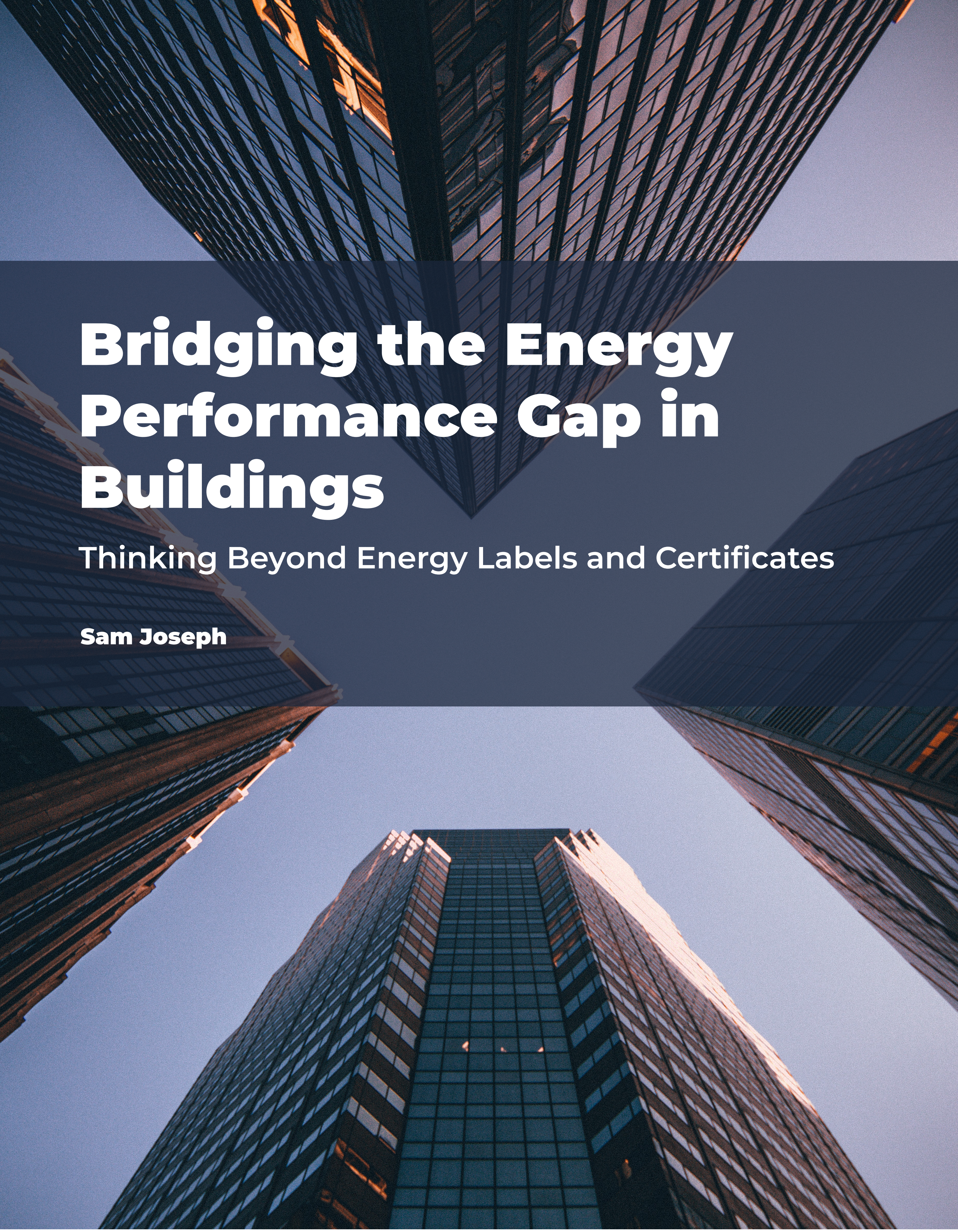

Bridging the Energy Performance Gap in Buildings

Thinking Beyond Energy Labels and Certificates

Sam Joseph

TU Delft Delft University of Technology

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“The greatest threat to our planet is the belief that someone else will save it.”

Robert Swan

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Bridging the Energy Performance Gap in Buildings

Thinking Beyond Energy Labels and Certificates

by

Sam Joseph
5518016

In partial fulfilment of the requirements for the degree of
Master of Science in Construction Management and Engineering *at the*
Delft University of Technology

In collaboration with ***NS Stations***

This thesis is confidential and cannot be made public until 30th November 2023

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http://repository.tudelft.nl/.

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Acknowledgement

"All our dreams can come true, if we have the courage to pursue them"
Walt Disney

Delft University of Technology has truly been a place where my dreams have come true. Indeed, TU Delft did live up to the academic hype and made me question my capabilities a few times. Any school can give you a lecture but only a few can give you an experience. As I reflect on my wonderful journey at TU Delft, little did I know as a young civil engineer foraying into the construction management and engineering world, that I would be able to achieve my dreams in the best possible way through a roller-coaster ride, filled with heavily contrasting emotions all at the same time. Being an international student, it is never an easy decision to move 8000kms away from home to chase your dreams. Being away from home and family for almost 840 days at a stretch or failing exams, all the struggles endured during this journey have only made me a stronger person. I am forever grateful for this opportunity and experience.

Sustainability is an important practice that we must introduce in our lives to create a better future for upcoming generations. In other words, we owe it to ourselves. As Helen Keller said, "Alone we can do so little. Together we can do so much", my masters at TU Delft has given me a further boost to help save our planet. This expedition at TU Delft has been an eye-opener for me regarding the impacts of the construction and real estate industry on the environment. Most importantly, this thesis is also my contribution towards a more sustainable planet for everyone. With the impacts of climate change costing lives, it has now become a matter of life or death. We must not take this planet for granted! I hope this thesis has triggered atleast a small thought in the minds of the readers regarding sustainability.

First and foremost, I would like to express my deepest gratitude to my graduation committee. Especially to Andy van den Dobbelsteen, who has been a colossal support and guidance throughout a major portion of my journey at TU Delft. Your supervision and guidance during this journey has been an immense learning curve that has further ignited my motivation to work towards a sustainable planet for everyone. Also to John L. Heintz and Erik-Jan Houwing, whose immense guidance has helped me gain better perspectives regarding my research. Your feedback and suggestions have been instrumental and helped in improving my master thesis in the best possible way. As the famous Japanese proverb goes, "better than a thousand days of diligent study is one day with a great teacher", you all have provided me with the best knowledge, not only about the topics related to my research, but also about life. Keeping aside some time from your busy schedules (I know, it is your job to do so) to guide me, is something I cannot thank enough. I would also like to thank all the faculty members involved in various courses that I have undertaken at TU Delft as part of my master program.

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I wish you all a pleasant and informative read!

Sam Joseph
Delft, November 2023

Executive Summary

In 1987, Brundtland published a report addressing a major challenge to the world community regarding environment and development, and introduced the term "sustainable development". Ever since, the world has undergone rapid changes through rapidly advancing science and technology. However, these advancements have left behind a negative effect on the environment which evident through climate change. Significant alterations in global temperatures and weather patterns have a major impact on all forms of life on earth. The average global temperatures have been rising since the past several decades at an alarming rate with no signs of slowing down. Several other irregular weather patterns such as more frequent and intensive rains, flooding, thunderstorms, wildfires and melting of the polar ice. These effects of climate change on various social segments are interconnected from food production to human health. Governments across the world have taken unanimous actions by signing the Paris Climate agreement to keep the global temperature rise below 2°C, preferably below 1.5°C.

Energy consumption has been a growing concern mainly due to the emissions resulting from energy usage in buildings. These numbers are predicted to rise with the increasing floor area to meet the demands of the rising population. Fossil fuels, namely coal, oil, and gas, are the primary drivers of global climate change, constituting more than 75% of global greenhouse gas emissions and almost 90% of CO_2 emissions. A major contributor to climate change in terms of greenhouse gas emissions into the atmosphere is the energy industry. Fossil fuels are primarily used to produce energy required for various activities and releases toxic greenhouse gases into the atmosphere which is the primary cause for global warming and climate change. The built environment, especially buildings, have a major impact on the environment throughout their entire life-cycle as they consume huge amounts of energy during their construction as well as operational phase. Buildings account for 40% of the overall CO_2 emissions, out of which approximately 28% are from operations alone. On the other hand, human population is increasing exponentially, creating an increased demand for buildings worldwide and thereby increase the emission figures. Energy usage in buildings have been rising at alarming rates for the past few decades, even though these figures went down during the COVID-19 pandemic.

Governments across the world are introducing strict measures regarding energy consumption in buildings to curb these emissions. Moreover, governments have set targets in terms of energy consumption in buildings to drastically reduce emissions and keep the global warming within the limits defined by Paris Climate agreement. In the Netherlands, the government has introduced mandatory energy labels for buildings according to the Energy Performance of Buildings Directive (EPBD). These energy labels provide an estimation for the energy consumed within buildings. However, these energy labels only take into account few aspects of energy consumption within a building such as energy consumed for heating, cooling, lighting and hot water supply. The actual energy consumption figures of a building entail several other aspects such as energy consumed by occupants of a building. The mismatch between predicted or estimated energy consumption and actual energy consumption within buildings is termed as energy performance gaps.

Real estate developers use these energy labels and certificates as a design support tool to design energy efficient buildings leading to energy performance gaps. These energy labels leave behind a grey area within energy consumption figures that are often overlooked or neglected by designers and developers during the design of buildings leading to the gap. This research strives to bridge the energy performance gap in buildings inherent due to these energy labels and certificates by shedding light on the grey areas of energy consumption which are often overlooked or neglected during the design process. The main objective of the research is to bridge this gap by developing a design strategy that focuses on the grey area in energy consumption figures. This requires a better understanding regarding the several aspects that constitute the grey area in energy consumption. The research explores this grey area and develops a suitable design strategy through a double diamond design methodology.

The research strives to answer the main research question:

How can we bridge the energy performance gap inherent in buildings due to energy labels and certificates during the design phase of a (re)development project?

The main research question is further broken down into the following sub-questions:

1. *What is the energy performance gap inherent in buildings? What are the underlying causes for energy performance gap in buildings?*
2. *What are the different aspects of occupant behaviour in buildings? What effect do these aspects of occupant behaviour have on the energy performance of buildings?*
3. *How can we incorporate these aspects of occupant behaviour into the design of buildings to bridge the energy performance gap?*
4. *How can we integrate these occupant behavioural aspects into a design process/strategy for a building (re)development project?*
5. *What are the practical implications of the design strategy for a (re)development project to bridge the energy performance gap?*

The double diamond method consists of two diamonds that resemble the problem space and solution space which are further divided into four different phases - discover, define, develop and deliver. The first phase (discover), involves divergent thinking approach to discover the problem through a broad perspective. In this phase, energy consumption within buildings and the concept of energy performance gaps are studied in detail. The underlying causes that leads to energy performance gap are identified from scientific literature. In the second phase (define), occupant behaviour is studied in detail with the help of scientific literature. A case study is used to understand the current practices within the industry that leads to the negligence of occupant-related aspects. Collectively, these information will help in defining the detailed problem statement at the end of the first diamond.

The third phase (develop), also the beginning of second diamond (solution space), takes a divergent approach again to develop a broad solution which will be further refined in the next phase to solve the detailed problem. In this phase, through expert panel discussions with the project team for Stichthage, the identified occupant behavioural aspects will be linked to the design of various components of the building. These will help in understanding the role of occupant behaviour within building design to improve the overall energy performance of the building. In the final phase (deliver) of this research, the broad solution will be narrowed down into a design strategy which will be further refined with the help of expert opinion. These expert opinion will provide insights into the practical implications of the design strategy and help improve the strategy and its application further.

Energy performance gaps are the mismatch between predicted or estimated energy consumption of buildings during the design phase and the actual energy consumption of building during the operations phase. In the Netherlands, these energy consumption predictions or estimations are done using energy labels and certificates. Early design decisions, uncertainty, lack of energy performance monitoring, occupant behaviour, etc. have been identified as underlying causes that lead to the gap. Amongst these occupant behaviour has been identified as the most important underlying cause that are often neglected by energy labels and certificates, and constitute a major portion of the overall energy consumption figures. With upcoming policies and regulations such as Paris-proof targets, bridging the energy performance gaps are becoming ever more important for real estate developers. Moreover, bridging the gap also helps in reducing the overall energy consumption of buildings.

Occupant behaviour has been classified into several different aspects according to literature - occupancy, interactions and behavioural efficiency. Occupancy refers to information pertaining to the status of occupants within a building. Presence (entry,exit), location (spatial presence, change in location) and activity (function, occupation) are parameters used to describe occupancy patterns. Interactions refers to the human-building interactions to maintain comfort levels suitable for occupants to occupy and carry out their activities within the building environment. Occupants interact with various components of the building to maintain visual comfort, thermal comfort and indoor air quality. These interactions are studied further based on the composition of a building - building services (HVAC, lighting, elevators, escalators, etc.), building facade/envelope (windows, blinds) and user systems (plug loads and electrical appliances). Behavioural efficiency relates to the social science aspects of occupant behaviour which are necessary to improve the occupant energy consumption behaviour. These behavioural efficiency can be ensured in three different ways - traditional approach, feedback approach and smart technologies. Traditional approach includes creating awareness, providing knowledge, signage, instructions and motivation to occupants. Constant feedback regarding energy performance of occupants will ensure behavioural efficiency. Smart technologies can be used to track energy performance and devise necessary behavioural interventions to ensure energy efficiency.

A case study was used to understand the current practices followed within the real estate industry and identify the issues and limitations within them that leads to energy performance gaps in buildings. The energy performance data for the building were also analysed to study the issue of energy performance gaps. The current design practices were identified as one of the most important issues that leads to energy performance gaps in buildings. The developers used energy labels and certificates as a support tool to aid their design decisions. Current design strategies require major interventions in order to bridge the gap and shed light on the grey areas of energy consumption such as occupant behaviour. Moreover, several asset management practices were also identified as major issues that lead to energy performance gaps in buildings. There was an evident lack of data and information regarding energy performance of buildings to identify the root cause or areas of excessive energy consumption. The asset managers were also not able to influence or control the energy consumption of occupants. Taking into account these issues and limitations from the case study, the detailed problem statement was devised as follows:

Developers and designers use energy labels and certificates as a support tool to aid design decisions and neglects occupant behaviour within the design of buildings. Occupant behaviour is found to have a significant impact on the overall energy performance of a building. Moreover, Such a design strategy leads to energy performance gaps in buildings.

Occupant behavioural aspects mentioned above are found to have a significant impact on the energy performance of buildings. Hence, these aspects can be linked to the design of buildings to improve their energy performance during the operations phase. Occupant focused design helps reduce overall energy consumption by making buildings less sensitive to occupant behaviour. An expert panel discussion with the project members of Stichthage were conducted to establish a link between occupant behaviour and design of buildings as well as understand the state-of-the-art available. Facades and spatial layouts of a building can be linked to the occupancy patterns as well as the interaction patterns for different types of offices or tenants. Similarly, building services such as HVAC systems, lighting, automation and controls can all be linked to interaction and occupancy patterns to improve the design to cater to the behavioural needs of the occupants. Additionally, on-site energy generation and energy storage will help in bridging the gap. Energy tracking is also considered to play a major role in keep tracking of energy consumption. Detailed energy tracking will assist asset managers maintain the energy performance of the building as intended during the design phase and thereby bridging the energy performance gap in buildings.

Using the link established between occupant behaviour and building design, an occupant focused design strategy was developed as illustrated in figure below. This strategy describes various activities and responsibilities for various members of the project team in three different phases - pre-design phase, conceptual design phase and detailed design phase. RIBA Plan of Work was used as a reference design strategy to develop the occupant focused design strategy. This strategy aims to bridge the energy performance gap in buildings by mainly focusing on occupant behaviour. The strategy will help designers and developers think beyond energy labels and certificates that do not provide a complete picture of energy performance of a building. The strategy also highlights the roles, responsibilities and activities for different members of the project team.

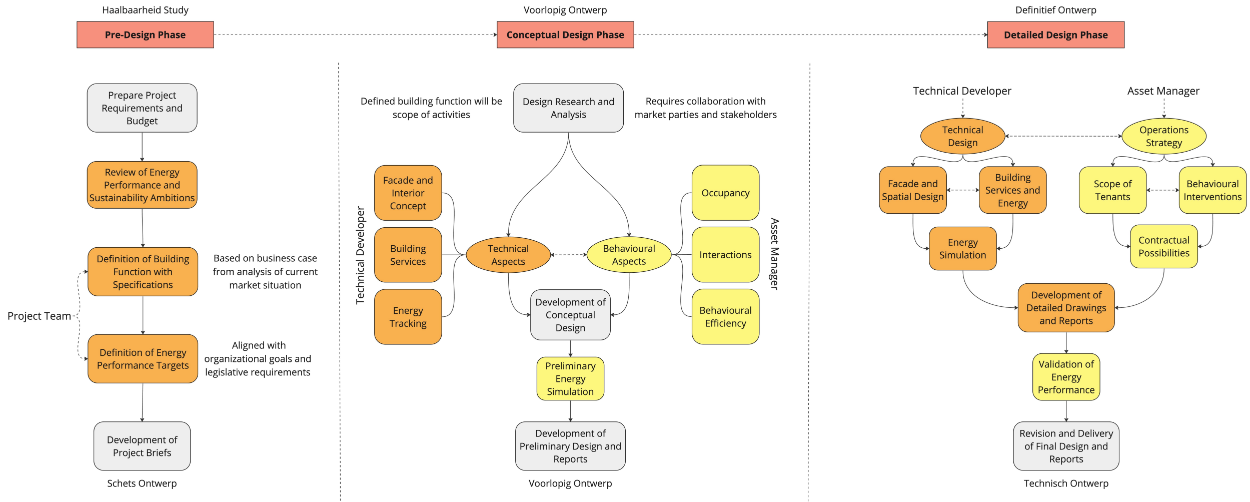

Figure 1: Occupant Focused Design Strategy

The pre-design phase determines and defines the main parameters of the project such as specific building function with details and energy performance targets that will aid the design process. Review of the current situation and insights from market analysis are important inputs for these main activities. The conceptual design phase includes two major activities carried out by the technical/real estate developer and asset manager. The former deals with the technical aspects of the building and the latter deals with occupant related aspects of the building. The asset manager collects information regarding various occupant behavioural aspects. The developers will explore the various possibilities for technical aspects of the building using inputs from asset managers regarding occupant behaviour. A conceptual design will be developed using these information gathere. Additionally, preliminary energy simulations will help in keeping track of the energy performance of the design to make necessary changes before delivering the preliminary design. The detailed design phase involves the development of detailed drawings for technical aspects of the building as well as an asset management strategy for the operations phase of the building. The developers will develop detailed drawings for technical components using the information gathered in the previous phase regarding occupants. At the same time, asset managers will further narrow the scope of tenants to aid the design process, explore various possibilities for behavioural intervention and draft special rental contracts. Energy simulations in this stage of the design process will provide estimations for energy consumption which will be close to real-life figures using occupant-related factors in the calculation. Following these activities, the detailed design of the building will developed and validated by the project team for energy performance before the final design is delivered.

Expert opinions were gathered regarding the developed design strategy to understand the practical implications of the design strategy. The design strategy that has been created seeks to address the energy efficiency gap in buildings by integrating factors of occupant behavior and other commonly ignored aspects. The implementation of this particular strategy holds significant importance for forthcoming laws and regulations, such as the establishment of Paris-proof targets, which aim to govern the overall energy usage of buildings. Experts emphasize the need of identifying building functions and defining energy performance targets at the early design phase to improve energy efficiency. Nevertheless, engaging in these activities could potentially expose developers and owners to financial risks. The integration of occupant behavior features in energy simulations has the potential to enhance the accuracy of predictions. The inclusion of energy performance tracking measures is crucial in addressing the energy performance gap. The proposed approach promotes a shift in developers' mindset, urging them to consider factors beyond the conventional use of energy labels and certifications. This entails placing emphasis on occupant behavior and actively addressing the ambiguous aspects of energy consumption. The implementation of an asset management strategy can facilitate the integration of technological interventions and provide support to asset managers throughout the operations phase. It is advisable to incorporate energy-related clauses into rental contracts in order to reduce occupant energy consumption and align with the objectives outlined in the Paris Agreement.

The research has several limitations such as:

- The examination of energy performance gaps in the Netherlands exclusively via the lens of energy labels and certificates. These labels and certificates may differ across different countries.
- The design concept has been specifically developed for renovation projects, under the assumption that there is currently existing data available on energy performance and occupant-related aspects. Additionally, it places emphasis on the behavior of occupants in non-residential buildings, which may not be directly relevant to residential buildings.
- The study employed a single building as a case study, perhaps limiting its ability to comprehensively address all difficulties within the real estate industry. Furthermore, a subset of the interviews was carried out in the Dutch language, which may have resulted in potential loss of participants' emotional expressions throughout the process of translation.

The scope for future research includes:

- In order to address the energy performance gap in buildings, it is imperative to possess a thorough comprehension of the fundamental factors contributing to this phenomenon. This underscores the necessity for additional research pertaining to alternative methodologies and underlying factors that affect real estate developers.
- The potential efficacy of occupant-centric design solutions should be further augmented by conducting additional case studies. Gaining an understanding of the viewpoints held by policy makers and the potential implications of forthcoming laws and regulations can offer valuable information for developers and asset managers.
- Doing research in the fields of social sciences and human psychology can provide valuable insights into predicting occupant behavior and enhancing the connection between building design and occupant behavior.
- Potential areas for future research could involve investigating behavioral treatments and the implementation of specialized rental contracts as means to restrict energy use by occupants in more detail.

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Chapter 1

Introduction

Approximately four decades ago, in 1987, Dr. Gro Harlem Brundtland published a report to address a major challenge to the world community regarding environment and development. In the report, Brundtland defined sustainable development as "a development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). Ever since, the world has progressed extensively and is continue to face the impacts of climate change in profound ways. Today, science and technology advances at an unprecedented rate. In this ever-changing world of engineering and technology, where each new day sees a spate of new concepts and applications with each passing day making things obsolete, there is an urgency to adopt sustainable measures to sustain the planet for future generations. The impacts of climate change that is still evident around the world shows that we have clearly not done enough in terms of sustainability. Climate change is characterized by enduring alterations in temperatures and weather patterns over an extended period according to UN (2023c). Intergovernmental organizations such as United Nations emphasize that these changes are not natural and has been induced by various human activities since the 1880s.

The world has been witnessing a rapid increase in global temperatures termed as the phenomenon of global warming. In order to understand how global temperatures fluctuate over time, NASA used the period from 1951 to 1980 as a baseline whereas some other organizations use the average of 1850-1900 as the baseline. Scientists believe that a temperature increase of 2°C over pre-industrial levels will have serious and catastrophic effects on the climate and the ecology (EU, 2018). Since the industrial revolution, average global temperatures have increased dramatically, with the most recent decade (2011–2020) being the warmest ever recorded as shown in figure 1.1 as 19 of the 20 warmest years have taken place since 2000 since modern record keeping began in 1880. In comparison to the end of the 19th century, the average worldwide temperature is currently 0.95°C to 1.20°C higher (NASA, 2023). According to data provided by Copernicus (2022), 2022 had the hottest summer and second warmest year on record. As per the most recent studies and articles, July, 2023 saw multiple previous global temperature records being broken (Copernicus, 2023). The exceptional rate of climate change brought on by heat-trapping greenhouse gases in the atmosphere is confirmed by the monthly climate monitoring reports from NASA, the US National Oceanic and Atmospheric Administration, and the European Union's Copernicus Climate Change Service.

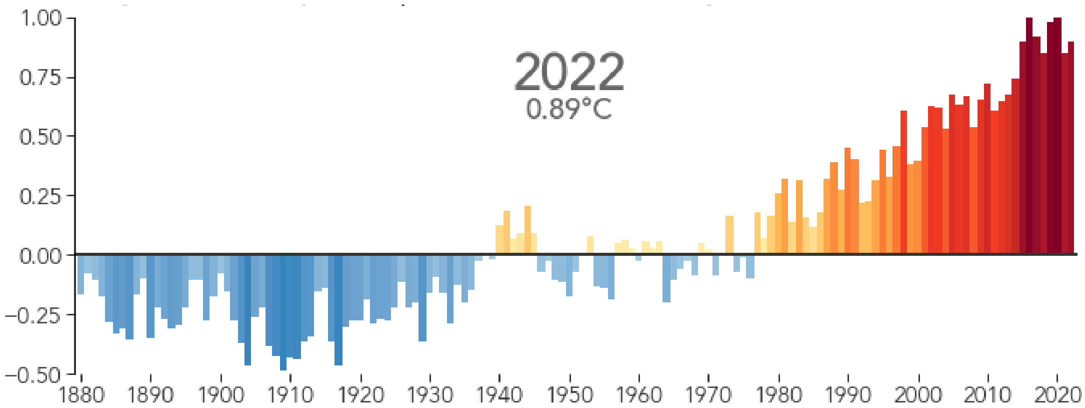

Figure 1.1: Global Average Temperature Anomaly (NASA, 2023)

The world is witnessing the impacts of climate change in many different ways ranging from wildfires to melting polar ice. 90% of disasters are now considered to be weather or climate-related, costing the global economy 520 billion USD annually and pushing 26 million people into poverty (UNEP, 2023a). Climate change exacerbates wildfires by lengthening fire seasons and making them hotter, dryer, and more frequent due to increased drought, high air temperatures, low relative humidity, lightning, and strong winds. Wildfires also destroy delicate and carbon-rich ecosystems like peatlands and rainforests. Wildfires are expected to become increasingly frequent and intense as a result of climate change and land use change, with a global rise in extreme fires of up to 14% by 2030, 30% by the end of 2050, and 50% by the end of the century (UNEP, 2022b). Wildfire seasons have broken records recently all around the planet, in Australia, the Arctic, Europe, North America, and South America claiming human lives as well.

Numerous glaciers all across the world have been quickly melting since the turn of the 20th century. More than a third of the existing glaciers on the planet will disappear before the year 2100, even if emissions are drastically reduced in the ensuing decades. 95% of the thickest and oldest sea ice in the Arctic has already disappeared. Scientists predict that if emissions rise unchecked, ocean and air temperatures will continue to rise quickly, and the Arctic might lose its summer ice cover as soon as 2040 (Hancock, 2023). These melting glaciers leads to rising sea levels and cause flooding around the world. Over 40% of the world's population lives within 100 kilometers of a coast, and over two-thirds of cities with a population of over five million people are situated in areas at risk of sea level rise (UNEP, 2023a). Frequent floods can increase chemical risks, accidents, and waterborne infections. The geographic ranges of ticks and mosquitoes are expanding due to these floods, and they can spread disease to new areas (NOAA, 2021).

The effects of climate change on various societal segments are interconnected. Food production and human health can be harmed by drought. Flooding has the potential to spread illness and harm infrastructure and ecosystems. Health problems can reduce work productivity, raise mortality, and have an impact on the availability of food. Human health is already being impacted by climate change. Life is at stake when weather and climatic trends change at such rate. Other natural disasters such as hurricanes are becoming more intense and wetter as ocean temperatures rise, which can result in both direct and indirect fatalities. The list of impacts of climate change is increasing day by day as frequency and strength of disasters are increasing exponentially. Most of these articles and reports point towards a common underlying cause of over-exploiting various resources such as fossil fuels, forests, etc. (NOAA, 2021; UNEP, 2023a).

Fossil fuels, namely coal, oil, and gas, are the primary drivers of global climate change, constituting more than 75% of global greenhouse gas emissions and almost 90% of CO_2 emissions. The Earth is enveloped by these GHG emissions, which result in the retention of solar radiation. This phenomenon contributes to the occurrence of global warming and climate change. The current rate of global warming exceeds any previously documented period in history. The gradual increase in temperatures is causing alterations in the established equilibrium of natural systems. This presents numerous hazards to the well-being of human beings and all other biological entities on the planet (UN, 2023a). With no indications of slowing down, human activity is producing greenhouse gas emissions at record levels as illustrated in the figure above. EU was recorded as the fourth largest greenhouse gas emitter after China, USA and India in 2019 but EU's share reduced from 15.2% in 1990 to 7.3% in 2019 due to the efforts to promote renewable energy (Corselli-Nordblad, Jere & Strandell, 2023). The growing global CO_2 emissions are illustrated in the graph below.

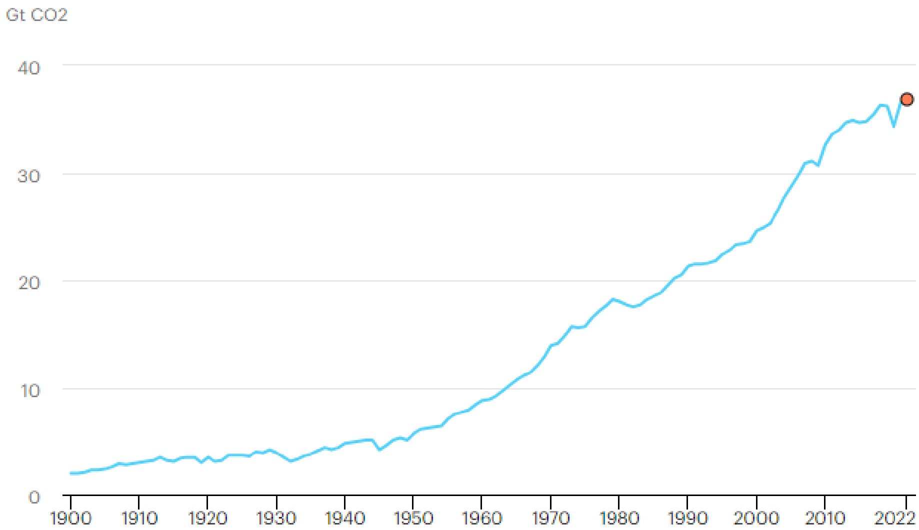

Figure 1.2: Global CO_2 Emissions from Energy Combustion and Industrial Processes, 1900-2022 (IEA, 2023b)

A major contributor to climate change in terms of greenhouse gas emissions into the atmosphere is the energy industry. Fossil fuels are primarily used to produce energy required for various activities and releases toxic greenhouse gases into the atmosphere, amongst which CO_2 is considered the most dangerous (UNEP, 2023a). This is mainly because most of the energy used today for daily human activities is produced from carbon-intensive fossil fuels. Global CO_2 emissions from energy increased by 0.9% or 321 Mt in 2022, setting a new record of more than 36.8 Gt overall emissions. The sector with the largest rise in emissions in 2022 was electricity and heat generating, with a 1.8% or 261 Mt increase in emissions. For instance, coal-fired electricity and heat generation emissions increased globally by 224 Mt or 2.1%, with growing nations in Asia leading the way (IEA, 2023b).

The built environment, especially buildings, have a major impact on the environment throughout their entire life-cycle as they consume huge amounts of energy during their construction as well as operational phase. Buildings emit approximately 40% of the overall CO_2 emissions across all sectors worldwide (UNEP, 2022a). Over one third of worldwide energy consumption and emissions are attributed to the buildings sector, which includes energy used to build and operate buildings. Building operations account for approximately 30% of the world's total final energy consumption and 27% of the world's energy-related emissions, with 9% of those emissions occurring directly in buildings and 18% occurring indirectly as a result of the creation of the electricity and heat that are consumed in buildings (IEA, 2023a). In most major economies in 2021, construction activities returned to their pre-pandemic levels, and building usage increased as offices reopened while hybrid working persisted. As a result, from 2020, the energy demand for buildings climbed by around 4%, to 135 EJ which was the highest growth in the previous ten years (UNEP, 2022a). If the building energy consumption continues to grow at the current rates the existing building stock will consume 35-40% more energy than current levels (IEA, 2023a).

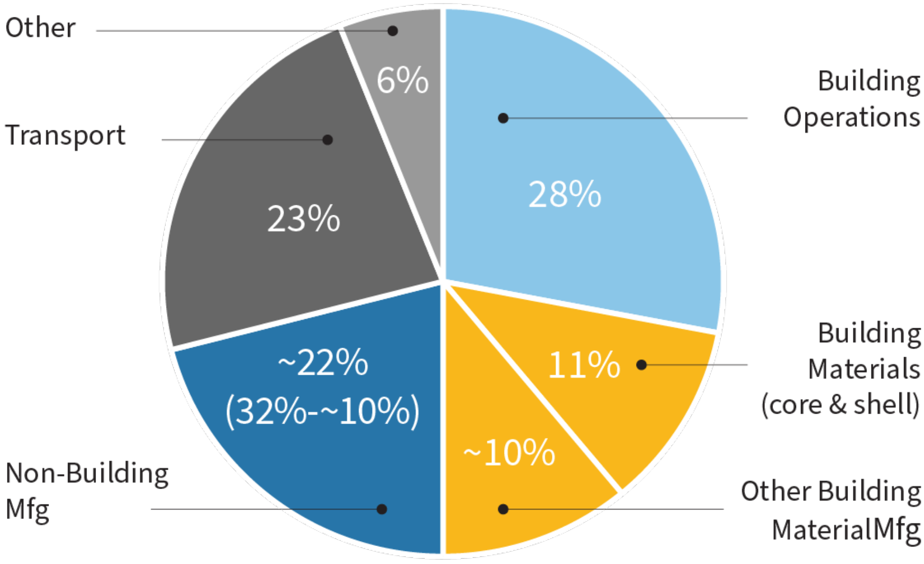

Figure 1.3: Global CO_2 Emissions from Different Sectors (UNEP, 2019)

On the other hand, from an estimated 2.5 billion people in 1950, the world's population reached 8.0 billion in mid-November 2022 and is projected to reach a peak of about 10.4 billion in the middle of the twenty-first century, an increase of nearly 2 billion people from November 2022 (UN, 2023b). The demand for civil infrastructure and buildings across the world increases with this ever-increasing human population which also implies the need for more resources and energy. The building industry has a huge impact on the economy, the environment, and society (EEA, 2023; Ibn-Mohammed et al., 2013). Hence, the demand for buildings and infrastructure will increase with the development of a nation. These numbers regarding emissions within the built environment are also going to further increase simultaneously in the coming years with the projected population growth which creates an urgent need for sustainable and circular measures within the built environment.

Governments across the world are unanimously taking stricter measures across various industries and sectors to curb these emissions and protect the environment. Several intergovernmental and government bodies across the world have joined hands to unanimously agree on policies and regulations to keep the climate crisis and climate change under control. An international agreement on climate change that is legally binding is the Paris Agreement. At COP 21 held in Paris, it was approved by 196 parties on December 12, 2015, and it became effective on November 4, 2016. Its main objective is to keep global warming far below 2°C, ideally below 1.5°C, compared to pre-industrial levels (UNFCCC, 2015). The aim of the agreement is to reduce the harmful greenhouse emissions from human activities that cause global warming.

Within Europe, European Union (EU) set a goal in 2008 to reduce emissions by 20% by 2020 compared to 1990 levels. The EU also made the 2050 target of zero net emissions and climate neutrality as a binding EU law in 2021. The European Green Deal serves as the EU's road plan for achieving carbon neutrality by 2050. the Dutch government intends to cut greenhouse gas emissions in the country by 95% by 2050 compared to 1990 levels, which would represent a 49% reduction by 2030. The strategy and strategies to accomplish these climate goals are contained in the Climate Plan, the National Energy and Climate Plan (NECP), and the National Climate Agreement (NCA) (van Algemene Zaken, 2023). In the Netherlands, on May 28, 2019, the Climate Act was passed, outlining objectives to reduce emissions.

Governments are also trying to regulate the energy consumption in buildings by introducing rules and regulations to promote energy efficiency in buildings and reduce emissions. Majority of the existing and upcoming environmental policies and regulations regarding the built environment are concerned about the energy usage and energy efficiency of buildings (EU, 2022a, 2022b; Magrini, Lentini, Cuman, Bodrato & Marenco, 2020). The usage of efficient and renewable building technology is rising, and minimum performance criteria and building energy regulations are becoming more comprehensive and stringent internationally. Through regulations and industry standards, major economies are raising the criteria for energy efficiency in both new and existing buildings (IEA, 2023a).

Energy Performance of Buildings Directive (EPBD) is the main policy regarding energy efficiency and energy reduction in building within EU (EU, 2018). The EU also seeks to increase energy efficiency with new goals that were supported by the Parliament in September 2022, including a 40% decrease in final energy consumption and a 42.5% decrease in primary energy consumption by 2030 (EU, 2022b). Moreover, the Dutch Green Building Council (DGBC) has also introduced various policies and targets for new buildings and existing buildings regarding energy consumption. For example, the targets for 2040 is to reduce the energy consumption in office buildings to 70kWh/m^2 (DGBC, 2023). However, the increasing emissions from buildings in recent years clearly highlight the fact that these legislative requirements are not enough to curb these emissions as there is much more to be done.

1.1 Problem Description

Improving energy efficiency within buildings is the main objective of most governments in order to curb emissions from energy usage. Several governments across the world have introduced policies and regulations to regulate energy consumption in buildings. Developed economies with substantial historic building stock and slow growth in new construction place a strong emphasis on reducing energy demand of existing buildings through renovation and retrofitting. Fast-developing nations like China put a lot of effort towards lowering the energy demands of new buildings that both replace older building stock and increase their overall building stock (Shrubsole et al., 2019). There are several legislative requirements put forward by governments to improve the energy efficiency of such building projects. In the Netherlands, Energy Performance of Buildings Directive is the main policy that provides measures to boost energy efficiency and performance of buildings. Energy labels were introduced in the Netherlands according to EPBD and mandated for all office spaces in 2023 (RVO, 2017). Eventually, this creates a huge dependency on policies such as energy labels and certifications for real estate developers and owners across the world. Designers and real estate developers use these energy labels certificates as a decision support tool to aid their design process to create energy efficient buildings.

The energy labels and certificates provide a prediction or estimation for energy consumption for a building based on certain factors and assumptions. The label is based on a theoretical calculation of energy consumption (gas and electricity) that takes into consideration certain physical features of the building such as its heating, cooling, lighting and hot water supply (Majcen, Itard & Visscher, 2013a). However, this is highly contrasting to the complete picture regarding the energy consumption of a building. The actual energy consumption numbers for a given building are often much higher than the predictions provided by energy labels, mainly because the actual energy consumption figures entail the energy consumed by other building components and occupants (tenants) as well. Although occupant consumption are not considered in most theoretical calculation methods such as calculations from energy labels, they are evident in energy bills and carbon footprint (and therefore in our database) giving them a significant role (Majcen, Itard & Visscher, 2013b). This mismatch or difference between predicted energy consumption according to energy labels and actual energy consumption in buildings leads to a phenomenon called energy performance gaps. The gaps create a grey area within energy consumption figures and also the emissions resulting from them that is often overlooked or neglected by the legislation. These grey areas of energy consumption are overlooked by legislation and therefore by designers of buildings as well.

Most design strategies used today by designers and real estate developers aim to achieve high energy labels and also use them as a design support tool to aid their design process and decisions for energy efficient buildings. Such design strategies leads to the energy performance gaps in buildings and does not help with improving the energy efficiency. These design strategies must change and shed light on the grey areas of energy consumption to meet major targets such as the Paris-proof targets. Designers and developers need to take into account those aspects that are often overlooked and neglected by legislation such as occupant behaviour and incorporate them into the design of buildings. It is evident from data provided through research that occupant consumption is a significant portion of the overall energy consumption and is one of the underlying causes for the gap (Van Dronkelaar, Dowson, Burman, Spataru & Mumovic, 2016). According to a study conducted by Majcen et al. (2013b) and Carpino, Loukou, Heiselberg and Arcuri (2020), the energy consumed by the occupants of a residential building account for approximately 35% of the overall energy consumption of the building which also holds true for non-residential buildings. Similarly, these figures are anticipated to be higher in non-residential buildings. Therefore it is important to include the occupant energy consumption behaviour in the design strategy for energy efficient buildings for the future.

Occupant behaviour within buildings and its impact on the energy consumption of the building have been studied by researchers for the past few years (Liang, Qiu & Hu, 2019; Niemann & Schmitz, 2020; A. J. Sonta, Simmons & Jain, 2018; Van Dronkelaar et al., 2016). These researchers also emphasize on the fact that the ignorance of occupant behavioural aspects during the design phase leads to the energy performance gap in buildings and that the gaps are a result of certain flaws within the design strategy currently used that mainly focus on legislative requirements such as energy labels. Targets such as Paris-proof targets set by the governments in the European Union regulate overall energy consumption figures of buildings, which also includes energy consumed by occupants. For this, designers require a design strategy that looks into occupant energy consumption behaviour and think beyond energy labels and certificates to produce energy efficient buildings. This defines the the main problem statement for this research - "the energy performance gap inherent in buildings due to energy labels and certificates creates a grey area in energy consumption and emissions resulting from them which needs to be bridged or closed". This will be further elaborated through the double diamond method through this research.

1.2 Research Gap

Energy performance gaps are considered to hinder the road to achieve the targets of Paris Climate agreement. The gap resembles a grey area in energy consumption figures that are often neglected by the legislation and designers. This gap could possibly grow in the future, if left neglected and lead to further emissions from building energy usage. Therefore, there is a necessity to address and bridge the gap as much as possible. Several researchers have explored the energy performance gap. Several different definitions were provided for the term through research. These researchers have also identified the underlying causes that leads to the gap. However, there is an evident lack of design strategies to improve the design process by thinking beyond energy labels and certificates that often lead to the gap in building energy performance. Using energy labels and certificate as a design support tool overlooks important aspects that are found to have a profound impact on the overall energy consumption of buildings. This research aims to partially fill this gap, if not completely.

Van Dronkelaar et al. (2016) and Liang et al. (2019) studied the underlying causes of the energy performance gap in buildings. De Wilde (2014) points out the flaws in current design strategy which will be elaborated in the upcoming chapters, but does not provide a solid design strategy to solve the problem. Allouhi et al. (2015) identified certain barriers and challenges that leads to the energy performance gap in buildings but lacks to provide a suitable design strategy to overcome them. These researchers have helped in gaining vital insights into the phenomenon of energy performance gaps and its underlying causes. However, scientific literature fails to provide a suitable design solution to bridge the energy performance gap during the design phase of a project by addressing these issues, challenges and underlying causes.

Initial literature reviews conducted for this research have helped define the initial challenge of energy performance gaps inherent in buildings due to energy labels and certificates. The importance of bridging the gap has also been highlighted through this research. The new upcoming rules such as Paris-proof targets for energy consumption in buildings regulate overall energy consumption of a building rather than a small portion of the overall energy consumption of the building like energy labels and certificate. According to Guerra-Santin and Itard (2012), energy performance regulations and policies introduced by the government such as energy labels in the Netherlands will only provide a good starting step towards energy efficiency in buildings but will require much more efforts to meet the targets of Paris Climate agreement. Moreover, these energy labels are only intended to be an indication for the energy performance of the building rather than being design support tools. There is also an urgent need to improve energy efficiency and reduce energy consumption within building due to the ongoing energy crisis around the world. Additionally, energy efficiency contributes to the diversification of utility resource portfolios and can act as a buffer against the risk brought on by volatile fuel costs (EPA, 2023b).

Therefore, this research focuses on bridging this gap in building energy performance by developing a design strategy that focuses on the earlier mentioned grey areas in energy consumption figures that have never before been addressed in a design stage. There are limited research conducted to bridge the energy performance gap by improving the current design strategies followed by several developers that consists of its flaws. This is identified as the initial research gap and will be explained in detail according to the research methodology followed for this research. The detailed problem definition and knowledge gap within literature will be highlighted in the later stages of research according to the double diamond research methodology.

Chapter 2

Research Description

A research methodology offers the study credibility and yields reliable scientific results. Additionally, it offers a thorough plan that aids in keeping researchers on course, facilitating a simple, efficient, and manageable approach. The reader can comprehend the strategy and procedures utilized to arrive at results by understanding the researcher's methodology. The main objective of the research and expected outcome of this research will be highlighted. The research question that drives the research will be mentioned along with the breakdown into sub-research questions. The scope of the research will also be explained to give insights into the focus of this research. This research was inspired by a Double Diamond Design method which will be explained in detail in this section. The research methodology will be explained according to each phase within the research process. This section provides a detailed explanation about the entire research process and describes the way it was carried out.

2.1 Research Methodology

The research is carried out to bridge the energy performance gap inherent in buildings due to energy labels and certificates by developing a design strategy that focuses on occupant behaviour within buildings. This research requires a strong understanding about the problem of energy performance gaps and its underlying causes in order to devise a suitable solution to bridge this gap. Simultaneously, deep insights about the current practices within the industry is also crucial to devise a solution that solves the problem. Therefore, this research was carried out using a methodology inspired by the double diamond design method that helps in catering to the requirements and needs of the users (occupants). This methodology helps in devising a detailed problem definition to which a focused solution will be developed.

2.1.1 Double Diamond Design Method

Double Diamond is a design methodology that was introduced by the Design Council in 2004 to assist designers and non-designers tackle complex problems (Design-Council, 2019). The two diamonds reflect a process of engaging in more in-depth or broad analysis (divergent thinking), followed by targeted action (convergent thinking) (Design-Council, 2019). As suggested by the methodology, this research will also progress through four different phases that will be mixed together in a creative process. The double diamond design method helps in understanding the role of the users (occupants) of a product (building) in a better way by identifying different ways in which users use the product. This will help in devising a solution that is able to deliver building designs that cater to the needs and requirements of occupants.

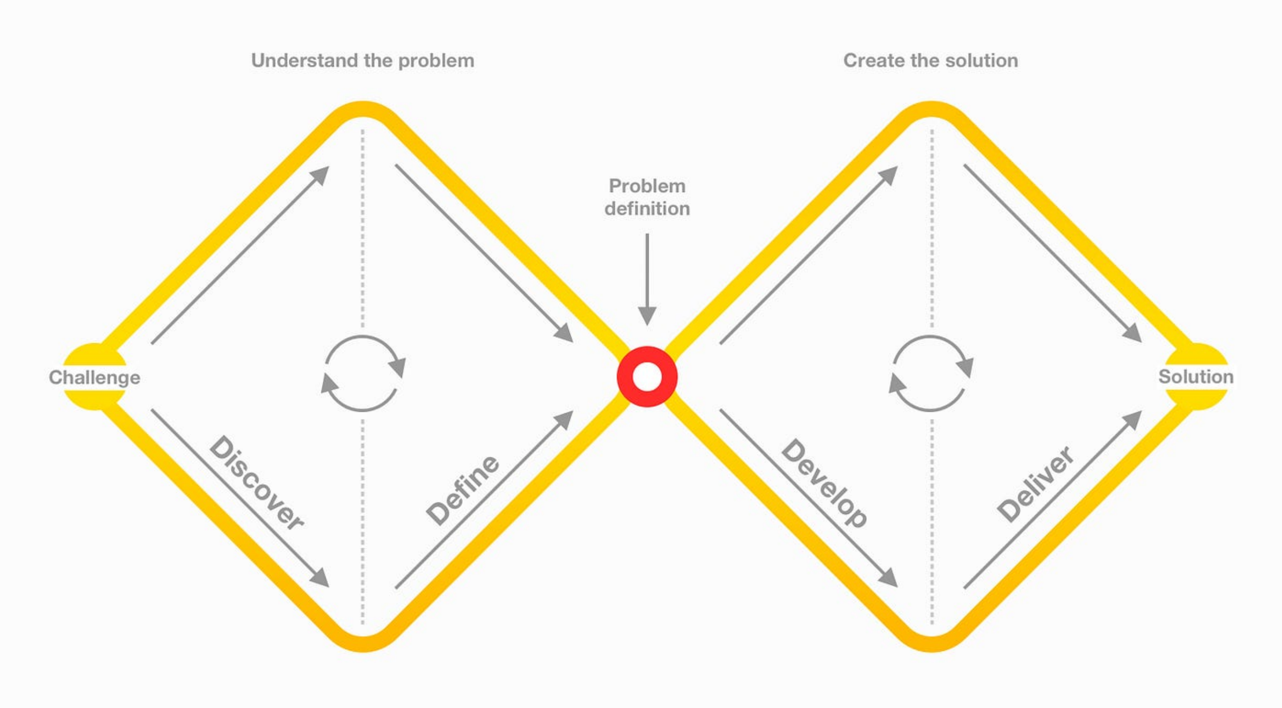

Figure 2.1: Double Diamond Design Method (Adapted from (Design-Council, 2019))

Within the first diamond, also known as the problem space, the problem is explored in detail. This diamond includes the 'discover' and 'define' phase of the research. In the first phase within the first diamond, known as discover phase, the problem is discovered through a broad lens. The problem is analysed through different perspectives to help narrow the problem definition towards a focused problem statement. Initially, divergent thinking is used to understand various aspects of the problem. The aim of this phase is to learn more about the problem, its effects, objectives and motive. During the second phase of the first diamond, also known as define phase, a focused problem statement will be developed through convergent thinking. A case study will be used to elaborate and define the detailed problem statement by the end of this phase (Design-Council, 2019).

Within the second diamond, also known as solution space, the solution is developed to solve the detailed problem statement. This diamond includes the 'develop' and 'deliver' phase of the research. In the first phase within the second diamond, known as the develop phase, a broad solution is developed for the problem defined in the previous diamond. The solution will be initially developed through a divergent thinking to make sure all aspects of the problem are being dealt with. Again, the case study project will be used to develop the solution with expert panel discussions. In the second phase of the second diamond, also known as deliver phase, the solution developed in the previous phase is refined to provide a focused solution for the focused problem using convergent thinking. The solution is refined further through expert opinion (Design-Council, 2019). An overview of the research process is provided in table 2.1 below according to each phase followed.

Phase	**Research Process**
Discover	Initial Challenge Identification, Literature Review and Broad Problem Exploration
Define	Exploratory Interviews (Semi-Structured), Case Study (Problem Definition) and Literature Review
Develop	Expert Panel (Case Study Project Team), Literature Review and Solution Development (Design Strategy)
Deliver	Expert Opinion (Semi-Structured Interviews), Solution Refinement (Final Strategy) and Delivery

Table 2.1: Research Process Overview

2.1.2 Phase 1: Discover

The first diamond is called the problem space, where the initial challenge will be explored broadly and then narrowed down to a detailed problem statement. This diamond is divided into two different phases, where the problem is explored from different perspectives in the initial stage and then narrowed down to finer detail in the later stage. The first phase of this research involves discovering the problem from multiple perspectives. This phase of the double diamond method identifies and contextualizes the problem or opportunity. The double diamond methodology begins with learning about the problem's variables. Understanding the issues faced by the organization and the project team, and prioritizing them to focus on a high-value area, is necessary. The broad topic of energy consumption within the built environment and emissions from the energy used in buildings will be explored to understand the problems caused within the industry. The issues and challenges regarding energy efficiency of non-residential buildings will be explored to obtain a broader perspective. Information regarding rules and regulations that govern and regulate the energy performance of buildings will be gathered to understand the current context. This will help in identifying and exploring the grey area within the energy performance figures that defines the gap mainly due to the negligence of certain aspects by these energy labels.

In this phase of the research, various trends in energy consumption within buildings will be explored to understand different ways in which energy is used in buildings and how they are regulated by the current legislation. The importance of energy efficiency in buildings and the root cause behind the pollution caused by energy consumption in buildings will be explored. This helps in identifying the issues related to energy consumption within the buildings and the damage it causes to the environment. Scientific articles and reports will be used to understand the energy consumption trends. Based on this desk research, the shortcomings related to energy consumption in buildings, especially related to the source fuel composition to highlight the importance for energy efficiency, and energy efficiency will be identified. The literature study will help in developing a strong theoretical background on energy consumption in buildings over the years, role of legislation and energy efficiency of buildings. Several reports and publications from inter-governmental bodies such as United Nations, International Energy Agency, European Union and various consultancy firms such as Deloitte, KPMG and PWC were also referred to gain vital insights into the energy consumption trends within the building industry.

Energy performance gaps have been identified as a growing concern related to energy efficiency of buildings. Following the literature review for energy consumption, scientific journals and reports will also be explored in detail to understand the issue of energy performance gap in buildings. Several definitions have been provided for this term and hence a specific definition will be selected from literature to support this research. Consequences of the energy performance gap in buildings will be highlighted in this phase through the literature review. The extensive literature review will also provide insights about various underlying causes that lead to the energy performance gap in buildings. The significance of bridging the energy performance gap and several ways to bridge the energy performance gap in buildings will also be described in detail through this phase. Extensive literature review will also help in identifying the most significant underlying cause according to literature which will be further explored in the following phases of research through a case study and interviews. Overall, this phase explores the initial challenge of energy consumption and energy efficiency of buildings through a broad perspective, in other words divergent thinking.

2.1.3 Phase 2: Define

The second phase of this research involves defining the problem statement in detail. This phase of the double diamond method uses convergent thinking to narrow the problem identified in literature to a detailed problem statement by diving deeper into the problem. In this phase, the problems regarding energy performance gap in buildings is explored in detail. The energy performance gap inherent in buildings mainly due to energy labels and certificates have been identified as a growing concern. The definition phase narrows ideas and refines information from the previous phase through literature into a concise problem statement, making it converge into a detailed problem statement using information from exploratory interviews and case study as well. This final problem statement will provide more context than the initial problem or challenge, which will aid solution development in the next diamond.

Literature will be reviewed extensively in this phase to understand the underlying causes leading to energy performance gap in fine detail. The most important underlying cause, occupant behaviour, will be further explored in depth with the help of literature. The different classifications and definitions provided for the term will help build the base for the development of a solution. Detailed insights about the various aspects of occupant behaviour as described within literature will help narrow the problem further down into a detailed problem statement. These insights will also help in understanding their impact on the energy performance of buildings and how occupants use energy within the building environment. Several insights gathered from literature will also be used as a basis for the exploratory interviews to relate to the real-life practices.

Simultaneously, data will be gathered from the NS Stations database to gain insights about the energy performance gap of the case study building, Stichthage. These data will be used to analyse the energy performance of the building and will be analysed in detail to understand the problem of energy performance gaps. This will help measure the gap in a real-life scenario and provide better insights into the issue of energy performance gap to identify the flaws leading to this issue such as the lack of detailed information on the energy performance of the building to accurately analyse the gap. This findings from this data can also be compared to the findings from literature to highlight issues within current practices in the industry. This data will also be used as a base for the exploratory interviews with the employees of NS Stations to understand the practices that leads this situation. In such a way, a concrete conclusion can be derived for the detailed problem statement.

Exploratory interviews will be carried out with employees of NS Stations, as mentioned in table 2.2, to gain an understanding about their extend of awareness and knowledge regarding energy performance gaps. The interviews were semi-structured in nature and the participants were selected based on their roles, responsibilities and work experience in the relevant field. Participants included project managers, technical developers, real estate developers, sustainability program manager and respective department managers. These interviews provide information regarding energy consumption of buildings within the portfolio of NS Stations in general and energy performance gaps. These interviews also help in identifying the issues and challenges that lead to the lack of awareness or knowledge regarding energy performance gaps in buildings. Additionally, these exploratory interviews also provide an idea about the current design practices followed to design non-residential buildings for energy efficiency, such as Stichthage. These interviews help in identifying the flaws within the design process in general that leads to energy performance gaps in buildings. In such a way, the detailed problem statement will be derived and stated at the end of this phase.

Participant	Job Title/Role	Experience (Years)	Expertise
A	Department Manager 1	20	Project Management
B	Technical Developer	16	Project Management
C	Station Developer	27	Real Estate Development
D	Asset Manager	18	Asset Management
E	Department Manager 2	7	Asset Management
F	Program Manager	14	Program Management
G	Department Manager 3	28	Real Estate Development

Table 2.2: Interview Participant Details (NS Stations)

2.1.4 Phase 3: Develop

The third phase of the research is the beginning of the second diamond, also called the solution space. The second diamond involves the development of a solution for the problem defined by the end of the first diamond. This diamond is divided into two different phases - develop and deliver. The first phase, develop phase, is about developing a solution for the problem using a divergent thinking approach. The broad solution will then be refined to cater to the needs of the focused problem statement and also the case study. To begin with, the information collected from literature review, energy performance data and exploratory interviews will be used to establish a link between occupant behavioural aspects that have an impact on the energy performance and the design of the building. Literature will be reviewed once again to find the state-of-the-art in linking occupant behavioural aspects to the design of buildings and its various components. This link will help in developing a design strategy that focuses on occupant behaviour to bridge the energy performance gap in buildings. Information gathered from exploratory interviews will help in further improving this link based on industry experience and practices.

An expert panel discussion was conducted with the members of the project team for the renovation of Stichthage. The solution will be developed with the help of insights gained from this expert panel discussion. The expert panel consists of the project team members for the renovation of Stichthage (case study building). The discussion included a project manager, developer, asset manager, sustainability program manager and respective department managers as mentioned in table 2.3 below. This expert panel discussion will provide details about the current stage of design process for the renovation of the building and the process intended to be followed from there on. This will help understand in detail and relate to the flaws identified initially and devise a suitable solution that will help counter the flaws that lead to the gap. These information gathered through the expert panel discussion will also help in developing a design strategy with required changes in the current process intended to be followed and to include occupant behavioural aspects into the design to bridge the gap.

The intended solution will be developed with different ideas to make alterations to the current design strategy and incorporate occupant behavioural aspects into the design of buildings to improve energy efficiency and bridge the energy performance gap. Occupant behavioural aspects are incorporated into the design strategy in a systematic way to shed light on the grey areas of energy performance of a building during the design process of the building. These ideas will be discussed with the expert panel members to identify possible practical implications and develop them further into an effective design strategy to bridge the gap. This expert panel discussion will also help relate the design strategy to the link established between occupant behaviour and building design in a structured and systematic way. Some of the people involved in the exploratory interviews are also part of the expert panel due to their involvement within the Stichthage project. The discussions will also help understand each members roles and responsibilities for the renovation project to highlight their importance in the design process.

Participant	Job Title/Role	Project Responsibility
A	Department Manager	Supervision
B	Technical Developer	Project Management and Technical Development
C	Station Developer	Office Concept and Interiors
D	Asset Manager	Asset Management
E	Department Manager	Supervision
F	Program Manager	Sustainability Ambitions and Goals

Table 2.3: Expert Panel Discussion Participants

Based on the information collected through these interviews and literature study, the occupant focused design strategy will be developed using the RIBA Plan of Work as a reference design process to describe the tasks and activities. The strategy will describe the activities and tasks to be carried out by each member of the project team with a focus on inclusion of occupant behavioural aspects and other aspects to bridge the energy performance gap. The strategy also describes the roles of asset managers within the design process and how their involvement could benefit the bridging of energy performance gap by developing an asset management strategy during the design phase of the project. The design strategy developed will be improved through further feedback sessions with the expert panel participants to refine the solution according to the double diamond methodology. At the end of this phase, an occupant focused design strategy will be developed to bridge the energy performance gap in buildings which will be improved, validated and delivered in the next phase through expert opinions.

2.1.5 Phase 4: Deliver

The final phase of the research and also of the second diamond is the deliver phase. In this phase the solution is refined into a focused solution to solve the focused problem defined at the end of the first diamond. This stage follows a convergent thinking process in order to meet the requirements of the detailed problem definition. This phase is also about further developing the broad solution into a focused solution for the focused problem statement derived at the end of the first diamond. The final solution, occupant focused design strategy, will be delivered by the end of this phase. This phase mainly involves semi-structured interviews with experts to collect their opinions to further refine the solution in order to make it suitable for other projects as well.

The experts were selected for the semi-structured interviews from external organizations. They were selected base on their expertise, experience and field of profession. The expert interviews were mainly carried out to gain a different perspective from that of the employees at NS Stations. This will help reduce the bias in developing a solution with the same set of participants involved in defining the problem statement and establishing the link between occupant behaviour and design of buildings. In such a way, the developed solution can also be validated without a bias. The interviews were also conducted with participants from different companies or organizations such as government, private real estate developers, researchers, etc. to gain several different perspectives. This helps in understanding the the problem in detail as faced by different organizations and tweak the design strategy in order to address these issues and challenges as well. The expert interviews will be carried out with participants as mentioned in table 2.4 below.

Participant	Job Title/Role	Organization	Expertise
Expert 1	Senior Project Manager	Research Organization	Project Management and Building Energy Performance
Expert 2	Director	Private Real Estate	Asset Management and Sustainability
Expert 3	Policy Officer	Government	Asset Management and Sustainability
Expert 4	Partner/Developer	Private Real Estate	Real Estate Development
Expert 5	Advisor Energy Transition	Government	Energy Transition
Expert 6	Manager	Private Real Estate	Real Estate Investment, Sustainability and Asset Management
Expert 7	Director	Private Real Estate	Asset Management

Table 2.4: Interview Participant Details (External)

Discussions will be carried out with the participants regarding the developed design strategy and also about the practical implications as identified from the expert panel. They begin with a briefing about the issue of energy performance gap in buildings followed by discussions to bridge the gap from their (organization's) perspective. These discussions provide insights about the different ways in which different organizations tackle the same issue of energy performance gap in buildings. Later, the developed design strategy will be introduced to them for discussions. These discussions also provide further practical implications regarding the design strategy from a different perspective. Additionally, researchers and policy makers, who conduct research regarding occupant behaviour and energy performance of buildings, were also interviewed to highlight the importance of an occupant focused design strategy to improve the energy efficiency of buildings and also meet future legislative requirements.

Information collected from the experts will be used to refine the design strategy further and make necessary changes to solve the problem and address practical issues. In such a way, the aspects that are often overlooked by designers and legislation will be taken into account to bridge the energy performance gap. In short, the broad design strategy developed in the previous phase will be narrowed down further into a focused solution using expert opinions. At the end of the phase, the final design strategy will be delivered along with its practical implications to bridge the energy performance gap inherent in non-residential buildings mainly due to energy labels and certificates with a focus on occupant behaviour. The figure 2.2 provides an overview of the process followed to develop the design strategy.

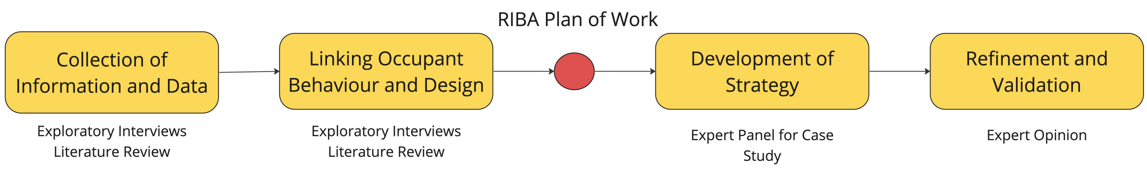

Figure 2.2: Design Methodology for Solution Development

2.2 Research Objective

The objective of this research is to mainly bridge the energy performance gap inherent in buildings due to the energy labels and certificates. According to several definitions provided by researchers for the term, there are several ways to bridge the gap in buildings. However the focus of this research is to bridge the gap by shedding light on the grey area in energy consumption figures as mentioned earlier. This grey area entails several aspects such as occupant behaviour, efficiency of building services, etc. which are often overlooked by energy labels and certificates but have a major impact on the energy performance of the building and represents a major portion of the overall energy consumption in a building. The energy performance gap has been addressed as a design flaw and therefore in order to bridge this gap, a solution or strategy that focuses on the overlooked aspects needs to developed through this research.

For developing a suitable and effective solution, it is important to gain a better understanding about how energy is consumed within buildings by exploring the energy consumption trends, especially trends related to important aspects such as occupant behaviour. A deeper understanding is required regarding these aspects of energy consumption as they are neglected by the energy labels and certificates or the legislation. Analysing different occupant behavioural patterns and their impact on the energy performance of buildings will help improve the design to cater to the specific needs. Literature will be reviewed to understand the different ways in which these aspects are described. The state-of-the-art will be identified about the incorporation or integration of these neglected aspects within the design of buildings for energy efficiency. The root cause for the negligence of these aspects from legislation and design of buildings will be identified. This will help addressing the issue in a better way to devise an effective solution to the problem.

Another main objective is to explore the current practices and understand the barriers and challenges that lead to the negligence of occupant behaviour within the design of buildings. A better understanding about the current practices will help identify the flaws within them that lead to energy performance gaps in buildings and devise an alternative solution or strategy with improvements to bridge the gap. This will be done through a case study building renovation project. The objective is also to find a link between occupant behaviour aspects and the design of various components of the building as well the degree to which they vary for different occupant behaviour patterns. This research also looks into ways to stimulate responsible energy consumption behaviour from occupants in a building with a better design. Finally, another major objective is to find the practical implications of the developed solution in a real-life scenario. These practical implications will help in further improving the application of the developed solution.

2.3 Research Questions

The main research question was addressed to steer the research in the right direction. The research questions described in this section will help in defining an investigation, set boundaries, provide direction and act as a frame of reference for assessing the proposed solution. This section states the main research question and sub-research questions that will be systematically answered through the course of this thesis to provide a focused solution to the focused problem.

2.3.1 Main Research Question

The main research question covers the the main objectives of the research. This research strives to answer the following main research question:

How can we bridge the energy performance gap inherent in buildings due to energy labels and certificates during the design phase of a (re)development project?

2.3.2 Sub-Research Questions

To simplify the main research question, it is broken down into various sub-research questions. The ultimate goal of the sub-questions is to address the primary research question and achieve the study objective. These sub-research questions help in systematically answering the main research question. These questions are a structured breakdown of the main research question. The sub-research questions are as follows:

1. *What is the energy performance gap inherent in buildings? What are the underlying causes for energy performance gap in buildings?*
2. *What are the different aspects of occupant behaviour in buildings? What effect do these aspects of occupant behaviour have on the energy performance of buildings?*
3. *How can we incorporate these aspects of occupant behaviour into the design of buildings to bridge the energy performance gap?*
4. *How can we integrate these occupant behavioural aspects into a design process/strategy for a building (re)development project?*
5. *What are the practical implications of the design strategy for a (re)development project to bridge the energy performance gap?*

These sub-questions were derived based on the research methodology followed by this research - double diamond method. The research methodology consists of four different phases or stages which covers each of the sub-questions. The answers to these sub-questions will be explained as each stage of the methodology is completed through the course of this research.

2.4 Scope of Research

The definition provided by Brundtland (1987) for sustainable development will be the basis for this research. The research aims to reduce the consumption of resources such as energy within buildings without effecting their respective availability for future generations. The research is conducted within the domain of built environment and is mainly concerned about the emissions from the energy used within buildings. The various problems regarding energy efficiency in buildings will be explored. Through the course of this research, the scope will be further narrowed down to the intricacies of energy performance gap and its underlying causes such as occupant behaviour as one of the major factors that leads to the gap. The energy performance gap is inherent in all types of buildings according to scientific research but the main focus of this research will be on non-residential buildings that are predominantly used as office spaces (Liang et al., 2019; Majcen et al., 2013b). This is mainly because the case study used for this research is a non-residential building which is mainly used as an office space with multiple tenants.

Additionally, this research strives to develop a strategy for (re)development projects. This is also mainly because the case study building used for this research is an already existing building that is sanctioned for renovation for energy efficiency. Moreover, in developed countries like the Netherlands, there are huge building stocks that need to undergo renovation or retrofitting for improved energy efficiency due to the tighter upcoming policies regarding energy consumption within buildings and their energy efficiency. This research also looks into aspects of occupant behaviour that have an impact on the energy performance of a building. These aspects are mainly studied for finding patterns or trends to analyse their impact on the energy performance. However, human behaviour is quite complex and cannot be accurately predicted or studied in detail without a solid understanding about many different disciplines of science and will not be covered extensively through this research due to its peripherality with the master study program. Therefore, only basic occupant behavioural aspects will be explored through this research.

Literature (scientific journals and reports) and information collected through interviews with industry practitioners and researchers will be used to develop the solution. Also, energy labels have different criteria for predicted or estimated energy consumption in different countries. This research will focus on the requirements mentioned within the energy labels used in the Netherlands. There are different ways in which energy consumption or performance of a building can be predicted through advanced simulations. This research will focus on the predictions or estimations for energy performance according to energy labels in the Netherlands which is widely used in projects across the country.

2.5 Case Study

A case study will be used within this research for two main objectives - (1) to derive the problem statement by understanding the difficulties or challenges faced by practitioners in a real-life scenario and (2) to identify the practical implications of the developed solution through an expert panel discussion with the project team for the case study building. NS Stations is a part of NS Group (Dutch Railways) that manages all railways stations across the country and real estate around the station premises. This case study building was selected from the real estate portfolio of NS Stations. The organization has high ambitions to meet in terms of sustainability and energy performance which makes this research a good addition for the organization.

Stichthage is a non-residential building situated in Den Haag, Netherlands. The building is primarily used as an office space and situated right next to one of the busiest railway stations in the Netherlands. The building is one of the biggest within the portfolio of NS Stations in terms of floor space and hence NS Stations wants to achieve high energy performance for the building through this renovation. The building has a total floor space of approximately 24000 m^2. The building is being renovated due to the facade at end-of-life-cycle, poor insulation, outdated installations and high energy consumption. Therefore, this building can be used to understand the design strategy currently followed within the industry by designers and real estate developers. The developed solution can be tested on this project to understand the practical implications of the strategy and refine the solution even further.

Figure 2.3: Case Study Building - Stichthage

Firstly, The case study will provide vital insights into the current energy performance of the building and the energy performance gap inherent due to energy labels and certificates. The case study will also be used to analyse the current design strategy or process followed for the renovation project. This mainly helps in identifying the challenges and barriers that leads to energy performance gap in buildings during the design stage. Secondly, the case study will be used to identify the practical implications of the developed solution through an expert panel review. This will help in further improving the solution or strategy to solve the issue of energy performance gaps in buildings.

Chapter 3

Energy Consumption in Buildings

The built environment affects every element of our life, including the homes we reside in, the water and energy distribution systems, and the highways, bridges, and other modes of transportation we use to get around. It can be broadly characterized as the man-made or modified buildings that offer people somewhere to live, work, and play (EPA, 2023a). Communities and infrastructures safeguard people's health and welfare. The built environment, however, is more than just a collection of structures; it is also the outward expression and manifestation of a wide range of economic, social, and environmental processes that are intimately connected to human activity and the shifting demands of society (Santamouris & Vasilakopoulou, 2021). As one of the most dynamic economic industries, built environment produces wealth and income while making a significant contribution to world progress. According to estimates, this industry contributes 5 to 10% of the nation's jobs and 5 to 15% of the GDP. Additionally, it offers housing, transportation, water, and sanitary facilities, and it serves as the physical setting for micro-economic development and social connections. There is also a connection between built environment and public health, as demonstrated by several researches (UNEP, 2023b). However, all this is at the expense of the energy consumed within buildings to make them functional.

However, buildings use energy throughout their entire life-cycle. Buildings require energy during their construction phase for various activities. Buildings use energy during their operations phase to support various daily activities of humans, which are primarily produced from fossil fuels. Energy is used for various purposes during the entire life-cycle of a building such as producing building materials, construction activities, maintenance, operations, etc. Amongst the entire life-cycle of a building, operations of the building consume the most amount of final energy across all sectors. This energy consumption within buildings pose a problem as the global floor area for buildings is rapidly increasing due to the exponential increase in human population which requires more buildings and infrastructure for day-to-day activities. With this increasing floor area, energy consumption and carbon emission numbers for buildings are also going to rise until a better greener solution is found (IEA, 2023a). 75% of the existing building stock, or over 220 million structures, are energy inefficient in Europe alone, with many of them reliant on fossil fuels for heating and cooling (WEF, 2021).

This chapter provides insights gained from literature regarding energy consumption within buildings and their fuel sources. The emissions resulting from production of energy used in buildings, which has a significant impact on the environment, are also highlighted in this chapter. Additionally, the current policies and regulations implemented by governments and other governing bodies are mentioned. This chapter will provide the basis that will be used to explore the initial challenge of energy efficiency and energy performance gap in buildings. This chapter will also highlight the importance of bridging the energy performance gap in buildings and thereby improve energy efficiency.

3.1 Current Trends in Energy Consumption

Over 1/3rd of worldwide energy consumption and emissions are attributed to the buildings sector, which includes energy used to build, heat, cool, and light homes and businesses as well as the equipment and appliances installed inside of them (IEA, 2023a). Buildings account for 36% of the world's total final energy consumption and 37% of the world's energy-related emissions, with 9% of those coming directly from buildings and 18% coming indirectly through the generation of the power and heat as illustrated in figure 3.1 (UNEP, 2021). These numbers are at an alarming rate and highlights the necessity to reduce energy consumption within buildings and thereby the emissions from the industry as well. Hence, the usage of efficient and renewable building technology is rising, and minimum performance criteria and building energy regulations are becoming more comprehensive and stringent internationally. However, the industry needs to shift more quickly to keep up with the Net Zero Emissions by 2050 (NZE) Scenario. Overall energy use in the building sector increased by about 1% in 2022 (IEA, 2023a). In 2022, around 35% of the energy used by buildings were electricity, which increased from 30% in 2010. The usage of fossil fuels in buildings has increased at an average annual growth rate of 0.5% since 2010, despite a steady shift away from them in favor of other energy sources and vectors, particularly electricity and renewable ones.

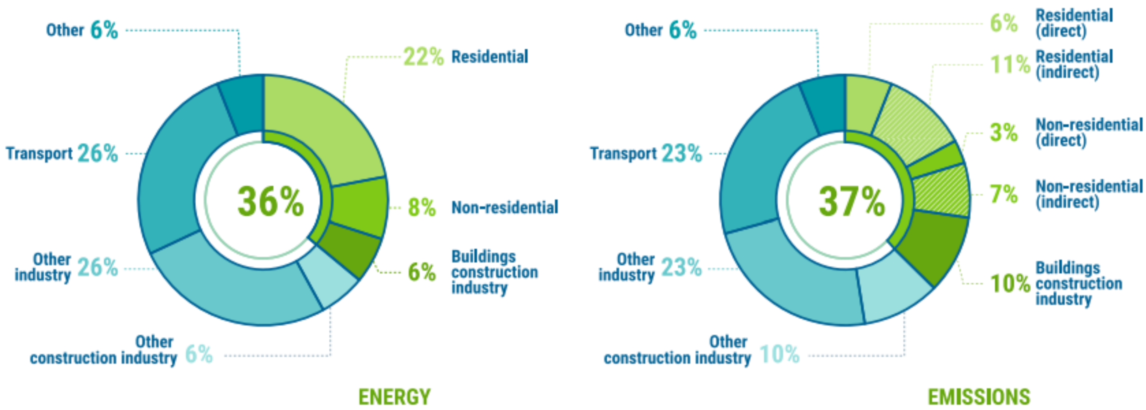

Figure 3.1: Construction Industry's Share of Global Final Energy and Energy-Related CO_2 Emissions (UNEP, 2021)

Operational energy is an important parameter used to understand the energy consumption within buildings. Operational energy is the energy consumed throughout the occupancy phase of a building's life cycle, encompassing activities such as space and water heating, space cooling, lighting, and the operation of equipment and appliances (Azari, 2019). According to data provided by IEA (2023a) and UNEP (2022b), building operational energy use makes up about 30% of total global final energy consumption. Within the context of commercial buildings, it has been observed that a significant proportion of operational energy, namely over 58%, is utilized for various purposes such as space heating (27%), water heating (7%), space cooling (10%), and lighting (14%). 6% of the total is allocated for ventilation purposes, while the remaining 36% is designated for plug loads from the occupants (Azari, 2019). Space cooling experienced the biggest growth in energy demand among all building end uses in 2022, rising more than 3% from the previous year due to the rise in temperatures worldwide. In contrast, the energy used for space heating declined by 4%, primarily as a result of a mild winter in several places, including Europe (IEA, 2023a). These numbers also provide evidence for climate change and global warming.

Various drivers and determinants were identified through research for operational energy consumption in buildings. These various drivers also impact the energy consumption trend of buildings and the emissions resulting from them. In the study conducted by Azari (2019) and Santamouris and Vasilakopoulou (2021), the authors find that thermal comfort within buildings is one of the biggest drivers of energy consumption within buildings during operations. Apart from thermal comfort, energy is also being consumed to maintain the required visual comfort and indoor air quality which are the other major drivers of energy consumption. The utilization of operational energy for the purpose of establishing pleasant interior environments exhibits considerable variation between buildings due to the influence of various factors, including meteorological conditions, occupant behavior, socioeconomic factors, and design and system-related variables of energy consumption. These drivers and determinants elevate the demand for more energy within buildings.

González-Torres, Pérez-Lombard, Coronel, Maestre and Yan (2022) identified population, income level, efficiency, climate, demography and behavioural aspects as drivers to energy consumption within buildings as well. The improvement in comfort levels and the expansion of human activities have caused 11.18% increase in per capita energy consumption during the past ten years. In the same study, it was found that in 2011, given that about $1/3^{rd}$ of the world's population still lacks access to electricity and that underdeveloped and developing nations primarily rely on fossil fuels as their primary source of energy, the increase in electricity consumption of 43.77% makes the future situation undoubtedly worrying. Currently, 770 million people, largely in Africa and Asia, lack access to electricity. The COVID-19 crisis ended years of advancement and made the already poor purchasing power of households in developing countries for energy worse (IEA, 2022). Hence, electricity usage is going to increase within the existing building stock in the coming years with infrastructure development.

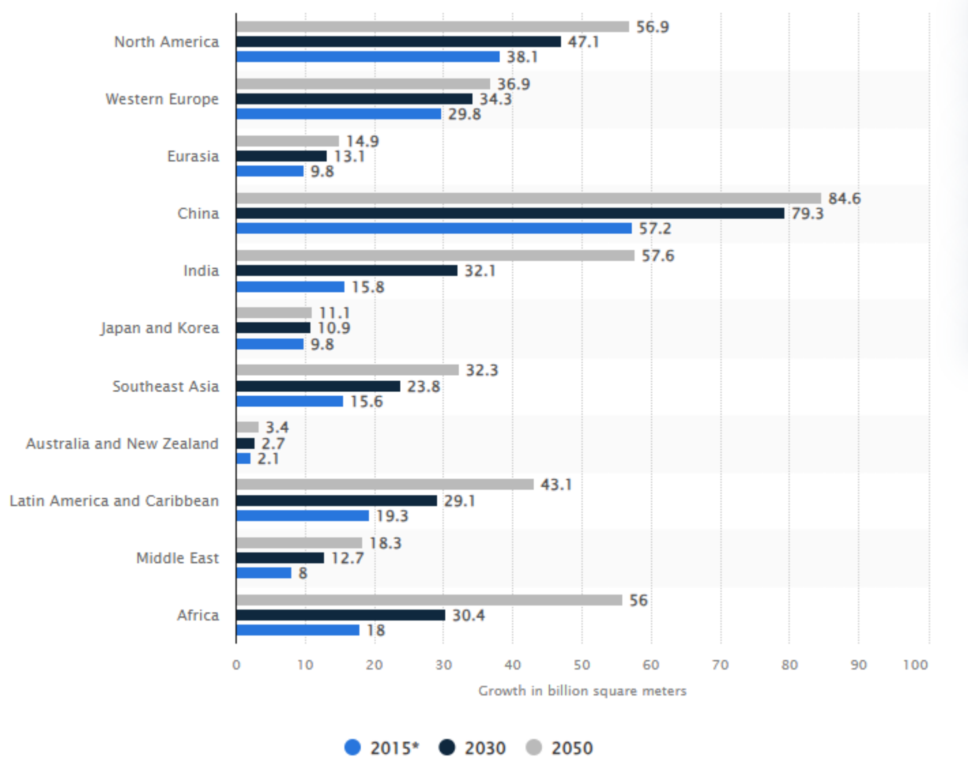

Figure 3.2: Projected Growth of Building Floor Area Worldwide (Statista, 2016)

According to an extensive study conducted by Allouhi et al. (2015), the total energy consumption in buildings was found to be growing faster than the human population. The human population is growing at an exponential rate. From an estimated 2.5 billion people in 1950, the world's population reached 8.0 billion in mid-November 2022 and is projected to reach a peak of about 10.4 billion in the middle of the twenty-first century, an increase of nearly 2 billion people from November 2022 (UN, 2023b). The demand for civil infrastructure across the world increases with this ever-increasing human population which also implies the need for more resources and energy. Santamouris and

Vasilakopoulou (2021) emphasizes on various challenges within the built environment towards improved energy efficiency and reduced energy consumption such as overpopulation and fast urbanisation, among other challenges. The ongoing issues of climate change and population increase will further elevate the energy demand for buildings to function. The increase in population results in an increase in demand for buildings as illustrated in figure 3.2 above. By the year 2030, there will be a 15% increase in global floor area, which is approximately similar to the current total developed floor area of North America. Approximately 80% of the projected increase in floor space is anticipated to occur in nations classified as emerging markets and developing economies.

The building industry has a huge impact on the economy, the environment, and society (EEA, 2023). Currently, there is a huge shortage of sufficient buildings (residential and non-residential) around the world which will further increase the demand for energy required in buildings (Santamouris & Vasilakopoulou, 2021). Altogether, this creates a growing demand for floor area around the world that simultaneously results in an increased demand for energy within buildings which is turning out to be an alarming situation due to their fossil fuel sources. Hence, there is a a huge demand to reduce the overall energy consumption in buildings and improve energy efficiency of buildings. In order to align with the Net Zero Energy (NZE) Scenario, it is required that the energy intensity of the buildings sector experiences a reduction that is approximately five times faster in the upcoming decade compared to the previous decade. This implies that the energy consumption per unit area in the year 2030 should exhibit a reduction of approximately 35% compared to the levels observed in 2022. All these figures highlights the need to reduce energy consumption within buildings and improve energy efficiency to reduce their harmful impacts on the environment.

3.2 Emissions from Energy Consumption

Various organizations such as International Energy Agency (IEA), United Nations (UN), World Green Building Council (WGBC), Dutch Green Building Council (DGBC), International Renewable Energy Agency (IRENA), Centraal Bureau voor de Statistiek (CBS), European Union (UN) and numerous consultant companies have been compiling data regarding emissions within the built environment that has been crucial for research organizations to conduct research into various ways in which these emissions can be reduced drastically to meet the targets set by the Paris Climate agreement. Buildings predominantly rely on a variety of energy sources, including electricity, bio-fuels (such as biomass, liquid bio-fuels, and bio-gases), natural gas, oil products (including LPG, gas-oil, and fuel-oil), coal, district heating, and other forms of renewable energy as illustrated in figure 3.3 below. These fossil fuels are mainly used to produce electricity required by the building for various functions and activities. The energy composition of a building is significant to analyse the harmful emissions that arise from them in the form of greenhouse gases such as carbon dioxide (CO_2). Apart from electricity generation, fossil fuels are also used to provide thermal comfort for occupants within the building environment by providing heating. Fossil fuels are commonly utilized as the predominant heat source, while the prevalence of heat pumps has resulted in a notable rise in electrical demand for heating purposes in recent times. In the context of cooling generation, electricity emerges as the predominant source (González-Torres et al., 2022). Today, even majority of the electricity used to power the buildings and infrastructure are produced from fossil fuels such as biomass, coal, oil and natural gas as shown in figure 3.4 below.

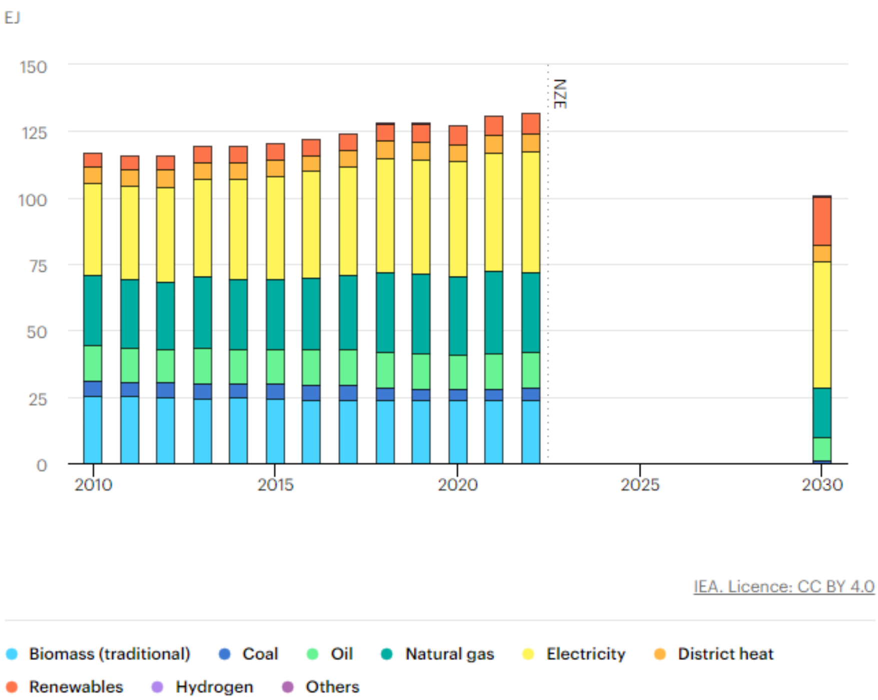

Figure 3.3: Energy Consumption in Buildings by Fuel Category (IEA, 2023a)

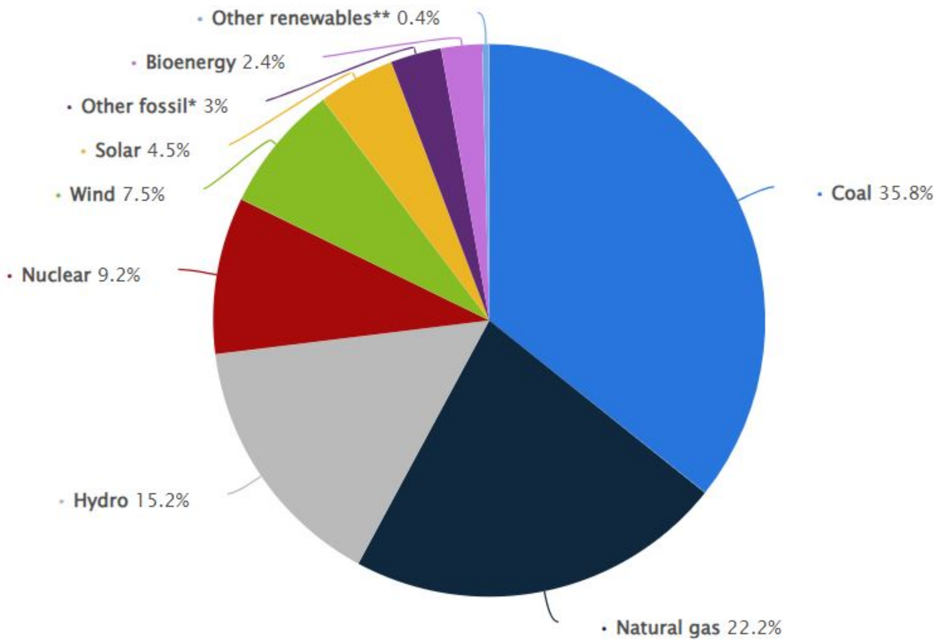

Figure 3.4: Global Electricity Generation Source (Statista, 2023b)

The use of fossil fuels for generating electricity and heat for buildings results in CO_2 emissions that have a harmful impact on the environment. As stated by UNEP (2022b), the occurrence of the worldwide pandemic resulted in a significant decrease in global CO_2 emissions, marking the most substantial annual reduction to date. These emissions declined by 6% compared to their peak in 2019, dropping from 35Gt CO_2 to 33.3 Gt CO_2. In the year 2022, there was a marginal decrease in direct emissions resulting from built environment compared to the previous year. This stands in contrast to the overall trend observed between 2015 and 2021, during which these emissions exhibited an average annual growth rate of about 1%. According to estimates for the year 2021, global emissions have experienced a recovery and are currently slightly below 1 percent of their peak in 2019, amounting to

34.9Gt CO_2. The operational energy-related CO_2 emissions originating from buildings experienced a growth rate of approximately 5% in the year 2021 when compared to the preceding year of 2020, resulting in a total of approximately 10Gt CO_2 emissions. This surpasses the previous peak of 9.6Gt CO_2 seen in 2019 by a margin of 2%. This is illustrated in the figure 3.5 below.

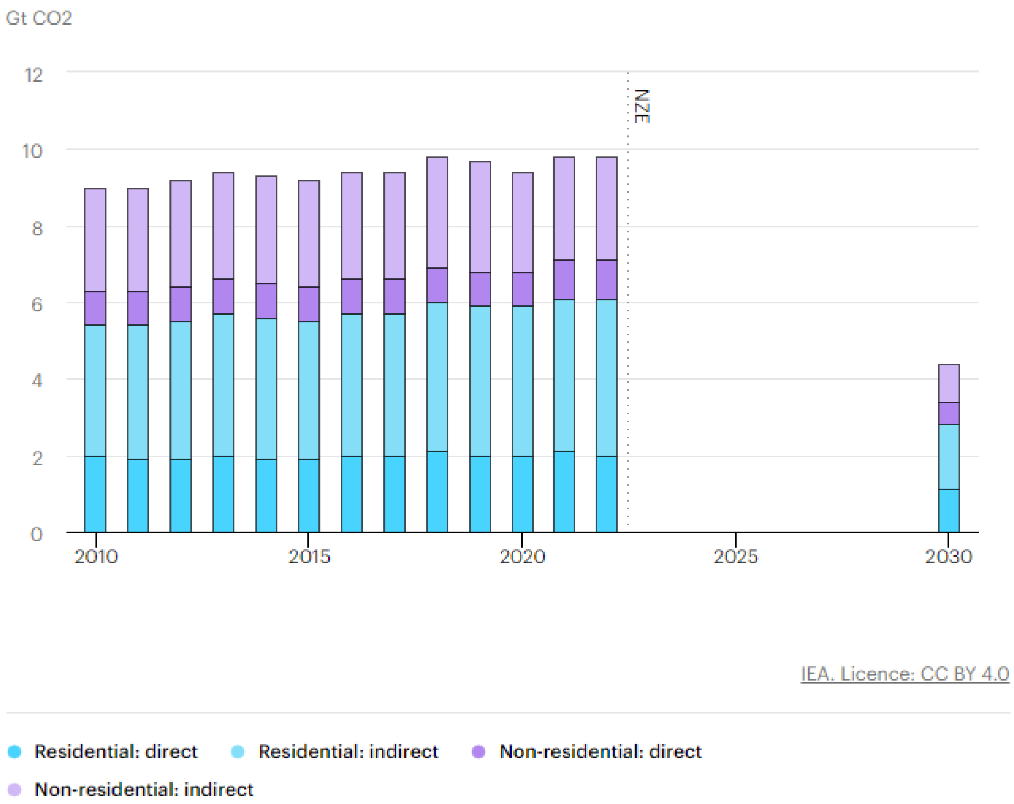

Figure 3.5: Global CO_2 Emissions from Operation of Buildings (IEA, 2023a)

The observed increase in CO_2 emissions within the buildings sector indicates a limited degree of transformation in the overall energy efficiency of pre-existing structures. The resurgence of global emissions is regrettable and indicates that the allocation of resources towards emission reduction initiatives through economic stimulus programs has thus far yielded minimal results and creates an urgency for better building design techniques (UNEP, 2022b). Santamouris and Vasilakopoulou (2021) identifies greenhouse gas emissions as a major challenge within the built environment. Despite the notable enhancement in energy efficiency per unit of floor space, the overall greenhouse gas emissions originating from the building sector have witnessed a 25% increase since the onset of the 21st century and can be attributed to the concurrent expansion of the floor space by 65% and the subsequent escalation in the electricity consumption of buildings (Statista, 2016). The energy intensity figures could also increase with the growth in floor area around the world. The significant increase in greenhouse gas emissions from the building sector is not aligned with the commitments made under the Paris Agreement, and there are no discernible indications of progress in this regard. These figures scream for urgent interventions to reduce emissions from the built environment. Policy makers around the world are introducing stricter measures and policies to curb these emissions from buildings to slow the rate of global warming and reduce its impact on the environment.

3.3 Regulations and Policies

The process of decarbonizing the worldwide building inventory is a crucial measure in order to effectively meet the obligations outlined in the Paris Climate agreement. An international agreement on climate change that is legally binding is the Paris Agreement. At COP 21 held in Paris, it was approved by 196 parties on December 12, 2015, and it became effective on November 4, 2016. Its main objective is to keep global warming far below 2°C, ideally below 1.5°C, compared to pre-industrial levels (UNFCCC, 2015). The aim of the agreement is to reduce the harmful greenhouse emissions from human activities that cause global warming. The nationally determined contributions (NDCs) of the United Nations Framework Convention on Climate Change (UNFCCC) hold significant importance in delineating the sector-specific commitments and strategies of nations (UNFCCC, 2015, 2020). A number of nations presently offer comprehensive information regarding their strategies for addressing climate change in the buildings sector, encompassing adaptation, mitigation, and buildings codes, as outlined in their Nationally Determined Contributions (NDCs).

Based on the Paris climate agreement, governments across the world have introduced various environmental rules and regulations to curb the emissions from buildings. This has been carried out through the implementation of regional, national, and municipal building energy codes, as well as green certification programs and minimum energy performance criteria, can effectively enhance efficiency and mitigate building energy consumption. As a huge part of the overall emissions come from energy consumption in buildings during their operations phase, governments are trying to regulate the energy consumption in buildings by introducing rules and regulations to promote energy efficiency in buildings and net zero energy buildings. Energy consumption remains the main focus for governments to regulate in order to reduce emissions from buildings. Majority of the existing and upcoming environmental policies and regulations regarding the built environment are concerned about the energy usage and energy efficiency of buildings (EU, 2022a, 2022b; Magrini et al., 2020). Governments are empowered to establish regulations for the construction and upkeep of buildings. These regulations, if effectively enforced, guarantee that the building's adhere to specific requirements such as heat insulation, ventilation rates, and energy consumption guidelines for operating equipment. The design of building energy codes prioritize local environmental circumstances and building usage and play a crucial role in enhancing the energy efficiency of buildings by mandating a prescribed minimum threshold of energy performance (UNEP, 2022b).

Most of these policies only regulate energy consumption related to certain building components or aspects which is only a part of the overall energy consumption figures. According to Allouhi et al. (2015), typically, building regulations encompass provisions pertaining to the thermal characteristics of a building's envelope, such as the incorporation of thermal insulation materials or the installation of double glazed windows. In addition, the scope of their responsibilities encompasses heating, ventilation, air conditioning (HVAC), lighting, electrical power, integration of renewable energy sources, and building maintenance. However, the overall energy consumption figures of a building entails several other aspects as well. Several researchers have pointed out the importance of human-related aspects such as occupant behaviour which have a huge impact on the overall energy performance of buildings and accounts for a significant portion of the overall energy consumption figures as discussed in detail in the following chapter.

The adoption of legal frameworks is a commonly employed technique to effectively and economically promote energy efficiency in buildings and have been widely recognized as proven measures in this regard. The primary impetus for the establishment of building thermal regulations in many European countries following the oil crisis of the 1970s was to mitigate energy dependency (Pérez-Lombard, Ortiz, Coronel & Maestre, 2011). European legislation has established a comprehensive framework of ambitious goals aimed at attaining great energy efficiency in buildings. One of the significant components of the European regulatory system is the Energy Performance of Buildings Directive 2002/91/EC (EPBD). Since the implementation of the Energy Performance of Buildings Directive (EPBD) in 2002, it has been mandatory for all European Union (EU) Member States to establish a comprehensive framework and establish building energy code criteria that adhere to the global building approach (Annunziata, Frey & Rizzi, 2013; Laustsen, 2008).

The Netherlands is actively pursuing a swift transition towards a carbon-neutral economy, with the objective of bolstering robust economic growth and ensuring energy security. In order to facilitate this transition, the energy and climate policy implemented by the government places emphasis on the reduction of greenhouse gas emissions. The policy sets specific targets to decrease emissions by 49% by the year 2030 and by 95% by the year 2050, in comparison to the emission levels recorded in 1990 (IEA, 2020). The Climate Agreement of 2019 in the country outlines a set of policies and initiatives aimed at facilitating the attainment of the aforementioned carbon reductions. This agreement was formulated through a collaborative approach that engaged various stakeholders from Dutch society (IEA, 2020; van Algemene Zaken, 2023). In the Netherlands, most of the policies, rules and regulations regarding buildings and its energy usage are as per the Energy Performance of Buildings Directive (EPBD). Existing buildings must have an energy label by law in Europe under the EPBD. Since 2008, a national labeling program has been in place in the Netherlands. The label is based on a theoretical calculation of energy consumption (gas and electricity) that takes into consideration the physical features of the building such as its heating, ventilation, cooling systems, and water heating (Majcen et al., 2013a). To mandate these policies, all office buildings in the Netherlands must have an energy label C by January 2023 which could be made stricter in the near future with hints towards a mandatory energy label A by 2030 for all office buildings (RVO, 2017).

Apart from energy labels and certificates, green certifications are also widely acknowledged but not mandated by governments. The field of building energy and sustainability rating systems is in a constant state of development, with the aim of addressing the goal of achieving net zero emissions. These systems have established specific criteria for evaluating sustainable practices within the building sector, encompassing various aspects such as energy, water, waste, transportation, materials and resource utilization, pollution, land use, and health considerations. As of the year 2021, there exists a total of 74 certification systems for green buildings worldwide, with the bulk of these systems being handled by members of the World Green Building Council (WorldGBC) (UNEP, 2022b). Some of these widely used certification are Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy Environmental Design (LEED) and WELL Building Standard. Apart from these certificates and labels, there are other targets such as Net Zero Energy (NZE) Scenario emphasized by governments where the aim is to have net zero CO_2 emissions by 2050 (IEA, 2023c). This scenario describes a pathway for energy sector to reach net zero emissions by 2050.

The significance of built environment sustainability in terms of reduced energy consumption to upholding their missions to safeguard populations, enhance energy system resilience and security, and tackle climate change has been demonstrated by commitments made by governments and heads of state (UNEP, 2022b). As highlighted in the problem statement, these policies and regulations lead to the phenomenon of energy performance gap in buildings and will be discussed in detail in the following chapter. Several important aspects that have a significant impact on energy performance of buildings have not been regulated or considered by these policies and regulations. Occupant energy consumption in buildings is one example for important aspects that are often overlooked or neglected. The energy consumption related to various occupant factors such as their behaviour have been overlooked or ignored by policy makers and governments across the world which leads to a phenomenon of energy performance gap as discussed in chapter 4.

Chapter 4

Energy Performance Gap

Buildings are responsible for a substantial consumption of energy, accounting for approximately one-third of the overall utilization of primary energy resources. Hence, the matter of building energy efficiency has emerged as a significant concern in mitigating the escalating energy requirements of the sector by policy makers around the globe. The global proliferation of energy efficient or green building measures has not yielded the projected energy-related advantages due to the under-performance of these structures in practice (Zou & Alam, 2020). With closer examination of advancements in the building industry currently, it becomes evident that energy performance is not experiencing any significant improvement (Gram-Hanssen & Georg, 2018). The energy efficiency of buildings must be drastically improved to tackle the energy crisis and climate change.

Building energy consumption is currently regulated across most of the countries and has helped newly constructed buildings to be more energy efficient than new ones. Despite the implementation of energy efficient building regulations and the integration of energy-efficient technologies, commercial buildings frequently fall short of achieving their intended energy consumption or conservation objectives. Instead, they consume up to three times the projected energy consumption, thereby highlighting a substantial disparity in building energy performance (Wu, Lin, Papachristos, Liu & Zimmermann, 2020). These regulations do not provide a complete picture regarding the energy performance of buildings as they only regulate certain aspects of the building which is not the complete picture and therefore leaves behind a grey area within energy consumption figures.

The building energy performance depends on multiple factors that are related to the energy consumption within buildings making it quite difficult to predict the actual energy consumption or performance of buildings due to the complexity of these factors and uncertainties related to them (Zhao & Magoulès, 2012). However, most of the policies and regulations is based on either various assumptions made regarding these factors or neglecting some of these factors to have an estimation or prediction regarding energy consumption as close as possible to the actual numbers. Often, the predicted figures could be much lesser than the actual figures causing a phenomenon called energy performance gap. This section discusses the energy performance gap inherent in buildings mainly due to these policies and regulations. The consequences that arise from these energy performance gap is also highlighted through this section. This section also sheds light on the several underlying causes for energy performance gap in buildings and focuses on occupant behaviour as an important underlying cause. Finally, a brief explanation about different ways to bridge the energy performance gap is also mentioned.

4.1 Definitions

Policies that regulate energy consumption within buildings help developers to design buildings in an energy efficient way and reduce the emissions from energy usage as much as possible during operations. The implementation of these policies aimed at decreasing energy consumption and promoting the utilization of renewable energy sources within the building sector are crucial steps in mitigating the European Union's reliance on energy imports, fossil fuels, and the subsequent emissions of greenhouse gases.Literature has provided several definitions for the term energy performance gap inherent in buildings with most of them having similar, if not exactly the same, meaning. These definitions are provided based on different research carried out to study the energy performance of buildings and energy consumption within them. Energy performance gap is becoming a growing concern due to the emissions from the built environment.

Majcen et al. (2013b) defines energy performance gap as the difference between predicted or estimated energy consumption of a building according to energy labels and the actual energy consumption of the building during operations. Van Dronkelaar et al. (2016) defines the energy performance gap as the discrepancy between measured energy consumption of the building and the predicted energy consumption of the building mainly due to differences in operating conditions and non-regulated loads being excluded from compliance modeling. The authors also identified and stated three different types of energy performance gaps such as (1) regulatory performance gap due to the mismatch in predictions from regulatory compliance modeling and actual energy usage, (2) static performance gap due to the mismatch between predictions from performance modeling and measured actual use and (3) dynamic performance gap due to the mismatch between calibrated predictions from performance modeling through a longitudinal perspective that looks into the underlying causes of the gap and their impact.

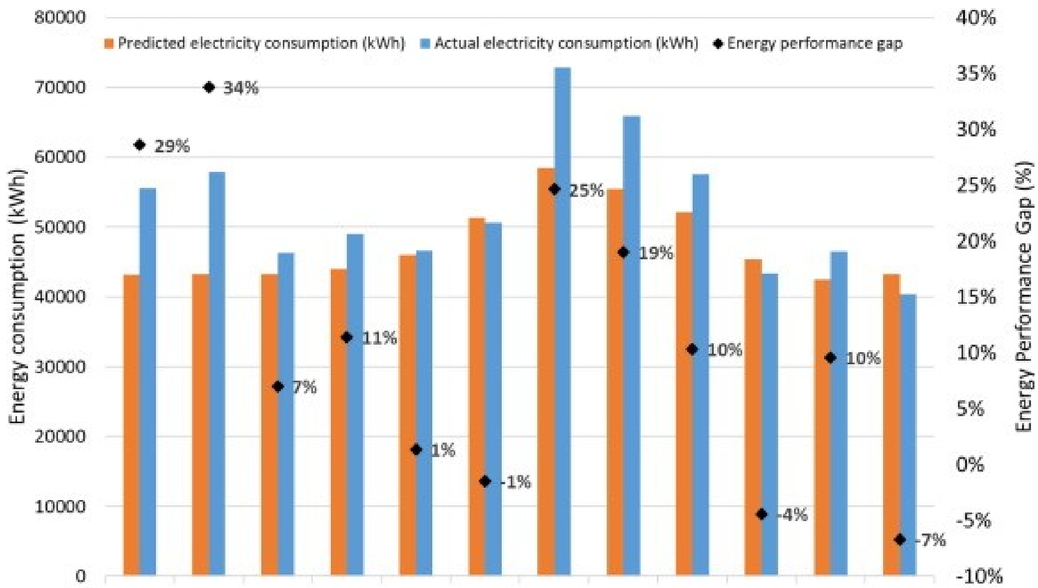

Figure 4.1: Energy Performance Gap in Buildings During Different Months of the Year for a Case Study Building (Zou & Alam, 2020)

Zou and Alam (2020) provides a similar definition for the term through their research as illustrated in figure 4.1. They define the term as the difference between actual measured energy consumption and the prediction through relevant building standard set by the governing authorities as depicted in figure 4.1. De Wilde (2014) defines the gap as a mismatch between the predicted energy performance of the building and the actual measured energy performance of the building. The author also identifies three different types of energy performance gap in buildings which are (1) mismatch between first principle energy models and measurements undertaken on actual building (excluding the tenants/users), (2) mismatch between machine learning approaches and actual measurement of the building (including the tenants/users) and (3) mismatch between energy ratings provided by compliance tests and energy display certificates and actual energy consumption during operations. Menezes, Cripps, Bouchlaghem and Buswell (2012) also provides a similar definition for the energy performance gap as the difference between actual energy consumption of the building and its predicted energy consumption during the design phase of the building.

A similar phenomenon is also evident in the case of green building certificates. Liang et al. (2019) states a similar definition for energy performance gap as the disparity that arises between the projected and actual energy conservation outcomes subsequent to the implementation of energy-efficient technologies in buildings. Fedoruk, Cole, Robinson and Cayuela (2015) also explores the performance gap in buildings with green certifications and provides a similar definition for the gap as the significant difference between designed energy performance and the actual energy performance of the building. Scofield (2013) studied the performance of 953 office buildings in New York based on their green building certification and found a similar gap in the design performance and actual performance providing a similar definition for the term. Turner, Frankel and Council (2008) conducted a study on the energy performance of 121 LEED New Construction Buildings and found a similar discrepancy between predicted or measured energy performance of the building and the actual energy performance of the building further contributing to the numerous definitions for the term.

Energy performance gap has been studied by several researchers in the past few years and this topic has grown into a hot research topic in the recent years due to its significance in improving the energy efficiency of buildings and reducing the energy consumption within buildings. This research focuses on a case study building situated in the Netherlands and hence will adopt a definition for the term energy performance gap as "the mismatch between predicted or estimated energy consumption of a building according to energy labels and certificates and the actual energy consumption of a building". This definition aligns with the various definitions provided through literature and will mainly focus on the predictions or estimations provided according to energy labels and certificates used within the Netherlands according to EPBD. There are several underlying cause that leads to the energy performance gap and can be linked to the term which are discussed below to further narrow the scope of this research.

4.2 Underlying Causes of Energy Performance Gap

Energy performance gap is inherent in buildings mainly due to the energy labels and certifications according to various definitions provided in literature. Several researchers have found various underlying cause or the root cause that leads to the energy performance gap in buildings. These root causes are all significant in closing the energy performance gap inherent in buildings due to energy labels and certificates. Within literature, frequently cited underlying cause that leads to the energy performance gap in buildings is the predicted energy performance of the building (Van Dronkelaar et al., 2016). This predicted energy performance of building is regulated by a set of standards or energy labels introduced by the government such as in the Netherlands. In some instances, developers also use green building certificates as a tool to predict the energy performance of buildings. These predictions only provide a basic idea about the energy performance of buildings and do not provide a complete picture.

Through their extensive study, Van Dronkelaar et al. (2016) also elaborates on the other underlying causes that leads to energy performance gaps. There is a limited understanding regarding the impact of early design decisions on the outcome of the project, especially related to energy efficiency. All decisions made during the design stage of a project such as materials, forms, choice of renewable sources, strategies, innovative solutions, etc. will have an immense impact on the energy performance of the building. They also elaborate on the complexity of design and uncertainties within building energy modeling as underlying causes that lead to the gap. Most of the uncertainties revolve around factors that have an impact on the energy performance of buildings such as occupant behaviour within buildings and efficiency of building services over the entire life-cycle of the building. Another set of researchers state various technical aspects that are the underlying causes for the energy performance gap. In a study conducted by Fedoruk et al. (2015), the lack of effective building energy monitoring capabilities to understand the building energy performance during the operations phase was found to lead to gaps. These data regarding building energy performance during the operations of the building is also important to keep a check on the predicted or estimated energy performance and will help asset managers keep track of their tenant's energy performance. This data will also help reduce the uncertainties during the design stage and in making better predictions regarding energy performance (De Wilde, 2014).

Van Dronkelaar et al. (2016) also specifies different types of uncertainties such as specification uncertainty, modeling uncertainty, numerical uncertainty and scenario uncertainty that are observed during the design phase of a project. The prediction of energy usage is conducted through several tools that have been standardized or regulated in different nations, serving different purposes. Consequently, these tools introduce a level of uncertainty in the findings when modeling the energy usage of a given building (Van Dronkelaar et al., 2016). The diversity observed among different tools in the context of building energy simulation can be attributed to many factors, including model simplification, user error, and numerical errors. These tools are employed for the aim of constructing performance prediction and, as such, must provide reliable and reasonably accurate outcomes (Raslan & Davies, 2010; Schwartz & Raslan, 2013). However most of these uncertainties revolve around the domain of occupant behaviour as it is quite hard to be quantified or anticipated during such simulations and predictions.

A major underlying cause of the energy performance gap as identified by Van Dronkelaar et al. (2016) is occupant behaviour. Occupants and their behaviour have a significant impact on the energy performance of buildings but they are not included in any energy predictions or estimations leading to a significant mismatch as mentioned earlier. Their interactions with the building services and environment determines the energy performance of the building and are often neglected or overlooked during predictions. These behaviours can also vary according to various factors such as geography, culture and education/awareness and cannot be predicted accurately in most scenarios. Studies conducted regarding the impact of occupant behaviour on energy performance of buildings have shown 10-90% variation in energy performance based on occupant behaviour (Azar & Menassa, 2012; Hong & Lin, 2013; Martani, Lee, Robinson, Britter & Ratti, 2012; Parys, Saelens & Hens, 2010). Through a survey based study conducted by Liang et al. (2019), higher energy consumption by the occupants of the building than designed was found to be a primary reason that leads to the energy performance gap in the buildings.

Interviews with experts working on different projects provided further insights into the underlying causes that lead to energy performance gaps in buildings. Some of the participants mentioned the negligence of certain important aspects such as occupant behaviour from the design of buildings as they are often overlooked by the legislation. The participants also mentioned that improving the energy efficiency beyond the requirements of the legislation requires huge investments and does not provide reasonable return on investments once the building is in operation. Moreover, there was a significant lack of data regarding the energy consumption within buildings due to lack of smart meters. This makes it difficult to understand the specific areas of energy consumption and identify the root cause that leads to excessive energy consumption within buildings. Eventually, this also leads to several uncertainties during the design process of similar buildings as there is not much detailed information available regarding energy consumption in existing buildings. One of the interview participants also mentioned that aspects such as occupants and their behaviour are known to have a significant impact on the overall energy consumption of buildings but these aspects are not regulated by the legislation.

The participants also mentioned that the predicted energy consumption are in line with energy labels in most projects carried out in the Netherlands as they are a legislative requirement. One of the interview participant also mentioned lack of awareness regarding the energy performance gap in buildings as an underlying cause.

Based on the literature review carried out, occupant behaviour is most frequently stated in literature as an underlying cause that leads to energy performance gap in buildings that are mainly inherent due to energy labels and certificates. Most of the energy labels and certificates that are mandated by governments to regulate energy consumption within buildings overlook various aspects such as occupants and their behaviour within buildings. However, occupant behaviour has been a hot research topic in the field of building energy efficiency in the recent years and there are several researches that point out the significance of occupant behaviour in building energy efficiency. Also based on the insights gained through interviews with experts from the industry, occupants and their behaviours have a huge impact on the energy performance of buildings but are unregulated by legislation leading to gaps. Additionally, lack of detailed information or data regarding energy performance of buildings also lead to significant gaps in energy performance. Hence, this research will focus on one of the main underlying cause, occupant behaviour, to bridge energy performance gap.

4.3 Consequences of Performance Gap

The significance of addressing the energy performance gap in buildings is extensively recognized in scholarly literature. Approximately 40% of the world's energy consumption is attributed to buildings, which are widely recognized as having significant potential for mitigating greenhouse gas (GHG) emissions. Electricity accounts for $2/3^{rd}$ of the overall carbon emissions of a building. Majority of the energy consumed in the buildings are produced from fossil fuels which results in GHG emissions as discussed in section 3. The unaccounted or unregulated energy consumption that falls within the energy performance gap will have major impacts on the environment and will continue to remain as a blind spot in our journey towards reduced carbon emissions. In order to reduce these carbon emissions from energy consumption in buildings, it is important to bridge the energy performance gap as much as possible. By bridging the energy performance gap, the overall energy consumed in buildings can also be drastically reduced and thereby the emissions from it.

The consequences of the energy performance gap inherent in buildings would have been lesser significant if the energy consumed within buildings were produced sustainably. However, currently fossil fuels are widely used to generate electricity that powers buildings around the world. In the year 2019, coal accounted for 37% of global electricity generation, surpassing renewable sources by a margin of 10%. The share of coal in power generation exhibited a degree of variability, hovering around the 40% mark from the mid-2000s. In the year 2019, renewable energy sources accounted for 27% of the global electricity generation, surpassing natural gas by a margin of three percentage points, which stood at 24%. In contrast, the oil industry accounted for less than 3% of the total global electricity production in the year 2019. Considering the sources of energy used in buildings currently, it is quite important to reduce energy consumed within buildings and bridge the energy performance gap with a focus on occupant behaviour to meet the Paris-proof ambitions and targets. Moreover, the energy performance gap represents a grey area that will continue to be neglected or overlooked by the legislation and also real estate developers if it is not addressed.

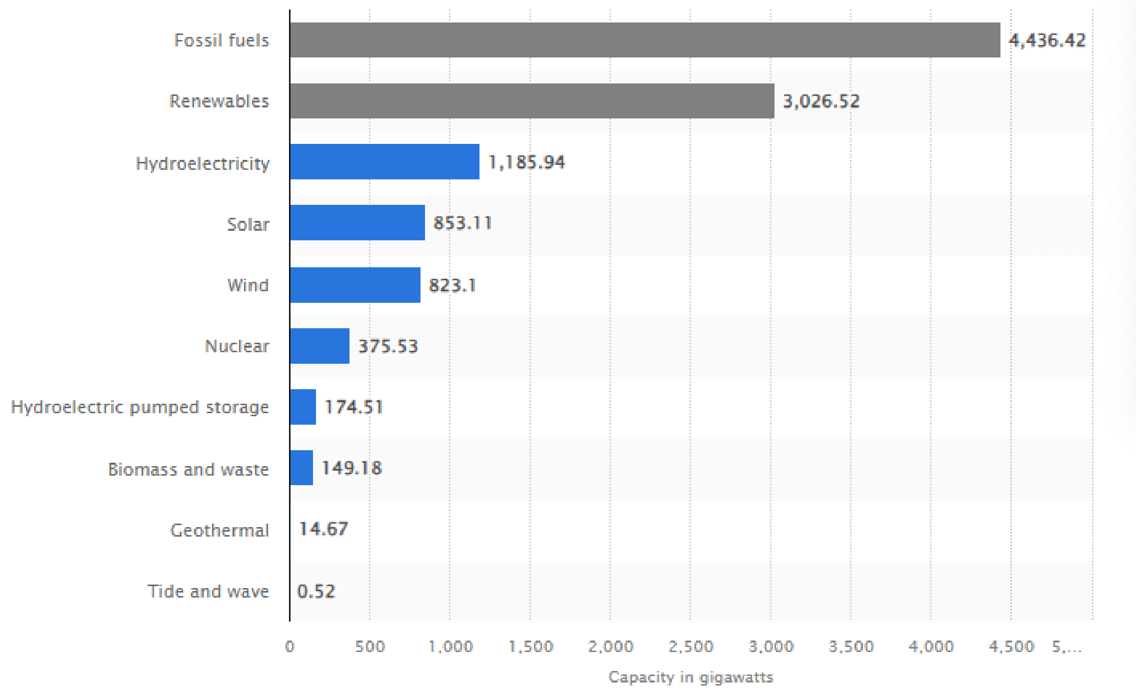

Figure 4.2: Global Electricity Capacity by Source (Statista, 2023a)

As discussed extensively in section 3.2, the emissions from using fossil fuels to generate electricity to power buildings is immense compared to other sectors or industries. This raises the importance to reduce the energy consumption in buildings to thereby reduce emissions. Research also shows that as the electricity demand reduces through reduced consumption, the renewable energy resources could be used to cover the entire demand for energy within buildings (IEA, 2021). With the increasing population around the world and growing demand for more buildings, the energy performance gap needs to be bridged to improve the energy efficiency of buildings. The global energy intensity is also on the rise and needs to be addressed to contribute to the overall sustainability goals. The energy performance gap is also not addressed by legislation which leaves them in the blind spot for developers and expands the grey area further. Based on these consequences mentioned, it is important for real estate developers to bridge the gap inherent in buildings to meet the sustainability targets set by the government within the mentioned time-frames respectively.

4.4 Bridging the Energy Performance Gap

The energy performance gap plays a significant role in the energy efficiency of buildings and also the emissions from the energy consumed in buildings. The consequences of energy performance gap in buildings have been highlighted and extensively discussed in the previous section. According to the definition selected for this research, energy performance gap mainly exist in buildings due to the mismatch between predicted or estimated energy consumption by energy labels and certificates and the actual energy consumption of the building during operations. These energy labels and certificates only take into account a few components of the building for estimating the energy performance of buildings during the design stage. This leaves behind a "grey area" within the overall energy consumption and energy performance of the building that is unregulated by the legislation. This grey area contributes heavily towards the emissions from the energy consumed and hence needs to addressed in the design of buildings.

Perhaps, the simplest way to bridge the energy performance gap according to the definition selected for this research is by making the predictions as accurate as possible to the actual energy consumption figures of a building. However, there are several issues with this strategy that contradicts with the ambitions of the government and Paris Climate agreement to reduce the emissions and help keep global warming below 1.5°C. Accurate predictions or estimations of energy consumption within buildings does not help in reducing the energy consumed within buildings or the emissions resulting from them. Thus, accurately predicting or estimating energy consumption is not the most favourable solution to bridge the energy performance gap in the modern world that requires sustainable development to fight against climate change.

Using greener energy within buildings would make the energy performance gap a lesser significant problem or even redundant. However, the current capacity to meet the energy demands within buildings through renewable resources is limited. According to statistics released by IRENA (2023), currently only 40% of total electricity demand can be met by renewable sources worldwide. This makes the bridging of energy performance gap in buildings even more important. Moreover, with the growing population and increased demand for buildings, the renewable energy capacity will not be able to meet the energy demands. Hence, there is an urgent necessity to reduce energy demands to bridge the energy performance gap. Also, in order to contribute towards the goals of the Paris Climate agreement, we need to drastically reduce energy consumption in buildings and then meet the energy demands through greener resources to reduce emissions.

Through exploratory interviews with experts from the industry, it was found that the developers use energy labels and certificates as a support tool to design buildings. These energy labels and certificates do not look into certain aspects such as occupant energy consumption behaviour and efficiency of the technical components throughout their life-cycle. As discussed earlier, occupant behaviour is regarded as the most stated underlying cause for the energy performance gaps in buildings through literature mainly because they are neglected by energy labels that are used as a tool by developers to design buildings for energy efficiency. Some of the interview participants mention that certain aspects overlooked by legislation such as occupant behaviour are not included in the design of buildings as they do not provide any financial gains for the organization for the high initial investments and hence continues to remain within the grey area.

We need better building designs through different design strategies and processes which helps reduce the overall energy consumption of the building. Designing the building by taking into account the requirements of the occupants of a building will help reduce energy consumption drastically. Robust design solutions, that incorporate occupant behaviour, have the potential to significantly mitigate the impact of occupant behavior by rendering buildings less vulnerable to its influence and thereby drastically reducing the energy consumption (Karjalainen, 2016). Incorporating occupant behaviour into the design of buildings will shed light on the energy grey area that is often neglected or overlooked by energy labels, certificates and legislation. Therefore, this research aims to bridge the energy performance gap by focusing on the impact of occupant behaviour as the underlying cause for energy performance gap. The objective is to incorporate occupant behaviour into the design of buildings which helps in reducing the energy consumption as well as improving the simulations used to predict or estimate energy consumption.

4.5 Significance of Occupant Behaviour

Occupant behaviour is stated as the main underlying cause that leads to the energy performance gap in buildings due to their negligence in energy labels and design of buildings. Occupant behavioural aspects also have a major impact on the energy performance of the building and have shown 10-90% variation in energy performance of buildings (Azar & Menassa, 2012; Hong & Lin, 2013; Martani et al., 2012; Parys et al., 2010; Van Dronkelaar et al., 2016). Most of the policies and regulations governing the energy efficiency of buildings do not take into account occupant behaviour. However, majority ambitions and targets set by several governments and intergovernmental organizations, such as Paris-proof targets, include occupant related energy consumption in buildings. These targets could be mandated in the near future as governments are taking stricter measures to meet the targets of Paris Climate Agreement within a reduced time-frame.

Chung (2011) mentions that occupant behaviour within the building are found to be the most common factor leading to variations in actual energy consumption and predicted energy consumption of buildings. According to a research conducted by Carpino et al. (2020), approximately 32.4% of the total electricity consumption in a household is consumed by the occupants which was later found to be as high as 35%. The energy balance of buildings is influenced by the mere presence of occupants, resulting in a passive impact (G. U. Harputlugil, Harputlugil, Pedergnana & Sarıoğlu, 2019). According to T. Harputlugil and de Wilde (2021), the primary influencer of energy consumption in buildings are the occupants, who possess diverse profiles and engage in various activity patterns. The authors also states that core function of a building is to provide a healthy and comfortable environment for humans to conduct their daily activities. The consumption of energy in buildings by occupants is driven by various factors, primarily aimed at optimizing their comfort levels (Hong, Yan, D'Oca & Chen, 2017). The performance disparity is attributed to occupant behavior, which is considered a significant factor due to its intricate nature and dynamic characteristics, posing challenges in its comprehensive understanding and representation (De Wilde, 2014). While there is a prevailing emphasis on enhancing technological advancements for energy efficiency, it is imperative to address the occupant behavioural aspects that have an impact on the energy performance (Masoso & Grobler, 2010). The consideration of inhabitants is crucial in the context of energy conservation in buildings.

A major significance of occupant behaviour is related to the Paris Climate Agreement. In line with the Paris Climate agreement, various councils such as the Dutch Green Building Council in the Netherlands have introduced targets such as Paris-proof targets for the real estate industry to help achieve the broader targets of the agreement. These targets are set in order to achieve desired levels of overall energy consumption within buildings. For example, office buildings must not consume more 70kWh/m^2 energy in a year. These targets include the energy consumption figures including the occupant consumption within buildings. Similarly, most of the future policies and regulations regarding energy consumption within buildings will include energy consumption from the occupants making it important to consider occupant behavioural aspects into the design of buildings to make them energy efficient. Such changes in the way buildings are designed will help reduce energy consumed by the occupants and make the building energy consumption less sensitive to occupant behavioural aspects.

Exploratory interviews with professionals from the industry have also helped in gaining a better understanding about the significance of occupant behaviour and highlighting the importance of including occupant behaviour within the design strategy for energy efficient buildings. One of the interview participant mentioned that "energy consumed by occupants within buildings are often the difference in predicted energy consumption and actual energy consumption because it is difficult to predict energy consumption by the occupants due to several complexities and its ignorance by energy labels". Another interview participant mentioned that most of the buildings today are not energy efficient as they are not designed according to occupant requirements. The participant also emphasizes that "if the office spaces were built according to the organizations' functional requirements, the energy consumed would have been significantly lower and reduce energy wastage. Developers design buildings for maximum flexibility to accommodate different types of occupants and only include energy efficiency measures mentioned in legislation". Currently, designers and developers use energy labels as a support tool to aid their design process for energy efficiency measures which leads to energy performance gaps. This design strategy needs major interventions to focus on the important grey area which is often not taken into account during the design of buildings. These aspects within the grey area need to be systematically integrated into the design of buildings in order to reduce energy consumption by catering to the specific requirements through improved design, improve energy efficiency and reduce emissions from energy usage.

Literature has an important association between the energy consumption of buildings and the behaviours and actions of the individuals occupying these facilities and this has been studied extensively but not incorporated into the estimation or predictions of energy consumption or even the design of buildings. The presence of occupants in a building not only results in energy consumption but also contributes to energy usage through their operational control, which is dependent on the type of building (T. Harputlugil & de Wilde, 2021). Research on occupant behaviour and interaction with building services pertaining to energy usage has contributed to the advancement of knowledge and comprehension regarding building energy performance. The inclusion of occupant behavior is a crucial determinant of energy consumption, necessitating a more comprehensive comprehension of this aspect for effective energy management strategies encompassing both efficiency and conservation measures within buildings (Hong et al., 2017). Therefore, through this research, in the following chapters, occupant behaviour will be explored in more detail to understand its role in improving the energy efficiency of buildings. The following chapter will dive deeper into the domain of occupant behaviour within buildings to gain a better understanding on their impact on the energy performance of buildings and how that information will help improve the design process.

4.6 Conclusion (Phase 1 - Discover)

In the first phase of this research, discover phase, the initial challenge of energy consumption in buildings were explored. The general patterns or trends of energy consumption within buildings and the emissions resulting from energy usage in buildings were analysed in detail through scientific literature and various reports. Various issues such as fuel source for energy used within buildings and the increasing demand for more buildings with the growing population were analysed. This has provided a better understanding about the importance of energy efficiency of buildings and the role of policies and regulations in ensuring energy efficiency. In line with the policies and regulations, energy performance gap was identified as an issue related to legislation for energy efficiency of buildings.

The energy performance gap in buildings were understood in finer detail through literature by exploring various definitions and underlying causes that lead to the energy performance gap in buildings. Exploratory interviews were also conducted with professionals from the industry to understand the extend of the problem and gather further insights into the problem apart from the findings from literature. Several underlying causes for the energy performance gap was found through literature and interviews. The consequences of the energy performance gap were also highlighted through literature. There were different ways in which the gap could be bridged based on the findings from literature and exploratory interviews. The significance of occupant behaviour in bridging the energy performance gap is also explained in detail through findings from literature and exploratory interviews.

In conclusion, energy consumption in buildings and emissions resulting from them were found to be alarming issues. Energy efficiency of buildings were promoted through various policies and regulations that eventually lead to the problem of energy performance gaps in buildings. These gaps are mainly inherent due to the energy labels and certificates leaving a grey area within energy consumption or energy performance of buildings. Occupant behaviour was found to be the most significant aspect within this grey area in energy consumption. Focusing on occupant behaviour was identified as one of the most important ways to bridge the energy performance gap, especially due to possible future policies and regulations. Occupant behaviour will be explored in detail and several flaws will be identified within the current industry practices that lead to energy performance gaps in the next phase.

Chapter 5

Occupant Behaviour in Buildings

Occupant behaviour has been studied extensively by researchers recently due to its significance within the energy efficiency of buildings with several explanations and classifications for the term. Occupant behaviour is the presence of occupants and their actions and interactions with the environment inside a building (Paone & Bacher, 2018). Occupant behaviour is also the quantitative depiction of the direct and indirect impacts that building occupants have on the energy performance of a facility (Chong, Augenbroe & Yan, 2021). The investigation of occupant behavior has emerged as a significant area of research due to the need to mitigate the escalating energy demands in the building sector. These studies aim to analyze occupant behavior both qualitatively and statistically, with the goal of promoting energy efficiency and minimizing the disparity between predicted and actual energy usage (Paone & Bacher, 2018). The potential influence of occupant behaviour was postulated as a plausible explanation for the observed disparities, attributing them to variations in actual energy usage and predicted or estimated energy usage due to the ignorance of certain aspects related occupant behaviour within buildings.

Quantifying the impact of occupant behaviour poses challenges due to methodological considerations. The complex and ever-changing nature of how occupants utilize energy presents a significant problem, necessitating the application of interdisciplinary methods to get fresh perspectives in this field. This understanding of various aspects of occupant behaviour is also important as they are often overlooked by the legislation. Extensive research that has been carried out in the recent years are paving the way for policy makers to regulate occupant energy consumption behaviour in buildings. The comprehension of occupant's behaviour within buildings and also the legislation holds significance for enhancing the energy efficiency of building systems and for equipping designers with sufficient knowledge regarding the utilization of spaces and building services by occupants and how they impact the energy performance (A. J. Sonta et al., 2018).

As discussed in section 4.5, occupant behaviour is found to be one of the most important aspects to bridge the energy performance gap in buildings and improve energy efficiency in buildings. Hence, it is important to possess an understanding about this topic in order to explore the problem in further detail and devise the detailed problem statement according to the double diamond methodology. This chapter marks marks the beginning of the second phase, define phase, where the detailed problem statement will be derived through convergent thinking and exploring the problem in depth. This chapter provides detailed insights into the various aspects of occupant behaviour within buildings, specifically office buildings as mentioned within literature. Current occupant behaviour trends related to these aspects are also highlighted. These aspects are discussed in detail to understand their impact on the energy performance of buildings and how they lead to energy performance gaps.

5.1 Classification of Occupant Behaviour

Occupant behaviour can be classified into various categories to understand their impact on the energy performance of the building. Various researchers have addressed the occupant behaviour and classified them into several categories based on various factors to understand the topic in a systematic way. (S. Chen et al., 2021) categorised occupant behaviour into three main categories through an extensive literature review - occupancy, interactions and behavioural efficiency. Other researchers have categorized occupant behaviour related to building energy performance based on their energy consumption patterns such as - saving, real and intensive energy users (Almeida, Tam, Le & She, 2020). Lazarova-Molnar and Mohamed (2017) classified occupant behaviour as interactions and events to study their impact on the energy performance of buildings.

The objective of this research is to improve the current practices within the industry, especially design strategies, with a focus on occupant behavioural aspects that are overlooked by legislation to improve the energy efficiency of buildings. This requires a categorization that clearly explains the various aspects of occupant behaviour based on how people behave within non-residential buildings and how it affects the energy performance when linked to various technical components of the building. As categorized by S. Chen et al. (2021), occupant behaviour can be linked to various building aspects in a systematic way. Hence this research will follow the classification provided by the author as occupancy, interactions and behavioural efficiency which will be further elaborated in the following sections of the chapter based on various research carried out in the respective domains or classifications.

5.2 Occupancy

Occupancy was defined by S. Chen et al. (2021) as data and information that encompasses a range of information pertaining to the status of inhabitants within a building. This includes details such as the total number of occupants, their specific locations within the structure, events related to their arrival and departure, the overall distribution of occupants throughout the premises, as well as the duration of their stay. Caucheteux, Sabar and Boucher (2013) also defines occupancy as all the actions of occupants of a building that have an impact on the energy efficiency of the building. Hoes, Hensen, Loomans, de Vries and Bourgeois (2009) defines occupancy as the phenomenon under investigation that pertains not only to the occupancy of individuals within the building, but also encompasses the behaviors shown by users that may impact the indoor environment. These factors and aspects regarding occupant behaviour have a major impact on the energy performance of the building.

Aspects such as occupancy are often not considered during the energy prediction or simulations carried out during the design stage of a building due to its complexity. It is quite difficult for designers to accurately predict and quantify the impact of occupancy on the energy performance. This is mainly because of the uncertainties related to these aspects and its complex nature which makes it hard to quantify and generalize them (Zou, Xu, Sanjayan & Wang, 2018). In the realm of building energy consumption estimation, it is becoming customary to employ models that incorporate occupancy scenarios. These scenarios are frequently derived from estimations of typical occupant behavior patterns that are contingent upon the specific purpose for which the building is being utilized (Caucheteux et al., 2013). These estimations are made from data and information gathered from buildings regarding occupancy patterns through various methods mentioned in literature.

In order to further analyse and quantify the occupancy aspect of occupant behaviour within buildings to understand their impact on the energy performance, they can be further classified into presence, location and activity. Various research has been carried out to analyse and quantify the occupancy aspect based on these classifications as discussed below. These patterns have been studied extensively in the recent years to gather an advanced understanding of their impact on the energy performance. However, most of the research is carried out on residential buildings rather than non-residential buildings, latter being the focus of this research. Some of the findings regarding residential buildings can also be related to non-residential buildings. Studying the recurring patterns related to these aspects will help understand a trend in energy consumption and help devise suitable strategies for energy efficiency. There are several ways in which these studies measured and quantified these aspects of occupancy.

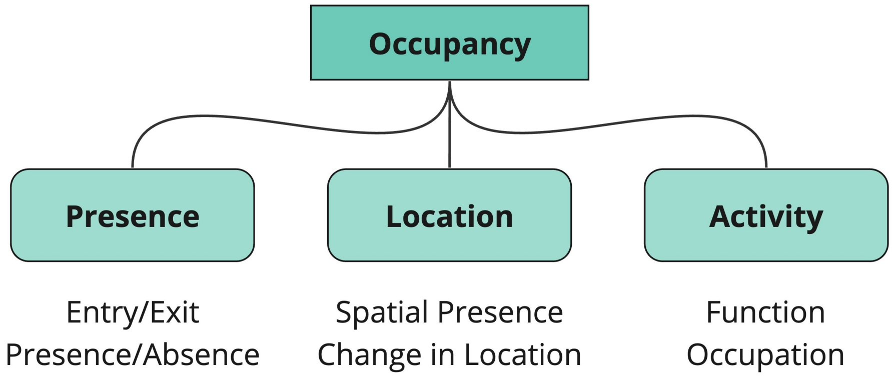

Figure 5.1: Classification of Occupancy Aspects

The presence, location and activity of occupants within a building environment will dictate the energy consumed by various technical components of the building such as lighting and HVAC systems. Moreover, through a study conducted by Azar and Menassa (2012), it was found that the outcomes of building energy models are significantly affected by these behavioral characteristics related to occupancy. Motuziene and Vilutiene (2013)'s study shows that assumptions concerning occupancy aspects have a huge role in energy simulations and helps designers design the building accordingly. However, these behavioural elements also depend on several other factors such as architectural design, weather conditions, building size, purpose of the building, etc. which is assumed to be already available for an existing building that has to renovated or retrofitted (Caucheteux et al., 2013).

There are different ways in which these attributes are measured or quantified. A diverse range of occupancy detection technologies is presently accessible. The utilization of passive infrared (PIR) sensors for the purpose of detecting occupancy is a longstanding practice. However, the efficacy of these motion sensors is generally limited due to their inability to detect the presence of stationary people (Guan, Li, Guo & Wang, 2014). The utilization of visible and infrared video analysis for indoor occupancy detection has witnessed a growing trend. However, privacy concerns have emerged as a significant point of contention (Liu, 2015). The accuracy of locating using Ultra-Wide-Band (UWB) technology is considerable; yet, the associated cost is frequently seen excessively expensive (Lee, Su & Shen, 2007). Bluetooth positioning technology is known for its accuracy and cost-effectiveness, as well as its low power consumption (Subhan, Hasbullah, Rozyyev & Bakhsh, 2011).

In terms of physical aspects, the individuals present inside a certain space produce CO_2, humidity, and temperature. The individuals residing within a room or apartment are regarded as a primary contributor to the creation of CO_2. Due to its significance in identifying the presence or absence of inhabitants and estimating their profiles, the CO_2 parameter is widely regarded as the most important parameter in the literature to measure such occupant behaviour aspects (Laaroussi et al., 2020; J. Yang, Santamouris & Lee, 2016). CO_2 sensors have been employed to aid in the estimation of occupancy. The affordability and widespread availability of the sensors render this methodology appealing. However, caution must be used when evaluating its dependability, as it can be influenced by factors such as fluctuating ventilation rates, door positions, and external concentrations of CO_2 which tarnish its accuracy (Gunay, Fuller, O'Brien & Beausoleil-Morrison, 2016). Persily and de Jonge (2017) also states that CO_2 generation also depends on other factors such as gender age and type of activity. Measuring these characteristics will provide a better link with the energy performance and help improve the design of buildings.

5.2.1 Presence

The energy consumption of office buildings is significantly influenced by the behaviours of occupants during their entry/arrival and exit/departure which defines their presence. This is due to the fact that many occupants, who have control over various appliances, choose to activate or deactivate these devices upon entering or leaving the building. Previous research have consistently shown that the energy-use actions of office-building occupants predominantly take place during these entry and departure events (Gulbinas, Khosrowpour & Taylor, 2015; Khosrowpour, Gulbinas & Taylor, 2016). As a result, individuals residing in a given space would have diverse energy consumption patterns that align with their entry and departure activities, which exhibit a recurring nature (Rafsanjani, Ahn & Eskridge, 2018). The findings of a study conducted by Rafsanjani et al. (2018) indicate that occupants of a building exhibit consistent delay interval patterns for both entry and departure events. The findings also demonstrate consistent patterns in the extent of fluctuations in energy usage during the entry and departure events of inhabitants in office buildings. The identified repetitive patterns have the potential to be associated with subsequent energy-intensive activities and are expected to facilitate the advancement of load disaggregation methodologies.

Various research has pointed out the importance of understanding the energy-use patterns during arrival and departure to understand the impact of occupancy on energy performance of a building (Rafsanjani et al., 2018). The state changes (e.g., turning on or off) of appliances and other building services utilized by occupants primarily occur during the occupants' arrival and departure events. The presence of diverse occupancy patterns, referring to variations in the timing and manner in which inhabitants enter/exit a facility, can potentially lead to an increase/decrease in loads that do not represent genuine needs for an HVAC (Heating, Ventilation, and Air Conditioning) system. This, in turn, might result in inefficiencies within the system (Z. Yang, Ghahramani & Becerik-Gerber, 2016). Z. Yang et al. (2016) developed a framework to quantitatively measure the implications of occupant presence and activity on the energy consumed by HVAC systems in a building. In a research conducted by Masoso and Grobler (2010), there is more energy used during the non-working hours than working hours as occupants tend to leave their devices and other technical components such as HVAC systems and lights on during the non-working hours.

5.2.2 Location

The comprehensive visualization and analysis of occupancy patterns, encompassing spatial distribution and temporal fluctuations, play a crucial role in the optimization of energy-efficient and productive buildings (Y. Wang & Shao, 2017). In contrast to conventional investigations on occupancy and energy consumption, the inclusion of more comprehensive data pertaining to indoor locations and occupant quantities has provided a more nuanced comprehension of occupant behavior within buildings. This information sheds light on the energy consumption patterns related to movement of people within office spaces. In a study conducted by Du, Jansen, Turrin and van den Dobbelsteen (2021), space layouts can have a major impact on the energy performance of office buildings. Again, these behavioural aspects are found to influence the activation/deactivation or change of state for several components of a building.

Eradicating the energy wastage identified through such occupant behaviour will help in reducing the energy consumption by 26% (Chong et al., 2021). A good understanding about this aspect will help assess the working style of employees within an office space and design the building in accordance to the specific working style. Most of the office spaces today are unable to use their space layout in an energy efficient way due to poor designs that do not incorporate occupant behaviour and thus have high energy consumption and significant energy wastage. Different methods have been used to gather data and information regarding the occupant spatial presence within buildings to understand and analyse its impact on the energy performance of buildings. Wi-Fi based indoor positioning systems were used in a study by Y. Wang and Shao (2017) to analyse the impacts of spatial presence on the energy consumed within buildings. This will help in identifying key regions of a building where occupants consume a significant amount of energy through their presence or movement. Real-time or accumulated historical data collected through the detection of Wi-Fi devices provides a detailed visualization of different movement patterns or spatial presence patterns.

5.2.3 Activity

The activity of the occupants also have a huge impact on the energy performance of the building. Activity basically refers to the condition in which the occupant does certain things or carries out their functions within the building. As discussed in the previous subsections, these activities determine the functioning of various electrical appliances and other building services that consume energy within a building. By acknowledging and discerning various activities and their corresponding potential for energy conservation, it becomes feasible to devise more efficient techniques for the design of superior buildings and automation systems (Ahmadi-Karvigh, Ghahramani, Becerik-Gerber & Soibelman, 2018). Recognizing and understanding occupant activity within buildings help in identifying the potential energy saving areas. The majority of electricity utilized in buildings are attributed to the operation of lighting systems and appliances that are triggered by occupant activity. In a study conducted by Gilani, O'Brien and Gunay (2018), understanding occupant activity and behaviour within a building will provide good approximations for energy consumption for lighting. Detailed examinations of energy consumption in buildings have unveiled that the conduct of occupants in managing building service systems exerts noteworthy influences on a building's energy consumption and, therefore, its building controls (Page, Robinson, Morel & Scartezzini, 2008).

Through a study conducted by Z. Yang et al. (2016), it was found that activity of occupants within a specific building environment has an impact on the energy loads on the HVAC systems. Researchers have also identified that the type of activity carried out in office spaces based on the type of office have an impact on the energy consumption. The number of devices such as computers, printers and other electronic devices used in an office space as part of their organizational function or activity dictates the energy consumption from the user's end. Ahmadi-Karvigh et al. (2018)'s study found 35.5% average energy saving potential through better usage of such devices within an office space that can be improved through better designs and there has been a growing interest globally in seeking ways to enhance the energy efficiency of building service systems by understanding the impact of occupant activity on them. According to Mantesi, Chmutina and Goodier (2022), highlights the significant shift in work culture and activities within office spaces due to the COVID-19 pandemic and their impact on the energy consumption.

5.3 Interactions

Energy practices often prioritize technological and physical aspects over human and social considerations, neglecting the fact that these technologies are intended for human use and benefit (Laaroussi et al., 2020). Understanding the way in which humans or occupants of a building use the technical systems or components of the building by interacting with them is important to analyse the energy performance of a building. The interaction between humans and buildings have been studied extensively in the recent years. In order to conduct a thorough examination of the topic, it is important to identify multiple elements and drivers that influence the energy-consuming occupant behaviour.

The identification of the aforementioned factors serves as a tool for designing buildings, as it enables a more comprehensive understanding of behavioral patterns and enhances the building energy efficiency through an appropriate design.

In order to understand the human-building interaction, it is important to understand the reason for humans to interact with buildings and their various components. The primary reason for humans to interact with various components of a building is to maintain comfort. Most important comfort required by occupants of a building to carry out their activities is the thermal comfort within the building environment. There are several other comfort attributes such as visual comfort, air quality, health and well-being, etc. The primary driver of energy usage in buildings is the preservation of optimal comfort conditions for occupants. Hence, occupants interact with various building systems to maintain their required optimal comfort within the building environment. These drivers creates a stimulus amongst occupants to interact with the building to maintain the required comfort levels for these various attributes (Fabi et al., 2012). For example, if a person feels hot inside a room he interacts with the air conditioning system to maintain a cooler atmosphere within that room. In this case, the 'thermal comfort' is the driver, 'indoor temperature' is the stimulus and 'adjusting the air conditioning' is the interaction scenario that has an effect on the energy performance of the building.

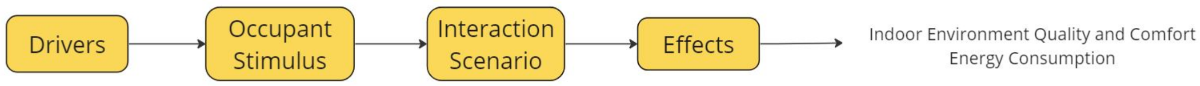

Figure 5.2: Human-Building Interactions and Effects (Adapted from (Fabi et al., 2012))

According to Park and Nagy (2018) and R. Yang and Wang (2013), given that people often spend a significant portion of their lifespan within buildings, it is crucial to ensure that these comfort requirements of occupants are met, while also facilitating energy conservation. Given that occupants' activities have a direct influence on the performance of the building, it is imperative for the building to possess the capability to engage with inhabitants by actively reacting to their requests and soliciting feedback based on their behaviors R. Yang and Wang (2013). The optimum balance between these interactions and occupant comfort will help in achieving energy efficiency within buildings. Laaroussi et al. (2020) identified various factors that drive the energy consumed through human building interactions as mentioned in table 5.1 below. Fabi et al. (2012) also categorised these drivers of human building interaction into 5 different categories unlike Laaroussi et al. (2020) but consist of the same drivers.

Environmental	**Time-Related**	**Others**
Building Characteristics	Season	Physiological
Location	Time of Day	Psychological
Building Orientation	Routine of Occupant	Social
Indoor Climate		Cultural
Building Layout		Economic
Outdoor Climate		Habits
		Lack of Knowledge

Table 5.1: Drivers of Human Interactions with Building (Laaroussi et al., 2020)

The interaction between humans and buildings, which involves the utilization of both passive and active control systems, adheres to the fundamental principles of human-machine interaction that are widely recognized in the field of engineering (T. Harputlugil & de Wilde, 2021). The individuals residing within a given space exhibit adaptive behaviors and engage in interactions with the building. According to T. Harputlugil and de Wilde (2021), one of the primary factors contributing to the energy performance gap and exerting the most significant influence on energy consumption is human building interaction aspect of occupant behaviour. Hence, it emerges as a prominent subject matter within the realm of energy conservation and energy efficiency in buildings. Information regarding human interaction with the building will help improve the energy efficiency of buildings. The interactions mainly occur with building components classified as - building services, building facade or envelope and user systems as shown in figure 5.3.

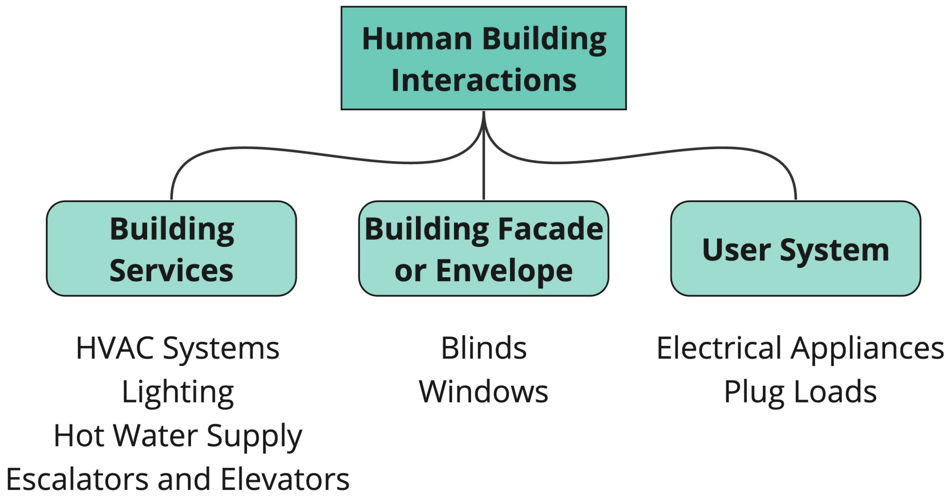

Figure 5.3: Human Building Interactions with Different Building Components

5.3.1 Building Services

Building services comprises of various components of the building such as Heating, Ventilation and Air Conditioning (HVAC), lighting, hot water supplies, escalators and elevators. These are basic facilities provided by the building owner to the tenants or occupants of the building while renting an office space. Human building interaction with these building services have been studied in the recent years to understand and analyse certain patterns in occupant behaviour and their impact on the energy performance of the building. These interactions mainly happen to maintain the comfort levels required by the occupants to carry out their activities and functions within the building. Comfort levels range from thermal comfort to visual comfort within the context of a building environment. Humans are constantly concerned about thermal comfort levels within a particular environment which drives them to interact with building systems that have a significant impact on the energy performance of the building.

According to estimates provided by IEA (2023a), energy required by space cooling in buildings is one of the leading drivers of electricity demand. Similarly, space heating consumes half the building's total energy. The average energy consumption per square meter was recorded at 185 kWh/m^2, with space heating accounting for a significant portion ranging from 60% to 80% of the total energy consumption (Martinopoulos, Papakostas & Papadopoulos, 2018). Ürge-Vorsatz, Cabeza, Serrano, Barreneche and Petrichenko (2015) found that 40% of total energy is used for space heating or cooling in commercial buildings. Lighting is also considered to be one of the major drivers for energy in buildings. Yun and Steemers (2008) and Roetzel, Tsangrassoulis, Dietrich and Busching (2010) have studied the impact of human interactions with windows and ventilation respectively. Approximately 50% of the total primary energy were by the occupants of the building through their interactions with these building systems (Niemann & Schmitz, 2020). Z. Yang et al. (2016) developed a framework to analyse the implications of occupant interactions and actions on HVAC systems and found that these interactions have a major impact on the energy performance.

In a recent study by Peng, Rysanek, Nagy and Schlüter (2017), the implementation of an occupant-centric demand-driven control system resulted in a significant energy saving of 20.3% when compared to a standard baseline control approach. Gilani et al. (2018) highlights that occupant interaction information has an important role in delivering good approximations regarding the energy consumed for lighting within buildings. The precise modeling of occupant behavior appears to be a feasible approach in the optimization process of a particular real-world building. In practice, energy modeling methods frequently rely on oversimplified and optimistic data inputs that do not accurately reflect real-world building systems and occupancy patterns. This can be changed with the help of a better understanding about the way people interact with building services and trying to incorporate them into the design.

5.3.2 Building Facade or Envelope

Building facades serves a crucial function in enhancing both the energy efficiency of a building and the overall degree of human comfort. Facades constitute an integral component of the architectural building envelope. The term "facade" is derived from the French language, specifically denoting the "frontage" or "face" of a building. It encompasses the outermost layer or surface of a building, incorporating distinctive architectural elements. Typically, the term "front" denotes the front facade of a building; however, it may encompass the lateral and posterior aspects as well (Moghtadernejad, Mirza & Chouinard, 2019). The facade design is also a key contributor towards energy consumption of the building as occupants interact with facade to maintain indoor air quality, thermal and visual comfort. The facade includes components such as windows and ventilation which dictates indoor air quality, thermal comfort and visual comfort within the building environment.

Several researchers have analyzed the impact of occupant interaction with the facade or the envelope of the building. Regarding the operations involving lighting, blinds, and shade, it is important to note that the primary factor influencing these interactions is the visual input (Laaroussi et al., 2020). The window opening behaviour of occupants is found to have a huge impact on the overall energy consumption of the building (Zhang, Bai, Mills & Pezzey, 2018). In a study conducted on office building by D'Oca et al. (2018), several insights were found regarding various window opening and blind control behaviour of the occupants. These interactions are mainly to improve air circulation, privacy requirements and adjust daylight entering the building (Roetzel et al., 2010). D'Oca et al. (2018) study also found important links with behavioural aspects such as satisfaction, productivity, knowledge about controls, attitude and intention to share control of blinds.

Ventilation is also an important factor that determines the interactions with the facade or envelope of the building which in turn affects the energy performance. The air change rate is a significant characteristic that exerts a substantial impact on both energy usage and indoor environmental quality (Fabi et al., 2012). Air change rates exhibit substantial variability across different buildings, and the manner in which inhabitants open windows exerts a notable influence on these rates. Given the significant influence of air change rate on energy consumption, it is apparent that variations in energy consumption will arise from distinct behavioral patterns. The frequency, duration, and extent of window opening are factors that influence the rate at which air changes occur. Similarly, L. Wang and Greenberg (2015) highlighted the notable impact of window opening patterns on the indoor comfort of occupants, emphasizing the importance of considering this factor in the design of facades.

5.3.3 User Systems

In the context of a conventional building, there are three primary components that jointly account for 85% of the overall energy consumption: HVAC system, lighting load, and electrical equipment, sometimes referred to as Plug Loads (Anand, Cheong, Sekhar, Santamouris & Kondepudi, 2019). These plug loads are also referred to as user systems which the occupants bring into the building during occupancy. It ranges from computers to coffee machines used in office spaces. The energy consumption of these devices are not regulated by any building codes, labels or certificates. The interaction of occupants with these devices in a building also have a huge impact on the overall energy performance of the building. Gandhi and Brager (2016) highlights that on average, the combined energy consumption of plug and lighting loads in buildings ranges from 12% to 50%. This consumption rate has been shown to increase by 0.8% year. Understanding the correlation between occupants and these systems, including the monitoring of plug loads and implementing actions based on occupant behavior, can result in more accurate estimations of energy conservation (Y. Wang & Shao, 2017).

According to a study by Kim (2014), a significant proportion of energy consumption, ranging from 26% to 65%, was observed during non-operational hours of buildings, in contrast to the designated work hours between 07:30 a.m. and 04:30 p.m. The consumption of energy during non-operational hours has the potential to be a substantial contributor to energy wastage. The inefficient operation of plug loads has the potential to result in significant energy wastage during periods of non-occupancy. In a study conducted by Masoso and Grobler (2010), 56% energy is used during non-working hours within office spaces largely due to occupants behaviour of leaving the electrical equipment on at the end of the day after work. Gandhi and Brager (2016) studied the energy patterns for 137 individual plug loads and found that desktops consume the most power per person within office spaces and users only switch them off before long breaks like weekends or holidays and usually leave them on during the weekdays. Anand et al. (2019) found that during unoccupied hours the plug loads have a potential to save energy by 12% and 3.1% during occupied hours in office spaces.

5.4 Behavioural Efficiency

The reliance on technological interventions alone is insufficient for attaining building energy conservation or energy efficiency objectives. It is imperative to incorporate human beings and their energy-related conduct within energy performance initiatives. It is of utmost importance that occupants possess a greater understanding of the energy use within buildings, particularly in terms of their influence on energy consumption and building performance. This knowledge enhancement is essential in order to elevate individuals' engagement and enthusiasm towards this subject matter (Laaroussi et al., 2020). Paone and Bacher (2018) states that the re-evaluation of the significance of integrating communication methods and tools for facilitating conversation among managers, building owners, and occupants is a thought-provoking endeavor. These aspects are crucial for the sustainable management of various building characteristics and the regulation of elements that impact energy efficiency.

T. Harputlugil and de Wilde (2021) defines behavioural change or efficiency as the process by which modifications are made to occupant conduct to save energy or reduce wastage due to occupant behaviour. This is primarily regarded as a feasible objective that may be accomplished with minimal or no financial investment, without requiring advanced technical expertise, and with the ability to reduce energy usage. Behavioural efficiency depends on the ability of asset managers to influence the behaviour of occupants to reduce the energy consumption within buildings through different strategies. This will also depend on several social science aspects related to occupant behaviour within office buildings. It is important to have an understanding about the way in which organizations function or behave sustainably within and office space and their organizational ambitions towards sustainability to be able to influence their energy consumption behaviour and improve behavioural efficiency.

Several researches highlight the effect of such aspects on the energy consumption of the building. According to EEA (2013), the implementation of various strategies aimed at modifying consumer behavior has the potential to result in a reduction of up to 20% in energy use. In a study conducted by Zhang et al. (2018), they estimated energy saving potential by behavioural efficiency as much as 5-30% for commercial buildings. Delmas, Fischlein and Asensio (2013) highlights the effect of behavioural efficiency that leads to almost 7.5% reduced energy consumption. Masoso and Grobler (2010) emphasizes that rather than technological interventions to reduce the overall energy consumption within buildings, behavioural efficiency amongst occupants will help save a significant amount of energy that is wasted usually due to irresponsible behaviour from the occupants.

According to a study by Karjalainen (2016), in contrast to houses, occupants of office facilities are generally not held accountable for the energy expenses. Occupants in office settings exhibit lower desire to conserve energy due to the absence of direct financial responsibility for energy costs and the perception that their respective energy consumption is inconsequential. Additionally, it is worth noting that energy expenses in office settings are very minimal in comparison to the expenditures associated with labor costs related to office work. From an economic standpoint for organizations, it is crucial to prioritize the establishment of productive work conditions over the emphasis on energy cost savings leading to unsustainable practices. There exist additional factors beyond economic considerations that may yield more efficacy in promoting energy conservation within workplace environments such as behavioural efficiency amongst the occupants. Behavioural efficiency can be achieved through several different strategies - traditional approach, feedback approach and smart technologies as discussed below.

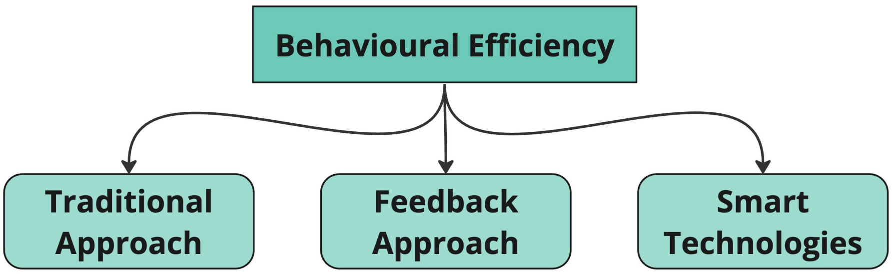

Figure 5.4: Classification of Behavioural Efficiency

5.4.1 Traditional Approach

Traditionally, energy efficient measures for buildings focuses on bringing alterations to the occupants behaviour to reduce their energy consumption through strategies and measures such as education and awareness among occupants. Traditional methods mainly consists of education and training provided to create awareness amongst occupants regarding their energy consumption behavior. This will help in stimulating a responsible behaviour amongst occupants to consume lesser energy in a very efficient way within office spaces. The existing body of evidence pertaining to behavioural interventions aimed at mitigating energy consumption reveals that treatments that employ a combination of antecedent strategies, such as the provision of information and training, tend to provide the most favorable outcomes (Gandhi & Brager, 2016). The author also identifies several strategies mentioned in literature such as energy budgets in lease agreements, educating and training the staff, occupant reminders on energy performance and encouraging change in habits that promote lower energy consumption within office buildings.

According to Masoso and Grobler (2010), energy wastage primarily stems from the behavioral tendencies of occupants to leave lights and equipment on at the end of the day. There exists a significant demand for building occupants to acquire the knowledge and practice of deactivating unused electrical devices. The principle known as the golden rule can be summarized as follows: "If an individual does not have a need for a particular item or resource, it is advisable for them to refrain from utilizing it" (Masoso & Grobler, 2010). The primary focus of energy conservation through behavioral changes lies in the act of turning off idle equipment, rather than limiting the utilization of equipment during operational hours. In a similar way, adjusting power management configurations on desktop computers can significantly contribute to power conservation efforts (Gandhi & Brager, 2016). These measures can be achieved by creating awareness among occupants through education and training. Carrico and Riemer (2011) found that through peer education energy consumption could be reduced by 4% in office buildings. Ali and Tyagi (2022) also highlights the effectiveness of behavioural training in reducing energy consumption within commercial buildings in India.

Another traditional strategy used by asset managers and facility managers revolves around motivation among occupants to reduce energy wastage and consumption. Leygue, Ferguson and Spence (2017)'s categorization of motivational factors for conserving energy in the workplace encompasses two distinct types: self-directed motivation, which is driven by considerations of self-image and the emotional satisfaction derived from energy-saving behaviors, and altruistic motivation, which is geared towards broader concerns such as environmental sustainability and the well-being of the organization, encompassing aspects such as the company's reputation and financial stability. Spence, Leygue, Bedwell and O'malley (2014) underscores the significance of explaining the correlation between climate change and energy savings, suggesting that such an association holds potential advantages for fostering pro-environmental behavior. Other traditional methods include providing instruction cards and signage around the office space that highlights several measures to improve the energy consumption behaviour within offices. Dennis, Soderstrom, Koncinski and Cavanaugh (1990) found that the implementation of signage near light switches has the potential to result in a 60% decrease in the utilization of needless illumination.

5.4.2 Feedback Approach

Research has demonstrated that the provision of feedback, such as information regarding the energy consumption of occupants, has proven to be more effective in promoting energy-saving compared to technical improvements or interventions (Coleman, Irvine, Lemon & Shao, 2013; Murtagh et al., 2013). The task of furnishing input regarding occupants in commercial environments remains highly complex, mostly due to the financial implications and logistical obstacles associated with acquiring energy consumption data from occupants (Rafsanjani, Ahn & Alahmad, 2015). According to a study conducted by Khosrowpour et al. (2018), the objectives of the energy feedback approach encompass three main aspects: (1) enhancing occupants' awareness regarding energy consumption, (2) fostering occupants' engagement in energy efficiency strategies, and (3) establishing a communication tool with residents to facilitate their acquisition of knowledge and skills related to energy control and conservation.

Delmas et al. (2013) emphasize through their study that individualized audits and consulting are found to be the most effective energy conservation measures through a feedback approach. The utilization of publicly available information for feedback, along with private input, served as a driving force behind a 20% reduction in electricity consumption. According to a study conducted in a professional setting by Carrico and Riemer (2011), it was found that the implementation of group-level feedback and peer education strategies aided in implementation of suitable behavioural interventions that resulted in a decrease of 8% and 4% in energy consumption, respectively. Through this research it was also highlighted that feedback could be provided to the occupants through simple communication methods such as emails that include a summary of their energy performance for a certain duration of time. In a study by Handgraaf, De Jeude and Appelt (2013), feedback on energy consumption in office spaces helped reduce energy consumption drastically, also with the help of social rewards rather than monetary rewards.

Post Occupancy Evaluation (POE) is also a feedback approach often used to improve the energy performance of buildings through occupant behavioural changes. The field of post-occupancy evaluation (POE) serves a valuable role in illuminating instances where outcomes do not meet anticipated standards (Durosaiye, Hadjri & Liyanage, 2019; Way & Bordass, 2005). The online-feedback approach is deemed to be more rational and efficient in comparison to traditional energy-saving education due to its ability to facilitate building users in (1) evaluating their daily energy usage profile, (2) making comparisons of energy consumption, and (3) recognizing inappropriate behaviors and receiving personalized energy efficiency recommendations (S. Chen et al., 2021). Resources such as sufficient workforce, skill, in-house knowledge and available in-house technology all play a crucial role in the implementation of such strategies.

5.4.3 Smart Technologies

Availability of numerous opportunities with smart technologies has improved the energy management strategies within buildings and helped in achieving better energy efficiency of buildings. Currently, there exists several technology capable of effectively monitoring, collecting, and storing vast quantities of data pertaining to occupant's energy consumption behaviour. Moreover, these technologies possess the ability to analyze and utilize such data in significant manners. Smart technologies such as advanced sensors, artificial intelligence, machine learning, data science, etc. are used to understand and analyse the occupant's behaviour related to energy consumption in a building. These technologies have proven to aid energy efficiency as well as reduce energy consumption or wastage due to occupant behaviour. Smart technologies are also vital to process large number of information within shorter duration which makes the process easier for asset managers rather than doing them manually. Currently, the built environment and real estate industry are far behind on implementation of such technology (Foucquier, Robert, Suard, Stéphan & Jay, 2013; Mehmood et al., 2019).

Several research has been carried out to study the effective implementation of such smart technologies to improve the energy efficiency of buildings. Unsurprisingly, there is a significant amount of attention and interest surrounding the application of data science approaches in the pursuit of enhancing energy efficiency which was reviewed by Molina-Solana, Ros, Ruiz, Gómez-Romero and Martín-Bautista (2017). Data regarding energy consumption in buildings is important to analyse the energy performance during the operational phase for which data science approaches will be beneficial. Wood and Newborough (2003) conducted an experiment including the utilization of smart meters and displays to explore the potential of providing feedback on energy consumption. The results indicated that, out of a total of 31 families, 14 were able to achieve energy savings exceeding 10%, among which 6 were able to save more than 20% energy. The average decrease in electricity consumption for households was found to be 15%. The same could be beneficial for office buildings as well.

In a study conducted by Gandhi and Brager (2016) and Orland et al. (2014), gamification strategies were used to understand, analyse and create awareness about the energy consumption behaviour of occupants through a game that feeds real world data regarding energy consumption. Research has also provided insights into the use of smartphone applications to help in reducing the energy consumption from the occupants end. Inyim et al. (2018) presents a sophisticated smartphone application that has been designed using the theoretical foundations of situational awareness theory. The primary objective of this application is to successfully implement a multi-method and individualized intervention strategy aimed at promoting energy conservation behaviours among those occupying buildings. The newly developed intelligent application has a range of novel functionalities, including energy conservation measures, personalized feedback mechanisms, and a visually enhanced user interface. These elements have been strategically integrated into the program to facilitate the implementation of multi-method interventions. The Edge, situated in Amsterdam, is an example of such an approach to stimulate behavioural efficiency through smart technologies (Randall, 2015).

The enCOMPASS project, spearheaded by Fraternali et al. (2017), endeavors to build and validate an integrated socio-technical approach to facilitate behavioral change with the goal of energy conservation. The objectives of this initiative are twofold - firstly, it aims to enhance the accessibility and comprehensibility of energy consumption data for various user groups and stakeholders, such as household residents, office employees, school pupils, building managers, utilities, and ICT providers. Secondly, it seeks to empower these entities to engage in collaborative efforts to achieve energy conservation, while effectively managing their energy requirements in a manner that is both cost-effective and conducive to maintaining comfort levels. The capacity of buildings to respond to unforeseen occupant behaviour can be improved at the systemic level by implementing AI-driven learning mechanisms and leveraging digital twins as platforms for training energy management systems. The integration of adaptive solutions holds significant promise for maximizing energy efficiency improvements within buildings today (Alanne & Sierla, 2022).

In conclusion, within scientific literature, occupant behaviour has been classified into three main categories - occupancy, interactions and behavioural efficiency. Occupancy describes various attributes such as presence of occupants within the building, spatial location of occupants within buildings and activities carried out by the occupants. Interactions describes the way in which occupants of a building interact with three different components of a building - building services, facade/envelope and user systems. Occupants mainly interact with these components to maintain the required comfort levels for their activities. Behavioural efficiency describes the different ways in which the behaviour of occupants can be altered or influenced to improve their energy consumption behaviour within buildings. Three different strategies have been described through literature to improve behavioural efficiency - traditional, feedback and smart technologies.

In the Netherlands, energy labels mandated by the government according to the EPBD is the main policy that regulates energy consumption in buildings. As mentioned earlier, these energy labels and certificates only take into account certain aspects of energy consumption within a building such as the energy consumed for heating, cooling, lighting and hot water supply. This chapter highlighted the factors or aspects that have a huge impact on the energy consumption or performance of buildings that are often neglected by the legislation (energy labels) and lead to the phenomenon of energy performance gap in buildings. Occupant behavioural aspects described here cover a major portion of the grey area within energy consumption figures of buildings as highlighted amongst the findings from literature regarding underlying causes of energy performance gaps.

Based on the information gathered from scientific literature as described above, a deeper understanding about the concept of occupant behaviour within buildings and their impact on the energy performance of buildings is gained that will help bridge the energy performance gap. These aspects cover a major portion of the grey area in energy consumption figures mentioned earlier as they are often overlooked by legislation. Literature has clearly pointed out the significant difference these aspects can make in terms of overall energy consumption of a building. These aspects are unregulated currently and will remain the same if not addressed now to improve the energy efficiency of buildings and also reduce energy consumption. This understanding about occupant behaviour and their impact on the energy performance of buildings will be used to further narrow the problem statement through the double diamond method. A case study will be used to identify and understand the flaws in the current practices in the next chapter using this understanding to formulate a detailed problem statement.

Chapter 6

Case Study: Stichthage

The inclusion of a case study in research enables comprehensive and multifaceted investigations of complex matters within their actual contexts. Qualitative case study research is an important methodology for addressing intricate inquiries in practical contexts. According to Yin (2009), a case study is characterized as an empirical investigation that explores a phenomenon inside its authentic real-life setting. Case studies will help cement the problem and often shed light into the practical implications of the solution developed through a qualitative study. Case studies also provides insights into several obstacles that could occur during the application of the solution in a real-life context. They are also a crucial part of research to gain validation for the developed solution and also provides information on the practice of application. Case studies help in bridging the gap between theory and practice.

For this research, Stichthage was used as a case study to provide several insights into the current practices followed within NS Stations, as a real estate developer. The renovation project of this building was used to understand the problem within current design strategies as well as the current asset management strategies to develop a detailed problem statement and a suitable solution. The building is situated in Den Haag, Netherlands, right next to one of the busiest railway stations. The building is planned for a major renovation due to several components of the building reaching its end-of-life-cycle. The owners of the building, NS Stations, have high ambitions regarding sustainability to be achieved through the renovation, specifically energy efficiency. Moreover, NS Stations, as an organization, have high overall sustainability ambitions to reduce energy consumption and emissions resulting from them within their entire real estate portfolio.

Firstly, this chapter provides an overview of the case study building and the energy performance of the building in its current state of operation to highlight the energy performance gaps. Secondly, exploratory interviews with members of the project team for Stichthage will provide insights into the current practices followed for asset management as well as design process for the renovation project. Thirdly, the limitations or flaws within the current practices will be highlighted and linked to the findings from literature that lead to the energy performance gaps. Finally, this chapter marks the end of the first diamond or the problem space and thus a detailed problem statement will be derived.

6.1 Overview of Stichthage

NS Stations is a Dutch company that owns and manages approximately 400 stations in the Netherlands and is a business unit of Nederlandse Spoorwegen (NS) which is the principal passenger railway operator in the Netherlands. NS Stations also owns and manages real estate properties around the railway stations, creating a valuable portfolio for themselves. Being a subsidiary of NS (parent organization), NS Stations have inherited several sustainability ambitions and goals from them. NS was the first train operator in the world to run entirely on sustainably sourced fuels. NS Stations has high ambitions to extend this targets to their real estate portfolio as well by 2040. Their main ambitions regarding energy and emissions from them is to reduce energy consumption, procure green energy and produce green energy (NS, 2023b). NS's main ambition is to be completely fossil free in all operation by 2040 by using as little energy as possible, buying completely green energy and use their own buildings and lands to generate as much green energy as possible to meet their needs (NS, 2023a).

Stichthage is a non-residential building that is situated in The Hague, Netherlands. The 14-storey building is situated right next to the Hague Central railway station with the ground and first floors integrated to the station. The building was constructed in 1972 and has been owned by NS Vastgoed and managed by NS Stations ever since. The building is situated in a location, right at the center of the third biggest city in the Netherlands and next to a railway station, that gives the owners ample opportunities to create a good business case through a major renovation. The building has a total floor space of approximately 24000m^2 and is one of the biggest buildings in terms of floor space within their real estate portfolio. The building was used an office space with multiple tenants and has not undergone any major renovations since its construction in the 1970s. The building was also given an energy label A in 2020.

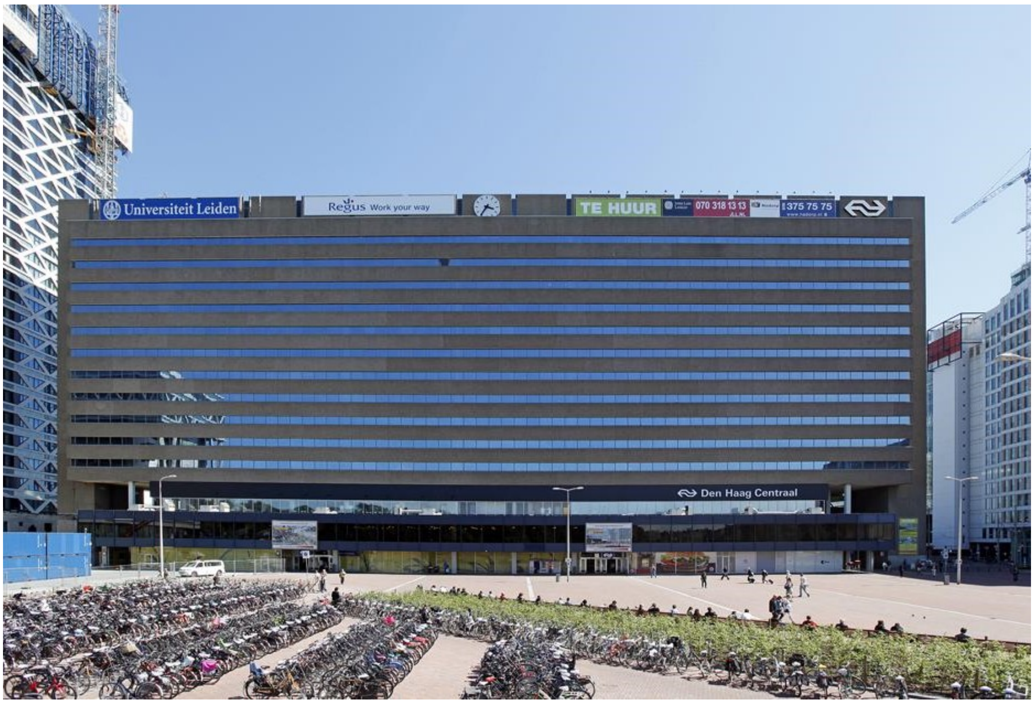

Figure 6.1: Stichthage Building (Front View)

The building is sanctioned for a major renovation due to several reasons as the building has been in operation for the past 50 years approximately. The facade of the building is the main component of the building that needs major renovation mainly due to its end-of-life-cycle, poor insulation and limited daylight entry into the building. The facade of the building was built in the 1970s which gives the building an outdated appearance or aesthetics. The outdated facade also provides a poor insulation to the building which creates huge demands for energy to cool or heat the interior spaces. Stichthage also has outdated installations that needs to be replaced due to high energy consumption leading to poor overall building energy performance.

Figure 6.2: Stichthage Building (Diagonal View)

Being one of the biggest building within their real estate portfolio in terms of floor space, NS Stations has high ambitions to renovate the building to achieve their organizational sustainability goals and ambitions. The building requires high investments for renovation and hence needs to comply with all future rules and regulations without room for another major renovation for the next 30-40 years. The renovation will also help tackle several challenges pertaining to energy performance of the building such as outdated facade, poor insulation, outdated installations and limited daylight entry into the building environment. Stichthage is also located in an important location that is part of a area development plan of the government called Central Innovation District and includes sustainability as a high priority. As part of this plan, the municipality wants to make the area sustainable, economical, innovative, liveable and inclusive (Gemeente, 2023). Moreover, this region has been designated as the Green Energy District with ambition of using completely clean energy within the next 10 years (Gemeente, 2019).

NS Station's main ambition is to be completely fossil free by 2040, including their real estate portfolio. In order to meet this goal, they have ambitions to (1) reduce their energy consumption, (2) generate green energy using their own real estate and (3) procure green energy from the market which is represented by the Trias Energetica (Energy Triangle Policy for NS Stations). According to their energy-saving measures, they have targets to deliver 2% energy efficiency per year. Another main ambition related to energy usage in buildings is to achieve the paris-proof target which mentions that office spaces should not exceed 70kWh/m^2 overall energy consumption. Moreover, NS Stations wants to fulfill the legislative requirements for energy efficiency across their real estate portfolio. In terms of energy consumption, NS Stations have set a target to reduce final energy consumption by 14% in 2026. This also translates to reducing electricity consumption by 2% every year and reducing final energy consumption by 5% every year with 2019 as the base year.

6.2 Building Energy Performance

Stichthage has been functional for the past 45-50 years and has been predominantly used as an office space with multiple tenants. The building is sanctioned for a major renovation mainly because of the poor energy performance of the building. The facade of the building and its installations have reached their end-of-life-cycle with a depreciating energy efficiency of technical components. The design of the facade does not allow sufficient daylight to enter the building environment which also contributes to the poor building energy performance. Currently, the building does not have any on-site energy generation from renewable resources. However, recently the building has been designated to city heating which reduces the use fossil fuels for heating the building. In this context, 2019 was selected as the base year to analyse the energy performance gap as it was from the pre-COVID era and had normal lifestyles and work cultures.

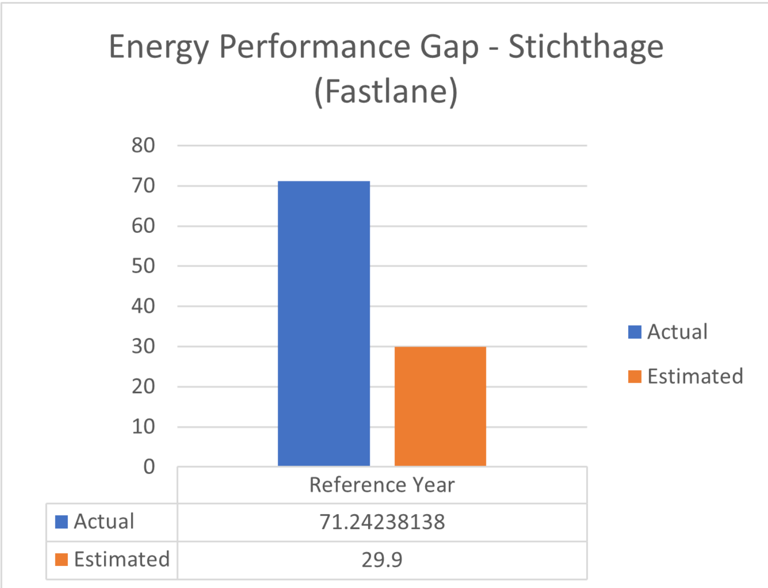

Figure 6.3: Energy Performance for Stichthage (Fastlane)

Year	Total (kWh)	Actual Consumption (kWh/m^2)	Estimated Consumption (kWh/m^2)	Floor Area (m^2)	Gap (%)
2019	1400326	71.24	29.90	19655.8	138.27

Table 6.1: Energy Performance for Stichthage (Fastlane)

$$\text{Energy Performance Gap} = \left(\frac{\text{Actual - Estimated}}{\text{Estimated}}\right) \times 100$$

As depicted in the picture above, Stichthage displayed a significant energy performance gap during the year 2019. The energy performance gap was estimated to be 138%. The energy performance gap was calculated according to the formula as shown above. According to the energy label A provided in 2020, the predicted or estimated energy consumption of the building is 29.9 kWh/m^2. However. the actual energy consumption of the building was found to be 71.2 kWh/m^2. This is mainly because the energy label in the Netherlands only look into aspects such as energy required for heating, cooling, lighting and hot water supply while predicting or estimating energy consumption of the building. The actual energy consumption of the building consists of many other factors such as occupant behaviour resulting in a much higher energy consumption as evident from the graph above.

6.3 Current Practices and Project Strategy

Stichthage is owned and managed by NS Stations. The asset management department within the organization is responsible for the operations phase of the building and currently interacts and manages with different tenants of the building. As the building is sanctioned for renovation, a project team is formed within NS Stations with representatives from 4 different departments - real estate developer, technical developer or project manager, asset manager and representative from the sustainability team. These major stakeholders within the organization are involved in the renovation project for the building and are collectively responsible for most major decisions during the project. Exploratory interviews were conducted with members of the project team as well as other employees in similar positions with similar responsibilities and working on similar projects to understand the project process in terms of design and asset management. These interviews provided vital insights regarding the current practices followed within the design process and asset management.

An important finding from the exploratory interviews is that very few interview participants were not aware of the term energy performance gaps, whereas most of them were actually aware of the issue. However, majority of the interview participants stated that they did not know the extend or size of the energy performance gap in buildings within their own portfolio. Moreover, some of the interview participants also mentioned that the energy consumption data available within their database was not enough to identify the root cause for the energy performance gaps. Additionally, one of the interview participants mentioned that "the energy performance gap was caused by the legislation and majority of the gap was contributed by the energy consumption of the occupants or tenants of a building which makes it a problem for them rather than the owner". Another interview participant also mentioned that "doing anything beyond the legislative requirements require higher initial investments and does not guarantee return on investments. The tenant is the one that reaps benefits of having highly energy efficient buildings in the form of reduced energy bills".

In the Netherlands, energy label C or above were mandated for all buildings used as or serving the purpose of office spaces since January 2023. This could be further tightened to mandatory energy labels A or above by the year 2030. This has triggered a large number of renovation projects within NS Stations, an organization that owns and manages several non-residential buildings across the country. Most of these renovation projects aim to achieve the highest possible energy labels within the allotted budget limits for the project. Most of the developers and designers use energy labels as a support tool to make design decisions regarding several aspects of the building, especially energy efficiency. Most of the interviewees stated that only meeting the legal requirements regarding energy efficiency provides them with a good business case. The primary motive or objective of real estate developers are to make profits from each real estate project. In most cases, building highly sustainable or energy efficient buildings do not provide much financial benefits for developers.

As Stichthage is sanctioned for a major renovation to improve its energy efficiency, the project team aims to achieve high energy labels and certificates through this renovation. It was found through these interviews that energy performance gap was not taken up as an issue to be addressed through this renovation due to lack of knowledge, awareness and data to address the issue currently within the organization. Moreover, project members also emphasized that high initial investments will be required to address the issue of energy performance gap and the occupants will be the only ones to gain benefits and does not provide NS Stations with any financial benefits. The project team members also mentioned that they did not have much knowledge about the impact of occupant behaviour on the energy performance of the building and how to incorporate them into the design of buildings. They emphasized that energy labels and other highly recognized green building certifications such as BREEAM and WELL were mainly used to aid their design process for energy efficiency. Several researchers have mentioned that energy labels and certificates are only intended to be used as a standard for compliance and not as a tool for building design (Carpino et al., 2020; Gram-Hanssen & Georg, 2018; Zou et al., 2018).

Energy simulations were found to be another important aspect regarding energy performance gaps in buildings. According to the definition selected for this research, energy simulation provide predictions or estimations regarding energy consumption or performance of the building in operations phase. According to the participants, these energy simulations are currently carried out in accordance with energy labels and are only carried out during the final phases of research as the final design is ready. These simulations are mainly done to meet legislative requirements and only take into account factors mentioned within these energy labels. Energy simulations do not take into account factors such as occupants due to their complexity and lack of knowledge. One of the interviewees mentioned that "energy simulations are carried out in the final stages of design as these simulations often require several information from design of the building, which is usually available once a major portion of the design process is completed".

Another important issue highlighted by the interview participants is regarding the Paris-proof targets. The participants were aware that the Paris-proof targets are important to achieve the Paris Climate agreement and hence have been included amongst the general targets and ambitions of each project. However, they were unsure about achieving these targets through operations as well as design since these targets include the energy consumed by the occupants or tenants of the building. The asset managers highlighted the difficulty in ensuring the overall energy consumption within office spaces to be below 70kWh/m^2 target. The team members also emphasized that these targets could be mandated in the near future by the governments as part of their commitments towards the Paris Climate agreement which makes these targets even more important to be addressed in recent projects. In section 4.5, it was highlighted that occupant behavioural aspects play a major role in bridging the energy performance gap as well as meeting targets such as Paris-proof targets that take into account the energy consumed by the occupants of the building.

Additionally, interviews were also conducted with asset managers of several buildings to understand the role of building operations in bridging the energy performance gap. Most of the asset managers were aware of the issue of energy performance gaps. Literature has clearly pointed out that asset managers play an important role in dealing with the issue of energy performance gap by analysing the tenants' energy performance and devising suitable measures to keep their energy consumption within a certain limit through different strategies such as traditional, feedback or smart technologies. However, the interview participants clearly mentioned that these strategies were currently not used. One of the interview participants also pointed out the reason for the lack of such strategies as the lack of sufficient energy performance data for each tenants. One of the interview participant stated that "we do not have smart meters in most of our buildings to gain a detailed understanding about the energy performance of each tenant to be able to give them feedback about their energy consumption. We also do not have any other smart technologies implemented in our buildings to track the energy performance in detail". This is also evident from the energy consumption data available for the building within their database as described in section 6.2.

Moreover, the asset managers also mentioned that "the tenants of an office space are employees of an organization and they do not have direct financial implications for the energy they consume and hence they do not exhibit very responsible behaviour with regards to energy consumption". Also one of the interview participants mentioned that "there are certain limits to how much we can control the behaviour of occupants of an office building to improve their energy consumption behaviour". These statements highlight the importance of an effective asset management strategy as well to bridge the energy performance gap. Asset managers play an important role in bridging the gap during the operations phase of a building. They can influence or regulate the occupant energy consumption behaviour to a certain extend to ensure that actual energy consumption of the building during operations are as close as possible to predicted or estimated energy consumption during the design phase of the building.

6.4 Limitations and Issues

Buildings are eventually designed for the users or occupants and hence needs to take into consideration the requirements of the end-user. The energy performance gap in buildings is an issue that stems from the ignorance of end-user requirements and hence requires addressing of occupant requirements to solve the issue. As identified through exploratory interviews with industry professionals, one of the root cause that leads to the energy performance gaps is the design strategy that is currently used within the industry to create energy efficient buildings. However, through interviews it was also found that the blame for the energy performance gaps in buildings were put on the occupants of a non-residential buildings for their irresponsible energy consumption behaviour. In reality, most of the buildings are not designed according to the requirements of the occupants which leads to energy wastage and excessive energy consumption by the occupants.

Developers clearly pointed out through interviews the usage of energy labels and other green building certificates as a support tool to design their buildings for energy efficiency. These energy labels and certificates do not take into account all factors that have an impact on the energy performance of a building. In the Netherlands, the energy labels mainly look into energy consumed for heating, cooling, lighting and hot water supply which only covers a part of the overall energy consumption within a building. Factors or aspects such as occupant behaviour are often neglected by these energy labels and certificates and thus from the design of buildings. This leads to a significant difference in the intended energy performance of the building during design and actual energy performance of the building during operations. Moreover, there is an evident hesitation from developers to go beyond the requirements of legislation in terms of energy efficiency of a building due to financial risks.

On the other hand, lack of information and data regarding the composition of the energy performance gap in buildings pose a major challenge towards bridging the gap. It is important to identify the root cause that leads to the gaps in buildings in a real-life scenario. However, literature has clearly emphasized that occupant behaviour and occupant-related energy consumption is the main underlying cause that leads to the gaps. This information will also benefit designers and developers to integrate occupant behavioural aspects into the design of buildings. Developers and designers at NS Stations are unable to integrate occupant behavioural aspects into the design due to lack of information or data regarding the same from their own buildings. The design will require inputs from industry experts regarding occupant behaviour. The lack of detailed information and data also poses a challenge for asset managers to ensure the desired energy performance levels during the design phase are achieved during the operations phase of the building as well.

Several major issues and limitations were also identified in the current asset management practices as well that leads to energy performance gap in buildings. Currently, the asset managers did not implement any traditional strategies or feedback strategies to influence or control the occupant energy consumption within buildings that eventually lead to excessive energy consumption as well as energy performance gap in the building. This was mainly because of the lack of data or information required to implement strategies such as feedback. The lack of detailed information and data regarding energy consumption within buildings with the help of technical interventions such as smart metering or other smart technologies were identified as a major issue within current practices that leads to energy performance gaps. Moreover, for meeting targets such as Paris-proof targets, asset managers require stricter measures to control or influence the occupant energy consumption behaviour. Energy tracking measures are also identified as a necessity to ensure these targets are being met.

Another major flaw identified within the current practices is the prioritization of financial benefits over other sustainability related benefits such as health and environmental benefits. Most of the interview participants mentioned that designing buildings for energy efficiency beyond legislative requirements does not provide desired return on investments. This attitude is identified as one of the main limitations that obstruct developers from thinking beyond energy labels to design energy efficient buildings. Moreover, focusing on specific aspects or factors such as occupant behaviour will limit the flexibility of design and occupants posing a financial risk towards the building developers or owners. Additionally, energy simulations were found to be carried out only to meet legislative requirements. These simulations carried out with the help of energy labels and certificates often provide energy consumption predictions or estimations much lower than actual energy consumption figures due to omission of several important factors such as occupants that have a huge impact on the actual energy consumption.

6.5 Conclusion (Phase 2 - Define)

In the second phase of this research, define phase, the problem of energy performance gap was explored in detail with a focus on occupant behaviour which was identified as a major underlying cause in the previous phase. Through an extensive literature review, occupant behaviour was described in three different categories such as occupancy, interactions and behavioural efficiency. Each of these aspects of occupant behaviour was found to have a significant impact on the energy performance of buildings. Moreover, energy labels which were mandated by the legislation in the Netherlands do not take into account these occupant-related aspects. Ignorance of several important aspects such as occupant behaviour from the legislation leaves behind a grey area in energy consumption figures which resembles the energy performance gap in buildings. Literature has also pointed out earlier that these occupant-related aspects cover a significant portion of this grey area making them important to bridge the gap.

Stichthage, a non-residential building, was used as a case study to further narrow the problem statement to derive the detailed problem statement. Exploratory interviews were conducted with project team members from the renovation project. These interviews provided insights about the current practices followed within the industry that lead to the energy performance gap in buildings. Several limitations and issues were identified within the current practices that eventually lead to the gaps. The design strategies currently used were identified as a major limitation that leads to the gap due to the lack of technical interventions within the building to track energy performance. Moreover, asset management strategies used currently do not track the energy performance of the building during the operations phase. These issues and limitations will be highlighted in the detailed problem statement as mentioned below.

Developers and designers use energy labels and certificates as a support tool to aid design decisions and neglects occupant behaviour within the design of buildings. Occupant behaviour is found to have a significant impact on the overall energy performance of a building. Moreover, Such a design strategy leads to energy performance gaps in buildings.

Chapter 7

Linking Aspects of Occupant Behaviour and Building Design

Buildings are widely recognized as being among the most energy-intensive components within a nation's economy. The interaction and correlation of several variables, including physical qualities, technological systems, equipment, and occupants, have an impact on the energy performance (Tam, Almeida & Le, 2018). Furthermore, an essential factor that influences actual building energy use is the behavioural patterns of occupants such as their interactions with various components of the building as described in detail in chapter 5. Acknowledging these behavioural aspects of occupants is not sufficient to make an energy efficient building. These aspects must be incorporated or integrated into the design of the building to make them energy efficient and thereby bridge the energy performance gap. The incorporation of such aspects into the design of buildings and its components makes them less sensitive to occupant behaviour (Karjalainen, 2016). This is one way to bridge the energy performance gap and also reduce the energy consumption by the occupants.

In an optimal scenario, individuals possess a comprehensive comprehension of the functioning of building systems and are driven to utilize these systems in accordance with their intended design. There exists a substantial body of information indicating that occupiers possess limited comprehension of the underlying principles governing the functioning of buildings, resulting in sub-optimal utilization of building services. This is mainly due to the missing link between occupant behaviour and the design of these technical aspects that exists mainly due to the use of energy labels and certificates as design tools. In a study conducted by Karjalainen (2016), the findings indicate that the impact of occupant behavior on energy consumption is significantly reduced by the implementation of robust design solutions, which aim to mitigate the negative influence of occupant behavior on building performance. The energy consumption of an average occupant can be reduced by 75-79% by the use of robust design solutions, as compared to standard design solutions that cater to their respective behaviour. The incorporation of a realistic understanding of occupant behavior is seen beneficial in the development of energy-efficient building designs.

In this chapter, the findings from scientific literature regarding occupant behavioural aspects will be used to develop a link with the design of various building components. An expert panel discussion will be used to establish this link along with state-of-the-art available from literature. The expert panel will consist of project team members from the Stichthage renovation project. This link will help in developing a design strategy as a solution that is suitable to bridge the energy performance gap in buildings with a focus on occupant behaviour. This chapter also marks the beginning of the second diamond or the solution space where initially a broad solution will be developed and narrowed down to a detailed solution that solves the detailed problem statement.

7.1 Facade and Spatial Design

Facade is one of the most important components of a building related to energy consumption and energy efficiency. Facade is the interface between the inside environment of the building and its outside environment and therefore has immense energy saving potentials (Attia et al., 2018). Several aspects related to the facade or envelope of a building have a significant impact on the energy consumption of office spaces (Ihara, Gustavsen & Jelle, 2015). Occupant behaviour aspects such as the interactions with facade elements have an impact on the energy consumption of the building as discussed in section 5.3. If the facade is not designed well, the interactions between occupants and facades can frequently lead to disruptions and discontent due to conflicts arising from competing demands, such as the need for energy efficiency and maintaining a high indoor environmental quality. In order to effectively address these conflicts, it is imperative to draw upon the knowledge and insights gathered from multiple fields, such as behavioural science (occupant behaviour) and building physics (technical aspects) (Luna-Navarro et al., 2020).

Building facade system, being the outer shell of the building, has a significant influence on the exchange of heat between the outside and internal environments (Abediniangerabi, Shahandashti & Makhmalbaf, 2020). Taking these aspects into consideration, building facade is an important component of a building when it comes to overall energy performance (Carlander, Moshfegh, Akander & Karlsson, 2020). Facades serve as a direct mechanism via which occupants can manipulate and modify the indoor environment, hence allowing substantial opportunities for interaction between inhabitants and building components (Bakker, Hoes-van Oeffelen, Loonen & Hensen, 2014). Occupants interact with components such as blinds, windows and ventilation to maintain thermal comfort and hence have a major impact on the climatic conditions within the building (Bayoumi, 2017; Luna-Navarro et al., 2020). Daylight is an important aspect of visual comfort within an office space (Lim, Kandar, Ahmad, Ossen & Abdullah, 2012; Robbins, 1985).

One of the experts from the panel mentioned examples such as "within an IT firm that occupies a certain office space, the requirement for visual comfort and thermal comfort could be different compared to another firm within the same space". An IT firm uses more computers and other similar electronic devices compared to a financial firm. This leads to increased demand for cooling within the office environment indicating different requirements for thermal comfort. Similarly, an IT firm might have different visual requirements. Due to the use of more computers and screens compared to a different organization, employees might not have high preferences for daylight entering the office spaces due to the glare from sunlight. Similarly, the preferences for daylight within office spaces could be different for other types of organizations that occupy office spaces. As highlighted by experts, these aspects have also been increasingly important due to their role in dictating health and well-being of people working in office spaces. Members of the expert panel emphasized on the importance of daylight within office spaces for both visual as well as thermal comfort.

According to the project team members, one of the main reasons to initiate the renovation of Stichthage is also insufficient daylight entering the building. The experts also highlighted energy wastage that could happen through frequent or unnecessary interactions with the facade that can also increase energy consumed by HVAC systems for heating or cooling. Identifying and understanding these occupant preferences or requirements from different types of occupants will help designers and developers incorporate them into the design of facade elements and cater to their specific user. Incorporating these occupant behavioural requirements will help reduce the energy consumed by making these systems less sensitive to occupant behaviour. Hence, the design of facade elements can be improved in such a way to improve the energy efficiency of non-residential buildings.

Space layout design holds significant importance in architectural design, as evidenced by recent research indicating its influence on building energy performance. The term "space layout" pertains to the distribution of various functions inside a building's layout, which is determined by the arrangement of inner partitions and outside walls (Du, Turrin, Jansen, van den Dobbelsteen & De Luca, 2022). In a study conducted by Du, Jansen, Turrin and van den Dobbelsteen (2020), the energy consumption associated with heating, cooling, lighting, and ventilation is significantly influenced by spatial layout, as well as considerations of thermal and visual comfort. A. Sonta, Dougherty and Jain (2021), Du et al. (2021) and Latha, Patil and Kini (2022) emphasizes that interior layout of workstations will influence the energy performance of the building through demand for heating, cooling and ventilation.

Experts mentioned that most office spaces need to be designed according to the work culture followed by most organizations today. In recent years, work culture has shifted significantly due to the effect of the pandemic. Hybrid work cultures are observed more frequently which leads to lesser demand for office spaces due to work flexibility between home and office. According to Mantesi et al. (2022), the significant shift in work culture within office spaces due to the COVID-19 pandemic has had a significant impact on the energy consumption. The work culture of different organizations provide a better understanding about the occupancy patterns and also aid the spatial design of office spaces. Similarly, the flexibility in working hours is also highlighted, by experts, as a driver of energy consumption in office spaces. The more flexible the work hours, longer periods of energy consumption are observed in comparison to fixed work hours. Some experts mentioned the availability of data regarding occupancy patterns within their databases but pointed out that these data have never been used to design energy efficient buildings as they were never required by any certificates or energy labels which is widely used to aid the design process.

Similarly, some of the experts mentioned that the spatial design requirements are different for different types of offices. One of the experts mentioned that "in an open office, like a bank, that receives customers or clients throughout the day, the spatial layout needs to be welcoming and cater to the needs of the activities performed within that office space. Whereas in a closed office, like an IT firm or even NS Stations, the spatial layout needs to be according to different departments or divisions according to the frequency in which teams interact with each other". These statements clearly highlight the relevance of occupancy patterns for different types of office spaces or different organizations occupying an office space and their spatial layout. The presence of people in office spaces, activity followed within offices, movement patterns of occupants, etc, will help in designing the spatial layout in an energy efficient way. Identifying and understanding these requirements for different office spaces will help in improving the design as well as the energy efficiency.

7.2 Building Services

Offering a comfortable indoor environment for occupants within a building is important to the success of the building and designing them in a sustainable way adds to the environmental benefits as well. In the past, most real estate developers and designers have designed and built building services in line with their economic considerations and did not look into the comfort requirements of the occupants and certain aspects that had a significant impact on the energy performance (Lück, 2012). Building services is an overarching term used to describe various technical components of a building that caters to the comfort requirements of the occupants of a building (Tymkow, Tassou, Kolokotroni & Jouhara, 2013). These components of a building mainly provide required levels of comfort to the occupants within the building environment and include HVAC systems, automation and control. Apart from these, energy systems also play a crucial role within buildings. Energy systems includes generation and storage solutions for buildings to achieve energy efficiency standards.

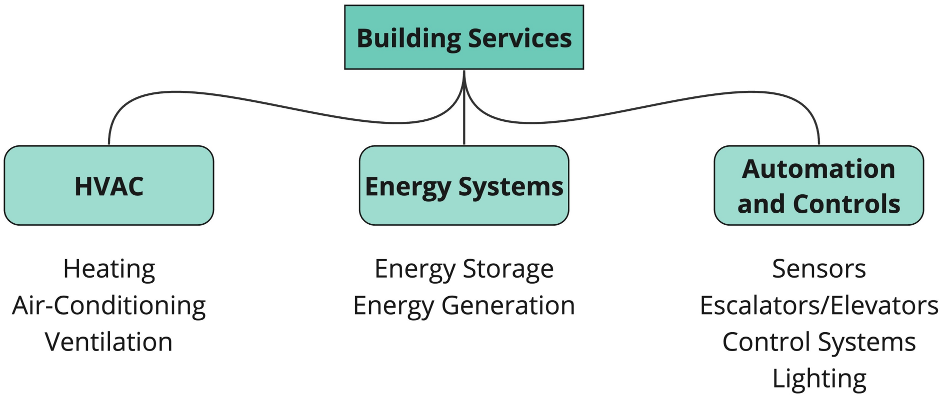

Figure 7.1: Classification for Building Services

Occupants interact with building systems to maintain an optimal comfort level for their functions and activities within the building environment and these interactions have a significant impact on the energy performance of buildings as discussed extensively in chapter 5. There were certain drivers that were identified as the reason for occupants to interact with building services and a detailed understanding about these drivers and the way they change within different office spaces will impact the way these building services are designed. In order to achieve energy efficiency and sustainability, it is imperative for buildings and its services to possess the capacity to engage with occupants and foster synergies with them (Domínguez-Amarillo, Fernández-Agüera & Fernández-Agüera, 2018). Therefore, taking into account these preferences according to the functions of an office space will help improve the design and thereby its energy efficiency.

7.2.1 HVAC Systems

Heating Ventilation and Air Conditioning (HVAC) systems are important building services that provide the required thermal comfort and indoor air quality for the occupants of the building and are one of the most important components of a building in terms of energy consumption. These systems need to provide the preferred indoor climate within the building environment through human control and energy consumption. Several research has highlighted the importance of occupant-centric design and control of HVAC systems by incorporating behavioural aspects to make them energy efficient. The high level of energy consumption may be attributed to the lack of consideration for occupant preferences in the design and construction of numerous new buildings, which mainly rely on technological solutions to ensure a satisfactory indoor environment (Simpeh, Pillay, Ndihokubwayo & Nalumu, 2022). Linking these preferences and relevant occupant behavioural aspects to the design of HVAC systems will help reduce energy consumption and improve energy efficiency.

An accurate understanding of the occupancy pattern in a building is necessary to design a demand-based HVAC control system to reduce the energy wasted during non-occupied hours. Dong, Winstead, Nutaro and Kuruganti (2018) developed an occupancy prediction method to provide occupancy-based controls for HVAC systems that displayed 20% energy saving potential. Z. Yang et al. (2016), Rinaldi, Schweiker and Iannone (2018) and O'Brien, Abdelalim and Gunay (2019) found that HVAC systems need to be designed taking into consideration occupancy aspects to reduce the energy loads. Pang et al. (2021) found that occupant counting (occupancy) sensors for HVAC systems have an additional 5-15% energy saving potential. Simpeh et al. (2022) and Pioppi, Piselli, Crisanti and Pisello (2020) emphasizes on the importance of occupant-centred and controlled HVAC systems to improve the energy efficiency and provide thermal comfort mainly due to energy wastage from poor design of HVAC systems. Chenari, Carrilho and da Silva (2016) specifies the role of occupant behaviour in ventilation systems to make them more energy efficient and provide better indoor air quality and climate.

One expert from the panel stated that "HVAC systems need to be designed according to type of work carried out within an office space and the insulation provided. Offices that use a lot computers and other electronic devices exhibit higher cooling demands than other due to the excessive heat generated by these devices." Similarly another expert mentioned that "interactive open offices have clients or customers walking in and out of the office spaces creating varying demands for cooling and heating, whereas in a closed office space the demands do not vary highly". One of the experts also highlighted the need for user-friendly control systems for HVAC systems to reduce energy wasted in adjusting the system to their preferred temperatures. In relation to these statements, occupancy aspect of occupant behaviour varies with different types of office spaces or different types of organization that occupy an office space. Hence taking into account such requirements from the occupants will help improve the design of HVAC systems and reduce the wastage of energy. Currently, there are sufficient data and information available regarding occupancy patterns which can be used to aid the design process. However, aspects such as interactions are difficult to be quantified or analysed through data but these aspects can be understood through feedback gained from occupants within the existing building. Market parties with an expertise in this domain could also help in providing insights about these aspects to improve the design.

7.2.2 Automation and Controls

Occupants interact with various components of the building such as HVAC systems, lighting, etc. to maintain the required levels of comfort as discussed in chapter 5. In a modern building, these interactions mainly occur through certain control systems that are mainly automated. These systems, often termed as Building Automation and Control Systems (BACS), play a huge role in the energy efficiency of buildings (Vandenbogaerde, Verbeke & Audenaert, 2023). Building Automation and Control Systems (BACS) facilitate efficient management of diverse building services such as heating, cooling, ventilation, lighting, and shading (Aste, Manfren & Marenzi, 2017). BACS consists of sensors that detect and perceive input emerging from the building environment that includes the occupants and their behaviour which are then converted by the actuators into commands for various building services according to logical directives (Martirano & Mitolo, 2020). These control systems often help reduce the amount of energy wasted in buildings.

Fabi, Barthelmes, Schweiker and Corgnati (2017) claims that automated control systems can help reduce the energy consumption by approximately 10-15%. Through their study, Vandenbogaerde et al. (2023) also found that these system's effectiveness heavily depends on various aspects of occupant behaviour. Most of the standards that are used today, such as EN 52120–1 (European Standard), to evaluate energy savings through BACS does not take into account various aspects of occupant behaviour which further leads to energy performance gaps in buildings (Van Thillo, Verbeke & Audenaert, 2022). Shah et al. (2022) explains the role of machine learning in buildings for energy efficiency. Metallidou, Psannis and Egyptiadou (2020) highlights the use of Internet of Things (IoT) in buildings to create energy efficient strategies such as Internet of Energy (IoE). The authors propose using a cloud platform to store huge amounts of data for building energy performance to devise suitable energy efficiency strategies.

Occupant-Centric Control is also a common control strategy used in buildings to ensure energy efficiency where a control system obtains diverse data from individuals occupying a space, the internal environment, and the external climate. Moreover, these systems by themselves alone cannot provide the required energy efficiency to deal with the ongoing energy and climate crisis and needs to be combined with certain aspects of occupant behaviour to achieve the desired results. This is mainly because occupants often try to override these systems when the required levels of comfort are not met by taking manual control. Understanding the occupant-building interaction patterns and also preferences of occupants in terms of comfort levels will help design these controls and systems to provide the optimum comfort and significantly reduce energy consumption and thereby improve energy efficiency of buildings.

During the expert panel discussions, one of the experts mentioned that "sensors play a major role in improving the energy efficiency of lighting and HVAC systems but these sensors are not designed according to the user requirements". The experts also provided examples such as "sensors for lights in office buildings are suitable but these sensors would also benefit HVAC systems, for which they are not implemented currently. If you look at some offices on a Friday, there are not many people at the office. Within a particular floor, only a small region will be occupied by the employees but the HVAC systems will still be running for the entire floor". These statements clearly highlight the need to identify, understand and incorporate occupancy patterns into the design of control systems for HVAC systems. Similarly, another participant mentioned that "electronic devices such as screens or the monitors used in office spaces are often left running during non-working hours and consumes significant amount of energy. There needs to be a central system that can turn these systems off during non-working hours". Based on the understanding gained from these discussions, it is important to take into consideration various occupant behavioural aspects such as occupancy and interactions during the design of control systems in order to align them with end-user requirements, reduce energy wastage and improve energy efficiency of buildings.

7.2.3 Energy Systems

Improving the energy efficiency of buildings has been a fundamental aspect of most energy policies that are introduced today. On-site energy generation and energy storage strategies are some of the solutions that could contribute towards improved energy efficiency of buildings. These are also important aspects when it comes to regulations such as Nearly Zero-Energy Buildings which is a regulation to be met by new construction in the Netherlands (EU, 2023). The primary objective is to reduce electricity consumption in order to decrease the environmental impact of buildings. The objective is pursued by designing buildings in an energy efficient way, as well as the utilization of renewable energy sources (Wilberforce et al., 2023).

Energy systems are an important aspect of a building to bridge the energy performance gap in buildings. Energy systems include possibilities for energy generation as well as energy storage. Green energy generation is considered to offset the fossil fuel based energy used in buildings (Akram, Chen, Khalid, Ye & Majeed, 2020). Generating energy on-site also reduces the dependency on grid energy that is usually generated from fossil fuels in most cases. The shift towards sustainable energy systems characterized by a significant proportion of renewable energy sources that are dependent on weather conditions presents the challenge of balancing the disparity between inflexible production and inelastic demand. This necessitates finding suitable solutions that are both technologically and economically feasible, while also considering environmental factors (Tronchin, Manfren & Nastasi, 2018). Most of the experts highlighted the importance of on-site energy generation in improving the sustainability aspects of a building and also provided supporting statements for its role in bridging the energy performance gap.

Energy storage is a crucial component in energy management systems, since it allows for the storage and subsequent utilization of extra energy during periods of energy deficiency (Vieira, Moura & de Almeida, 2017). In instances of surplus renewable energy generation, energy can be effectively stored in many forms such as heat, potential energy, chemical energy, among others, and subsequently released during periods of insufficient renewable generation. It is imperative for building owners to do an assessment in order to determine whether the advantages of implementing a storage system are superior to the increased initial expenses and intricacies associated with the system (Y. Yang, Bremner, Menictas & Kay, 2018). Battery energy storage systems are commonly recognized as a very feasible option, offering numerous benefits like rapid response, sustained power supply over extended periods, and less reliance on the electrical grid (Ahmed et al., 2022). However, these systems are also subject to safety regulations in different countries. The experts pointed out that "these systems can only be implemented according to the fire safety regulations of the country as batteries and other energy storage systems pose a huge fire hazard".

7.3 Energy Tracking

The drive towards energy efficiency in buildings requires data and information regarding the energy performance of buildings. These are vital to identify the areas of high energy consumption and devise a suitable solution or strategy to reduce energy consumption and improve energy efficiency. This has acted as a catalyst to prioritize energy tracking within buildings today. Several researchers have emphasized on the importance of measuring and analysing the energy performance of buildings. This collection of information and data regarding energy performance is currently done with the help of energy metering devises that provide energy consumption information (Ahmad, Mourshed, Mundow, Sisinni & Rezgui, 2016). According to Martirano, Manganelli and Sbordone (2015), metering plays a crucial role in energy audits and initiatives aimed at enhancing energy efficiency. It offers comprehensive, precise, and dependable data regarding the functioning and effectiveness of energy systems.

Currently, most of the buildings use traditional metering systems that are only equipped to gather data regarding the total energy consumption of buildings that do not have breakdowns regarding energy consumption (Li, Yu, Zhao, Hou & Mao, 2023). Through the exploratory interviews conducted in the early stages of this research, it was found that one of the underlying causes that lead to energy performance gaps or excessive energy consumption in buildings is due to the lack of detailed energy performance data. This has clearly highlighted the importance of smart metering and use of other smart technologies as highlighted in sections 5.4.3 and 5.1 to track the energy consumption within buildings. Moreover, one of the participants also mentioned a famous Dutch expression, "Meten is weten" which translates to measuring is knowledge. The experts highlighted that measuring the energy performance is key to reducing energy consumption and improving energy efficiency of buildings. Experts also highlighted that "high levels of details in energy consumption figures are important to meet Paris-proof targets that regulate overall energy consumption in buildings. With smart metering, asset managers can make distinctions regarding the energy consumed by tenants and building separately".

Smart meters are the most common strategy used by real estate developers to track the energy performance of buildings. Karthika, Valli, Srinidhi and Vasanth (2019) provides insights into the application of Internet of Things (IoT) to track and store energy performance data for buildings. This helps in automatic collections of readings as well as storage of data in a database. Collection of detailed energy performance data will also provide plenty of insights to policy makers, helping them to introduce future policies and regulations as needed (Miller, 2019). Generalisation can be done with the availability of more data regarding energy performance. Li et al. (2023) proposes a sub-metering technique and suggests that the utilization of the energy consumption sub-evaluation approach is advantageous for enhancing energy efficiency and investigating the energy-saving possibilities of structures. Such technological advancements within this domain has helped in gaining a detailed understanding about building energy performance. Therefore, it is important to take into consideration these aspects during the design phase in order to allocate such systems accordingly to measure the energy performance accurately in a detailed manner. They also provide much needed insights about the composition of the energy performance gap as well as shed light on the grey areas of energy consumption highlighted earlier. These energy tracking measures are vital to bridge the energy performance gap in buildings and thereby improve their energy efficiency.

7.4 Conclusion (Phase 3 - Develop)

The second diamond, solution diamond, involves the development of a solution to solve the detailed problem statement. The detailed problem statement highlighted the flaws within the current design practices that lead to energy performance gaps. Occupant behaviour was also identified as an important factor regarding energy consumption or energy performance of buildings and were often neglected within the design process for energy efficient buildings. In the third phase of this research, develop phase, the solution is being developed with the help of an expert panel and a case study building. The expert panel provided several ideas about linking occupant behavioural aspects, identified earlier through literature, to the design of various components of a building to improve their energy performance and energy efficiency. This helps in creating a broad solution for the problem of energy performance gaps.

Through the expert panel discussions, several insights were gained to link occupant behavioural aspects such as occupancy and interactions to various building components based on their expertise and experience. This helps in improving the design process for energy efficient buildings by focusing on important aspects such as occupant behaviour which were often overlooked or neglected earlier. Moreover, the state-of-the-art identified through scientific literature has also been highlighted in this phase of the research. These insights and links established will form the basis for developing a structured design strategy with a focus on occupant behaviour to bridge the energy performance gap in buildings. This phase also explored and gathered insights about various other important aspects to bridge the energy performance gap such as energy systems and energy tracking measures through the expert panel discussions. Together these measure will help bridge the energy performance gap as well as improve the overall energy efficiency of buildings.

In the following phase, deliver phase, a design strategy will be developed for real estate developers with tasks, responsibilities and activities described to focus on occupant behaviour. This design strategy will be the final solution for the detailed problem statement designed in the first diamond. Moreover, expert opinion will be gathered to identify the practical implications of the design strategy. Identifying and gaining a better understanding about these practical implications will help in refining the design strategy to effectively solve the detailed problem statement. Moreover, these practical implications will provide a better idea for future scope of research to further improve the design strategy.

Chapter 8

Thinking Beyond Energy Labels

Energy efficiency policies have a crucial role in improving the energy efficiency of buildings and reduce the energy consumption of buildings and the emissions from them. These policies are pivotal in reducing the energy consumption within buildings and reducing their dependence on fossil fuel based energy. Energy labels and certificates were introduced through these policies and regulations to indicate an estimated or predicted energy consumption for the building. In the Netherlands, these energy labels were introduced through EPBD and have been mandated for buildings in the recent years. As discussed in detail in chapter 4, these energy labels only estimate the energy consumption of few building components and does not provide the complete picture for energy consumption of the building. Most of these labels and certificates have not been customized to meet the specific requirements of the end-user (Zuhaib et al., 2022). These energy labels were not intended to be used as a design support tool by developers for energy efficiency, rather was just intended to be a depiction of the energy performance of a building.

In order to achieve targets mentioned within the Paris Climate agreement, it is important that real estate developers think beyond energy labels and certificates to take effective measures to reduce overall energy consumption within buildings and thereby the emissions resulting from them. The Paris Climate agreement is an important commitment for all governments and citizens across the world to save the planet. Based on the understanding gathered through this research thus far, energy performance gaps in buildings needs to be bridged to improve energy efficiency of buildings and reduce overall energy consumption. This requires a focus on one of the significant underlying causes, occupant-related aspects such as their behavioural patterns, and their integration within the design of buildings based on the link established in chapter 7. There is an urgent need of interventions within current design strategies to bridge the energy performance gap with a focus on occupant behaviour. Instead of altering the occupant behavior, which has demonstrated little effectiveness, resilient design aims to enhance buildings to accommodate a certain range of occupant behaviour (O'Brien, 2013).

In this chapter, a design strategy will be developed using the information and knowledge gathered so far through this research. This design strategy will help real estate developers think beyond energy labels and certificates to focus on occupants of the building and thereby bridge the energy performance gap in buildings. The design strategy describes the various tasks, responsibilities and roles of each member of the project team for a (re)development project of a non-residential building. The design strategy will be briefly explained in comparison to a mainstream design strategy currently used within the industry to highlight the significant differences. Finally, the practical implications of the design strategy will be highlighted and discussed to further refine the design strategy, making it suitable and effective to solve the detailed problem.

8.1 Developing Occupant Focused Design Strategy

Occupants and their behaviour within buildings accounts for approximately 10-90% of the total energy consumption in buildings according to various researchers which is generally not accounted by energy labels and certificates or regulated by any other policies and regulations. Clearly, so far, we found that occupant behavioural aspects such as occupancy, interactions and behavioural efficiency have a major impact on the energy performance of buildings and their negligence during the design of buildings lead to energy performance gaps. We also found that design flaws such as dependency on energy labels to aid design decisions lead to energy performance gaps in buildings. In the previous chapter, we found that occupant behavioural aspects, also found to have a significant impact on energy performance, can be vital inputs for design of various components of the building and state-of-the-art has evidently shown that such design practices have had a significant improvement in the energy performance of buildings. However, these information gained thus far through this research needs to be structured into a design strategy that can be used by real estate developers to bridge the energy performance gap in buildings through a (re)development project and thereby achieve the objectives of this research.

In order to decarbonise the existing building stocks, there is a huge renovation wave across Europe. These waves of renovation or re-development were stimulated by the introduction of stricter measures according to the Energy Performance of Buildings Directive (EPBD). For example, in the Netherlands, energy labels were mandated for all office buildings by 2030 which triggered a huge wave of renovation and retrofitting activities throughout the country. However, these renovations were mainly carried out to meet the legislative requirements, which could be stricter in the near future through the introduction of Paris-proof targets requiring further investments. These targets require better design strategies that focus on much more important aspects than those covered by energy labels and certificates. Moreover, focusing on these aspects helps in drastically reducing the overall energy consumption in buildings contributing to Paris Climate agreement.

According to IEA (2023a), building operations consume approximately 30% of final energy globally among which a significant portion such as occupant energy consumption is not regulated by energy labels or certificates. Therefore, a crucial intervention is required in the way buildings are designed to reduce energy consumed by occupants and also to make buildings less sensitive to occupant -related factors that have a significant impact on the energy performance. Future policies and regulations will also concentrate on these aspects of building energy performance due to their growing significance which makes the design strategy a necessity for designers and developers today. These aspects basically constitute the grey areas of energy consumption in a building that have not been acknowledged before within design. The case study used to define the problem statement has highlighted the flaws within the current practices followed by real estate developers.

Taking into account these findings, the design strategy will focus on occupants and their behaviour within buildings. These aspects of occupant behaviour will help a designer or developer design the building to cater to the specific requirements of the occupant and thus reduce the overall energy consumption. Although buildings are intended to prioritize the comfort of inhabitants, empirical data indicates that they frequently fall short of meeting standard requirements. These shortcomings appear in several ways, including discomfort experienced by occupants, limited control over building conditions, and inefficient operation that fails to align with occupants' preferences and presence (O'Brien et al., 2020). Moreover, O'Brien (2013) mentions that designers often label occupant-related aspects as 'beyond their control' and hence neglect them during design. Developers and asset managers often lay the blame on occupants for their energy consumption as found through exploratory interviews conducted in this literature.

According to D'Oca et al. (2018), there are several potential advantages associated with a deeper comprehension of the human aspects of energy consumption. These include cost reductions for building owners, improved comfort and productivity for building occupants, enhanced efficiency of building energy management and automation systems for operators and energy managers, and the integration of more precise control logic into future human-in-the-loop technologies. In the modern world, it is hard to blame occupants within buildings for their behaviour and its impact on the energy consumption of buildings. Rather, the building design should incorporate these behavioural aspects to become more robust and help occupants reduce their energy consumption within buildings. Designers and developers can design buildings in such a way that it is easier for the occupants to occupy buildings and making them less resistant towards their behaviour within the building environment by consuming lesser energy. This is especially important in the case of office spaces where the occupants showcase lesser responsibility towards their energy consumption behaviour as they are not responsible for the energy costs incurred.

8.2 Design Strategy

To begin with, the Royal Institute of British Architects (RIBA) Plan of Work is taken as a reference design process to develop an occupant focused design strategy through this research. The RIBA plan of work systematically organises the tasks from briefing, designing, constructing and operating projects. The focus of this research will only be the initial stages of a project, specifically the design stage of the project. This plan of work will help provide insights about the order of tasks in which a design process is carried out and will be used as a base to develop the occupant focused design strategy. The tasks, roles and responsibilities within the RIBA Plan of Work will be modified to incorporate occupant behavioural aspects that will help in bridging the energy performance gap. The RIBA design process is divided into 4-5 different phases depending on projects but the developed strategy through this research will be divided into three different phases - pre-design, conceptual design and detailed design as illustrated below in figure 8.2.

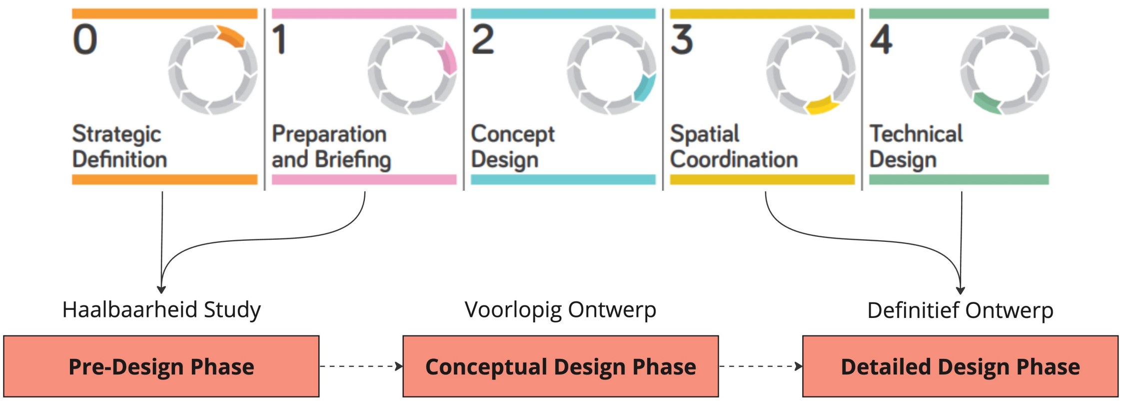

Figure 8.2: Depiction of RIBA Plan of Work as reference for Design Strategy (Adapted from (RIBA, 2020)))

The occupant focused design strategy developed through this research, as depicted in figure 8.1, consists of three important phases during the design process. These phases are in line with the 5 different phases of design as followed within the RIBA Plan of Work. The three main design phases are (1) pre-design phase (haalbaarheid study), (2) conceptual design (voorlopig ontwerp) and (3) detailed design (definitief ontwerp). The design strategy focuses on (re)developmen projects where certain information and data are available for the time period in which the building has already been operational. Additionally, this design strategy takes into account the factors applicable for a non-residential building, predominantly used as an office space.

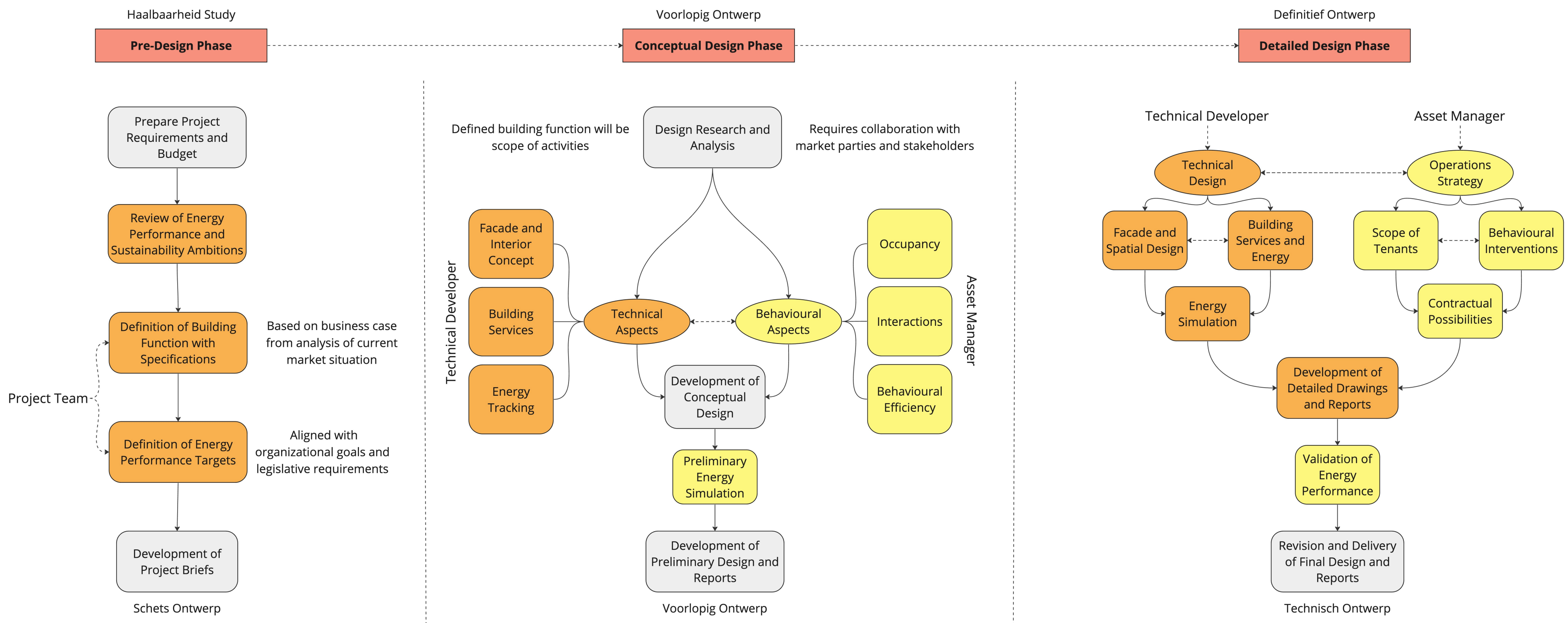

Figure 8.1: Occupant Focused Design Strategy

The design strategy was developed using two sets of information available as a base on which it was developed. The first set of information is collected from the case study building, Stichthage, which is a non-residential building, predominantly used as an office space for the past 40 years approximately. The information regarding the design practices currently followed for the building were collected through exploratory interviews and expert panel discussions to understand the design process in detail as well as identify the limitations and issues within them. The second set of information was gathered from the RIBA Plan of Work to understand the tasks, responsibilities and roles of different project team members for a mainstream design process. This was mainly used because the Stichthage renovation project was in the pre-design phase at the time of this research, making it difficult to anticipate the future activities that will be followed.

For each phase of the developed design strategy, there will be certain inputs and outputs that will aid the current and following processes respectively, as briefly mentioned in table 8.1. The roles and responsibilities of each project member and their contributions to the design of the building will also be highlighted. The primary aim of the design strategy is to bridge the energy performance gap in buildings with a focus on occupant behaviour. The tasks highlighted in orange represent the activities already followed within the design process but with alterations and tasks highlighted in yellow represent completely new activities and responsibilities that are not done currently.

	Input	**Output**
Pre-Design	• Set of Requirements • Input from Current Tenants • Preliminary Budget • General Organizational Ambitions and Goals • Market Analysis for Developing Business Case	• Preliminary Project Brief and Reports • Detailed Budget Reports • Project Specific Targets and Goals • Detailed Business Case • Selected Building Function • Energy Performance Targets • Specific Sustainability Targets
Conceptual Design	• Preliminary Project Brief and Reports • Selected Building Function • Energy Performance Targets • Specific Sustainability Targets • Collaboration with Market Parties • Data (Occupancy) • Detailed Budget Reports	• Preliminary Design and Conceptual Drawings • Project Reports (Possibilities and Cases) • Research Reports (Occupant Behaviour) • Preliminary Energy Simulation Reports • Revised Budget Reports
Detailed Design	• Preliminary Design and Conceptual Drawings • Project Reports (Possibilities and Cases) • Research Reports (Occupant Behaviour) • Preliminary Energy Simulation Reports • Revised Budget Reports	• Detailed Technical Drawings and Reports • Final Energy Simulation Report • All Documents for Tender Procedure • Asset Management Strategy including Draft Contracts

Table 8.1: Inputs and Outputs of Each Design Stage

8.2.1 Pre-Design Phase

The pre-design phase is the onset of a project where the main parameters of the project are determined and defined. These parameters include various aspects of the project such as budget, goals, ambitions, targets, set of requirements, business case, etc. These parameters play an important role throughout the entire project as they define the scope and purpose of the project. This design phase includes several activities that take a holistic view of the project to determine several important aspects of the project such as budget and ambitions in detail. Pre-design phase is also considered as the most creative stage where various different possibilities are explored for a particular project through a broad lens. These possibilities along with information collected regarding them shape and influence the design process to be followed in the project.

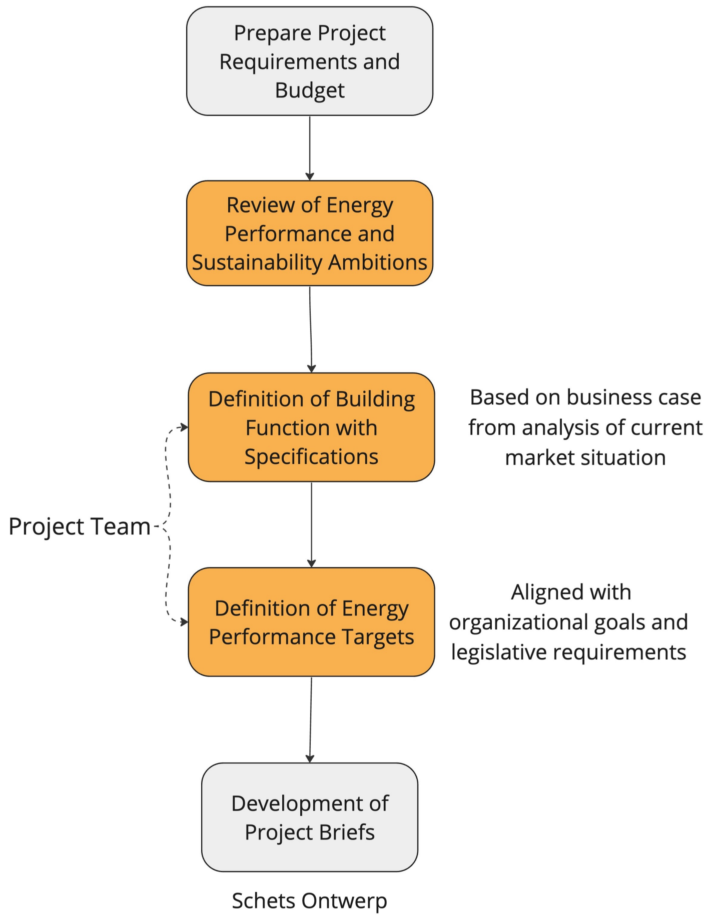

Figure 8.3: Pre-Design Phase (Haalbaarheid Study)

Every project begins with the preparation of a set of requirements for the renovation and preliminary budget. The set of requirements is usually an answer to the question - "Why do we (building owner/investor) need to renovate the building?". The answer to this question entails different reasons to carry out the renovation such as the end-of-life-cycle of various components of the building, increase in floor area, better aesthetics, better business case, legal requirements, etc. A certain budget will be allocated to the project at the initial stage. However, this could change over the course of the project. At the same time, several general information currently available regarding the existing building will also be gathered highlighting issues and problems to be solved through this renovation.

Most importantly, data available regarding current energy performance of the building will be analysed to gain a detailed understanding. This will also provide an idea about the amount of data and information available and help identify areas that require vital interventions to improve the overall energy performance of the building. This helps the project team to identify the issues related to the energy performance and devise suitable measures to aid the design process in the following stages of design. In the case of Stichthage, due to lack of smart meter, there was an evident lack of detailed information regarding the energy consumption of each tenant. Thus, to gain a better understanding about the energy consumption patterns of different types of tenants, the project team can seek help from market parties such as consultants or advisors and experts to collect these information. Moreover, the sustainability ambitions of the organization and those specific to the project will be identified and translated to achievable targets and milestones.

All project team members will be involved in the pre-design phase as several important decisions will be made during this phase. These early design decisions are crucial, as highlighted within literature, and will shape the outcome of the project. All major stakeholders of a given project from the client's side is termed as the project team in the context of this research. This could vary according to size of the project, different organizations and their respective structure. Technical developers, real estate developers, asset managers, project managers and sustainability department representatives are members of the project team. Here, real estate developers are responsible for office concepts and technical developers are responsible for technical aspects of a building. The project team as a whole, plays an important role in the initial stages of design due to their influence on early design decisions that will have a significant impact on the project.

The next important step in this design process is to define a building function with specifications based on the business case developed for this project. This was found to a major challenge within the current practices followed in the industry where developers try to increase the flexibility in design in order to accommodate different types of tenants within the same space rather than catering to one group of tenants or their specific needs. The project team members can also make use of a market analysis to further enhance the initial business case. In the case of Stichthage, the ideal location provides an advantage for the owners as it is situated in a business district with high demands for various office spaces, as highlighted by one of the project member through the expert panel. This information about the demands for office spaces will help the project team to decide specific types of office spaces and their target tenants. This will help them narrow the scope of design and develop a design that will cater to the specific needs of the tenants.

Additionally, the project team has to derive and define energy performance targets to be achieved through renovation. These targets also has to align with the (1) organization's goals and ambitions regarding sustainability and (2) the legislative requirements. With upcoming policies and regulations, targets such as Paris-proof targets are becoming important for real estate developers and also poses a major challenge towards them. One of the project team members highlighted that, "we need to make rough distinctions between the energy consumed by the building and energy consumed by the occupants to collectively keep them below targets such as 70kWh/m^2". Using these information, the project team can develop project briefs that consist of reports on several aspects such as business case, detailed budget, project risks and specific targets that will aid the successive design phases.

8.2.2 Conceptual Design Phase

The conceptual design phase serves as a formal establishment of the initial notion. Within this design strategy, this phase integrates a sufficient amount of knowledge regarding engineering and behavioural aspects to furnish management with a credible evaluation of anticipated performance, potential aesthetics, fundamental comprehension of the extent of the re-development project, including market potential and projected expenditures. In the conceptual design phase for the proposed design strategy, the asset managers and real estate/technical developers provide crucial inputs into the design process of the building. The activities, roles and responsibilities included in this phase will narrow the scope of design further to focus on occupants and their behaviour within buildings. The scope for this design phase will be the selected building function with specifications from the previous phase and the energy performance targets as well.

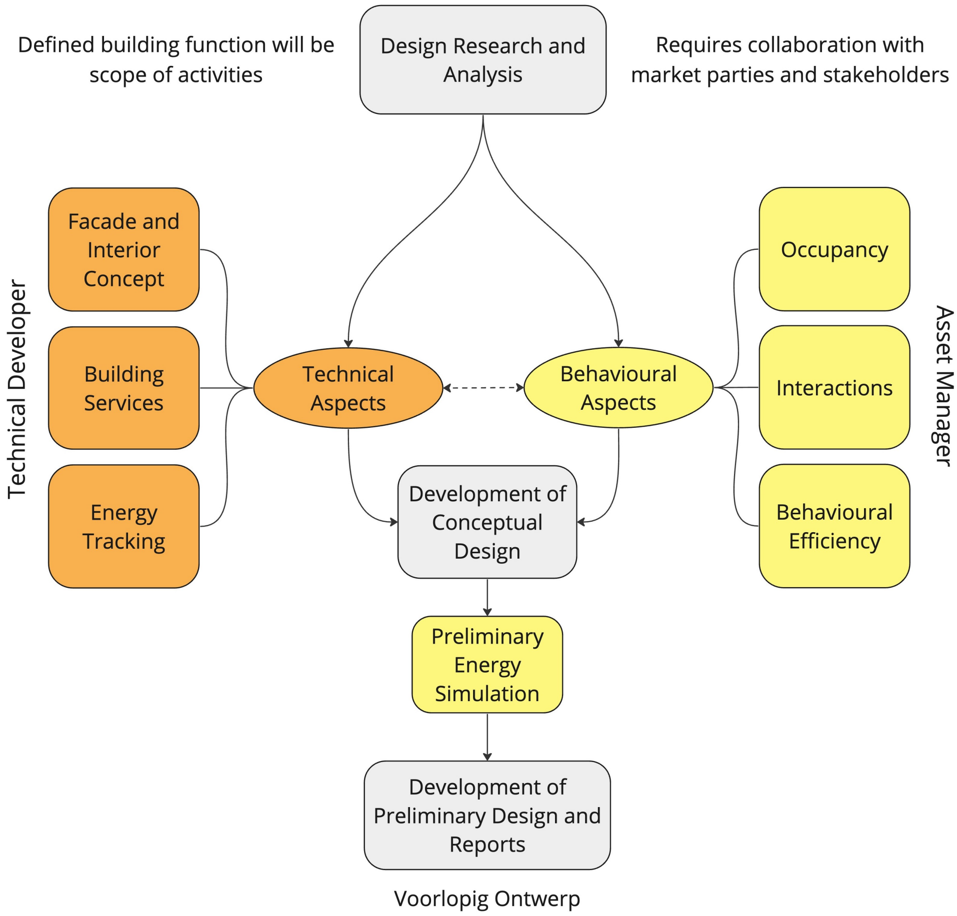

Figure 8.4: Conceptual Design Phase (Voorlopig Ontwerp)

The conceptual design phase consists of specific roles and responsibilities for asset managers and technical/real estate developers apart from the mainstream tasks undertaken. The technical developer and real estate developer deals with the technical aspects of a building whereas the asset manager deals with the occupant-related aspects of the building. The inputs from both these parties will benefit each in devising an effective and suitable design for an energy efficient office space. As described extensively in chapter 7, the primary task in this design phase is to gather information regarding various occupant-related factors such occupant behaviour aspects described in chapter 5. These information will help the technical developer and real estate developer to develop a conceptual design for the technical aspects of the building with a focus on occupant behaviour.

The asset managers will collect information regarding occupant-related factors that have a significant impact on the energy performance of the building. Occupant behavioural aspects such as occupancy, interactions and behavioural efficiency will help improve the design of buildings, especially regarding energy performance, as they are often neglected or overlooked by the legislation and hence current design as well. In the case of Stichthage, information regarding certain occupant behavioural aspects such as occupancy were available. This information can be used by developers to explore various possibilities in design as described in chapter 7. To tackle the challenge of lack of data regarding aspects such as interactions and possibilities for behavioural efficiency, the asset managers can seek help or collaborate with market parties to gather information required to aid the design process and decision making. These information will also aid the asset managers to develop an asset management strategy in the final phase of the design process.

At the same time, the technical developers and real estate developers, explore the different possibilities for technical aspects of a building such facade, spatial layout, building services (HVAC, lighting, energy systems, automation and controls) and energy tracking measures. The developers use information gathered by asset managers regarding occupant behaviour to aid their decision making and develop a design according to the specific building function specifications selected in the pre-design phase. The developers also take into account obvious aspects such as project budget and risks. Moreover, energy tracking possibilities are also explored as they play an important role in bridging the energy performance gap in buildings. The developers can also collaborate with market parties and experts to discover various possibilities according to the specific requirements of different types of tenants that were selected as the target tenants. In such a way, developers will be able to think beyond energy labels and take into account several aspects that were earlier omitted from the design of buildings.

Using the information collected as described above, the project team develops a conceptual design for the building. These conceptual design consists of various possibilities and cases for the building. Preliminary energy simulations will be carried out with all available design and information to gain insights about the energy performance of the design developed so far. This will help in keeping track of the energy performance targets set during the pre-design phase. These simulations also play an important role as several project team members highlighted that these were only carried out during the final stages of design to meet legislative requirements. Carrying out energy simulations in the conceptual design phase will also help avoid several uncertainties during the energy simulations in successive stages of design. Moreover, these energy simulations will iterating the design to further improve them and keep them below the initial targets. Based on the energy simulation, necessary changes can be brought to the design to develop the preliminary design and related reports to conclude this phase of the design process.

8.2.3 Detailed Design Phase

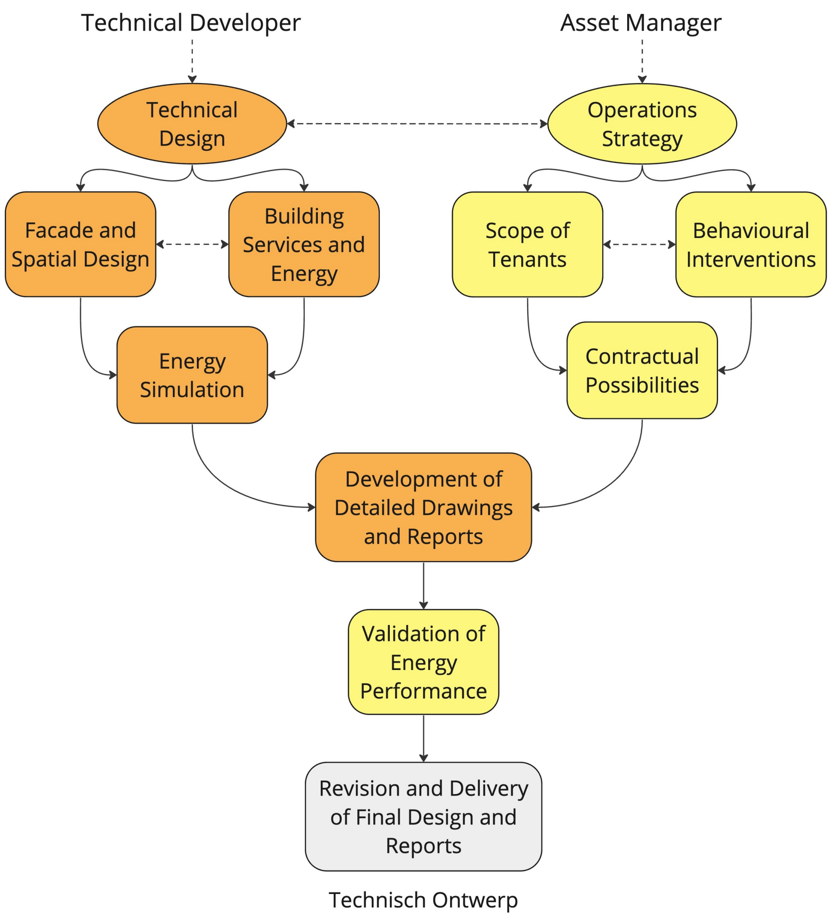

Figure 8.5: Detailed Design Phase (Definitief Ontwerp)

The detailed design phase is the phase in which the concepts developed in the previous phase will be converted to detailed drawings and reports, in other words, final design. In this phase, the design of the building will gain further resolution by incorporating the information gathered regarding occupant behavioural aspects in the previous phase. This phase also includes the development of an asset management strategy for the building during its operational phase as it was identified as one of the main limitations or issues that lead to energy performance gaps in buildings based on the current practices followed within the industry. The development of asset management strategy is important in order to ensure that the predicted or estimated energy performance of the building is maintained even during the operational phase to bridge the gap. Moreover, at the end of this phase, the design developed will cater to the specific needs of the targets tenants and thereby reduce energy consumption in buildings as well.

In the detailed design phase, again, the asset manager and technical/real estate developer play an important role in developing a detailed technical design as well an asset management strategy. The real estate developer and technical developer deals with the technical aspects of the building to develop a detailed design whereas the asset manager deals with occupant-related aspects to develop an asset management strategy. Towards the end of this design phase, the entire project team collectively plays a major role by validating the final design, asset management strategy and its energy performance. This helps in bridging the gap between design and operations of a building and also the gap that exists due to the same.

The technical developer and real estate developer develops the detailed design for various components of the building such as facade, spatial layout, building services and energy tracking measures using several inputs from the previous design phase. Several information related to various technical possibilities and cases for different occupant behavioural patterns can be used to narrow the design further into a detailed design. Additionally, narrowing of the scope of tenants further will help in improving the detailed design. Energy simulations can also be carried out as the detailed design takes shape. These energy simulations provide several vital information regarding the energy performance of the building in a near-real-life scenario. These energy simulations can also take into account several occupant-related aspects into account to improve their prediction or estimation for energy consumption within the building.

At the same time, the asset managers will develop an asset management strategy. The first step is to further narrow the scope of tenants by identifying suitable tenants for the building after renovation. The asset managers can use information gained from the market analysis to aid their decisions. This is important as the building should be occupied by tenants for whom they were specifically designed based on their occupant behavioural traits and will suit those traits the best to reduce energy consumption. This will also help developers to improve the detailed design as well, making them more specific for the occupants. Secondly, the asset managers will explore and select various behavioural intervention options as described in section 5.4. These are important to ensure that the asset managers can assert a certain level of control or influence over the energy consumption from the occupant's side during the operations phase of the building. Combining these information the asset managers can also various contractual possibilities that will be used during the operations phase.

The contractual possibilities will include the development of a draft contract that will be used with the future tenants of the building. This is a task that has significant relevance during the final stages of design. The final stages of design will provide several information to create a final picture of the building at delivery. The energy simulations will provide information regarding the energy performance of the building which can be used to set up the contract with distinctions for energy consumed by the building and energy consumed by the occupants. This helps in keeping track of the energy performance of each tenant during the operations phase and meet targets such as Paris-proof targets. Moreover, it was also highlighted during the exploratory interviews as an issue that leads to excessive energy consumption amongst tenants. One of the members from the expert panel stated that "such clauses will help create a boundary within the Paris-proof targets like 30 kWh/m^2 for the building and remaining 40 kWh/m^2 for the tenants". In such a way, the asset managers can ensue that the overall energy consumption is within the targets of 70 kWh/m^2.

Combining the information and data collected through these tasks and activities, the detailed design and related reports can be developed. The project team, collectively, can now assess the detailed design and related reports to validate the energy performance. The project team needs to ensure that the energy performance targets set during the early stages of design have been met by using the reports generated through energy simulations during the design process. Simultaneously, the project team can also validate the feasibility of the developed asset management strategy. The most important aspects to be validated are related to achieving the desired energy performance during operations phase of the building using different behavioural intervention techniques and customised rental contracts to ensure the energy consumption from the occupant's side within a certain limit. Necessary changes can be made at this stage, to improve the design the design and ensure reduced overall energy consumption and thereby bridge the energy performance gap. The final design and reports can be finalised by the end of this design stage.

8.3 Implications of Occupant Focused Design Strategy

Expert opinion were gathered from experts working within the real estate industry and several government organizations to identify and understand the practical implications of the occupant focused design strategy. These experts were selected from external organizations apart from NS Stations to gain a different perspective to the problem and to avoid a possible bias towards the solution, which will help in identifying the practical implications of the design strategy. This will help in further enhancing the application of the design strategy to a real-life project and reap maximum benefits to bridge the energy performance gap. In this way, the design strategy can be further refined to solve the detailed problem statement derived through this research.

Defining energy performance targets were found to have a profound impact on the design process as these targets help designers to keep their design activities under check or within a certain limit. This will help in creating a design that will cater to the specific requirements of the tenants. Contradictorily, the experts questioned selecting a building function with specification regarding type of office or target tenants. The experts stated that "this imposes a huge risk on the real estate developer as they will now have to look for specific tenants which could also create a huge financial risk for the owners". Reducing the flexibility of design as well tenants will help developers cater to a smaller group in a much better way and improve the energy efficiency. However, these will not be favoured by real estate developers as their main ambitions or targets are maximise return on investments from the project.

Energy simulations were found to play a significant role in the design process. One of the experts highlighted that "energy simulations is the first indication of energy consumption when the design is converted to a building". Energy simulations were mostly not carried out during the conceptual design phase due to several uncertainties but carrying them out with the limited information will also help in identifying the flaws in design as some of the missing information itself will highlight the missing aspects from the design. According to the expert opinions, energy simulations play a major role throughout the design and helps in keeping track of the design process within the targets. Additionally, the experts also stated that taking into account the occupant behavioural aspects for the energy simulations conducted during the detailed design phase will help in improving the accuracy of the predictions or estimations. This will help in bridging the energy performance gap with better predictions that match the energy consumption in a real-life scenario.

Using several information regarding occupant behavioural aspects were also found to have a positive impact on the design process according to several opinions provided by the experts. "In a mainstream scenario, energy labels and BREEAM certificates were used to design buildings for energy efficiency, leaving behind several important factors leading to a gap. Whereas, including factors related to the end-users of a building will bridge that gap immensely." Occupant behavioural aspects are often not covered by most energy labels and certificates even though they have significant effect on the overall energy performance of buildings. Moreover, including these aspects into the design of buildings will help reduce energy consumption by occupants as they are able to meet their specific needs. Moreover, collaboration with market parties will further enhance the design process with vital inputs that were not available to the developers earlier. "Further narrowing the scope of tenants during the detailed design phase will also help developers further improve the design and tweak them specifically for a smaller audience", as mentioned by one of the experts.

"Energy performance tracking is often an after-thought for most developers" stated one of the experts. Including the possibilities for various techniques to track the energy performance of buildings will help developers to install required energy performance tracking technologies into the design of buildings. This will also help asset managers to analyse the energy performance of the building in a detailed way during the operations phase. One of the experts also stated that "detailed information regarding energy consumption by occupants is one of the main reasons for excessive energy consumption in buildings. If the tenants actually had knowledge about any activities that lead to excessive energy consumption, they would definitely make necessary changes to it". Lack of data and information on energy performance in buildings is one of the core reasons why asset managers are not able to fix the issues of excessive energy consumption. "Without this information, it is impossible for asset managers to point out the flaws", stated another expert.

One of the most highlighted implications of the design strategy is the development of an asset management strategy, which was usually never done before, as mentioned by one of the experts. One of the expert also mentioned that "developing an asset management strategy during the design phase creates a huge impact on the way the building will be operated as this will bridge the gap between design and operations". In most of the cases, the energy performance gaps are inherent in buildings mainly due to the mismatch between design of buildings and their operations. This will help bridging this gap. Moreover, exploring the behavioural interventions during the detailed design phase will also help the developers include the technical interventions required to support them as well. One of the experts also highlighted that technical interventions are necessary to ensure that the asset manager can influence the occupant's energy consumption.

Another important aspect highlighted by the experts were the drafting of rental contracts during the detailed design phase. One of the experts explicitly stated that "including energy-related clauses within rental contracts are the best way to share energy consumption responsibilities with the tenants of the building". Energy-related contracts are important to ensure that targets such as Paris-proof targets are being met even during the operations of the building. Otherwise, it is a near impossible task to ensure that the overall energy consumption are within the 70kWh/m^2 targets. Another expert stated that "energy-related clauses within rental contracts will help improve the sense of responsibility within tenants as they are now legally bounded to keep their energy consumption within a certain target". The experts also emphasized that these practices are currently not undertaken within the industry and hence asset managers find it difficult to control the energy consumed by the tenants. The experts also highlighted that this solution is also subject to legal implications as well because their are certain limits to controlling occupant energy consumption.

8.4 Conclusion (Phase 4 - Deliver)

The final phase of the research, deliver phase, strives to deliver the detailed solution to the detailed problem stated at the end of the first diamond (problem space). The solution developed in the previous phase (third phase) is structured into a design strategy that focus on occupant behavioural aspects that have a significant impact on the energy performance of the building. The design strategy was developed using the inputs from the exploratory interviews and expert panel opinion highlighting the problems faced within the current practices that eventually lead to energy performance gaps in buildings. RIBA Plan of Work was also used as a base to understand the tasks and activities carried out in different stages of a standard design process. The design strategy consists of three different phases - pre-design, conceptual design and detailed design.

Each phase of the design strategy describes the roles, responsibilities, tasks and activities for each member of the project team. The design strategy is specifically developed for non-residential renovation projects. The project team generally consists of real estate developer, technical developer, asset manager, project manager and sustainability representative. These individuals play a collective role in the pre-design phase and final stages of design to make important decisions that will help bridge the energy performance gap in buildings. During the conceptual design phase and detailed design phase, the technical developer and real estate developer deals with technical aspects of a building and asset manager deals with the occupant-related aspects.

Finally, expert opinions were gathered to understand and highlight the practical implications of this design strategy. This understanding will help practitioners to implement the design strategy in the best possible way. The expert opinion has also helped in further refining the design strategy into a detailed solution for the detailed problem statement. Hence, the final solution is delivered in the form of an occupant focused design strategy to bridge the energy performance gap in buildings and help real estate developers think beyond energy labels and certificates.

Chapter 9

Findings and Discussions

Through an extensive empirical study conducted through case studies and interviews, it was found that energy performance gaps in buildings were mainly due to certain flaws within the current practices followed within the real estate industry. Real estate developers use energy labels mandated by legislation and other green building certificates as a support tool to aid their design decisions for energy efficient building projects. Such a process neglects several important factors related to occupants of the building that have a significant impact on the energy performance of the building. There were also other significant flaws amongst current practices such as lack of sufficient detailed data regarding energy consumption in building to be able to track performance. Subsequently, this leads to several issues with asset management strategies followed within the industry. Collectively, these issues lead to the phenomenon of energy performance gaps in buildings.

Through expert panel discussions with members of the project team for the renovation of the case study building, Stichthage, it was found that several information and data regarding occupant behavioural aspects will help improve the design of several technical components of the building such as building services (HVAC, lighting, automation and control), facade and spatial design. Moreover, energy performance tracking measures were also found to have a significant role within the design process. Using these information gathered, a design strategy was developed with a focus on occupant behaviour in buildings for the renovation of non-residential buildings, that are mainly used as office spaces. This design strategy focuses on all the identified issues within the current practices such as design, asset management and energy tracking, that were found to be the underlying causes that lead to energy performance gaps in buildings. With upcoming policies and regulations such as Paris-proof targets, current design practices required significant interventions to focus on reducing overall energy performance of buildings.

In this chapter, the major findings from this research will be highlighted to emphasize on the need for an occupant focused design strategy. Several important insights gained through the empirical research will be mentioned in detail to support the findings. Moreover, the findings of this research will be discussed in relation to the findings from literature. This will help gain a better understanding about the relevance of the developed design strategy within the industry today. Finally, the limitations of the research will mentioned. These limitations are the shortcomings of this research that limits the generalizability of this study.

9.1 Major Findings

Asset managers play an important role throughout the entire life-cycle of a non-residential building and are mainly responsible for the operations phase of a building. Through this research, it was found that asset managers play an important role within the design process as well. They are able to provide several vial input that will help improve the design by taking into account overall energy consumption of the building. Asset managers will be able to provide vital information and data regarding occupant-related factors that are often neglected due to the use of energy labels and other green building certificates as a design support tool. Occupant-related factors were often not included in the design of buildings as they were not regulated by the legislation. The asset managers can also provide a distinctive perspective to the design of the building using information gathered from the tenants that will further improve the design of buildings to meet the end-user requirements.

One of the most important role for the asset manager during the design process is to develop an asset management strategy during the final stages of design. Through the empirical research, several asset management practices were found to lead to energy performance gaps in buildings such as lack of feedback, lack of energy performance tracking, etc. Hence, developing an asset management strategy during the final stages of design will help in evading this issue with a better technical design integrating several technologies that supports better asset management practices to reduce overall energy consumption of buildings. The process to develop an asset management strategy through the developed design strategy takes into account one of the most important issues related to energy performance gaps, lack of sufficient energy performance data. Sufficient and necessary technical interventions can be implemented into the design according to the needs of the asset managers to track the energy performance and keep them on track.

Within the developed design strategy, asset managers, along with the project team, need to narrow the scope of their tenants by filtering possible future tenants or defining their targets tenants after renovation. This helps in improving the overall design process in several ways to bridge the energy performance gaps in buildings. In the early design phase, scope of tenants can be narrowed by specifying building function with specification such as type of office. Towards the end of the design phase, scope of tenants can be narrowed by describing targets tenants for whom the building was designed for. Narrowing the scope of tenants through the design process will help developers and designers to develop design that caters to the specific needs of the tenants rather creating one design that fits all. Taking into account these specific needs will help in reducing the overall energy consumption within buildings. Moreover, technical components such as facade, spatial design, HVAC systems and lighting need to be designed according to the needs of specific users in order to reduce energy consumption. This is also found to pose a financial risk for the developers or owners but will reap several benefits in terms of energy performance of the building, according to experts.

Another major finding, according to expert opinion gathered regarding the design strategy, is the development of draft rental contracts, specifically with energy-related clauses. Including clauses related to energy consumption by the occupants will provide a sense of responsibility amongst the tenants. These clauses will also help asset managers keep the overall energy consumption within a certain target such as Paris-proof targets. These energy-related clauses should specify distinctive limits of energy consumption by building and energy consumption by the tenants. This will further simplify Paris-proof targets. Moreover, drafting these contracts during the final stages of design will provide several information such as prediction of energy performance and possibilities for behavioural interventions that will aid the drafting of rental contracts. However, some experts also cautioned the legal implications related energy clauses in rental contracts.

Data and information regarding energy performance of buildings is a vital resource that is required to bridge the energy performance gap. In order to reduce the overall energy consumption of buildings, asset managers require data and information with high levels of detail to understand and identify the areas of high energy consumption and devise suitable measures to reduce them. There are plenty of technologies available in the form of smart meters and different sensors to measure and track the energy consumed in buildings. Exploring various possibilities for these measures during the design process will improve the asset management during the operations phase as well. More importantly, these measures are also very important to ensure targets such as Paris-proof can be met during the operations of the building. Energy performance tracking will also benefit the inclusion of energy-related clauses in contracts and add more value to it.

Energy simulations also play an important role in bridging the difference between predicted or estimated energy consumption and the actual energy consumption of the building during the operations of the building. Carrying out energy simulations during the initial stages of the design process will help developers and the project team to keep track of the energy performance of the design developed. These simulations will also help in carrying out iterations during the respective stages of design to further improve them and align it with the energy performance targets. Additionally, these energy simulations only included a few aspects of energy consumption in buildings earlier as they were carried out using energy labels. To the contrary, these energy simulations can also take into account several aspects of occupant behaviour to provide estimations or predictions that are close to a real-life scenario and thus bridge the gap.

Through this research, we found that occupant behaviour is an important aspect that has a major impact on the overall energy performance of buildings. Moreover, literature fell short on providing a suitable design strategy for real estate developers to meet targets such as Paris-proof targets which are becoming increasingly important and might be mandated in the near future. The design strategy developed through this research focuses on occupant energy consumption behaviour within buildings. In other words, the design strategy helps reduce the overall energy consumption of the building by taking into account aspects related to occupants of the building, who contribute immensely to the overall energy consumption. This helps real estate developers tackle several challenges within the real estate industry and accelerate towards Paris-proof targets.

9.2 Discussions

The primary goal of every (private) real estate developer is to make profits (X. Chen, 2023; Fazilet & Artan, 2022). In order to reap profits from real estate, developers ensure that their building can meet the basic needs of a wider target audience. This leads to poor design practices to create a real estate that fits all. This research has found that such practices lead to poor energy performances of buildings. Energy consumption by the occupants were never a worry for real estate developers as they did not face any direct consequences from excessive energy consumption by the occupants of a building. However, with stricter measures regarding energy consumption being implemented, this attitude of real estate developers need to change. With targets such as Paris-proof targets, real estate developers need to think of different ways to reduce the overall energy consumption of their buildings. Reducing the flexibility to accommodate any tenant within a given space will help developers achieve this goal.

In the modern world, real estate is valued in financial terms. This creates huge pressure on real estate developers to maximise their return on investments from every real estate project. However, several authors have highlighted the importance of valuing real estate using other parameters such as sustainability, environmental benefits and health benefits (Warren-Myers, 2012, 2013). Through this research, one of the most highlighted practical implication of the design strategy is the financial risk related to narrowing the scope of tenants and developing an occupant specific design to improve energy efficiency. Experts mentioned that such designs would work effectively for single tenant buildings but might have a financial impact in the case of multi-tenant buildings where huge initial investments might be required but might compromise returns. This valuation techniques must be changed in order to contribute towards the goals of Paris Climate agreement.

Improving the predictions or estimations for energy consumption in buildings is one of the best ways to bridge the energy performance gap (Van Dronkelaar et al., 2016). Literature has provided several solutions to improve the simulations that predict or estimate the energy consumption in buildings. However, taking into account the overarching important concept of sustainability, it is imperative to reduce the energy consumed in buildings. The ultimate aim is to reduce emissions from energy usage for which we need to eventually reduce the amount of energy consumed in buildings. To reduce the energy consumed in buildings, we require better design that can cater to the specific requirements of the occupants. The developed design strategy takes into account these aspects to improve the design and also improve the energy simulations and predictions. Using the design strategy, predictions or estimations for energy consumption can be made by taking into account occupant-related factors as opposed to energy simulation procedures used earlier according to energy labels.

Through this research, initially, energy performance gap in buildings were identified as a flaw within the design process. However, in the later stages of this research, it was found that asset management, or in other words, operations of the building also had certain flaws that lead to energy performance gaps. This highlights the fact that improving the design of technical components of the building will only be complemented with an effective and efficient asset management strategy. Designing buildings with a focus on occupant behaviour alone will not bridge the energy performance gap in buildings and will required asset management interventions such as special rental contracts, behavioural interventions, energy performance tracking, etc. This is crucial with regards to targets such as Paris-proof targets where the energy consumption during the operations phase is regulated.

The drafting of rental contracts and exploring behavioural interventions have a significant effect in improving the overall energy performance of the building. However, these solutions are subject to legal implications. Experts highlighted that "currently, occupants of a building have the ultimate freedom to consume as much energy as they want, provided they are able to pay for it". This way of thinking within the industry leads to issues with rental contracts having energy-related clauses. However, targets such as Paris-proof targets are currently not mandated but could be mandated in the near future by the legislation. In such a scenario, occupants are legally bound to reduce their energy consumption below a certain target that will be established. Currently, these energy-related clauses are not a mainstream practice but could shift towards that direction in the near future with the upcoming policies and regulations. Until such targets are mandated by the legislation, such special contracts might not have huge legal consequences for the tenants, which could reduce the effectiveness.

Energy tracking measures have been highlighted as an important component to bridge the energy performance gap in buildings. Fedoruk et al. (2015), De Wilde (2014) and Martirano et al. (2015) have emphasized on the importance of energy tracking measures to help asset managers keep track of the energy performance during the operations phase and keep them in-line with the established energy performance targets. A. Sonta et al. (2021) emphasizes that these data regarding energy performance of buildings will also improve the design of buildings in future. Through the design strategy developed, several necessary measures to track the energy performance of buildings can be implemented. One of the experts also highlighted that "governments are not introducing new regulations or policies to regulate energy consumed by the occupants because they do not have sufficient data or information regarding the same to cement the arguments and claims". Hence, it is imperative for buildings to incorporate energy performance tracking measures to improve the body of knowledge available currently.

9.3 Limitations of Research

One of the major limitations of this research is that the definition for energy performance gaps were based on the energy labels and certificates within the Netherlands. These energy labels and certificates could look into different aspects in different countries which could limit the generlizability of the developed solution. For example, in France, the energy labels are based on the actual energy consumption of the building unlike the energy labels in the Netherlands. Similarly, energy labels in different countries look into different aspects related energy consumption in buildings and the concept or definition of energy performance gaps could vary by large. Moreover, the developed design strategy is tailored for renovation projects with the assumption that several data and information regarding energy performance and occupant-related factors are already available during the design phase of the project, thereby limiting its generalizability to all kinds of projects. However, some aspects of the developed design strategy can be used as a base to develop a case specific design strategy.

Another major limitation of the research is that the design strategy is developed using information regarding occupant behavioural aspects within a non-residential building. Different aspects of occupant behaviour could be different in the case of a residential building. The developed design strategy focuses on factors that are important and applicable to non-residential buildings that are mainly used as office spaces and hence limits it applicability to residential building projects. Also, only one building was used as a case study to identify the issues and challenges within current practices followed within the real estate industry and devise a solution for these issues and challenges. However, there could be more or different challenges for different projects that needs to be addressed in order to bridge the energy performance gaps. Some of the interviews conducted for this research were in Dutch. Some information such as emotions of the participants might have been in lost in translation of the transcripts.

Chapter 10

Conclusion and Recommendations

Buildings are an essential component of human life. Due to the exponential population growth creating a huge demand for more buildings and infrastructure, the energy consumption in buildings are a growing concern as most of the energy is produced from fossil fuels emitting huge amounts of GHG emissions into the atmosphere that eventually deteriorates the environment. Hence, energy efficiency is an important aspect within buildings as far as governments are concerned. Most of the rules and regulations regarding energy efficiency only look into certain aspects leading to the aforementioned concern regarding energy consumption within buildings. Developers use these legislative requirements as a tool to support their design decisions and therefore neglect several important aspects that have a significant impact on the overall energy performance of buildings. Through an extensive literature review, the underlying causes for the energy performance gap in buildings were found to be occupant related aspects and their significance within the design of buildings.

Through further examination of occupant behaviour and their impact on the energy performance of buildings, they were classified into three different categories - occupancy, interactions and behavioural efficiency. These aspects were found to have a significant impact on the overall energy performance of non-residential buildings. A case study was used to gain vital insights into the current practices that lead to the energy performance gap in buildings. The current design practices that focus on energy labels and certificates as support tool to aid design decisions were found to be a major issue. Moreover, the current asset management practices were also found to have seevral flwas such as energy performance tracking and influence on occupant energy consumption. Using these information and the case study, aspects of occupant behaviour were linked to the design of several components of the building such as building services (HVAC, lighting, automation and controls), facade and spatial design. Information regarding occupant behavioural aspects will improve the design of buildings and help cater to the specific requirements of the end-user.

An occupant focused design strategy was developed through this research to bridge the energy performance gap in buildings by incorporating aspects that represented the grey area of energy consumption and were often neglected or overlooked within current practices. The roles, responsibilities and tasks for members of the project team are described through this strategy. The asset managers play an important role during the design phase to provide several vital information and different perspective on occupant-related factors. The design strategy also involves the development of an asset management strategy during the design phase of the project with several tasks such as drafting special rental contracts and exploring the possibilities for behaviour interventions. Collectively, this design strategy will help real estate developers to think beyond energy labels and create energy efficient non-residential buildings with much lower energy performance gaps. This design strategy is important for developers to meet targets such as Paris-proof targets which regulates the overall energy consumption in buildings and are important to fulfill the goals of Paris Climate agreement.

10.1 Answers for Research Questions

What is the energy performance gap inherent in buildings? What are the underlying causes for energy performance gap in buildings?

Energy performance gap is defined as the mismatch between predicted or estimated energy consumption in buildings through energy labels and certificates, and actual energy consumption in a building. Energy labels and certificates, especially those implemented in the Netherlands, only take into account few aspects such as energy consumed for heating, cooling and lighting. Designers and developers use these energy labels and certificates as a support tool to aid design decisions leading to energy performance gaps. The actual energy consumption figures include several other aspects related to energy consumption in buildings such as occupant-related factors. Several underlying causes were identified through this research that leads to the gap such as early design decisions, lack of effective building energy performance monitoring and relevant energy performance data, uncertainties during the design stage and occupant behaviour. Through further examination, occupant behaviour was found to have significant impact on the energy performance of buildings as they constitute a major portion of the actual energy consumption figures and are often overlooked during the design process. Moreover, future policies and regulations such as Paris-proof targets set limits for overall energy consumption of buildings that include occupant-related energy consumption.

What are the different aspects of occupant behaviour in buildings? What effect do these aspects of occupant behaviour have on the energy performance of buildings?

Through literature, occupant behaviour was classified or categorised into three main aspects - occupancy, interactions and behavioural efficiency. Occupancy refers to the information pertaining to the status of occupants within a building. Parameters such as presence (entry, exit, presence, absence), location (spatial presence, change in location) and activity (function, occupation) can be used to describe occupancy patterns of occupants within a building environment. Interactions refers to the way in which occupants control or use technical components of a building to maintain required levels of comfort within a building environment. Occupant interactions are further classified into interactions with building services (HVAC, lighting, escalator, elevators, etc.), facade or building envelope (windows, blinds, ventilation, etc.) and user systems (electrical appliances and other plug loads). Behavioural efficiency refers to the ability of asset managers to influence occupant behaviour to improve the energy performance of buildings. Literature and industrial practices suggest several different ways to ensure behavioural efficiency such as traditional approach, feedback approach and smart technologies.

Occupancy patterns have a significant impact on the energy performance of the building as these behavioural aspects trigger several sensors to activate or deactivate various technical systems such as HVAC, lighting, etc. For example, as occupants of an office space arrive, they switch on heating/-cooling systems, lighting, etc. and vice versa as they leave. These aspects also determine the comfort levels required by occupants within the building resulting in significant energy consumption. Humans interact with various components of the building to maintain comfort levels such as thermal, visual, air quality, etc. within the building. Each interaction with different components of the building consumes energy to cater to the comfort requirements, thereby impacting the energy performance of buildings. Behavioural efficiency can be ensured amongst occupants by asset managers to improve the occupant energy consumption behaviour. Traditional approaches such as creating awareness, providing education or training, motivation, instruction and signage helps in improving energy consumption. Asset managers can also ensure behavioural efficiency by providing essential feedback to tenants regarding their energy consumption patterns with the help of data. Several smart technologies can be used to detect and analyse energy consumption behaviour of occupants within building to devise necessary interventions.

How can we incorporate these aspects of occupant behaviour into the design of buildings to bridge the energy performance gap?

Due to the significance of occupant behaviour within the energy performance of buildings, it is important to incorporate these aspects into the design of buildings. Robust building design strategies that integrate occupant behavioural aspects will mitigate the negative impact of occupant behaviour on the energy performance of buildings. Developers and asset managers require better design strategies that will help them develop building design that caters to the specific behavioural needs of occupants and help them reduce energy consumption through occupant focused design. This also helps occupants reduce their energy consumption within buildings and thereby reduce the overall energy consumption of buildings. An expert panel discussion was conducted with project team members of the renovation project for the case study building, Stichthage. This expert panel discussion was used to develop a link between occupant behaviour aspects and the design of technical components of a building.

Facade design for a building can be improved using several information regarding the type of activities carried out within the office space. Facades have an impact on the energy performance of the building as they are the outer shell of the building that separates the inside of the building to the outside of environment. Information regarding the type of activity carried out within an office space and other occupancy patterns will help develop an energy efficient spatial design. Similarly, several vital information regarding occupancy patterns and interaction patterns will help developers design other technical components of the building such as lighting, HVAC systems, automation and control. Additionally, energy systems of a building also play an important role to bridge the energy performance of buildings and bridge the inherent gap through energy storage and on-site energy generation options. Finally, energy performance tracking were found to be an inevitable aspect to bridge the energy performance gap in buildings. Detailed data and information regarding energy performance of buildings is required to track energy consumption.

How can we integrate these occupant behavioural aspects into a design process/strategy for a building (re)development project?

Occupant focused design strategies will help developers think beyond energy labels and certificates to bridge the energy performance gap. Occupant-related factors are aspects that are often overlooked or neglected by designers and legislation leading to energy performance gaps in buildings. Using the important information gained to link occupant behavioural aspects and the design of buildings, a design strategy was developed to help real estate developers to take into account factors that are often neglected but at the same time time, have a significant impact on the overall energy performance of the building. RIBA Plan of Work was used as a reference design strategy to develop the occupant focused design strategy. The design strategy includes three different phases - pre-design, conceptual design and detailed design as illustrated in figure 8.1.

The pre-design phase includes activities and tasks for the project team, collectively, to define the parameters of the project that will aid their design process. The project team members will review the set of requirements and all issues related to the current energy performance of the building. Next, the project team defines a particular building function for the building after renovation with specifications. This can be done based on the business developed for the project and analysis of the current market situation. Then, an energy performance target will be defined that will be achieved through the renovation based on the organizational goals and legislative requirements. Collectively, these information will define the scope of the project and initial project briefs could be developed.

The conceptual design phase includes two major activities and responsibilities for technical developer as well as the asset manager. The technical developer and the real estate developer deals with the design of technical components of the building such as facade, spatial design, building services and energy performance tracking. The asset manager provides several inputs regarding occupant-related factors such as occupancy, interactions and behavioural efficiency. The inputs from the asset manager will help the technical developer and real estate developer to improve the design of technical aspects of the building by exploring several different possibilities. A conceptual design will be developed using these information. Moreover, energy simulations will be carried out on the conceptual design using all available information at that stage of the design to determine the energy performance of the design so far. Necessary changes can be made to keep the energy performance of the design in line with the initial targets determined and a preliminary design can be developed.

The detailed design phase includes the development of detailed design for components such as facade, spatial layout, building services and energy-related aspects of a building. These designs will be developed using information gathered from the previous phase regarding occupant behavioural aspects. Simultaneously, asset managers will develop an asset management strategy which includes a draft rental contract, possibilities for behavioural interventions and further narrowing the scope of tenants to define their target tenants based on the design developed. Energy simulations carried out in this phase will include several information regarding occupant aspects to enhance the prediction or estimation of energy consumption during the operations phase. These prediction will also be significant inputs for the asset managers to draft special contracts with energy-related clauses. The project team will validate the detailed design developed along with the asset management strategy and make necessary changes to deliver the final design.

What are the practical implications of the design strategy when implemented in a (re)development project to bridge the energy performance gap?

Expert opinion was gathered to understand the practical implications of the developed design strategy. Overall, the design strategy helps to bridge the energy performance gap in buildings by thinking beyond energy labels and certificates, and incorporating aspects that are often overlooked and have a significant effect on energy performance such as occupant behaviour. Most important practical implication is regarding future policies and regulations such as Paris-proof targets which regulates overall energy consumption of buildings including the energy consumption related to occupants and their behaviour. In order to meet such targets, the design of the buildings should incorporate occupant behavioural factors and take into account the overall energy consumption of buildings. Experts also highlighted that such targets are very important for all recent real estate projects and could be mandated in the near future.

Selecting a building function with specifications (type of office) and defining energy performance targets during the early design phase will help improve the design process and energy efficiency of the building. However, these activities might pose a financial risk for the real estate developer and owner. Also, most real estate developers and owners will value financial benefits rather than sustainability benefits. Energy simulations are also an important part of the design process and can be further improved with the integration of occupant behavioural aspects to provide more accurate predictions that are close to a real-life scenario. Moreover, carrying out these energy simulation in multiple phases of design will further enhance the predictions and reduce uncertainties. Additionally, energy performance tracking is a major implication and will help in bridging the energy performance gap to a significant extend. Expert highlighted the importance of energy performance tracking measures to accurately measure and track the energy consumption of buildings.

Another major implication highlighted is that the design strategy will stimulate developers and designers to think beyond energy labels and certificates to design buildings to reduce their overall energy consumption rather than few aspects covered by the energy labels. Important factors such as occupant behavioural aspects will shed light on the grey areas of energy consumption which were often neglected or overlooked earlier. Experts also highlighted the implications of developing an asset management strategy. During the detailed design phase, developing an asset management strategy will also help developers incorporate required technical interventions as well to aid asset managers during the operations phase. According to their opinion, rental contracts with energy-related clauses is the best way to reduce energy consumption by the occupants. Having energy-related clauses will make the tenants legally responsible to reduce their energy consumption. Moreover, such special contracts are a necessity to meet targets such as Paris-proof targets which also regulate energy consumed by the occupants within a building.

How can we bridge the energy performance gap inherent in buildings due to energy labels and certificates during the design phase of a (re)development project?

The energy performance gap inherent in buildings due to energy labels and certificates can be bridged during the design phase of a (re)development project by incorporating different aspects of occupant behaviour that are often overlooked by developers as well as the legislation into the design of buildings. Additionally, developing an asset management strategy to ensure the energy performance predictions during design phase is met in he operational phase as well. In such a way, the overall energy consumption of the building can be reduced drastically. Moreover, such a design process sheds light on the grey areas of energy consumption that needs to be addressed to meet the important Paris-proof targets. Inclusion of these aspects in the design process will reduce the mismatch between predicted or estimated energy consumption and actual energy consumption within buildings.

10.2 Scope for Future Research

Closing of energy performance gap in buildings requires a much wider perspective regarding the underlying causes that lead to the gap. The focus of this research was on occupant behaviour and does not cover all identified underlying causes that lead to the energy performance gaps. Future research could focus on several other underlying causes that lead to these gaps in buildings as stated in literature. A better understanding about the other underlying causes will help in bridging the gap completely in buildings. Moreover, there are several other ways to bridge the energy performance gap in building by focusing on other underlying causes which can be explored through further research. Such research will also help provide alternative methods for real estate developers to bridge the energy performance gap with a better financial advantage to occupant focused design strategies.

Future research could also focus on analysing the effectiveness of this design strategy using more case studies. Using one case study for this research is also identified as a limitation for the work. The design strategy could be further enhanced for generalization using more case studies to understand and highlight its effectiveness. The perspectives of policy makers could help gain a better understanding about energy performance gaps and its significance. Research on the role of policy makers in bridging the energy performance gap in buildings and a better understanding about future policies and regulations will provide better insights for real estate developers. These insights could also help address the financial risks related to the design strategy that requires developers and asset managers to reduce flexibility and diversity among occupants. Further research can also explore the trend of future policies and regulations regarding energy performance of buildings and their impact on the energy performance gap in buildings.

Human behaviour is complex and requires in-depth knowledge on various aspects. Future research could focus on the role of certain aspects related to social sciences and human psychology that will help in anticipating occupant behaviour within buildings with much more clarity. These insights will improve the link between building design and occupant behaviour. Future research could also be carried out to gain a better understanding about the role of asset managers during the operations phase to bridge the energy performance gap. The operations phase of buildings also play a crucial role in bridging the energy performance gap in buildings which requires further attention. Future research could explore various possibilities for behavioural interventions and special rental contracts to limit the energy consumption from the occupant's side.

10.3 Recommendations for NS Stations

The case study has highlighted several organizational challenges that hinders the effective application of the design strategy within the project undertaken at NS Stations. These challenges include lack of awareness and knowledge regarding the behavioural aspects of the design strategy, lack of information and sufficient data to incorporate occupant behavioural aspects into the design of buildings and lack of in-house skill-sets and personnel to implement this strategy. Addressing these challenges can take time within an organization and might require interventions that affect other domains of the organizations sole function. However, the organization can start with the basics of bridging the energy performance gap which relates to the tracking of energy performance of their buildings currently.

Energy tracking is found to have a significant impact and play a crucial role in bridging the energy performance gap. Installing smart meters and a strong energy evaluation database will be good starting steps to track and analyse the energy performance of buildings within their portfolio. In the case of a renovation project, budget plays a huge role regarding the extend of addressing the energy performance gap in buildings. Developers and asset managers can begin with addressing the most important behavioural aspects of a non-residential building such as occupancy patterns and behavioural interventions within projects of relatively smaller scale. Behavioural interventions that can be stimulated by asset managers, that found to have relatively less or no financial impact on projects, can be starting steps. Setting up rental contracts that ensure the energy performance targets during the design stage are also met during the operations phase will help them achieve important targets such as Paris-proof targets.

Based on the size of investments in projects, developers can incorporate various aspects of occupant behaviour into the technical design of buildings to help tenants reduce overall energy consumption and thereby improve the energy efficiency of buildings. A strong recommendation for NS Stations and other major real estate developers, having high sustainability ambitions, is to start valuing real estate beyond its financial value. Several research highlights other important gains, apart from financial gains, to play a major role in determining the value of projects. A major change in attitude towards real estate valuation, by taking into account the environmental, health and other sustainability benefits, will help the real estate industry to move forward and contribute immensely in mankind's fight against climate change and protect the environment and resources for future generations to come. As Albert Einstein rightly stated, **"we cannot solve our problems with the same thinking we used when we created them"** adds further value to this notion. In the very essence of sustainable development, nothing is more important than the life we can sustain on earth.

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Appendix A

Interview Protocol

A.1 Exploratory Interviews and Expert Panel

1. Participants were selected according to their respective roles within the organization, responsibilities related to the case study project and years of experience.
2. The selected participants were contacted via email with a short description of the research and intend to conduct interviews with them.
3. Based on their response, an appointment was made according to mutual availability and the participants were given a brief regarding the interview process along with the informed consent form. The informed consent form was mainly to obtain consent from the participants to participate in the interviews and record the interviews for further analysis.
4. The participants were provided the themes for interviews 2-3 working days prior to the appointment for preparation purposes.
5. Prior to the interviews, the signed informed consent forms were collected and recording arrangements were made accordingly. The recordings were mainly arranged via Microsoft Teams.

A.2 Expert Opinion

1. Participants were selected mainly according to their experience levels within the industry and their expertise with building energy efficiency and real estate (re)development.
2. Participants were initially contacted via email or LinkedIn to identify their interest in the research topic and willingness to participate in interviews or discussions.
3. Based on their willingness to participate, appointments were made and they were provided the informed consent forms to obtain their consent to participate and record the conversation.
4. The participants were provided a brief explanation about the problem description obtained through the research and themes for discussion roughly 3-4 working days in advance.
5. Prior to the interviews, the signed informed consent forms were collected and recording arrangements were made accordingly. The recordings were mainly arranged via Microsoft Teams.

TEMPLATE 2: Explicit Consent points

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated *25/04/2023*, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves: Audio/Video recorded interview which will be transcribed as text and the recording will be deleted after the course of the study.	☐	☐
4. I understand that the study will end on 31/10/2023 (tentative). This date will be decided during the green light meeting.	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
6. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) collecting specific personally identifiable information (PII): name, designation, location and email address and associated personally identifiable research data (PIRD) with the potential risk of my identity being revealed public.	☐	☐
7. I understand that some of this PIRD is considered as sensitive data within GDPR legislation, specifically data related to their specific roles and responsibilities.	☐	☐
8. I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach securely storing the data on TU Delft one drive with limited access and deletion of recording after the study duration.	☐	☐
9. I understand that personal information collected about me that can identify me, such as name, email address, job designation and location will not be shared beyond the study team.	☐	☐
10. I understand that the (identifiable) personal data I provide will be destroyed immediately after the duration of the study.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
12. I understand that after the research study the de-identified information I provide will be used for the master thesis report that will be publicly available on the TU Delft repository.	☐	☐
13. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐
14. I agree that my real name can be used for quotes in research outputs	☐	☐

D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		
16. I give permission for the de-identified video/audio recording and excel sheets that I provide to be archived in TU Delft repository so it can be used for future research and learning.	☐	☐
17. I understand that access to this repository is open but can be restricted on request from the collaborating company/organization.	☐	☐

Signatures

____________________________ ___________________________ _________

Name of participant [printed] Signature Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Sam Joseph

__________________________ ____________________ _________

Researcher name [printed] Signature Date

Study contact details for further information:

Sam Joseph

Back to text

Appendix B

Themes for Interviews

B.1 Exploratory Interviews and Expert Panel

- **Energy Consumption in Buildings and Data/Tracking** - Energy consumption data was reviewed and discussed for buildings within the NS Stations portfolio. The issues and challenges regarding energy usage were the main focus to identify the problem. Current measures used to track energy performance in buildings to understand the impact of various occupant behavioural aspects.
- **Energy Labels and Certificates** - Prediction or estimation of energy consumption in buildings according to energy labels were discussed. The importance of energy labels and their role in improving the energy efficiency of buildings.
- **Energy Performance Gaps** - Awareness and knowledge regarding energy performance gaps were discussed along with analysis of data from NS Station's portfolio.
- **Underlying Causes** - The underlying causes that leads to energy performance gaps found through literature were discussed to relate them to current practices.
- **Current Design Strategies** - The different strategies used to approach different projects were discussed briefly to understand the design process and identify flaws within them.
- **Design Process** - The design process followed for most renovation projects were discussed in detail to understand the methodology used.
- **NS Ambitions and Goals** - Sustainability ambitions, goals and targets of NS Stations was discussed to understand their sustainability approach and translation of these ambitions into achievable targets for projects carried out.
- **Stichthage Renovation Process** - Detailed discussions were carried out to understand and analyse the entire process of renovation.
- **Stichthage Renovation Approach** - Ambitions and goals to be achieved through the renovation were discussed. The project strategy and approach were analysed in detail to detect the flaws within the process that leads to energy performance gaps.
- **Occupant Behaviour** - Occupant behaviour within buildings and their impact or effect on the energy performance of office buildings were discussed. This helped in understanding the negligence of such aspects from the design process. The knowledge and awareness among practitioners regarding these aspects were analysed.

B.2 Expert Opinion

- **Energy Labels as Design Tool** - The issues and challenges related to using energy labels and other certificates as a design support tool were discussed.
- **Future Policies and Regulations** - Trends towards future policies and regulations regarding energy efficiency and energy usage are discussed. This helps in understanding the role of anticipating them during the design process.
- **Energy Performance Gap** - Awareness and knowledge regarding energy performance gap and its significance regarding energy efficiency were understood.
- **Bridging the Gap** - Different strategies and ways to bridge the gap was discovered. Also, current practices were analysed with their effectiveness.
- **Early Design Process** - Role of various decisions made during the initial stages of design and their impact on the outcome of the design process or the entire project is studied.
- **Design Process for Energy Efficiency** - Various strategies and design processes used by real estate developers to design building for high energy efficiency were discussed.
- **Importance of Occupant-related Aspects** - Occupant behaviour and other aspects related to occupants that have a significant impact on energy performance were discussed.
- **Complexity of Occupant Behaviour** - The depth or width of knowledge required to understand occupant behaviour within buildings were discussed with experts.
- **Energy Tracking** - Various methods used currently to track energy performance of buildings as well occupants and their effectiveness was discussed.
- **Linking Occupant Behaviour to Design** - The different ways of linking occupant behavioural aspects to the design of buildings and its components were discussed.
- **Current Extend of Occupant Focused Design** - Different ways in which occupant behaviour or any other aspects related to occupants were incorporated in design were discussed.
- **Energy Simulations** - The role of energy simulation in energy efficiency of buildings and different methods and procedures for simulations were discussed. The main factors and attributes considered for energy simulations were identified.
- **Asset Management Strategies** - Different asset management strategies used currently within the industry to improve energy performance was discussed.
- **Rental Contracts** - Different types of rental contracts used within the real estate industry to improve energy efficiency of buildings was analysed.
- **Energy-related Clauses** - The importance of energy-related clauses and the current practices related to them are studied in detail through discussions.
- **Extend of Controlling Occupant Behaviour** - Different strategies and methods used by asset managers to control or influence occupant behaviour for reduced energy consumption were analysed. Its importance and complexity were also discussed.
- **Role of Asset Managers in Design Process** - Inclusion or role of asset managers in design process was discussed to find their importance in the design process.

Appendix C

Interview Summary

C.1 Exploratory Interviews

Energy Consumption in Buildings

- Reducing energy consumption is the most important step towards sustainability and is implemented within NS as Energy Triangle.
- Main ambition for NS Groep is to be fossil free by 2040. But apart from this for real estate the ambition is to be Paris-proof according to the norms set by DGBC.
- Lack of smart meters within most of the buildings does not give a clear picture about the energy performance gap in buildings.
- The tenants of an office space are employees of an organization and they do not have direct financial implications for the energy they consume and hence they do not exhibit very responsible behaviour with regards to energy consumption
- Energy consumption is turning out to be a huge problem for most real estate owners and developers but are only regulated by energy labels which is clearly not enough.
- We need stricter rules to control energy consumption by users to improve energy efficiency of buildings and reduce overall energy consumption.
- Reduction of overall energy consumption must be the main priority of all real estate developers but this is mainly from building energy consumption which is the only thing that can be controlled by developers right now.
- We need better technical interventions within our buildings to understand the actual energy consumption trends. This is important to detect the areas that need improvements.
- Track the energy consumption behaviour of the tenants. Implement smart meters and other technologies that help give a better idea about the energy consumption behaviour. Information and data about the energy consumption behaviour is the most important tool for designers and developers to design buildings in the most energy efficient way.
- DGBC looked at the overall emissions within the Netherlands and divided them according to the functions of the building and set targets for energy consumed by buildings per square meter per year for buildings with different functions.
- Currently working on both long term and short term strategies. Also has an agreement with the government to reduce primary consumption by 3.5% per year and fossil consumption by 5.5%

per year. This has to be reported every year till 2026.

- Not enough data is available to track the carbon emissions and energy consumption from the users alone.
- More attention is being paid day by day to energy consumption within buildings. Especially, reducing the energy consumption.
- Energy consumption should be a responsibility for the tenants as well in order to reduce energy consumption.

Energy Performance Gaps and Underlying Causes

- The energy performance gap cannot be seen as a problem of the real estate owner or client. It is the problem of the users of the building.
- EPG is always a problem of the users. Reducing the energy consumed by the users is the best possible solution to close the gap.
- We currently don't know the root cause for the gap. We do not have information or data to prove that the energy performance gap is caused completely by the users or inefficiency of the building systems. Also not enough in-house data management skill and tools to understand the energy performance gap.
- Most of the time we are the owners of the building and we provide energy, gas, etc. to the tenants but we do not have enough technology implemented to understand the specific behavioural patterns regarding energy consumption behaviour of the occupants.
- No information available on the composition of the energy performance gap. Details are needed to understand the problem in depth and to find a feasible solution to close the gap.
- Maybe use the idea of 'champagne glass tower' to understand the distribution of energy to the building and its usage within different sections of the building. Smart meters can be used for understanding the energy usage in each section of the building, maybe according to floor or tenants.
- Energy performance gap was caused by the legislation and majority of the gap was contributed by the energy consumption of the occupants or tenants of a building which makes it a problem for them rather than the owner

Energy Labels and Certificates

- Energy labels are not specific enough and only looks at basic building features and does not look into the important aspect of users of the building.
- Government is monitoring buildings only for basic consumption and looking at the gap the energy labels do not serve a purpose.
- Energy label is just a gimmick introduced by the government to indicate sustainability but not enough to meet the targets of sustainability in reality.
- Energy labels only make the users aware of the performance of the building as an individual unit but does not provide any idea to use the building in an energy efficient way.
- Energy labels do not help make a building energy efficient. Lacks provision of awareness to the user of the building on using the building in an energy efficient way.
- The estimation method suggested by the legislation should be the changed because it is giving a wrong impression for the designers and developers.The estimations never look at how the

building is used in real-life. This is why we can never get correct estimates and designers never look into the users part because of this.

- Sustainability must go one further than energy labels to be actually sustainable or energy efficient but also requires investment.

Current Design Strategy and Process

- Start with requirements that give specification and boundaries of a project. These can be financial, technical or based on planning. Sustainability mainly comes under technical requirements. Make an outline of the ambitions and targets for the renovation of the building.
- Research on different possibilities to achieve these targets and ambitions. Conduct desk research on various available technologies to meet these ambitions and targets. Make an estimate for various cases and present them to the top management/board.
- The preliminary design is formed based on these basic requirements. This design is reviewed by NS and other stakeholders for further changes or additions. The review also looks if all the requirements are met.
- Information collected and plans devised at the end of every stage of the project is analysed also by the sustainability department. A summary report is made at the end of each stage of the project and discussed with the top management and sustainability department for revisions and checks.
- The concept of the office being designed for Stichthage is going to look into occupant behaviour but only to certain extend due to financial constraints.
- Energy simulations are carried out in the final stages of design as these simulations often require several information from design of the building, which is usually available once a major portion of the design process is completed.
- Doing anything beyond the legislative requirements require higher initial investments and does not guarantee return on investments. The tenant is the one that reaps benefits of having highly energy efficient buildings in the form of reduced energy bills

Stichthage Renovation Strategy and Process

- The main target for Stichthage was to fix issues with Facade and installation/insulation of the building. The building was nearing end-of-life-cycle. Fire safety problems with building and station due to overlap with station. The project was part of making the entire portfolio Paris-proof. Being fossil free, having high energy labels for energy efficiency, etc.
- Paris-proof is the main ambition for Stichthage and green energy generation is also an important ambition or goal for the building as it is the biggest building within our portfolio.
- Improvements with the facade and insulation of the building is also prioritized as it has a huge impact on the energy performance of the building based on current understanding.
- EPG was not considered for Stichthage renovation at the moment. The main reason it was overlooked was due to unclear picture regarding technical possibilities. Problems with energy suppliers due to high demand that could not be met.
- Plans to use smart meters to monitor energy consumption for each floor. This is already being used at train stations. But the implementation is confusing - should it be per tenant or portion of the building?
- Ambitions to achieve BREEAM certificates. BREEAM certification was selected mainly be-

cause of the broad scope compared to LEED and WELL that only focus on the well-being aspects of the users of the building and a few others. BREEAM covers everything from energy efficiency, waste management, user well-being to land-use and materials. BREEAM also needs to be considered during operations due to different certificates for construction and operations.

- Budget of the project was fixed in two different aspects. One was by making an estimate on assumptions for technical interventions of the building for renovation. Second was made through market research for return of investments and rental income after renovation based on market conditions. The combination of the two methods was used to decide the budget of the renovation project.

Challenges for Stichthage Renovation

- The project started in 2017 but was delayed due to pandemic and was resumed with a different project team and project manager.
- The external environment of the Stichthage building causes a huge hinderance to the adoption of lot of technical interventions for energy efficiency. Live train station is part of the building or situated just next to the building.
- No feedback was extensively taken from tenants of the building till date. Only few complaints regarding cooling and heating issues were received till date. Cannot get a lot of inputs from the tenants regarding energy efficiency measures and tenants do not have a supporting attitude towards sustainability and reduced energy consumption.
- Not much opportunities for on-site electricity generation due to limited roof area and surrounding environment. The surrounding building also reduces the possibility for renewable electricity production and also natural lighting of the building.
- Return on investment for sustainability from the renovated building must be as high as possible due to the market bounce back from COVID pandemic.
- Safety aspects of the project increases the load on the budget and reduces the budget towards sustainability.
- No technical information about the composition/breakdown of the gap. EPG was not prioritised as a sustainability target.
- Top management need not be aware of the energy performance gap and its consequences. For the top management, revenue is important than sustainability. NS is a private organization and needs to make profits to sustain in the industry.
- It is always a dilemma between revenue generation and sustainability ambitions for Stichthage, but sustainability will be prioritized to a certain extend for Stichthage.
- We do not have smart meters in most of our buildings to gain a detailed understanding about the energy performance of each tenant to be able to give them feedback about their energy consumption. We also do not have any other smart technologies implemented in our buildings to track the energy performance in detail

Occupant Behaviour

- We do not have sufficient in-house knowledge and resources to implement extensive study regarding the energy consumption behaviour of the tenants within the buildings. We rely highly on market parties and experts from the industry to gather information regarding energy consumption behaviour of different types of tenants.
- Providing comfort for the tenants with different aspects such as thermal comfort, lighting com-

fort, etc. is also equally important as reducing the energy consumption of the building.

- Not enough manpower and knowledge within the organization to implement behavioural interventions for tenants to reduce the energy consumption.
- Tenants are the most important stakeholder but cannot help in many ways. Tenants have different demands and energy usage behaviour. Their inputs will only help with improving comfort and their needs but will not contribute to energy efficiency. The users are not aware or sometimes do not care about sustainability. Climate control uses most energy due to the behaviour of the users.
- Currently not a lot of targets focus on occupant or tenant behaviour. But slowly being set in motion to study the energy efficiency through occupant behaviour.
- There are certain limits to how much we can control the behaviour of occupants of an office building to improve their energy consumption behaviour

C.2 Expert Panel

Energy Labels as Design Tool

- Currently, most of the projects focus mainly on energy labels due to financial limitations and demand to generate revenue that matches the investment made on the renovation.
- Awareness within the project team is important to set the sustainability efforts in motion. The easiest starting point is energy labels but definitely not enough.
- Energy labels are always an easy target when it comes to sustainability because it is mandated by legislation and needs to be met irrespective of other aspects.
- Energy labels are not specific enough and only looks at basic building features and does not look into the important aspect of users of the building.
- Energy labels only make the users aware of the performance of the building as an individual unit but does not provide any idea to use the building in an energy efficient way.

Future Policies and Regulations

- Tenants will be held responsible for energy consumption within buildings through future rules and regulations regarding building energy performance. Rules will start to focus on the occupant consumption within buildings. Thinking about the possible future policies regarding sustainability of the buildings will also help in being prepared for them and also increase the demand amongst tenants as they do not want to shift offices every time the rules and regulations change.
- Energy performance gap will be the next main focus to devise sustainability ambitions, policies and targets. Right now it is too much of asking within the given budget.
- The ambition for bigger buildings needs to be higher or else it becomes harder in future to meet targets set by government.
- Carbon reporting is not going to be mandated soon in the EU. However, some countries within the EU might mandate it nationally.
- Policy makers are aware of the issue with energy efficiency in buildings but do not have sufficient evidence from research to introduce policies and regulations. Rules, regulations and policies are not being changed or directed towards occupant behaviour due to the lack of sci-

entific evidence.

- Governments need more evidence regarding the occupant behaviour impact on energy performance of buildings to be able to introduce regulations.
- EPBD Directives are changing every 6 months to make the energy performance of buildings regulated to reduce the carbon emissions from their usage and also reduce the dependency on fossil fuels for building energy.
- Not a lot of research has been done in the recent past to motivate policy makers that energy performance gap is important to be bridged to reduce emissions from buildings.

Bridging the Gap

- EPG has been a hot research topic for the past 10 years and is becoming more significant day by day due to energy crisis and climate crisis. IBPSA is the international governing body for regulating energy performance in buildings.
- Most of the project team members were aware of the energy performance gaps in buildings. However, some of the team members were not aware of the term. The main concern raised was about the extend of energy performance gap which was unknown to most project team members.
- Awareness of the energy performance gap within the project team is important to meet the targets. Also the mindset and motivation of the people working on projects is important to implement these sustainability ambitions in each project.
- An alternative method to close the energy performance gap from the methods mentioned in literature is to evaluate the carbon performance of buildings and reduce the energy consumption accordingly. Understanding the sources of carbon emission from building energy consumption will help in detecting the areas of excessive energy consumption and reduce accordingly.
- Green energy consumption will not be counted within the energy performance gap of buildings as there is no carbon emissions from these consumption. Hence, carbon performance of buildings with respect to energy consumption will give a better idea for reduction measures and close the performance gap.
- Designing a building revolving around occupant behaviour is important to bridge the energy performance gap with regards to occupant behaviour.
- Reduction of energy consumption in buildings should be the basic solution to close the energy performance gap in buildings.
- Consuming completely green energy is not a typical solution as the production capability for the current demand does not match. Green energy production on-site should be considered in the energy performance as positive energy and compensate or offset the fossil fuel energy used by the building.
- Also carbon offsetting measures such as planting trees or having a green roof or facade will help offset the carbon emissions from the energy used by the building.

Design Strategy for Energy Efficiency

- Ambitions regarding sustainability is higher if the building remains in the portfolio for a longer period of time due to a bigger duration to generate revenue to earn back the money invested and also make profits.
- The most widely used strategies for building energy efficient buildings is by aiming for high en-

ergy labels or sustainable building certificates such as LEED and BREEAM. These certificates and energy labels are used as support tools to design buildings for energy efficiency.

- Currently, energy efficiency has its limits, which are the ones stated by the legislation. Developers and designers will not think beyond these legislative requirements until and unless they provide a good business case or guaranteed return on investments. Unfortunately, currently such initiatives pose a huge financial risk for investors or owners.
- Most of the legislation in the Netherlands focus on reducing energy consumption of technical components rather than tenants of the building which gives the tenants freedom to consume energy in an irresponsible manner.

Importance of Occupant Behaviour and Complexity

- Occupant behaviour is very important to understand the energy performance of a building. It covers a huge portion of the actual energy consumption in buildings.
- However, the limitation with occupant behaviour is the uncertainty or lack of knowledge about the best practices for improving occupant behaviour to reduce energy consumption.
- The way offices operate are changing and favourable for sustainability. More work from home is being encouraged by companies to reduce energy consumption in offices. This makes it even more important to incorporate certain aspects of occupant behaviour into the design of buildings.
- Occupants are also supposed to be held responsible for the energy performance gap and this sense of responsibility will help in reducing the energy consumption from their end.
- There will, at least, be a 20% gap existent in buildings if the modelling and simulations are done right due to variations in human behaviour.
- This gap is mainly because the human behaviour is unpredictable beyond a certain extend and there will always be variations in real-life scenario.
- There is a relation between occupant energy consumption behaviour and social sciences which makes anticipation of occupant behaviour quite complex.
- Behaviour patterns of people and their relation with energy consumption in a building can be studied through social sciences.
- Social sciences and ethical aspects will help give a better picture of the energy consumption behaviour of occupants within buildings. Connecting these social and ethical aspects to technical aspects will help in achieving the optimal building design for energy efficient operations.

Linking Occupant Behaviour and Design

- Connecting design of the building to the occupant is difficult and requires more evidence based research to further enhance the knowledge and understanding.
- We can always design the building in such a way that the energy used by the people within the building is the least. We have to think about ways to help the tenants use less energy within the buildings with effective design.
- If the design of the building is right, people can use the building in a normal way without altering their behaviour in a significant way but reduce the overall energy consumption of the building.
- Think about how organizations work and their work culture. This will give more inputs for designing their office spaces exactly according to how they function normally and helps reduce

the amount of energy consumed. Thinking about using the least amount of energy without hindering an organizations normal functioning within office spaces.

- Some of the basic building functions can be designed in such a way that it provides motivation for tenants to reduce the amount of energy consumed.
- Investigate how different companies function within a particular office space in order to create a flexible design for the building. This will help in being prepared for different types of tenants within the building and also reduce the energy consumption and reduce the gap.
- Think about what activity or component within the building consumes the most amount of energy from the users end.
- Study about the impact of devices used by the tenants on the energy performance of the building. Energy performance of the building should be studied in detail with respect to the impact of different appliances on the energy performance.
- Think about having more people in the building and still be energy efficient rather than having few people and consume huge amounts of energy.
- Within an IT firm that occupies a certain office space, the requirement for visual comfort and thermal comfort could be different compared to another firm within the same space

Current Extend of Occupant Focused Design

- Revenue generated from the investment made to close the energy performance gap in buildings with a focus on occupant behaviour will be the main concern for building owners and investors. Revenue should include a wider scope than just monetary benefits and should also include environmental and health benefits.
- Most of the building owners and investors overlook the environmental and health benefits of the investment in buildings to include occupant behaviour within design and close the energy performance gap.
- Occupant focused building designs are too ambitious as they require data and knowledge regarding several aspects of occupant behaviour.
- Only certain aspects related to occupants are considered while designing buildings such as ergonomics but they do not have a significant effect on energy performance.
- Occupant behaviour is always neglected in design strategies as they are not required by legislation and does not provide a good business case for the real estate developer.

Energy Simulations

- Energy simulations are the most important aspect when it comes to bridging the energy performance gaps. They provide estimated energy consumption figures that needs to be met during the operations phase as well.
- Most of the energy simulation carried out now use energy labels as a support tool. These simulations are mainly carried out to meet legislative requirements.
- Energy simulations do not take into account occupant behavioural aspects due to its complexity and lack of quantifiable data.
- Energy simulations are mainly done once the detailed designs are ready as they require plenty of information to make estimations or predictions.

Asset Management Strategies

- The future of asset management is going to revolve around energy consumption in buildings and limiting user consumption in buildings.
- According to regulations, there is a limit to how much an asset manager can control the behaviour of tenants to reduce the energy consumption.
- Revenue generation was always the most important responsibility for an asset manager within NS Stations.
- Sometimes agreements are made in different ways where everything from lighting, taxes, insurance, etc. are all transferred to the tenant. For example, something like triple net lease.
- Aiming for tenants who value sustainability is the best way to ensure that the building will also be used in a sustainable way.
- There should be continuous feedback loops to ensure we are within our energy performance targets and also our budget for the project.

Rental Contracts and Energy-related Clauses

- Introducing restrictions within contracts or lease agreement will be a solution to reduce the energy consumption from the users side.
- Design of the building is crucial to set sustainable lease agreements for the office and retail spaces within the portfolio.
- Energy budgets are an effective way of limiting the energy consumption from the user's end. Maintain the budget each year and revise them according to each year's performance.
- Most of these sustainable rental agreements must be first tried in smaller office spaces to reduce the size of the risk and its consequences if it does not work well.
- Measuring user behaviour is key to set up sustainable lease agreements to control user behaviour because if you don't know what you are controlling then it doesn't make sense.
- Behaviour control measures and green lease agreements become much easier with single tenants but with multiple tenants it becomes hard to control occupant behaviour due to its complex nature.

Extend of Occupant Behaviour Control

- Moving towards Paris-proof needs interventions with the tenant's energy consumption behaviour as targets include the user consumption as well.
- Not much experiment is done with behavioural interventions for current tenants but we have tried doing different tenants to work out energy efficiency of buildings.
- Asset managers cannot force the renters but only try and influence tenants to reduce energy consumption within buildings.
- Limiting the tenant's behaviour towards energy consumption will also reduce the varieties of tenants which is also a financial risk in terms of revenue generated.
- Some real estate companies suggest to have behaviour templates along with rental contracts and agreements so that the tenants are aware of the way they are supposed to behave to reduce their energy consumption and help in closing the energy performance gap.
- These behaviour templates and rental agreements can also have clauses to share data regarding energy consumption and have discussions regularly to keep track of the gap or consumption pattern.

- There is also an ethical aspect related to the extend of control on occupant behaviour to reduce the energy consumption within non-residential buildings.
- The main issue is providing awareness and knowledge to the tenants on using these technical systems in an energy efficient way.

Appendix D

Expert Opinion

D.1 Pre-Design Phase

- Portfolio approach document is important for every project. Sustainability goals are derived from that document. Targets are explicitly mentioned in this document that will be followed for every project that is carried out at NS Stations.
- Paris-proof is an important goal for Stichthage. Being the biggest building in the portfolio, it is a pilot project and has high sustainability ambitions.
- Another ambition for real estate is to reduce energy consumption by 40
- Stichthage does not have any specific ambitions for itself apart from the ones mentioned on approach document. (Mention goals and ambitions from the document in report and highlight sustainability goals and ambitions in specific)
- The main question about paris-proof is how do we achieve paris-proof targets? How do we also control the consumption from the occupants? How to tackle this problem?
- BREEAM Excellent is also an ambition that NS Stations wants to achieve for Stichthage.
- How can we make the paris-proof target in the form of a contract? How can we jointly achieve paris-proof with the tenants?
- Looking into future policies is also very important for renovation with significantly big investments to avoid further investments in future just to meet legislative requirements.
- Defining energy performance targets and functions of the building will help in the later stages of design to ensure that the design is according to the intended energy performance.
- 5 years can be a long enough time to have significant changes with environmental rules and regulations and also regulations regarding energy consumption. Maybe being able to predict these changes in advance is necessary. Or maybe you can be prepared to embrace this change when it comes. The design of the building should also be able to deal with these changes as the building is quite big and will be functional for the next 40-50 years before a major renovation.
- Moving into a sustainable office is going to be the new norm for companies as well. The market is shifting towards more sustainable office spaces which creates more demand for sustainable office spaces in the future.

D.2 Conceptual Design Phase

- When looking into interactions, is it safe to say we have to minimise the interactions to a "no interaction at all" or make the interactions more efficient with lesser energy used as an effect of these interactions?
- Behavioural aspects within a design also contribute towards health benefits for the occupant.
- Climatic conditions within the office space is the biggest drivers of energy consumption and hence needs to be addressed during the design according to strong preferences by occupants.
- Understanding the thermal comfort preferences of occupants will help in saving a significant percentage of energy used for heating and cooling the spaces.
- The thermostat control needs to be user friendly and incorporate aspects of occupant behaviour to reduce energy consumption or avoid wastage.
- The thermal insulation of the building also plays a crucial role and can be designed to maintain the preferred thermal conditions for the occupant to reduce interactions with HVAC systems.
- Occupant behaviour needs to be generalised for different organisations that work in different ways within an office space.
- Another way is to maybe consider the maximum energy used by different occupants and design the building using this value as a general value for all occupants.
- This might also help with improving the flexibility or diversity in occupants and reduced energy performance. Some sacrifice has to be made.
- The other situation is to focus on one group of people and design specifically for one type of organisation and improve energy performance of the building.
- We also need to take into account the differences in the way people will behave in future and take into account the work cultural shift towards the future. Currently there is a significant change in work culture with the new hybrid way of working.
- The energy simulation in conceptual design phase will not be detailed and hence will not give exact numbers for energy performance but will give a basic idea about the energy consumption patterns for the selected conceptual design. This energy simulation will also help for further simulations in the upcoming phases of design.
- Including certain other aspects such as safety regulations will also help and is also important to estimate the energy performance of the building. For example, how many people can be accommodated on a floor according to safety regulations.
- Will we be able to differentiate the energy consumption of the building and the occupants through the preliminary energy simulation? Do we have enough information to make this differentiation in this phase?
- Maybe also try and mention all the factors that will be considered in this energy simulation? Provide an idea about how detailed this energy simulation is going to be?

D.3 Detailed Design Phase

- Only the detailed design phase energy simulations will provide a complete picture about a real-life scenario for energy performance.

- Maybe sometimes defining the scope of tenants before construction begins might be difficult due to the changes that could take place in design during the construction process.
- Searching for tenants 4-5 years in advance is wishful thinking mainly because the market conditions can change in such a short span. This selection could also be something like a wild guess that might not work well in the end.
- If we have a definite idea about what we want to achieve through this renovation, we can define the scope of tenants and not make a lot of changes during construction. However, in reality this need not be the case, lot of change orders can be issued but might not be significant ones to affect the energy performance.
- It is hard to control occupant energy consumption through contractual clauses related to energy consumption. Within NS, it is not done with the case of Kiosk or Julia's due to the complexity of incorporating energy clauses within contracts.
- Also have to look into social science aspects as to how willing people or businesses are ready to accept energy-specific contracts for renting office spaces. Energy-specific contracts are not mainstream within the real estate industry in the Netherlands.
- Most of the contracts are mainly money-driven and aims to make maximum profits rather than reduced energy consumption or better energy performance. Ofcourse energy consumption and efficiency is important but only second place to money.
- Contract cannot be derived before the construction is completed because there can always be changes during the construction process due to uncertainties. Possibilities for various contracts with energy specific clauses can be explored in this phase and matched with the energy performance simulations and validations.
- For the future, these energy-related clauses are important to meet the paris-proof targets by 2040 as they also include the energy consumption by the occupants. It is near impossible to meet paris-proof targets without these contractual clauses. These energy-related clauses can be linked to paris-proof targets as the occupants are also responsible to meet these targets in a rented space.
- Energy tracking in a very precise way is also important for these clauses otherwise they become redundant and invalid due to lack of data to keep track.
- Data about energy consumption by the occupant is important to ensure these clauses are met otherwise it might backfire the owners of the building. It is the owners responsibility to measure energy consumption within the building.
- To make a distinction between energy used by the building and the occupant requires accurate energy tracking measures that can measure these. This might add to the expense of the project.
- Using incentives is one good way of making occupants accept these energy-clauses in contracts. Incentives can act as motivation to reduce energy consumption and keep them in control.
- These energy management systems and energy tracking is solely done by asset managers and within NS Stations there is not enough manpower and resources to handle this for the entire portfolio.
- There are several other challenges that relate to the implementation of this design strategy such as organisation's priority, capacity, in-house skills and knowledge, etc. These also have to be addressed further to successfully implement this design strategy.

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