly linked to enhanced gain and power density.

The total average radiation for an isotropic antenna is expressed as:

$$P_{rad} = \int_0^{2\pi} \int_0^\pi U(\theta, \varphi) \sin(\theta) d\varphi d\theta \quad (6 - 30)$$

Correspondingly, the average power intensity is expressed as:

$$U_{average} = \frac{P_{Average}}{4\pi} \quad (6 - 31)$$

Consequently, the directivity of an isotropic antenna is also expressed as:

$$D = \frac{U_{average}}{P_{rad}/4\pi} \quad (6 - 32)$$

Then the corresponding gain is expressed as:

$$G = \frac{4\pi U}{P_{in}} \quad (6 - 33)$$

These equations are related to directivity and gain; it follows that the power intensity—also referred to as power density—is directly proportional to directivity, underscoring that an increase in the directivity of a specific isotropic antenna leads to a rise in travelling power intensity.

Table 6-4. The directivity of multiple antennas increases as the frequency of the simulation increases

Frequency (GHz)	2.4	2.45	Increase	2.45	2.5	Increase
Directivity (dBi)	1.81	2.45	0.64	2.45	3.53	1.08

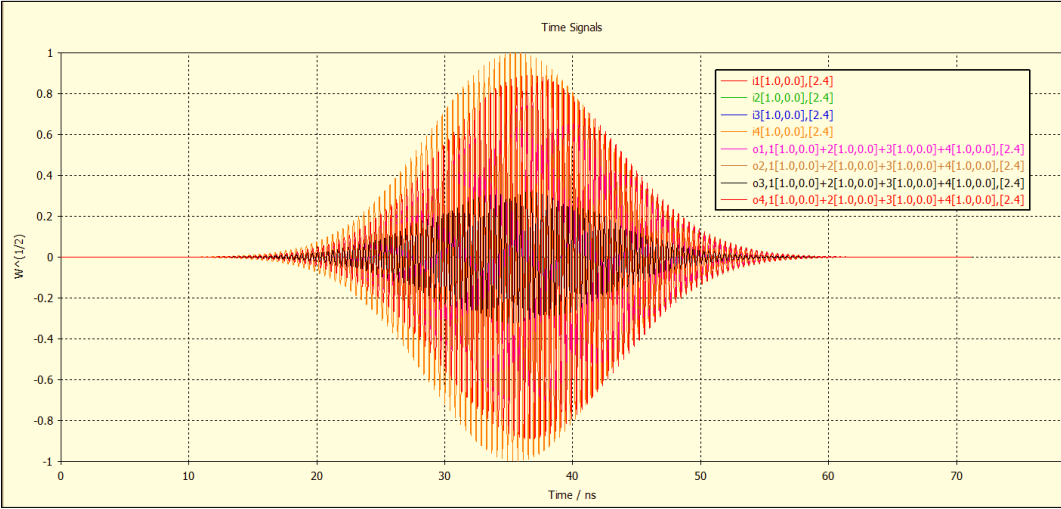


Figure 6-14. Instantaneous port excitation of multiple antennas' without phase changes

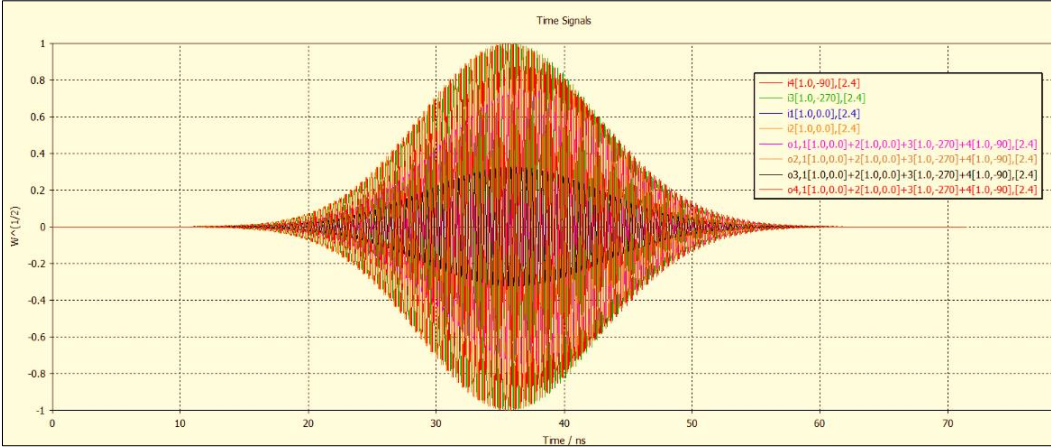


Figure 6-15. Instantaneous port excitation of multiple antennas' with phase change made

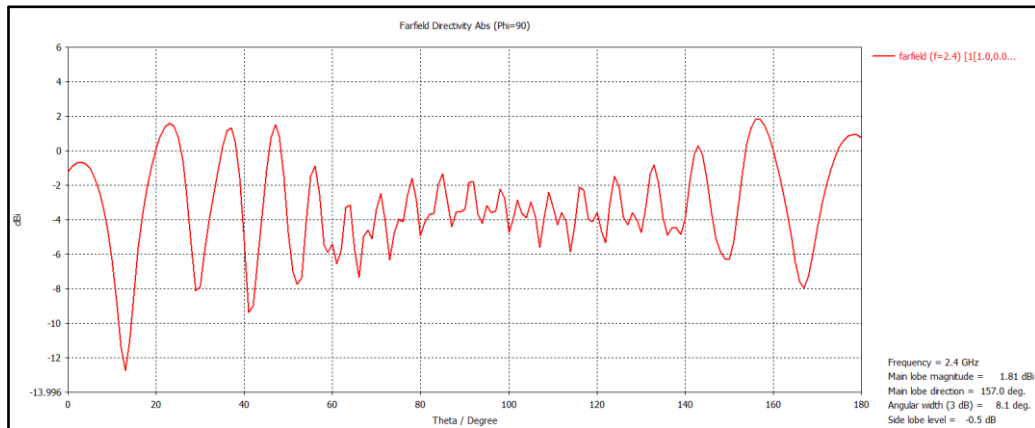


Figure 6-16. 2.4 GHz antenna's instantaneous radiating port directivity performance

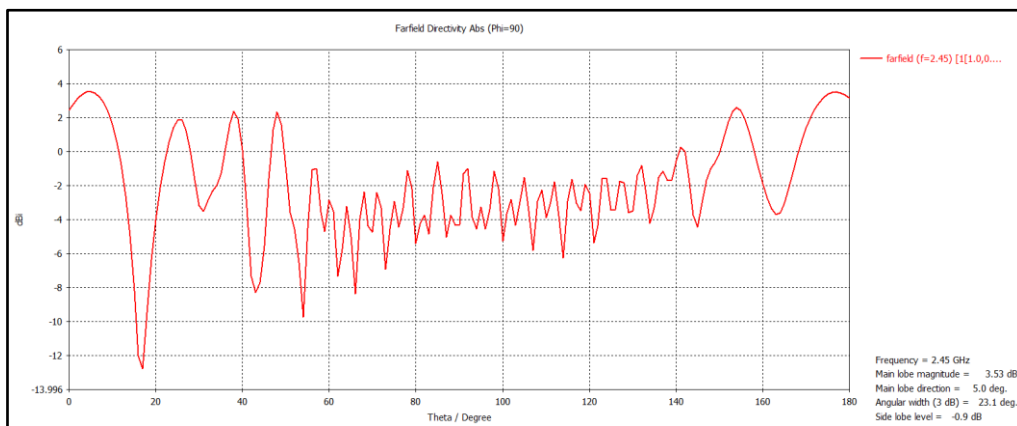


Figure 6-17. 2.45 GHz antenna's instantaneous radiating port directivity performance

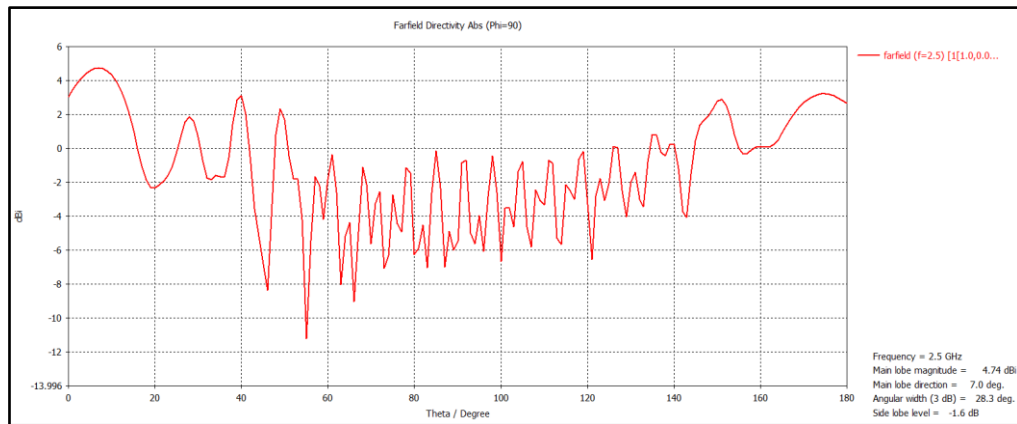


Figure 6-18. 2.5 GHz antenna's instantaneous radiating port directivity performance

6.7 Energy Harvesting from Indoor and Outdoor Wireless Propagating Waves'

One of the objectives in designing sustainable smart buildings is the repurposing of materials. This concept extends to the use of wireless radiated energy. Significant

amounts of energy are emitted through radiating antennas from various substations, residential and commercial properties. If this radiating energy is not transformed and reused, it is wasted. Transforming energy into a usable resource for energy harvesting is crucial in a sustainable energy consumption environment.

The findings from this research demonstrate through indoor and outdoor simulations that a considerable quantity of passive energy is accessible, particularly in near-field zones. This harvested energy can be implemented to supply power to low-power IoT devices. For this reason, a circuit was modelled to convert passive RF AC signals into DC power. This ensures RF technology captures the energy contained within radio waves for effective power transfer.

6.7.1 Indoor Multipath Transverse Wireless Transmission Coverage and Direction of Signal Tracing Simulation

Indoor ray-tracing software Wireless inSite is used to examine the characteristics of multiple transmitter and receiving antennas. Figure 6-19 shows the results of the simulation of the 14 transceiver signals duplicated from walls and objects.

Rays reflected from the walls and objects may either combine or cancel, depending on the propagation delay. As shown in Figure 6-19, the transmitted rays pass through the internal partition walls and are completely reflected from the exterior wall. This is because the internal and external walls have different dielectric properties. These objects create an opportunity for significant energy harvesting, especially in areas where multipath interference results in constructive gain. This also helps identify the strongest and weakest signals in indoor areas.

Moreover, the path gain is where the energy harvest location can be obtained. This indicates that the magnitude of the 2.4 GHz wave signal reduces inversely to the distance travelled and to the ratio of the reflection coefficient.

Therefore, most signals diminish within internal areas. Signals replicate internally, and generate a considerable amount of potential energy that can be used, particularly in regions where multipath effects lead to constructive interference. This aids not only in distinguishing between the areas of higher and lower magnitude signals in indoor environments, but also in deterring occupants from areas of higher power density.

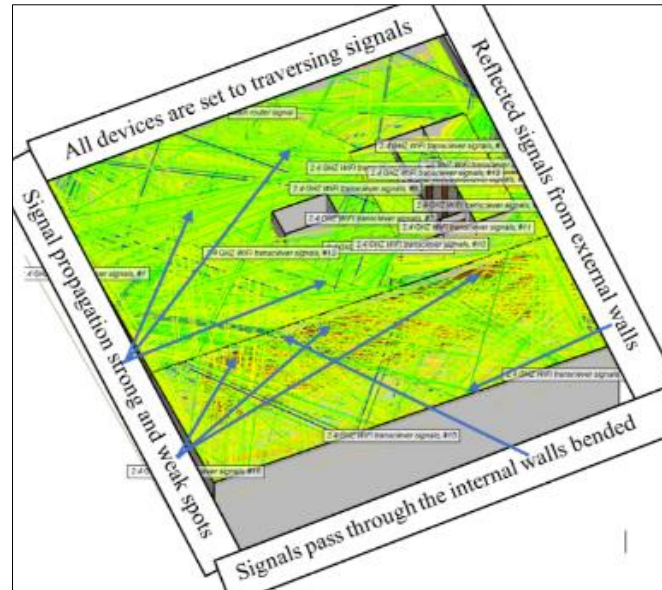


Figure 6-19. Indoor 2.4 GHz transceiver signals propagate from the primary sources and experience reflection from the walls

6.7.1.1 Design and Modelling of a Circuit for Reusing Indoor RF Energy

The passive receiver antenna component is modelled after considering the energy dissipation in indoor and outdoor environments. The earlier WET applications were primarily designed to reduce or eliminate the need for cables. Eliminating the use of a cable can save the energy dissipated in the cable through attenuation, that is, $P_d = I^2 R$, where P_d is the power dissipated on the entire length of the cable, I is the amount of current passing through the cable and R is the product of resistance per unit area (Ω) and the total length (L) of the cable in metres. In recent decades, with the increase of RF higher energy implementations, energy harvesting applications have also increased by designing passive circuits. The central concept is expressed thus:

1. Electromagnetic wave energy radiates from wireless devices for communication and automation control systems. It is freely propagating in the space around where we live, work or travel.
2. The free propagating energy can be repeatedly reused by designing a circuit.
3. The propagating energy is higher near the field of radiation and decreases with the square inverse of the distance.
4. Hence, higher energy from nearby radiating elements can be captured using receiver antennas only.

5. This study illustrates five leading bands, and their electromagnetic radiating energy is converted to DC to charge low-current consumer wireless devices.

The measured values shown in Figure 6-20 are collected from the outdoor and indoor case studies in Sections 6.3.2 and 6.3.3. The left and right sides of the line and bar graph in Figure 6-20 show the average E-field and power density in the indoor environments. The average highest value of the E-fields is 8.79 V/m. $E = \text{Potential difference/distance}$ (V/m), where d is the distance in metres. Assume $d = 5$ m distance between the transmitting and measuring spots. $V = E \times d = (8.79 \text{ V} \times 5) = 0.32 \text{ V}$. This generates the average power density values represented in the right-hand bar graph in Figure 6-20. Assume the progressing power density arriving at the location of measurement is radiating isotopically, i.e. $P_{\text{travelling power density dissipation}} = \frac{P_{\text{in}}}{4\pi d^2} = \frac{0.00183W}{314} = 5.828 \mu W$. Furthermore, assume the E-field voltage and the power to the spectrum analyser approach the individual RF combiner circuits in Figure 6-23, which is further fed to the DC power converter circuit connected using the 10K load to a low-powered IoT device.

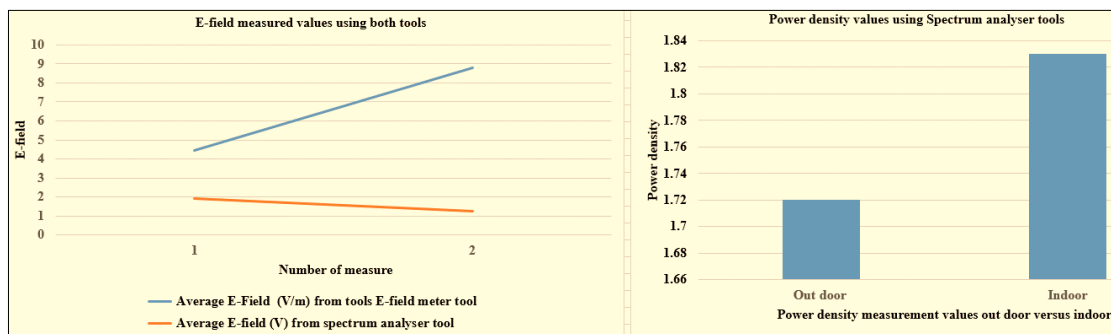


Figure 6-20. Power density and E-field measured values from outdoor and indoor environments

6.7.1.2 Theoretical and Mathematical Approach to Receiving Antenna

To deliver the receiving power to the load, the effective antenna aperture must be modelled to convert the incident wave energy to the maximised load impedance. The maximum energy is delivered to the load when specific criteria for antenna parameters are met. Figure 6-21 shows the basic configuration for capturing incoming wave energy using a dipole antenna, but the configuration applies to all types of antennas. Polarised waves are incident on the length of $(L/2)$, but the effective length is dependent on the

incident angle of the wave to the antenna (θ), and the effective length ($L_e/2$) is energised. Taking the fundamental circuit model analysis, the average peak power delivered is:

$$P_{Recieved} = \frac{1}{2} Re\{VI^*\} \quad (6 - 34)$$

The expression of the effective length of the antenna aperture is in the form of L_e . The length of the antenna is different from the effective vector length. The vector length of the incident wave measures the effective antenna aperture. This is considered the portion of the antenna that has been influenced. For instance, considering the open circuit theory is: $V_{oc} = Li \times L_e$ (6 – 35)

This configuration also applies to all types of receiver antennas.

The maximum power depends on the meeting of the following parameter criteria:

- a. vector effective length of L
- b. conjugate matching the series impedance, known as characteristic impedance (Z_0), but for this study, (Z_s) is preferred to the load (Z_L).
- c. antenna co-polarisation with incoming incident waves (S_{ico})

Where:

$$S_{ico} = \frac{|\vec{E}|^2}{2\eta} W/m^2, \text{ E is the electric field, and } \eta \text{ is the free-space wave impedance.}$$

The maximum power converted is:

$$P_{Recieved Max} = \frac{|\vec{E}|^2}{2\eta} \times A_e W \quad (6 - 36)$$

A_e is the effective area of the antenna aperture, and expressing L_e aperture areas using the open circuit model is:

$$(V_{oc}) = \frac{|\vec{E}|}{m} \times L_e m \quad (6 - 37)$$

Hence, as shown in Figure 6-21, the voltage divider circuit is:

$$V_{max} = \frac{V_{oc} \times Z_s^*}{Z_L + Z_s^*} \quad (6 - 38)$$

at time $Z_L = Z_s$, the expression changed to

$$V_{max} = \frac{V_{oc} \times Z_s^*}{2Z_s} \quad (6 - 39)$$

Similarly, in terms of Current:

$$I_{max} = \frac{V_{oc}}{2Z_s} \quad (6 - 40)$$

Hence, the average peak:

$$P_{max} = \frac{1}{2} Re(IV^*) \quad (6 - 41)$$

Substituting Equations (6-37) and (6-38) into Equation (6-39) yields

$$P_{max} = \frac{1}{2} \left[\left(Re \frac{\vec{|E|}}{2Z_s} \times L_e \times Z_s^* \right) \left(\frac{\vec{|E|}}{2Z_s} \times L_e \right) \right] = \frac{1}{2} Re \left[\frac{\vec{|E|}^2}{2Z_s} \times L_e^2 \times Z_s^* \right] \quad (6 - 42)$$

As mentioned earlier, the maximum is delivered when the complex conjugate matches the characteristic series impedance to the load impedance.

Hence, it became interesting when $Z_s^* = Z_L$, then Equation (6-42) yields:

$$P_{max} = \frac{\vec{|E|}^2}{8Z_s} \times L_e^2 \quad (6 - 43)$$

Assume the results of Equation (6-43) is obtained when the co-polarised incident wave angle theta is 90°. In cases where theta is not equal to 90°, the effective length is:

$$\frac{L_e}{2} \sin(\theta) \quad (6 - 44)$$

Then the values of Equation (6-44) will change accordingly. In addition, it is also necessary to know the maximum aperture area:

$$A_e = \frac{P_{max}}{S_{ico}} = \left[\frac{\left(\frac{\vec{|E|}^2}{8Z_s} \times L_e^2 \right)}{\left(\frac{\vec{|E|}^2}{2\eta} \right)} \right] = \eta \frac{L_e^2}{4Z_s} \quad (6 - 45)$$

The maximum power delivered by the receiving antenna is required to be transferred smoothly, with minimum reflection, from the transmission line to the load using power combiner and impedance matching circuits, as shown in Figures 6-21 and 6-22.

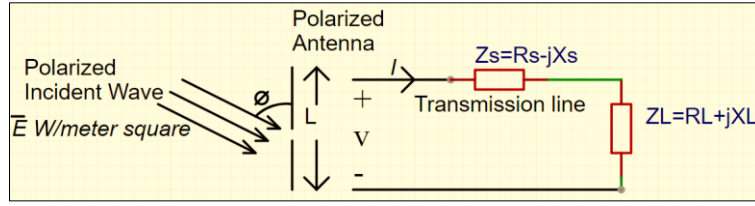


Figure 6-21. Modelling of an effective receiver antenna aperture to transfer maximum power to the load

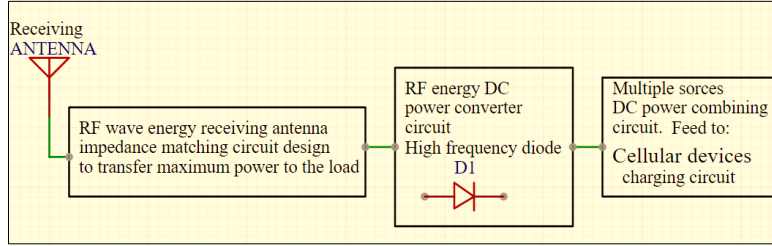


Figure 6-22. Wireless energy reuse, RF to DC power converting block circuit

Figure 6-23 shows a multi-circuit port that emerges to a single RF port. Star-connection is used for the isolation resistors. The multi-circuit receiving antenna RF energy is a combiner using the Walkison formula $\lambda/4$ impedance concept. The length of the series inductor is assumed to be $\lambda/4$:

1. Port isolation resistance $R_{in} = NZ_0$
2. The series inductance $Z_L = \sqrt{N} \times Z_0$
3. And the series inductor is $(L) = \frac{Z_L}{\omega}$
4. The shunt capacitor $C_{shunt} = \frac{1}{(2\pi f)^2 L}$

Where,

N is the number of ports.

In this section of the thesis, five indoor wireless bands are combined to generate an RF signal from the power combiner. These bands are prevalent in modern buildings, and this study aims to harness the available energy, although the combined output is not yet sufficient for practical applications. The principle involves radiating energy from the antenna, where the power supplied is transformed into wave energy.

The indoor antennas are isotropic, meaning their radiation is not focused on a single point; instead, it disperses uniformly throughout the surrounding space. While this allows for

wave energy to be accessible everywhere, the amount of energy that can be harvested is lower than that of directive radiation.

Therefore, by extracting all available bands within the building and aggregating the fractional energy from each radiating band, a significant amount of energy can be achieved. This objective underpins the design of the multiple RF ports power combiner circuit and RF-DC converter circuit illustrated in Figure 6-24. The converted DC power will be used to charge low-power IoT devices.

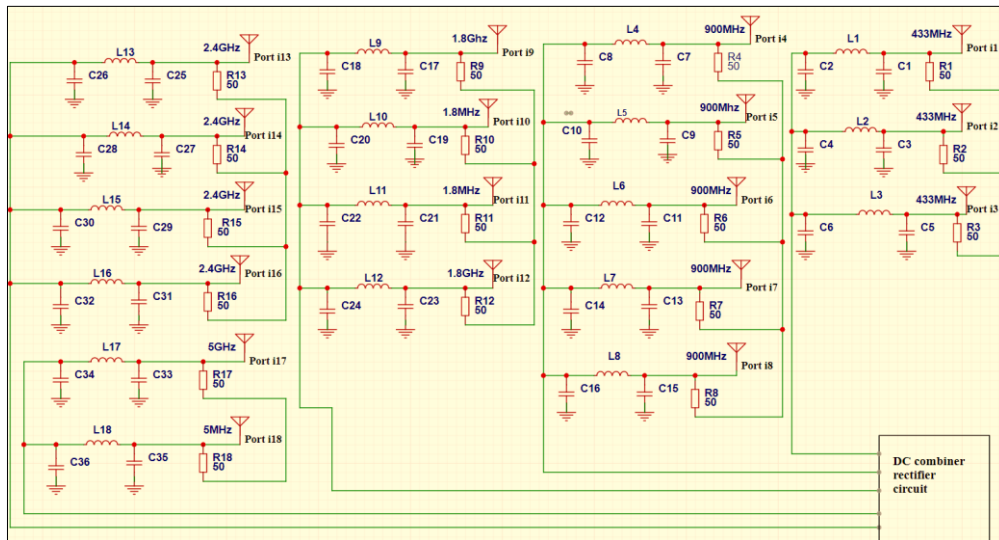


Figure 6-23. Multiple RF band schematic diagrams, converting RF to DC power, DC power combiner and charging unit circuits

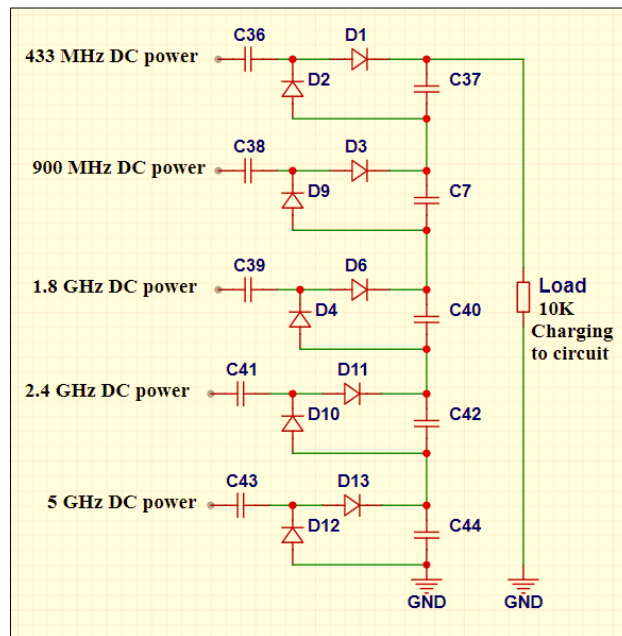


Figure 6-24. WET harvesting RF-DC conversion circuit

6.7.1.3 Impedance Circuit Matching Characteristics Analysis

2.4 GHz, which is used for indoor Wi-Fi devices, its resonant circuit is selected as an example to calculate the receiver circuit's matching impedance characteristics. The resonant frequency component of 2.4 GHz is calculated using the parameter values of the resonant capacitor (C_1) = 130.1 pf and the resonant inductor (L_1) = 0.24 nH, using the basic Equations (6-46) and (6-47).

$$X_c = \frac{1}{2\pi f_c} \quad (6 - 46)$$

$$X_l = \frac{1}{2\pi f_l} \quad (6 - 47)$$

Assuming the circuit matching antenna wire resistance is 50Ω , which is connected in series with the resonant circuit. The impedance of the resonant circuit is shown in Figure 6-25.

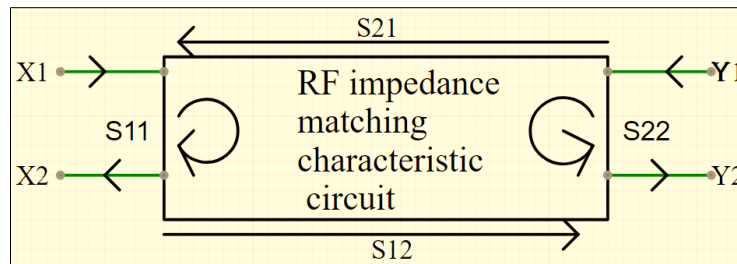


Figure 6-25. Two-port transmission line characteristic impedance matching technique:
General concept

The multiport impedance matching network is based on transferring the generated energy; in this case, the received energy, which is entered through the port, is considered the source and is to be matched to the output load. To demonstrate, let us start with the concept of S-parameters (S_{11} , S_{12} , S_{21} and S_{22}).

Where,

$S_{11} = \frac{X_1}{Y_1}$ is the reflected wave ratio related at the incident port.

$S_{22} = \frac{X_2}{Y_2}$ is the ratio of reflected and incident waves, known as return loss and voltage standing wave ratio.

$S_{21} = \frac{X_2}{Y_1}$ is the forward propagation or the insertion loss

$S_{12} = \frac{X_1}{Y_2}$ is the reverse gain or the insertion loss.

$$X_1 = Y_1 S_{11} + S_{12} Y_2 \quad (6 - 48)$$

$$X_2 = S_{21} Y_1 + S_{22} Y_2 \quad (6 - 49)$$

At perfect matching, impedance reflection from port 2 tends $\rightarrow$ zero, which lets maximum power transfer to the load. This leads to Equation (6-49), which depends on the incident parameters, that is $S_{11} = \frac{X_1}{Y_2}$ and $S_{21} = \frac{X_2}{Y_2}$ (6 - 50)

Similarly, at perfectly matching load $Y_1 \rightarrow$ zero, and Equation (6-50) depends on

$$S_{12} = \frac{X_1}{Y_2} \text{ and } S_{22} = \frac{X_2}{Y_2} \quad (6 - 51)$$

6.7.1.4 Analysing the Results of the Impedance Matching Circuit Simulation

At resonance, the reactance of the capacitance and the inductance are almost equal and possess opposite values. Because both are equal and have opposite directions, they cancel each other out. The resonant circuit remains on the pure resistive impedance, which is, in this case, 50 Ω , ideally, at the resonant point, where maximum energy is transferred.

To obtain maximum power transfer from the antennas to the load, a minimum power reflection is required to put this into practice. Hence, the following impedance matchings are considered:

1. Real-to-real impedance matching using resistances.
2. Real-to-real impedance matching using transformers.
3. Complex-to-real impedance matching using reactances.

Impedance matching using resistances is real-to-real matching. The resistive matches the input impedance to the load impedance by balancing both impedances, that is, $Z_{in} = Z_{Load}$.

Hence, it is not suitable for $Z_{in} \neq Z_{Load}$, as it is lossy.

Similarly, the transformer impedance matching is real-to-real, and it is bulk, not ideal for this application.

The complex-to-real impedance matching is perfect for this application. This is because of the impedance suitable for $Z_{in} \neq Z_{Load}$ matching. The reactive component complex conjugate cancels out at the time of resonance, and maximum power is transferred from the input to the load on pure resistance. The effective impedance matching circuit for this application is a network that is selected according to the appropriate quality factor (Q). First, the L-matching impedance network concept is adapted to prove the derivation of Q. At a specific frequency, the general impedance is $Z = R + jX$, and can be implemented in a series or a parallel form. At this specific narrow frequency, these two forms of circuit yield equivalent circuit behaviour and can be reversible, while the circuit operates with the same result.

Consider the series impedance $R + jX = R_s + jX_s$, which is a pure addition. On the other hand, consider the parallel equation (6-52).

$$R + jX = R_p || jX_p = \frac{R_p + jX_p}{R_p + jX_p} \quad (6 - 52)$$

Multiplying the numerator and denominator of equation (6-52) by the conjugate

$$R_p - jX_p, \text{ yields } \frac{(R_p + jX_p)(R_p - jX_p)}{(R_p + jX_p)(R_p - jX_p)} = \frac{R_p^2(jX_p) + R_p(X_p^2)}{R_p^2 + X_p^2} \quad (6 - 53)$$

Separating Equation (6-53) into real and imaginary yields:

$$\frac{R_p(X_p^2)}{R_p^2 + X_p^2} + \frac{R_p^2(jX_p)}{R_p^2 + X_p^2} \quad (6 - 54)$$

Matching Equation (6-54) to series and parallel impedances, the series impedances yields:

$$R_s + jX_s = \frac{R_p(X_p^2)}{R_p^2 + X_p^2} + \frac{R_p^2(jX_p)}{R_p^2 + X_p^2} \quad (6 - 55)$$

$$R_s = \frac{R_p(X_p^2)}{R_p^2 + X_p^2} \quad (6 - 56)$$

$$jX_s = \frac{R_p^2(jX_p)}{R_p^2 + X_p^2} \quad (6 - 57)$$

Then, multiplying by $\left(1/X_p^2\right)$ the nominator and denominator of Equations (6-56) and (6-57).

Defining Q in relation to the series equations to solve the parallel impedance of real and imaginary parts. Where, $Q = R_p/X_p$, and substituting it into Equation (6-59):

$$R_s = \frac{R_p(X_p^2)}{R_p^2 + X_p^2} \times \frac{\left(\frac{1}{X_p^2}\right)}{\left(\frac{1}{X_p^2}\right)} = \frac{R_p}{\frac{R_p^2}{X_p^2} + 1} = \frac{R_p}{Q^2 + 1} \quad (6 - 59)$$

$$jX_s = \frac{X_p \frac{R_p^2}{X_p^2}}{Q^2 + 1} = j \frac{X_p \times Q^2}{Q^2 + 1} \quad (6 - 60)$$

$$R_p = (Q^2 + 1)R_s \quad (6 - 61)$$

$$X_p = X_s \left(1 + \frac{1}{Q^2}\right) \quad (6 - 62)$$

Conceptually, Q ranges from 10 to 100. Choosing Q for the appropriate application requires trials and probably also simulation tests. For this study, Q = 10, 15, 20, 25, 30, 35, 40 and 45 are among the selectable range to match the antenna's 50 Ω source to a 10 k Ω load.

Figure 6-26 shows the schematic circuit of multiple ports simulated using an RF transmission line impedance matching circuit. The values of the components are calculated using the lumped sum elements equations. Port 5 is the summed output value, while ports 1 to 4 are the inputs from the receivers. Pi-network matching with a virtual middle resistance is implemented to find the series stray inductance.

$$Q = \sqrt{\left(\frac{R_{High(H)}}{R_{Virtual(V)}} - 1\right)} \quad (6 - 63)$$

From Figure 6-26, R_H is 10 k Ω and $R_{(Low)}$ is 50 Ω . Finding the virtual resistance helps to determine the appropriate value to match the high and low impedances.

Considering that the $R_V < R_H$ and R_L ,

$$R_V = \frac{R_H}{Q^2 + 1} = \frac{10000}{255 + 1} = 39.1\Omega.$$

Determine the load side parallel and series elements using $Q_p = 15$.

$$X_{pc1} = \frac{R_p}{Q_p} = \frac{R_L}{Q} = \frac{10000}{15} = 666.667\Omega ,$$

$$X_{SL2} = R_V \times Q = 39.1 \times 15 = 586.5\Omega.$$

For the source network, apply a similar method and using the R_V , defining Q as Q_{new} .

$$Q_{new} = \sqrt{\left(\frac{R_S}{R_V} - 1\right)} \quad (6 - 64)$$

Then match the source pi-network to the parallel and series reactants.

$$X_{pc2} = \frac{R_p}{Q_p} = \frac{R_S}{Q_{new}} = \frac{50}{0.528} = 94.71\Omega$$

$$X_{SL1} = R_V \times Q_{new} = 0.528 \times 39.1 = 20.644\Omega.$$

The corresponding reactant values are taken to calculate the capacitance value and the inductance values using the resonant equations, illustrated as follows:

$$C_1 = \frac{1}{2\pi f X_{pc1}}$$

$$L_1 = \frac{1}{2\pi f X_{SL1}}$$

$$C_2 = \frac{1}{2\pi f X_{pc2}}$$

$$L_2 = \frac{1}{2\pi f X_{SL2}}$$

Where:

f is the resonant frequency, 2.4 GHz.

Figure 6-26 excludes the 50 Ω start-connected resistors, which are the isolation resistors between the ports. This is because it is a single circuit that lacks an isolating resistor to match the source to the load. The components are calculated using the resonant formula and schemed for resonant simulation as shown in Figure 6-27. Consequently, the impedance matching circuit is resonated at 2.4 GHz, as shown in the simulation results in Figure 6-28.

In this scenario, four ports resonate at 2.4 GHz with a maximum loss of -12.98 dB. This is an acceptable sensitivity level at which the circuits can capture the combined magnitude of 2.4 GHz signals. Furthermore, the circuit was supplied by an E-field 8.9 V/m, which is equivalent to 0.32 V at an estimated five-metre distance from the radiating sources, summarised and simulated using live simulation software, as illustrated in Figure 6-29. The summed values from the sources are supplied to a $10\text{ K}\Omega$ load. Simulation values across the loads are shown in the bottom-left side of Figure 6-29. Approximately $12.257\text{ }\mu\text{A}$, 122.568 mV and $1.502\text{ }\mu\text{W}$ are obtained. Indeed, this is a significant achievement, which ensures that the circuit's reflection signal is minimised.

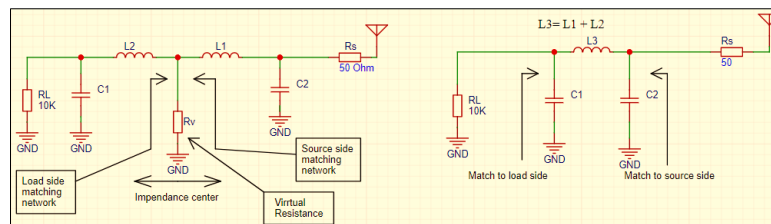


Figure 6-26. Series and parallel components to match the load impedance

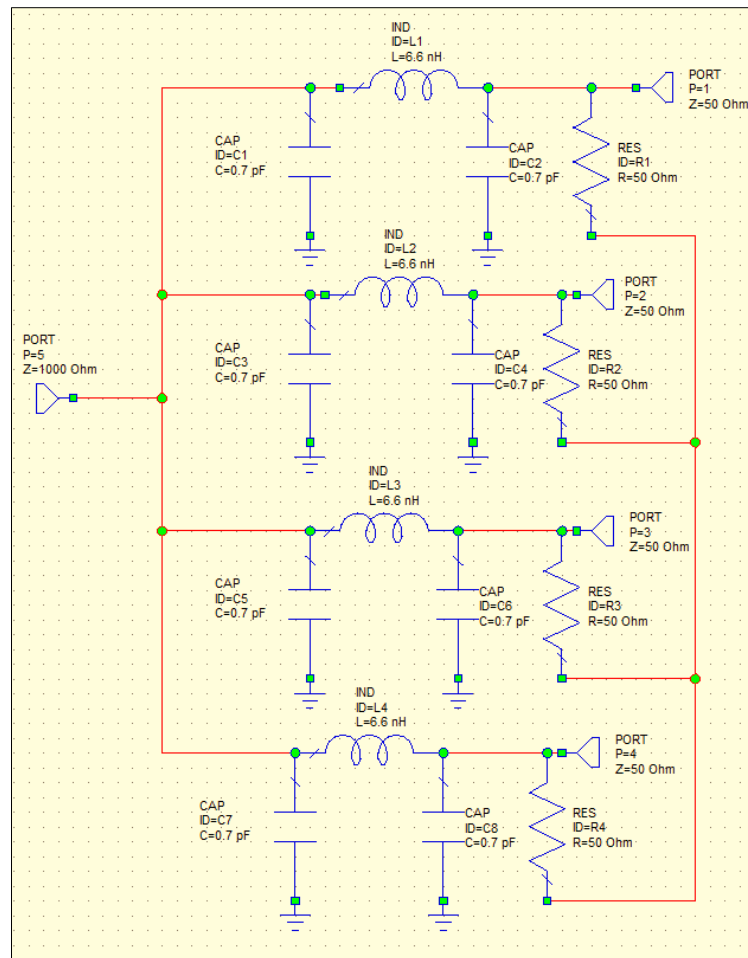


Figure 6-27. Five-port 2.4 GHz Wilkinson lumped sum element power combiner circuit

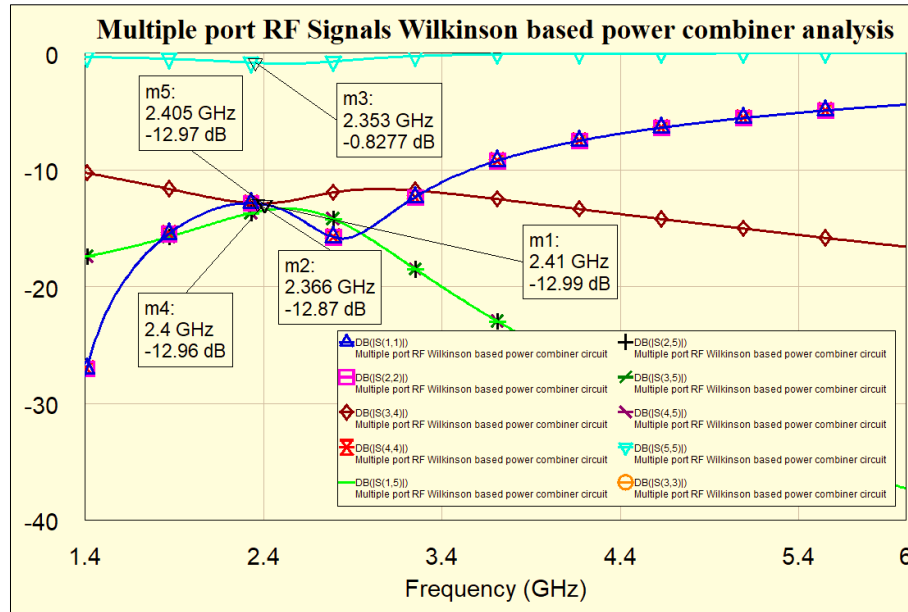


Figure 6-28. A five-port Wilkinson lumped sum element power combiner circuit resonates at 2.4 GHz

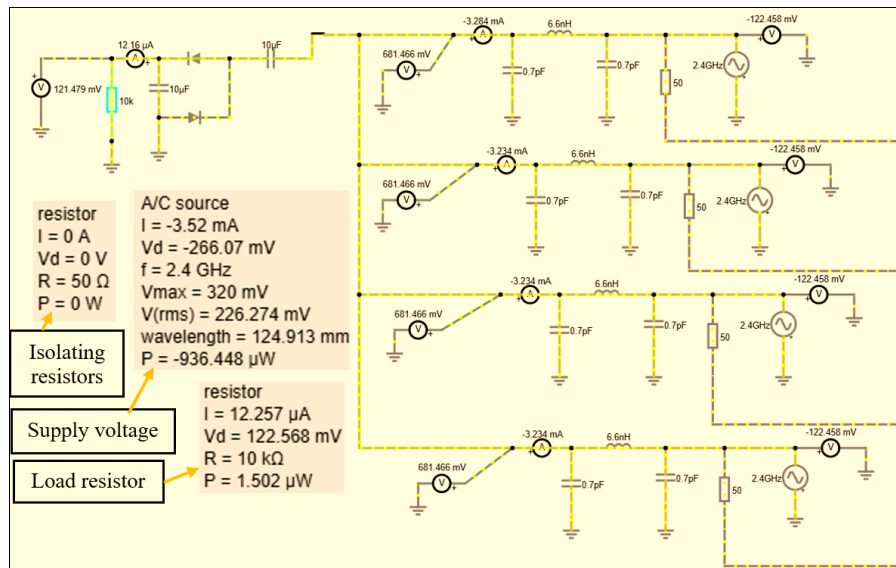


Figure 6-29. Five-port 2.4 GHz Wilkinson lumped sum element-based RF power combiner, simulated results

6.8 Conclusion

Smart building technologies, especially indoor wireless capabilities, represent one of the fastest-growing sectors in modern technology. These structures are outfitted with sensor networks, including BIoT, as well as wireless control and communication systems. Advanced technologies are increasingly being implemented in smart and innovative buildings within the constructed environment. For instance, 5G technology is currently

transitioning to 6G, both of which offer greater energy efficiency than 4G. This enhancement facilitates quicker communication with building AI systems, healthcare facilities and emergency response situations.

Because of the shorter wavelengths associated with higher frequency wireless signals, such as those used in 5G and 6G, these signals require more devices to cover areas previously serviced by 4G or lower frequencies. This increase in frequency results in elevated power density levels. Thus, the objective of this study has been to assess the indoor power density generated by various wireless devices. To achieve accurate estimations, regulations regarding power density from multiple standards have been taken into account. Wireless energy measurements were conducted in six public open areas in Melbourne. Concurrently, multiple indoor antennas were conceptually designed and modelled. Then, simulations of indoor multi-wave propagating energy were carried out. The resulting power density was translated into practical applications through a process known as ‘energy harvesting’. This led to the development of a passive charging circuit intended for use as an emergency charger in regions with a high concentration of RF devices.

Chapter 7

Indoor Environmental Pollution Protection, Air Quality Enhancement and Occupant Comfort Simulation

7.1 Introduction

A sustainable, smart building is essential for adhering to principles and guidelines designed to protect against indoor and outdoor environmental pollution. Environmentally enhanced structures also contribute to the comfort and wellbeing of their occupants. Achieving this begins with ensuring high AQ, including IAQ, which pertains to the condition of air within enclosed spaces. Low levels of toxins and pollutants characterise a building that maintains good AQ. Optimal AQ can be attained through proper ventilation with fresh outdoor air while minimising the introduction of indoor pollutants and those released from materials within the space.

Sustaining good IAQ necessitates strategies incorporating clean, fresh outdoor air. This can be accomplished by effectively maintaining exhaust systems and employing high-efficiency filters in HVAC systems. Other measures include placing walk-off mats at entrances, banning smoking in rooms near windows and air intakes, incorporating indoor plants and using only low-emission devices or non-toxic materials.

This chapter involves a comprehensive simulation to enhance occupant comfort while identifying discomfort-related issues associated with smart buildings. In addition to assessing AQ, the study comprehensively simulates indoor electromagnetic radiation from multiple wireless devices installed in the building. Furthermore, this study develops a radiofrequency electromagnetic field (RF-EMF) radiation exposure monitoring meter circuit, aiming to ensure that the combined radiation from a group of populated indoor wireless devices does not exceed the maximum permissible power density as deemed by various recognised standards.

7.2 Environmentally Healthy Buildings

IEQ [236] is defined as the characteristic conditions inside the building. The definition focuses on AQ but also includes access to daylight, views, pleasant acoustic qualities, occupant control over lighting and thermal comfort. The definition also covers the functional aspects of rooms: for example, whether conditions such as easy access to tools and sufficient spaces for occupants are met. Building engineers, contractors, owners and operators can increase the satisfaction of building occupants by considering all the aspects of IEQ rather than narrowly focusing on temperature or AQ alone.

7.2.1 Outdoor AQ

Buildings let many harmful pollutants from the surrounding outdoors into the building. Particulate matter is a hazardous pollutant because of its tiny size; extremely tiny microscopic particles can penetrate deep into the lungs and even the bloodstream. Outdoor air pollution from the burning of fuels—including gas, oil, biomass and traditional wood—has health impacts, including possible early death.

7.2.2 Indoor AQ

Construction activities pose a risk to the IAQ within building spaces. It is essential to implement protective measures for both the health of construction workers and the occupants of the building. This includes isolating airborne particles generated from construction work away from permanently installed HVAC systems, ensuring that toxins are removed before occupancy, maintaining dry absorptive materials and keeping the facility free from mould by utilising construction materials with low levels of harmful VOCs.

Additionally, it is crucial to provide sufficient ventilation in occupied areas. However, precautions should be taken to avoid energy wastage through excessive ventilation. Installing monitoring systems can help detect elevated CO₂ levels, which indicate the need for additional fresh outdoor air to maintain healthy IAQ.

7.2.2.1 Sources of VOCs

VOCs are harmful substances present in various materials such as paints, adhesives, cleaning agents, carpets, particle boards, floor sealants, composite wood products, agri-fibre items, ceiling fixtures and wall systems. These organic compounds are released into indoor environments, thereby degrading AQ. For instance, adhesives serve to join different surfaces and include bonding primers and adhesive primers specifically designed for plastics. Adhesives frequently release significant amounts of toxic VOCs. Similarly, binders function to combine two or more components and can also contain elevated levels of detrimental VOCs.

7.2.2.1.1 Prevention of VOC

Smart buildings offer a healthy and comfortable environment for living and working through the following measures:

1. Ensuring proper ventilation and using exhaust fans, which help eliminate the accumulation of odours, CO₂, allergens and toxins in indoor air. It is essential to provide dedicated exhaust systems for areas such as copying, printing, break rooms and food preparation zones.
2. Ventilating spaces thoroughly before occupancy is advisable. Utilising energy-efficient devices and variable speed fans can effectively enhance air circulation.
3. Allowing more fresh air into the building should be considered, while building management personnel should perform regular preventive maintenance on all exhaust systems.
4. During construction or renovation projects, it is crucial to seal off ventilation duct openings to minimise dust and particle accumulation.
5. Adequate, separate ventilation for occupied areas is vital; however, caution should be exercised to avoid unnecessary energy consumption through excessive ventilation.
6. To ensure IAQ remains healthy, monitoring systems that trigger alarms when elevated levels of CO₂ are identified must be installed.
7. An actuator should automatically engage to introduce additional fresh air from outside when needed.

8. Selecting building materials that emit low levels of VOCs is essential for compliance with established standards and minimising VOC release.

7.2.2.2 Decarbonization Mitigation for Sustainable Building Design

Carbon emissions release toxins that spread into the indoor atmosphere. CO₂ is the most abundant gas in terms of the quantity produced through the burning of fossil fuels. CO₂ emissions from human activities are also significant contributors to rising CO₂ levels. Hence, comprehensive indoor and outdoor environmental assessments of poisonous gases are necessary for sustainable smart building design.

This study aimed to model and optimise energy use through conceptual simulations using Autodesk Insight to achieve a consistent reduction in annual energy consumption. The analysis and findings of the simulations are presented in Figure 7-1, which illustrates the total, embodied and operational CO_{2e}, along with the overall annual energy intensity. ‘Embodied carbon’ refers to the carbon emissions produced throughout all stages of a building’s construction process. This includes the extraction of raw materials, their production and processing, transportation, installation and eventual disposal of existing materials. Each phase contributes to the total embodied carbon emissions. Therefore, implementing these configurations alongside strategies for CO_{2e} reduction promotes sustainability in building design and modelling, as well as in innovative buildings within the built environment.

This study aimed to develop measurement methods for evaluating ventilation in buildings and the levels of indoor pollutants. The techniques employed range from sophisticated tracer gas methods, primarily employed in building research, to more straightforward methods suitable for use by building operators. This study is therefore centred on creating and field-testing innovative assessment protocols to evaluate their effectiveness and reliability. Figure 7-2 illustrates the CO₂ concentration at a stable state during primary and alternative phases. Figures 7-3 and 7-4 present the source particle deposits and airborne concentrations, exposure levels and surface loading on various components of building structures.

Not adequate monitoring and management of IAQ can result in heightened and potentially avoidable risks. This is because of airborne particles, encompassing both inorganic materials and allergens, which may contribute to serious health problems. Addressing

these serious pollutants is crucial; implementing strategies like air filtration and pressure balancing can effectively control biological pathogens while also reducing odours, dust and other non-living airborne contaminants.

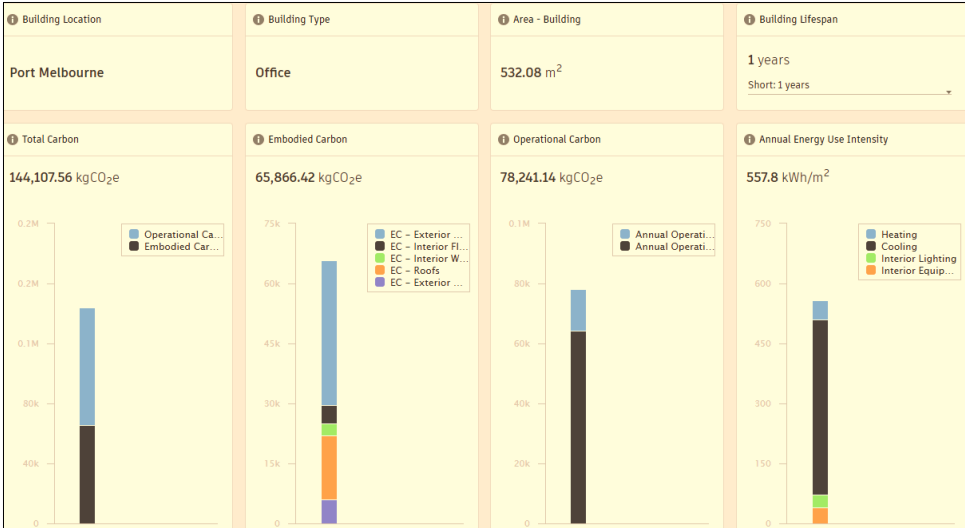


Figure 7-1. Conceptual sustainable building design, estimated annual carbon footprint

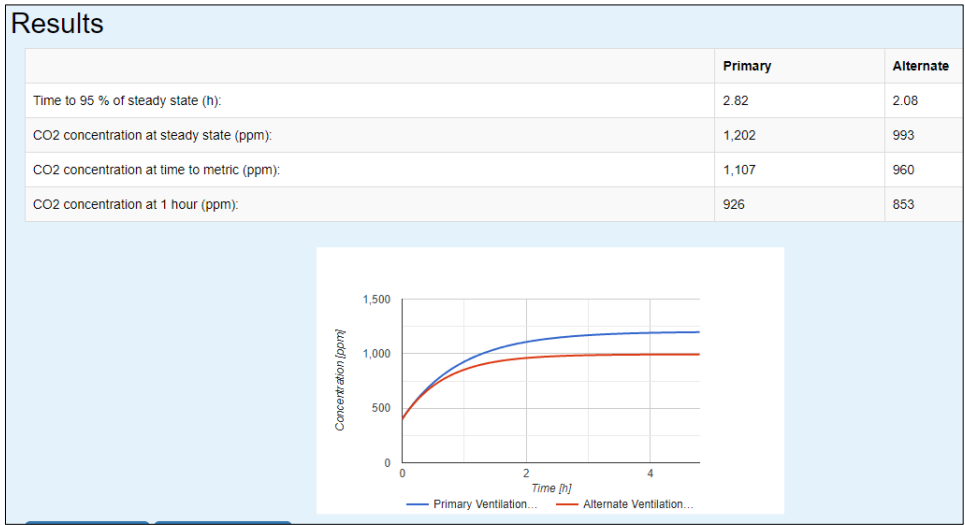


Figure 7-2. Sustainable method of mitigating indoor air pollution using ventilation

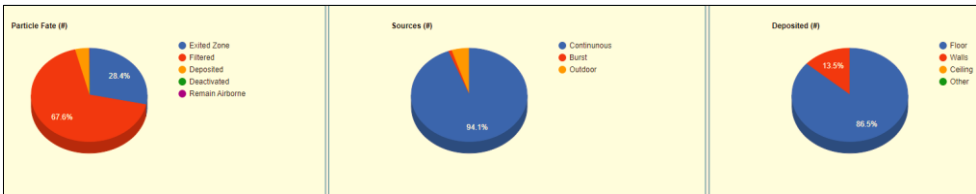


Figure 7-3. Fate, source and deposits of indoor particles

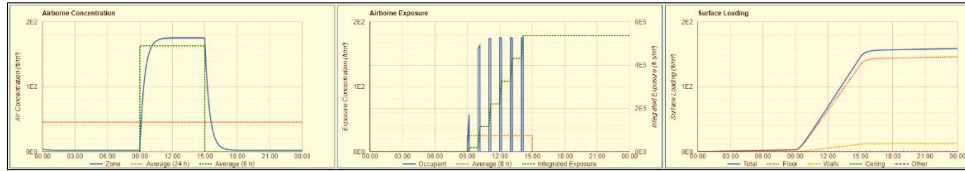


Figure 7-4. Conceptual, indoor air pollution mitigation simulation results

7.3 Strategy for Environment Monitoring

Maintaining optimal AQ is essential for the overall health of a building. Implementing environmental monitoring techniques can safeguard occupants from harmful contaminants, thereby creating a healthy environment that enhances their wellbeing and productivity. Studies show that when individuals are in good health, they are more likely to engage effectively and perform their tasks efficiently [237]. It is imperative to conduct ongoing assessments of pollutants and various comfort parameters within these environments. This involves monitoring levels of total VOC, CO₂, carbon monoxide as well as particulate matter (PM_{2.5} and PM₁₀), temperature and relative humidity [165]. This is essential because airborne particulate matter with a diameter of less than 10 or 2.5 micrometres can penetrate deep into the lungs. The levels of total VOC, including CO₂ and carbon monoxide, should be kept below approved exposure thresholds.

7.4 Practical Assessment of Occupants' Health

In this research, an experimental portioned room was constructed for conducting case studies, as illustrated in Figure 7-5. This building was designed to reflect the specifications of a real structure adequately, and so was equipped with the latest technology available. The objective of integrating modern wireless technology into the constructed facility was to align with contemporary building modernisation. The virtual building was modelled to investigate various health issues related to occupants' concerns, particularly those arising from excessive wireless RF-EMF radiation. Investigations were conducted using both virtual and actual case studies as follows:

1. **Virtual case studies:** Utilising the Wireless inSite software application, this aspect examined the characteristics of numerous wireless devices installed within an enclosed environment, as depicted in Figure 7-6. These devices were strategically placed to transmit and receive signals inside the building. Figure 7-6 illustrates how multiple signals underwent transmission, reflection, refraction and

unlimited penetration through internal walls but rarely breached external walls. This resulted in significant signal duplication and variations in propagation loss or gain, as shown in Figures 7-7 and 7-8. This analysis aids in pinpointing areas within the indoor space that have both strong and weak signal reception, and by extension, further assists occupants to avoid strong RF-radiating spots.

2. **Actual measurements:** Practical measurements were carried out over a duration of two hours using a spectrum analyser and an RF field meter. Data of power density and electric field strength were gathered from these instruments. The collected information was subsequently analysed and compared against various established standards.

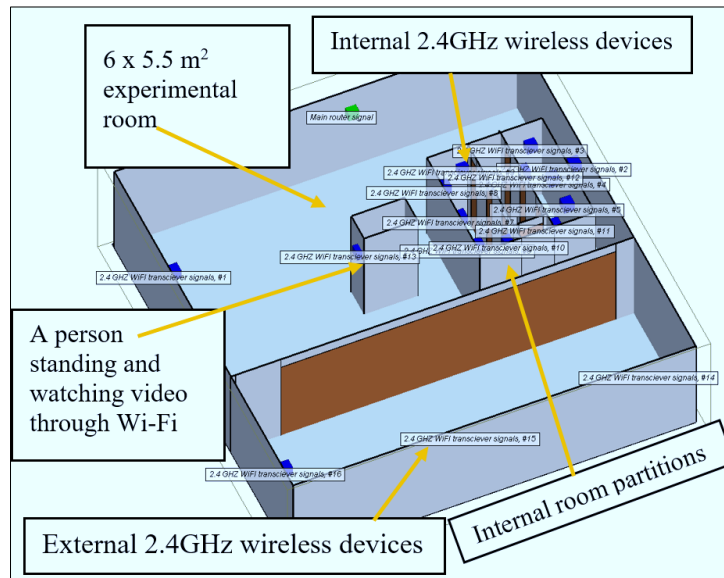


Figure 7-5. Experimental room measuring $6 \times 5.5 \text{ m}^2$

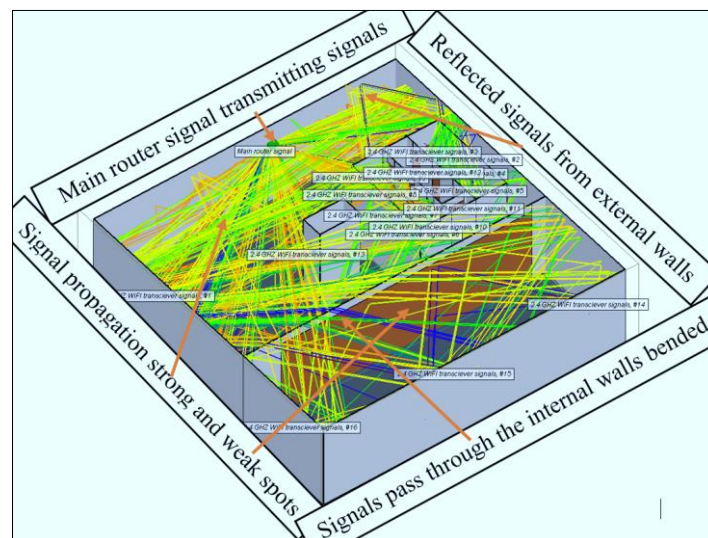


Figure 7-6. Multipath propagation of multiple transverse signals indoors

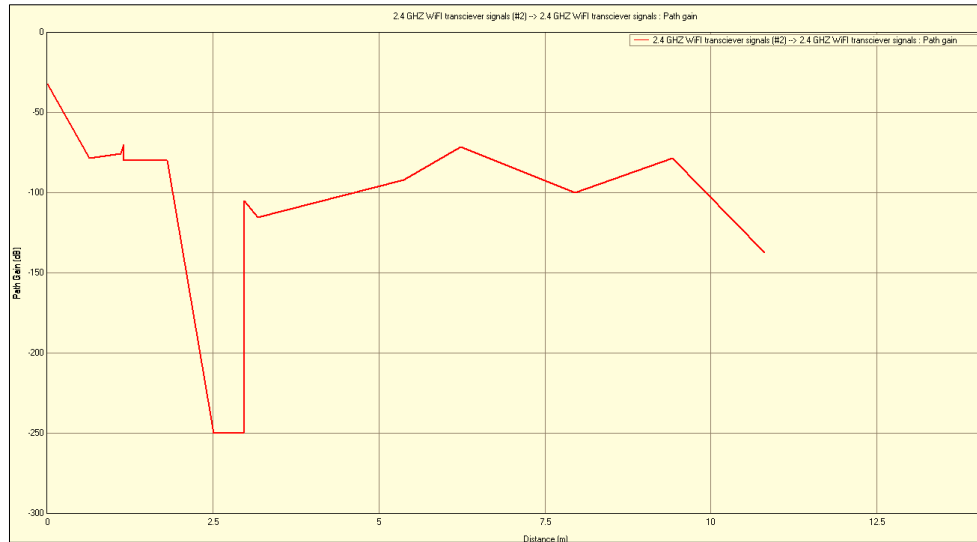


Figure 7-7. Indoor wireless propagating signal path gain

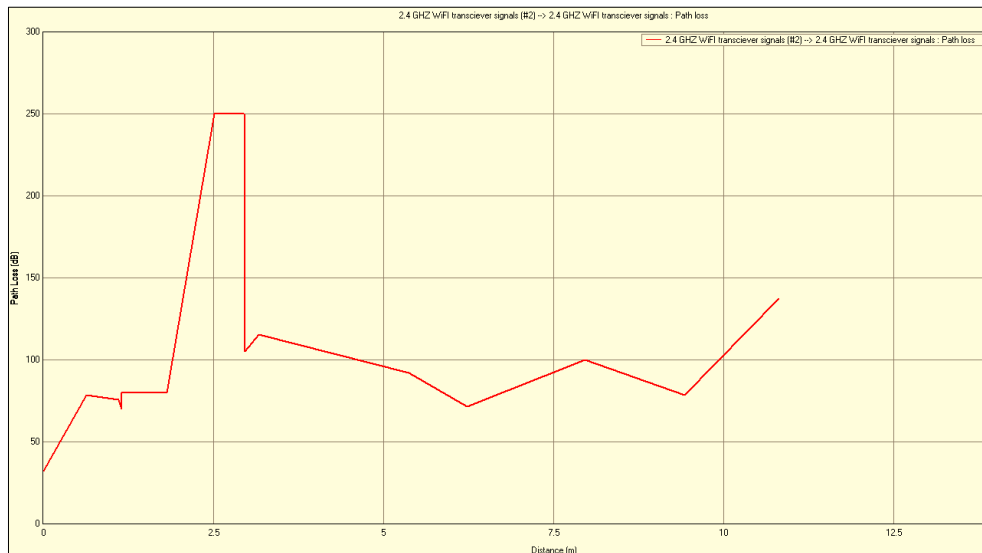


Figure 7-8. Indoor wireless propagating signal path loss

7.4.1 Evaluation of Indoor Wireless Transmitted and Re-radiated Copy Multipath Propagating Waves Using Measurement and Simulation

As mentioned previously, people living or working in a building with dense wireless communication could be concerned about various high-energy frequencies [38, 95, 96]. In the last decade, several studies have concluded with results warning that the occupants of smart buildings could be exposed to excessive RF radiation [39]. This is because of the unlimited implementation of IoT wireless devices, which form a constellation in smart buildings [238]. In addition, there is an increase in the implementation of the emerging technology of multiple short-wave, known as mmWave, higher energy wireless frequency

communication applications [99, 100]. Suspicion of non-ionising radiation has raised concerns for the general public about health impacts [96, 98]. Even recently conducted research contains confused arguments about potential health effects, and so the topic remains controversial [101] until resolved. Thus, this study attempts to evaluate the impact of power density, E-fields, and SAR using conceptual simulations by concentrating on the two main uncontrolled areas:

1. Occupied areas of the indoor environment, and
2. Outdoor areas accessible to the general public. RF data were collected from the Victoria University compound, including the library, café and building corridors.

For the simulation of indoor exposure, the conceptual simulation models multiple antennas and applies two types of simulation methods:

1. Sequential simulation, in which the multiple antenna ports excite one another while terminating the other ports.
2. Simultaneous simulation [239], in which all the multiple antenna ports are simulated simultaneously.

Furthermore, several simulations were conducted by changing the distance, phase shifts and number of antennas to be simulated simultaneously. This was to investigate accurate RF-EMF exposure results.

7.4.1.1 Sequential Simulation of Indoor 2.4 GHz Wireless Transmitters: Case Study 1

In this case study, multiple wireless transmitter antennas and the multipath propagating wave energy were simulated. The simulation standard used in this study is that of the IEC/IEEE. This is because the CST Studio Suite software uses the IEC/IEEE standards for simulation, averaged at (1 g), (10 g) and point SAR of tissues. The IEC/IEEE is the standard averaging method according to the ‘dual logo standard IEC/IEEE: 2017 version’, determining the peak spatial-average SAR in the human body from wireless communications devices, 30 MHz to 6 GHz, using the finite-difference time-domain (FDTD) method.

7.4.1.1.1 Analysis of Multiple Antennas Sequential Simulation E-Field Results

The E-field graphs illustrated in Figure 7-9 present an example of results of sequential instantaneous simulations. The frequency range used is from 2.4 to 2.5 GHz, selected to align with the indoor wireless network operating at 2.4 GHz Wi-Fi. The simulation process involved varying the frequency range, the simulated distance from the specimen material, and the number of antennas activated to excite specific ports sequentially, while ensuring that other antennas were terminated to prevent interference during the simulation.

The findings from the sequential E-field simulations differ from those obtained through simultaneous simulations, revealing that a rise in simulation frequency does not correspond to the E-field result. A detailed examination of this case study indicated that the optimal E-field level was achieved at a frequency of 2.4 GHz. However, the frequency of 2.4 GHz represents the lower end of the simulated frequency spectrum, and its outcomes contradict the theory regarding higher frequencies. According to that theory, higher frequencies carry greater energy, which in turn can generate a stronger electric field. Consequently, the result further shows that increasing the number of simulation frequencies decreases the electric field strength. When assessing the results of sequential simulations against those of simultaneous simulations at identical frequencies, it is observed that the E-field values from the sequential simulations are greater than those obtained from simultaneous simulations. Conversely, the power density recorded in simultaneous simulations exhibits higher values.

Table 7-1 presents a comparison of sequentially simulated E-field results against various standard exposure limits for E-fields. Notably, recent standards do not specify E-field exposure levels for selected frequencies. As a result, Columns 3 to 6 of Table 7-1 are marked with dashes (-) to indicate this absence of data.

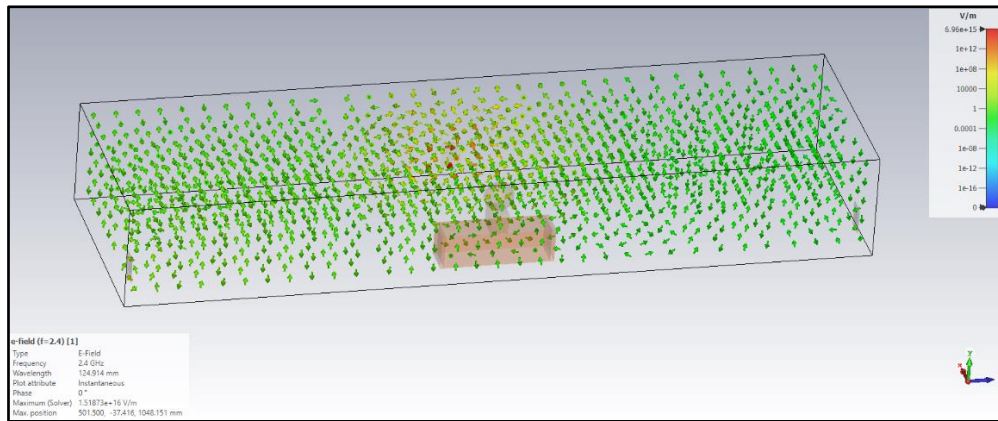


Figure 7-9. 2.4 GHz, sequential simulation E-field result

Table 7-1. Sequentially simulated E-field exposure compared with various standards for E-field exposure limits

Frequency (GHz)	Simulated (E) V/m	Australian standard (E) V/m	FCC standard(E) V/m	IEC/IEEE standard(E) V/m	ICNIRP standard (E) V/m
2.4	$6.96e^{+15}$	-	-	-	-
2.45	$6.03e^{+15}$	-	-	-	-
2.5	$6.78e^{+15}$	-	-	-	-

7.4.2 RF Sequential and Instantaneous Multiple Frequencies Power Density and SAR Simulation Analysis

Power density is most accurately applied when the measurement location is sufficiently distant from an antenna port. It is defined as the amount of power per unit area and is commonly used to indicate the intensity of exposure levels.

The results from sequentially simulated SAR exposure illustrate that variations in the frequencies used by multiple antenna ports influence the outcomes of simulations; however, altering the number of antennas does not affect these results. This occurs because sequential simulation evaluates each antenna independently, leading to no interference between transmitted signals—one antenna’s instantaneous wave signal completes before another begins. Consequently, a combined result cannot be generated through this method.

The SAR outcomes derived from sequential simulations pertain solely to one antenna.

Hence, in this section, three distinct simulation methods are employed:

1. Utilising IEC/IEEE 1 g tissue standards for every 1.6 W/kg, graphical example is depicted in Figures 7-10, 7-11 and 7-12. This indicates that when simulating 1 g of biological tissue fat, the response or simulation results should not exceed 1.6 W per kilogram of tissue.
2. Applying IEC/IEEE 10 g tissue standards. This indicates that simulating 10 g of biological material means that responses or simulation results must remain below 4 W for each kilogram of tissue.
3. Implementing IEC/IEEE point SAR standards for tissues. This entails that simulating point SAR for biological materials should also yield results under the limit of unspecified per kilogram by the various standard guides' limits. As a result of this point, future consideration is highly recommended.

To identify a safe and effective approach, results obtained from methods (1), (2) and (3) are compared as shown in Figure 7-13. According to Method (1), a simulated SAR for 1 g of tissue should not surpass 1.6 W; conversely, for Method (2), a simulated result must be less than or equal to 4 W for the SAR in tissues weighing 10 g.

The point SAR did not specify the amount of tissue in grams, which makes it difficult to compare with other methods. This comparison shows Method (2) to be more practical than Method (1). The significance lies in lowering exposure guidelines to enhance public safety through stricter exposure standards.

Moreover, SAR findings from both methods have been contrasted against various established SAR exposure limits presented in Tables 7-2, 7-3 and 7-4. The simulated SAR values remain substantially below these limits across different exposure standards, which indicates that results from sequential simulations are unlikely to exceed those set by single-frequency exposure standard guidelines.

Hence, this finding supports numerous funded studies asserting that higher frequencies used in indoor wireless communication continue to pose no significant effects for the occupants of the buildings.

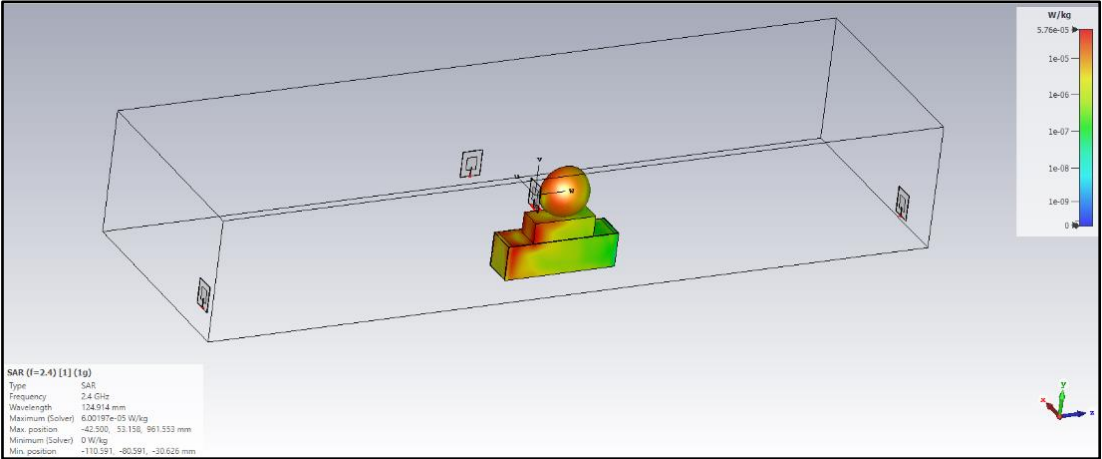


Figure 7-10. 2.4 GHz, four antennas are sequentially simulated using the 1 g method

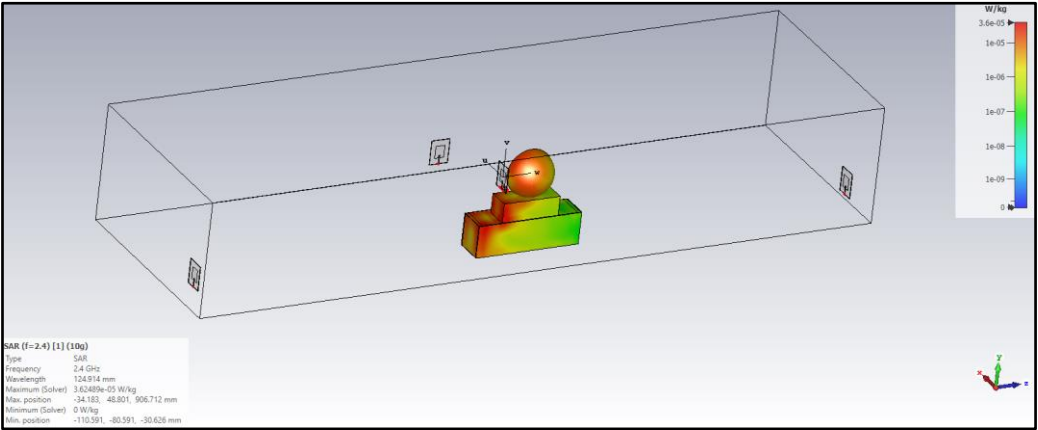


Figure 7-11. 2.4 GHz, four antennas are sequentially simulated using the 10 g method

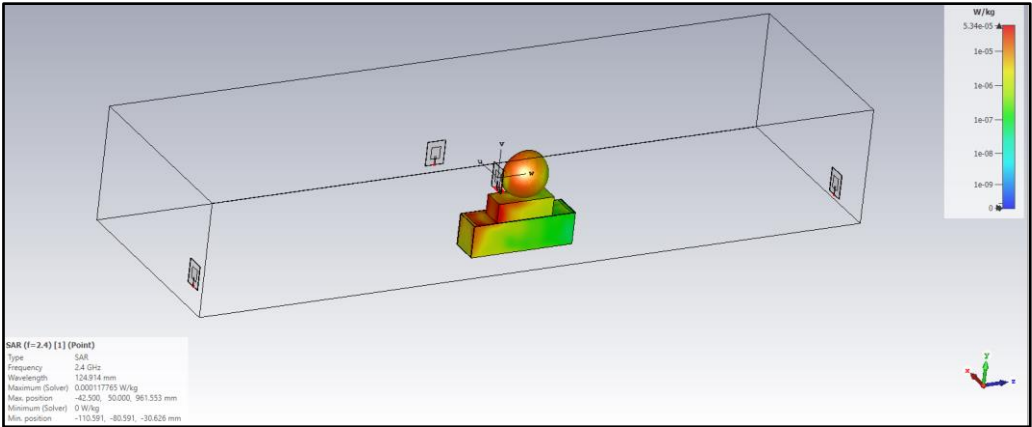


Figure 7-12. 2.4 GHz, four antennas are sequentially simulated using the point SAR method

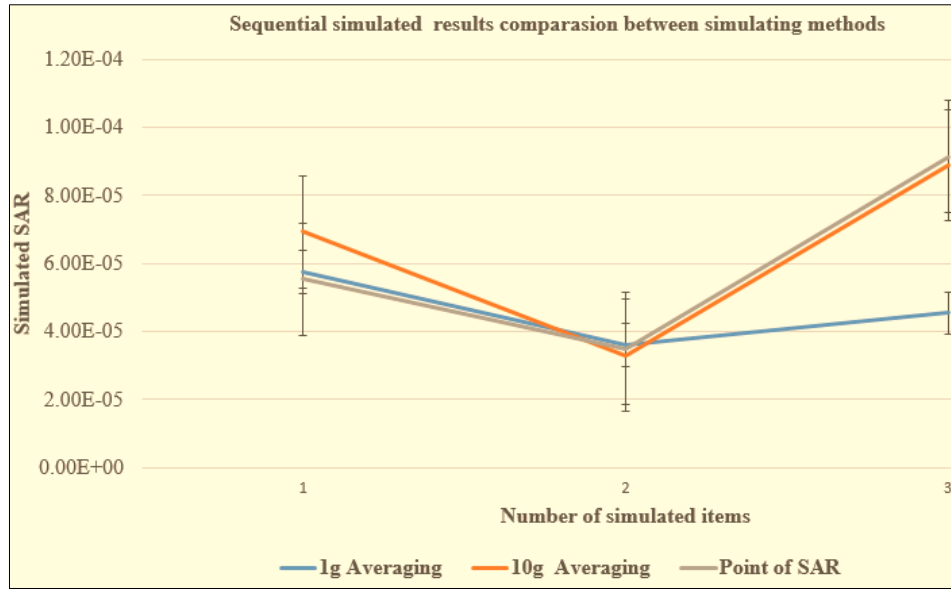


Figure 7-13. Sequentially simulated SAR comparison method

Table 7-2. Sequential simulation of RF-EMF IEC/IEEE averaged over 1 g results, comparing with different exposure standards

Frequency range	IEC/IEE (1 g) SAR	Australian standard (W/kg)	IEC/IEEE standard (W/kg)	ICNIPR standard (W/kg)	FCC standard (W/kg)
2.4	$5.76e^{-05}$	2	-	-	1.6
2.45	$6.93e^{-05}$	2	-	-	1.6
2.5	$5.55e^{-05}$	2	-	-	1.6

Table 7-3. Sequential simulation of RF-EMF ICE/IEEE averaged over 10 g results, comparing with different exposure standards

Frequency range	ICE/IEE (10 g) SAR	Australian standard (W/kg)	ICE/IEEE standard (W/kg)	ICNIPR standard (W/kg)	FCC standard (W/kg)
2.4	$3.6e^{-05}$	2	-	2	4
2.45	$3.3e^{-05}$	2	-	2	4
2.5	$3.5e^{-05}$	2	-	2	4

Table 7-4. Sequential simulation of RF-EMF ICE/IEEE averaged over point results, comparing with different exposure standards

Frequency range	ICE/IEE point SAR	Australian standard (W/kg)	ICE/IEEE standard (W/kg)	ICNIPR standard (W/kg)	FCC standard (W/kg)
2.4	$4.54e^{-05}$	-	-	-	-
2.45	$8.9e^{-05}$	-	-	-	-
2.5	$9.14e^{-05}$	-	-	-	-

7.4.3 Indoor RF Simultaneous Simulation: Case Study 2

The RF transmitter and re-radiated signal wave properties exhibit a significant likelihood for both constructive and destructive interference at various locations, including the receiver device. When these waves converge from different directions at a single point, there is an increased probability of forming a dominant combined wave. Consequently, it is crucial to conduct simultaneous simulations for all multiple antenna ports. This section, therefore, simultaneously simulates E-field, power loss density and SAR to examine their combined effects. The findings from this integrated simulation are then compared against those from the sequential simulations as well as various exposure standards. Except for E-field results, all other outcomes from the simultaneous simulations exceed those obtained from sequential simulations; moreover, in some instances, the simultaneous results surpass established standard exposure limits.

7.4.3.1 Analysis of Simultaneous Multiple Frequencies E-field Simulation Results

The E-field graphs presented in Figures 7-14 to 7-16 illustrate the results of simultaneous Method 1 simulations of four antennas oriented at ports i1 and i2, which are 2.1 metres apart, laid at 180° on the horizontal axis. In contrast, port i3 is oriented at 1.05 metres apart, 90° on the Z-axis. The fourth antenna is assumed to be a cellular device and oriented close to the human ear.

Similarly, Method 2 represents four antennas oriented at port i1, and i2 are at 1.05 metres apart, laid at 180° line horizontal axis, while port i3 is oriented at 0.525 metres apart, 90° at line Z-axis.

Method 3 represents four antennas oriented port i1, and i2 are at 2.1 metres apart, laid at 180° line horizontal axis with phase shift $\pi/2$ and $-\pi/2$ respectively, while port i3 is oriented at 1.05 metres apart, 90° at line Z-axis with phase shift $-3\pi/3$. The simulation frequency range is set between 2.4 and 2.5 GHz, consistent with the sequential simulation parameters. The simulation process involves varying the distance between antennas and altering phase shifts. A simultaneous exciting method is conducted on all antenna ports to produce combined interference.

The outcomes of the simultaneous E-field simulations differ from those obtained through sequential simulations. In the simultaneous setup, it is observed that an increase in the simulated frequency correlates with higher E-field values, and reducing the distance between transmitting antennas also enhances these results. Notably, the peak E-field measurement occurs at 2.4 GHz when the separation between transmitting antennas is halved from its initial value. Table 7-5 provides a comparison between the simulated measurements and various standard guideline limit values.

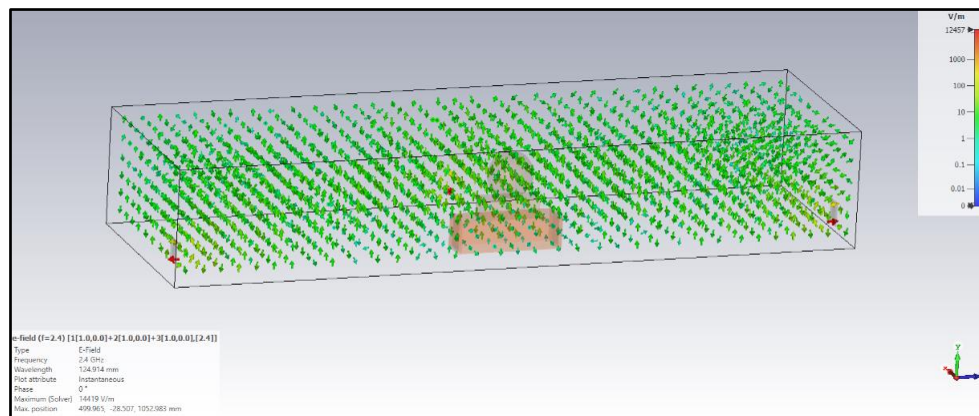


Figure 7-14. 2.4 GHz, three antennas simultaneously simulated, combined E-field result

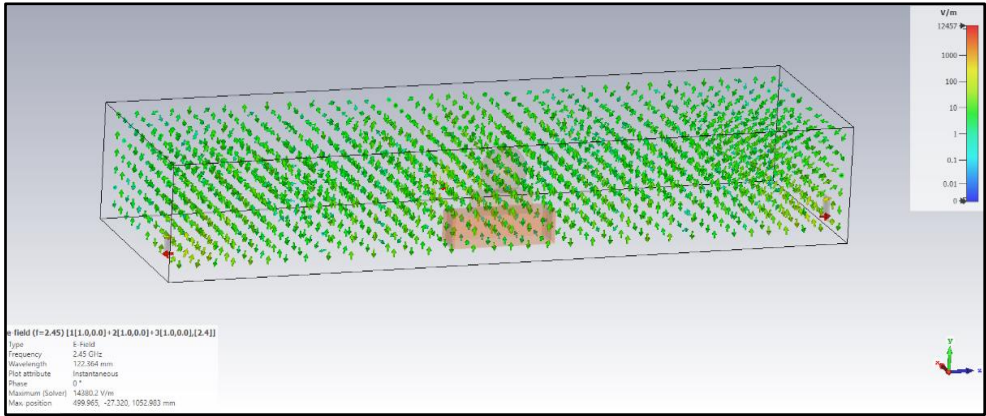


Figure 7-15. 2.45 GHz, three antennas simultaneously simulated, combined E-field result

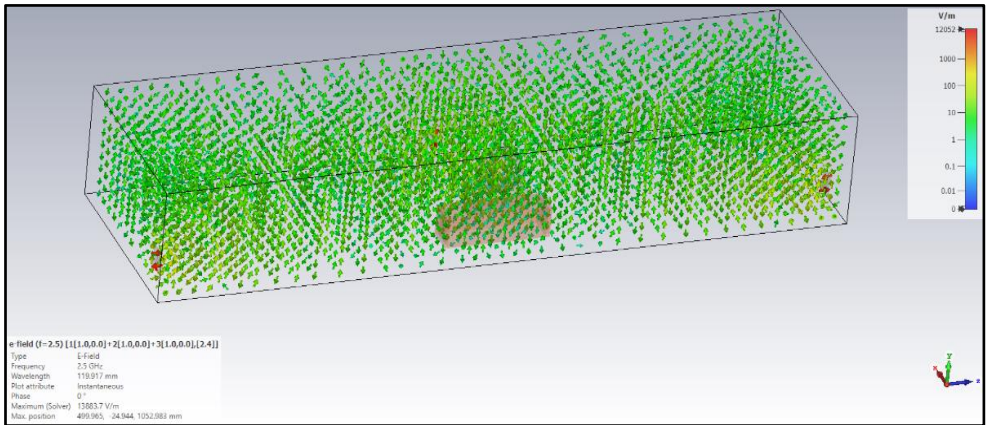


Figure 7-16. 2.5 GHz, three antennas simultaneously simulated, combined E-field result

Table 7-5. Simultaneously simulated E-field values compared with different exposure guide limits

Frequency (GHz)	Simulated (E) V/m	Australian standard (E) V/m	FCC standard (E) V/m	ICE/IEEE standard (E) V/m	ICNIRP standard (E) V/m
2.4	12457	-	-	-	-
2.45	12457	-	-	-	-
2.5	12052	-	-	-	-
Simulating distance reduced by half of the original distance					
2.4	12421	-	-	-	-
2.45	12232	-	-	-	-
2.5	12212	-	-	-	-

Frequency (GHz)	Simulated (E) V/m	Australian standard (E) V/m	FCC standard (E) V/m	ICE/IEEE standard (E) V/m	ICNIRP standard (E) V/m
Excited ports are simulated by altering the phase					
2.4	33115	-	-	-	-
2.45	32794	-	-	-	-
2.5	32550	-	-	-	-

7.4.4 Simultaneously Simulated Combined Power Loss Density

Power density is the power flow of the electromagnetic field per unit area. It represents the value of the power flow at every spatial point, averaged over one period, with respect to the given frequency. Power loss density (PLD) represents the electric or magnetic losses inside the medium—that is, energy is deposited inside the medium. It can also be expressed as the sum of the electric and magnetic power dissipated inside the medium. This shows that the PLD (W/m^3) and SAR (W/kg) correlate. As a consequence, SAR is defined as the time derivative of the incremental energy (dW) dissipated in incremental mass (dm) contained in a volume element (dv) of a given mass density.

$$\text{SAR} = \frac{d}{dt} \left(\frac{dW}{dm} \right) = \frac{d}{dt} \left(\frac{dW}{\rho dv} \right) = c \frac{dT}{dt} \quad (7-1)$$

$$\text{AND PLD} = \frac{d}{dt} \left(\frac{dW}{DV} \right) \quad (7-2)$$

Where the SAR is correlated with temperature rise, T , C is the tissue's specific heat capacity ($\text{J}/\text{kg}/\text{C}$) and t is the duration of the exposure in seconds.

7.4.5 Simultaneous SAR Simulation of Multiple Frequencies, Combined Result Analysis

In this section, simulations are performed with reference to two distinct scenarios. The first scenario involves three antennas positioned at various angles. The second scenario introduces a fourth antenna located near the human ear, which is assumed to represent a cellular device. The procedural steps for the simulation process are as follows:

1. **First step:** uses three antennas as shown in Figures 7-17 to 7-19. A simulating method, IEC/IEEE guides of 1 g, 10 g and point SAR, is applied, and the corresponding result shows less than the various standard exposure guide limits.
2. **The second step** is conducted by reducing the simulated distance between the multiple antenna ports by half. Similarly, the simulation applied the ICE/IEEE guides of 1 g, 10 g and point SAR, and the result shows less than the various standard exposure guide limits.
3. **The third step** involves placing four antennas near the human ear and adjusting the phase of the excited ports as shown in Figures 7-20 to 7-22. Like the other steps, the simulation applied the IEC/IEEE guides limits of 1 g, 10 g and point SAR. However, contrary to the first and second steps, the results from the third step exceeded the various standard guide limits. This was owing to the addition of the fourth antenna, because the spot was already experiencing a propagating electromagnetic field, and introducing an extra electromagnetic field caused a further increase.

Thus, these simulation results and comparison analysis confirm that variations in distance, antenna quantity and phase shifts have a significant influence on SAR outcomes. Comparisons with various local methods, as presented and summarised in Figure 7-23, show that the point SAR is leading, followed by the 1 g averaging method. Furthermore, Tables 7-6 to 7-8 show the detailed summarised comparison of the simulated SAR of:

(A) The 1 g averaging method, used across multiple antennas, along with specific parameters, is employed to compare their results to identify the higher values:

1. Antenna ports i1 and i2 are positioned 2.1 metres apart, oriented towards one another. The third antenna port i3 is located 1.05 metres from the central point of the specimen and is aligned perpendicularly to antenna ports i1 and i2. All antennas are set to a phase of 0°.
2. Antenna ports i1 and i2 are positioned 1.05 metres apart, oriented towards one another. The third antenna port i3 is located 0.525 metres from the central point of the specimen and is aligned perpendicularly to antenna ports i1 and i2. All antennas are set to a phase of 0°.
3. Antenna ports i1 and i2 are positioned 2.1 metres apart and oriented away from one another. The third antenna port i3 is located 1.05 metres from the specimen's

centre and is oriented at a right angle to both antenna ports i1 and (i2). The phases of all antennas are configured to 90° , -90° , -270° , and -90° respectively.

(B) The 10 g averaging method, used across multiple antennas, along with specific parameters, is employed to compare their results to identify the higher values:

1. Antenna ports i1 and i2 are positioned 2.1 metres apart, oriented towards one another. The third antenna port i3 is located 1.05 metres from the central point of the specimen and is aligned perpendicularly to antenna ports i1 and i2. All antennas are set to a phase of 0° .
2. Antenna ports i1 and i2 are positioned 1.05 metres apart, oriented towards one another. The third antenna port i3 is located 0.525 metres from the central point of the specimen and is aligned perpendicularly to antenna ports i1 and i2. All antennas are configured to a phase of 0° .
3. Antenna ports i1 and i2 are positioned 2.1 metres apart and oriented away from one another. The third antenna port i3 is located 1.05 metres from the specimen's centre and is oriented at a right angle to both antenna ports i1 and i2. The phases of all antennas are configured to 90° , -90° , -270° , and -90° respectively.

(C) The point SAR averaging method, used across multiple antennas, along with specific parameters, is employed to compare their results to identify the higher values:

1. Antenna ports i1 and i2 are positioned 2.1 metres apart, oriented towards one another. The third antenna port i3 is located 1.05 metres from the central point of the specimen and is aligned perpendicularly to antenna ports i1 and i2. All antennas are set to a phase of 0° .
2. Antenna ports i1 and i2 are positioned 1.05 metres apart, oriented towards one another. The third antenna port i3 is located 0.525 metres from the central point of the specimen and is aligned perpendicularly to antenna ports i1 and i2. All antennas are set to a phase of 0° .
3. Antenna ports i1 and i2 are positioned 2.1 metres apart and oriented away from one another. The third antenna port i3 is located 1.05 metres from the specimen's centre and is oriented at a right angle to both antenna ports i1 and i2. The phases of all antennas are configured to 90° , -90° , -270° , and -90° respectively.

Thermal loss distribution simulations were also performed; results are illustrated in Figures 7-24 to 7-26. Electromagnetic thermal waves transfer into human skin with a

conductivity measured at approximately 5.8 S/m. The evaluation involves examining the E-field or particle movement to establish loss distribution patterns through sequential steps, incorporating thermal losses derived from interpolated time-domain dynamic E-fields. This process generates two categories of losses: electric volume loss and magnetic surface loss, resulting in two distinct thermal power loss outputs:

1. The material's conductivity does not affect thermal loss distribution outcomes, but variations in simulated frequencies affect results;
2. E-field thermal volume loss diminishes with increasing frequency, while H-field surface losses fluctuate unpredictably.

The most significant recorded loss was an H-field surface loss of 8.116 W at 2.45 GHz; however, these findings represent preliminary analysis of thermal loss distributions and necessitate further scientific investigation to comprehensively elucidate their biological exposure effects.

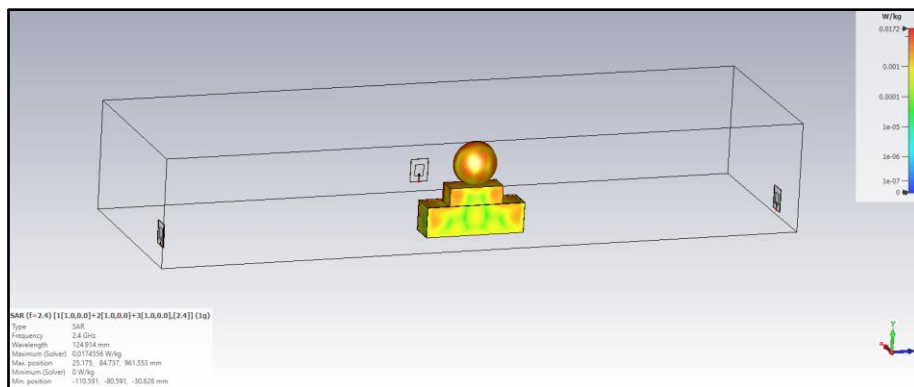


Figure 7-17. Three antennas were simultaneously simulated to produce a combined 1 g SAR result

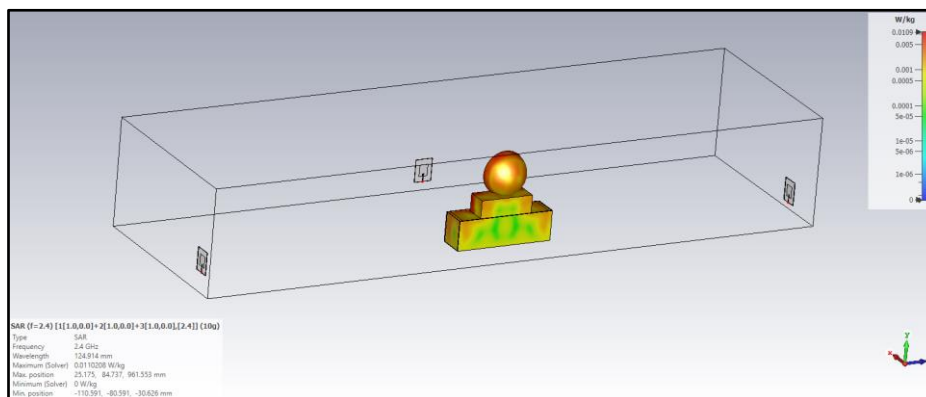


Figure 7-18. Three antennas were simultaneously simulated to produce a combined 10 g SAR result

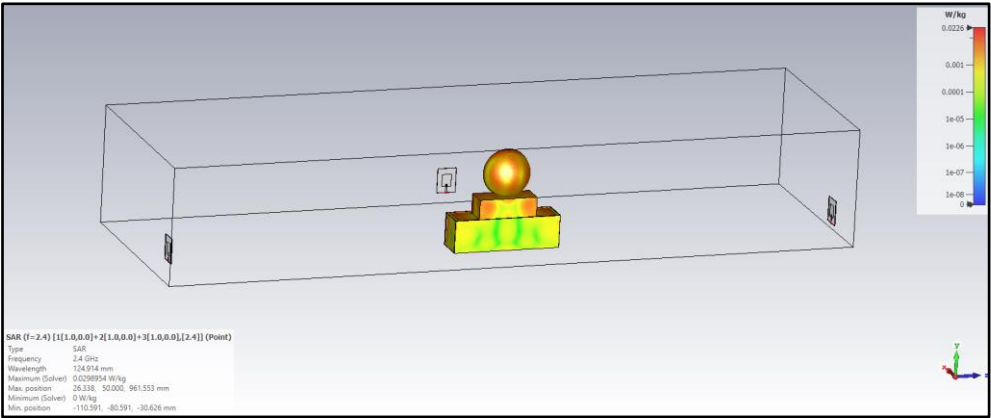


Figure 7-19. Three antennas were simultaneously simulated to produce a combined point SAR result

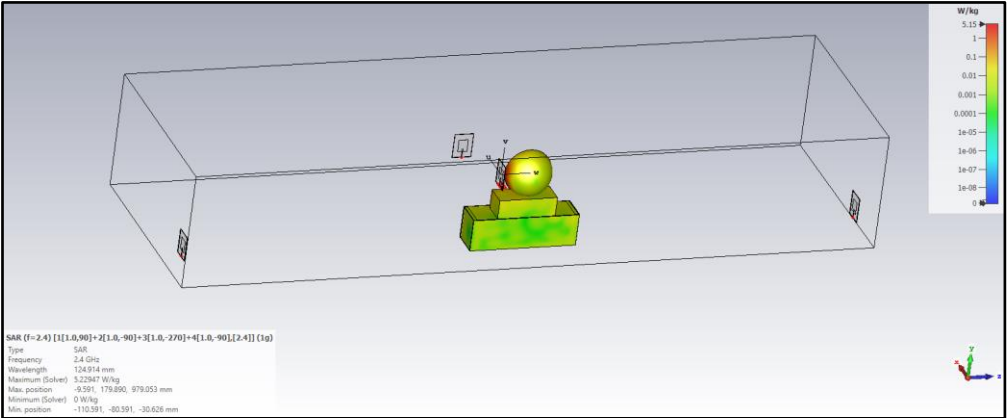


Figure 7-20. Four antennas were simultaneously simulated to produce combined 1 g SAR result

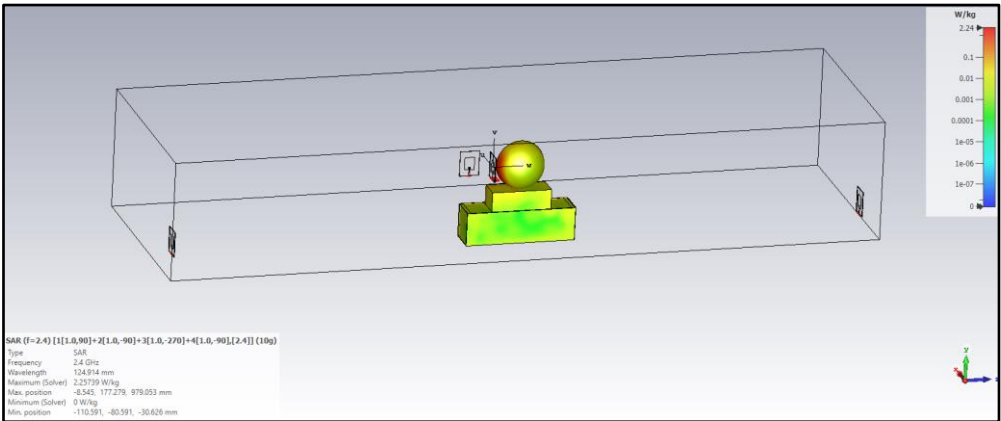


Figure 7-21. Four antennas were simultaneously simulated to produce a combined SAR 10 g result

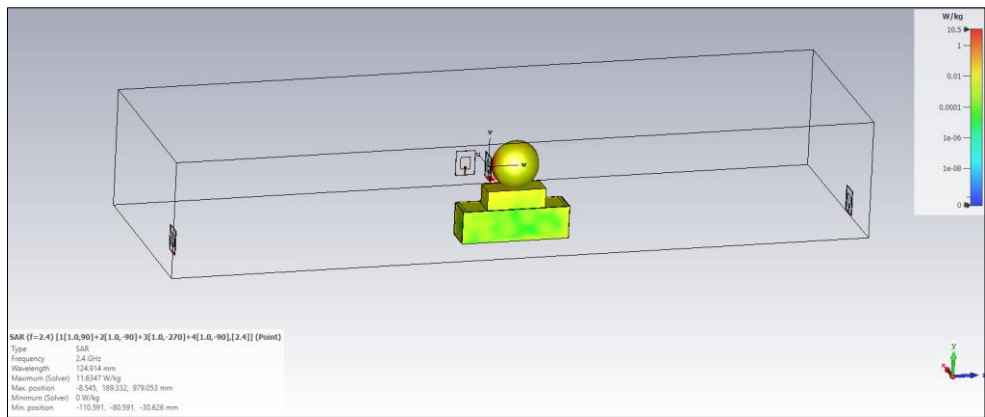


Figure 7-22. Four antennas were simultaneously simulated to produce a combined point SAR result

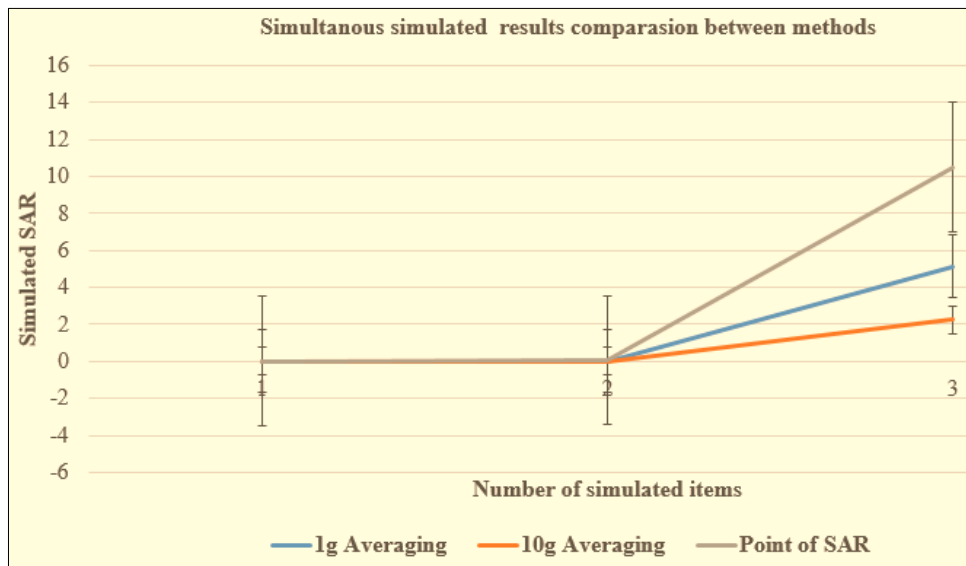


Figure 7-23. SAR summary results for three antennas simulated simultaneously

Table 7-6. Multiple antennas’ simulated SAR averaged at 1 g and compared with various exposure standards

Simulating frequencies (GHz)	Simulated at ICE/IEEE (1 g) SAR (W/kg)	Australian standard SAR (W/kg)	ICE/IEEE standard SAR (W/kg)	FCC standard SAR (W/kg)	ICNIPR standard SAR (W/kg)
2.4	0.0172	0.0086 < 1	-	-	0.0086 < 1
2.4	0.0207	0.011 < 1	-	-	0.011 < 1
2.4	5.15	-	-	-	-

Table 7-7. Multiple antennas' SAR, averaged at 10 g simulated results and compared with various exposure standards

Simulating frequencies (GHz)	Simulated at IEC/IEE (10 g) SAR (W/kg)	Australian standard SAR (W/kg)	IEC/IEEE standard SAR (W/kg)	FCC standard SAR (W/kg)	ICNIPR standard SAR (W/kg)
2.4	0.0109	0.0051 < 1	-	-	0.0051 < 1
2.4	0.0134	0.0067 < 1	-	-	0.0067 < 1
2.4	2.24	1.12 > 1	-	-	1.12 > 1

Table 7-8. Multiple antennas' simulated SAR averaged at point SAR compared with various exposure standards

Simulating frequencies (GHz)	Simulated at IEC/IEE (10 g) SAR (W/kg)	Australian standard SAR (W/kg)	IEC/IEEE standard SAR (W/kg)	FCC standard SAR (W/kg)	ICNIPR standard SAR (W/kg)
2.4	0.0226	-	-	-	-
2.4	0.0478	-	-	-	-
2.4	10.50	-	-	-	-

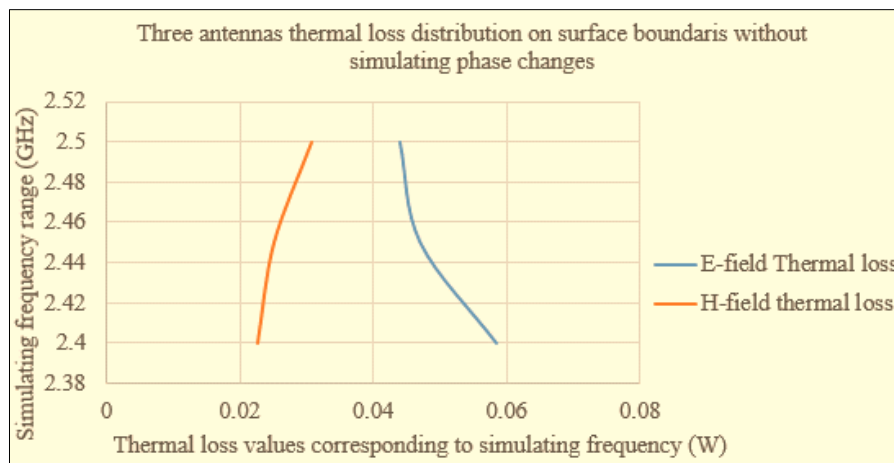


Figure 7-24. Four antennas' combined thermal values corresponding to simulating frequency without antenna phase change

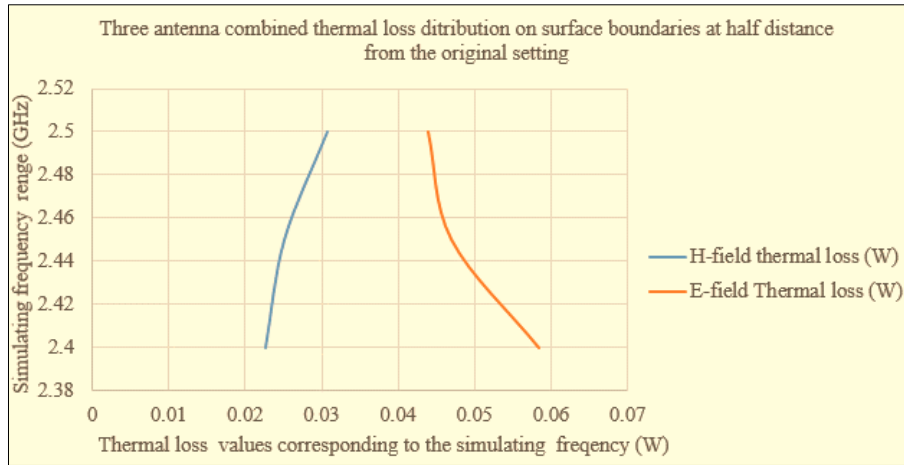


Figure 7-25. Three antennas' combined thermal values corresponding to the simulated frequency at half the distance from the original setting

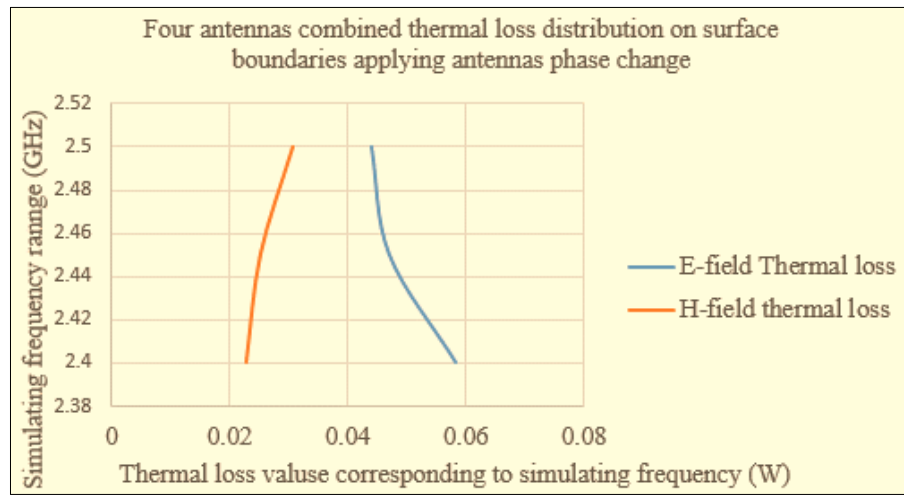


Figure 7-26. Four antennas' combined thermal values corresponding to the simulated frequency

7.4.6 Simulated RF Radiation Pressure and Momentum

Electromagnetic propagating waves incident into the medium deposit energy in the form of particle kinetic energy [240]:

$$U = \frac{1}{2}mv^2 = \frac{1}{2}pv \quad (7-3)$$

Equation (7-3) is absorbed by the medium, and the corresponding incident wave momentum is: $P_{Incident(i)} = \frac{U}{v}$ (7-4)

The reflection momentum is: $P_{Reflection(f)} = \frac{U}{v}$ (7-5)

Then the total transfer momentum is: $P_{total} = \frac{2U}{v}$ (7 – 6)

Where:

v is the velocity of the RF propagating wave inside the medium, and $v \cong C$, where C is the speed of light, and it is convenient to replace it.

$$P_{Momentum} = \frac{U}{C} \quad (7 - 7)$$

When momentum absorption and energy transfer within the medium are completely realised, pressure can be defined as a force applied over a unit area of that medium, as demonstrated in Equation (7-8):

$$P_{Pressure} = \frac{F}{A} \quad (7 - 8)$$

and it is equal to the rate of the surface at which the momentum is moving as per Equation (7-9).

$$P_{Pressure} = \frac{F}{A} = \frac{dP}{A\Delta t} = \frac{dU}{CA\Delta t} = \frac{I}{C} \quad (7 - 9)$$

This the radiation pressure for complete absorption [241] and its intensity and power relationship are defined in Equation (7-10).

$$I = \frac{dU}{A\Delta t} = \frac{P}{A} = \frac{P}{4\pi r^2} \quad (7 - 10)$$

Hence, the transferred momentum is:

$$\Delta p = P_i - P_f = \frac{2\Delta U}{C} = \frac{2IA}{C\Delta t} = \frac{2IA}{C} \quad (7 - 11)$$

7.4.6.1 Plane Wave Propagation in a Lossy Medium

Consistent with the characteristics of an insulating medium placed inside the E-field, the molecules and the atoms become dipoles. Owing to the E-field strength, the dipoles line up in parallel with the E-field, and partial cancellation can occur depending on the orientation of the dipole and the direction of the E-field applied. The current density (J) inside the lossy medium is:

$$J = \sigma E \quad (7 - 12)$$

Where:

ε_c is the electric permittivity, and σ is the conductivity inside the medium as denoted by Equation (7-13).

$$\varepsilon_c = \varepsilon' - j \frac{\sigma}{\omega} \quad (7 - 13)$$

The E-field wave equation for a known propagation varies in the X-axis and propagates in the Z-axis as shown in Equation (7-14), and the corresponding propagation constant (γ) equation is illustrated in Equation (7-15).

$$E_x(z) = E_0^\pm e^{\mp \gamma z} \quad (7 - 14)$$

$$\gamma = jk_c = \alpha + j\beta \quad (7 - 15)$$

Where:

K_c is the complex dielectric, α is the attenuation, and β is the propagation phase constant:

$$\alpha = \omega \sqrt{\frac{\mu\varepsilon'}{2} \left(1 + \sqrt{\left(\frac{\sigma}{\omega\varepsilon'} \right)^2 - 1} \right)} \frac{Np}{m} \quad (7 - 16)$$

$$\beta = \omega \sqrt{\frac{\mu\varepsilon'}{2} \left(1 + \sqrt{\left(\frac{\sigma}{\omega\varepsilon'} \right)^2 + 1} \right)} \frac{radians}{m} \quad (7 - 17)$$

Similarly, the intrinsic impedance of the lossy medium is complex as well. The real and the imaginary parts of the intrinsic impedance expressions are presented according to Equation (7-22), and the tangential loss is also expressed as complex as illustrated in Equation (7-18).

$$\tan \delta_c = \frac{\sigma}{\omega\varepsilon'}, \text{ then } \delta_c = \tan^{-1} \frac{\sigma}{\omega\varepsilon'} \quad (7 - 18)$$

In some special cases, the loss tangent in Equation (7-18) can be derived to ease the complexity of Equations (7-16) and (7-17). Two special cases, approximation conditions, are derived, which, when either of the equations results in a value less than 1 or greater than 1, determines the conductivity of the propagating waves inside the medium. The tangent loss is satisfied for good conductor propagation when:

$$\frac{\sigma}{\omega\varepsilon'} \gg 1 \quad (7 - 19)$$

$$\gamma = \alpha + j\beta \approx (1 + j)\sqrt{\pi f \mu \sigma} \quad (7 - 20)$$

$$\beta \approx \sqrt{\pi f \mu \sigma} \quad (7 - 21)$$

$$\eta_c = \sqrt{\frac{\mu}{\epsilon_c}} \approx (1 + j) \frac{\alpha}{\sigma} \quad (7 - 22)$$

7.4.6.2 RF Depth of Penetration Inside the Medium

Electromagnetic waves encountering biological tissues experience reflection, refraction and penetration at the interface between air and the tissues. The dielectric properties of the biological tissues influence the extent of these phenomena. As the wave penetrates, it diminishes in strength over distance.

The depth of penetration into the medium is inversely related to frequency; higher frequencies result in shallower penetration depths, while lower frequencies allow for greater depths, as shown in Figure 7-27 [242]. Using Equation 7-22, the cumulative wave travel depth is determined as illustrated in Tables 7-13 and 7-14. Consequently, the simultaneous electromagnetic wave excitation from the port that propagates through the skin medium experiences gradual and proportional attenuation as frequency rises. Columns in Tables 7-9 and 7-10 indicate that the depth of penetration diminishes with an increase in frequency, as per Equation (7-23).

$$\delta = \frac{1}{\alpha} = \frac{2}{\sigma} \sqrt{\frac{\epsilon_0 \epsilon_r}{\mu_0 \mu_r}} \quad (7 - 23)$$

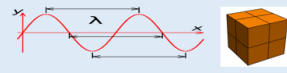
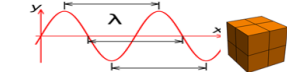
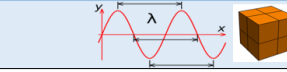
Frequency	Human-Tissue thickness variation	1 wavelength Penetration
2.4 GHz, $\lambda = 124.914\text{mm}$	Skin, 0.05 to 1mm, Muscle and fat, 3mm to 20mm. Total Maximum Thickness = 24mm	
2.45 GHz $\lambda = 122.36\text{mm}$	Skin, 0.05 to 1mm, Muscle and fat, 3mm to 20mm. Total Maximum Thickness = 24mm	
2.5 GHz $\lambda = 119.917\text{mm}$	Skin, 0.05 to 1mm, Muscle and fat, 3mm to 20mm. Total Maximum Thickness = 24mm	

Figure 7-27. Depth of penetration of human tissue (indoor operating frequencies)

Table 7-9. Combined simultaneous simulation propagation, conductivity, magnitude attenuation and skin penetration depth

Simulating frequency (GHz)	Conductivity (s/m)	Skin thickness (mm)	RF-EMF attenuation (Np/mm)	Skin penetration depth (mm)
2.4	4.71	0.075	0.1434	6.96
2.45	4.81	0.075	0.147	6.82
2.5	4.91	0.075	0.150	6.68

Table 7-10. Combined simultaneous simulation propagation, conductivity, magnitude attenuation and medium penetration depth

Simulating frequency (GHz)	Conductivity (S/m)	Muscle fat thickness (mm)	RF-EMF attenuation (Np/mm)	Penetration depth (mm)
2.4	0.113	15	0.0093	108
2.45	0.115	15	0.0094	106
2.5	0.118	15	0.0097	103

7.4.7 Effect of Propagation of Polarised Wave, Molecular Displacement and E-Field on Polar and Non-Polar Molecules

Polarisation of the E-field occurs when the plane of the progressive wave tip of the instantaneous field vector traces out the time at a fixed observation point. According to the Eigenstates of material [243], there are two polarisation directions for any direction of wave propagation, in which the displacement vector component is parallel to the E-

field [244]. Polar molecules possess a positive charge centre that does not align with the negative charge centre. In the absence of an external electric field (E-field), these dipolar molecules orient randomly and can form closed chains, resulting in a net dipole moment of zero. When an external E-field is introduced, these closed chains disintegrate, causing the polar dipole molecules to align parallel to the direction of the applied E-field. However, this alignment is often incomplete because of thermal motion and molecular agitation. Achieving complete alignment is possible if the strength of the E-field increases and the thermal temperature decreases.

Non-polar molecules behave differently under an external E-field. The centres of positive and negative charges within them experience a displacement, resulting in an induced temporary polarity and the creation of a dipole moment. Once the external E-field is removed, this induced dipole moment dissipates, and the molecule reverts to its original state. The alignment of this induced dipole moment enhances the effectiveness of the applied E-field.

7.4.8 Designing and Modelling an Indoor Electromagnetic Radiation Monitoring Meter Circuit

Smart buildings are integrated with contemporary technologies to facilitate rapid responses from IoT devices and support higher data transfer rates or bandwidth communication within control systems. As a result, there is a significant reliance on wireless communication and control sensors to minimise costs. However, excessive dependence on wireless technology can lead to increased electromagnetic radiation. This escalation contributes to a greater presence of simultaneous electric fields, resulting in elevated IPD.

Electromagnetic wave energy, categorised as a non-ionising type, can cause thermal effects when prolonged exposure occurs in uncontrolled spaces, raising concerns among occupants. To address these apprehensions, this study introduces an indoor IPD monitoring device designed for wall mounting within any building. This unique meter is capable of simultaneously monitoring combined radiation levels and estimating the direction of arrival with higher power density. Through case studies, indoor areas were explored to investigate the density of electromagnetic radiation travelling wave quantities.

Data were collected using measurements of open areas and indoor enclosed environments using a spectrum analyser (SPECTRAN HF-60105) and an E-field, 3-axis RF field strength meter (TM-196). The measured data quantities contribute as input for designing a power density monitoring meter. The design draws on the reality of indoor RF devices operating a system, where the transmitting and receiving data are drawn from demand and dynamic probabilities.

The chances of simultaneous and continuous transmission can differ according to Chapter 6.3 and Equation 6-13. For this study, a 6 m × 5.5 m × 2.75 m room, representing a smart building, was used for a practical simulation exercise.

In a real smart building, there will be an ‘N’ number of wireless transceivers, with different bands installed and set to transmit and receive data, as shown in Figure 7-28. However, owing to capacity limitations, sixteen 2.4 GHz, one 900 MHz and three 433 MHz devices were installed in this experimental room. These 20 devices are arranged sequentially to represent four devices of the same band in a quadrilateral rectangle to receive signals from each side for practical measurement of direction of arrival estimation, as shown in Figure 7-29, where the signals are taken before being summed to evaluate the combined power density result.

Furthermore, these signals are amplified and converted to digital processing as shown in Figure 7-30, before being fed to the programmable interface control (PIC).

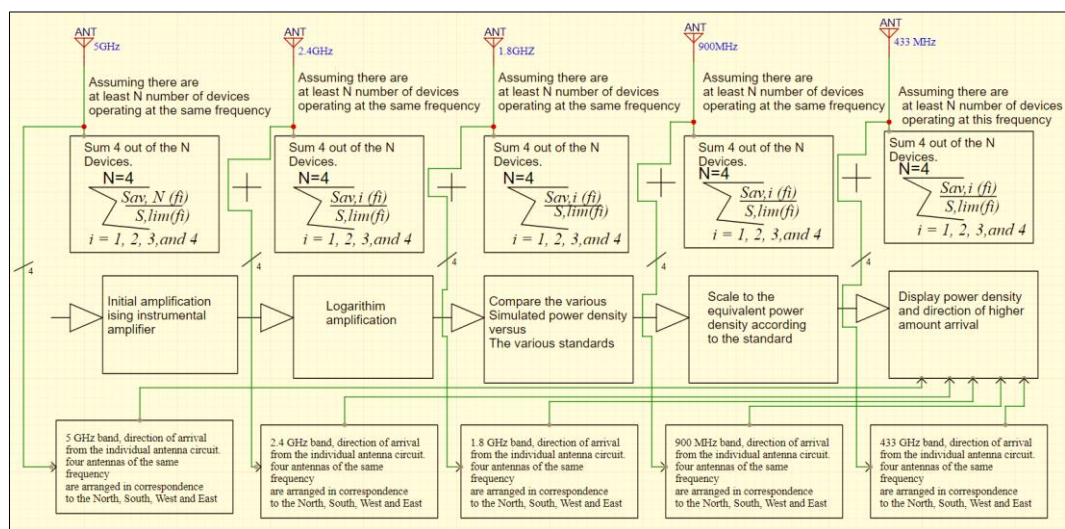


Figure 7-28. Indoor wireless power density summing and direction of arrival estimating method

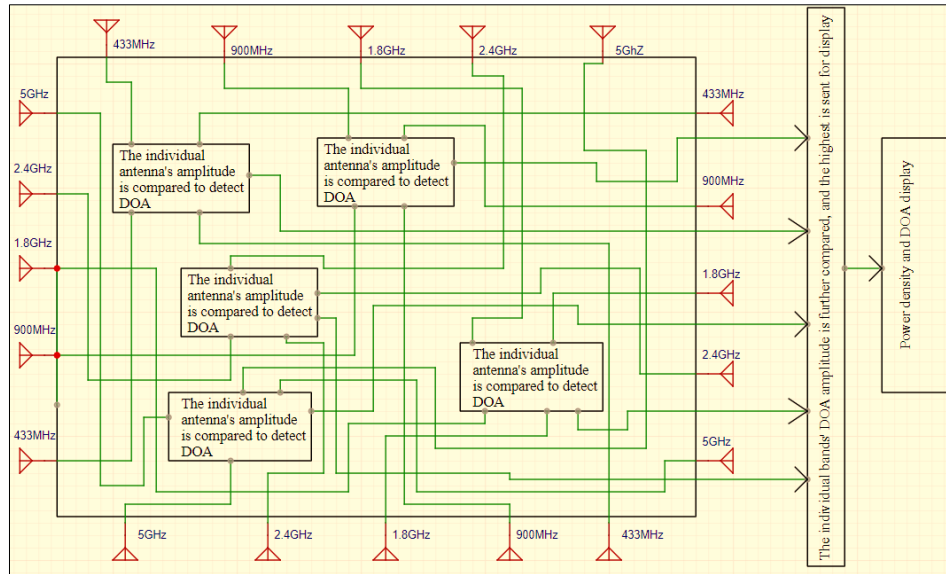


Figure 7-29. Indoor wireless propagating wave directions of arrival estimating method

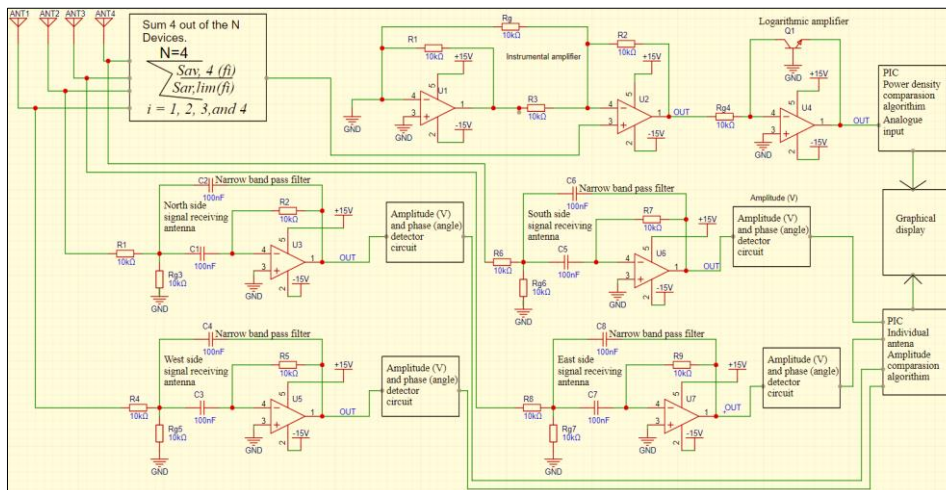


Figure 7-30. An example of a method of amplifying 2.4 GHz indoor wireless propagating signals

7.4.9 Implementation of an Indoor RF Power Density Meter Algorithm

The code for the power density algorithm is developed using the C programming language. C is recognised for its straightforwardness and effectiveness, particularly in facilitating remote communication, monitoring and configuration of parameters with PIC devices.

The travelling power density summed from the individual bands is a vector quantity that has a magnitude and direction. Applying the Poynting vector theorem, the power density (P_d) travelling in the X-axis is expressed as:

$$P_d(x) = E_y(x)H_z(x) \quad (7 - 24)$$

Further, the Poynting vector at the far-field region is expressed as space and time in the form of polarised plane waves. The electric field and magnetic wave travelling in the Z-axis direction in the space domain is E-field:

$$E_y(z) = E_A e^{-jkz} \quad (7 - 25)$$

The corresponding magnetic field is:

$$H_x = H_A e^{-jkz} \quad (7 - 26)$$

The minus sign indicates that waves propagate in the positive or negative direction along the Z-axis. On the other hand, in the time domain, the wave equation is expressed as:

$$E_y(z) = E_A e^{-jkt} \quad (7 - 27)$$

$$H_x = H_A e^{-jkt} \quad (7 - 28)$$

Combining both space and time equations yields:

$$E_y(z, t) = E_A e^{-jkz} e^{j\omega t} \quad (7 - 29)$$

$$H_x = H_A e^{-jkt} e^{j\omega t} \quad (7 - 30)$$

However, for power density evaluation, the magnitude of the modulus of the $|E \times H|$ velocity vector quantities, that

$$|E \times H| = \frac{1}{c} E^2 = CH^2 \quad (7 - 31)$$

Where:

C is the speed of light.

Then at any given point, the travelling wave energy is:

$$P_d = \frac{1}{2} \epsilon_0 E^2 + \frac{1}{2\mu_0} H^2 \quad (7 - 32)$$

Where:

ϵ_0 is the electric permittivity.

μ_0 is magnetic permeability of free space.

The rate of total energy deposited by the propagating wave on the surface of an object in a given time (dt) is:

$$\frac{dP_d}{Adt} = \frac{1}{2} \epsilon_0 E^2 + \frac{1}{2\mu_0} H^2 \quad (7 - 33)$$

Where:

A is the surface area of the object.

Hence, the following parameters are initially recorded as standard default settings values:

1. *IEC/IEEE standard (Ice1g =)*←
2. *ICE/IEEE standard (Ice10g =)*←
3. *ICNP and Australian standard (Ica1g =)*←
4. *ICNP and Australian standard (Icnpa10g =)*←
5. *FCC standard (Fcc1g =)*←
6. *Monitored power density (P_m)*←
7. *P_m = Calculated power density (P_A)*
8. *FCC standard (Fcc1g =)*←
9. *DOA 2.4 GHz North amplitude (Dna2.4 =)*←
10. *DOA 2.4 GHz South amplitude (Dsa2.4 =)*←
11. *DOA 2.4 GHz West amplitude (Dwa2.4 =)*←
12. *DOA 2.4 GHz East amplitude (Dea2.4 =)*←

The actual monitored $P_m = \begin{cases} P_A \geq Ice1g, \text{the indoor power density is exceeding} \\ P_A \geq Ica1g, \text{the indoor power density is exceeding} \\ P_A \geq Fcc1g, \text{the indoor power density is exceeding} \end{cases}$

The actual monitored $P_m = \begin{cases} P_A \geq Ice10g, \text{the indoor power density is exceeding} \\ P_A \geq Ica10g, \text{the indoor power density is exceeding} \\ P_A \geq Fcc10g, \text{the indoor power density is exceeding} \end{cases}$

If $P_m \geq Ice1g$ or $Ica1g$ or $Fcc1g$ or $Ice10g$ or $Ica10g$ or $Fcc10g$ then estimate the DOA;

Then, north, south, west and east amplitude $A_{pnw} = \begin{cases} Dna2.4 > Dsa2.4 = North \\ Dwa2.4 > Dea2.4 = West \end{cases}$

Then, north and west amplitude $A_{pn} = Dna2.4 > Dwa2.4 = North$

Then, west and north amplitude $A_{pw} = Dwa2.4 > Dna2.4 = West$

Then, north, south, west and east amplitude $A_{pse} = \begin{cases} Dsa2.4 > Dna2.4 = South \\ Dea2.4 > Dwa2.4 = East \end{cases}$

Then, south and east amplitude $A_{ps} = Dsa2.4 > Dea2.4 = South$

Then, east and south amplitude $A_{pe} = Dna2.4 > Dwa2.4 = East$

7.4.10 Features of Monitoring System and Display Configuration

The meter is equipped with a parameter setting that allows users to choose between displaying either power density or electric field strength. Initially, it was set up with reference values in accordance with the guidelines established by four primary standards: FCC, INCRP, IEC/IEEE, and Australian standards. The display is customisable, enabling users to use preference guides for monitoring and visualisation on the screen.

Two principal types of detectors are used:

1. Logarithmic detector converts RF power to a DC voltage proportional to the logarithm of the measured value.
2. Root mean square (RMS) detector generates a DC output proportional to the RMS value of the signal.

The meter is designed to be monitored either in person or remotely via applications. Building occupants can select which standard they wish to use for monitoring.

7.5 Conclusion

This chapter has outlined two approaches to address indoor environmental pollution through simulations. It has examined the effects of IAQ and the debated effects of indoor non-ionising RF-EMF radiation. In the first scenario, a simulation focused on IAQ mitigation was performed to reduce carbon deposits and VOCs, which are harmful substances found in various materials and released by products. The simulation indicated

that continuous monitoring and sufficient air ventilation are essential after removing the accumulated particles.

In the scenario, the study used RF-EMF simulation to evaluate the power density and E-field quantities of indoor wireless signals transmitted from multiple sources at any arbitrary location inside the smart building. The study also included outdoor areas that are open to the general public in order to accurately estimate quantities of power densities from those areas.

Further, the study attempted two simulation methods: sequential and simultaneous simulations. Their results were analysed and compared. It was found that the E-field and H-field values obtained using sequential simulation were higher than those obtained in simultaneous simulation. In sequential simulation, increasing the simulation frequency decreased the E-field and increased the H-field results, whereas in simultaneous simulation, increasing the simulation frequency increased both the E-field and H-field results.

The results of both simulations were compared with various E-field and power density established standards, namely those from Australia, the FCC, the IEC/IEEE and ICNIRP. The sequential local spatial SAR results were significantly below the various standard guidelines, while the simultaneous simulation spatial local SAR results increased when a fourth cellular antenna was added close to the human ear. Hence, according to the simulation results, both indoor and outdoor public areas are safe as long as adequate distance from radiating sources is maintained.

In addition to alleviating the potential concerns of occupants of smart buildings, a RF-EMF monitoring meter circuit was developed. The meter was designed specifically to display the indoor wireless combined radiating power density.

Chapter 8

Conclusions and Recommendations for Further Research

8.1 Introduction

This chapter presents the key conclusions related to the research topic. It provides a succinct overview of the development of smart buildings. It outlines the primary elements of this thesis, including the methodologies employed, the process of simulating solar irradiation for buildings and the integration of renewable energy sources, along with strategies for optimising their efficiency and performance. The initial sections examine conventional buildings, offering a brief history that connects traditional structures with smart buildings and highlights that the heritage of smart buildings lying in traditional buildings is disadvantageous to smart buildings.

In addition, it emphasises the interoperability of BIM capability in modern building design and addresses simulations concerning building stability and indoor occupant comfort. The initial phase of this study involved reviewing existing literature review on smart buildings while identifying gaps within this field. Furthermore, a mitigation solution to specific drawbacks of smart buildings was approached. Two distinct software programs designed for simulating solar radiation were assessed to identify effective strategies for reducing energy consumption; their results were thoroughly examined. The discussion of this chapter also covers topics like building orientation, water efficiency initiatives, structural flaws and intelligent management approaches.

8.2 Objectives and Goals of Smart Buildings

The primary objective of sustainable building design that incorporates renewable energy is to conserve natural resources by identifying environmentally friendly alternatives to traditional energy sources, thereby reducing pollution levels. Sustainable building design entails developing land and approaching construction in such a way as to minimise environmental impact by promoting energy efficiency through the use of self-sustaining

structures. Accordingly, projects aimed at environmental sustainability should encompass initiatives like reforestation, wetland conservation and protection of natural habitats from resource exploitation.

In this thesis, considerable efforts were made to achieve the principles of sustainable building design through the use of renewable energy sources and the development of methods for mitigating against drawbacks and enabling emerging technologies. The optimisation of renewable energies was modelled alongside simulations for solar irradiation within these structures. Results of initial simulations were collected and analysed prior to a deeper investigation into alternative solar irradiation energy modelling using automatically selected packages of energy-efficient materials and components. Additional analysis was conducted on another design approach that employed manually selected energy-efficient material packages for evaluating solar irradiances. Efforts focused on maximising the efficiency of solar panels cells and wind turbines through mathematical equations combined with conceptual simulations. For optimising potential energy from wind turbines, three established methods—coefficient of performance (C_p), tip speed ratio (TSR) and Optimum Turbine Coefficient (OTC)—were evaluated. Simultaneously, a conceptual methodology for tracking sunlight intensity enhanced the efficiency of solar panel cells. Additional considerations included the integration of the IoT, applications of smart grid technology and objectives aimed at reducing energy consumption in buildings for eco-friendly certification systems.

Attaining comprehensive energy efficiency in commercial smart buildings presents several ongoing challenges, even though recent research efforts have intensified focus on addressing these issues by developing innovative strategies. This research project has showcased several methods specifically geared towards optimising energy reduction and occupant comfort. It designed and modelled an innovative building that is optimised for energy efficiency and resilience.

8.3 Mitigation of Smart Buildings' Drawbacks

Achieving comprehensive energy efficiency in commercial smart buildings remains a complex task, with numerous unresolved challenges. Nonetheless, there has been a recent uptick in research aimed at addressing these challenges. This study focuses on overcoming several fundamental limitations associated with smart buildings as follows:

1. Exploring optimal strategies for reducing energy consumption. In response, two distinct solar radiation simulation software tools were used, and their outcomes analysed.
2. Exploring the issues for energy efficiency in commercial smart buildings using methodologies used in previous studies that address the crux of the challenging problems. This included a conceptual energy simulation for maximum optimisation of annual energy consumption, which analysed two different solar radiation simulation software programs and their results to identify effective strategies for building an energy-efficient model.
3. Smart buildings reduce the need for occupant involvement through a computerised automation system that facilitates dynamic and interoperable responses, requiring minimal physical interaction from users. These smart commercial structures enhance convenience, productivity, security and comfort within business environments. However, they also face several challenges that necessitate resolution. A notable issue related to electrical systems is the nuisance tripping of RCDs.
4. The objectives of smart buildings focus on minimising resource use while maximising energy savings. The study detailed modifications made to the conventional bulk wiring approach to meet these goals. Such alterations represent one of the limited methods available for enhancing building efficiency through innovation or construction practices. Beyond current economic and energy benefits, this method also contributes towards preserving construction materials for future generations.
5. The imported conceptual mass building group was modelled with the aim of optimising energy-efficient buildings through two case studies. The first case study incorporated a ‘built environment conceptual building’ into the simulation software. The contexts for multiple conceptual mass buildings were simulated concurrently to accurately reflect actual environmental weather conditions; however, only one mass building was subjected to simulation at a time. This approach ensured that surrounding structures and environmental conditions effectively influenced solar irradiation within the simulated building. As a result, an annual energy intensity reduction (kWh/m^2) was achieved. The second case study investigated the concept of decarbonisation by modelling buildings designed for maximum energy reduction using efficient materials conceptually

simulated within two phases: a ‘base run’ followed by an ‘alternative design run’. A comparison between both stages revealed that alternative design results indicated a notable decrease in fuel consumption alongside a slight increase in electric energy use—a trend suggesting a transition towards greater reliance on electric power.

8.4 Building Solar Irradiation Building Energy Simulation

Optimising conceptual mass simulations for solar radiation in the design of energy-efficient buildings: Insights from three case studies are:

A first case study examined the integration of ‘conceptual building mass within a built environment’ in simulation software. This process simultaneously simulated various conceptual mass building contexts to replicate actual scenarios. This methodology enabled the simulation to correspond effectively with neighbouring structures and the natural surroundings, thereby affecting the influence of solar irradiation on the modelled building. Consequently, the results obtained from the simulation were significantly well estimated in terms of annual energy intensity.

The simulation of a building’s solar intensity absorption within a built-in environment, the influence of surrounding structures and ambient natural conditions account for satisfactory estimation outcome results. Hence, the total annual intensity absorbed by a randomly constructed building was 6,212.54 kWh/m²; however, when orientation was taken into account, this figure increased to 8,687.2 kWh/m². This represented a 39.84% increase in energy absorption, which is particularly advantageous in cold climates where it helps lower heating consumption, making it more suitable for regions in the northern hemisphere. However, the building could be oriented in the opposite direction.

A second case study examined a simulation of solar irradiation on a newly developed conceptual mass, excluding the influence of the surrounding building context and natural ambient conditions from the adjusted building circumstances. This approach yielded an estimated absorption rate of 85.6%. Hence, findings from both software tools revealed a notable decrease in energy consumption, resulting in a reduction in overall annual energy use.

In the third case study, attention was directed towards the concept of decarbonisation, focusing on modelling structures intended for optimal energy reduction. This phase also included simulations of conceptual materials that enhance energy efficiency. The simulation process was conducted into two stages: a ‘base run’ and an ‘alternative design run’. The findings from these stages were compared to determine which scenario achieved the most substantial decrease in annual energy consumption. Results from the alternative design phase revealed a marked reduction in fuel use, accompanied by a slight increase in electrical energy consumption, indicating a shift towards electrical energy and increasing dependence on electric power. An overall 69.78% annual energy consumption reduction was estimated, referring to the base run results.

This study concentrated on examining three key limitations related to smart buildings: Two separate solar radiation simulation software tools were employed to investigate optimal methods for minimising energy use, and the results were thoroughly analysed. Additionally, the research provided a detailed analysis of key elements including building orientation, water efficiency, structural deficiencies and advanced management strategies.

8.5 Sustainable Smart Building Design With Renewables

Designing and modelling a smart building incorporating renewable energy sources is an advanced and intricate task. This process necessitates the collaboration of various engineering specialists. However, this study focused on intelligent energy solutions and contributions with reference to the building’s size, available resources and orientation. It is crucial to select suitable modern technologies during the design and modelling phases to meet the objectives of a smart building while avoiding additional construction expenses. This research examined seven renewable software applications using five distinct case study methodologies. The outcomes of each software simulation were analysed according to their specific applications and intended goals. For example, Autodesk Revit enhances rooftop PV cell generation. SCAPS1D simulates the thickness of PV cell layers and their material energy bandgap. DesignBuilder assessed the PV cells’ annual energy consumption for a newly constructed building, examining the rooftop space available for optimum contribution. Hence, the study demonstrated that up to 85.6% of annual energy consumption can be covered by utilising rooftop space in a maximised manner. Rhino, Grasshopper and Ladybug were used for detailed simulations

of PV cells' hourly energy production throughout the year within a built environment. PVsys7 evaluated the shading effects on PV cells. Setfos analysed layer absorptance, transmittance and reflectance properties of PV cell panels. Ashes focused on optimising power generation from wind turbines while tracking their output performance. Additionally, a mathematical model was developed to accurately estimate the amount of renewable energy needed for installation, thereby minimising estimation errors. The results derived from these software simulations indicate an alternative optimised capacity for renewable energy in commercial building consumption.

8.6 Implementation of Emerging Technology in Smart Buildings

This thesis has discussed both existing and emerging technological devices that are being or will be incorporated into sustainable smart buildings over the coming decades. The research has examined the technologies currently accessible for indoor environments, highlighting advancements such as wireless devices up to 6G, BIoT, digital twin technology and artificial intelligence. The study has extensively addressed the applications enabled by these devices. Furthermore, the primary objective of smart buildings is to reduce resource consumption and enhance energy efficiency in targeted scenarios, thereby contributing to the reduction of CO₂ emissions. As a result, smart buildings depart from traditional construction methods. The study has compared traditional building practices with smart buildings' technologically advanced design practices. The comparison has focused on their shared goal of reducing resource use, particularly with regard to electrical devices. It has been noted that there are no considerable differences in wiring techniques for these electrical systems, except for the BACS, which streamlines control wiring.

A revised approach to traditional wiring methods is employed to achieve one of the key objectives of smart buildings. This new method enhances the cost-effectiveness of electrical systems, as exemplified by Variable Frequency Drives (VFDs), electrical circuit design and LED drivers, which are discussed in this study. Implementing this system yields initial and ongoing economic savings and energy efficiencies but also represents a sustainable strategy for conserving construction materials for future use, eliminates urgent fault device replacement, saves time and increases productivity.

8.7 Harvesting Energy from Indoor Wireless Propagating Waves

Smart buildings' indoor wireless technologies rank among the most rapidly advancing technologies in today's buildings. These buildings are outfitted with sensor networks, including BIoT and wireless control and communication systems. Furthermore, cutting-edge technologies are being actively integrated into smart buildings and innovative structures within the built environment. For instance, 6G is beginning to take the place of 5G; both of these technologies offer greater energy capabilities than 4G and its predecessors. The enhanced energy capacity facilitates quicker communication, especially with the building's AI and healthcare facilities, and during emergencies.

Because of their higher energy frequencies, 5G and 6G exhibit shorter wavelengths that require less distance for transmission than lower-frequency signals. Consequently, a greater number of devices is necessary to adequately cover areas previously serviced by 4G or lower frequencies. Increased energy translates to higher power density levels. This study aimed to assess the indoor power density generated by various wireless devices. To achieve accurate estimations, power density regulations from multiple standards were considered. Wireless energy levels in public open areas were measured across six locations at Victoria University. Concurrently, several indoor antennas were conceptually designed and modelled. The propagation of multiple indoor wave energies was simulated. The resulting power density was transformed into actionable outcomes known as 'energy harvesting'. Consequently, a passive charging circuit was developed for use as an emergency charger in environments with a high density of RF devices.

8.8 Modelling a Less Polluted Environment and Comfortable Living

This thesis has aimed to develop conceptual measurement methods for evaluating a building's adequate and optimised outdoor ventilation and concentrations of indoor pollutants. The techniques ranged from sophisticated tracer gas approaches, mainly employed in building studies, to more straightforward methods designed for building operators. The study focused on creating and testing new assessment protocols in real-world settings to evaluate their effectiveness and reliability in measuring CO₂ levels at equilibrium during various phases of airborne concentration, exposure and surface loading on construction materials. This involves separating airborne particles produced during construction from permanently installed HVAC systems, ensuring the removal of

toxins before occupancy, preserving dry absorbent materials and selecting construction materials with minimal harmful VOCs to prevent mould growth. It is essential to ensure adequate ventilation in occupied spaces while being cautious about energy loss caused by over-ventilation. The installation of monitoring systems can assist in identifying high CO₂ concentrations, signalling the necessity for additional fresh outdoor air to sustain healthy IAQ.

The thesis also assessed the power density levels of indoor wireless signals emitted from multiple sources within any designated area of the smart building. The study employed the CST Studio Suite software to simulate multiple-radiated RF signals in the indoor environment. As a result, both sequential and simultaneous simulation outputs were evaluated. A comparison between these two approaches revealed that the sequential simulations yielded higher E-field values than those obtained through simultaneous simulations. In the case of sequential simulations, an increase in frequency led to a decrease in both E-field results; conversely, for simultaneous simulations, an increase in frequency resulted in higher E-field values. Apart from E-field results, other metrics from simultaneous simulations significantly exceeded those from sequential ones. Furthermore, comparisons were made between the outcomes of both simulations and various exposure guidelines, including Australian standards, FCC regulations, IEC/IEEE criteria and ICNIRP recommendations. The local spatial SAR results from sequential simulations remained well below established standard guide limits. In contrast, those derived from simultaneous simulations—obtained by adding additional cellular devices close to the human ear, adjusting distance and phase shifts—exceeded these standards when a fourth cellular antenna close to the human ear was added. Judging from the simulation results, indoor and outdoor public areas are safe as long as adequate distances from radiating sources are provided. To further allay the concerns of smart building occupants, an RF-EMF monitoring meter circuit was developed. The meter was explicitly designed to display the indoor wireless combined radiating power density.

8.9 The Unique Contributions of this Thesis

The primary objective of designing smart buildings revolves around energy efficiency and the reduction of CO₂ emissions. While the concept itself is not entirely new, having existed for quite some time, its practical implementation has only recently gained traction. The traction was driven by environmental conditions and rising fuel oil prices, which

helped to shift the interest in smart building design. As a consequence, there has been a marked increase in demand for these structures, representing a notable progression for both smart buildings and urban environments. Current state-of-the-art research characterises a smart building as any facility that employs automated systems to manage its operations, such as heating, ventilation, air conditioning, lighting and security. Smart buildings require minimal manual intervention and are driven by advancements in digital technology and intelligent systems.

A second objective in designing smart buildings is to leverage simulation techniques to optimise the construction process through BIM, which is receiving heightened attention from professionals in architecture and engineering, as well as from building owners and operators. In this context, ‘building’ pertains to both the data associated with a structure and the processes involved; BIM serves as a digital representation that encapsulates the physical, technical and functional attributes of that building. BIM facilitates data sharing and knowledge exchange among all stakeholders involved, including those responsible for smart maintenance and operations of the facility.

These objectives primarily advocate for energy efficiency and information exchange to achieve sustainability. However, several issues remain unaddressed or persist as substantial gaps within the literature on sustainable smart building design practices. To attain comprehensive environmental sustainability, an extensive investigation was required that considered the most crucial factors contributing to the smart building’s sustainable development. This thesis has addressed these gaps and conducted a comprehensive study that meets the present needs and proposes solutions for future generations. Therein lies its unique contribution.

8.10 Challenges and Limitations of this Thesis

Smart buildings produce and process extensive data generated by the numerous IoT sensors and AI systems integrated within them. The primary challenge is to securely and efficiently collect data while interpreting it accurately. A robust data management platform is essential for the real-time processing and analysis of sensor data, providing valuable insights that support informed decision-making. The installation of sensors typically necessitates significant wiring and power infrastructure, which can elevate initial expenses for new constructions and add financial burdens to modernising existing

structures. This situation may also result in disruptions and discomfort for occupants or owners. Adopting wireless sensors, along with battery-operated alternatives, can minimise the need for extensive wiring, thereby simplifying installation processes and enhancing scalability. However, an overabundance of wireless devices could lead to increased radiation levels, sparking concerns among occupants about potential health implications. The challenge remains to design and manage a smart building that incorporates such devices without causing significant issues.

There are inherent limitations in smart building design practices. These limitations often stem from a lack of emphasis on human interests. Smart buildings should be designed with the comfort, productivity and wellbeing of their occupants as priorities. Unfortunately, numerous smart building designs focus heavily on automation and data-driven strategies aimed at minimising energy use, often neglecting the needs and interests of the occupants. This lack of consideration can lead to suboptimal living conditions, creating a disconnect between the building and its occupants.

8.11 Recommendations for Further Research

This research project aimed to conduct a comprehensive energy simulation using computer simulation software applications, resulting in a significant reduction in annual energy consumption. The result indicates that the commercial building heading to be self-sufficient. This will be true if more research is conducted globally on the cost-effective, resource-minimising and occupant-centring features of the smart building revolution. Further, the smart building revolution should emphasise concepts such as intelligent energy, circular economy and perception to make buildings smarter.

This study has contributed to the literature on sustainable smart buildings. It has:

1. Designed and modelled a conceptual smart building that satisfied energy efficiency and resource minimising objectives by simulating a passive energy using solar maximum absorption, implemented with proportional renewable energy. This was preceded by mathematical equations used to avoid guess estimation when calculating the adequate number of renewable devices required for a particular building.

2. Developed and modelled circuits followed by mathematical equations of a feasibility study for an interconnected electrical wiring method that uses fewer electrical devices.
3. Designed a circuit to mitigate nuisance failures. This system allows the smart building to preserve its intelligent functionality and enables remote fault diagnostic processes in the event of electrical supply issues or internal partial failures.
4. Created a circuit for WET harvesting utilising the benefits of the current high-density wireless RF and increased energy levels. This circuit is capable of powering IoT devices with low energy consumption.
5. Using virtual simulations, designed a smart building to continuously protect against environmental pollution, improving methods for safeguarding IAQ and Outdoor Air Quality (OAQ).
6. Designed a smart building that assesses RF-EMF radiation power density and implements ongoing mitigation strategies to eliminate excessive radiation exposure, addressing the needs of its occupants effectively.

Because this study focused on simulation analysis, it is recommended that further practical research be conducted to verify the significant results obtained using computer-aided simulation software applications. In particular, the following topics require further investigation:

(A) RF-DC WET harvesting: The communication and automation sectors are progressively adopting and advancing towards the use of much higher energy frequencies. It is crucial to assess the potential for harvesting WET to measure the radiated energy emitted into space by multiple devices through the aggregation of their outputs. To effectively gather and integrate all indoor wireless radiation, both simulation and practical approaches are essential.

(B) RF-EMF power density and simultaneous combined effects: In the initial stages of wireless cellular device development, the quantity of cellular devices found in commercial buildings were limited, and the devices were operated on lower energy bands than in present times. The simulation of RF-EMF power density was effectively conducted using single or sequential simulations. However, as the technologies has developed, both the variety of frequency bands and the number

of devices operating on the same frequency have significantly increased, leading to a greater likelihood of simultaneous radiation.

(C) The interconnect wiring system theory: This study demonstrated the theory in practice using just two LED drivers to power five LED lights. It is noted that sophisticated buildings and industrial buildings may not use all their equipment simultaneously. To confirm these results in a complex building, further practical investigations are recommended.

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