Enhancing Building Performance and Automation Deployment in Oman

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DEDICATION

All praise is for Allah—Lord of all worlds

To my mother's and father's spirit, may Allah my Lord grant them the Paradise

To my beloved wife Raiya for her endless support

To my children and my family for their encouragement

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Abstract

Oman buildings encounter many challenges that cause increased energy consumption. To evidence this, occupants in Oman have identified concerns about soaring increase of electricity cost. They also indicated a high willingness to invest in enhancing their dwelling to save electricity use. In Oman, high building energy usage is caused by many reasons; some of them related to the types of building materials used, and others related to building practices that impact indoor environmental quality. For instance, using concrete blocks instead of Lightweight Expanded Clay Aggregate (LECA) blocks for walls impacts indoor environmental quality and causes low building energy performance and consequently occupants' dissatisfaction. Concrete is known for its high thermal conductivity (1700-2500mW/mK) which allows high thermal transmission to building indoor that requires heavy use of Air Conditioning (AC) to maintain comfortable indoor environment. Oman buildings encounter many challenges that influence their energy performance. An example of these challenges is the lack of insulation in the walls and roof which cause thermal mass transmission to the building and increase the electricity consumption. Another challenge in Oman building is the use of aluminum single-glazed windows instead of double or triple-glazed Unplasticized Polyvinyl Chloride (UPVC) windows, aluminum is known for its high thermal conductivity which allows heat exchange between outdoor and indoor environment. Furthermore, windows and doors lack sealants and therefore they don't prevent heat exchange. Additionally, excessive use of reinforcement steel contributes to building heating through heat flush from walls and roof. In Oman and adjacent hot countries, the practice is to use AC heavily during summer to reach a comfortable indoor environment because buildings lack insulations. AC ducts are commonly not insulated and in some cases the ducts are installed in the external walls facing direct sunlight.

The challenges of building performance in Oman encompass issues that should be addressed in a holistic approach in each phase of the building cycle. For example, in design phase, building orientation should be considered so that rooms with more occupancy should be built in the opposite direction of the direct sunlight to reduce walls thermal mass. Furthermore, sustainable building materials, sustainable building method

should be embedded in the design phase. In Construction phase, the sustainable design should be implemented, and sustainable building materials should be utilized. For example, professional insulation could save up to 65% of the energy used for cooling.

Building performance could be tackled in the post-occupancy phase without major impact in the building by utilizing building automation systems (BAS) which can be installed in existing buildings to control and optimize energy use post-occupancy. Towards this a literature review to identify building energy performance challenges was conducted. This was a literature review into holistic building performance across all building stages from design phase to a post-occupancy. It identified the key factors that influence building performance. Solutions for the identified challenges in each phase were suggested.

Next, occupants' feedback was collected to identify building performance gaps and concerns. This was achieved by a post-occupancy evaluation (POE) survey that was distributed to 105 occupants in Oman. The results of this POE helped to identify building energy performance challenges, understand occupants concerns and to find solutions to enhance building energy performance and attain occupant's satisfaction.

Finally, a case study has been conducted to measure the impact of BAS on energy use. The case study was a residential dwelling that has extensive documented energy use history prior to BAS deployment. The dwelling performance was upgraded in two ways; retrofit of building systems and deployment of home automation to control energy. The results of this case study have evidenced that, even though the retrofit increased the floor area by 114% along with a necessary increase in HVAC and lighting, the BAS provided energy savings, showing the potential of BAS to control and reduce energy use.

The deployed BAS realised 12.6% of energy saving in residential building case study in Oman and has promising energy saving in many case studies as documented in this thesis. BAS has many applications where it can be deployed in residential buildings, commercial offices, and industrial use.

To achieve this target, Oman building code needs to be improved to consider the use of sustainable materials in all building phases, consider sustainable building methods and measures and exploit BAS to enhance building energy performance, attain comfortable indoor environment and achieve occupants' satisfaction. This will allay occupants concerns in Oman about the energy costs, promote the use of BAS and, most importantly, it will save energy and mitigate carbon footprint of domestic building stock in Oman.

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List of abbreviations

Building automation systems (BAS)

Building automation and control system (BACS)

Gulf Cooperation Council (GCC)

life cycle assessment (LCA)

Green buildings (GB)

Greenhouse gas (GHG)

Passive infrared (PIR)

Photovoltaic (PV)

Internet of things (IoT)

Post-occupancy evaluation (POE)

Indoor Environment Quality (IEQ)

Artificial intelligence (AI)

Building Management Systems (BMS)

Machine learning (ML)

Intelligent Building (IB)

Smart Building (SB)

Nearly Zero Energy Building (nZEB)

Unplasticized Polyvinyl Chloride (UPVC)

Vacuum insulation materials (VIM)

Gas insulation material (GIM)

Argon (Ar)

Krypton (Kr)

Xenon (Xe)

Nano insulation materials (NIM)

Dynamic insulation materials (DIM)

European Union (EU)

lifestyle consumer (LC)

Post-occupancy Review of Building Engineering (PROBE)

Center for Built Environment (CBE)

Building Performance Evaluation (BPE)
underflow air distribution (UFAD)
displacement ventilation (DV)
National Environmental Assessment Toolkit (NEAT)
Center for Building Performance and Diagnostics (CBPD)
Protocol for Commercial Building (PMP)
Centre for the Built Environment (CBE)
National Australian Built Environment Rating System (NABERS)
Energy Use Intensity (EUI)
Emission Intensity (EMI)
Water Consumption Intensity (WCI)
IEQ Score (IEQS)
New Building Institute (NBI)
Energy Use Intensity (EUI)
Device-Free Localisation and Activity Recognition (DFLAR)
return on investment (ROI)
School Research Ethics Committee (SREC)
United Arab Emirates (UAE)
Wood-plastic composite (WPC)
Energy performance gap (EPG)
Distribution board (DB)
Lightweight Expanded Clay Aggregate (LECA)
Authority for Public Services Regulation (APSR)

1 Chapter 1 Introduction

1.1 Introduction

Global energy use is rapidly increasing driven by transportation and construction sectors. Building sector alone accounts for one-third of global energy consumption which raise the flag for conserving natural resources and save the environment. Building also responsible for 27% of total energy pollution emissions (IEA, 2021) which cause lots of hazards, increase global warming, flooding coastal countries, and cause major health issues. This calls for adopting sustainable measures and practices to mitigate carbon footprint and preserve the environment. Use of sustainable materials and exploiting technology to enhance energy use in building sector is increasingly demanding today before any other time.

This chapter provides an overview of this research, the motivations and drivers that influenced the research questions, and the strategies and approaches adopted to answer these questions.

The primary motivation for this research is the fact that electricity in Oman was formally supplied to residential and non-commercial buildings with a subsidy. In 2020, the subsidy was removed (Tariq, 2022) and a tax policy implemented (Tariq, 2020). This increased cost of electricity, especially during summer, represented a new challenge for occupants in Oman.

There is a review of the Oman building code to explore the measures and practices used in Omani buildings and to recommend sustainable measures and practices that could enhance building energy performance.

Therefore, this research explores solutions that can mitigate the significant increase in the cost of electricity through a holistic review of building performance across three phases of the building lifecycle, namely, the preconstruction phase (Section 2.5), the construction phase (Sections 2.5 and 2.6), and the post-occupancy phase (Section

2.10). It also includes recommendations for state-of-the-art solutions for each phase that can enhance building energy performance. For each phase, there is a discussion about the challenges and issues that affect building performance, suggestions of strategies to tackle the issues, and the recommendation of practices, measures, and technologies to enhance building energy use and provide satisfaction to occupants. This study was conducted in Oman to recommend solutions and practices to enhance Omani building energy consumption, as temperatures in Oman reach 40 to 50°C during the summer months. The recommendations will motivate authorities, architects, contractors, and building owners in Oman to adopt sustainable building designs, materials, techniques, and practices to enhance building energy performance and promote the use of technology, such as building automation, to enhance building energy use.

1.2 Research Motivation

Electricity in Oman used to be subsidized by the government, but, recently, the cost of utilities has increased, and the subsidy has been lifted gradually (Tariq, 2022). For many citizens in Oman, the increased cost of utilities, and the new tax implementation has resulted in a challenge to their lifestyle especially during the summer months in which electricity bill is significantly higher compared to other months. Occupants in Oman complained about the soaring cost of electricity during the summer, and there was civil request for electric distribution companies to review their tariffs since the occupants are not used to paying such high bills until recent years. The Council of Ministers directed the Authority for Public Services Regulation (APSR) to review the cost of electricity, which resulted in an increase in the previous reduction in the electricity rate from 15 to 30 percent of the total bill value for the months of July and August for the residential buildings category for all subscribers with basic and national subsidy accounts (Raj, 2023) (Khalid, 2023). This led to a substantial review of the Omani building code and building performance to explore the potential for reducing electricity consumption by implementing practices and techniques that could improve building performance and deploying technology that could help reduce electricity use without prejudicing the indoor environmental quality (IEQ) and occupant satisfaction.

Some of the practices and measures should be considered in the design phase of the building, some could be applied in construction phase, while other challenges could be addressed in the post-occupancy phase.

Examples of pre-construction practices include utilizing sustainable building design, building orientation, and building energy performance simulation (L. Vandenbogaerde, Optimizing building energy consumption in office buildings: A review of building automation and control systems and factors influencing energy savings, 2023). A recommendation to use sustainable building materials during the construction phase includes using Lightweight Expanded Clay Aggregate (LECA) bricks instead of concrete bricks and walls and roof thermal insulation. Meanwhile, an example of sustainable post-construction practices is deploying an automation system that could reduce electricity consumption and living costs without affecting the quality of life of the occupants or reducing their level of satisfaction.

Toward this end, occupants played a major role in this research by providing feedback about their living experience based on their understanding of the dwelling they lived in, as an assessment of the building performance evaluation from their perspective, and their willingness to enhance their building's energy performance. Furthermore, feedback from the occupants provided insights into their perception of their dwelling performance, the challenges they faced, and the potential to solve the issues through a holistic approach that encompasses sustainable building enhancement and automation deployment.

This thesis assesses occupants' readiness to invest in their dwelling's energy performance by embracing some practices that enhance energy use in their dwelling. Building performance evaluation helps researchers to find solutions and recommend sustainable practices and measures to tackle the issues and challenges and so enhance building performance, motivate the use of sustainable building materials in construction, and promote home automation as a technology to optimize building energy performance. The contribution of this thesis is encompassed in reviewing Oman building energy performance and identifying building issues that cause intensive energy consumption. This thesis explores the solution for leaks in building energy performance in three phases; design phase, construction phase and post-occupancy phase as elaborated in section 2.5 Review of Oman's building code and section 2.6 Sustainable materials. The review of sustainable building practices and recommendation to enhance building energy performance to be embedded in Oman building code. State-of-the-art sustainable building method, practices and measure such as upgrading insulations, discussing the best insulation alternatives and choosing appropriate façade materials for Oman weather. Furthermore, POE survey is utilized for enhancing building performance and automation deployment as it reflects occupants' perspective. This provides a review of the best solutions and practices to enhance building performance in Oman and other countries that have similar weather and building condition. The outcome saving realised form BAS case study discussed in Chapter 5 provides promising saving in dwellings energy consumption and to the total building stock which will reduce energy consumption and attain occupants' satisfaction.

1.3 Research Location: Oman

Oman is an Arabic country in the west of Asia located in the southeast of the Arabian Peninsula. It shares borders with the United Arab Emirates in the northwest, Saudi Arabia in the west, and Yemen in the southwest. Its population is 4.9 million (Information, 2020). The hot season in Oman is from May to September; temperatures can reach 50°C on some days, but the average summer temperature is 35°C (Travel, 2024).

Building and construction is responsible for 30% of total global energy consumption and 27% of total energy emissions (Agency, 2020). Sustainable energy is a global concern since the present energy system relies on about 80% fossil fuel, which causes hundreds of thousands of deaths and results in millions of people having major health issues. It also leads to interruption in oceanic ecological systems and climate change (Breyer, 2020). It is therefore crucial to mitigate mankind's carbon footprint and its disruptive effects.

These challenges are particularly clear in Oman, as more than 90% of electricity generation depends on natural gas, according to the 2021 Authority for Public Services Regulation annual report. The Authority set a target to reduce the carbon footprint by using 10% renewable energy by 2025 and 39% by 2040. Working towards this target, the Authority launched the "Mirror" Solar Thermal Project in 2018, which produces 1000MW of photovoltaic (PV) and wind energy; the Dhofar Wind Project in 2019, which produces 50MW; the "Amin" Solar PV Project in 2020, which produces 100MW; and Ibri Solar PV in 2021, which produces 500MW. It also launched the National Hydrogen Alliance in 2022 to achieve the future security of sustainable energy. In total, 44.7% of energy production is used for residential buildings compared to non-residential with 9.5%, 0.8% for agriculture and fisheries, and 45% for Commercial Registered Tariff (Regulation A. f., 2022).

Cooling consumes 60 to 70% of the total energy used in residential buildings in Oman (Regulation A. f., 2022), and therefore it is natural that the occupants' biggest concern is indoor temperature control, especially in the summer. Therefore, enhancing building performance is an important target that needs to be addressed in any discussion about sustainability in Oman and the Gulf Cooperation Council (GCC) region. This research explores sustainable solutions to enhance building performance in Oman.

1.4 Aims and Hypothesis

The aim of this thesis is to study Building Automation systems practices that will enhance Oman building energy performance through a holistic review of the building from the design phase throughout the construction phase and to the post-occupancy phase. The aims are fulfilled through a logic methodology that addresses the research questions, and justification is given for the strategies that have been used to achieve the objectives. The aim of this research is to assess the potentials of BAS in enhancing building energy performance which will lead to generation of a set of recommendations for stakeholders in Oman to implement sustainability. The challenges and issues were gathered from the occupants' feedback through a post-occupancy evaluation survey. The solutions to the poor energy performance utilize an up-to-date literature review and the most recent technology to enhance building performance in Oman and secure the occupants' comfort and satisfaction.

The aim of this research is to explore the potential sustainable solutions to enhance building energy performance to allay occupants' concerns in Oman about soaring energy cost. To achieve this aim, a set of research questions were formed to specifically address building energy performance challenges. The following objectives are defined:

1. Conduct a literature review to explore state-of-the-art sustainable building products, sustainable building methods, measure and practices to enhance building energy performance.
2. Conduct a case study to explore Building Automation Systems (BAS) potentials in reducing building energy use.
3. Conduct a post- occupancy survey to identify occupants concerns in Oman about their building performance and the level of satisfaction and convenience.
4. Identify the level of readiness of occupants in Oman for automation deployment through the post-occupancy survey.
5. Suggest research area to identify the obstacles that hinder BAS widespread in Oman.
6. Suggest recommendations to allay occupants concerns over BAS deployment.
7. Utilize a case study building in Oman to identify the potentials of BAS deployment in energy saving.

The hypothesis analysed in this thesis is as follows:

The use of building automation systems (BAS) has the potential to achieve a significant reduction in energy use in dwellings in Oman.

This research addresses the following questions:

1. What techniques and measures can be applied to Omani buildings to reduce energy use and attain occupants' satisfaction?
2. From an occupants' perspective, is the energy consumption of buildings in Oman too high?

3. Are building owners in Oman familiar with and ready to deploy building automation systems in their dwellings?
4. From the perspective of occupants, what are the obstacles to the deployment of building automation systems?
5. What can be done to allay the concerns occupants have over the deployment of building automation systems?
6. What potential energy improvements can be realised through the deployment of building automation systems?

1.5 Research Gap

Building energy performance in Oman faces many challenges that affect energy use efficiency. These challenges can occur in the design, the construction process, the construction materials, and postconstruction as well as the commissioning. The importance of building design lies in the reduction of building CO_2 emissions, as studies has shown that 78% of CO_2 was released from building reinforced concrete (Noha Ahmed, 2021). Royal Institute of British Architects (RIBA) developed a framework that defines eight lifecycle stages of a construction project. RIBA focuses in sustainable building and post-occupancy evaluation, integration of Building Information Modelling (BIM), emphasis on early-stage collaboration and project coordination achieve project efficiency and sustainability (RIBA, 2020). The eight stages are:

1. Strategic definition that defines business case, project objectives and feasibility.
2. Preparation and briefing that defines project requirements, appoint consultants, and develop and initial brief.
3. Concept design that develops early concept design and feasibility.
4. Spatial coordination that coordinates architectural, structural and services design.
5. Technical design that finalizes technical aspect before construction inception.
6. Manufacturing and construction that executes construction process including off-site manufacturing such as precast.

7. Handover which is project completion and handing over assuring building readiness and operational.
8. Use that encompasses post-occupancy evaluation, maintenance and commissioning review.

The eight stages can be categorized into three main building lifecycle phases which we will tackle in this thesis: design phase, construction phase and post-occupancy phase.

Sustainable design specifications should be considered in a holistic building process starting from building orientation, which should consider sun direction; building layout, by considering placing rooms to be in the opposite direction of direct sunlight; and specifying building materials by considering sustainable building materials that have the minimum environmental impact. The European Commission published a framework listing the life cycle assessment (LCA) of building materials to address the whole life cycle of greenhouse gases (GHG) in which the holistic environmental impact of raw material production is quantified for building materials (Catherine De Wolf, 2023), (Dodd, 2016). This motivates the use of sustainable building materials rather than ordinary building materials, which have many negative impacts on the environment and on people.

In postconstruction, the retrofitting of buildings has a high potential to enhance building energy performance and achieve occupant satisfaction. Retrofitting buildings for energy enhancement is influenced by improving building systems and building renovation. This entails but is not limited to upgrading the building envelope insulation, upgrading windows to resist thermal transmission, changing the colour of the exterior façade to a light colour in hot areas and a dark colour in cold areas, upgrading HVAC and the lighting system, and deploying building automation systems (BAS) and building management systems (BMS). There have been numerous attempts at retrofitting building retrofits aimed at minimizing energy use by adopting retrofit strategies (Ascione, 2019), (Zhao, 2019), (Jafari, 2018), (Nielsen, 2016). Although the initial investment in some retrofit strategies could be costly, studies have shown that suitable retrofitting can lead to a significant improvement in energy use at a reasonable return on investment (Mata, 2019), (Pedinotti-Castelle, 2019).

Studies have demonstrated that single item upgrading could result in a dramatic reduction in energy use in the building. For instance, changing single-glazed windows to double- or triple-glazed windows enhanced building energy performance in all United States climate zones regardless of the orientation and size of the windows (Minne, 2015). However, in general, building energy performance enhancement measures and strategies vary according to the climate zone. For instance, a study by Qiong He et al. (2021) demonstrated retrofit for energy performance enhancement with the associated cost used in different climate zones in China. Retrofitting buildings to optimize energy use by utilizing building automation in the heating system involves flow balancing valves, thermal metering, and temperature sensors. Upgrading ordinary thermal radiators to contain automatic thermostatic valves is one retrofit measure that utilizes building automation. Adding passive infrared (PIR) detectors could be adopted in lighting energy use retrofitting to switch off a lighting system when there is no occupant in the room. Dimming control enhances lighting energy use, as it gradually dims when daylight reaches the desired programmed level (Qiong He, 2021).

Retrofitting buildings for energy enhancement is crucial; it is not limited to equipping the building with an automation system but extends to retrofitting all building elements that affect energy performance, such as the building envelope, which includes window and door thermo-transition, wall and roof insulation, façade design and colour, and lighting and HVAC upgrade given that building systems and equipment have become more energy efficient. BAS could be feasible as a stand-alone system for building energy enhancement without any maintenance work or building upgrade. This could reduce costs especially as BAS devices use available wireless networks and do not need trenches for cabling, which makes them an attractive solution without any impact on the building. However, building performance could be affected if the building has issues that nullify the work of BAS. Such a scenario may arise when the building has major performance issues such as the leak of solar transmission from the windows in a way that renders HVAC efficiency negligible. The same could happen if the building has very poor insulation. In such a case, BAS is not the best solution to enhance building energy performance.

Building automation and control systems (BACS) have many advantages; these are not limited to occupants' comfort and convenience but encompass building and occupants' safety, facilitate building management, and enhance building energy use (Luigi Martirano, 2020). In a three-bedroom apartment case study conducted in Italy, BAS achieved considerable energy use reduction. The case study utilized UNI EN 15232 standard, which divides BAS into four classes of energy efficiency. The calculation of the impact of BACS on energy consumption utilizes the BACS-factor method, which is based on the table of standards of efficacy (Figure 1.1).

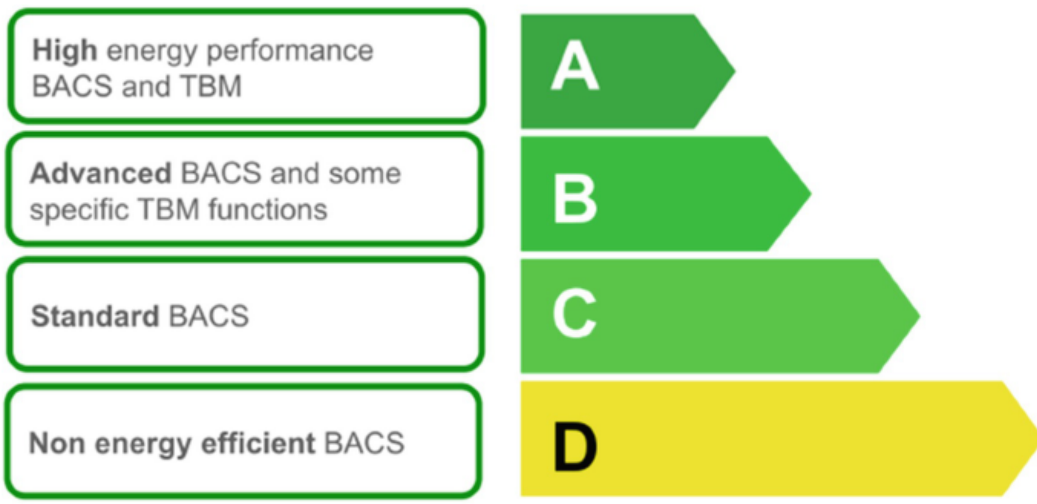


Figure 1.1 UNI EN 15232 automation classes (Standardization, 2012)

The results showed a reduction of up to 26% in energy consumption for winter heating, up to 26% for summer cooling, up to 10% in lighting, and up to 14% for unnecessary electricity use (A. Flamini, 2022).

A field test "SmartHome Rösrath" that investigated the heating energy saving in residential buildings in Germany used a sample of more than 120 representative households between 2015 and 2017; the results showed a broad range from up to 33.4% saving to 26.5% higher consumption. This is because there were variables in the data comparison pre-smart home and post-smart home, such as change in the household, presence time, and improper use of the smart home system. However, on average, a 4% saving in water heating and hot water demand was achieved (T. W. Rehm, 2018). Occupancy-based control can result in up to 40% energy saving in an HVAC system (Tuan Anh Nguyen, 2013). In lighting system control, a 40% energy reduction could be realised by adopting occupancy sensing, scheduled shading, and daylight harvesting; the latter responds to the amount of natural light in the space by dimming or adjusting the room light automatically (Mills, 2002). In an evaluation of a lighting control system, a 58% energy saving was demonstrated by highlighting areas of energy loss and recommending solutions to reduce energy loss (D.T. Delaney, 2009). Other studies have revealed a potential lighting saving of 48% (Y.-J. Wen, 2008), and 33% (V. Singhvi, 2005). Energy savaging could be realised by dealing with behavioural patterns recognition (G.R. Newsham, 2010).

A study to investigate the impact of BAS on energy efficiency on university classrooms demonstrated that the general statement that the integration of BAS into higher BACS efficiency class guidelines has a greater impact in building energy use. The investigation revealed that the real impact is not always obvious and the guidelines in the standard EN15232 should be analysed and verified for each specific kind of building (Grela, 2017).

The stochastic variable in building automation is the occupant presence and occupant behaviour, which have a large impact in the cooling, warming, ventilation, and lighting of the space (K.U. Ahn, 2017), (F. Oldewurtel, 2013). Real-time occupancy detectors play a crucial role in energy management and occupants' comfort. However, occupancy detectors work via a programmed timer in lighting control, for instance, which turns lights off after a set time if no motion is detected. Simulations of occupants' behaviour patterns and preferences for building energy management to simulate human behaviour and interaction with windows (Sebastian Herkel, 2008), lighting control (H.B. Gunay, 2014), (Reinhart, 2004), and HVAC (Xuebo Liu, 2024) have received more attention to help in energy demand calculation.

In the context of occupant comfort, BAS has been used in seniors' housing to reduce the dependency on carers and provide comfort to aging occupants (Yared, 2016), (Landau, 2013). A comprehensive office building energy retrofit audit for thermal analysis in Malaysia was proposed for a cooling demand reduction; it was found that 71% of building heat was obtained from the lighting system and solar heat via the windows. It suggested that a 40.2% reduction in building cooling would result in an estimated 47% reduction in total energy consumption (Wan Mohd Nazi, 2017). A study for optimizing energy use in a major touristic building in Australia involved integrating solar panels with a BMS utilizing several measures such as increasing the indoor temperature by 1.5 °C at no cost and no impact in thermal comfort; meanwhile, peak demand was decreased by 46% by upgrading BMS, HVAC, lighting, and photovoltaic (PV) solar power. A 13% energy cost saving was achieved in the first year (Thyer, 2018).

A customised experimental BACS was designed to control lighting and air conditioning systems in a case study of ten offices in Italy; the energy saving from the offices' lighting system when equipped with an automation system was between 17% to 32% (C. Aghemo, 2014). BAS are proven to reduce energy consumption in HVAC control without affecting thermal comfort, and to reduce energy consumption in lighting control by occupancy sensing, scheduled shading, and daylight harvesting. Furthermore, BAS play an important role in BMS by facilitating building safety, security, and maintenance.

Overall, there are insufficient studies to verify the effectiveness of BAS in a hot-climate zone such as Oman and the GCC region in reducing energy consumption during the summer. Furthermore, work must be done to demonstrate whether the knock-on impact of utilising BAS for energy saving does not excessively degrade occupant comfort.

This research gap will be tackled by testing the feasibility of BAS deployment in hot region building in overall building energy performance. A case study of a building in Muscat undergone a retrofit and BAS deployment to enhance building energy performance, the procedure and results will be furnished in Chapter 5 Case study and data validation.

1.6 Thesis overview

The current chapter is followed by Chapter 2, the literature review, covers key concepts of building evaluation elements that affect building performance and occupant satisfaction. This chapter forms the knowledge to design post-occupancy evaluation survey that is covered in Chapter 4. It covers future sustainable building materials as an important product that play a crucial role in building performance. It also discusses the smart home concept, BAS, and IoT architecture. As part of BAS integration, the IoT is the underpinning connectivity and enabling technology for many devices to gather real time information, which aids home automation and control, and building certification, an important tool to encourage building owners to enhance their buildings. Research question 1 and elements of research question 5 will be answered in Chapter 2 Literature review by suggesting techniques and measures that can be applied to enhance building energy performance.

Chapter 3 discusses the methodological choices, philosophy, approach, analysis type, strategy, and time horizons are identified. Key theories of research methods are covered, and Saunder's 'research onion' as one of prominent research philosophy and approaches to theory development is utilized to develop this research. The paradigm that led to the formation of the research hypotheses and questions and the methodology followed to answer each question are described.

Chapter 4 presents the post-occupancy evaluation survey; this was distributed to 105 occupants in Oman to evaluate their dwelling's performance and to find solutions for issues and challenges regarding building energy performance and occupants' comfort. This chapter answers research questions 2, 3, 4 and part of research question 5 utilizing archival data to allay occupants' concerns regarding home automation. A holistic review of building energy performance and its impact on occupants' comfort will be conducted that will pave the road for automation widespread by removing the obstacles that hinder automation market thriving. Furthermore, the POE survey helped in understanding and evaluating building performance in Oman, and it revealed the challenges to buildings' energy use in Oman that require solutions to enhance their performance.

Chapter 5 utilizes a case study to explore the potential energy saving from BAS deployment for a retrofitted house in Oman. The POE survey is used as a data collection tool to gather information about the case study details and the details of deployed BAS to find out the potential energy improvement that can be realised from BAS deployment by comparing historical energy use before and after BAS deployment which furthermore answers the research question 6. Finally, Chapter 6 summarizes the thesis aims, hypothesis, research questions, and recommendations, and provides a roadmap for future research.

2 Chapter 2 Post-occupancy Evaluation for Enhancing Building Performance and Automation Deployment, State-of-the art Sustainable Building Practices

2.1 Introduction

This chapter covers the key factors that influence building performance and occupant satisfaction. POE survey is used to evaluate building performance from occupants' perspective, which is covered in Chapter 4. Building energy performance involves understanding the building and the factors that influence its performance in a holistic building lifecycle from preconstruction to post-occupancy. This entails understanding the building process, the sustainable building materials, and the building envelope performance regarding the weather, and recommending the best practices and measures to enhance its performance. Issues affecting IEQ, such as utilizing natural lighting to minimize the use of electric light during the day and robust control of indoor temperatures especially in hot countries like Oman, are addressed. The indoor environment has several important aspects that have a crucial impact in energy use and occupants' comfort. HVAC is an important building element that consumes the largest part of electricity use in the dwellings.

Post-occupancy Evaluation for Enhancing Building Performance and Automation Deployment aims to evaluate buildings' performance from several aspects that influence building energy use and occupant satisfaction. These aspects vary from building systems that can be enhanced, and building performance in terms of energy control challenges that require building maintenance or modification to attain robust indoor environmental control.

This research was conducted in Oman to explore the solutions for the existing energy consumption challenges in Omani buildings that encounter low building energy performance and consequently consume excess electricity.

The research encompasses a review of building performance following a holistic approach from design to post-occupancy lifecycle phases. The outcomes, results and recommendations will enhance building energy performance and increase occupants' comfort. These results could be applied to adjacent hot weather Gulf Cooperation Countries (GCC).

This chapter provides a thorough review of the state-of-the-art in the following:

(1) future sustainable building materials, since sustainable materials play a crucial role in building performance especially through evolving technology in advanced materials that are introduced to improve building performance
(2) the smart home concept, where technology has been developed to control and manage homes remotely
(3) building automation systems (BAS), where the extensive spread of connected devices and smart home applications and the deployment of artificial intelligence (AI) would enhance building energy performance and achieve occupant satisfaction
(4) Internet of Things (IoT) architecture, where, as part of BAS integration, IoT is the underpinning connectivity and enabling technology for many devices to gather real time information, which aids home automation and control
(5) building certification, which is an important tool to encourage building owners to enhance their buildings to obtain tax reductions or incentives
(6) post-occupancy evaluation (POE), which was used to design the survey in Chapter 4 to collect information and understand the perception of and readiness to deploy automation in the dwellings
(7) building energy design, which helps identify the gap in knowledge regarding the potentials of reducing the energy and exploring the solutions.

These topics were chosen as they are the basis that introduces the concepts and architecture of sustainable building elements. This will facilitate understanding of the challenges faced by Oman buildings and help to explore the solutions for enhancing building performance and attaining occupant satisfaction.

This chapter aims to answer the following research questions:

Research question 1: *What techniques and measures can be applied to Omani buildings to reduce energy use, and to attain occupant satisfaction?*

This chapter will also contribute to the answering of RQ5 which is answered in Chapter 4 through the POE survey, which suggests a roadmap for the research community for the spread of automation and removing the obstacles that hinder automation widespread.

Research question 1 is answered from the literature review with literature about utilizing state-of-the-art building practices and technology as discussed in Sections 2.4, 2.5, 2.6, and 2.8. This sheds the light on the latest sustainable building materials and sustainable measures and practices that can solve many building performance issues. Utilizing building energy designs and a post-occupancy survey identified the gaps in knowledge and provided feedback on building performance issues and occupants' concerns as discussed in Sections 2.11 and 2.13. This chapter addresses the challenges of energy use in Oman by identifying techniques and measures that are expected to enhance building energy performance in the country. The building energy performance challenges, sustainable materials and building practices that enhance building performance will be discussed in this chapter.

Research question 5 is answered from two angles. The first is discussed in this chapter Section 2.3 through an understanding of building energy performance that is influenced by many factors. This chapter contributed to addressing the research question 5 by discussing the building challenges encountered in Oman so the occupants should be aware of their dwelling's energy performance. Understanding the factors influencing building energy performance, such as building insulation, wall-to-window ratio, sustainable building materials and practices, and the home automation concept and its role in enhancing building energy and achieving occupants' comfort, as discussed in section 2.10, will remove occupants' concerns and motivate them to adopt the sustainable measures and practices mentioned in this chapter. The second angle to answer research question 5 is through the POE survey in Chapter 4, which suggests a roadmap for the research community for the spread of automation. A during the operational phase building energy performance is reviewed to define the challenges that cause poor energy performance. This entails a review of the building process in three phases, namely, the design/preconstruction phase, the construction phase, and the post-occupancy phase, to explore building energy challenges and the potential methods to enhance building performance and attain occupants' comfort and satisfaction.

2.2 Literature Review Methodology

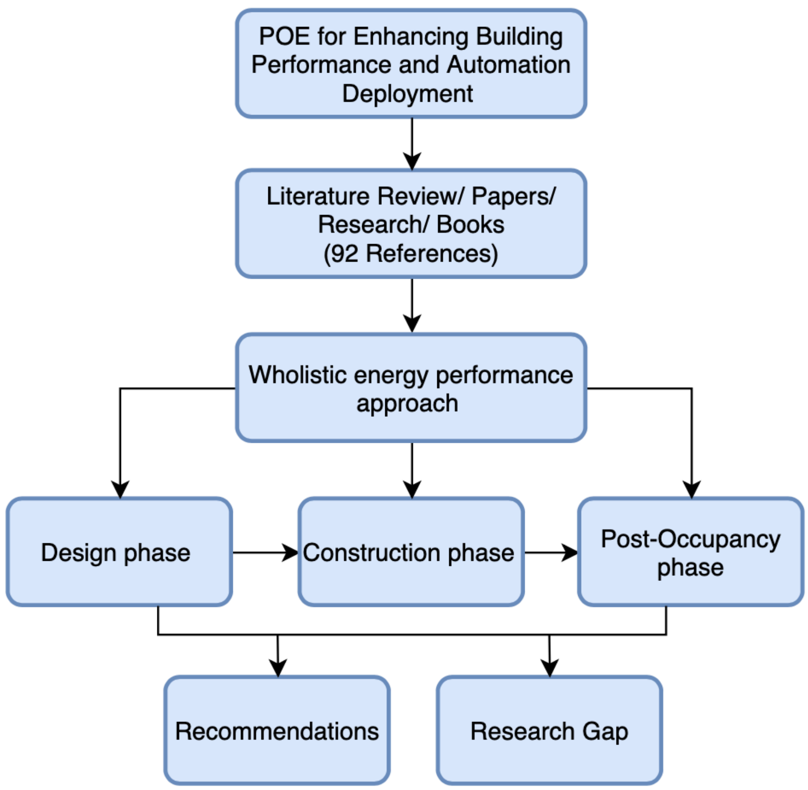


Figure 2.1: Flowchart for POE literature methodology

To understand the review of the literature in this field a wide range of references were utilized for each keyword. The aim was to support this research with scientific evidence for building performance and building automation, and to explore potential sustainable and state-of-the-art building materials that could benefit Oman's construction sector; to enhance building performance, building automation systems and landmarks and the role played in building performance, as well as green certification tools and techniques, and POE and its role in building performance and occupant satisfaction. These keywords are discussed below.

The literature review is used to identify techniques and measures suitable for Oman and neighbouring countries to enhance building performance, reduce energy use, and attain occupant satisfaction, and to explore alternative sustainable building materials and sustainable maintenance techniques, and promote home automation for energy use optimisation and address occupants' concerns about BAS deployment.

The literature review enriched this research with information and supported the findings in some parts of the POE survey discussed in Chapter 4, such as using nanomaterials for sustainable building, enhancing the building envelope with insulation materials, and understanding techniques to enhance building performance. The literature also provided important information to address occupants' concerns about issues such as indoor temperature control and the role of automation in building management. Furthermore, it provided robust information on insulation techniques, isolation of the indoor environment, and the use of IoT to optimise energy use. On the other hand, as will be discussed in Chapter 4, the survey showed only low use of automation in Oman, and therefore, the literature promotes the use of BAS and clarifies its role in occupants' convenience and satisfaction.

Only 92 reports and relevant references were found that could be used to support this paper in three main areas: informative references that were used to construct this paper with field knowledge, references that have views that contrasted with the author's view, and supportive references that were used to support the author's view. The references were obtained from Scopus, Elsevier, ScienceDirect, IEEE, and Google Scholar using specific keywords that were searched for randomly, such as "building automation", "building automation system", "building performance", "sustainable buildings", "green building", "smart buildings", "sustainable building materials", "Internet of Things", "post-occupancy evaluation", and "building rating systems".

2.3 Building Challenges in Oman

Electricity in Oman used to be subsidized by the government and supplied to buildings in Oman at a reasonable rate (Regulation A. F., 2020). This caused cultural barriers which hindered the thriving of sustainable buildings in the region due to a variety of reasons such as easy access to mortgages and the free attribution of lands to residents (Naief A. Aldossary, 2015). Therefore, recently, the cost of utilities has been increased, the subsidy has been lifted gradually (Tariq, 2022), and a tax policy has been implemented (Tariq, 2020).

The increased cost of utilities and the new tax implementation resulted in a challenging lifestyle for many citizens in Oman especially during the summer months in which the electricity bill increases significantly compared to other months. This led to complaints by occupants in Oman, and there was a civil request to electric distribution companies to review their tariffs since the occupants were not used to such high costs. Hence, the Council of Ministers directed the Authority for Public Services Regulation (APSR) to review the electricity prices, which resulted in an increase in the previous reduction in the electricity rate for the residential buildings category from 15 to 30 percent of the total bill value for July and August for all subscribers with basic and national subsidy accounts (Raj, 2023) (Khalid, 2023). Electricity use hike during summer is normal in Oman as the weather hot and temperature is between 40 and 50 °C. The lack of sustainable building methods and the lack in the use of sustainable building materials exacerbates the challenges for keeping comfortable indoor temperature. Air conditions must be used massively during summer to attain comfortable indoor temperature. Thus, the consequence is the soar increase in the electricity bills which can be mitigated by implementing sustainable building practices that have to be included in Oman building code. Building colling solely accounts for nearly 70% of total energy use in the building in Oman (Regulation A. f., 2022).

The increase in the cost of utilities triggered new occupancy behaviours aimed at reducing the cost by considering a sustainable building design that specifies and embeds sustainable building materials and sustainable building processes in the construction plans. Some of the sustainable practices involve building orientation and a design-centric goal aiming to reduce energy consumption to make the building environmentally friendly by reducing carbon emissions in the building process (Nengmou Wang, 2014). Strategies include utilizing insulated bricks for construction, selecting new building materials with high performance to resist thermal conductivity, deploying smart devices to optimise energy use, installing solar products, exploring home automation (especially since smart products have become widespread in the market with the emergence of the IoT, 5G internet, and the connected-home concept). The advent of smart homes has the potential to reduce and shift energy use, especially during peak hours when demand is high and tariffs are also higher than in normal hours (Jiakang Lu, 2010); (Pietro Cottone, 2015); (Zhihong Pang, 2021) and to reduce water usage thanks to laser sensor water taps equipped with a flow timer, and smart maintenance of building systems. Smart homes also enhance the IEQ and improve comfort, convenience, and quality of life. An emerging building paradigm takes a holistic approach to the building process starting from the very early design phase and does not end by handing over the building to the owner but predicts building age and the recycling of the building materials that were used in the construction, so they are used sustainably. This revolutionary holistic approach to the building process exploits technology to execute construction on or off-site in what is known as Construction 4.0 (C4.0) (Casini, 2022).

This calls for a substantial review of the Oman building code to use less electricity by implementing practices and measures that could improve building performance and reduce electricity use without affecting the level of indoor satisfaction (Shaikh P.H., 2014), (Al Mindeel T., 2024). Some of the practices and measures have to be considered in the design phase of the building while others could be addressed post-occupancy. Examples of pre-construction practices include the use of sustainable building design and use of sustainable building materials, while post-construction measures include the deployment of automation that may reduce electricity use and living cost without affecting living quality or occupant satisfaction and building maintenance such as upgrading the building’s insulation.

Occupants played a major role in achieving this research aims, as it was important to gather their feedback about their living experience based on their understanding of the dwelling they live in, as an assessment of the building performance from the occupants' perspective and their readiness to enhance their building's energy performance. Furthermore, feedback from the occupants provided insights into their perception of home automation and made it possible to assess their readiness to deploy automation in their dwellings. Building performance evaluation would help to find solutions for the issues and challenges to enhance building performance and to motivate the use of sustainable building materials in construction and promote home automation as a technology to optimize building energy performance.

Buildings are not only shelters from external weather conditions; they should also provide comfort and convenience in different aspects of life, such as the need for natural daylight and for artificial light in the evening, providing the occupant with a good quality living atmosphere, and offering control of indoor air quality and room temperature throughout the seasons. A building that lacks any of the essential aspects for occupant satisfaction has to be renovated and enhanced to attain the occupant's comfort and convenience. Deploying building automation is a part of building management that reduces the efforts of physical administration of the building and remotely controls building systems for optimum energy use and maximum occupant satisfaction (Bing Dong, 2019). Sensors and actuators can be deployed to manage room temperature; switch lights on/off and control light intensity; open and close curtains to attain a comfortable indoor environment; secure the building by surveillance cameras and security alarms; protect the building from potential hazards, such as fire, gas, and smoke; and advise of any potential building maintenance.

Construction is one of the sectors that has high potential to reduce these impacts by using sustainable building materials and techniques to achieve sustainable energy use. Therefore, this research surveys the issues around building performance in Oman from the occupants' perspective. This involves considering the energy consumption of buildings as well as sustainable building materials and their efficiency in reducing energy consumption in Oman and similar countries in GCC.

Following this, the paper then explores the techniques and measures that can be used to enhance building energy usage and attain occupant satisfaction. Among these are promoting BAS, which are often touted as a key solution to concerns regarding building energy use (Louis, 2012). To understand how this particular concept affects Oman, this paper also studies whether people in Oman are ready to deploy automation systems in their dwellings.

2.4 Technology in Construction

The construction industry has never undergone disruptive transformation, and it is slowly responding to technology. This is in contrast to other industries, such as the automotive and aerospace industries, which have exploited digital technology and adapted to quick productivity and accuracy in quality. This radical shift in the industry towards digital technology is known as Industry 4.0 (L.S. Dalenogare, 2018), (A.G. Frank, 2019), (M. Gattullo, 2019).

The slow response of the construction industry to technology is due to unskilled and low-income labourers and the nature of construction projects, which are frequently limited in time and budget, making it hard to respond to technology and innovations. Construction projects are limited by a scheduled time from planning to handing over, and because using technology onsite requires implementing technology methods during the construction process, which in turn, requires extra time, that can affect the delivery schedule and so can have a direct impact on project cost (Casini, 2021). Implementing technology in the construction industry also requires collaborative work between architects, contractors, project owners, authorities, and all the stakeholders involved in construction to make a transformation towards the use of construction technology.

The nature of modern life and the arrival of the fourth industrial revolution has changed the pace of people’s lives, especially in busy cities, as many hours are consumed in traffic and on the commute from one place to another. This caused a transition in the construction industry as many other industries to shift from ordinary methods to utilize digital era which increased organizational performance (Calış Duman M., 2021). In the past, people were more relaxed although the time used to accomplish a single task could be multiples of the time currently used to complete the same task. Automation in manufacturing has increased the production of merchandise to cover the huge demand not only in the local market but globally. Also, the movement of merchandise is becoming easier and faster due to rapid logistics and the smooth movement of products between countries. The emergence of same-day or 48-hour delivery couriers has brought the global market to our doors with a single click, meaning many products are securely delivered in just a few hours. Tracking products and following them from order point to delivery has provided extra convenience and better customer satisfaction. The construction industry, however, has taken longer to make the changes required to adopt the use of technology compared to other industries like manufacturing and the automobile sector, which by their nature differ significantly from the construction industry.

The two major drivers of construction projects are the project budget and the project schedule. These are interrelated and must be kept under strict control to avoid any costly variation that could affect project delivery. This entails a thorough follow up of the construction progress to deliver the project within its scheduled timeframe, and hence, this rushed pace does not allow sufficient time to experience new technology or implement a new construction method except in very limited circumstances where there could be a way to expedite project delivery or in some cases when the project delivery method is a turnkey project where the contractor has all in-house products. Construction industry encountered slow transition towards utilizing technology compared to other industries such as medical and automotives industries (Casini, 2021). However, in recent years, there has been progress in the use of technology post-construction thanks to the emergence of 5G, the IoT, smart sensors, and actuators.

The quick pace of construction allowed the production of prefabricated buildings in the United States in the 1940s. In the post-war period, there was a huge demand for economical and quickly delivered housing for humanitarian aid. The shortage of materials and skilled labourers led to poor-quality prefabricated houses and created the perception of prefabricated houses being a poorly made, cheap, and ugly option (B.-G.

Hwang, 2018). However, the continuous demand for less costly buildings and the requirement for the quick delivery of construction projects have spurred off-site prefabrication, which has been facilitated by better design and engineering which reduced many of the in-situ costs, such as labour, construction waste, and environmental pollution, and has proven to improve the workflow and reduce the time required for construction (M. Kamali, 2019).

BAS, also known as BACS or BMSs, are one of the technologies and tools to manage, integrate, and control most if not all building components including lighting, HVAC, safety and security, and the building envelope (Casini, 2022). BAS aims to integrate building systems to communicate with each other in order to achieve high building performance, reduce operating costs, and optimise energy use. This requires deploying a set of smart devices, sensors, and actuators to obtain information from the surroundings and the occupants to control building systems and provide comfort and convenience for occupants with the lowest possible energy use. Automation began with the use of hardware devices to control TVs, sliding gates, socket timers linked to electric devices, and so on. The importance of hardware was the focus of research rather than the importance of software (A. Kumar, 2018) (P. Misra, 2013) (B. Dong V. P., 2019) with the advent of sensors, actuators, and control over gateways, all of which require algorithm data to operate and tackle many real-time commands and stochastic occupant behaviours. However, IoT, cloud computing, machine learning (ML), and big data processing have drastically shifted the focus from hardware to software in BAS. No one would argue about the benefits of building automation in building management, reducing electricity consumption and water usage particularly after the advent of ML and concepts such as Intelligent Building (IB), Smart Building (SB), and nearly Zero Energy Building (nZEB), which respond to external dynamic weather conditions (Joud Al Dakheel, 2020). While ‘intelligent’ refers to the infusion of ICT in the building, ‘smart’ is more about improving interaction with humans, though the terms are used synonymously (Peixian Li Y. L., 2021). Automation system is a network of connected devices and technologies that executes predefined tasks automatically based on preset system (K. Shafique, 2020).

A smart system is also a network connected devices and technologies, it uses artificial intelligence (AI) and machine learning (ML) to learn and adapt for real-time decision making and often connected to Internet of things (IoT). This indicates that a smart system is more intelligent and encompasses automation systems but also clarifies that not all automation systems are smart since many do not learn or adapt.

Building automation drastically improves the control of the building system to ensure optimum energy use and the highest level of occupant satisfaction, and it exceeds occupant expectations not only in controlling building systems, but it even predicts occupant behaviours and reacts accordingly with ML. A building's readiness for coupling with automation should have three indicators: readiness to adapt to occupant needs and control over energy, readiness to adapt to the needs and response of the grid, and readiness to facilitate building operation and maintenance in an automated manner (S. Verbeke, 2019).

Early research focused on building automation to control building systems such as lighting, HVAC, security, safety alarms, and overall building automation aimed at reducing energy use. However, this could impact occupants negatively since building systems are usually programmed to maximise the reduction of energy consumption and therefore to reduce the use of light, HVAC, and so on for other building systems (Joshua Butzbaugh, 2021), (Giorgos N. Spyropoulos, 2011). This usually happens in the buildings with third party management, such as commercial residential buildings, i.e., condominium apartments in which the building management aims to reduce the cost and maximize profit through a severe reduction in the use of lighting, HVAC, and other building systems, even though this can affect occupants' comfort negatively. However, for private dwellings, the occupants can choose to control their dwelling to achieve optimum comfort and satisfaction, balancing energy consumption and comfort.

2.5 Review of Oman's Building Code

The construction code in Oman needs to be reviewed to fulfil the 2030 UN Agenda for Sustainable Development, namely, Goal 7: Affordable and Clean Energy; Goal 9:

Industry Innovation and Infrastructure; Goal 11: Sustainable Cities and Communities; as well as Goal 13: Climate Change (Programme, 2023). Though the temperature during the summer is between 40 and 50°C, buildings are constructed with concrete bricks that are known for their high thermal conductivity (1700-2500mW/mK) and without any additions that might improve insulation. In addition, no insulation materials are used in the roofing or in the envelope walls. However, in recent years, white bricks that contain LECA have become popular, and many landlords have requested that the exterior walls be built with such bricks, which are basically made by heating clay to around 1,200°C in a rotary kiln and the final product yields clay pebbles expanded by small bubbles. This forms a porous heterogeneous structure with a rigid outer shell and a porous core, which means it offers lightweight insulation against heat and cold, is soundproof, and has fire-resistant properties (Elías Roces, 2021) (Rashad, 2018). These are added to a concrete mixture to form lightweight bricks that increase thermal and sound insulation and fire resistance. However, LECA bricks have been introduced to the market without a mandatory code to use them in construction, and they are available as an alternative at a higher cost compared to solid concrete bricks. Nonetheless, despite the initial cost, building insulation would save a significant amount energy that is currently used for cooling during summer and thus could save the environment from the use of unsustainable natural resources for energy generation.

The majority of detached houses in Oman have four to five bedrooms, one family hall, and a kitchen with an AC split unit in each space, and these units are switched on for more than ten hours daily for at least eight months of the year (March to October). Building cooling represents a huge cost due to the lack of any insulation in the exterior walls and roofs of the buildings; the home space needs AC to work for long hours so that the room temperature reaches a temperature of 24°C or lower, which is necessary for occupant satisfaction and comfort. Furthermore, achieving a comfortable room temperature exhausts ACs meaning these have to undergo maintenance during the season or there could be a failure in the compressor unit. Nonetheless, switching off the AC for a few minutes then requires turning it on again for much longer in order to regain a comfortable room temperature. Professional building insulation could save up to 65% of the energy used for cooling (Ahmed FaikAl-Mudhaffer, 2021). Nonetheless, despite its importance, insulation is not a mandatory practice in Oman buildings since electricity used to be subsidised by the government to the extent that it was virtually free, but this could also be related to the lack of experience about and the perception of the role of insulation in reducing energy use.

In old buildings in Oman, natural wadi stones were used to reinforce the structural stability of the building (Esry, 2024). The ceiling slab is supported by date palm trunks, which are usually vertically cut into four equal columns to attain the maximum length especially for the family hall and master bedroom, which tend to have long span slabs. Wall thickness is usually not less than 40cm, especially if the building is more than one level high. Old buildings have small windows to prevent heat penetration into the building, especially as there was no air conditioning, and the rooms get fresh air circulation from circular holes of approximately 25cm diameter every 1m distance along the walls just under ceiling level to allow room ventilation during the summer. They were built with clay mud mixed with palm leaves with the combination then burned to form a sticky mixture that was added to white cement for extra binding. This primary mixture, known locally Sarooj, provided high efficiency in cooling the indoor environment and resisting thermal conductivity during the summer. It has, however, has been replaced by concrete bricks and mortar.

Picture 3.1. Omani heritage house built with Sarooj, wadi stones, and date palm trunks. Picture attribute Bait Al Safah Museum.

Buildings in Oman must be painted with a white colour paint by code, or the building owner must get approval from the municipality if the paint is other than white (ATKINS, 2019). The light colour paints such as white or light colour shades must be used to reduce heat absorption and maintain a better indoor temperature. In general, building architecture in Oman has a similar theme in terms of colour, and the only rare use of a glass curtain wall façade, but windows are either aluminium or Unplasticized Polyvinyl Chloride (UPVC). Although wood has better insulation and lower thermal conductivity compared to aluminium and UPVC, it also expands and shrinks depending on the weather and temperature, so the use of wood is undesirable for windows given the radical change in temperature between summer and winter. Keeping a comfortable constant room temperature in Oman during the summer means needing to keep the air conditioning on 24 hours a day during the summer months, as the temperature in the room quickly becomes hot and uncomfortable when the AC is turned off for a few minutes especially during the day due to an external weather temperature that exceeds 50°C some days in June and July specifically. In the summer daytime hours, the building envelope walls store heat radiation from the sun in concrete blocks and reinforced steel columns, beams, and slabs and release the heat during the night time if the AC is turned off. Concrete has a high thermal mass, which is defined as the capacity of a material to absorb, store, and release heat. This is noticeable, as walls remain hot during the night and flush heat indoors meaning room temperatures are uncomfortable even with the AC on in some circumstances. Although, currently, AC cooling efficiency is high, and a comfortable room temperature could be achieved by keeping the AC compressor on a lower thermostat temperature, this is more costly than setting a room temperature to auto-mode where the AC compressor turns off as it reaches the desired temperature.

Several construction practices contribute to exhausting ACs and defer in achieving a constant, comfortable room temperature. In addition to the lack of wall and roof insulation and the use of concrete bricks, a massive quantity of rebar steel is used for reinforcement during the construction process without any thermal-conductivity-reducing additives that could assist in reducing heat transmission on the walls. The use of aluminium and single-glazed windows is another practice that needs to be changed by the building code. Aluminium is known to have good thermal conductivity, so it works as an effective medium for heat exchange between outdoor and indoor environments. Double- or triple-glazed windows have argon gas, which is 40% denser than air, between the glass layers, as it works as a good insulator (Ahmed FaikAl-Mudhaffer, 2021) and thus should be mandated in the Omani market, especially as the architectural trend nowadays is to use big windows as part of modern design. However, insulating the AC ducts through which the air flows is important to maximise AC efficiency. Furthermore, the annual servicing of AC compressors is also essential, especially as Oman is an arid country where rain is rare; this means the air carries a lot of dust, which then finds its way into the compressor causing it to fail if it is not serviced regularly. Usually, contractors install a one-and-a-half-inch duct pipe to insert the AC copper pipe, which comes pre-insulated in the factory. However, this fixture is sometimes installed in the external building walls that receive direct sunlight, which reduces the cooling efficiency; this must be avoided by installing a duct in the interior building walls to prevent the pipe being in direct sunlight and to maximise AC efficiency. The duct could be made of bricks or insulated gypsum boards and should be painted a bright colour to reduce thermal conductivity.

As mentioned previously, concrete has high thermal conductivity (1700-2500mW/mK); therefore, adding nano insulation materials to the concrete mixture can reduce concrete's thermal conductivity without affecting its mechanical strength and-load bearing properties. Currently in Oman, there are three types of concrete blocks: the first is the normal concrete blocks that consist of cement, sand, and gravel of different ratios according to desired compression strength; the second type is concrete bricks with a layer of insulation foam (Group, 2024); and the third type of bricks is the LECA bricks (Blocks, 2024), which are manufactured from clay with minor or no lime content. Construction in Oman is shifting towards using LECA bricks given the fact of high temperatures during the summer and the reduction in the electricity subsidy, so energy costs have increased. This has triggered a new behaviour from landlords in considering the use of sustainable materials and looking for new solutions in the market to increase building performance and reduce energy consumption. This also highlights the awareness and perception of using sustainable buildings.

2.6 Sustainable Materials

The use of sustainable building materials is essential to preserve the environment, save energy, and reuse materials since the construction industry accounts for 40% of the annual consumption of aggregates (sand, gravel, etc.), 30% of global greenhouse gas emissions, 25% of the world's timber consumption, and 16% of water consumption (Ahmed Soliman, 2022). Therefore, the construction industry has a significant impact on the renewable resources used; however, the advance in the construction industry shows promising potential in exploiting technology to use alternative additives in the production of building materials that reduce the environmental impact on the renewable resources and produce new products with high performance and less use of renewable resources. For instance, adding nanomaterials to building materials enhances the features of these materials; for example, adding nano-limestone to the concrete mixture reduces the curing period and improves its cementing properties (Camiletti et al., 2013).

Another good example of how to enhance the sustainability of building materials is adding nanomaterials to glass, which improves its energy efficiency by 75% compared to normal glass (Ahmed Soliman, 2022). In some cases, it is estimated that 80% of building energy can be saved when using high-performance insulation. Ordinary insulation that is embedded in the drywall is thick and heavy and, when installed, it reduces the usable area. Therefore, innovative materials have been investigated, manufactured, and made available in the market with high levels of insulation that keeps the indoor environment isolated. This includes such materials as double- and triple-glazing for windows, rock wool, polystyrene and polyurethane foam, vacuum insulation panels, and nano and dynamic insulation materials (Jelle, 2011). Aerogel is a special insulating material; it is a puffed-up material with nano-meter scale pores <1/3000th the diameter of a human hair providing the lowest thermal conductivity (0.014 W/m K) and high acoustic insulation (Saffa B. Riffat, 2013). Aerogel is considered the best assured insulator compared to all other materials as it is flexible in form and derived from gel, which also known as “frozen smoke” for its ultra-light weight and transparency.

Future insulation techniques could have better potential with respect to thermal conductivity, durability, freezing-thawing resistance, adaptability, and constructability. Such future materials include vacuum insulation materials (VIM), which are homogeneous materials with a closed small pore structure filled with a vacuum and a thermal conductivity of less than 4mW/(mK), and gas insulation material (GIM), which is basically a homogeneous material with small pores and filled with a low-conductivity gas, such as argon (Ar), Krypton (Kr), or Xenon (Xe) thus providing thermal conductivity of less than 4mW/(mK). In addition, nano insulation materials (NIM) are derived from VIM but have a smaller pore size to achieve thermal conductivity of less than 4mW/(mK) and provide a service life of at least 100 years. Finally, dynamic insulation materials (DIM) are where the thermal conductivity can be controlled within a desirable range (B.P. Jelle R. B., 2015), (B.P. Jelle A. G., 2010), (Jelle, 2011).

Technique/Material	Affect	Section

Lightweight Expanded Clay Aggregate (LECA) bricks	light-weight bricks low thermal conductivity high sound insulation high fire resistance	2.5 Review of Oman’s Building Code
Building envelope insulation	reduces thermal conductivity. soundproof	
White/light colour façade paint	reduces thermal conductivity	
Use of double- or triple-glazed Unplasticized Polyvinyl Chloride (UPVC) windows with argon gas	reduces thermal conductivity. soundproof	
Steel reinforcement (rebar) to be designed to a minimum structural requirement	reduces heat flush from walls and floor during hot season	
AC duct insulation	increases AC efficiency.	
Annual service of AC compressors is essential especially as Oman is an arid country where rain is rare.		
Avoid exterior installation of AC air flow duct where it could be installed in the interior walls		
Nano-materials additives to concrete mixtures such as nano-limestone	reduces curing period and improves cementing properties. reduces thermal conductivity	2.5 Sustainable Materials

Aerogel is a special insulation puffed-up material with nano-meter scale pores.	provides the lowest thermal conductivity (0.014 W/m K) and high acoustic insulation	
Nano insulation materials (NIM) are derived from vacuum insulation material but have smaller pore size.	achieves thermal conductivity less than 4mW/(mK) service life of at least 100 years	
Dynamic insulation materials (DIM)	thermal conductivity can be controlled within a desirable range	
Tinted window glass with several grades that reflect direct sun radiation	reduces sunlight heat penetration and greenhouse effect	2.8 Techniques to Improve Building Performance in Oman
Sealing window borders with silicon	reduces thermal exchange between outdoor and indoor environment	
Use of blackout curtains	blocks direct sunlight	
Automation of windows and curtains (scheduled/ thermostat)	attains controlled indoor environment.	
Use louvres and window shutters	provides a solid block of sunlight compared to fabric curtains	
Blind automation	maximises heat reduction and at the same time exploits natural light	
Applying white colour protective coating over the polyfoam (roof system)	increases thermal resistance	

Table 2.1 Techniques and measures that can be used to reduce energy use and attain occupant satisfaction.

2.7 Global Energy Use and BAS for Energy

Energy use in the world is rapidly increasing, and concerns have been raised regarding a global energy supply shortage in addition to the environmental impacts of the heavy use of natural resources, which contributes to the carbon footprint. Globally, the building construction sector is responsible for one-third of global final energy consumption, and this continues to rise driven by easy access to energy in developing countries, greater ownership and use of energy consuming devices, and the rapid growth of the building sector globally (IEA, 2021). Furthermore, the environmental impact of the heavy use of fossil fuels increasingly contributes to CO_2 emissions, the greenhouse effect, depletion of the ozone layer, and global climate change. However, the demand for energy use has increased dramatically driven by the transportation and construction sectors, which collectively account for two-thirds of energy use. However, new technologies and products become more energy efficient, and the crafting and implementation of efficient policies is viewed as the cornerstone for energy use reduction (APS, 2021).

In the European Union (EU), buildings are responsible for 40% of energy consumption and 36% of greenhouse gas emissions. Approximately 75% of buildings in EU are energy inefficient, and a large portion of supplied energy is lost as waste. Renovating existing buildings is suggested by the EU to increase their efficiency, reduce this loss of energy, and minimise CO_2 emissions. New ambitious policies have been introduced to encourage landlords to renovate their buildings and increase their efficiency. The EU has also implemented some strategies for all member states to reinforce long-term building renovation, increase energy performance, and achieve nearly zero-energy buildings. These measures will feed into an overall target of 32.5% energy efficiency at a national level of EU members by 2030 (EU, 2020). BAS are an important aspects that has been proved to reduce energy use in buildings (M. Magno, 2015), (E. Uken, 2009), (A. Williams, 2012), (Dubois, 2015), (R.C. Tesiero, 2014), (Valentina Fabi, 2017) with regard to two factors for energy use reduction: BAS and conscious users or sustainable lifestyle consumers (LC). BAS control building systems such as electrical, HVAC, and mechanical, to reduce energy consumption for the benefit of building owners to ensure optimum building performance and attain the safety, security, and comfort of occupants (J. Lazim, 2015). BAS can be digitally simulated and designed through building modelling software based on computational modelling and can provide advantages over field experiments in that they permit energy saving prior to implementation, save time, allow repetitive tasks to check and balance the results, are non-intrusive for building occupants, simplify performance indicators that are difficult to measure on site, and provide easily interpreted results (T. Yang, 2016), (W.I. Wan Mohd Nazi, 2017).

2.8 Energy Modelling

Using building modelling software is powerful in the sense that energy simulation results are accurate and provide predictions for energy consumption through virtual simulation. This is beneficial, as implementing experiments can be costly and difficult to apply for research purposes. The major landmark software programs in the market are EnergyPlus, RADIENCE, MATLAB, and eQuest. While those software programs and others are powerful in energy design taking into account occupant behaviour, research has revealed that there is a discrepancy in the designed energy and the actual building performance (Tao Yang, 2016), (W.I. Wan Mohd Nazi, 2017) mainly due to stochastic occupant behaviour, which refers to the presence of people in building spaces and their interaction with the building, such as switching lighting on/off, opening and closing windows and curtains as well as occupants' preferences regarding lighting intensity, desired room temperature, and so on. Occupancy modelling is multidisciplinary, where different application scenarios require various disciplines to support building simulation and operation. For instance, occupancy design is used for HVAC sizing, elevator size and schedule, lighting, and crowd management, which are under different disciplines. Hence, collaboration between all disciplines is essential for occupancy modelling (B. Dong D. Y., 2018).

Occupant satisfaction entails the flexible control of many variables granted to occupants to modify to their preferred settings. For instance, some occupants like a warm light colour temperature 2700-3000k while others like a cold light colour temperature 4000-5000k, most LED lights in the market fall within the two ranges. The technique of changing the light temperature in the same fixture has nowadays become popular and available similar to a dimmer switch, which provides flexibility to suit the occupants' preferences. The same concept is also available for room control systems where automation or the AC thermostat is pre-set to a preferred temperature, and the sensors/actuators attain the desired room temperature. Home automation, then, has become an important tool to be embedded in energy modelling and simulation considering occupants' preferences to achieve positive POE.

2.9 Oman Building Energy Calculation

In Oman, the majority of architects sketch the initial plans that show the layout of the rooms and spaces for the house being built. Regarding energy calculation, this is usually done for government buildings and some commercial large-scale buildings. However, for residential buildings, no software is used, but the electrical load of each electrical appliance, the AC, and the lighting are added together based on precalculated loads for each component to get the total load. Each electrical device is connected to electric cables that have specific amperage loads, and these are connected to the distribution box that contains fuses of different loads usually from 6 to 60A. The distribution box is connected to the main distribution meter or a smart meter. This is the basic concept that most architects use in Oman based on the precalculated loads of electrical fixtures. A distribution box which has all the fuse switches for all the electrical fixtures in the building is connected to a meter box that is customised to provide the required load from the main electricity distribution line. The majority of residential buildings are equipped with a split-unit AC in each room; these are available on the market starting from 1.5 to 3.5 tons for home use. Those of three tons and above require a 3-phase cable connection. Setting ACs to 24°C would save energy use almost 25% on electricity bill According to the Bureau of Energy Efficiency (BEE) (Panasonic, 2024), as the thermostat works automatically to keep the room within the desired temperature; however, this may not save energy during the summer in hot countries like Oman since the ambient temperature is hot and could reach 50 °C, so that reaching the desired room temperature requires the compressor to operate for long hours given that buildings do not have any insulation but are built using high thermal conductivity concrete bricks, as discussed earlier. BAS would ultimately optimise the operating and scheduling of home systems with the use of occupancy sensors, motion sensors, and time-linked tasks, especially lighting and exhaust fans.

2.10 IoT and BAS for Smart Buildings

The smart building market is forecast to grow from USD72.6 billion in 2021 to USD121.6 billion by 2026 (Market, 2022). Research on BAS started in the 1980s with the rise of information and communication technology and the need to provide comfortable accommodation for occupants with less use of energy. Specifications and fundamentals of BAS are prescribed by EN15232 and EN52120-1 standard energy performance of buildings, Impact of Building Automation, Control and Building Management. It classifies the functions of BMS and the potential for savings in energy consumption with the use of building control systems. The standard structures function based on the energy requirement, and its provision is classified into four levels: 0-no automation control, 1-time control, 2-presence control, and 3-demand control (LAFIVENTS, 2021). Four ranks for energy performance are classified from A-Class to D-Class where A is high energy performance control, B is advanced BAS, C is standard control, and D is non-energy efficient. The EU mandated Class B implementation for both non-residential and deep renovation; however, the majority of existing buildings are still in Class D (Casini, 2022).

The smart building concept thrives with the integration of technology in buildings triggered by the cost effectiveness of smart sensors to control the home remotely, providing both comfort and convenience. Smart buildings cannot be smart without deploying BAS components, which consist of both software and hardware. The last components, such as deploying sensors, actuators, storage drives, and gateways, need cloud storage and human-computer or smartphone application interaction. The IoT is one of the enabler technologies for many industries, and it is defined as the point in time when more “things or objects” were connected to the internet than people. In 2003, the ratio of connected things (500 million) to the number of people (6.3 billion) was 0.08, which is less than one, and therefore the IoT had not yet been achieved according to

Cisco IBSG's definition; this is reasonable since smartphones were not yet ubiquitous, as the iPhone was not launched until 2007. However, in 2010, there were 12.5 billion connected devices, making the ratio of connected devices per person 1.84 revealing that the IoT was invented between 2008 and 2009 (Evans, 2011). The number of estimated IoT cellular and non-cellular connections is forecast to be 25 billion in 2025 (Office, 2018). This prediction reveals the rapid growth of the IoT between 2009, where each person had one connected device, and 2025, when the ratio is expected to have tripled so that each person would have three connected devices. The IoT and BAS both work to achieve the same goal in the context of home automation; however, BAS is a closed system that is interconnected and pre-programmed to manage specific events or coordinate home automation scenarios that are pre-set. The IoT uses the internet to collect data from the surrounding environment, processes the collected data, and provides the optimum scenario of functions for home management. Data security in a BAS is higher since it is a closed system compared to IoT, which requires the internet to collect data and is therefore susceptible to cyber-attacks and data hacking.

As researchers have proposed, IoT architecture is divided into layers depending on the applications and the industries (A. Al-Fuqaha, 2015), (J. Lin, 2017), (A.J. Trappey, 2017), (B.N. Silva, 2018). IoT architecture is also divided into layers in the smart building industry, and some researchers prefer to use conventional architecture of three-layers: a perception layer (sensing and actuation), a network layer (data transportation), and an application layer (user interaction) (Mengda Jia, 2019).

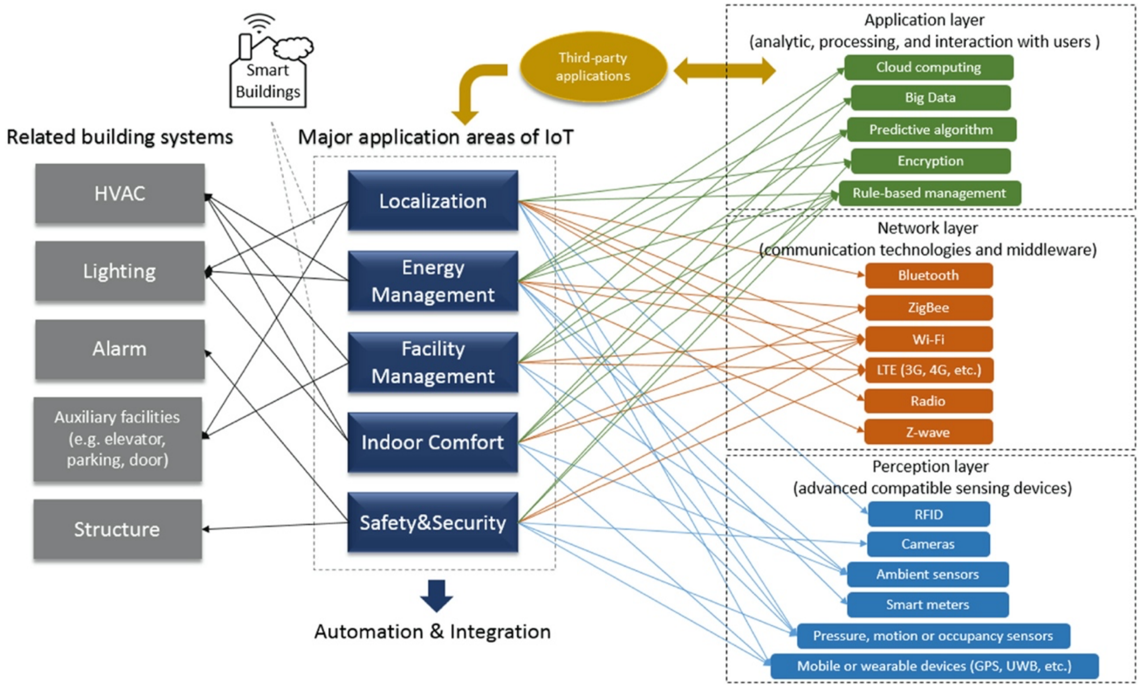


Figure 2.2 IoT architecture application in a smart home (Mengda Jia, 2019)

One IoT application in the building industry integrated with the electricity sector is smart grids; these enable two-way communication between the electricity provider and the consumer to control and manage peak-time electricity use since its cost is higher. Smart meters feed back to the electricity station about the use of energy in the building and interact to optimise energy consumption, which helps both the power infrastructure and the consumer (S.S.S.R. Depuru, 2011). Utilizing the IoT in smart building management has many applications and software, some of which requires subscription fees for pro-features. Good examples of smart management software that help to enhance energy use are Desigo, Energis.Cloude, Wattics and e3m. The Active Energy Management CrowdComfort platform works as an interface between building management and the occupants that allows the occupants to report any maintenance requirement or comfort issues to the building management with little training and without any required hardware, such as sensors; this helps management to respond in a timely manner regarding building issues and to achieve occupant satisfaction. The platform can be integrated with existing BMS (Svenja Binz, 2023). The potential energy saving from BAS deployment is sometimes overestimated according to some researchers. (L. Van Thillo, 2022), (L. Vandenbogaerde, 2023).

BAS in BMS have many applications that integrate building components, such as HVAC; lighting; fire, smoke, and surveillance alarms (Christopher Morales-Gonzalez, 2024); assisting facility management, such as elevator schedule, door control, and parking management.

The application of BAS in building management has many uses, for example, localization to control an auxiliary facility component such as elevators and doors, energy management to control HVAC and lighting, facility management to control HVAC and auxiliary facilities, and control of the building to attain safety, security, and indoor quality. BAS controllers' logic can learn from human behaviour by employing ML to act or react according to real-time scenarios. The sensors and actuators in BAS gather historical and real-time data that provide insights for future decision making. In fact, BAS have the ability to predict future scenarios utilizing historical data to form patterns and anticipate the solution scenarios. For example, water usage in the building can be identified to correct any failure, such as a water leak, by shutting down the valves to avoid severe water damage. Likewise in power usage, the diagnostics of HVAC reveal an important maintenance schedule before any system failure occurs. Similarly, smoke and gas sensors and actuators provide important safety to the building by setting off alarms and opening water sprinklers for firefighting. One useful application of such sensors is parking identification especially in commercial buildings and malls; these provide real-time parking availability and help to reduce traffic instead of drivers blindly looking for a parking space (Casini, 2021). A remarkable example of the role of BAS in reducing energy use is Google's DeepMind AI, which reduced the electricity use for cooling Google's data servers by 30% on average in 2016 (Chris Gamble, 2018).

A BAS supports the building's whole lifecycle as indicated by researchers in design, construction, operation and even retrofit phases. For example, during the design phase, the BAS enables HVAC simulation optimization, while in the construction phase, it reduces the energy consumption during construction and improves construction management, safety, and efficiency. During the operation phase, the BAS attains occupants' comfort and satisfaction, reduces operation costs, monitors the facility, and manages safety and security. During the retrofit phase, BAS quantifies the specific impact of the building retrofit, such as the building envelope, improvements to indoor environmental quality, and energy savings (Guofeng Qiang, 2023). BAS initial investment is not high, and the estimated payback period is between two and six years depending on the complexity and function of the BAS system (Association, 2023). The potential to reduce energy use by exploiting BAS in commercial office buildings is high especially if the occupancy is linked to work hours. Control of building systems such as HVAC, lighting, blinds, and louvres, and controlling office devices such as computers, printers, vending machines, and projectors through smart outlets that automatically turnoff unused devices and HVAC and lights in unoccupied spaces will reduce the unnecessary use of energy (Joshua Butzbaugh, 2021) (Giorgos N. Spyropoulos, 2011) (McKenney, 2010).

2.11 Post-occupancy evaluation

Modelling building energy use without occupant participation affects the accuracy of the energy measurement since the nature of human interaction is stochastic, and humans' behaviour in and interaction with their surroundings differ from one human to another. This is one of the factors that causes a gap between energy modelling and the real energy use post occupancy, which could lead to occupant dissatisfaction (F. Pan, 2018), (B. Dong D. Y., 2018), (M. Bisadi, 2018), (Troy Malatesta, 2022). Building automation controls building systems to efficiently provide the optimum home needs of HVAC, lighting, and water supply, and to provide maintenance, safety, and security to the occupants. Setting up a home automation design and schedule, however, should not neglect occupants' comfort and convenience at the same time as providing energy use efficiency. Comfort and convenience are vague terms, as they differ according to occupant preference. This is obvious since room temperature preference differs, as does lighting intensity and warm or cold light colour preference, AC/heater schedule, wake up/sleep schedule, and so on. Indeed, each person's needs and preferences change from time to time and over the seasons. This complexity in human nature and the changes in mood and desires should be addressed when designing and scheduling home automation.

Towards this end, POE has gained importance for designing building energy, verifying building performance, and measuring occupant satisfaction and convenience. Although building certification intent is designed in the preliminary drawings, it is not always checked and balanced during construction and throughout the commissioning phase. Many buildings have shown poorer performance post occupancy than in the energy modelling, and many of buildings are given the performance certification as designed but show less performance when tested and measured in the field. This gap in energy causes a shortfall in building performance and may result in occupant dissatisfaction even for highly certified buildings regardless of the massive use of energy for large scale buildings. POE has thus become an essential part of building performance evaluation and should be added as a mandatory part in the rating system evaluation and should have an impact on the overall certification process given that humans spend up to 90% of their lifetime indoors (N.E. Klepeis, 2001). POE, if added into the rating system evaluation, will certainly improve the accuracy of the building performance, collect data about occupant behaviour, provide better management of resources, improve Indoor Environmental Quality (IEQ), inform decisions based on feedback, and achieve occupant satisfaction (Peixian Li T. M., 2018).

There are some institutional POE protocols which are considered as landmarks for their comprehensive building performance evaluation in the building’s early design stage to post occupancy. Evaluation may contain energy-performance assessment, occupant-satisfaction comfort, air quality, acoustic, lighting, insulation, IEQ, and thermal comfort. It can be conducted by survey, interview, focus group, utility bills review, walkthrough, web-based, portable UFAD and an in-situ cart-and-chair equipped with sensing devices. Post-occupancy Review of Building Engineering (PROBE), UK, is considered a remarkable landmark in POE for building energy performance assessment (Peixian Li T. M., 2018).

Another remarkable pioneer in POE is the Center for Built Environment (CBE) Building Performance Evaluation (BPE) developed by the University of California, Berkeley, which uses an occupant satisfaction survey and reporting toolkit that has been used widely for measuring numerous indoor parameters. The integration includes sensors and software for the real-time evaluation of HVAC performance. It is also equipped with special capabilities for a detailed analysis of a building's underflow air distribution (UFAD) or displacement ventilation (DV) systems by aim of a mobile measurement cart and up to 70 sensors that may be installed in air flow diffusers. Mobile measurement carts are configured to collect a series of real-time data, which are made available in a timely manner and stored for historical retrieval. However, several field studies have shown that UFAD and DA are not commissioned in the optimum capacity and therefore they tend to consume more energy than is stipulated in the building's design. The reporting toolkit provides accurate information in real-time and data history storage to optimise building systems and energy performance (CBE, 2021).

Another pioneer in POE is the National Environmental Assessment Toolkit (NEAT), which was developed at Carnegie Mellon's Center for Building Performance and Diagnostics (CBPD). The Performance Measurement Protocol for Commercial Buildings (PMP) is another remarkable landmark that has three levels of measurements and has the most published data. In Asia, however, POE is rarely used although green and sustainable construction projects are thriving; this is probably due to the use of walkthrough check-ups and maintenance post occupancy.

2.12 Building Certification

Green building, or sustainable building, is a popular term for a high-energy performance building to attain optimum IEQ that satisfies occupants and provides comfort, safety, and security. For this purpose, building ratings and green label certification tools have been used to certify that a building is sustainable and has high-energy performance. However, building certification systems lack some sustainability aspects, such as testing toxic substances and emissions embodied in buildings and the infrastructure (Wangel, Wallhagen, & Malmqvist, 2016).

Feedback from tenants who have lived or worked in a building for several years or more and have experienced the living or working environment is a crucial tool to assess building performance even if it has been certified green and granted a green label.

Surveys have shown that in Singapore, for instance, buildings certified with the Green Mark and considered sustainable buildings have many limitations, and the feedback obtained from occupants showed dissatisfaction in several IEQ parameters. A survey from the CBE at the University of California, Berkeley, has been modified to form a survey tool that has been implemented in over 900 buildings and has gathered more than 90,000 occupant surveys to compare LEED- and non-LEED-certified buildings. The modified survey was distributed to 666 occupants in seven Green Mark certified commercial buildings in Singapore, and it was found that occupant dissatisfaction with sound privacy was the highest (42%), then personal control (32%), and temperature (30%) (Toby Cheung, 2021).

Sustainable buildings are designed to save energy, reduce the use of natural resources and adverse environmental impacts, and maximise occupant satisfaction and wellbeing. Studies and surveys have been conducted to verify if the green buildings perform better than conventional buildings in terms of energy saving and suitability as well as providing better living or working environments and IEQ. Some studies conducted a comparison between certified green buildings and non-green buildings and revealed that green buildings showed better energy performance while other studies showed the opposite; this is probably because of the high-occupancy rates of green buildings compared to non-green buildings. Xuechen Gui et al. collected a set of 2,657 certified green building data from the National Australian Built Environment Rating System (NABERS) and analysed the relationship between rating certification and energy performance. The study revealed that there is a linear relationship between performance indicator data and certification level for Energy Use Intensity (EUI), Emission Intensity (EMI), Water Consumption Intensity (WCI), and IEQ Score (IEQS). A rise in the certification level decreases EUI, WMI, and WCI but increases IEQS (Xuechen Gui, 2020).

A study was conducted by Newsham (2009) to answer a critical question regarding LEED-certified buildings regarding whether they are living up to expectations in energy performance after being constructed. The study acquired data from the New Buildings Institute (NBI) and the US Green Buildings Council for certified commercial and industrial buildings. They found that LEED buildings use 18-39% less energy per floor area than conventional buildings. The also study revealed that the energy performance of the buildings has little correlation with the certification level, or the number of energy credits granted to buildings at the design phase. The study calculated statistically the data collected from LEED-certified buildings and found that there is no significant relationship between the certification level and EUI saving. That means a building with a Gold or Platinum LEED certificate does not signify less EUI than a building with a silver LEED certificate (Guy R. Newsham, 2009).

Furthermore, Professor Josef Lstiburek (2008) criticised many green buildings for consuming more energy than conventional buildings and stressed that any building has to stand up, resist winds and hurricanes; be flexible in earthquakes; be fire resistant and rainwater proof; not become mouldy; not rot; and not corrode; and has to meet applicable building codes, so providing green awards for the basic building requirements that are literally required by codes to be called buildings is a pointless practice. Hence, the use of green programmes wastes time and money on things that are irrelevant or unimportant and do not save energy, while some practices have proved to consume more energy such as a glass façade (Lstiburek, 2008).

The NBI is considered to be the most comprehensive LEED database for U.S. high-performance buildings. While being credited for publishing open-source data, the NBI is criticised for being biased on data collected voluntarily from building owners. The fact that the NBI focused on so-called “medium energy” LEED buildings and ignored data from buildings with higher EUI resulted in the conclusion that the mean EUI of the buildings is lower than other commercial buildings whereas the opposite is true. Analysis for NBI LEED energy-consumption data was conducted from energy sources and energy consumption on-site and off-site to measure use in the building and energy loss due to distribution; the result was that a LEED-certified building, on average, does have lower source energy consumption and therefore does not reduce the carbon footprint. However, with on-site energy, on average, LEED-certified buildings use less energy than non-LEED buildings, and the saving is between 10-17%. It is worth mentioning that the majority of LEED-certified buildings use less energy than their counterpart non-LEED buildings; however, a few large LEED offices are not using less energy than their non-LEED counterparts (H.Scofield, 2009).

In Oman, there is no certification programme for building performance except an incentive programme for buildings that integrates solar panels on the buildings' rooftops. Power supply companies provide a list of qualified contractors for solar panel installation and then connect the grid to the main distribution line. The maximum allowed grid capacity to be installed on a rooftop is 50% of the building electrical load. This is entirely used after consuming the first 50% of non-green electric supply from the utility companies. Only if the consumption exceeds the 50% of non-green electricity, will the remaining supply use solar-generated power, and the surplus will be taken and used by the power supply companies. Therefore, this policy does not encourage the use of green energy since the use of generated power cannot exceed 50% of the total building load, and the consumption of generated solar power is allowed to be used only after consuming the power share provided by the utility company. This approach promotes heavy use of non-green energy in order to reach the credit of the solar power system and has a heavy impact on sustainability and the use of green energy.

2.13 Energy Design and Post-occupancy Gap

It is common that the energy performance for a building during the design-construction phase shows gaps when the building is being used. This is because the use of the building is subject to occupants' behaviours and is density dependent especially in institutional buildings. Utilising the conventional EUI (kBtu/sq. ft) is not an accurate measure for buildings with variable occupant density. There are several approaches to address this gap: having an occupant lifestyle history and using it as a benchmark to identify the average occupant's energy consumption would reduce the gap between energy modelling and actual energy use post occupancy. Calculating actual occupancy in a building, however, is necessary to maintain the energy use, and this could be achieved by many techniques, such as fisheye cameras, radio frequency, Passive Infra-Red (PIR), CO_2, GPS, and Device-Free Localisation and Activity Recognition (DFLAR). By applying a deep learning method, Wang J. et al. (Wang J., 2017) leveraged DFLAR deep learning to recognise location, activity, and gesture, which achieved 85% accuracy. An advantage of DFLAR is that it does not need the target to be equipped with a device, and nor does it interfere in occupants' privacy, which promotes its use for many smart applications.

BAS limitations can be mitigated through the following recommendations:

1. BAS modelling and simulation, as discussed in Section 2.7: Global Energy Use and BAS for Energy.
2. Post-occupancy Evaluation as a tool for re-setting and programming of BAS to optimal occupancy satisfaction as discussed in Chapter 4: POE survey.
3. Occupant lifestyle history, as discussed in this section.

2.14 Conclusion

Research has shown that large-scale, green-certified buildings consume more energy than their conventional counterparts; however, certified buildings have a better energy performance in general. Furthermore, the energy performance of buildings post occupancy is usually less than that of their energy design preconstruction. This sometimes happens because of a higher occupancy rate than that calculated in the design phase and because occupants' stochastic behaviour and lifestyle contribute to the energy gap. BAS deployment is not the sole solution for the energy gap since a BAS only manages, controls, and integrates building systems to enhance the living experience and optimise energy use. To overcome this limitation, it is essential that benchmarking occupants' behaviour be embedded in an early energy design to reduce the energy gap between design and post-occupancy energy use. This requires the integration of occupant behaviours into historical data, analysis, and calculation to add an occupant lifestyle coefficient in the energy design. Thus, BAS modelling and simulation has to be considered during design phase.

To answer research question 1 *What techniques and measures can be applied to Omani buildings to reduce energy use and attain occupant satisfaction?,* this chapter conducted a holistic review that tackles building performance issues from the design phase through construction and post-occupancy and beyond by utilizing an aged building to exploit the demolished debris for recycling the materials.

Preconstruction Phase: In this phase, there are important aspects to be considered in the design stage. Sustainable building materials should be embedded in the drawings to ensure the selection of such materials during the construction phase. Building orientation for passive design is another important aspect that considers sun and wind for better building energy performance. For example, building orientation should consider sun direction in the design phase so that bedrooms and sitting areas where occupants spend most of the time could be designed to be on the internal part of the building and away from those walls that are directly hit by sunlight (Section 2.5).

Construction phase: Choosing sustainable alternatives from the market in the construction phase will help to gain robust control of the indoor environment with optimum energy use. For example, choosing sustainable materials, such as LECA bricks, which contain additives and microporous materials that hinder heat exchange, will reduce thermal conductivity and maintain indoor temperature control compared to concrete bricks, which have high thermal conductivity. There should be mandatory codes for the use of insulation especially on external walls and the building envelope and a mandatory code for the use of double- or triple-glazed UPVC windows instead of aluminium windows, as research has proven that UPVC has less thermal transmission. Another recommended practice is to install insulation on the roof slab and the application of a white colour exterior protection coating to reflect sunlight and reduce thermal transmission (Sections 2.5 and 2.6).

Post-occupancy phase: This should consider the use of building automation to optimize energy consumption especially in lighting and HVAC. Aged buildings can be utilized by recycling building materials to achieve the materials' sustainability goal and reduce the carbon footprint (Section 2.10).

This chapter answered research question 1 through a holistic review of building performance and by recommending state-of-the-art sustainable building materials and sustainable practices, and by exploiting technology to enhance building energy performance. It was found that, in the preconstruction phase, sustainable building design should consider embedding sustainable building materials and sustainable building techniques and practices in the construction drawings. The construction phase should ensure the use of the sustainable materials that were embedded and specified in the construction documents as a sustainable material alternative even if they are more costly since these products have minimum or no impact on the environment. Practising sustainable construction methods, such as the use of precast walls to reduce site waste, reducing transportation and CO_2 emissions, utilizing recycled and recycling materials, installing wall insulation, and selecting tinted double-glazed windows, are some examples of sustainable building practices. In the postconstruction phase, strategies include exploiting BAS in building management to manage building systems, optimize energy use, and achieve an outstanding living experience. Aged buildings could be utilized in material recycling after demolition as nowadays even concrete is being recycled for reuse, and recycling such materials is cheaper and more ecological.

This chapter has also contributed to answering research question 5: *What can be done to allay the concerns that occupants have over the deployment of building automation systems?* The contribution of this chapter is through a review of low building energy performance throughout building cycle aiming at identifying the causes of low energy performance and exploring the potential and practices to enhance building performance and attain occupant satisfaction. Awareness of sustainable building design, sustainable building process and exploiting BAS and BMS to tackle building energy performance are crucial measures and practices to enhance building performance to allay occupants' concern about the increase in the energy cost of their dwellings. All the practices, recommendations, and measures mentioned in this chapter provide the potential to reduce energy use, implement robust control of buildings, enhance the occupancy experience, and improve occupants' health, comfort, and convenience. Solving the challenge of improving building energy performance is particularly difficult in that low performance can occur because of the many reasons originating at different stages of the construction process. Furthermore, this literature review tackled building performance challenges in a holistic approach from preconstruction to post-occupancy utilizing state-of-the-art sustainable materials, employing technology, and recommending sustainable measures and practices to encourage the design and construction of sustainable buildings, enhance building energy use, and reduce the carbon footprint (Sections 2.3 and 2.10).

This chapter documented the causes of low building energy performance and recommended sustainable practices and technologies that can enhance building energy consumption . All the mentioned advanced sustainable building materials, sustainable building process and exploiting of technology such as utilizing BAS have contributed to raise occupants' awareness on the BAS potentials to enhance building energy performance. Additionally, this chapter has documented the promising results of BAS deployment and the realised saving in energy use which contributed to allay occupants' concerns (Section 2.10).

Occupants' concerns are tackled in this chapter by familiarising them with and reassuring them about the role of home automation in enhancing their dwelling performance, attaining robust building control, and improving their living experience and comfort.

The literature review conducted in this chapter will be utilised to design a POE survey in Chapter 4 which will be distributed to occupants in Oman. POE data will provide insights to answer the second part of research question 5 concerning the obstacles that hinder widespread automation in Oman, and it will allow the research community to evaluate the automation market, initial cost and maintenance, occupants' behaviour, and safety and security concerns, setting out the road map for future work as it will be discussed in Chapter 6.

To this end, this literature review identified occupants' awareness of and readiness to deploy home automation for energy consumption purposes. It explored state-of-the-art sustainable building materials and techniques to enhance building energy performance as a holistic process in all building stages from the design phase, the selection of sustainable building materials, the implementation of sustainable building practices, and the exploitation of materials' lifecycle in aged buildings (Casini, 2021), (Kedar Mehta, 2024), (Xinyue Wang, 2024), (Berta Garcia-Fernandez, 2023), (Yamna Soussi, 2023).

The Omani building code was critically reviewed with the aim of enhancing building practices to exploit sustainable building design, sustainable building materials, and sustainable building processes. Exploring building energy enhancement and occupants' comfort and satisfaction is the main goal of this thesis.

3 Chapter 3: Research Design and Methodology

3.1 Introduction

This chapter covers the research background and key theories of research methods. It also defines the approach followed to conduct this research. The research questions of this thesis are stated, and the methodology followed to answer each question is described. The methodology in this thesis comprised a POE survey and a case study that entailed data collection, analysis, and interpretation to solve and answer the research problem and answer the research questions.

The remainder of this chapter provides a brief background of research methodological options and Saunder's 'research onion' as a prominent research philosophy and approach to theory development. It discusses three types of research philosophy assumptions, namely, ontology, epistemology, and axiology and examines the research methodological choices. Furthermore, this chapter elaborates on the motivations and triggers for this research and the paradigm that led to the research hypothesis and questions. Finally, the reasons for making these methodological choices are justified, and a research plan is outlined dividing the research into three main phases.

The research questions are tackled utilizing Saunders' Onion research methodology, the overarching research philosophy used two paradigms: positivism, which is concerned with facts that are obtained from scientific physical/natural measurements and laboratory experiments, and interpretivism, in which the reality is subjectively constructed through the understanding of the participants' views. Two approaches were adopted to answer the six research questions; these were a deductive approach, which entails testing the research questions' validity with existing theories and hypotheses, while an inductive approach, which involves constructing theories and hypotheses, was used to tackle some questions. Some questions were answered using a quantitative method, which relies on measurable data and interpretation, while other questions were answered by the qualitative method, which relies on description and analysis. Three strategies were used to answer the research questions: a post-occupancy evaluation (POE) survey, a case study, and archival research through the literature review

3.2 Research Background

Research is defined in the Oxford English Dictionary as a “systematic investigation or inquiry aimed at contributing to knowledge of a theory, topic, etc. by careful consideration, observation, or study of a subject (Dictionary, 2024). In later use also: original critical or scientific investigation carried out under the auspices of an academic or other institution.” One of the most frequently used approaches to research is the ‘research onion’ introduced by Mark Saunders, Philip Lewis, and Adrian Thornhill.

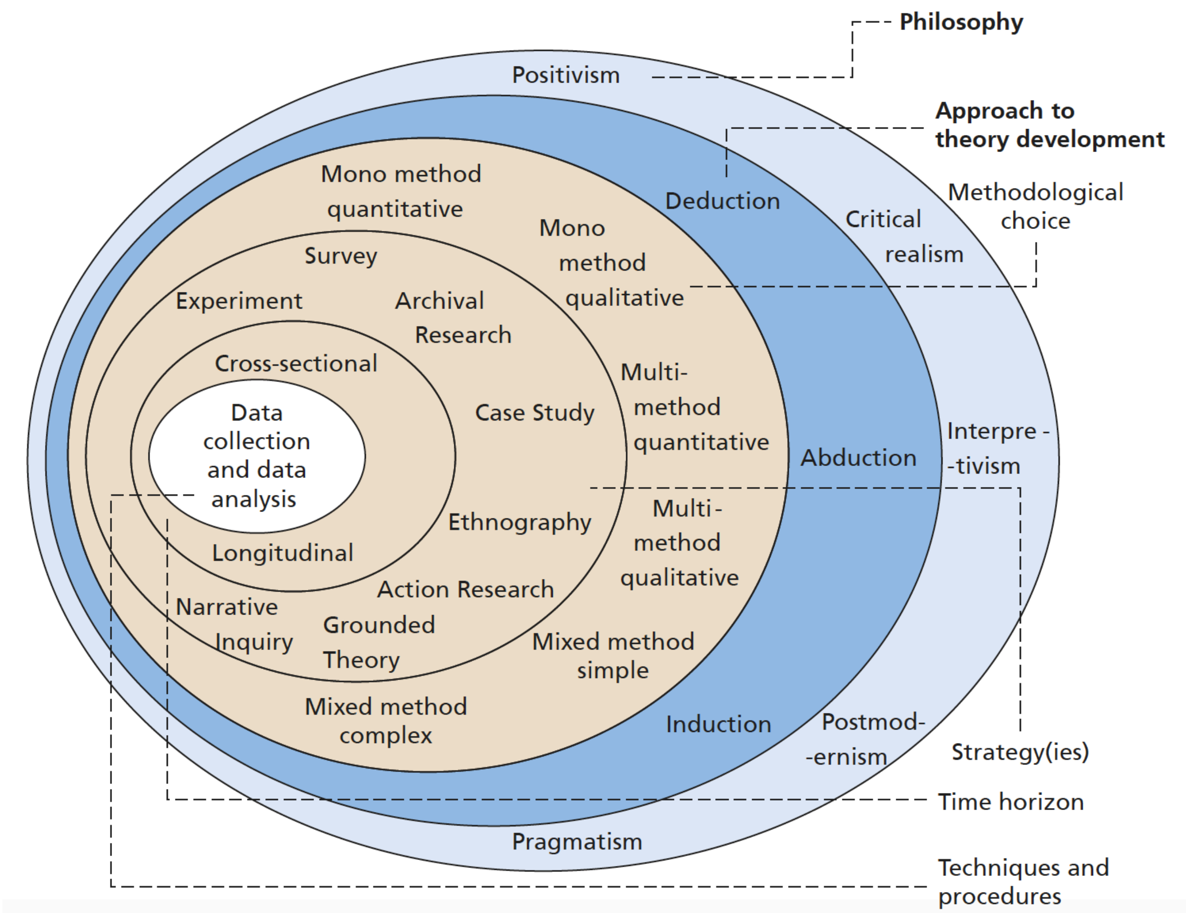


Figure 3.1 Saunders’ research onion shows research plan choices for developing a research methodology (Mark N.K. Saunders, 2019).

The research onion consists of six layers as shown in Figure 3.1, and each layer is a stage in the research journey.

The first layer is the research philosophy, which refers to a system of beliefs and assumptions about the development of knowledge (Mark NK Saunders, 2018). The research philosophy is the researcher's opinions and views of understanding the world and their intent, motivation, and expectation (Noella Mackenzie, 2006) and interpretation of things; this will influence the research strategy, which is the plan or method adopted to conduct the research. The planning and design stage, which is contained in the outer layers of the onion, is the most important part of the research in order to reach the core layer, which is data collection and analysis (Arunaditya, 2016). There are several assumptions regarding the research philosophy, but we will consider three types of assumptions: ontology, which studies the questions of existence; epistemology, which studies knowledge and knowing; and axiology, which studies values and morals (Mark N.K. Saunders, 2019).

It is crucial to have a clear understanding of the philosophical basis for the research strategy that is to be followed by the researcher. This helps to determine whether the research design is suitable to address the research questions; to provide a grounding for research methods, which set a benchmark between academic work from lay knowledge (Hines, 2000); and to create a design that goes beyond past experience (Easterby-Smith M., 1994). The research philosophy also guides the approach of the research and develop its methodology. The term 'research paradigm' is used interchangeably with the term 'research philosophy', and there are different methodologies depending on the discipline and the approach of the researcher to identify the research aims. These methods are positivism, pragmatism, and interpretivism.

Positivism is concerned with the facts that are derived from scientific physical/natural measurements and laboratory experiments; its results and analysis are quantitative in nature, which emphasizes objective measurements and the statistical, mathematical, or numerical analysis of data collected through polls, questionnaires, and surveys or by manipulating pre-existing statistical data (Babbie, 2012) (Muijs, 2010). The knowledge can be obtained through objective observations and emphasises the empirical method used in the natural sciences (physics, chemistry, and biology) (Ponelis, 2015), and the researcher should be impartial in conducting their research (Gray, 2018).

On the other hand, following interpretivism, the reality is subjectively constructed by the researcher through the understanding of the participants' views (Mark N.K. Saunders, 2019) (Onwuegbuzie, 2004), and it is conducted using the qualitative approach (Guba, 1990), which generally involves unstructured and non-numerical data (Mason, 2002) using "why" and "how" questions (Myers, 2009), such as collecting data from focus groups and interviews for descriptive and exploratory studies (Mouton, 2001).

However, pragmatism takes a middle approach combining both quantitative and qualitative measurement and analysis. Some of the research questions cannot be solved by using only a positivist or interpretivist approach, as they are multi-dimensional and require both qualitative and quantitative analyses. Pragmatists claim that the research issue is the most crucial part of the research theory, and so it has led practitioners and researchers to produce a knowledge-based organization (Baškarada, 2018).

The second layer of Saunders' research onion is regarding the three research approaches: deductive, inductive, and abductive. The deductive approach is utilized when the theories and hypotheses are available, and the research questions are tested to validate them. In contrast, with the inductive reasoning approach, theories and hypotheses are constructed. Meanwhile, the abductive reasoning approach focuses on collecting data to identify themes and explain patterns to generate a new or to modify an existing theory (Mark N.K. Saunders, 2019)

The third layer focuses on the selection of a methodological approach; this could be qualitive, which relies on descriptions and analysis; quantitative, which relies on measurable data and interpretation; or a mixed approach, which contains both qualitative and quantitative methods (Bryman, 2006) (Alan, 2007) (Dilanthi Amaratunga, 2002).

The fourth layer of Saunders' research onion is the selection of the strategy for conducting the research, which could be through a survey, laboratory experiment, archival research, a case study, ethnography, action research, or grounded theory.

The fifth layer concerns the research timeline. It can be cross-sectional, which involves the study of a particular phenomenon at a particular time, or longitudinal, which involves conducting research over a period of time with two or more repeated measurements for the same sample population (Mark N.K. Saunders, 2019).

The final layer is about the techniques and procedures used for data collection and data analysis. The aims of this research are fulfilled through a logic methodology that has to address and justify several aspects of the research strategies used to achieve its objectives.

3.3 Hypothesis and Research Question

The hypothesis analysed in this thesis is as follows:

The use of building automation systems (BAS) has the potential to achieve a significant reduction in energy use in dwellings in Oman.

This will address the following research questions:

1. What techniques and measures can be applied to Omani buildings to reduce energy use and attain occupant satisfaction?
2. From an occupants' perspective, is energy consumption of buildings in Oman too high?
3. Are building owners in Oman familiar with and ready to deploy building automation systems in their dwellings?
4. From the perspective of occupants, what is seen as the obstacles for the deployment of automation systems?

5. What can be done to allay the concerns that occupants have over the deployment of building automation systems?
6. What are the potential energy improvements that can be realised through the deployment of building automation systems?

3.4 Research Design

Saunder's research onion (figure 3.1) is used in this thesis for research methodology as one of the prominent research philosophies and approaches to research development. From this figure, the choices for the methodology followed in this thesis are highlighted in figure 3.2.

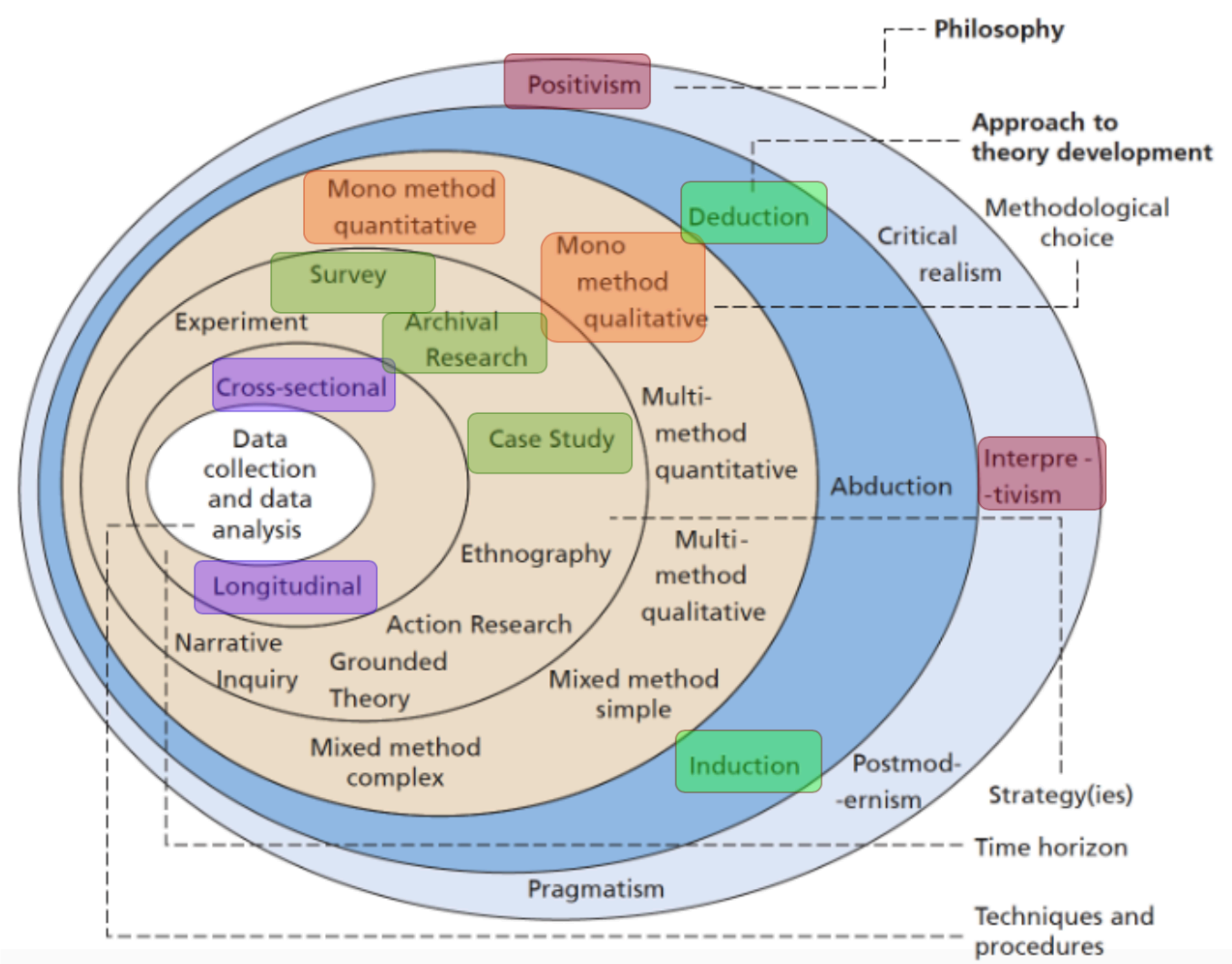


Figure 3.2 Research plan choices from Saunders' research onion

To evaluate the hypothesis and answer the research questions, a pragmatic approach that combines positivism and interpretivism was followed as indicated in Figure 3.2. The overall research approach of this thesis uses deductive reasoning in which theories and hypotheses are explored and the research questions are tested to validate them. In this research, the problematic questions of the hypothesis that energy consumption is too high in Oman buildings and the hypothesis that automation as an alternative will reduce energy consumption are tested and validated. The research also uses the inductive reasoning approach regarding the questions involving the occupants’ perspective. This takes the form of eliciting recommendations for the Omani building code to enhance building performance and to find solutions for existing challenges that the Omani construction sector faces to help improve building energy performance and attain occupant satisfaction.

Quantitative analysis and the interpretation approach are utilized to emphasize objective measurements and the statistical, mathematical, or numerical analysis of data. This is applicable to research question 1, which is concerned with the techniques and measures that can be applied to reduce energy use and attain occupant satisfaction, and to research question 3, which is concerned with measuring the readiness level of building owners in Oman to deploy automation. A quantitative approach is also applicable to research question 6 regarding the potential energy improvements that can be realised through the deployment of building automation systems since there will be a measurement and comparison of energy use.

On the other hand, the qualitative analysis of the occupants’ perspectives was conducted through the gathering of occupants’ views. Occupants outlined their views about energy consumption in research question 2. Research question 4 also required the gathering of occupants’ views on the obstacles of BAS adoption. Furthermore, a qualitative analysis approach is applicable to research question number 5, which requires an analysis of how occupants’ concerns over the deployment of building automation systems can be allayed.

Archival research was used to answer research question 1 and as support in answering research question 5. The POE survey was used to gather information and data from occupants to answer research questions 2, 3, 4 and 5. Research question 6 was addressed through conducting a case study including a comparison of data between pre-occupancy and post-occupancy.

As for the time horizon, all research questions were addressed longitudinally except questions 3 and 4, which were addressed cross-sectionally.

Table 3.1 summarizes the research strategy for each of research question. The choices selection from Saunders' research onion indicates the strategies to tackle each question in terms of the research philosophy, the research approach, choices for the typical method of analysis, the approach strategy, and the time horizon.

	RQ1	RQ2	RQ3	RQ4	RQ5	RQ6
Philosophy overarching pragmatist view	Positivism	Interpretivism	Interpretivism	Interpretivism	Positivism	Positivism
Approach	Deductive	Deductive	Inductive	Inductive	Inductive	Deductive
Choice	Quantitative	Qualitative	Qualitative	Qualitative	Quantitative	Quantitative
Strategy	Archival research	POE survey	POE survey	POE survey	Archival research	Case study
Time Horizon	Longitudinal	Longitudinal	Cross-sectional	Cross-sectional	Longitudinal	Longitudinal

Table 3.1 Research questions tackling strategies

3.5 Research Plan

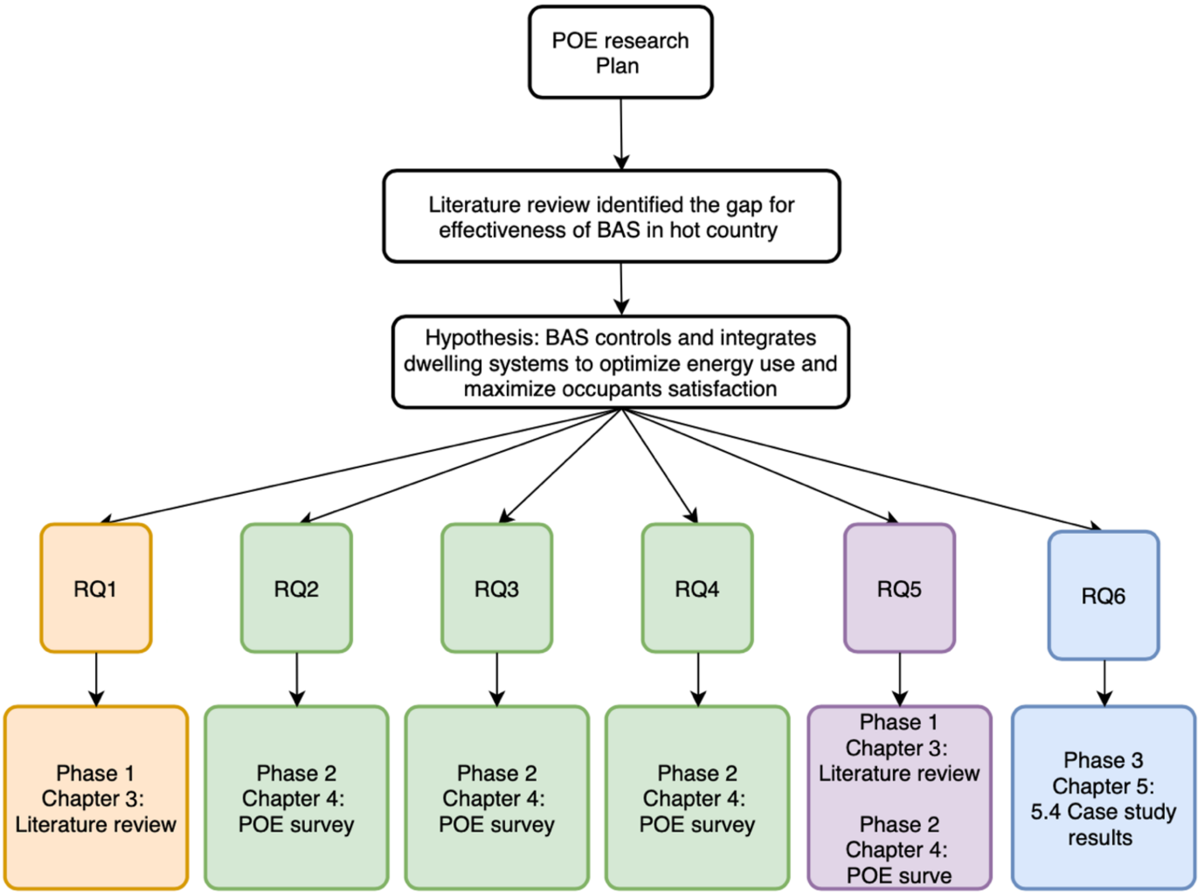


Figure 3.3 Research plan

This research involves three phases:

Phase 1: This phase involves a literature review covering the key concepts and architectures that serve as an introduction to the later chapters. It provides a thorough review of the state-of-the-art in (1) future sustainable building materials, (2) the smart home concept, (3) BAS, (4) IoT architecture, (5) building certification, (6) POE, and (7) building energy design.

This phase aims to answer research question 1 and elements of research question 5 through literature review (Chapter 2) by suggesting techniques and measures that can be applied to enhance building energy performance and consequently attain occupant satisfaction; these can be used to address and improve the challenges of energy use in Oman. The recommended techniques and measures cover the whole construction process starting from preconstruction, such as building orientation, and continue through construction into post-occupancy.

Phase 2: In this phase, a POE survey was conducted with 105 occupants living in Oman. The survey was designed to obtain information about building performance in Oman as well as occupant satisfaction levels and their concerns. The strategy used in the survey sampling is Stratified Random Sampling since there was a set of criteria for participation. The criteria are; (a) the occupant must be resident in Oman and (b) the occupant age is between 18 and 65 years old.

The survey was distributed by WhatsApp to 230 private and public participants in Oman with a note that this survey is for the purpose of conducting academic research targeting residents in Oman. The demography of the participants' age was grouped into 6 age groups and the number of participants in each group is summarized in Table 4.1. The survey also revealed that, of the participants that gave their gender 92 were male and 11 were female. The survey results also revealed that 87% of participants owned the dwelling they lived in.

The survey data was collected utilizing Microsoft forms. The data is then analysed, and this analysis used to support answers several of the research questions. The results of the analysis were also validated through the literature review by comparing the survey results with the data obtained from previous research papers. The obtained responses evidenced occupants concerns in multiple questions in the survey. For instance, the gathered information on dwelling indoor environment quality (IEQ), and the willingness of the occupants to enhance their building.

The data showed a consistency in the responses by analysing the percentage of participants who were interested in a certain aspect as in the (IEQ). The detailed and overall data showed a clear pathway of the occupants' concerns which paved the roadmap for the thesis outcomes. *In terms of validating the result of the survey, the quantity of the results was checked against similar studies and found to be similar. Peretti C. conducted a case study in northern Italy to evaluate indoor environmental quality (IEQ) utilizing web-based occupant satisfaction survey. The survey was sent to*

160 occupants; 81 participants submitted their questionnaire (Peretti C., 2010)*. Xiaodan H. conducted a post-occupancy evaluation for indoor environmental quality of sport buildings at hot and humid climate from the perspective of exercisers. There were 125 participants in this survey* (Xiaodan Huang, 2022)*.* The given references and analysis of their surveys demonstrates that the number of responses for this work are in line with other similar studies and thus, confidence can be had that these results are representative.

The survey obtained information and data about building automation and occupants' perception of their dwellings and their readiness to enhance energy performance. Additionally, it explored the level of automation in the dwellings and occupants' level of readiness to deploy building automation. The survey also evaluated building system performance in the dwellings, such as HVAC, lighting, safety systems (fire, smoke, and gas), security and access control, surveillance, indoor air quality, and waste management.

This phase answers research questions 2, 3, and 4 identifying occupants' perspectives on the cost of energy in Oman, the perception and readiness level of building owners for automation deployment, and occupants' perspective of what are seen as the obstacles for the deployment of automation systems.

Phase 3: This phase involved a case study to test the feasibility of building automation in achieving a reduction in energy use in Oman by collecting and comparing energy use data for a dwelling before and after automation deployment. This will address the gap in the effectiveness of BAS in Oman and the GCC region in reducing energy consumption during the summer when temperatures can reach 50°C and the impact of BAS on occupant satisfaction and convenience given that BAS aims at reducing energy consumption and maximising occupant satisfaction.

This phase addresses research question 6 by comparing energy use pre-automation and post-automation and thus calculating the potential energy improvement.

3.6 Conclusion

In this chapter, Saunders' research onion was utilized to develop the research methodology for this thesis by choosing the appropriate and relevant methodological options to address the research questions. A pragmatic approach of positivism and an interpretivist paradigm were utilised. Some questions were addressed by quantitative analysis while others were addressed by qualitative analysis. A POE survey and a case study were selected as strategies to conduct the research. The research was organised in three phases, namely, literature review, POE survey, and case study, and the methodological choices were justified.

4 Chapter 4 Post-Occupancy Evaluation Survey

4.1 Introduction

This chapter covers the use of the survey as the methodological approach used to collect data from occupants in Oman. As indicated in Chapter 3, which explored the methodology, a POE survey was used to gather data and information from occupants related to their dwellings. This chapter aims to answer the following research questions:

- **Research question 2**: From an occupants' perspective, is the energy consumption of buildings in Oman too high?
- **Research question 3:** Are building owners in Oman familiar with and ready to deploy building automation systems in their dwellings?
- **Research question 4:** From the occupants' perspective, what are the obstacles for the deployment of automation systems?
- **Part of research question 5**: What can be done to allay the concerns occupants have over the deployment of building automation systems?

To answer these questions, a survey was conducted with 105 occupants to obtain information about their dwellings and building performance, and to assess their readiness to deploy technology for building management.

The research questions are answered through the strategy and approach identified in Chapter 3. A summary of how the research questions were tackled is given in the next section. The strategy and structure of the POE survey particularly for the evaluation of Omani buildings is elaborated on, and the methodology for obtaining data is clarified in Section 2.4. Finally, the research questions are answered using data from the POE survey and supported with facts in Section 4.5, which analyses the survey results.

4.2 Research questions strategy

A survey methodology was chosen to answer the above research questions because the data to be collected required the occupants' perspective depending on their specific circumstances. This was achievable only through a dynamic survey that used conditional branching logic that would change according to the responses. This was important to get very specific information about dwellings from a personal perspective. Hence, the survey seemed to be an evident choice for obtaining personal perspectives and beliefs (Della Porta D, 2008).

Furthermore, it was decided that a survey would best fit the interpretivist philosophy chosen to tackle research questions 2, 3 and 4 using a qualitative approach since the reality is constructed through the collection and subsequent understanding of occupants' views. Hence, the questions in the survey were designed to obtain occupants' views. Research question 5 is answered in two parts. The first part was tackled in Chapter 2 (Sections 2.3 and 2.10) through a qualitative approach utilizing archival data obtained from the literature review. The second part is tackled in this chapter by identifying the research gaps regarding the obstacles that hinder widespread automation and it indicates directions for further research in this field.

Research question 2 is tackled by a deductive approach where the theories and hypothesis are established, and the research question is tested to validate it. On the other hand, research questions 3 and 4 are tackled by an inductive approach which focuses on collecting data to identify themes and explain patterns to generate a new or to modify an existing theory. The research questions are summarized in Chapter 3, Table 3.1.

A survey is a technique used to collect data from the respondents through predefined questions that provide the research with information that can be evaluated and interpreted (Ponelis, 2015). POE is one of the strategies used in this research to collect information from the occupants and utilise the data for outcomes and recommendations. POE is a popular survey that helps real estate stakeholders and owners to evaluate their building from the users' perspective. The feedback from users helps building owners understand their building performance, building maintenance, and enhancement requirements in real time by responding to imminent faults or scheduling future maintenance. POE is an essential tool for business sustainability since occupants' feedback calls for action to improve building performance and occupant satisfaction and therefore facilitate continuous tenancy in the building. Communication with occupants in high-rise residential buildings is difficult to manage due to the big number of occupants, and therefore, POE can be used to address occupants' demands and complaints in a timely manner in addition to the long-term during the operational phase enhancement plan for building performance.

The POE survey is essential for enhancing building performance through occupants who have experienced the building and so have a better understanding of the space they live in. Users' convenience and satisfaction is crucial for a business to continue in any market, and this is especially true for real estate and building management. Therefore, occupants' feedback about building performance, the issues they face, and any complaints they have should be considered to improve the building and services and attain their satisfaction through the timely response to any claim or maintenance request. This is in addition to pre-occupancy satisfactory parameters, such as room design and layout, and IEQ, which includes air quality, light intensity, temperature control, humidity, and security. To achieve this, home automation plays an important role to control and manage all the aforementioned parameters.

POE is conducted for numerous direct purposes and aims at design evaluation, occupants' evaluation, energy performance evaluation, IEQ evaluation, and facility evaluation. Furthermore, POE is conducted for other indirect purposes and aims at identifying issues such as the need to rectify defects, provide future retrofit projects, inform building software or the development of a questionnaire, provide bases to obtain guidelines or standards for building systems such as lighting and HVAC, or to test existing green building standards. It is also used to assess the effectiveness of building technology and validate building models, such as thermal-comfort models and glare-probability models.

The POE survey was utilized to collect data about building performance from the occupants' perspective. The collected data provided crucial information about building performance and occupants' perception of and readiness to enhance and deploy home automation in their dwellings to reduce energy consumption. To get the answers from occupants that would help to answer the research questions, the POE survey was designed to contain questions about indoor temperature control and the willingness to reduce the energy consumption cost. There was also a question about the benefits expected from automation deployment, a question about each occupant's opinion regarding whether automation will reduce electricity bills and increase safety, security, and comfort. All these questions allow the occupant to provide insightful answers to prove or reject the hypothesis that automation has the potential to achieve a significant reduction of energy use in dwellings in Oman. Thus, the survey contained questions to test the automation awareness of building owners in Oman and their willingness and readiness to deploy automation in their dwellings.

It is essential to address methodological choices that are used to 1) collect general data from occupants aged between 18 to 65 years old, 2) collect data about the dwellings in Oman and assess their performance, 3) assess occupants' perception about their dwellings, 4) motivate occupants to enhance their dwellings' performance, and 5) motivate occupants to explore new building techniques, sustainable building materials, and building measures that would improve building energy performance, enhance living experience, and attain comfort and satisfaction. To achieve these aims, participants must be involved in the research to get feedback from them and collect the essential data required to address these research questions.

The decision to use a survey to collect data is part of positivism and is the result of using a quantitative approach to obtain accurate data that can assist in quantifying the results and extracting factual evidence to tackle the problematic questions of this research. The survey was designed to be in three sections to gather information from occupants in Oman who potentially own dwellings and have a decent living experience and so could provide real insights about the dwelling they were living in.

Utilising big data obtained from carts with sensors requires special visualisation software, with some POE using carts that take measurements in short intervals over a long period of time. Such amounts of environmental condition data about the building are not easy to understand and not communicable for many people. Therefore, digital visualisation is a powerful way to interpret, understand data, achieve accuracy and easy comparison of different spaces in the building through use of three-dimensional and four-dimensional models (Patlakas, 2014). In this research, purposive sampling of occupants was used since the targeted occupants potentially owned their dwellings so they could sustainably enhance their dwelling and could deploy building automation to achieve the aims of this research. This technique of selecting a specific sampling method provided the focused information to answer the research questions and achieve the aims and objectives of this thesis.

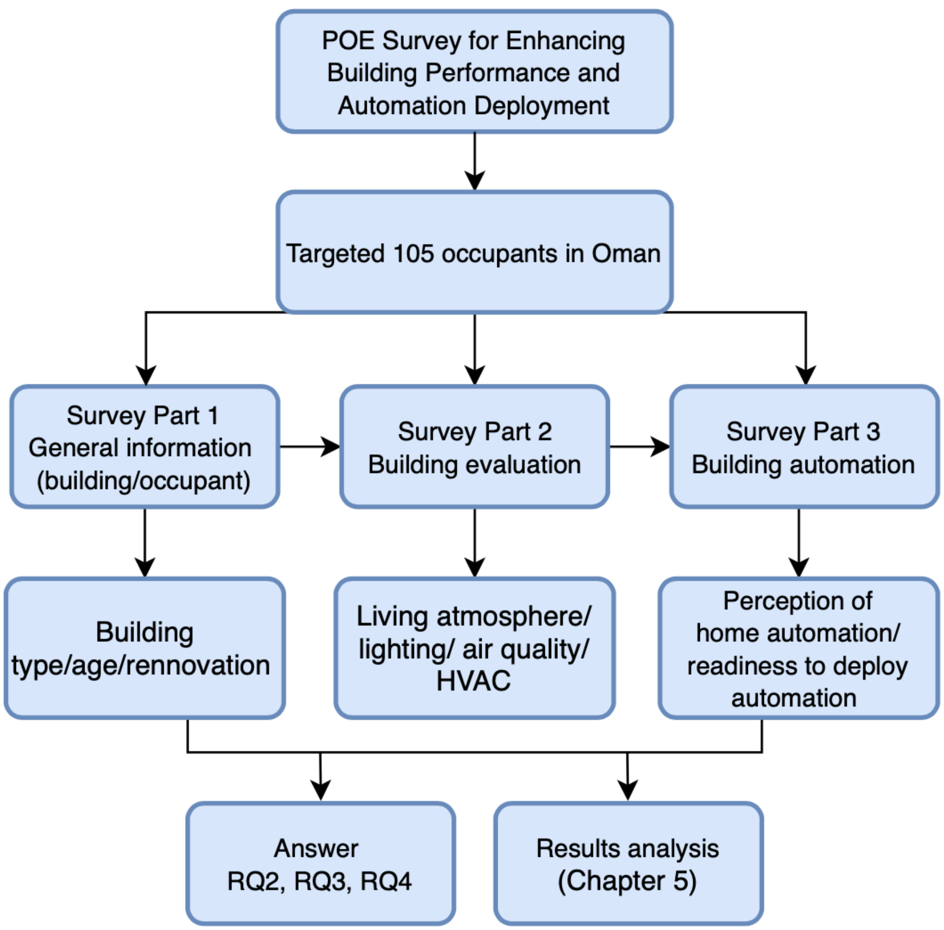


Figure 4.1 Flowchart for data-obtaining methodology

POE is conducted through several methodologies varying from subjective methods to physical in-situ measurements. Subjective methods include the occupant survey, which is the most widely used method for data collection, interview, and walkthrough to identify issues. Meanwhile, physical measurements include in-situ measurements (thermal condition, lighting, IAQ, and acoustics) and energy and water assessment. In general, subjective methods are less costly, as there is no requirement for in-situ measurements and equipment, and they are easy to conduct by digital distribution such as using a link participants can use to access the survey, answer the questions, and submit it immediately by clicking 'submit' at the end of the survey. It mostly contains Likert-style open-ended questions to gather information from occupants. The replies are usually available immediately even from mass participants, and the data are digitally easy to access, and are saved securely in the Cloud for future retrieval. Some software programs are smart and provide insightful data results and a communicable analysis of the collected data, and can generate basic graphs and charts. In this thesis, Microsoft forms was utilized in the survey design and distribution, and in data collection.

Understanding and assessing building performance in Oman requires data collection from buildings, utilities providers, field measurements, and occupants' feedback. The perception of building performance by occupants and their ability to evaluate the dwelling they live in is an important tool to assess and enhance building energy performance and building renovation, and to exploit all tools and measures, such as the use of BAS and of sustainable building materials to optimise building performance and attain occupant satisfaction. Hence, the POE survey was used in this research to collect information from the occupants and utilise the data for outcomes and recommendations.

The POE survey in this thesis was designed to allow the information to flow from basic to deeper concepts and to gather information related to the occupants-building relationship which helps in understanding occupants' perception of the building performance without detriment to any person's privacy, as this research fulfils the Cardiff University Research Integrity and Governance Code of Practice. POE evaluates the during the operational phase building energy performance from preconstruction to post-occupancy and provides awareness about energy saving practices and measures that are intended to motivate the participants in the survey to explore and understand some sustainable concepts that, if implemented, would enhance their dwellings' energy performance. Research questions 2, 3 and 4 were answered through the POE survey and the supporting literature review.

4.3 Post-occupancy evaluation survey design

The POE survey distributed to the participants consists of 32 questions divided into three sections, and the questions are multiple choice, Likert-type questions, and short-answer questions. A branching logic is used for dynamic questions whereby the choice of question is made according to how the occupants respond. The survey was designed to motivate occupants to evaluate their dwellings from several aspects, so they would have a better understanding of the place they live in. It also explores occupants' readiness and willingness to enhance their dwelling's performance by introducing new aspects, such as sustainable building materials and BAS. It also contains a drop-down list or multiple questions in addition to short-answer questions that help in obtaining more information from the occupants to explain a specific concern or recommend a specific idea. Once the survey had been completed, the submitted answers were then uploaded into an Excel sheet to get insightful meanings of occupants' answers. The results revealed information regarding occupant satisfaction with their dwellings; concerns they might have over specific building systems, such as indoor air quality, lighting, indoor temperature control, and other building performance aspects. This helps in understanding and assessing building performance and planning to solve low building performance by establishing general maintenance, the use of sustainable materials, and use of home automation to attain occupants' comfort and satisfaction.

The first section of the survey contains demographic questions about participants' gender, age group, and the type of dwelling they live in. Participation from both genders provided greater diversity, inclusivity, and equality in the data collection and validation. The participants' age group provided insights regarding the correlation between age group and the subsequent answers. Specifying age group helped filter the required data and eliminate irrelevant participants whose participation would not contribute to the aims and objectives of this research. The section was also intended to evaluate the perception of occupants in Oman of their dwelling if it is detached, semi-detached (twin), or apartment, which would help understand the consequent questions related to building performance and occupant satisfaction. This section gathers information about how long they have been living in the building, that is, the occupants' experience span; the age of the building, which provides insights into building performance; and any required renovation or future renovation plans are covered in the next questions. Furthermore, this section introduces the occupants gradually to their dwelling and recalls dwelling information in order to refresh occupants' minds before progressing to the next section, which uses deep building performance concepts, such as IEQ, AI, smart home, building automation, and energy performance, and their impact on overall comfort and satisfaction.

The second section introduces building performance concepts that affect occupant satisfaction in terms of natural light use, air quality, and ventilation in the dwelling since these have a big impact in providing brightness and freshness, and in improving IEQ. This section also focuses occupants' attention on the artificial light rating in the building and the level of indoor temperature control during the summer and winter seasons, so they recognize the importance of these elements in improving IEQ and attaining living satisfaction. As mentioned previously, Oman's weather is hot during the summer with temperatures ranging from 40 to 50°C. Control of the indoor temperature to a satisfied level is not attainable without the heavy use of AC for continuous hours, which is challenging in the sense that a maintaining a comfortable ambient temperature incurs a high cost due to the use of electricity. This has triggered new behaviours since the cost of utilities has increased significantly in recent years following the gradual removal of the subsidy, so occupants are willing to explore alternatives that could be helpful in attaining a comfortable indoor temperature for a minimum cost. These include building performance improvement alternatives such as the use of sustainable building materials and building maintenance by using wall insulation and nano-materials, and by applying additives such as LECA bricks, using double- or triple-glazed windows with argon gas as the insulator, using UPVC windows frames instead of aluminium to reduce thermal conductivity, and many practices and measures which are explored in greater detail in

Chapter 2. This section also provides an indication about indoor building quality and performance during the summer and winter seasons, which provides useful information to the concerned authorities to evaluate and assess the building process and materials to improve building performance, especially building envelope insulation, and recommendations to add mandatory articles to Oman's building code to use low thermal conductivity building materials to achieve a robust controlled indoor environment with the minimum use of energy, especially during the high temperatures in the summer. The questions were designed to increase occupants' attention regarding building architecture and their awareness of building systems. For instance, use of natural light, building insulation, indoor temperature control, indoor air quality, and use of smartness and automation are given as questions to increase occupants' understanding of the dwellings they live in.

The third section of the survey introduces the concept of automation and quantifies the spread of automation in dwellings in Oman and its role in building energy performance from the occupants' perspective. It assesses occupants' understanding of home automation and their readiness to deploy it to enhance their dwellings' performance. Automation is introduced as one of the alternatives that does not need any building alteration and that is easy to control and monitor through mobile apps. In particular, nowadays, the use of automation is linked to AI where the user easily instructs the gateway to follow commands and perform tasks by vocal instruction. This has become common and is available on the market for a reasonable cost; it is user friendly in that no professional training or expertise is required. Examples include Amazon Alexa, Apple Siri and Google Nest. This section explores current automation levels in Oman's buildings and the potential of future widespread automation; it raises occupants' awareness of the importance of automation in reducing energy consumption and providing comfort and convenience, and it aims to understand occupants' concerns about and interest in automation. Towards this goal, promoting POE is significant to evaluate several aspects of building performance from the occupants' perspective. A copy of the survey questions is enclosed in the Appendix of this thesis. The given questions aimed to collect information from the occupants that would help assess building energy performance and occupants comfort. The provided answers will help to understand the indoor environmental quality issues and occupants’ concerns. The POE survey will determine the issues and challenges that the occupants encounter so the optimum solutions and practices could be suggested.

4.4 Survey distribution

A pilot was conducted to explore any errors that might occur, ensure respondents understood the questions and found it easy to respond, and ensure there was no uncertainty in the distribution and response process. The survey questions were written in the Arabic and English languages and utilized a Microsoft forms link which offered easy access without restrictions. Thus, the link to the pilot survey was distributed to five participants. There was one issue in that the link was not accessible because the permission to access was limited, and this was solved by granting access to everyone who had the link. The pilot was successful, and the submission was within the planned timeframe of 6 to 8 minutes.

The survey link was then distributed through WhatsApp to 230 participants with the link being sent to private and public groups of Omani residents with a note that this survey was for the purpose of conducting academic research targeting residents in Oman who owned their own homes. Participants were also invited to forward the survey to their friends and contacts, only 105 out of 230 participants have submitted survey responds.

4.5 Survey Results

This section provides some results from the survey that answer research questions 2, 3, and 4. The results are validated, and it is confirmed that they support the aims and objectives of this thesis. The information obtained from the occupants was put in Excel, and then reviewed, analysed and interpreted to answer the research questions as described below.

4.5.1 Survey Respondent Demographics

The survey was designed to collect some demographic information such as participants' age, participants' gender, and the ownership of the dwelling they live in. This meant the survey results were accurate and inclusive. It also validated the assumptions by confirming the results from the correlated questions. This means the survey can aid the targeted group with motivations and decision making related to their dwelling energy enhancement.

The participants' age was grouped into 6 age groups as shown in Table 4.1; this helps in understanding participants' level of perception and understanding of building performance and automation. Participants' age also helped filter the desired data for a specific age group and find clues and patterns among the required group and what decision a certain age group had made related to the willingness to deploy home automation. Understanding the responses of a certain age group could help in targeting the same age group for future research. Table 4.1 below shows the number of participants in each age group.

Age group	Number of participants
18 to 25	4
26 to 35	23
36 to 45	55
46 to 55	23
56 to 65	0
More than 65	0

Table 4.1 Survey participants' age groups

The survey showed that the age group between 36 to 45 years is the largest group of participants living in their own dwellings at 42% compared to those aged between 26 to 35 years at 9%, and those aged between 46 to 55 years at 19%. This age group (36 to 45 years old) of individuals who own their dwelling could provide a better experience and real insights about their dwellings and could enhance their dwellings' energy performance and their decision to deploy automation if they so choose.

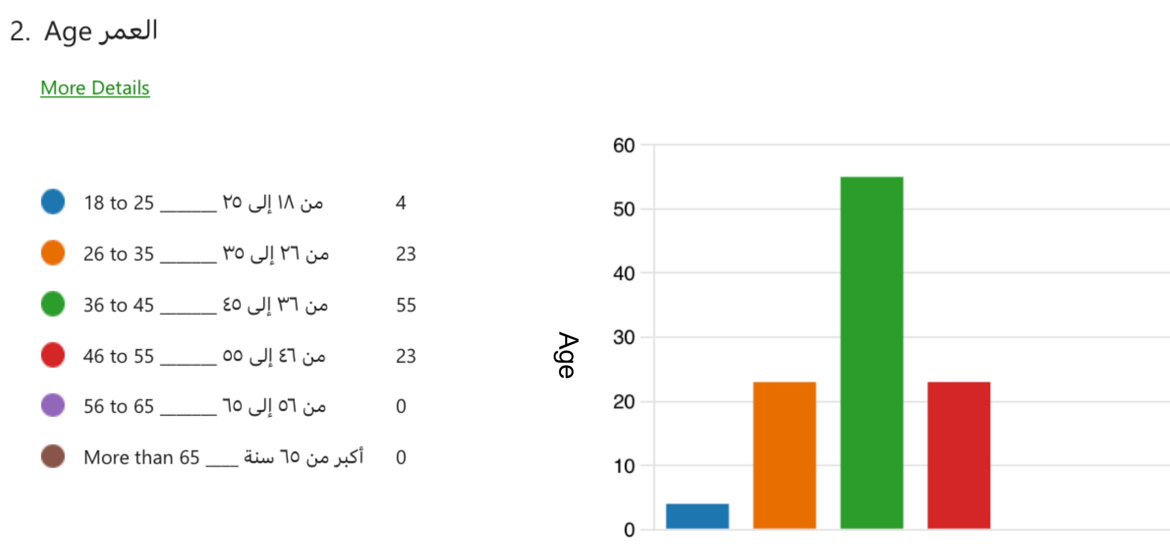


Figure 4.2 Survey participants' age groups

The survey also revealed that of those participants who disclosed their gender, 92 were male and 11 were female. This indicates that more males participated in the survey although the survey was distributed to WhatsApp groups that contained both genders.

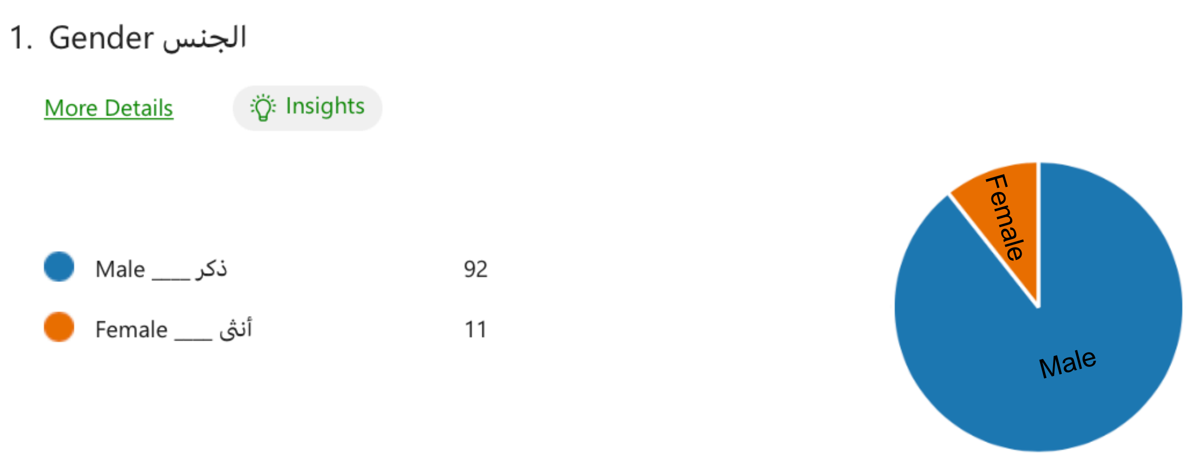


Figure 4.3 Number of participants per gender

The survey results also revealed that 87% of participants owned the dwelling they lived in, as shown in Figure 4.9. This validates that our targeted participants had the potential to modify and enhance their dwellings to improve building energy performance and occupant satisfaction.

4.5.2 Research question 2

The survey contained some questions that provided insights about the specific facts that we are seeking in this research. There are two questions in the survey designed to answer research question 2 *From an occupants' perspective, is energy consumption of buildings in Oman too high?* The first issue was to explore the occupants' position regarding whether they agreed that the installation of an automation system would reduce their utilities bill. The survey revealed that 78% of the occupants agreed that installation of an automation system in their dwelling would reduce their utilities bill and increase safety, security, and comfort as shown in Figure 4.4. This highlights that the driving reason for occupants to install automation is the high cost of electricity and reveals occupants need solutions to reduce the high cost of energy in Oman.

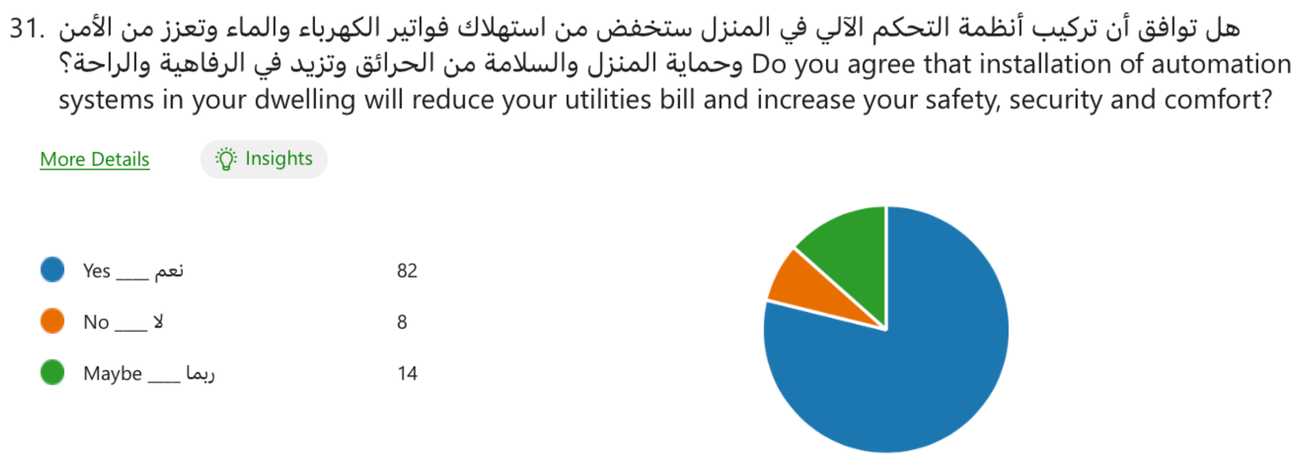


Figure 4.4 Occupants' position regarding automation role in reducing energy cost and increasing safety, security and comfort.

The second question in the survey to answer research question 2 is a short-answer question that requires the occupants to write their opinion of the benefits that installing an automation system will provide. The answers to this survey question revealed the reasons behind occupants' interest in deploying a home automation system; some occupants related their interest to safety and security at 28%, temperature control at 28%, comfort and convenience at 14%, and use of technology at 2%. However, the majority of the occupants wanted to install automation to reduce the cost of electricity at

66%, as shown in Figure 4.5. This reveals occupants' concern about the high cost of electricity in Oman compared to the income, which motivated the occupants to explore solutions to reduce their energy bills. It also highlights the awareness of occupants in Oman about the role of building automation in enhancing building energy performance and providing safety, security, and indoor environmental control and attaining comfort and convenience.

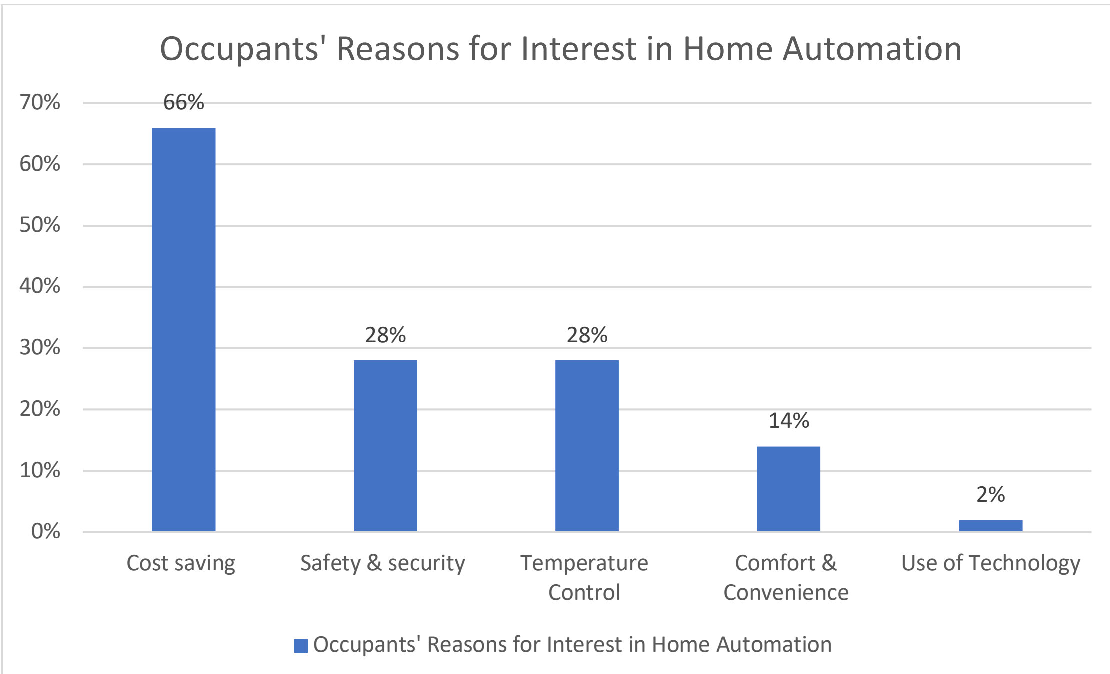


Figure 4.5 Occupants' reasons for showing interest in deploying home automation

4.5.3 Research question 3

To answer research question 3, *Are building owners in Oman familiar with and ready to deploy building automation systems in their dwellings?* there were six questions in the automation section of the survey. A given question about the availability of any automation in the dwelling is shown in Figure 4.6, and the next question was about the interest in deploying home automation. The answers provided information about the level of automation and therefore revealed the perception level of automation systems. The survey data showed that although 89% did not have any automation systems in their dwelling, 60% of those were interested in installing automation as shown in Figure 4.7.

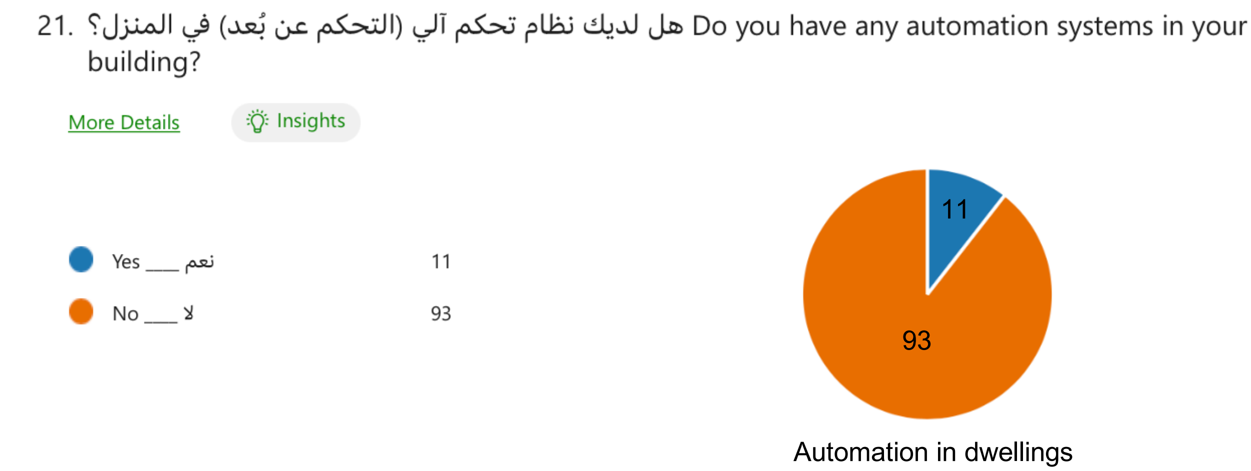


Figure 4.6 Level of automation in occupants' dwellings

This high level of interest reveals a high level of awareness and perception of home automation and shows a good understanding of automation importance in building management to reduce energy consumption and increase comfort and convenience.

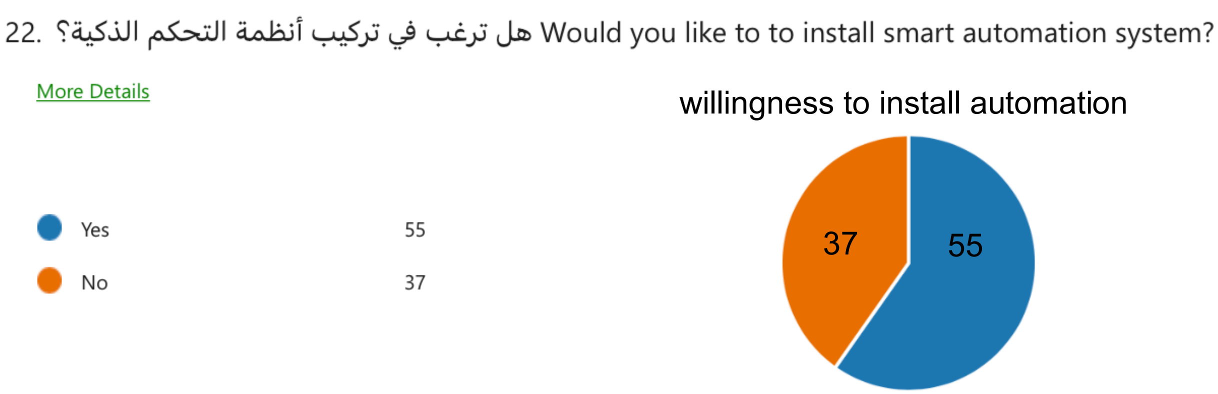


Figure 4.7. Occupants' willingness to install automation in their dwellings

The survey asked a conditional branching logic question if the participant is interested in automation system deployment and if the answer is yes, the branching followed up with a short- answer question about the participant's opinion of the benefits that installing an automation system will provide them. The following paragraphs analyse the answers to this question.

The readiness level of occupants in Oman shows that most respondents highly ranked (in terms of their preference) temperature control (77%) which is logical since keeping indoor comfortable temperature is challenging during summer months in which thermal mass influences the comfort and convenience of occupants and therefore the readiness to install BAS is the second (60%) because of the challenges the occupants face in their building performance encompassed in high consumption of electricity and the need to find solutions to this issue. It's also an indication of a good perception about BAS that could have the potentials to allay their concerns. Natural light is not a big concern for occupants in Oman since the sunlight is intensive, the daytime hours are long and the trend in Oman building architecture is to have large windows. Moreover, Indoor Air Quality (IAQ) is the lowest ranked in the readiness to invest in as it differs from temperature control because it refers to the condition of the air quality inside the building and how it affects the occupants' health and well-being which is not a big challenge in the indoor of Oman dwellings if compared to temperature control. This could be related to a good indoor ventilation, low indoor humidity level and low contamination in the dwellings in Oman so it came the least preference of occupants.

The survey also measures the level of occupants' readiness to invest money in their dwellings to improve temperature control (78%); instal a BAS (60%); enhance natural and artificial light control (49%); and enhance indoor air quality (39%) as shown in Figure 4.8.

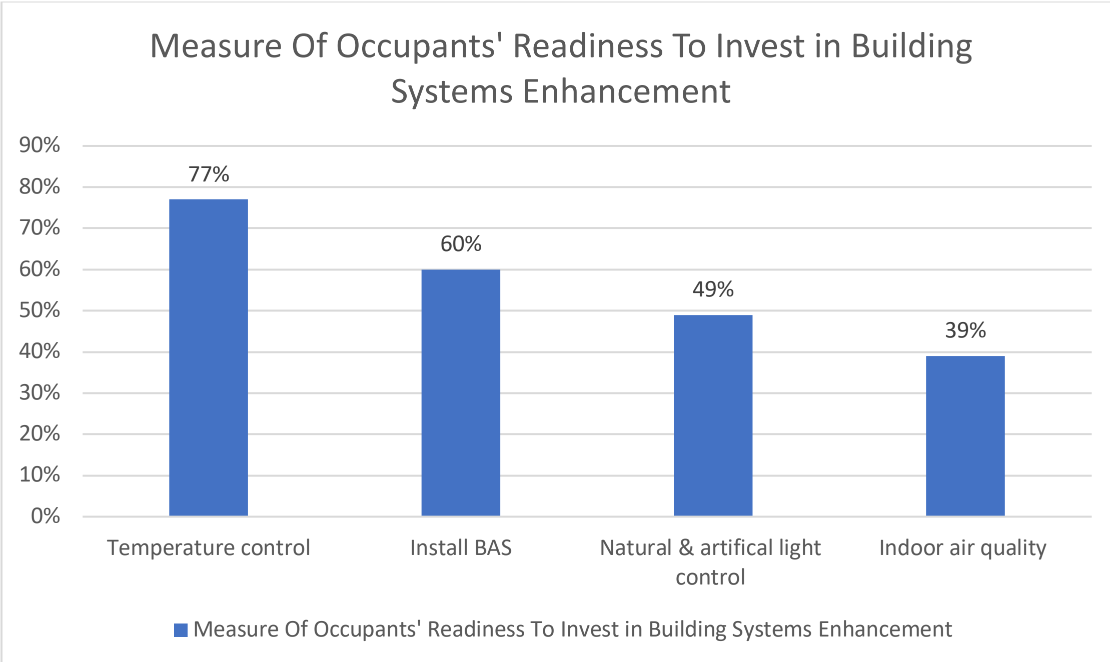


Figure 4.8 Measure of occupants' readiness to invest money to enhance building systems

The readiness level of occupants in Oman shows that most respondents highly ranked (in terms of their preference) temperature control (77%) which is logical since keeping indoor comfortable temperature is challenging during summer months in which thermal mass influences the comfort and convenience of occupants and therefore the readiness to install BAS is the second (60%) because of the challenges the occupants face in their building performance encompassed in high consumption of electricity and the need to find solutions to this issue. It's also an indication of a good perception about BAS that could have the potentials to allay their concerns. Natural light is not a big concern for occupants in Oman since the sunlight is intensive, the daytime hours are long and the trend in Oman building architecture is to have large windows. Moreover, Indoor Air Quality (IAQ) is the lowest ranked in the readiness to invest in as it differs from temperature control because it refers to the condition of the air quality inside the building and how it affects the occupants' health and well-being which is not a big challenge in the indoor of Oman dwellings if compared to temperature control. This could be related to a good indoor ventilation, low indoor humidity level and low contamination in the dwellings in Oman so it came the least preference of occupants.

The collected data showed that 66% of occupants related their interest in home automation to cost saving, 28% to safety and security, 28% to the need for home and temperature control, 14% to comfort and convenience, while 2% were interested in the use of technology as shown in Table 4.2.

What benefits do you expect to get from automation system?						
Answer	Comfort	Cost saving	Home and temp control	Technology	Safety & security	Total
Occupants	7	33	14	1	14	50
%	14%	66%	28%	2%	28%	

Table 4.2: Occupants' expectations from home automation

For most of the occupants, their concern was in reducing their energy bills, and this is the main reason triggering the use of technology to improve the efficiency of home appliances and use of sustainable materials. The IoT also deployed home automation for the same reason, that is, to reduce energy consumption and provide safety, security, and convenience.

The collective survey results revealed occupants' position regarding the role of automation in reducing energy bills and increasing safety, security, and comfort. As shown in Figure 4.4, 78% of occupants agreed that automation will reduce utility bills and increase safety, security, and comfort. The survey also revealed occupants' willingness to install automation in their dwellings; as shown in Figure 4.7, 60% of occupants were interested in installing automation. Furthermore, the survey shows occupants' expectations of the benefits from home automation as shown in Table 4.2, which summarizes occupants' responses to a short answer question regarding the expected benefits of home automation. The given answers revealed that the building owners had a good understanding of role of home automation. All this evidence helped answer the first part of the research question regarding the building owners' familiarity with and awareness about automation.

The survey measured occupants' readiness to invest money to enhance their dwellings for many reasons to improve temperature control, installing a BAS, enhancing natural and artificial light control, and enhancing indoor air quality. This highlights the big interest in home automation because of the good level of awareness about the role of BAS in building performance and occupants’ comfort and convenience.

4.5.4 Research question 4

Finally, to answer research question 4*, From the perspective of occupants, what is seen as the obstacles for the deployment of automation systems?* the survey showed that 87% of the surveyed occupants lived in owned dwellings as shown in Figure 4.9. This means that 87% of occupants would choose to enhance their buildings. Some buildings need maintenance work to deploy automation cables, which entails making some modification in the existing walls. This restriction is not applicable for owned dwellings since the owner does not need permission from a third party. This affects the answers to questions in the survey related to the decision to install automation if the dwelling is not owned.

Figure 4.9 Occupant-owned dwellings

The survey showed that 60% of the occupants would like to install an automation system in their dwelling. As shown in Figure 4.7, the survey also revealed participants’ high readiness level to install automation. However, 89% of the occupants did not have any automation as shown in Figure 4.6. This reveals big interest and high readiness to deploy home automation but there are challenges and obstacles made occupants hesitant to adopt it. The obstacles require more study and further research of the automation market in Oman, the cost of automation and associated maintenance, occupants' behaviours and their perception of the role of automation.

4.5.5 Research question 5

The first part of the answer to research question 5 was tackled by archival data, as revealed in Chapter 3, which provided a thorough review of building energy performance in a holistic building lifecycle. Future research is required to explore the obstacles and challenges that hinder the widespread use of automation in several areas involving occupants' hesitation to deploy building automation. It is recommended that the research community explore the obstacles identified below and furnish the roadmap for widespread automation in Oman. Based on the results of the survey, the obstacles were identified in the literature review. Based on this review, these obstacles were classed into five categories. However, more data are required to explore the solutions that could start a momentum for widespread automation in the Omani market:

1. **Market status:** the global automation market threshold is expected to reach USD8.4 billion by 2027 (Markets, 2020), which fits the forecast annual growth of smart buildings between 7.3 and 11.6% and revenues between USD65.2 billion to USD82.7 billion in 2025 (Casini, 2022) spurred by increased connectivity of devices, Big Data, ML, and mobile apps (Fletcher, 2018). The limited spread of BAS and unknown products by users are the main reasons for the high cost of products and installation (M.G. Ippolito, 2014). Research is required to explore the market monopoly in Oman given that branded products usually have a sole distributor or agent who may set higher prices for automation products. Market competitiveness; the availability of alternative products; accessibility, as these are high tech products and require a specialized tech contractor for installation, programming, and training; as well as quality and cost should be identified.
2. **Initial investment cost:** although the survey showed that the average budget the occupants are willing to invest to deploy home automation is approximately USD 2635. However, a study of the cost of installing an automation system and

return on investment (ROI) is required to find out the exact cost of automation of building systems such HVAC, lighting, safety, and security that control indoor environment. Making this data available will help occupants to select their desired level of automation, which will benefit the automation market in Oman. Research has shown that ROI in the United States for automation system payback is 1.7 years (Paul Ehrlich, 2009), while the payback period for building energy management systems is within 3 years with a potential improvement to ROI in less than one year (Chin-Chi Cheng, 2018).

3. **Maintenance cost:** Giuseppe Parise and Luigi Martirano integrated BACS to design the lighting system in an adaptive approach to optimize visual comfort and to reduce the costs of energy and maintenance (G. Parise, 2009). However, wireless automation devices, such as IRs that control ACs, PIRs motion and security sensors, and smoke and fire detectors, all require batteries, which will need to be replaced. Furthermore, remote control automation needs an active internet/WiFi to remotely manage the system. The regular maintenance and associated cost should be identified and made clear to promote home automation. Research is required to identify the required maintenance schedule and associated cost to help occupants make a deployment decision when the costs of installation and maintenance of all the systems is clear.
4. **Occupants' behaviour:** the research reviewed occupants' behaviours for energy simulation and recognized how occupants interact with the building (Valentina Fabi, 2017). Occupant behaviour is known to be an uncertain factor in building energy use, and it is one of the major factors that influences energy consumption (William O'Brien, 2020). Occupants' reluctance and hesitation to deploy home automation require further research to identify their concerns about home automation and furnish the roadmap address for every concern that hinders the spread of home automation. This could be through a survey focused on obtaining occupants' concerns of home automation and their perspective to address the concerns. This could be achieved by a cooperative interdisciplinary work between engineering and psychology.

5. **Security and privacy:** the reasons that hinder the spread of automation, especially automation devices, include the need for the internet to remotely control the home automation system; however, this exposes it to hacks and attacks (Basu, 2023). Attacks to the automation systems could happen on two levels: network level and device level (Vitor Graveto, 2022). The threat of cyber-attacks in BAS can cause several types of damage, like financial loss, environmental loss, and health issues for the occupants (Basu, 2023). Further research is required on how to address occupants' concerns about threats to their security and their privacy.

The above challenges can be addressed by further research and by collaborative work between the concerned authority and stakeholders by adding automation in the code to familiarize people about its role in building management, energy control, and occupant satisfaction. There should be promotion and incentive programmes similar to the incentives given to rating systems such as BREEMA and LEED to motivate architects, building owners, and contractors to consider specifying automation in the construction drawings, building process, and retrofitting as a sustainable building alternative. Market study and control is important in filtering out low-quality products that do not make a positive contribution to energy saving, to reducing maintenance cost, and to achieving a good reputation and the success of the automation market.

4.6 Conclusion

The POE survey was utilized to answer three of the six research question of this thesis. To answer **research question 2:** *From an occupants' perspective, is the energy consumption of buildings in Oman too high?* the survey revealed that the main reason for occupants' interest in automation deployment was to reduce their energy consumption. The survey highlighted that the biggest interest in deploying home automation was to reduce their electricity bills, as shown in Figure 4.4 and Figure 4.5. The occupants agreed that installation of an automation system in their dwelling will reduce their utilities bill and increase their safety, security, and comfort.

The survey also answered **research question 3** *Are building owners in Oman familiar with and ready to deploy building automation systems in their dwellings?* The survey data showed that although 89% did not have any automation systems in their dwelling, 60% of these were interested in installing automation (see Figure 4.6 and Figure 4.7). This high level of interest revealed a high level of awareness and perception of home automation and shows participants had a good understanding of the role of automation in building management to reduce energy consumption and increase comfort and convenience. The survey also revealed occupants' expectations and benefits of home automation as shown in Table 4.2, which summarizes occupants' responses to a short-answer question regarding the expected benefits of home automation. The given answers revealed that the building owners had a good understanding of the role of home automation.

Regarding **research question 4**: *From the perspective of occupants, what are seen as the obstacles for the deployment of automation systems?* the survey showed that 87% of the surveyed occupants lived in owned dwellings, which means that 87% of occupants would be able to carry out enhancement to their buildings if they chose to do so without any restriction from a third party. The survey showed that 60% of the occupants would like to install an automation system in their dwelling as shown in Figure 4.7. The survey also showed a high readiness level to install automation. However, 89% of the occupants did not have any automation, which reveals the challenges and obstacles that hinder the widespread use of home automation. These obstacles require further research to explore automation system market in Oman, automation and associated maintenance costs, address occupants' reluctance to deploy automation, and their concerns about security and privacy.

Research question 5 asked *What can be done to allay the concerns that occupants have over the deployment of building automation systems?* This was answered in two parts. The first part was tackled in Chapter 2 through the literature review utilizing archival data. The second part identified the research gap in this chapter concerning the obstacles that hinder the wider use of automation in Oman which indicated the future direction for the research community to evaluate the automation market, initial cost and maintenance, occupants' behaviour, and their safety and security concerns.

This POE survey was crucial in identifying occupants' perspective related to their buildings' performance and the convenience in their daily lives. It provided robust answers to the research questions based on the collected data that fulfilled the aims and objectives of this research. It also provided a future research roadmap to address the challenges and obstacles that hinder widespread automation. Furthermore, the POE survey feeds the results and data validation in Chapter 5.

5 Chapter 5 Case study and data validation

5.1 Introduction

The POE survey in Chapter 4 provided data about building energy performance in Oman from the occupants' perspective. The data demonstrated occupants' perceptions of aspects of building energy performance such as building enhancement and the home automation perspective. This survey revealed the significant interest of occupants in Oman in building automation and their high readiness level to invest in automation deployment. However, the data highlighted that few dwellings were equipped with a BAS and those that were had mostly only basic automation such as main door remote control and CCTV; few dwellings were equipped to manage the building systems that have a crucial impact on electricity consumption, such as HVAC and lighting. This led to a roadmap plan to address occupants' hesitation to deploy home automation although they had shown a major interest and in readiness to deploy home automation.

BASs are one of the potential elements we rely on for building energy optimization in this research especially for existing buildings, since the retrofit alternative has many limitations and differs from one dwelling to another. This contrasts with a BAS, which is a solution that can be deployed with a minimum impact on the building, its cost can be easily determined, there are no unforeseen risks, and it can be customized to manage different building systems with a flexible budget.

This chapter will utilize the case study of a dwelling in Oman inhabited by a family for several years. A retrofit was conducted last year to add more facilities in the dwelling with an increased usable area and upgraded windows and lighting. The retrofit contained more rooms and more electric equipment and utilized building automation to reduce electricity consumption.

A POE for BAS survey was utilized to gather information about the case study, and details of the BAS were collected from the occupant and from the automation company that installed the BAS in the dwelling. The data from the survey and the information about the deployed BAS helped to answer the following research question.

RQ6: *What are the potential energy improvements that can be realised through the deployment of building automation systems?*

This research question was answered through a case study that utilized real meter readings of electricity consumption of the dwelling before and after BAS deployment. Some of the case study details were obtained by a survey that has several questions related to the occupants' demography, building information, and details of the deployed automation system. The information collected by the survey was essential to evaluate and validate the impacts of building energy performance and occupant satisfaction as described in the methodology section. The case study was a residential building equipped with a BAS and had a history of energy use before BAS deployment. A comparison of electricity use was assessed by obtaining monthly electricity bills to check the difference of energy consumption before and after BAS deployment. Electricity consumption was demonstrated for six months before BAS and 6 months after the retrofit and BAS deployment to explore the impact of BAS on energy use.

This chapter also explores the potential for exploiting a BAS to attain indoor environmental quality IEQ in Oman buildings without affecting occupants' comfort and without any increase in energy use.

5.2 Methodology

Case study is used as a methodology in various disciplines to investigate, collect data about, and provide insights into a phenomenon related to individuals, small numbers of social entities, or organizations. Results of a case study of a single individual or a small sample could provide useful data offering insights into the nature of the phenomenon (Geoff, 2010).

Some researchers have argued that ideally between 4 to 10 case studies are required (Eisenhardt, 1989) to find consistent results from all cases. However, the case study in this thesis utilized a comparison of electricity bills for a minimum of 6 months to compare energy consumption data, that is, 6 months of electricity use records before BAS and 6 months after BAS deployment.

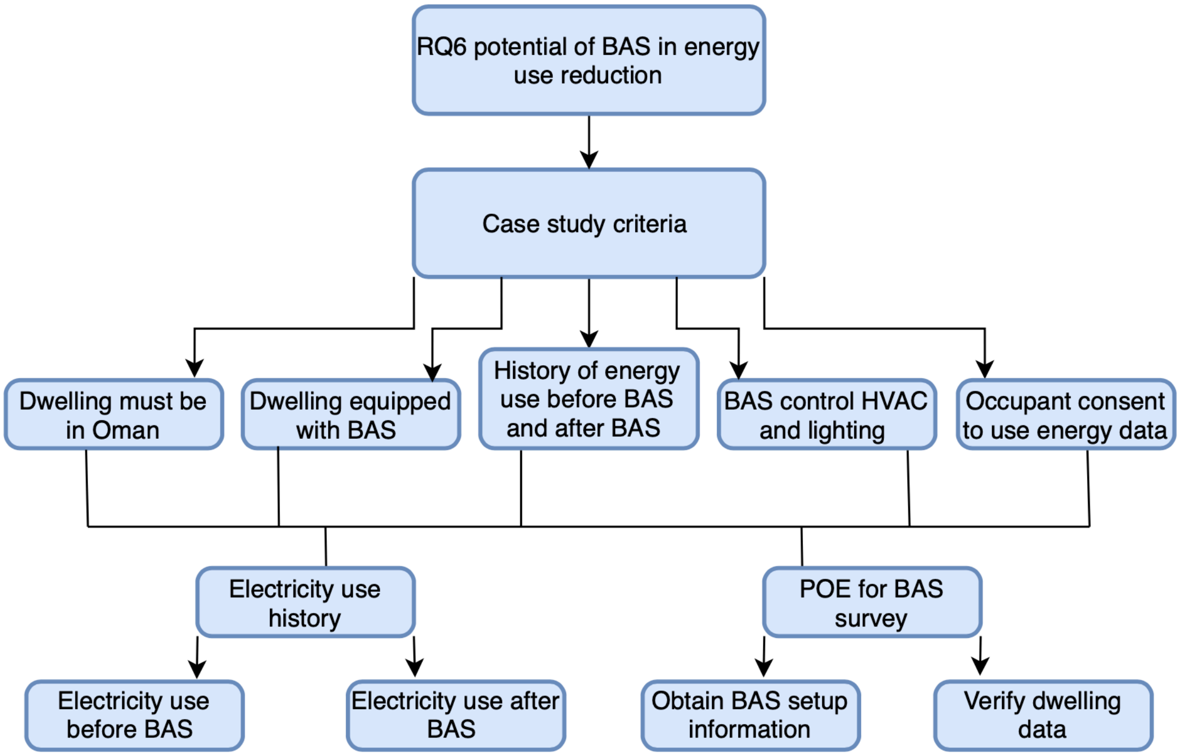


Figure 5.1 Methodology for answering research question 6

To answer research question 6, the aims of the case study within the POE-BAS survey are as follows:

- Gather information about the impact of a BAS on dwelling energy performance in Oman.
- Collect information about the occupants' demography, which will help understand occupancy load and regularity of occupants' interaction and behaviour with an automation system.
- Understand occupants' perception of aspects of building performance, which will help identify building performance issues and potential building enhancement for energy performance.
- Identify BAS deployment purposes, BAS architecture, and potential BAS improvement for its maximum efficiency exploitation.

- Validate the results of the electricity consumption comparison before and after BAS deployment.

The criteria set to choose the case study were as follows:

1. The dwelling must be in Oman.
2. The dwelling must be equipped with an automation system but not from the construction phase.
3. The dwelling has a history of energy use before BAS deployment.
4. The minimum BAS requirement is to have control of HVAC and lighting systems.
5. Occupant’s consent to obtain electricity use bills for a minimum of 6 months before BAS and 6 months after BAS deployment.

Smart home automation contractors in Oman were approached to support the findings of the case study since BAS installation is a specialist technology, and they may have had the contact details of their clients. The required case study and the criteria were explained to contractors, and a copy of the survey was provided to check as a pre-requisite for participants’ information disclosure. BAS installers then provided seven contact information of potential participants after getting their approval to share the information. Next, the participants were contacted to match the case study to the criteria. The seven participants were contacted individually to make sure the dwelling was equipped with a BAS and specifically that it controlled HVAC and lighting, as these two systems together consume the biggest part of electricity use in residential properties (Section 1.3). The criteria were applicable to only one case out of the seven possible cases, and hence, the case study participant was selected. This case study met the five criteria mentioned earlier, and the owner confirmed that he had installed a BAS in his dwelling in the retrofit, which also included adding more rooms and facilities, and upgrading the windows, lighting, and ACUs. The other six participants did not fit the criteria because they had installed BAS from construction, and they did not have any electricity use history for pre-BAS deployment. Furthermore, most of the participants had only partial automation, which was not useful in performing a comparison of electricity usage.

The purpose of the BAS survey was explained to the selected participant, and the link was shared via WhatsApp. The participant completed the survey and submitted the form. The details of the BAS that had been deployed in the dwelling are given in the following section. This case study information and data do not rely only on the feedback from the occupant, as this could be biased and not accurate; the aim of obtaining data from the occupant in the survey was to understand the demography of the occupants and gather building information that would help evaluate the impact of BAS on building performance. The last section of the survey dealt with information about the installed BAS to clarify the occupant’s perspective.

The occupant provided their electricity account number with an authorization letter to obtain electricity consumption history. The obtained data from the electricity distribution company (NAMA) to provide the historical meter readings which were used as the baseline for comparing electricity consumption before and after BAS deployment. Furthermore, BAS architecture and the details of the deployed devices in the dwelling were documented, their control of energy consumption was verified through data comparison.

5.3 Survey structure

The POE-BAS survey conducted was designed to gather information for a case study purpose to verify BAS impact in dwellings to optimize energy use and attain occupants’ satisfaction given that in accordance with the Oman building code, it is not obligatory to insulate any building envelope walls, and the summer temperature reaches 50 °C. The survey consists of four sections: survey introduction to participants, general information about the occupant and their dwelling, dwelling evaluation, and home automation.

The first section of the survey introduces the survey to the occupant and obtains the occupant’s consent to participate in the survey.

The second section of the survey was designed to gather general information about the case study dwelling and the occupants. It contains demographic questions concerning the number of occupants in the dwelling, as well as their gender and their ages. This helped to understand the occupancy load and occupants' interaction with the automation system. This section also contains questions about dwelling type, such as if it is a villa, twin villa, or an apartment and if it is owned or rented since with an owned property, the possibility of installing a BAS is higher than with a rental property because in some cases, BAS installation needs wall trenching and cabling. Furthermore, in an owned dwelling, the decision to retrofit is in the hands of the occupant as opposed to a rental property where the decision is made by the landlord. The survey contains questions related to electricity use, such as the number of air conditioning units in the dwelling and the number of rooms, including bedrooms, reception rooms, kitchen, and other spaces that might have appliances that consume electricity. This section also gathers information about the age of the dwelling and the number of years the occupant had lived there, which helped to understand the occupant's experience in the dwelling and the accuracy and validity of the provided answers.

The third section is about dwelling evaluation, and the aim was to motivate the occupant to consider important aspects that influence energy use, such as asking about approximate dwelling area, which will help in calculating the HVAC efficiency compared to available AC units. Questions about wall insulation, window size, and window-wall ratio provide insights into the building's efficiency in maintaining the indoor environment. There are also questions about the occupant's satisfaction with the IEQ of their dwelling, which includes aspects such as air quality, artificial and natural light, temperature and humidity control, security, and automation. This section obtains the occupant's rating regarding natural light and artificial light and their willingness to enhance the indoor lighting. Building evaluation also encompasses questions about window type, such as if they are aluminium or UPVC and if they are single or double glazed, which impacts the indoor environment. There is a question about the use of LED lamps, and finally, a question about the occupant's the willingness to improve the room temperature control and reduce the cost of electricity consumption. The data obtained from the survey helped to answer the research question about realising the potential energy use saving through building quality because a BAS's efficiency in controlling building systems and achieving energy saving is influenced by aspects of building performance that are discussed in this section.

The fourth section of the survey is about home automation and is intended to gather information from the case study about the details of deployed automation. It contains a brief introduction about the home automation concept and its role in building management. This section obtains information from the occupant about the details of automation in the dwelling and the rooms and spaces that are equipped with automation devices. This section also gathers information about the occupants' interactions with automation and if they can configure the system; the aim is to understand the level of perception and interaction with automation system, which could provide insights about the automation being set to the optimum capacity to control electricity use in accordance with the occupants' preferences. There is also a question about if the occupants had encountered any automation malfunctions and the cost of automation.

The occupant was required to answer a question about the benefits received from automation, and their opinion about whether the automation system reduced utility bills. As the occupant confirmed that there had been a reduction in the utility bills, then the approximate percentage of the reduction was required. This was validated by a comparison of the electricity costs before and after BAS deployment, and it verified if the occupant had a good understanding about the role of the BAS in building energy management. This section also considers the luxury and security part of automation by asking a question concerning the role of automation in the home and security and if the occupant believed automation to be a necessity, a luxury, or both.

This section is also used to obtain information to answer research question 4 about the obstacles that hinder the widespread use of automation in Oman, so there is a question about the reasons for the limited use of automation systems in the country. The answer from the occupant concerning the obstacles that hinder the spread of automation in Oman was important because it would provide insights from a real experience to answer the research question from the occupant's perspective. In this question, the occupant related the limited spread of automation in Oman to the cost of automation, which is one of the obstacles discussed in research question 4.

This case study survey provided crucial information concerning the role of the automation system in building energy management in a retrofitted building. It reflected the occupant's satisfaction with the IEQ and the ease of dwelling systems management, and it revealed the approximate cost of home automation.

5.4 Case study details

This case study fulfilled the prerequisite criteria that the dwelling was in Oman, was equipped with an automation system, and had a history of energy use before and after BAS deployment with the participant consenting to provide electricity bills for a minimum of 6 months before BAS and 6 months after BAS deployment.

Picture 5.1 case study villa in Muscat before and after the retrofit

The house was in the capital Muscat, in the Al Maabilah area. It was constructed in 2007 as a ground floor villa with a total built area 253 m^2 and consisted of master bed room(6x4.5m) with a private bathroom (1.8x4.4m), a bed room (4.5x4m) with a private bathroom (2.6x1.7m), a family hall (4x9.7m), a dining room (4.1x3m) with a bathroom (2.1x1.5m), female guest rooms (4.5x4m) and male guest room (4.5x6m), and an external attached kitchen (3.5x6m). The dwelling was equipped with 7 ACUs, tube lights and spotlights, 6 exhaust fans in the toilets and kitchen, and 6 water heaters. The walls were not insulated, and there were some trees that provided shade for the walls.

The retrofit project started in September 2021 and was completed in August 2023. The retrofit work included demolition of an existing toilet, replacing of all ceramic tiles and sanitary ware in all toilets, construction of a precast swimming pool, construction of a laundry room, addition of a new storeroom, and construction of car porch, as shown in Figure 5.2. The new spaces were equipped with LED light fixtures, an audio music system, electric switches to control the lights by dimming or turning them off, and AC and blinds control. Large aluminium double-glazed windows were installed on the first floor. The façade was painted on four sides with white paint to reflect solar radiation and reduce heat absorption as shown in Picture 5.1. The total retrofit built area was 336 m^2 compared to the original 253 m^2 previously. The first floor was entirely constructed as part of the retrofit; it contained four bedrooms with four toilets linked to the rooms, a study room, a lobby, and a balcony as shown in Figure 5.2. In the retrofit, the trees were removed, and the car porch was constructed in their place. The first-floor extension did not utilize LECA bricks that have a high thermal transmission and better insulation. Instead, rebar steel and concrete bricks were used for the walls and ceiling construction with no heat insulation. Concrete has a high thermal conductivity (1,700-2,500mW/mK) compared to LECA bricks. The retrofit did not use sustainable materials and there was more than double the area following the new construction with the corresponding increase in HVAC and lighting systems. This would inevitably increase the use of electricity consumption in the dwelling.

Retrofit work is summarized in Table 5.1.

Retrofit work	Details
Building area	Building of first floor with additional 336 m^2
HVAC	5 air conditioning units were added. 5 exhaust fans were added. 5 water heater units were added.
Windows	Large size aluminium double-glazed window
Lighting	Dimmable LED energy saver light fixtures were used in all the rooms.

BAS	Distribution boar (DB) for lighting control and schedule Infrared communication (IR) for AC units' control Real-time home system control
Curtains	Smart blinds were added and scheduled to reduce heat transmission effect.
CCTV	CCTV system to maintain home security
Intercom	Intercom system for security and two-way communication for when there are visitors.
WIFI	To connect smart devices and remotely control building systems (home automation control)

Table 5.1: Summary of retrofit work

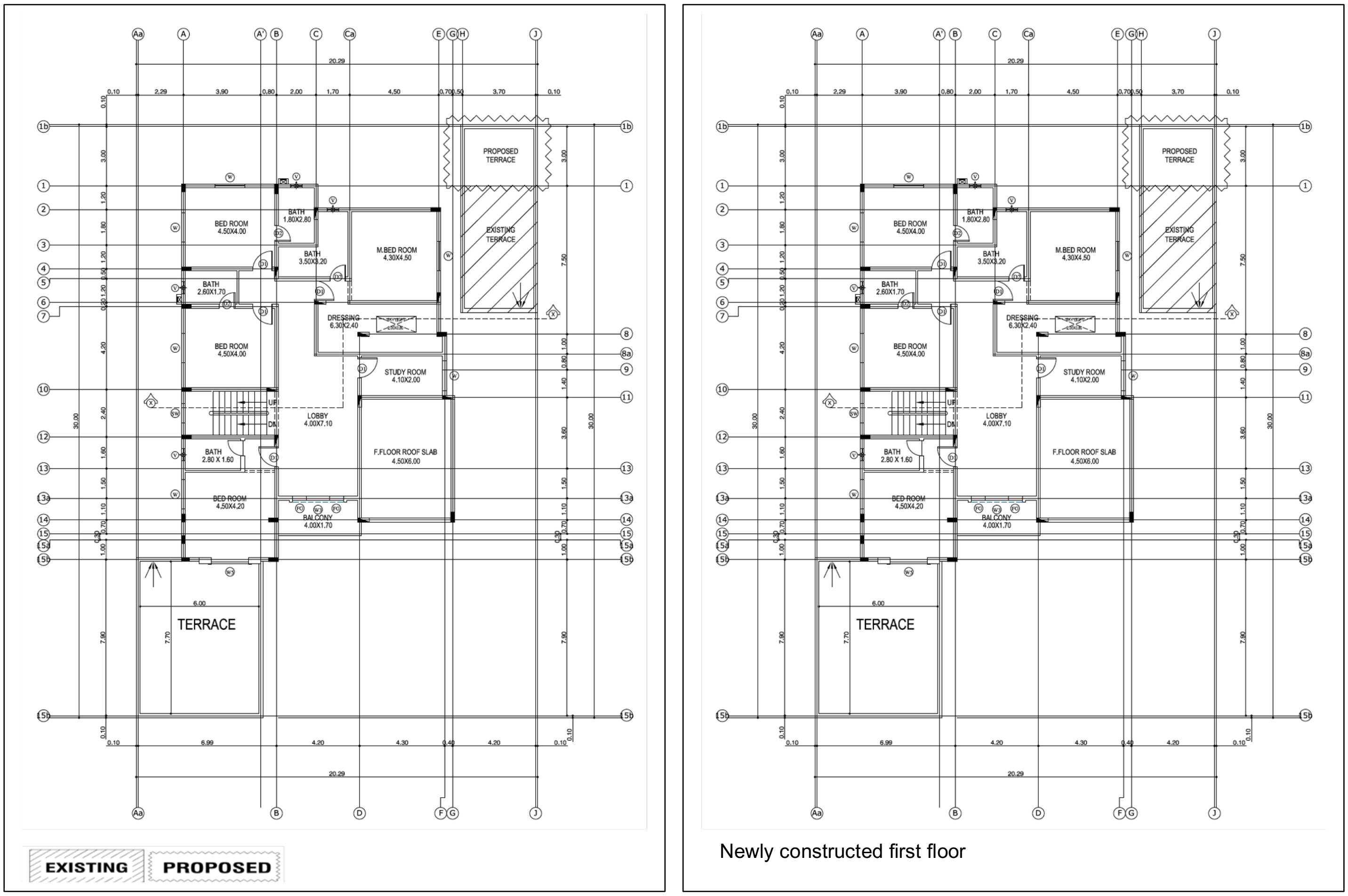


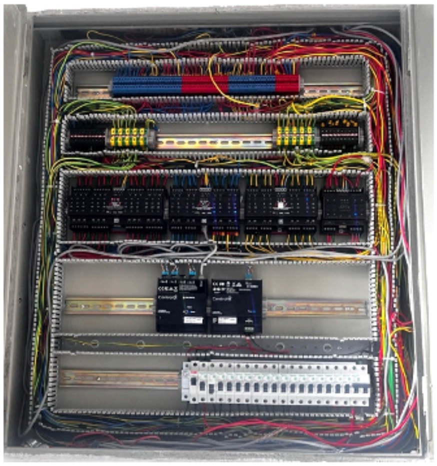
Figure 5.2 Villa layout before retrofit showing existing structure and proposed retrofit

Old tube lights and spotlights on the ground floor were replaced with LED lights, and the first-floor new rooms were equipped with new LED light fixtures that can be dimmed and scheduled to be turned on and off to save energy. In addition, five more AC units were added on the first floor making a total of 12 AC units in the building. Old curtains were replaced with new smart blinds that could be scheduled to open and close.

The dwelling was equipped with a home automation system from the Control4 company, which is based in Utah, USA and specializes in providing automation and networking for homes and businesses. It offers home systems with controls including lighting, audio, video, climate control, intercom for two-way communication and history recording, and security (Warren, 2018). The Control4 platform interoperates with more than 13,500 third-party products and it is available in more than 100 countries managing more than 370,000 homes and businesses as of 2019 (Wikipedia, 2024). Apex module was used for the automation actuator in the distribution board (DB). The automation system that was deployed included a DB lighting control schedule, infrared communication (IR) with indoor AC units for remote control, an intercom for security and communication with arriving guests and it also has the function to record and save data for retrieval history events, and blinds automation that is scheduled to open and close the blinds according to the desired timing, as well as a CCTV system that maintains home security. The automation scenarios were discussed between the contractor and the occupant. Then the programming of the system was set according to the preferences of the occupants. Their focus was on achieving luxury and ease of home control instead of focusing in energy saving. Following this, the electricity consumption meter readings were taken for twelve months and six months before retrofit and smart automation system deployment. After deployment readings were again examines six months after deployment. The results will be shown in Section 5.6 Electricity comparison.

Limitations are now mentioned in Section 5.8 BAS for energy control, and the following paragraph will be added.

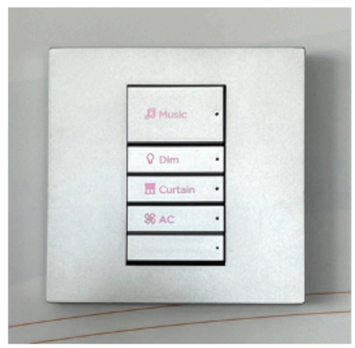
The impact of energy saving from BAS deployment will be more accurate if a year of meter readings were compared before and after smart home automation deployment instead of six months. This limitation was encountered because, at the time of data collection, only six months meter readings were available after the occupants moved to their retrofitted dwelling. However, the saving from BAS could be bigger in summer months that found in the months studies as shown in Table 5.2.



Automation system distribution board

CCTV box

AC unit with IR control



Smart switch

Smart blinds

Picture 5.2 Smart system devices used in the dwelling

The automation systems control the building systems utilizing smart home operation system (OS) software that connects many home systems in one platform for easy accessibility and customization. The smart home devices deployed in the dwelling managed the following functions:

- Control indoor and outdoor lighting to save energy.
- Optimize indoor temperature to maximize occupants' comfort.
- Send alerts when a door or a window is open.
- Remote control of lighting, AC units, and blinds when occupants are absent.
- CCTV provides extra level of home security.
- Secure two-way communication using an intercom system with a recorded data.
- Real-time home system control and notification.

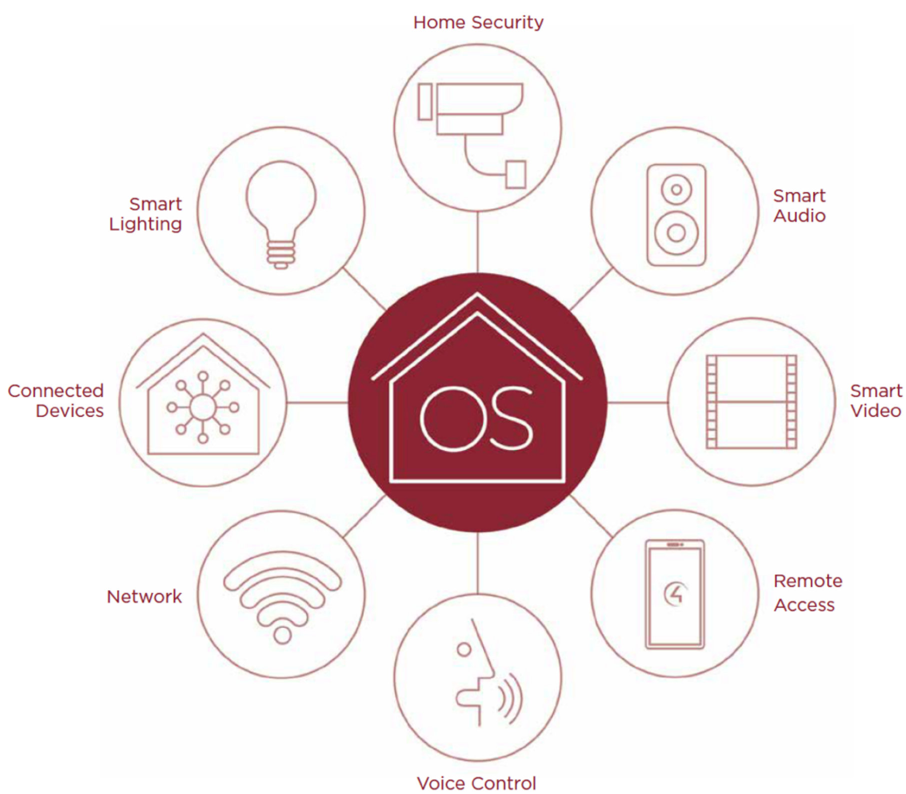


Figure 5.3 Smart home operation system (AV, 2020)

A Wi-Fi network is essential to keep all the devices and systems connected. Wi-Fi also allows remote access and control of the connected devices, and it should be sufficiently powerful and robust to handle many smart home operations.

5.5 Survey results

The survey was explained to the case study participant, and the link was sent by WhatsApp. The form was submitted by the participant, and the answers will be explained in this section. The survey revealed demographic information about the case study dwelling and the occupants. It showed that the occupant belonged to the age group 46 to 55 years old, and he owned the dwelling and lived there with his family, which comprised a spouse and four children. The automation was deployed in an owned villa, which made wall trenching and cabling for BAS installation possible as it was not a rented property, which is a crucial factor for installing BAS in a retrofit project.

The dwelling contained 6 bedrooms, two halls for guests, a family hall, a dining room, 7 toilets, a kitchen, a storeroom and a swimming pool. The dwelling has 12 ACUs, LED fixtures in all rooms, 8 exhaust fans, 7 water heater units, and various home appliances. The total building area after retrofit is 589 m^2 including the external kitchen, storage room and car porch. The survey revealed that the walls were not insulated, and this could impact BAS efficiency to attain a comfortable indoor environment. Wall insulation is very important to reduce thermal conductivity given that the walls were constructed with steel bars and concrete, resulting in high thermal conductivity as explained previously. There are sustainable alternatives and concrete additives that can improve the properties of concrete and enhance its thermal resistance to reduce the temperature exchange between indoor and outdoor environments.

The occupant was very satisfied of his dwelling's quality, and this could be due to moving into his dwelling 26 months after the retrofit project. Moreover, the period that the occupant moved to his retrofitted dwelling was September 2023 when the weather temperature started to be moderate between 20 and 30oC.

The survey showed that the occupant was very satisfied with natural light and artificial lighting in the dwelling, and he showed no interest in improving the natural and artificial light in his dwelling.

The windows in the dwelling were big with approximate size of 2x2m, and they were double-glazed and made of aluminium. Aluminium in terms of thermal transmission is a good conductor and not suitable for Oman's weather compared to UPVC windows, as demonstrated in Chapter 2. Although wood has a lower thermal conductivity and provides better insulation than UPVC, it is likely to shrink and expand corresponding to the weather, and it needs more maintenance. This could reduce the BAS's efficiency in attaining a comfortable indoor environment with minimum energy use. The double-glazed windows used argon gas between the panels and so function as a good insulator against heat transmission in the outdoor and indoor temperature exchange. However, the large wall-window ratio could have a negative impact given that the walls were not insulated, and so the heat could penetrate inside the rooms through the walls. Windows can work as insulators that prevent weather exchange but on the other hand can also prevent the transmission of heat that is gained from the uninsulated walls. This can cause a heavy use of HVAC to reduce the heat gained from the walls to attain a comfortable indoor environment, which will impact energy consumption. Furthermore, window-wall gaps must be sealed after installation to prevent weather exchange. Sealing window-wall gaps and doors leakage could be done by different sealant materials. An experimental assessment of six sealing materials was conducted in a residential building in the United Arab Emirates (UAE). An air blower test and infrared imaging was used to identify the impact of airtightness on energy use before and after application. The experiments demonstrated that foam was the best sealant, as a 3% reduction in annual energy consumption was realised (Taleb, 2022).

Sealing the windows and door frames not only affects indoor comfort but also protects the building from air draughts and water leaks, which cause occupants' dissatisfaction and could result in mildew, and could rot wooden window frames, leading to the paint peeling (Wolf, 1991).

The survey revealed that the occupant gave a maximum 4 out of 4 points for room temperature control in the dwelling during the winter but only 3 out of 4 for room temperature control during the summer. This indicates that in hot weather during the summer, when the temperature reaches 50 °C, it is challenging to maintain a comfortable indoor temperature, which affects the IEQ and occupants’ comfort.

There are many factors that influence IEQ, such as the weather, building orientation, building envelope insulation, colour of the façade, wall-window ratio, windows and choice of sustainable material for doors, airtightness, HVAC load capacity, and occupants’ number and their stochastic behaviour.

Although the occupant retrofitted his dwelling more than 6 months before this survey, the survey showed that the occupant still had concerns about the cost of electricity and the indoor temperature control.

The dowelling was equipped with AC control utilizing IR sensors, which work by setting the desired indoor temperature and allowing remote control of the AC by turning it on and off when the occupant is absent from his dwelling. In addition, motion sensors for lighting work via motion detection and scheduled lighting, curtain control utilizes a curtain connected to a motor that can be scheduled to automatically close and open the curtains, and there is a CCTV system which contains a camera for monitoring, and an alarm for home security and surveillance. The automation is deployed in all the rooms of the building. The occupant frequently interacted with and modified the settings to take account of new automation scenarios or change the existing scheduled automation according to his preferences. The automation installer configured the automation system, and whenever there was a malfunction of and issues with the automation system, the occupant was unable to solve it, and it required the contractor to fix the issues.

The deployed automation cost around USD24,000, as the Control4 brand is one of the leading brands in automation systems and their products are expensive compared to other home automation systems especially products from China. As discussed in Chapter 4, this is one of the obstacles that hinder the widespread use of automation, and it is supported by case study research conducted in Italy to underline the impact of building automation and control systems (BACS) and technical building management (TBM) in building energy performance. The authors highlighted the role of BACS and

TBM in enhancing building performance and related the limited spread of building automation to the high cost (M.G. Ippolito, 2014).

The occupant stated that his interest in home automation was to ease the control of home systems and to enhance comfort. The survey showed that the occupant was not sure if the automation system helped him reduce his electricity consumption, as he had not done any cost comparison. The occupant requested to be given the results of this case study about the impact of automation on his dwelling and the potential saving in the cost of electricity although his intent for automation deployment was not connected with reducing electricity consumption. The occupant stated his opinion that home automation is both a necessity and a luxury at the same time. He declared that home automation helped him secure his dwelling's safety and security. This is one of reasons that occupants deploy home automation, that is, for providing surveillance and remote monitoring of their home through CCTV. The survey revealed that the cost of BAS was the main reason that hinders the widespread use of automation, and this is validated by the cost of the deployed automation system (USD24,000) which is expensive when taking account of the low per capita income in Oman.

The survey data provided important information that influences BAS efficiency. Knowing the building systems and the building materials used in the retrofit helped understand and justify the BAS's performance. Furthermore, the details of controlled systems in the dwelling helped understand the level of control in the dwelling and its impact on building energy performance. The lower the level of automation, the lower the impact on energy consumption since there will be only limited control of building systems. Knowing the quality and specification of the building, such as window types, window-wall ratio, and wall insulation, has a significant impact on automation performance and on the overall potential of automation to realize energy savings.

5.6 Electricity comparison

It has been suggested that BAS can affect building performance to reduce energy use as indicated in the literature review in Chapter 2 and the data from the POE survey in this chapter. However, in hot countries such as Oman where the summer temperature reaches 50 °C, and the buildings are not sustainable, HVAC is required to work continuously to attain a comfortable indoor environment. The aim of BAS deployment is to optimize energy use and attain occupant satisfaction. However, in conditions such as those in Oman, while a BAS could save electricity in the lighting system, any saving in HVAC needs to be measured.

This case study was chosen as it fulfilled the case study requirements: the dwelling was in Oman, was equipped with a home automation system, had a history of energy use before BAS deployment, fulfilled the minimum BAS requirement control of HVAC and lighting systems, and the occupant's consent was obtained to utilize electricity use data for a minimum of 6 months before BAS and 6 months after BAS deployment. This made it possible to explore the impact of the BAS on building energy performance in hot countries.

The data collected from NAMA electricity distribution about the electricity consumption of the case study dwelling is summarized in Table 5.2. The electricity distribution company was contacted, and electricity consumption data were collected from January 2019 to February 2023. A comparison of electricity consumption before retrofit and after retrofit including BAS deployment for the same months was made. The retrofit was started in February 2022 and was completed in July 2023. During the retrofit, the family moved to stay elsewhere, so there was no electricity use during the retrofit except for maintenance and tools. Therefore, the comparison of energy consumption was for the same months before retrofit and after retrofit and BAS deployment as shown in Table 5.2.

Month	Sep 2020	Oct 2020	Nov 2020	Dec 2020	Jan 2021	Feb 2021	Total 6 months
Electricity consumption (kWh)	4,699	3,132	2,414	1,733	1,328	1,490	14,796

Before BAS							
Month	Sep 2023	Oct 2023	Nov 2023	Dec 2023	Jan 2024	Feb 2024	Total 6 months
Electricity consumption (kWh) After BAS	2,378	3,078	2,981	1,979	1,110	1,400	12,926

Table 5.2 Electricity consumption in (kWh) for 6 months before BAS and 6 months after BAS.

The dwelling had been retrofitted, and the usable area had been increased by 114%. This increase was followed by an increase in all building systems, such as lighting and HVAC, which increased the electricity use in the dwelling. However, as demonstrated in Table 5.2, the total energy use for 6 months from September 2020 to February 2021 before retrofit was 14,796 kWh compared to the same months after retrofit and automation deployment from September 2023 to February 2024, which was 12,926 kWh. This highlights a considerable reduction in energy use of 1,870 kWh within 6 months, given that the dwelling area had more than doubled after the retrofit and the BAS still achieved an energy saving of 12.6%. The achieved electricity saving for the BAS system in 6 months would have been more than 12.6% had the dwelling area and other building systems not been increased in the retrofit project. This is an encouraging indicator and will help pave the way for the widespread use of automation in Oman.

The energy consumption of this case study dwelling was collected from NAMA, the electric distribution company in Muscat. The collected data for same months before retrofit and after retrofit were compared, and the monthly meter readings were used as an indicator of electricity consumption as shown in Table 5.2. The total consumption of six months before retrofit and BAS deployment was 14,796 kWh, and subsequently, the retrofit meant an increase in HVAC, lighting, water heaters, and building area. The total consumption of six months post-retrofit and BAS deployment was 12926 kWh. The realised saving in electricity consumption for six months was 1,870 kWh, which is 12.6%. This highlights the role of BAS in energy saving although the dwelling systems and area were increased. The saving in electricity consumption is significant and would have been greater were it not for the increase in area and building systems. As can be seen in the table, the BAS plays an important role in this.

To this end, there is a high level of confidence that the achieved saving 12.6% was realised from the BAS deployment. This is because:

- The newly built extension area (336 m^2) is more than the original dwelling area (253 m^2), this would have increased the energy consumption.
- The dwelling lighting and HVAC systems sizing is also increased by at least double which prove that the realised saving in energy consumption was achieved from BAS deployment since the energy consumption for same months before and after BAS deployment was compared and the result was that the energy consumption was less after BAS deployment although HVAC and lighting systems were increased. The role of BAS in energy reduction did not cause any negative impacts on occupants' satisfaction.

5.7 Retrofit for energy performance

Building retrofitting is a form of technical intrusion in the building to enhance its energy use which can be classified into four categories; aesthetic upgrading, acoustic retrofitting, energy efficient retrofitting and hazards mitigation retrofitting (P.H. Shaikh, 2017). Although retrofit is costly and, in some projects, costs more than the dwelling especially if new facilities are added as in our case study where the newly constructed area in the retrofit was bigger than the dwelling, a retrofit can lead to a significant energy optimization and will show a return on the retrofit investment in a reasonable time. Furthermore, the retrofit utilizes new sustainable materials and technology that enhance building energy performance and provide a better living experience. Retrofit targeting energy performance has many scales and can be done in all building stages.

In post-occupancy, building performance issues that impact energy consumption are the most important aspect that should be addressed to exploit the potential of BAS. This can be solved in different stages. For instance, the design should be reviewed for energy leaks that affect the IEQ. One element that could affect building energy performance significantly, affect BAS efficiency, and lead to energy leaks is the window material; for instance, windows can be made from different materials that are not suitable for the climate in the area. In Oman, the best material to be used for window is UPVC, which has a lower thermal conductivity than aluminium. In comparison, wood has the least thermal conductivity, but it cracks, expands in hot weather, and shrinks in cold weather. It also requires regular maintenance compared to the other two materials, but it provides less transmission of heat and cold.

Using double-glazed windows with Argon gas between the glass panels forms a good insulator that reduces heat transmission from external weather to inside the building. The window frames should be sealed to prevent weather exchange and water leakage, which damages building structure, can lead to the development of cause mildew, and, where the window frames are made from wood, can result in them rotting and rotting of window frame and the paint peeling. Wood-plastic composite (WPC) is a promising material that can be utilized for windows and has recently been used in building façades and urban furniture due to its rigidity and durability. However, it is more costly than aluminium, UPVC, and wood. A retrofit for energy performance should target building systems that impact building energy performance, and the system that consumes most electricity is HVAC, followed by the lighting system. An HVAC upgrade is needed to fit the required load with energy efficiency. HVAC performance is affected by many variables, such as BTU, which is defined as the amount of heat required to raise the temperature of one pound of water by one degree. HVAC is also affected by the external weather; the building envelope performance, which includes wall and roof insulation; building size and orientation; the number of occupants in the building; the lighting heat load; the climate; and the building location.

5.8 BAS for energy control

The achieved energy saving from BAS deployment in this case study is in line with the published research. An auditing design evaluation of BACS based on an eu.bac system audit in Denmark for a university office building with a BACS retrofit realized 12.6% for a standard C retrofit package and 28.5% for the highest retrofit package (AA) (Jacob Alstrup Engvang, 2021). The impact of BACS on energy efficiency in a university classroom according to the efficiency classes defined in the EN15232 standard highlighted improved energy use with a higher efficiency BACS class (Andrzej Ożadowicz, 2017). The impact of BAS and TBM systems were used to improve the BAS efficiency class from D to A class according to EN 15217 (M.G. Ippolito, 2014).

BASs work best with buildings that have a high quality of insulation to keep the IEQ constant without exhausting building components such as HVAC, which could affect occupants' comfort. BASs have a proven potential to save energy, but the saving results differ depending on external weather severity, building envelope quality, insulations, and HVAC efficiency.

In this case study, although a retrofit project was done and BAS was deployed, better performance could be anticipated if some sustainable practices and materials had been implemented during retrofit. For example, aluminium double-glazed windows could be replaced with UPVC double-glazed windows. columns were built with steel rebars, and ready-mix concrete and concrete blocks were used in construction of the walls without any insulation, although white paint was used in the façade, which offsets part of the heat conductivity in the concrete walls. Nevertheless, BAS has proven its ability to control the use of electricity in the dwelling and reduce energy use while maintaining complete occupant satisfaction.

The results of this energy saving (12.6%) are in line with the published research that showed improved energy efficiency as in Germany, for instance, BAS saved up to 40% of energy of occupancy-based HVAC, up to 26% of energy for heating in cold countries, and 40% energy reduction in lighting system control. Research showed that 58% of energy was demonstrated by highlighting the area of energy loss and recommending solutions to reduce energy. The results have been demonstrated in Sections 1.5, 5.8 and 6.5.

To this end, the answer to the research question 6 *What are the potential energy improvements that can be realised through the deployment of building automation systems?* is that the case study has proven that there is energy saving from BAS deployment after a retrofit project. It is recommended that building performance be reviewed regarding the energy enhancement target, and the systems that influence achieving a comfortable IEQ should be identified and upgraded before BAS deployment. HVAC, lighting, window materials and quality and door leakage, and the use of sealants are important elements that should be tackled so that the BAS can realize its full potential. Although the retrofit in this case study did not fully utilize sustainable materials and sustainable building practices, the BAS still achieved an energy saving of 12.6% even though the building area had been increased by 114% and all the building systems that influence energy use had been increased as well. The owner/occupant admitted his satisfaction with his dwelling, and this highlights the significant role of BASs in building energy performance and in attaining occupant satisfaction.

5.9 Conclusion

Building performance in Oman faces many challenges that affect energy consumption and IEQ. Occupants in Oman revealed their concerns with the electricity cost in their dwellings as demonstrated in Section 4.5.2. Occupants in Oman showed significant interest in BASs and their readiness to invest in their dwellings' enhancement and BAS deployment to reduce electricity costs. This case study was utilized to verify BAS's role in building energy performance in hot countries such as Oman. The case study was a house that was built in 2007 and had a history of energy performance for more than 13 years. The dwelling underwent a retrofit project in 2021 that involved upgrading the building systems and more than doubling the floor area with the new construction. A BAS was deployed for lighting control, ACs IR control, blinds automation, an intercom utilizing Alexa for home control with voice command, and CCTV for security and surveillance. Data were obtained regarding electricity consumption six months before retrofit and BAS deployment and six months after retrofit and BAS deployment. A comparison of electricity usage before and after BAS showed a 12.6% reduction in energy consumption without any negative impact on then occupants' satisfaction although the building area and building systems had been increased. This promising result in energy saving highlights the role of BASs in energy saving, which will allay occupants' concern about the high energy cost in Oman.

The BAS was deployed in the retrofitted building and achieved energy savings. From a six months comparison before and post retrofit and automation deployment, the realised return on investment was calculated by dividing the achieved energy saving (kWh) and converted to its energy price and then the total cost is divided by the saving amount. The case in this thesis utilized a high end leading brand smart system (Control4) which cost USD24,000. Oman energy is heavily subsidized (0.014 OMR per kWh) and therefore, ROI is excessively long and rendering the investment is impractical. For a logical comparison, Table 6.1 compares ROI in Oman and UK energy rate for the high end used BAS in this case study and a commercial BAS:

Assumptions	ROI
Current BAS Pricing (8,464 OMR) Energy Savings for six months x2 Total annual saving	19 years (Per UK energy rates 2025) 1,870kWh x 2 = 3,740/ year, UK rate @ 24p per kWh. Total saving = £897.6 Equivalent OMR 446, so the ROI = 8,464/446 = 18.97 year.
Economic BAS Pricing (2,350 OMR) Total annual saving	5.3 years (Per UK rates 2025) Total saving = £897.6 equivalent 446 OMR, so the ROI = 2,350/446 = 5.26 year.
Current BAS Pricing (8,464 OMR) Energy Savings for six months x2 Total annual saving	161.5 years (Per Oman energy rates 2025) 1,870kWh x 2 = 3,740/ year, Oman subsidized rate @ 0.014 OMR per kWh. Total saving = 52.4 OMR ROI = 8,464/52.4 = 161.5 year.
Economic BAS Pricing (2,350 OMR) Energy Savings for six months x2 Total annual saving	44.8 years (Per Oman energy rates 2025) Total saving = 52.4 OMR ROI = 2,350/52.4 = 44.8 year.

Table 6.1 Comparison of ROI for BAS (Case study VS. economic) in UK energy rate and Oman subsidized rate

A recommendation to review the building systems that influence building performance, and a retrofit should be done before BAS deployment to achieve the maximum potential energy saving. This chapter answered research question 6 about the potential energy improvements that can be realised through the deployment of a BAS and shows that there was a reduction in energy consumption through BAS deployment without any negative impacts on occupant satisfaction. Therefore, the answer to the research question 6 is yes there was energy use improvement achieved from BAS deployment as shown in Table 5.2.

6 *Chapter 6 Conclusion*

6.1 Thesis Summary

Buildings in Oman face many challenges, such as the climate, where the temperature reaches 50°C during the summer, which leads to a poor-quality indoor environment, high electricity consumption, health issues, and occupant dissatisfaction. Poor building methodology, a lack of exploitation of sustainable building materials, and a lack of any policy to implement sustainable building techniques all contribute to low building energy performance. Building performance issues were addressed using a holistic approach to tackle building process issues from the design phase to the post-occupancy phase. In each phase, challenges were identified, and potential solutions were introduced to solve the issues. State-of-the-art building materials and techniques were introduced to enhance building energy performance and achieve indoor environmental quality.

Electricity and water in Oman used to be subsidised, but in 2020, a tax was implemented, and the utilities subsidy was lifted. The increased cost of utilities posed a new challenge to occupants in Oman, and there were civil requests to reduce the cost of utilities especially during the summer. These requests led to a direction from the Council of Ministers to the Authority of Public Services (APSR) to review the cost of electricity, which resulted in a greater reduction in the cost of electricity rates.

In this study, a POE survey was utilized to identify the challenges faced by dwellings in Oman from the occupants' perspective. The survey was designed to motivate occupants to evaluate their dwellings from several aspects, so they would have a better understanding of the place they were living in. The aim was to explore occupants' perception of their dwellings and their understanding and interest in BAS, and it measured their readiness level to invest to enhance their building's energy performance through BAS deployment.

Data were collected from 105 occupants. The occupants aged between 36 and 45 years were the biggest age group who owned their dwelling (42%) followed by the age group

46 to 55 years (19%); in total, 87% of the occupants in all age groups owned their dwelling, which revealed the authentic experience and real insights from the occupants about their dwellings. The survey revealed important information about occupants' concerns and the reasons for their interest in deploying home automation. However, the research explored that although there was significant interest in automation and a high readiness to use home automation, few dwellings were equipped with BAS. This led to the development of a plan to address occupants' hesitation in deploying home automation.

A case study was utilized to verify the impact of BAS in building energy consumption as one of the promising alternatives to address the building energy challenges in Oman. The case study was a house that was built in 2007 and had a history of energy performance for more than 13 years. The dwelling underwent a retrofit project in 2021 that included an upgrading of the building systems and building the first floor as a new construction. A BAS was deployed for lighting control, ACs IR control, blinds automation, intercom utilizing Alexa for home control with voice command, and CCTV for security and surveillance. Six months of data were obtained regarding electricity consumption before the retrofit and BAS deployment and six months after the retrofit and BAS deployment. A comparison of the electricity use before and after BAS deployment showed a 12.6% reduction in energy consumption without any impact on occupant satisfaction although the building area and use of building systems had been increased.

6.2 Hypothesis and Research Questions

This research was conducted based on the challenges faced by buildings in Oman. One of the suggested solutions that has the potential to address occupants' concerns and to manage energy consumption is to deploy building automation in existing buildings.
The thesis has answered six research questions, each of which was tackled utilizing Saunders' research onion methodology, which is one of the most prominent research philosophies and approaches to theory development.

Research question 1 *What techniques and measures can be applied to Omani buildings to reduce energy use and attain occupant satisfaction?*

This question was answered through a holistic building review that tackled building energy issues from the design phase to the post-occupancy phase. In each phase, the challenges were discussed, and solutions were explored.

- In the design phase, building layout and orientation should be considered so that the building's main rooms should not be in direct sunlight. Energy simulation will help in understanding building energy performance. The design drawings should specify sustainable building materials, and sustainable building methods should be stipulated in the construction documents. Sustainable building materials include the use of wall insulation and the selection of sustainable alternatives such as LECA bricks instead of concrete bricks as discussed in Section 2.5 Review of Oman's Building Code.
- During the construction phase, sustainable building practices should be followed, such as using precast materials, which will save on transportation costs while reducing CO_2 emissions, site waste, and debris. Embedding the specified sustainable materials shall be fulfilled and used in construction. Building with LECA bricks will reduce thermal transmission and will increase IEQ. Double-glazed UPVC windows should be used instead of aluminium windows to reduce thermal conductivity; more information about sustainable building materials and sustainable building practices can be found in Sections 2.5 and 2.6.
- In the post-occupancy phase, a BAS should be utilized to control and optimize energy use. Building automation has a crucial impact on building energy control and has the potential to make a significant saving in the costs associated with maintenance and operation. It also provides a better living experience and helps attain occupant comfort and convenience; more details are given in Section 2.10 IoT and BAS for Smart Buildings.

Research question 2 *From an occupants' perspective, is the energy consumption of buildings in Oman too high?*

This question was answered using data obtained from a POE survey and insights from the occupants' perspective. The survey contained questions to collect data from the occupants regarding their interest in home automation, and the results revealed that 78% of the occupants agreed that installation of an automation system in their dwelling would reduce their utilities bill and increase safety, security, and comfort. The significant interest in BAS highlighted that the driving reason to reduce energy consumption was the high cost of energy in Oman compared to income. The survey data showed several reasons for occupants' interest in home automation, such as temperature control and safety and security at 28% each, then comfort and convenience at 14%, and use of technology at 2%. However, many of the occupants (66%) wanted to install BAS to reduce electricity bills, as the cost of electricity in Oman has motivated occupants to look for solutions to the high cost of electricity. This highlights the awareness of occupants in Oman about the role of building automation in controlling energy use. The answer to the research question is yes, as the above data revealed that the energy cost in Oman is high from the occupants' perspective as explained in more detail in Section 4.5.2

Research question 3 *Are building owners in Oman familiar with and ready to deploy building automation systems in their dwellings?*

This research question was answered in Section 4.5.2 utilising the data from the POE survey. The data showed that although 89% of participants did not have any automation systems in their dwelling, 60% of them were interested in installing automation. This highlights a significant awareness of and interest in BAS and demonstrates the good understanding occupants in Oman have about the role of BAS in building management and energy optimization. The survey data also showed the level of occupants' readiness to invest in their dwellings to improve temperature control (78%); install a BAS (60%); enhance natural and artificial light control (49%); and improve indoor air quality (39%). The driving expectation of occupants in Oman from automation deployment was energy cost saving (66%), which also revealed a good perception of home automation. In total, 78% of the occupants agreed that automation would help them reduce their energy bills and increase safety, security, and comfort. Furthermore, the data showed the high interest of occupants in Oman in deploying BAS in their dwellings.

Thus, the answer to this research question is that occupants in Oman have a good awareness about the role of BAS in building energy management, as 60% of the occupants were interested in installing BAS in their dwellings. Furthermore, 60% of the occupants showed a readiness to invest in BAS deployment in their dwellings, and the driving reason for their willingness to install BAS was to reduce costs (66%). However, few dwellings were equipped with BAS.

Research question 4 *From the perspective of occupants, what are seen as the obstacles for the deployment of automation systems?*

The POE survey data showed that 87% of dwellings were owned by the residents (see Section 4.5.4), meaning the occupants can modify their dwellings to comply with BAS installation requirements, such as wall trenching, cabling, and device installation in walls and ceilings, without the need for approval from a third party. The data demonstrated a high readiness for home automation deployment with 60% of the occupants interested in installing BAS in their dwellings. However, 89% of the dwellings were not equipped with BAS. This highlights the challenges and obstacles that hinder occupants from installing BAS. Given occupants' reluctance to deploy home automation, further research is required to review the following challenges:

- **BAS availability in Oman market:** Regarding the availability of the BAS products, branded products, market monopoly and alternative solutions, the available products, and automation solutions should be reviewed and made available for occupants in Oman to customize and choose their preferred solution.
- **Automation cost**: BAS devices breaking down, approximate cost of installation, and configuration and training should be clearly explained and clarified to clients so there will be no misleading information or unforeseen costs.
- **Cost of maintenance**: Issues include warranty period, regular maintenance, maintenance costs, self-maintenance and contractor maintenance, maintenance

challenges such as malfunctions, slow automation system response, wrong automation commands due to sensors interlinks, and other maintenance issues.

- **Occupants' stochastic behaviours:** Impacts of the variable number of occupants on an automation system, BAS efficiency review, stochastic occupancy behaviours and occupancy patterns, and all factors that influence automation systems should be identified and clarified to avoid future dissatisfaction which could result in BAS having a negative reputation.

Therefore, the answer to this research question is that several obstacles hinder occupants from deploying automation (as described in Section 4.5.4). These obstacles must be removed, and occupants' concerns must be allayed to pave the way for widespread automation. The obstacles were identified as listed above, and further research is required regarding BAS in the Omani market.

Research question 5 *What can be done to allay the occupants' concerns over the deployment of building automation systems?*

This question was tackled through two strategies: the first was a literature review utilizing archival data that identified building energy performance challenges in all building phases and showed how occupants' stochastic behaviour affects BAS efficiency and consequently IEQ and occupants' comfort. In each phase, sustainable measures, practices, and building methods were recommended (see Chapter 2).

The second part was tackled in Section 4.5.5, where the research community was recommended to address six obstacles that hinder widespread BAS deployment given that occupants in Oman showed a good perception of the role of BAS in building energy control and showed a high readiness level to invest in automation deployment. The six research areas will increase understanding of the BAS market in Oman and remove the obstacles that hinder widespread automation:

1. **Market status:** Study the causes of the limited spread of BAS, market monopoly and price control, market competitiveness, and alternative products.

2. **Initial BAS investment:** Examine the cost of BAS in Oman market given that in some markets, such as the USA, ROI for automation is 1.7 years. ROI is a good indicator to promote BAS although there is a variety of products, and BAS can be customized to fit each occupant's budget and preference.
3. **Maintenance cost:** Given that wireless sensors, actuators, and PIR devices need their batteries changed approximately every year, other costs related to software and hardware maintenance should be clarified to users to avoid any misunderstanding or hesitation in BAS deployment.
4. **Occupants' behaviour:** The causes of behaviours such as occupants' reluctance and hesitation should be identified, and a roadmap constructed to address their concerns and any risks in order to smooth the way for widespread automation.
5. **Security and privacy:** Concerns regarding BAS, should be explored. In particular, the system requirement of internet use to remotely control the system, which makes it susceptible to hacks and attacks, should be scrutinised.
6. **Successful case study examples:** This will help promote the use of automation systems by showing the energy saving results from real case study examples that project an ROI that would help the BAS market to thrive.

Occupants in Oman showed high interest in automation as one of the solutions with the potential to control and reduce energy use. However, 89% of the surveyed dwellings were not equipped with any automation, and the remaining 11% were equipped with only minor automation that does not utilize the potential of BAS in energy-use reduction. This hesitation regarding BAS deployment and occupants' reluctance means more effort is required to remove the obstacles identified in the POE data to allay occupants' concerns. The suggested measures from the researcher's point of view to tackle the challenges faced by the BAS market in Oman are as follows:

1. Installing building automation is costly; reliable alternatives should be made available.
2. Associated maintenance cost should be presented clearly to the occupants.
3. Occupants' behaviours and tendencies that cause hesitation in deploying home automation should be addressed and allayed.

4. Solutions to security and privacy concerns should be presented to the occupants.
5. Successful case studies involving the impact a BAS has on building energy performance and occupant satisfaction should be disseminated to promote the widespread use of BAS.

The suggested measures could allay occupants' concerns in Oman, as they will provide more information about automation systems and will clarify any misunderstanding and allay certain concerns. This would be particularly so if the given data were based on a neutral market study and the deployment of BAS were supported with case study results.

Identifying the above concerns, finding the solutions to the identified challenges, and explaining the challenges and solutions to the targeted occupants needs collaborative work from the concerned authority and stakeholders by including automation in the building code to familiarize people about its role in building management, energy control, and occupant satisfaction. There should be promotions and incentive programmes like the incentives given to rating systems to motivate architects, building owners, and contractors to consider specifying automation in the construction drawings, the building process, and retrofit as a sustainable building alternative.

Research question 6 *What are the potential energy improvements that can be realised through the deployment of building automation systems?* The case study in Chapter 5 showed that there is energy saving from BAS deployment after a retrofit project. It is recommended that building performance be reviewed for energy enhancement targets, and the systems that affect IEQ should be identified and upgraded before BAS deployment. HVAC, lighting, window quality and materials, doors leakage, and the use of sealants are important elements that should be tackled in retrofit so that any BAS can realise its potential. Although the retrofit in the case study did not fully utilize sustainable materials and sustainable building practices, the BAS still achieved an energy saving of 12.6% without any negative impact on occupant satisfaction and IEQ, despite the building area having been increased by 114% and all building systems that influence energy use having been increased as well.

Thus, the hypothesis analysed in this thesis is as follows:

The use of BAS systems has the potential to achieve a significant reduction in energy use in dwellings in Oman.

In answer to this hypothesis is that the use of BAS systems does indeed have the potential to achieve a significant reduction in energy use in dwellings in Oman. This has been evidenced by the following:

- That the case study dwelling energy consumption before BAS deployment was higher.
- That the case study dwelling has undergone a retrofit that included area extension of 114% of the original area and the sizing of the HVAC and lighting systems were approximately doubled.
- The energy consumption after BAS deployment realised energy saving of 12.6%.

6.3 Contributions

This thesis has focused on exploring the challenges that arise from poor building performance in Oman and has recommended solutions to major issues that influence building energy performance that, if implemented, have the potential to reduce energy use and attain occupant satisfaction. Occupants' perspective was central to the research to evaluate their dwellings and express their concerns about the challenges that affect their dwellings' performance and IEQ and their own comfort and convenience. This thesis contributes to the knowledge in this field in the following areas:

1. Recommendation of sustainable building practices for Oman's building code: This contribution includes a detailed review of the factors influencing building energy performance, sustainable building materials, and sustainable building practices and methods. This review will help the relevant authorities in Oman, especially regional municipalities, to consider the sustainable building

recommendations in this thesis, which will motivate the authorities to enhance building quality and consider exploiting sustainable building alternatives to reduce energy consumption and increase occupant satisfaction. The review of the Omani building code provides knowledge on advanced building materials, advanced building practices, and crucial measures that affect building energy performance. Furthermore, although the recommended practices and measures are up to date, construction technology, building materials, and sustainability are still evolving, and thus it is crucial that construction practices be updated to take advantage of the new technology. To this end, the review of Oman's building code as well as the results and recommendations can be utilized by the research community in future work. This work has paved the way for the construction of sustainable buildings and for exploiting BAS for building energy performance and occupant satisfaction. The findings could be implemented in Oman and neighbouring countries. Researchers are recommended to improve the practices and measures in the future by promoting and updating alternative measures to encourage sustainability in Oman and hot countries.

2. A holistic review was utilized to explore and examine state-of-the-art sustainable building materials, sustainable building methods, and sustainable practices and measures that enhance building performance and IEQ and attain occupant satisfaction. A holistic building process was reviewed to identify the challenges that influence building energy performance, and solutions to solve the challenges were recommended in each phase from the design to the post-occupancy phase. This knowledge can be utilized by the research community to overcome building challenges in Oman and hot countries and can serve as a reference to the best practices and measures to enhance building energy performance.

3. A POE was used for enhancing building performance and automation deployment that evaluated building performance and occupants' comfort in Oman. The literature review was published in Journal of Building Engineering, 19 November 2023. Utilizing the POE survey, data from 105 occupants in Oman were collected and analysed, and the results were used to recommend strategies to address building energy challenges and to allay occupants' concerns

regarding BAS deployment. The research can serve as a reference to evaluate buildings in Oman from the occupants' perspective. It contains important information regarding challenges to building performance, how to solve many of the issues that affect IEQ, and how to address occupants' concerns. The POE survey highlighted the importance of involving occupants in building management. Occupants play an important role in building evaluation beyond regular maintenance and building management; hence, they can be utilized to provide important IEQ feedback to improve the living experience especially in high rise rental buildings.

4. A total energy saving of 12.6% was realized from a case study investigating the impact of BAS on building energy performance. A comparison was made of electricity consumption before and after BAS installation. The case study is a dwelling in Muscat that was built in 2007 and underwent a retrofit project in 2021 that contained an upgrading of building systems and more than double the floor area due to new construction. A BAS was deployed for lighting control, ACs IR control, blinds automation, intercom utilizing Alexa for home control with voice command, and CCTV for security and surveillance. Six months of data were obtained regarding electricity consumption before the retrofit and BAS deployment and six months after the retrofit and BAS deployment. A comparison of electricity use before and after BAS showed a 12.6% reduction in energy consumption without any impact on occupant satisfaction although the building area and building systems had been increased.

6.4 Limitations

The thesis has the following limitations:

The thesis results relied on a POE survey and a case study. The survey results were based on the occupants' perspective, which reflected their concerns, and which is important especially in rental units. However, on the other hand, the building owners should be allowed to give their opinions regarding occupants' concerns. By listening to occupants and owners, there could be some solution to allay occupants' concerns from the owners' point of view.

The conditions required for the case study, specifically, that the dwelling should be equipped with BAS and have a history of energy use pre-BAS deployment, made it difficult to find such a case. Four BAS installers were approached, and they provided cases that had installed BAS in new buildings. Since BAS is a new technology, almost all equipped dwellings had installed them in new buildings with no historical energy use. Moreover, most of the potential dwellings had partial automation, such as external lighting control only, or CCTV and gate control only, but it was difficult to find a full BAS.

The case study compared energy consumption of a dwelling before and after BAS deployment. Although a 12.6% energy use saving was realized, the potential of BAS in energy saving was higher since the building had simultaneously undergone a retrofit where the floor area was increased by 114% and the capacity of the building systems that consume the most energy were approximately doubled. It is estimated that the BAS system provided an energy saving of 12.6%.

However, even taking the more conservative estimate of 13%, this still proved that a BAS energy saving was achieved and there would be more energy saving if the building area has not been increased and the systems that strongly effect energy use (HAVC and lighting) were not doubled.

Ideally, this case study would have been conducted on a building that could be analysed without any change before and after BAS deployment, to provide consistency and reliability. However, no such case study building was available.

6.5 Future Work

Research the obstacles and challenges that hinder the widespread use of BAS and explore possible solutions: BASs are a technology that has been proven to reduce energy consumption in Oman by a minimum of 12.6%, as demonstrated in Chapter 5, and should have a similar potential for energy reduction in other hot countries. Given that most of the GCC countries' residents live in their own dwellings and can deploy BAS with minor building modifications for BAS installation, BAS can be customized to control all or some of the building systems, and it is available for different budgets according to the desired control level. Obstacles that hinder BAS from thriving as one of the solutions that have the potential to enhance building energy consumption in the post-occupancy phase should be studied and addressed. This thesis showed that 89% of the surveyed dwellings were not equipped with BAS, and the remaining 11% were equipped with only basic automation that did not exploit the potential of BAS to reduce energy. Although BAS cannot do its work separately from enhancing other building systems, as retrofit could be costly and usually not many occupants will do it except for adding new facilities to the building, BAS will generate energy saving in a short time to make it economically viable. However, BAS is not thriving in Oman and many other countries although its potential in building energy enhancement has been proven by many researchers and studies as demonstrated in Section 1.5. BAS has saved up to 26% of energy consumption in cold countries for heating, up to 10% in lighting, and up to 14% in unnecessary electricity use. In Germany, BAS saved up to 40% of energy in occupancy-based HVAC control by adopting occupancy sensors, scheduled shading, and daylight harvesting, whereas a 48% to 58% of energy saving from lighting control was realised. All these potentials and others are not exploited in many countries.

Stakeholders in Oman should exploit the potentials of BAS to save energy use and reduce carbon footprint by implementing sustainable building methods and using sustainable building materials. This must be led by governmental authorities which have the power to enforce the policies by code. Oman code should encompass the measures and practices that reduce electricity use, enhance building performance and allay occupants concerns about electricity cost. The realised saving from BAS case study should encourage authorities to adopt the use of BAS for energy saving. This is through encouraging architects and contractors to embed BAS in the new buildings, and in retrofit projects. The positive implications of BAS should be explained to landlords to encourage them to deploy automation in their buildings.

There are some barriers that hinder scaling up the BAS implementation in Oman. These involve occupants' hesitation to deploy automation, although mitigating this the survey data demonstrated a high readiness for home automation deployment with 60% of the occupants interested in installing BAS in their dwellings.

Therefore, to scale up BAS implementation in Oman, The Oman market status should also be studied to explore the automation alternativeness in terms of the cost, initial investment, alternatives and return on investment. Maintenance and other running cost such as access to WIFI and other security and privacy concerns should be studied and become logic for scaling up automation as discussed in Section 4.5.5.

Thus, it has been found that the best practices and recommendation for BAS deployment are to enforce the use of sustainable building, sustainable retrofit and exploitation of BAS by adding these practices as mandatory clauses in the municipality building code in Oman, promoting the sustainability with incentives such as fees and tax reduction will encourage building stakeholders to implement sustainability in which will promote BAS widespread in Oman.

The municipality code should be amended to consider incentives for sustainable buildings such as tax rebates, expedited permitting for meeting sustainable building standards, allowing more floor area and encouraging green roofs. Incentives will boost innovation in sustainability and should be granted for sustainable implementations such as the use of sustainable building materials.

These amendments will expedite the adoption rate of sustainability in Oman which will enhance building performance, reduce environmental impacts by reducing energy consumption and minimize the waste.

Future researchers are encouraged to highlight the best practices to promote and exploit BAS as a successful technology that is proven to enhance building energy performance especially in Oman and hot countries given that massive energy consumption is wasted in cooling low performance buildings that were not built to reduce electricity use compared to sustainable buildings. This requires further research firstly to provide a holistic solution to enhance the low building performance and promote the use of BAS to optimize building energy use mainly from the occupants' perspective, and secondly, to address the BAS challenges that make occupants hesitant to deploy it, which could be related to many reasons as discussed in Chapter 4. Future research is also required to work to improve Oman's building code to encompass sustainable building materials, sustainable building practices, and BAS as a promising technology that has the potential to enhance building energy performance.

Retrofit and BAS deployment promotion for energy saving in hot countries. A comprehensive building energy review, upgrading building systems that affect building performance, and equipping the building with BAS is the best scenario to enhance building energy consumption for existing buildings, as demonstrated in the case study in Chapter 5. A retrofit strategy for Oman and hot countries should be identified, and the retrofit impact in building energy performance should be calculated and promoted. New buildings or retrofit should utilize sustainable building materials to enhance building energy performance. This should be added to Oman's building code to reduce energy consumption and attain indoor quality. A cost comparison of sustainable building materials and ordinary building materials should be conducted, and the impact of sustainable building in building performance should be promoted. Besides, an assessment should be made of the impact of BAS in every building phase and building systems in hot countries and the results made available to stakeholders to encourage the BAS market. For instance, there are many studies on the impact of BAS on indoor heating but very few studies have been done in hot countries regarding its impact on indoor cooling. The factors influencing the ability of BAS to efficiently control building systems in hot countries should be identified, and solutions to improve BAS potentials in enhancing building systems performance should be announced and promoted.

6.6 Conclusion

This thesis was inspired by several reasons that motivated the researcher to think about and study this topic and try to find solutions to the challenges encountered in building energy performance and that affect occupants' comfort. The causes were the increase in the cost of electricity, the new tax implementation, Oman's hot climate, and building performance quality. These factors affect occupants while increased electricity bills have caused them dissatisfaction. To address the challenges, a holistic review approach was adopted to explore all the factors that affect building energy performance in all building phases. Oman's building code was reviewed to identify the issues and recommend new practices and measures to mitigate the effects of these challenges. State-of-the-art sustainable building methods, sustainable building materials, maintenance and retrofit practices and measures were recommended to tackle the challenges in each phase. A POE survey was utilized to evaluate buildings in Oman from the occupants' perspective. The survey helped in gathering data related to building performance and building enhancement potentials, and in tackling high energy consumption by exploiting BAS. The survey revealed data and information about dwellings and occupants' concerns; these were then addressed, and solutions were recommended to solve the challenges. A case study of a BAS was conducted to verify the impact of BAS deployment on building energy performance in Oman, and the results showed that a 12.6% energy saving was achieved in 6 months. This saving would be more than 12.6% if the dwelling area and dwelling systems had not been increased, as the electricity consumption would be less. BAS have high potential to control the energy consumption in dwellings without affecting the IEQ and occupant satisfaction.

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Appendix A: Post-occupancy evaluation survey

Appendix B: Case study building automation system for building energy performance

Appendix C: Survey Participant information form