Towards energy sufficient buildings and thermal comfort in the built environment.

P5 Report

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Abstract

In order to ensure the sustainable development of cities, the existing building stock has to be transformed to stay relevant to the changing needs of urban dwellers and to reduce the economic and environmental impacts of cities on the planet. Thus, innovating and developing a strategy that prepares the built environment for 2050 is of significant importance. On the other hand, a few researchers explored the problem of energy performance gap in retrofitted buildings due to a lack of knowledge in energy consumption and a proper way to access the data. Therefore, this study aims to deepen knowledge on the relationship and interaction between the end-user and building's energy performance, thereby contributing to the academic discussion on the energy performance paradox of retrofitted buildings. With the help of various smart energy tools, it is possible to acquire better insight and to regulate the energy performance of the building with respect to thermal comfort and occupant well-being. This study presents the importance of energy sufficiency through passive design and BMS implementation as a path towards those goals by answering the following main research question 'How to integrate the Building Management Systems (BMS) requirements to optimize the energy performance and user satisfaction in retrofitted residential buildings?' Through a case study, the outcome of this master thesis is achieved: A strategic approach towards energy sufficient building design that focusses on adding value to the environment, economy and end-users. By promoting the right ecological solutions and having a conscious user behaviour, energy can be consumed efficiently whereas temperatures are kept at a very comfortable level. The MOR Team's proposal for the Rotterdam Europoint Complex is an example of self-sufficient high-rise tower relying solely on renewable energy: High performance, Low energy.

Keywords – Climate change, retrofitted residential buildings, energy performance gap, thermal comfort, energy consumption, energy sufficiency, building management system, project management.

Preface

From not knowing how to realize my goal as an architect and manager, this long journey taught me a lesson: to embrace the uncertainty and to trust the process. Some days were slower than others were, but each day I was getting closer to the realization of this thesis. With this, I would like to take the opportunity to express my gratitude to a group of people. Without their contribution, the realization of this thesis would not have been possible.

First, I am grateful to be part of the MOR team. This two years project from design phase to the construction of the prototype was an incredible experience for me. At the same time, this project provided me the right resources to pursue this research.

In addition, I would specially like to thank my main supervisor Alexander for his patience and guidance during this long journey and for his valuable ideas, advices and critical eye for improving and finishing this study. I am also grateful for the support of my second mentor Philomena for her advice for the development of this research.

Finally, I want to thank my family and friends for their support throughout my entire study at TU Delft, and specially Hanna and Danyan for their help and presence during this research. My special gratitude goes to Álvaro, who provided me with motivation and support whenever needed the most.

Enjoy reading,

Aylin Ozcan
Delft, January 2020

Management Summary

Introduction

Together with climate mitigation and energy security goals, energy efficiency in the building sector has become a dominant issue in developed countries, since it is responsible for 36% of the greenhouse gas (GHG) emissions in the European Union and accounts for 40% of the EU's final energy consumption (European Commission, 2017). As a response, the Paris agreement states a reduction of 80 to 95% of the carbon emissions by 2050. The biggest challenge to limit this energy consumption is within the existing building stock since approximately 87% of the current building stock will remain by 2050 (Wilkinson, Remøy & Langston, 2014). Hereby, many European countries have launched initiatives to improve home energy efficiency and established various directives to reduce human environmental footprint.

In order to ensure the sustainable development of cities, the existing building stock has to be transformed to stay relevant to the changing needs of urban dwellers and to reduce the economic and environmental impacts of cities on the planet. On the other hand, a few researchers explored the problem of energy performance gap in retrofitted buildings due to a lack of knowledge in energy consumption and a proper way to access the data. Therefore, this research contributes to the existing body of literature regarding energy efficient retrofitting in the built environment to fill out the gap between the calculated energy consumption and actual energy consumption.

Simultaneously, the current comfort level of the existing buildings become unsuitable towards future conditions (Chappells & Shove, 2005). Buildings do not use energy, but people do. According to Fang, Liu, Li, Tan & Olaide (2018), people spend about 80 to 90% of their lifetime indoors. Thus, seeking for an optimum level of comfort and Indoor Environment Quality (IEQ), this way of behaving is hindering to stand up for climate change actions. Therefore, it is detrimental that the building is able to be in full dialogue with the local climate and incorporate the culture and needs of its occupants to prevent rebound effects that act to increase the energy consumption (Azevedo, 2014).

Research Objective

Since the existing guidelines are lacking a holistic design perspective that integrates a balance between comfort and energy sufficiency, this master thesis focusses on an approach that can help to solve the presented paradox by doing further research on finding solutions for synergies between building design, building climate control and occupants needs. Future buildings must be resilient against extreme climate changes, occupant behaviours and function at the building and construction level (passive and active solutions), at the indoor environmental quality level (management of indoor environment controls) and at the occupant's level. For this reason, the main aim of this study is to gain insight into (1) the factors influencing the energy consumption in residential buildings, and (2) the possibilities to optimize the energy performance on a technical and user level. Thus, finding an answer to the following research question: *'How to integrate the Building Management Systems (BMS) requirements to optimize the energy performance and user satisfaction in retrofitted residential buildings?'* several sub-questions and research objectives are formulated as stated in the following table.

Sub-question	Research objective	Research methodology
What are the influential factors related to energy consumption?	To obtain more insights into the contribution of the building characteristics and end-users on the energy performance gap. A thorough understanding is necessary to find possible solutions to mitigate this discrepancy.	Literature Study Type: Qualitative
How should the project be organised with respect to these influential factors in order to achieve energy performance?	To determine the organizational structure that leads to elaborate an optimal energy performance strategy.	Literature Study and Case Study Type: Qualitative
What are the drivers and barriers for project managers for the BMS implementation to optimize the energy performance of retrofitted residential buildings?	To formulate sustainable strategies that solve the conflict of interests amongst stakeholders.	Literature Study and Case study Type: Qualitative

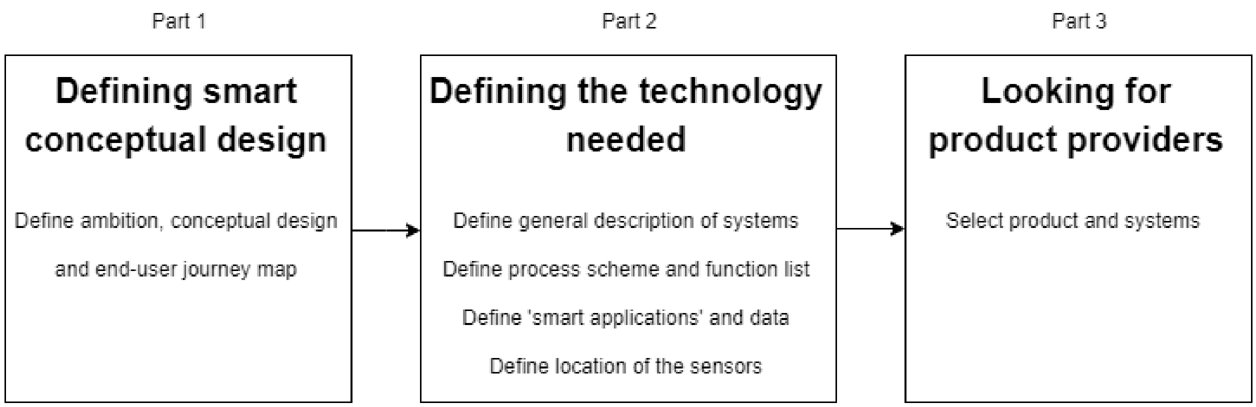
In order to conduct a proper research on this subject and to make the design guideline more tangible, choosing a case study that prioritize the transformation of the existing building stock into a low energy performance is key. The selected case study is the MOR project of the TU Delft's DreamTeam for the Solar Decathlon Europe 2019. MOR – Modular Office Renovation – is a transformation project of a vacant office building into a circular, energy positive and adaptable residential building. The main purpose of choosing this project is the fact that the team got the chance to design, build a prototype and prove its viability in energy, comfort and functionality, while being exposed to extreme summer conditions, high occupancy and daily testing.

Findings: BMS implementation process

The developed strategy for this study has a dual perspective: project-oriented and process-oriented. Passive design solutions and advanced technologies are applied to ensure energy efficiency. Following the Trias Energetica, energy consumption is reduced, energy flows are reused where possible and electrical demand is supplied sustainably. Technology plays an important role to ensure net-positivity. Additionally, in order to achieve the optimum solution for energy retrofitting, choosing the right method and organization structure that suits the best for solving the problem is crucial since it can influence the whole design process and outcome. To achieve a balanced sustainable design, the cohesion of different disciplines through collaborative and interdisciplinary strategies is important.

This project has developed a strategy for prolonging the lifespan of existing building structures where the role of project managers are crucial throughout the whole process of shaping the BMS implementation initiative. In order to close the energy performance paradox and design a self-sufficient retrofitted building, the project manager must consider the economic, social and environmental impact of the project, its results and its effects. Meaning that the manager is required to consider the full life cycle of the project and should take several aspects into account. Additionally, managers should acknowledge a mind shift (taking responsibility for sustainable development), a paradigm shift (having a holistic perspective on managing change) and a scope shift (managing social, environmental and economic impact) in order to make buildings healthy and comfortable while improving the energy efficiency of retrofitted buildings (Silvius & Schipper, 2014).

As mentioned before, this master thesis focusses on an approach that can help to solve the presented paradox by doing further research, which afterwards elaborates upon the implementation of Building Management System (BMS) requirements in order to add value to the energy performance of retrofitted residential buildings. An approach that raises up awareness to the project managers of the process and benefits related to BMS implementation while taking into account the different stakes in the design process. The main design criteria for the use of an integrated building management system is to serve mainly the end-user for comfort, domestic hot water, energy savings and safety purposes while creating awareness for future behaviour changes. On the one hand, the system controller aims at achieving a balance between People, Planet and Prosperity based on the collected data. While on the other hand, with the used strategy the intention is to understand how to close the energy performance gap, to understand the gap between simulated and measured data and finally to get input for predictive maintenance for the building use. The integration of the BMS requirements consists of mainly three parts: (1) defining smart conceptual design, (2) defining the technology needed and (3) looking for product providers.



Finding: BMS and its added value

The BMS cabinet is ‘’the brain’’ of the house and contains the building management system. It connects all house systems together to monitor and operate all systems of the house, from HVAC to home electronics and windows in an efficient way. In this way, energy consumption is controlled. From the collected data, the following can be extracted: the difference between the predicted and actual energy consumption is POSITIVE. This meaning that there is no energy performance gap.

Additionally, based on the analysis of the data obtained through the sensors, it is visible that there is a clear connection between the temperature’s fluctuations, energy consumption and the committed activities. However, by promoting the right ecological solutions and having a conscious user behaviour, such as deciding on certain tasks to do based on the outdoor weather, energy can be consumed efficiently whereas temperatures are kept at a very comfortable level. The BMS provides for an interaction between the end-user and the building in order to improve the indoor environment quality based on the user’s needs and wishes. The MOR Team’s proposal for the Rotterdam Europoint Complex is an example of self-sufficient high-rise tower relying solely on renewable energy: High performance, Low energy.

Conclusion

Based on the literature findings, several parameters are proposed to enhance the energy efficiency of the existing building stock. One of these parameters is the implementation of a Building Management System. The main design criteria for the use of an integrated building management system is to optimize the energy performance and user satisfaction in retrofitted residential buildings.

Throughout the whole process, project managers have a crucial role to shape the team towards a purposeful design that contributes to a sustainable, flexible, adaptive, affordable and future-proof built environment. In an integrated design process, all stakeholders from different disciplines are working together in an iterative way until a holistic and user-centred design is achieved that is satisfying to all involved stakeholders.

To conclude, this project has developed a strategy for prolonging the lifespan of existing building structures by embedding functional modules for an energy efficient, liveable space. Whereas, this research has proven that the implementation of the BMS adds value to the energy performance of retrofitted residential buildings.

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List of abbreviations

ASHP	Air Source Heat Pump
BMS	Building Management System
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
DHW	Domestic Hot Water
DW	Dishwasher
EPBD	Energy Performance of Building Directive
EPC	Energy Performance Coefficient
GHG	Greenhouse Gas
HVAC	Heating, Ventilation and Air Conditioning
IEQ	Indoor Environment Quality
IoT	Internet of Things
MBE	Management in the Built Environment
MOR	Modular Office Renovation
PCM	Phase Changing Material
PM	Project Manager
SDE19	Solar Decathlon Europe 2019
WM	Washing Machine

Readers guide

This study consists of six parts, which are briefly explained here below.

Part I Research basis

This part introduces the problem statement and elaborates on the research objectives and questions within the defined boundary conditions of this master thesis.

Part II Research methodology

This part explains the chosen research strategy and research design. The research design is conducted using four research techniques: literature review, case study approach, desk research (case study) and the validation of the data.

Part III Literature review

Part three looks at the literature on energy performance and possible adaptations in retrofitted buildings.

Part IV Case study

This part introduces the chosen case study. It starts with the incorporation of the literature study in the project, such as the design adaptations and process overview. Thereafter, the Building Management System (BMS) implementation is explained with the aim to better understand the relationships between occupant behaviour, thermal comfort and energy consumption for heating within the built environment.

Part V Analysis

This part examines the collected data in order to validate the guideline design and process. It analyses the interaction of the users with the building and temperature flow, theoretical and actual consumption, but also the drivers and barriers encountered during the BMS implementation process.

Part VI Findings, conclusion and discussion

The last part answers the research questions, discusses limitations encountered during the process and design, and provides further recommendations.

Part I Research Basis

1. Introduction

After the industrial revolution during the 19th century, while before our energy needs were modest and solely relying on the sun, wind and animal power, the world became quickly a high-energy civilization. Together with the evolution of the engines, population growth and urbanization, the transition to modernity did not last any longer (Smil, 1994). The world changed at a faster pace than our imagination can. Innovation after innovation, partly driven by a demand for innovation, and partly driven by the need for change determines our lives increasingly in a strong degree. Almost every society-changing development of the past twenty years can be attributed to the same driving force: economic growth (Aazami, n.d.). In order to meet these community needs, growth and changing industry, this transition has at the same time resulted in a robust increase in global energy-related to CO_2 emissions and other pollutants, causing for irrevocable changes to the planet environment (Horton et al., 2015).

Data from the Intergovernmental Panel on Climate Change (IPCC, 2007) reveals that global average surface temperature during the last century has risen by 0.748C due to human activity. This unprecedented trend of warming caused to break historical temperature records. However, as Nicol & Humphreys (2002) stated "If a change occurs, such as to produce discomfort, people react in ways to restore their comfort". Thus in order to restore their comfort, based on the latest assessment of global energy consumption, the International Energy Agency (2019) found out that the demand for cooling and heating detrimentally increased and corresponded to one fifth of the energy demand in 2019.

Together with climate mitigation and energy security goals, energy efficiency in the building sector has become a dominant issue in developed countries, since it is responsible for 36% of the greenhouse gas (GHG) emissions in the European Union and accounts for 40% of the EU's final energy consumption (European Commission, 2017). As a response, the Paris agreement states a reduction of 80 to 95% of the carbon emissions by 2050. The biggest challenge to limit this energy consumption is within the existing building stock since approximately 87% of the current building stock will remain by 2050 (Wilkinson, Remøy & Langston, 2014). Hereby, many European countries have launched initiatives to improve home energy efficiency and established various directives to reduce human environmental footprint.

Despite the initiatives and technological developments through increasingly efficient systems and equipment, energy consumption in retrofitted buildings is not decreasing at the rate it should be (Majcen, 2016). This resulting in dwellings that have a poor label using less energy and those with high-energy efficiency having a poor energy performance. This shows that retrofitting the existing building stock should not rely exclusively on energy efficient systems and the given standards, since the outcome still leads to an executive amount of energy consumption.

2. Problem statement

The current policies are steering to stimulate energy efficiency in the built environment by retrofitting the existing building stock. However, several studies reveal that due to climate change, the use and implementation of only energy efficient equipment are potentially far reaching. The problem of reducing energy consumption in buildings must be approached objectively and scientifically from its root causes. Therefore, the reduction of energy demand in the building sector should in the first place explore the potential to reduce energy needs (sufficiency) by making use of passive systems to achieve the desired conditions and then, secondly, use the energy efficient active systems only when they are required to guarantee the comfort.

Simultaneously, the current comfort level of the existing buildings become unsuitable towards future conditions (Chappells & Shove, 2005). Buildings do not use energy, but people do. According to Fang, Liu, Li, Tan & Olaide (2018), people spend about 80 to 90% of their lifetime indoors. Thus, seeking for an optimum level of comfort and Indoor Environment Quality (IEQ), this way of behaving is hindering to stand up for climate change actions. Therefore, it is detrimental that the building is able to be in full dialogue with the local climate and incorporate the culture and needs of its occupants to prevent rebound effects that act to increase energy consumption (Azevedo, 2014).

In other words, the main problem is that despite the various technological developments for energy efficiency retrofitting, there is still a lack of design principles considering user satisfaction. Furthermore, design factors have not been evaluated by users' perspective resulting in an energy performance gap where the actual energy use deviates from the predicted energy use.

3. Research scope

This master thesis focusses on an approach that can help to solve the presented paradox by doing further research, which afterwards elaborates upon the implementation of Building Management System (BMS) requirements in order to add value to the energy performance of retrofitted residential buildings. An approach that raises up awareness to the project managers of the process and benefits related to BMS implementation while taking into account the different stakes in the design process.

The sections below will be addressing the research limitations, research objectives, research output, research questions, and relevance of the research and will define how multiple definitions are understood within this study.

3.1 Research objectives

The existing guidelines are lacking a holistic design perspective that integrates a balance between comfort and energy sufficiency. Synergies between building design, building climate control and occupant needs are required to improve future designs. Future buildings must be resilient against extreme climate changes, occupant behaviours and function at the building and construction level (passive and active solutions), at the indoor environmental quality level (management of indoor environment controls) and at the occupant's level. For this reason, the main aim of this study is to gain insight into (1) the factors influencing the energy consumption in residential buildings, and (2) the possibilities to optimize the energy performance on a technical and user level. Thus, finding an answer to the following research question: 'How to integrate the BMS requirements to optimize the energy performance and user satisfaction in retrofitted residential buildings?' several sub-questions and research objectives are formulated as stated in Table 1.

Table 1. Sub-questions and research objectives

Sub-question	Research objective	Research methodology
What are the influential factors related to energy consumption?	To obtain more insights into the contribution of the building characteristics and end-users on the energy performance gap. A thorough understanding is necessary to find possible solutions to mitigate this discrepancy.	Literature Study Type: Qualitative
How should the project be organised with respect to these influential factors in order to achieve energy performance?	To determine the organizational structure that leads to elaborate an optimal energy performance strategy.	Literature Study and Case Study Type: Qualitative
What are the drivers and barriers for project managers for the BMS implementation to optimize the energy performance of retrofitted residential buildings?	To formulate sustainable strategies that solve the conflict of interests amongst stakeholders.	Literature Study and Case study Type: Qualitative

Until now, various initiatives have been taken to create an efficient building stock in Europe. However, these efforts did not meet the energy targets set out in the Energy Efficiency Directive since the pace of growth in energy demand is bigger than the pace of improvements in energy efficiency (IEA, 2019). Thus, this project is dealing with the paradox of energy performance in retrofitted buildings and is focused on a strategic approach towards energy sufficient building design. The main goal is to develop a guideline through BMS implementation that can be applied in future retrofitting projects in order to add value to the building: guaranteeing energy efficiency, sustainability and occupant comfort. In other words, the main goals of this master thesis are to create awareness, develop a guideline and to give advice on how to solve the paradox of energy performance in retrofitted buildings.

As Figure 1 presents in a schematic way, the main objective is to close the energy performance gap. The collaboration of several stakeholders can shape the future of the built environment, thus raising up the awareness about the actual situation and bringing them on the same page is substantial. However, in this paper the research outcome – guideline – is intended for informing and advising the managers on how to shape BMS implementation initiative while taking into account the stakes of other stakeholders. The guideline depicts the BMS implementation process that acknowledges end-users, identifies the barriers that have to be resolved and understands the adaptations that are realistic and feasible.

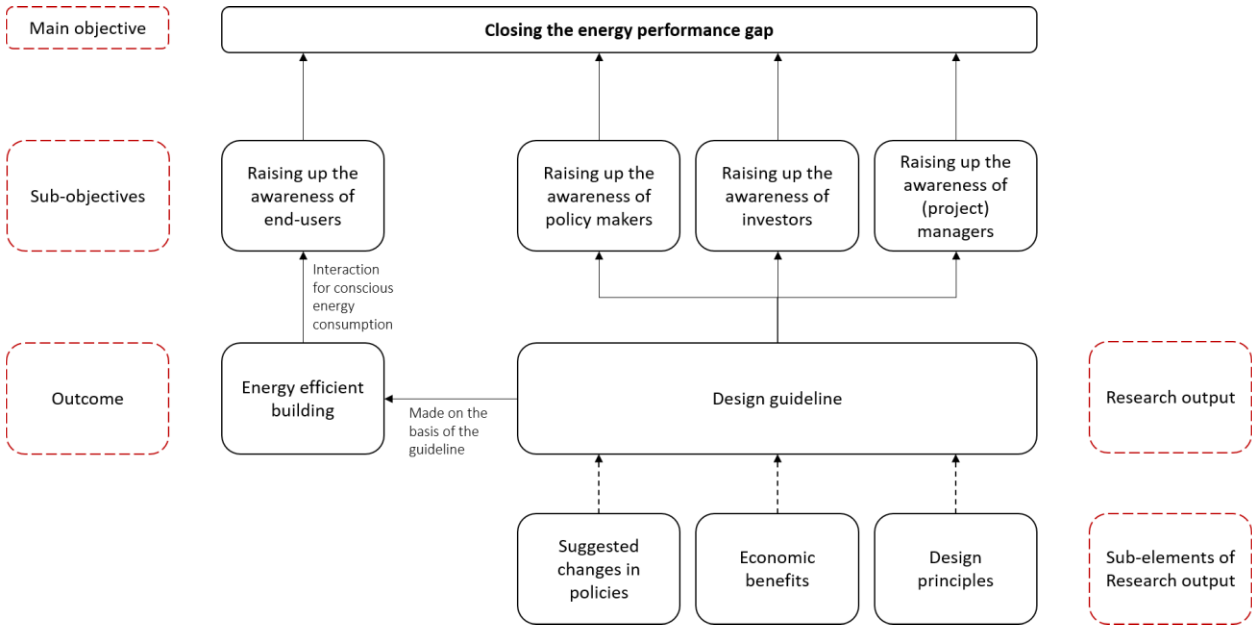

Figure 1. Research objectives

3.2 Research questions

Derived from the problem statement and research objective, the following main research question has been formulated:

- *How to integrate the Building Management System (BMS) requirements to optimize the energy performance and user satisfaction in retrofitted residential buildings?*

Sub-questions:

- *What are the influential factors related to energy consumption?*
- *How should the project be organised with respect to these influential factors in order to achieve energy performance?*
- *What are the drivers and barriers for project managers for the BMS implementation to optimize the energy performance of retrofitted residential buildings?*

3.3 Research definitions

To narrow down the focus and make the scope of this master thesis more understandable, various definitions are defined.

Energy Performance Gap – The energy performance gap equals to the negative outcome of the predicted energy consumption minus the actual energy consumption in retrofitted buildings.

Retrofitted Buildings – In order to provide a healthy indoor environment for the end-users and to reduce the energy performance coefficient (EPC) of the existing building stock, buildings are being retrofitted or in other words renovated. Upgrading the buildings to a better label is not only achieved through the implementation of energy efficient systems, but by designing in the first place in a passive and resilient way.

Building Management System – This cabinet is ''the brain'' of the house and contains the building management system. It connects all house systems together to monitor and operate all systems of the house, from HVAC to home electronics and windows in an efficient way. Additionally, the BMS provides for an interaction between the end-user and the building in order to improve the indoor environment quality based on the user's needs and wishes.

Energy sufficient building – An energy sufficient building is a building that is designed with the primary values of passive low energy architecture to reduce the energy needs and then, secondly, use the energy efficient active systems only when they are required to guarantee the comfort. In order to achieve the desired conditions, the building is in full dialogue with its local environment and end-users.

Energy sufficiency – Energy sufficiency equals to the positive outcome of the energy production minus the energy consumption in retrofitted buildings.

4. Research relevance

Societal relevance

The built environment accounts for approximately 40% of the EU's final energy consumption (European Commission, 2017). Therefore, innovating and developing a strategy that prepares the built environment for 2050, when the built environment must be completely CO_2 neutral and circular is of significant importance. Today, the challenge is to find the right adaptations to lower the energy consumption. A better understanding into the actual energy consumption is necessary to reduce the environmental impact of the built environment. Thus to meet the climate goals, all the stakeholders (designers, engineers, clients and users) need to be encouraged for participation. Decision makers at all levels and scales have crucial roles in tackling these challenges effectively (deOliveira Fernandes, 2015).

At the same time, due to the evolution of modern globalized trends in the building regulations, the existing building stock has become strongly dependent on heating, ventilation, and air conditioning (HVAC) systems. This has led to further environmental impacts, strengthening the demand to find a way to improve the energy efficiency of buildings. Nowadays, the society needs sustainable buildings that are comfortable at the same time. With the help of various smart energy tools, it is possible to acquire better insight and to regulate the energy performance of the building with respect to thermal comfort and occupant well-being. This study presents the importance of energy sufficiency through passive design and BMS implementation as a path towards those goals.

Scientific relevance

In order to ensure the sustainable development of cities, the existing building stock has to be transformed to stay relevant to the changing needs of urban dwellers and to reduce the economic and environmental impacts of cities on the planet. On the other hand, a few researchers explored the problem of energy performance gap in retrofitted buildings due to a lack of knowledge in energy consumption and a proper way to access the data. Therefore, this study aims to deepen knowledge on the relationship and interaction between the end-user and building's energy performance, thereby contributing to the academic discussion on the energy performance paradox of retrofitted buildings.

This presented gap in literature has already drawn the attention of several researchers, however, due to its complexity, not much knowledge is available on how to solve this problem. Even if there are various adaptations known, concrete steps to close the energy performance gap in retrofitted buildings still seem to be missing. The aim with this research is to gain knowledge on making the existing building stock more energy sufficient and future proof.

Part II Research Methodology

1. Research methodology framework

1.1 Research strategy

The conceptual model (visualized in **Figure 2**) provides an overview of the research structure, which consists mainly of three parts. It starts with the context, explaining the topics and concepts that constitute to the reason. In this case, the change in the community needs over the years resulted in a robust increase in energy consumption leading to climate change. Several energy agreements and policies took action to improve the built environment by retrofitting the existing building stock in order to meet the climate goals. However, since standards are obsolete and end-users wishes and needs are not taken into account while designing, an energy performance paradox arise. The second part is researching on how to close this energy performance gap through the use of a case study, which leads to a final outcome of this master thesis: A strategic approach towards energy sufficient building design that focusses on adding value to the environment, economy and end-users.

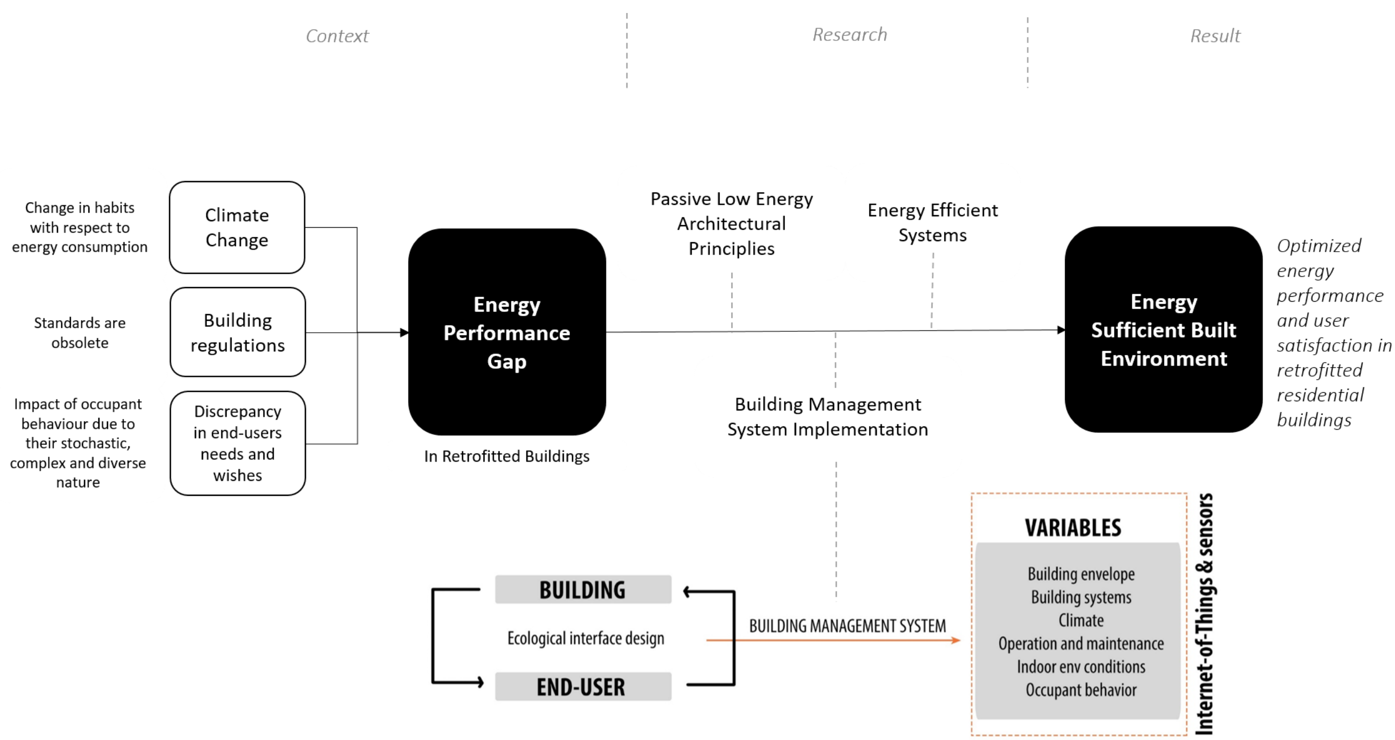

Figure 2. Conceptual model

1.2 Research design

This research focuses on the paradox of energy performance in retrofitted residential buildings in the Netherlands and its adaptation towards energy sufficient buildings through BMS implementation. In order to conduct a proper research on this subject, several inputs and data are required.

As stated before, the main research question is:

- *How to integrate the BMS requirements to optimize the energy performance and user satisfaction in retrofitted residential buildings?*

Table 2 represents the research sub-questions and the selected research methodology to obtain the relevant input to formulate answers.

Table 2. Sub-questions and methodology

Sub-question	Type of data	Research method	Data collection
What are the influential factors related to energy consumption?	Qualitative	Literature Study	Academic literature
How should the project be organised with respect to these influential factors in order to achieve energy performance?	Qualitative	Literature Study and Case Study	Academic literature, desk research
What are the drivers and barriers for project managers for the BMS implementation to optimize the energy performance of retrofitted residential buildings?	Qualitative	Literature Study and Case Study	Academic literature, Data from the conducted case study.

The overall research design, visualized in Figure 3, gives a clear overview of the used methodology and the steps taken to conduct the study.

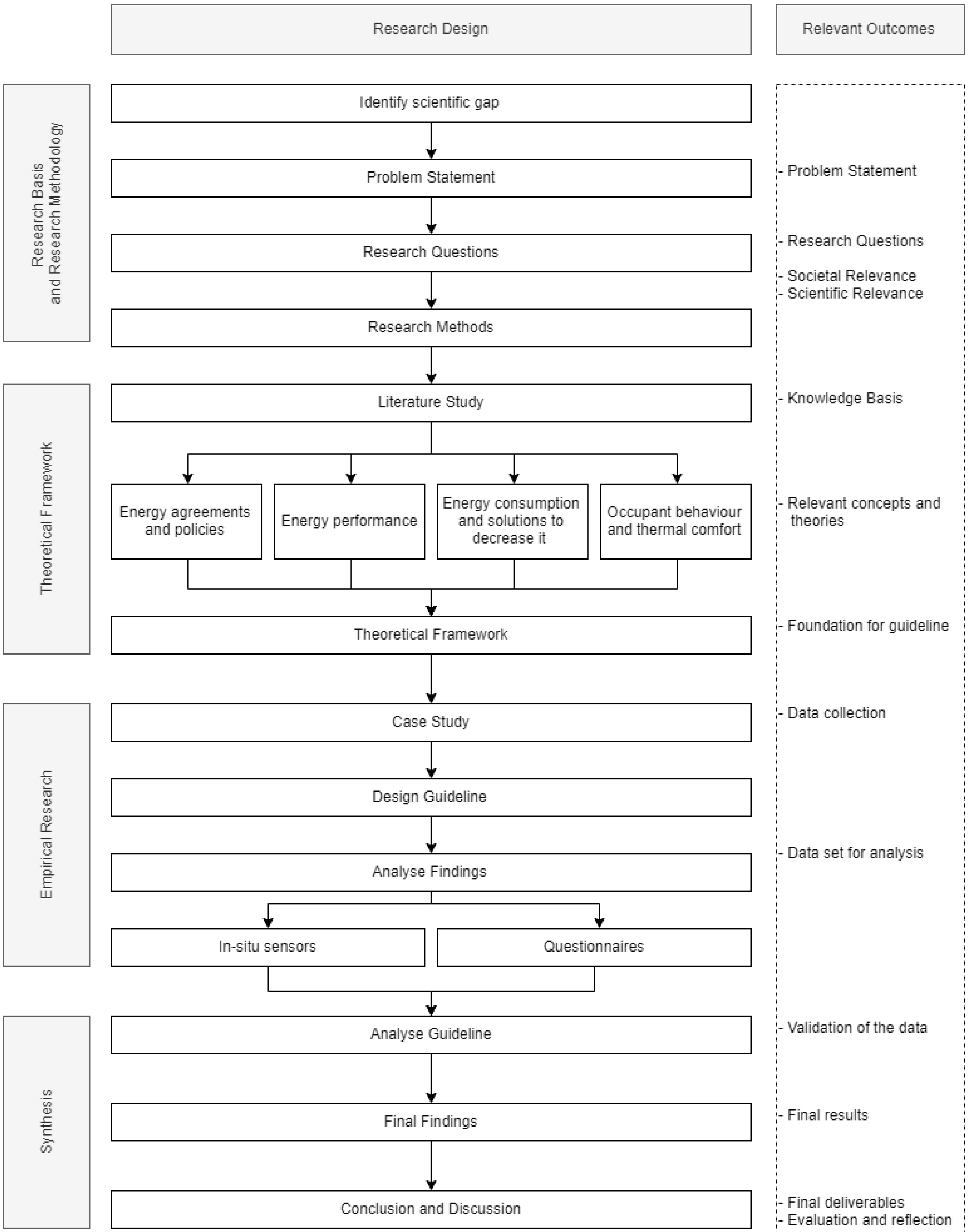

Figure 3. Research Design

2. Research techniques

The research design is conducted using four research techniques: literature review, case study approach, desk research (case study) and the validation of the data. Each of them is explained in more details in the paragraphs below.

2.1 literature Review

The literature review focuses on developing a theoretical framework to gain background in the following topics: energy agreements and policies, energy performance, energy consumption, thermal comfort and user behaviour. The main purpose of the literature study is to learn more in depth about the already researched concepts, theories and the correlation between these concepts. Moreover, this literature study addresses what the scientific gaps are which enables to formulate the research problem, whereas afterwards this knowledge will serve as a basis for the guideline.

2.2 Case study approach

One of the most frequently used qualitative research methods is a case study. The goal of a case study is to gain an in-depth understanding of ‘‘a contemporary phenomenon within its real life context’’ as Yin (2002) interprets a case (p.13). Moreover, according to Yin (2002) case studies are useful in qualitative research methods since they are a “comprehensive research strategy” meant to answer the how or why questions concerning the phenomenon of interest (pp. 13-14).

In order to support the design of this qualitative research method, this research will perform one in-depth case study to understand the importance of the phenomenon of BMS integration in retrofitted buildings. The goal of this case study is to harvest descriptive results of the individual case and to provide a heuristic understanding of the phenomenon.

Case study selection criteria

As mentioned before, the built environment is responsible for 36% of the greenhouse gas (GHG) emissions in the European Union and accounts for 40% of the EU’s final energy consumption (European Commission, 2017). Most of the time, the focus is on new buildings and their possibilities to reduce the energy consumption. However, the biggest potential to limit the energy consumption is within the existing building stock (longevity of 50-100 years), which were constructed prior to the current era of low energy regulations (Power, 2008). Thus in order to make the design guideline more tangible, choosing a case study that prioritize the transformation of the existing building stock into a low energy performance is key.

The selected case study is the MOR project of the TU Delft’s DreamTeam for the Solar Decathlon Europe 2019. MOR – Modular Office Renovation – is a transformation project of a vacant office building into a circular, energy positive and adaptable residential building. The main purpose of choosing this project is the fact that the team, which I am part of, got the chance to design, build a prototype and prove its viability in energy, comfort and functionality, while being exposed to extreme summer conditions, high occupancy and daily testing.

2.3 Desk research

The third step of the study is a desk research that is supplementing the methodology. This is necessary in order to clarify the case study findings and to present extra insight to the analysis of the case study. The desk research is done by reviewing the provided documents – Project Manuals and Project Drawings – of the MOR project.

2.4 Data collection

The final step of the research is the collection of data to understand the intermediate relationships between the predicted and actual energy use, and user comfort. Since measuring the impact of occupant behaviour is not straightforward, different methods such as monitoring through sensors and user surveys can help to quantify this influence. Additionally, the data from the simulations will be examined to understand the energy performance of this retrofitted prototype. All these collected data will be used for validating the performance of the guideline. The collected data relevant for this study is shown in Table 3.

Table 3. Data collected during the observation period from 14th of July – 24th of July 2019

Method	Parameter
Simulations	Energy consumption calculations: Heating, ventilation, cooling
In-situ sensors	Indoor temperature Outdoor temperature Relative humidity CO_2 levels Interaction with windows Hot water Occupancy
Questionnaires	Time of day Actual temperature Level of comfort Activity Age Gender Nationality Health state

On the other hand, during the ten days observational period from 14th of July until 24th of July 2019, the SDE organization monitored two types of measurements as shown in Table 4. From the task-based monitoring (House Functioning Contest), the influence of certain occupant behaviour related to the type of household will be examined, whereas, the dinner activities will be evaluated through surveys by the guests.

Table 4. Monitoring types (SDE, 2019)

Monitoring	Type	Contest	Calculation
Electrical	Continuous	Energy Balance	- Load consumption / surface area - Positive electrical balance - Temporary generation-consumption correlation - House adjustment to network load state - Power peaks
Instrumentation	Continuous	Comfort Conditions	- Temperature - Humidity - Indoor quality air CO_2 - Indoor quality air VOC
		House Function	- Refrigerator - Freezer
	Task	Comfort Conditions	- Lighting - Acoustics
		House Function	- Clothes Washer - Clothes Dryer - Dish Washer - Home electronics - Oven - Cooking - Hot water draws - Dining - Water

3. Ethical consideration

Several ethical considerations have to be taken into account in order to conduct a proper qualitative research: (1) trustworthy and unbiased introduction of information have to be ensured, (2) the obtained data must be deliberately analysed so that there is no space for individual elucidation of findings, and (3) appropriate copyright techniques must be consolidated.

Part III Literature Review

1. Energy agreements and policies

In order to combat climate change, the Paris agreement (2015) aims to keep the global temperature rise below the 2 °C and states a reduction of 80 to 95% of the carbon emissions by 2050. Since in the European Union the existing building stock is responsible for 40% of the energy consumption and accounts for 36% of CO_2 emissions, the European Commission (2017) implemented energy strategies and policies to steer towards a low-carbon economy in line with the global agreements. The goal for the EU is to cut of 80% in Greenhouse Gas (GHG) emissions compared to 1990 by 2050. Whereas on the national scale, the Dutch government presented in June 2019 a new climate agreement, a national reduction goal of 49% compared to 1990 by 2030. For the built environment, this means a transition to energy-efficient, fossil-free and CO_2-free buildings (Rijksoverheid, 2019).

2. Energy Performance

In order to regulate and keep track of the energy efficiency improvements in the building stock, the European Union introduced the Energy Performance of Building Directive (EPBD). According to this directive, the energy performance of every building was assessed and labelled based on an energy performance coefficient (EPC). This EPC calculation indicates the building's energy consumption meaning buildings with a low EPC (energy efficient) result in lower consumption than buildings with a higher EPC (energy inefficient). However, previous research remarks that there is a discrepancy between the predicted and actual energy consumption, which is referred to as the energy performance gap (Majcen, Itard, & Visscher, 2013).

Energy performance gap = | Predicted energy consumption - Actual energy consumption |

At the same time, the average energy professional has no clear answer to give to the question "what is energy?" The conventional answer - the ability to perform work often fails to give a clear understanding to the end-user. Because even if energy is available in our daily basis life, there is a lack of awareness in the actual consumption. After all, how can we know if we use a lot or a little energy, or if we use our sources consciously or unconsciously, if we cannot explain what energy really is? (Aazami, Opdrachtgevers, & Ecp, n.d.).

Therefore, in order to achieve the energy efficiency targets, it is key to understand and strengthen knowledge regarding the robust prediction of total energy usage in buildings, which will later on enable the assessment of energy-saving measures, policies and techniques. The basis to achieve efficiency in energy consumption is understanding the factors that contribute to this energy consumption. In his book Energy: Management, Supply and Conservation, Dr Clive Beggs (2002) stated that energy is being wasted due to different reasons, such as poorly designed buildings and installations, inadequate control systems, inefficient control settings, poor maintenance and irresponsible use of equipment. Additionally, scientific research has proven that the building's energy consumption is mainly influenced by factors that can be separated into 6 different categories; (1) climate, (2) building envelope and other characteristics, (3) building equipment, (4) operation and maintenance, (5) indoor environmental conditions and (6) occupant behaviour (Yan et al., 2015).

While significant progress in the first five focus areas has been achieved, occupant behaviour in buildings still leads to an excessive energy consumption due to their stochastic, diverse and complex nature. This scientific lack in understanding the end-user in a comprehensive way causes for the phenomenon of the underestimated theoretical consumption, which can be explained as the rebound effect. Efficient technologies reduce energy bills, but thus boost consumption (Majcen et al., 2013). Therefore, a clear knowledge base of how end-users actually use energy is necessary to improve the effectiveness of energy-savings and to bridge the gap between the predicted and actual energy consumption in buildings.

3. Adaptations

Lately adapting existing buildings gained an increasing recognition in ensuring a sustainable built environment. As long as during the adaptive reuse decision-making process the project remains viable, retrofitting the existing building is preferred to demolition (Bullen & Love, 2011). Besides several other drivers that pushes to retrofit the existing built environment as shown in Table 5, one of the main goals of these adaptations is to enhance sustainability and resiliency guiding the way towards energy efficient buildings. Adding to this argument, the Trias Energetica strategy by Duijvestein (1996) emphasizes the importance of a sustainable living environment by maximizing the performance of all subsystems without compromising on the comfort level of the end-users. This principle consists of three steps: (1) minimizing the energy consumption, (2) use of renewable energy sources and (3) efficient use of fossil fuels.

Table 5. Drivers of adaptation and retrofitting stock (Amoah, Kissi and Oteng, 2018).

To meet the demand of the tenants
To meet building regulations
To reduce the energy consumption of the existing building
To increase the stability of the existing building
For implementation of sustainable building practices
Change of function of the existing building to meet the current market demand
To avoid building obsolescence
To increase building aesthetics
Update existing building to modern standards
To reduce the adverse impact of the existing building on the environment
To increase the internal comfortability of the existing building

Additionally due to technological developments, the optimization of the energy performance can be achieved more easily than before. Smart meters and sensors allow collecting data to give new insights on the building characteristics, energy consumption and occupant behaviour (Valks, Arkesteijn, den Heijer & Vande Putte, 2016). Through an integrated building management system (BMS) and Internet-of-Things (IoT), the collected data can be analysed to operate and control the building systems while raising up the awareness of the end-users (Hossain, 2019).

4. Occupant behaviour

As mentioned before, there is a discrepancy between the given standards and end-users wishes and needs. Occupant behaviour in buildings still leads to an excessive amount of energy consumption due to their stochastic, diverse and complex nature. This scientific lack in understanding the end-user in a comprehensive way causes for the phenomenon of the underestimated theoretical consumption. In order to face these gaps and challenges to ensure an energy efficient built environment, it is crucial to raise a culture that is environmentally conscious fostering behavioural change to adopt low-carbon lifestyles (Fink, 2011). Thus while retrofitting the existing building stock; buildings must take into consideration the end-users in order to provide a healthy, comfortable and safe environment besides technical adaptations. By doing so, a tremendous improvement in lowering energy consumption and carbon emissions could be attained (Fink, 2011).

According to Bluyssen (2009), the end-users' prerequisites for being able to adjust building systems and components refers to the interaction with the building in order to improve the Indoor Environment Quality (IEQ), which is described by environmental factors such as indoor air quality, thermal comfort, acoustical quality and visual or lighting quality. The main drivers behind energy-related occupant behaviour include the inhabitants' desire to look for pleasant conditions and satisfaction within their environment (Peng et al., 2012). "If a change occurs, such as to produce discomfort, people react in ways to restore their comfort" (Nicol & Humphreys, 2002). For example, an occupant may adjust the thermostat or open the window to enhance their comfort. Several personal factors, such as (1) demographic variables, (2) states and traits, (3) lifestyle and health status, and (4) genetics, event and exposures, can influence a person to respond in a certain way (Bluyssen, 2013).

While seeking for a personal comfortable condition, the occupant will interact with the building systems to obtain the desirable thermal comfort level, which is a major determinant of the energy consumed for space heating and cooling accounting for 44% of a building's energy consumption (Raish, 2018). To reduce this consumption, one need to understand the complex relationship between the end-user and its interaction with the building. On top of that, it is relevant to come up with a strategy that contributes to behavioural change as it has been proven to achieve more energy savings (Pacala &Socolow, 2004). To foster sustained behavioural change, Fink (2011) distinguishes five key elements:

(1) Information and education
(2) Financial incentives and energy services
(3) Modern technologies and sustainable design
(4) Social and community norms
(5) Biophilia; contact with the natural environment

On the other hand, thermal comfort refers to ''… that condition of mind which expresses satisfaction with the thermal environment'' (ASHRAE, 2004a). This state of mind can vary from person to person due to physical, physiological and psychological differences, for example the regulation of the body temperature (Delzendeh et al., 2017). Albeit, beyond the fact that the current building standards are based on averaged data, the present drivers are not the same as the one's from 100 years ago (Bluyssen, 2013). This means that an urgent update of these standards is detrimental to mitigate the current challenges.

5. Design process

5.1 Tradition design process

In traditional or sequential design processes, an 'over-the-bench methodology' is often used. Once a stakeholder has finished the work that needed to be done and passed it over to the next one, the person does not take any more responsibilities. This way of working often results in conflicts due to communication problems, lack of information sharing and transparency. Additionally, decision-making is often complex due to different interests and expectations and thus is easily determined by the stakeholder with the most power (Bluyssen, 2009).

5.2 Integrated design process

In an integrated design process, all stakeholders from different disciplines are working together in an iterative way until a holistic design is achieved that is satisfying to all involved stakeholders (Bluyssen, 2009). In order to achieve a successful team integration, Ibrahim, Costello & Wilkinson (2013) created a framework of 10 indicators to transform the struggling teams into more integrated ones:

- Goals and objectives
- Trust and respect
- Free flow communication
- No blame culture
- Commitment from top management
- Team flexibility and responsiveness to change
- Collective understanding
- Seamless operation with no organizational boundaries
- Sharing information
- Encouraging initiative

6. Summary and brief discussion

The following drivers were found to be important to health and comfort in the indoor environment: climate change, the needs of the end-user, the requirements of stakeholders and regulatory developments. Although, various adaptations are available to improve the energy performance of retrofitted buildings and to determine end-users wishes and needs, it is difficult to identify one single technique as the best. Therefore, a strong collaboration between the different stakeholders can pave the way to find out which design process and method suits the best for their problem depending on the final goal.

Part IV Case Study

1. Case introduction

Solar Decathlon Europe 2019

Initiated in 2002 by the United States Department of Energy, the Solar Decathlon is a university-level student competition for sustainable, responsible, energy-efficient architecture and engineering. Twenty University teams from all around the world are brought together to compete in the design, construction and management of individual energy and resource-efficient solar powered homes.

The goal of the Solar Decathlon is to transfer knowledge, research and experiments in the field of renewable energy and solar energy. The competition is also a means to create awareness within a larger audience in the area of materials, products and techniques that will be used in the houses of the future. Ultimately, the underlying idea of the competition is also bringing together universities, students, professors, researchers, building professionals and the business world, who are looking forward to develop research, innovation and understanding of renewable energy in the construction sector and on inventing and testing new processes and materials with which the house of tomorrow can be equipped.

Every edition of the competition has a specific topic that the proposals should address. The 2019 edition that took place in Szentendre, Hungary, emphases the topic of sustainable renovation, where at the same time every team is competing in ten different contents:

(1) Architecture
(2) Engineering and Construction
(3) Energy efficiency
(4) Communication and social awareness
(5) Neighbourhood integration and impact
(6) Innovation and viability
(7) Circularity and sustainability
(8) Comfort conditions
(9) House functioning
(10) Energy balance

MOR Team TU Delft

After the Second World War, the built environment was faced with pressures for rapid construction. From an ecological perspective, these buildings are no longer favourable, unfit for purpose, and are unable to meet the new European legislation with respect to the energy consumption. This means that empty 1960s and 70s office blocks will have to be upgraded (Roaf & McGill, 2018). Meanwhile, as the Dutch housing market is growing, the available affordable housing stock is dramatically decreasing; most notably in the big cities where the supply does not meet the demand. Especially starters who are entering the housing market have difficulties in finding a home. Before 2030, 1 million new homes must be built to compensate for the housing shortage.

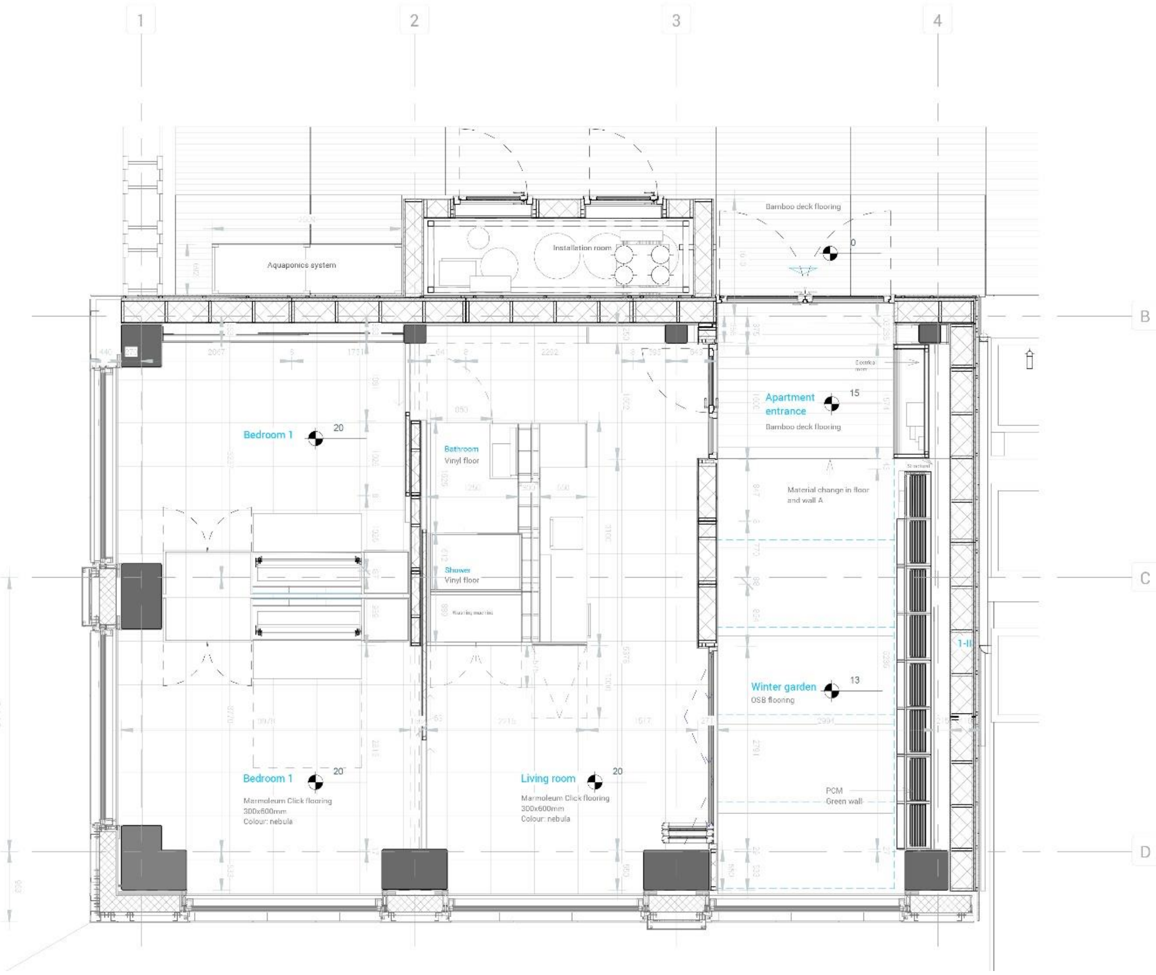

Figure 4. Floorplan of the prototype (MOR, 2019)

Consequently, the MOR team, which stands for Modular Office Renovation, studied the Europoint Complex or Marconi Tower in Rotterdam as a case study to tackle these two challenges – the renovation of underperforming office building stock into affordable net positive housing, while mitigating the negative economic, ecological and societal effects (MOR, 2019).

The design for the office tower, which is a typical office typology from the 70's that exists all over the world, is adaptable at all scales and builds on today's sharing economy and community-building principles. The concept is flexible in program and the interior is modular which allows for change over time. Public and communal spaces, like shared spaces for working, food production and entertainment among the living areas, are included in the tower, which allows for a highly social environment while promoting sustainable behaviour. The five net-positive aspects (biomass, water, air, materials and energy) of the building improve the impact on its surroundings and its resilience for decades to come. By reducing the building's demand on all five fronts and using passive strategies, the need for active systems can be eliminated. MOR's office renovation represents the evolution of the conventional environmentally taxing office building into one that gives back more to its surroundings than what it takes away from it (MOR, 2019).

In order to compete in the Solar Decathlon Europe 2019 competition, a cut-out form the Marconi Towers displaying a 50-m^2 apartment with a 25-m^2 indoor garden has been designed and built (**Figure 4**).

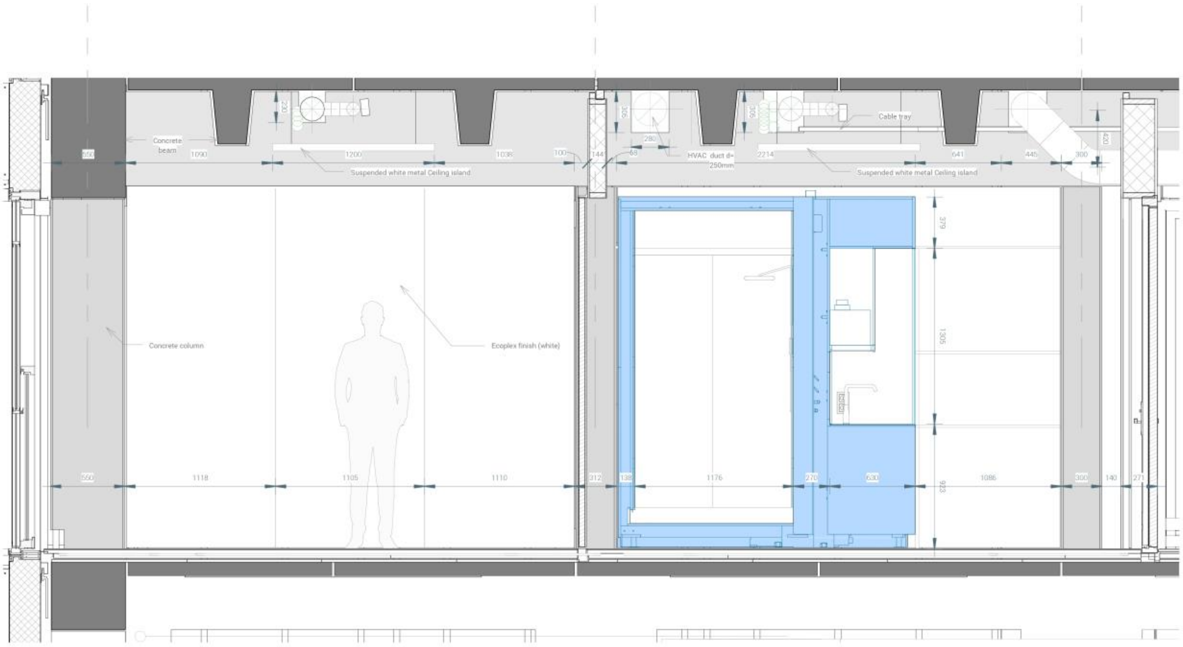

Figure 5. Section of the prototype (MOR, 2019)

This project has developed a strategy for prolonging the lifespan of existing building structures by embedding functional modules for an energy efficient, liveable space. Whereas, the idea of converting an office building into housing is generally benefited by the existing structural conditions. A typical office building is made to bear higher variable loads than used in housing. Building regulations state variable loads in housing of around 1,5 to 2 kN/m2, while for offices a value of 2 to 5 kN/m2 is considered. This means, that in converting the space to housing, lower variable loads are applied, and the structure is likely to provide spare structural capacity for its new use (MOR, 2019).

On the other hand, due to retrofitting, the existing load-bearing structure can be a constraint to include the new required technical systems, modules and components that match the existing cavities (**Figure 5**). Nevertheless, by having a well-thought design and by understanding the spatial quality, functionality and adaptability, as well as occupant well-being, extending the life span of the building type can be achieved successfully.

2. Incorporation of literature review in project

2.1 Design adaptations overview

Following the Trias Energetica, energy consumption is reduced by using a highly insulated thermal skin, sharing household appliances, using a BMS to operate services at maximum efficiency, using passive heating, cooling and ventilation when possible with indoor buffer zones and using very efficient (hot) water fixtures. Similarly, the design itself is kept as robust as possible by minimizing pump and ventilation loads.

Secondly, energy flows are reused where possible. This includes the usage of heat recovery ventilation and a shower heat recovery. Additionally, waste heat that is extracted through the central core fills the rooftop greenhouses where the heat can be captured. Blackwater is treated to biogas, which is used to supply heating in the coldest months through a CHP plant (Combined Heat and Power) or to generate H2 for usage in mobility.

Remaining electrical demand is then supplied sustainably through PV(T) systems on the facades and rooftops, while heating and cooling is provided through an Air Source Heat Pump (ASHP) system and the usage of Phase Changing Materials (PCM). Heat from PVT panels on the rooftops are used to recharge the thermal loop, while facade PVT panels are used to provide for domestic hot water in the prototype in conjunction with a heat pump boiler. PCM's are used in the green walls in the buffer space (private garden) and can provide for free cooling of incoming air. Additional high-temperature heat can be generated using a CHP plant running on site-sourced biogas for the coldest months.

The final goal is to maximize the performance of all subsystems that compose the design without compromising on comfort or the future adaptability and flexibility of the building.

2.2 Process overview

Based on the literature findings, several parameters are proposed to enhance the energy efficiency of the existing building stock. However, in order to achieve the preferred outcome, an optimum organization structure is needed since it can influence the whole design process and outcome. The MOR team started the competition with a traditional organization structure, where information about the design is being transferred in sequence. This vertical flow of information, as shown in **Figure 6**, resulted in a lack of communication. In order to improve this situation, the committee Leaders of the MOR Team, as well as some other team members, had a meeting to discuss and evaluate the current way of working. This meeting resulted in three main outcomes:

(1) Working on islands: Most of the people mentioned that every committee is working on their own and in the end, not enough information is being shared. That causes, of course, communication problems, as information is not being shared correctly within other committees.
(2) Top-down vs. Bottom-up organization of the team: So far, the team is using mainly a top-down way of working. The committee leaders are organizing the team members, giving them tasks and are defining the goals.

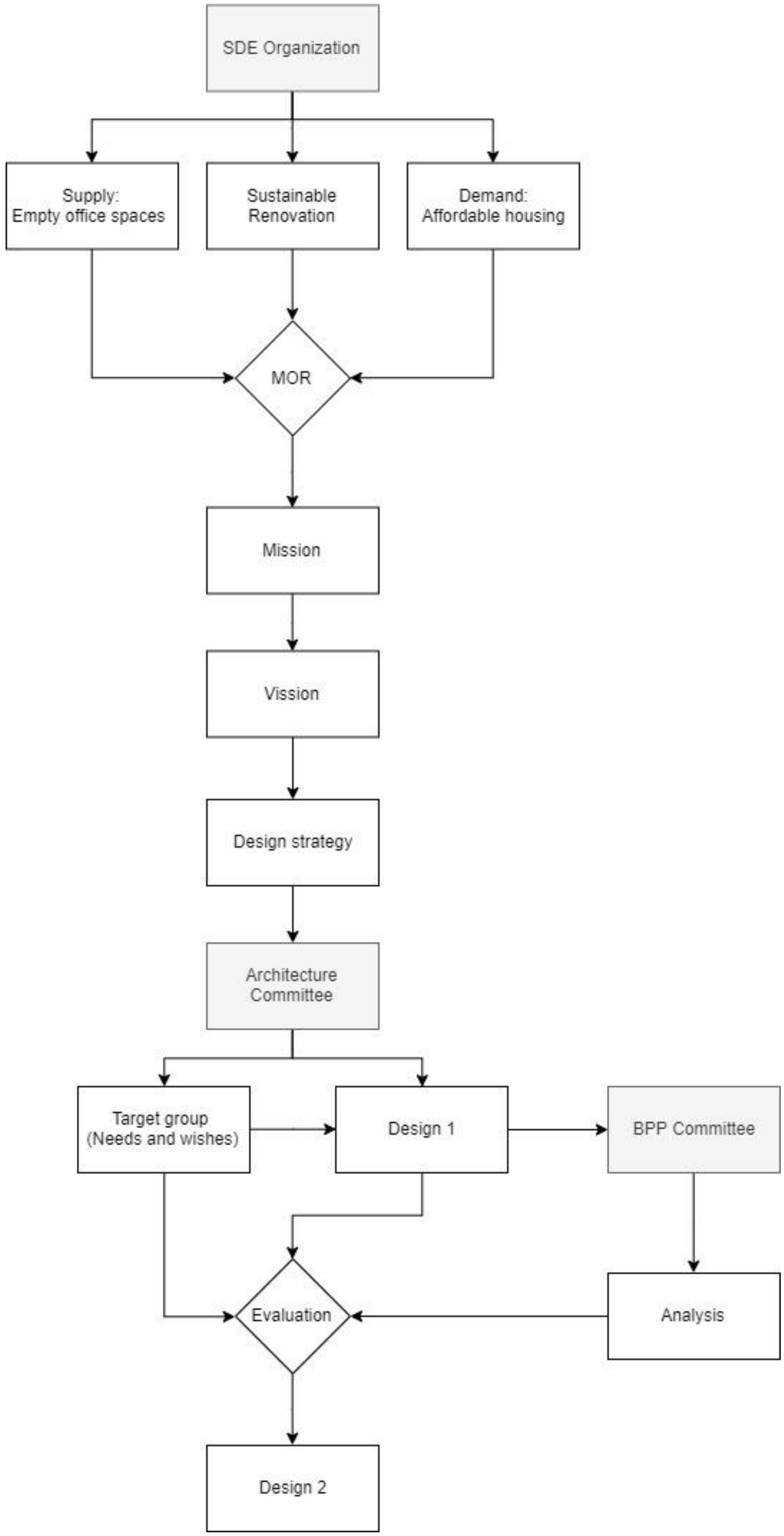

Figure 6. Organization scheme: Traditional design process

(3) No use of a central model in a shared program: Members prefer not to use Revit due to unfamiliarity with the program and a lack of knowledge; therefore, the team is not using it correctly.

The above mentioned problems can be tackled within the following ways;

Solution 1. Information must be shared in a more efficient way. Collaboration of committees. New organization structure (**Figure 7**). Structured weekly design meetings, where the goal of the meetings is to agree on the design of the prototype and on the integration of all the different systems/concepts.

Solution 2. People have to be more proactive and have a more "entrepreneurial mind-set". Team members should be more committed, more active on taking responsibilities and not only waiting to take up their tasks. A middle-top-down approach is needed. Leaders have to motivate their members and clearly define tasks and goals for them, but also that has to be made in a participatory way, where the team members have the "space" to influence planning and scheduling. In that way, they can be more involved. In order to move forward, the team has to be built on trust and commitment.

Solution 3. By using the program Revit and having a central model, details and information can be shared easy. It can also help to solve the "Working on islands" problem and that can save up a lot of time. In addition, clashes on the different design drawings can be identified.

Figure 7. New organization structure

What can be learned especially from this change in structure and process into an integrated one (Figure 8) is that every person, every discipline must collaborate in order to design a resilient built environment. It is crucial to share knowledge and to consider the team as one team, where everyone is able to recognize his or her own individual strengths and weaknesses but also the team's strengths and weaknesses. First, it is necessary to see the bigger picture to know what the best decisions are. This is especially difficult with how complex, integrative and dynamic the modern world is, which is also why it is so important. Solutions are often found in networking and sharing resources with mutual gains. Thus having a structured communication within the team. Then a plan need to be formed together in order to achieve an integrated and holistic design outcome. This result can be obtained through iteration with continuous feedback loops between the different committees. Additionally, it needs to be recognised that every input from every stakeholder is valuable and that some decisions are made because of constraints, such as competition rules, existing load-bearing structure, truck sizes, time and budget and not due to personal reasons. This means that every stakeholder need to be able to be open and to accept every information to improve the project.

Table 6. Sustainable development versus project management concepts (Silvius & Schipper, 2014).

Sustainable Development	Project Management
Long-term/Short-term oriented	Short-term oriented
Considers the interest of this generation and future generation	In the interest of sponsor/stakeholder
Life-cycle oriented	Deliverable/results oriented
People, planet, profit	Scope, time, budget
Increasing complexity	Reduced complexity

However, having only a new structure is not enough. The role of project managers are crucial throughout the whole process. The integration of sustainability in project management is carried out on the basis of Brundtland Commission's interpretation of sustainable development which says that "development that meets the needs of the present without compromising the ability of future generations to meet their own needs", (World Commission on Environment and Development, 1987). Thus, in order to close the energy performance paradox and design a self-sufficient retrofitted building, the project manager must consider the economic, social and environmental impact of the project, its results and its effects. Meaning that the manager is required to consider the full life cycle of the project and should take several aspects into account as stated in Table 6. Moreover, Silvius and Schipper (2014) claim that managers should acknowledge a mind shift (taking responsibility for sustainable development), a paradigm shift (having a holistic perspective on managing change) and a scope shift (managing social, environmental and economic impact) in order to make buildings healthy and comfortable while improving the energy efficiency of retrofitted buildings.

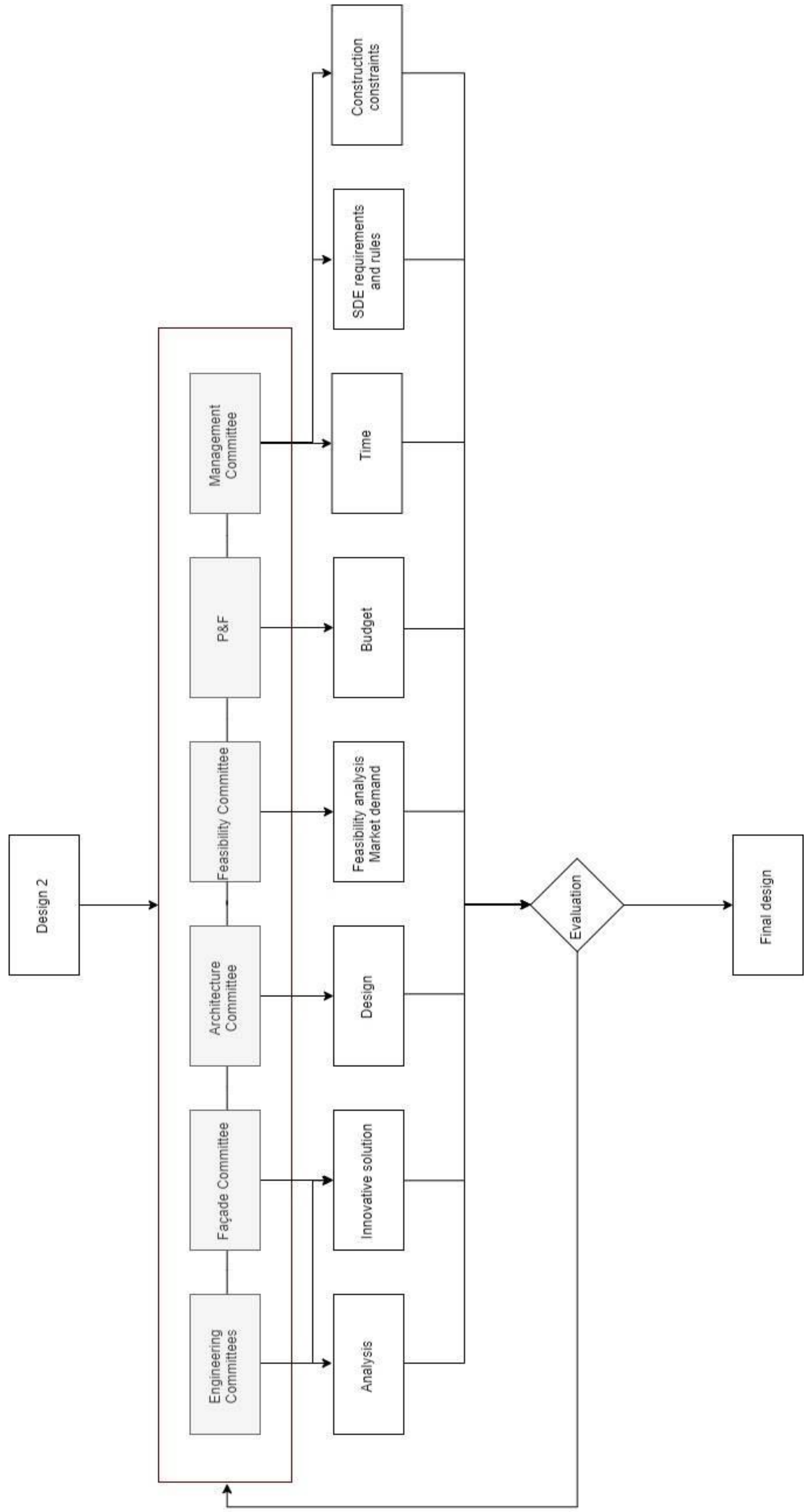

Figure 8. Organization scheme: Integrated design process

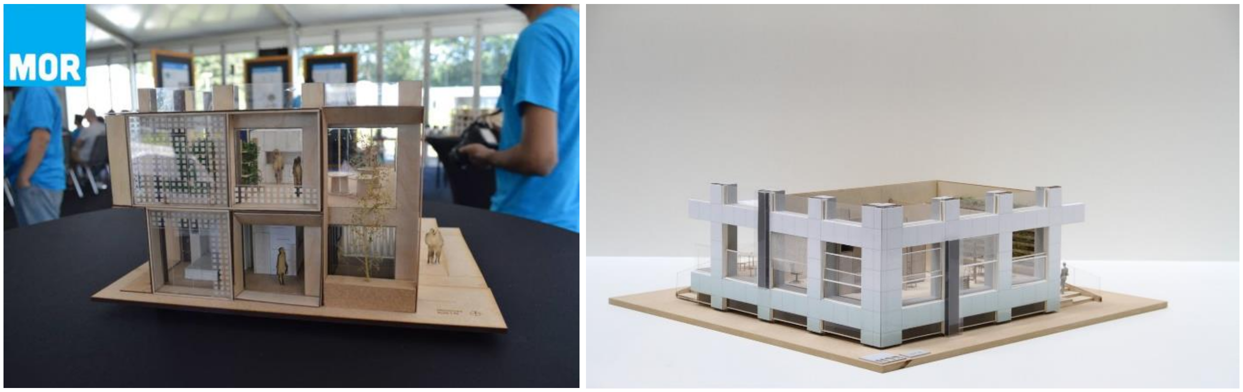

Figure 9. (L) prototype two floors (June 2018) – (R) Prototype one floor (April 2019) (MOR, 2019)

Figure 9 represents an important milestone in the project: changing the prototype design from two floors to one floor. This decision could only be possible with a strong collaboration of the different committees that strived to produce solutions that were ''best for the project'' within a ''no blame'' culture.

The process of choosing the best design variables means optimization and often requires computationally intensive simulations. Therefore, the design started with assumptions on primary energy use (in kWh/m2a for HVAC, lighting and user energy) based on similar projects and references from literature. The maximum allowable number of residences calculated this way has been used as a guiding principle for the layout of the tower as well as the financial feasibility of the project. In later stages, Excel, DesignBuilder and Matlab have been combined in order to analyse and optimize the designs for both annual and competition performance with respect to primary energy use and peak heating/cooling loads.

3. BMS implementation process

The use of BMS in the built environment can help to better understand the relationships between occupant behaviour, thermal comfort and energy consumption for heating. In the context of residential buildings, the placed sensors can detect the interaction of the end-users with the building. For example, how often they open the window or change the settings of the mechanical ventilation, which thermostat settings they use, but also what type of clothes they wear and what type of activities they carry out in their homes. By relating these actions to the experienced thermal comfort, the parameters influencing the thermal comfort and its relation to energy consumption can be understood.

3.1 Process overview

The BMS implementation process consists of three main parts and several subparts as it is shown in Figure 10. The steps that need to be taken in order to implement the BMS are explained in the paragraphs below.

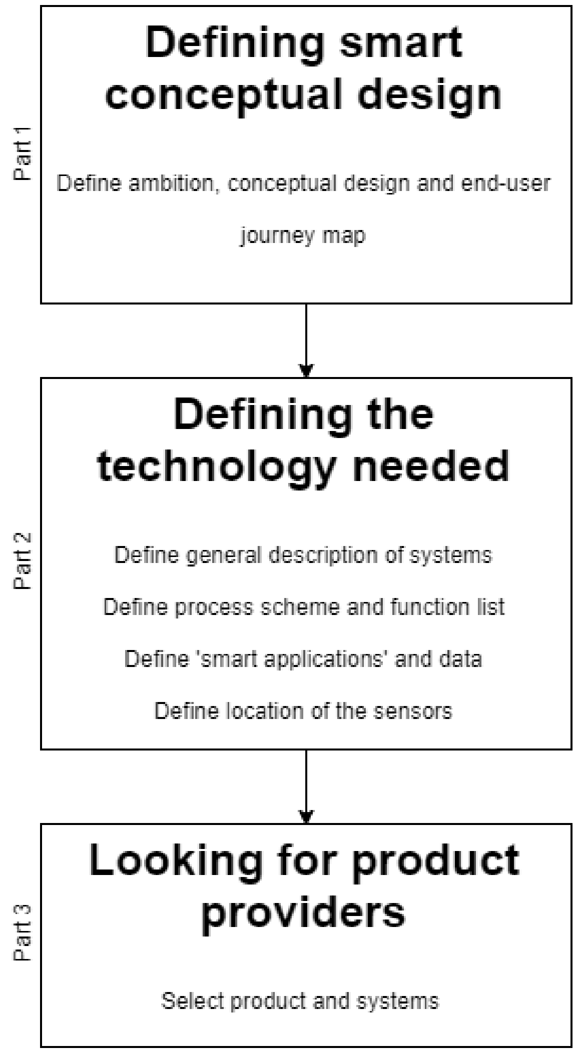

Figure 10. BMS implementation steps

PART 1. Defining the smart conceptual design

The first step in the BMS implementation process is to understand what is crucial to improve the daily life of the end-users. The smart applications aim to add value to the building and urban environment disciplines, whereas the wider goal is to achieve resiliency and climate adaptation. The main reason for choosing a smart building management system is to improve the energy efficiency while keeping the comfort level and satisfaction of the building users high. To understand what kind of smart technology is needed to implement in the building, a first general analysis is done as well as an end-user journey map (see Appendix A) has been created to obtain an integral smart application design. In the broader picture, the smart application system can be divided into 7 different main topics as shown in Figure 11 : well-being, behaviour, energy, operational performance, circularity, security and outdoor climate.

Well-being: Keeping the end-user satisfied is detrimental. Therefore, it is important to achieve a good air quality level, indoor thermal temperature, sufficient lighting and accessibility of electricity and water.

Behaviour: Influencing people behaviours is one of the key factors to achieve a sustainable environment. For example, by varying the prices for the laundry, people might be intrigued to start using the washing machines during non-peak hours. These kinds of plays can definitely help to balance the demand-supply profile of the source generation. Moreover, the usage of sustainable vehicles and bicycles can be promoted by making use of collecting points, which then can be used for other services in the building. The same system can be done to promote social activities while reducing food waste and energy.

Energy: A digital system is proposed that allows the users to monitor their household consumption of electricity and water, but also of the amount of waste they have generated. This active monitoring allows the user to see their consumption and compare it with other building users; this could lead to behavioural changes to reduce consumption in the future as well. Moreover, this predictive energy control is beneficial to reduce the supply and demand mismatch and can be seen as a strategy to use generated energy efficiently, such as heating the house around 2 hours in advance at low temperature before coming back home.

Operational performance: In order to have an effective and efficient operation and maintenance life of the building, predictive maintenance is being used with the help of smart sensors.

Circularity: The first goal would be to minimise waste as much as possible and as the second step to reuse and recycle. Therefore, collecting rainwater and reusing grey water for other purposes might be beneficial to reduce water usage. Besides this, a material passport has been created to have an optimum LCA.

Security: Security can be divided into technical and Physical security. With technical security, it is meant to prevent equipment overheating, shortcuts, etc., while in physical security, the building needs to be protected against external factors such as robberies.

Outdoor climate: Detecting the outside temperature, air quality, wind speed and giving weather advice.

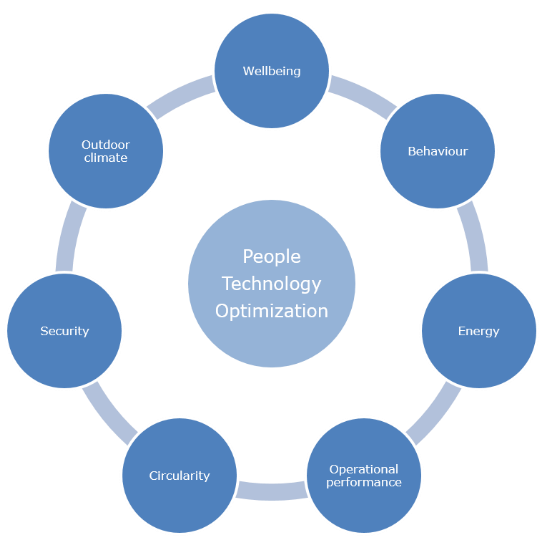

Figure 11. Concepts for smart application

PART 2. Defining the technology needed

In order to reach the goals set for the conceptual design in part one, the next step is to define the technology needed. This part consists of several phases. First, a general overview of the building systems (see Appendix B) are described in order to gain knowledge on the possible collection of data that is necessary to make the smart application happen. Afterwards, to determine the type of the required sensors (see Appendix C); the building systems are split in different control categories based on the six categories of ISSO69. **Table 7** represents the process scheme and the function list. Finally, the last step in the sensor design strategy is situating the specific locations of the sensors on the electrical, mechanical and architectural schemes (see Appendix D).

Table 7. Process scheme and function list (based on the six categories of ISSO69)

Automatic controlling	• Windows (opening in %) • Blinds open at night and close at day if temperature is too high • Temperature control from systems, opening and closing
Switching	• HVAC off if windows or garden wall is open • Lights off if there's daylight
Guarding	• Deploying blinds and windows only during safe weather conditions.
Optimizing	• Cloud system to upgrade the house/systems
Manual controlling	• Windows • Blinds • Lights
Managing	• Energy consumption per appliance

PART 3. Looking for product providers

Once all the decisions are made based on what services are needed, it is time to look for product providers. However, before contacting any supplier, it is recommended to first define boundary conditions and constraints (e.g. wired-wireless) and to find solutions that are not controlled by only one manufacturer (what happens if that company get bankrupt?). Afterwards, all the wishes, available systems and implementation typologies are discussed with the suppliers. This process will be an iteration of several steps until the final preferred outcome is obtained through a multi-criteria analysis.

3.2 Systems description

For the prototype, a design strategy was created so it could control the different systems present. In this case: window and blind control system, HVAC and control of the storage system are all controlled and connected to each other. All in order to make these systems work together and improve the quality of life of the inhabitants and the energy efficiency of the prototype. The different control schemes of each control are presented now and the overall control strategy and how these controls operate with each other.

For a comfortable indoor climate, a proper function of the BMS is important. For this specific prototype, a Priva Blue ID system was selected. The convenience and reliability of the system made it a perfect fit for the prototype. It consists of HVAC controllers that communicate through BACnet. BACnet is a communication protocol in building automation. It has been developed for use at all levels of building automation and for all systems, be it air conditioning, lighting or security. It has the ISO16484-5 global standard for building automation. Another reason for choosing the Priva Blue ID is due to the flexibility options it presents which are going to be needed due to the nature of the building. Showcasing the importance of being able to change or add functionalities in the automation system.

Besides this, the system can also communicate with through these communication protocols: Echelon, KNS, M-bus, Modbus, SNMP, XML. This makes it suitable to connect to other systems which do not share the same communication protocol but have a common one. The following image shows a visual representation of the system:

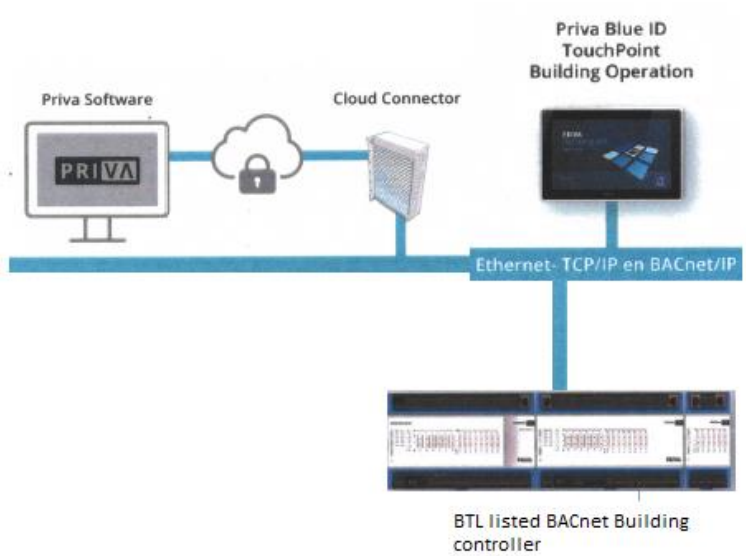

Figure 12. Building controller (Based on Priva)

Temperature sensors are used in the HVAC system in order to ensure a comfortable temperature for the user. Every sensor is compatible with the Priva Blue ID process computer. There is a number of systems in every room that control the room temperature. Added to that, they are also used to control the air quality in each room. In order to determine the inside conditions that are to be kept, outside and inside conditions are measured. The basic principle is that passive systems should work to maintain the pre-established conditions and only use the active systems when they are required.

In order to measure the indoor conditions, several sensors are installed. Firstly, a combined temperature and CO2 sensor is provided per room (living room and the two bedrooms). The outdoor conditions i.e. solar radiation wind and temperature are measured with the weather station. Furthermore, the weather station is linked to the substation. For measuring the indoor conditions, a combined temperature / CO2 sensor must be provided per room (living room, bedroom 1 and bedroom 2). The outdoor conditions (solar radiation, wind, temperature, etc.) are determined with the help of a weather station. This weather station must be software linked to the substation. Although the aforementioned sensors are used for temperature control, they are not only intended for this purpose. Mechanical ventilation and windows are also controlled based on air quality.

Heating and cooling overall strategy

If the temperature exceeds a certain temperature "T", the passive system will be activated in order to decrease the temperature in the house. The window and blind control are the first in the order. If certain conditions are encountered, such as occupancy levels, outdoor temperature and wind speed then the other systems will be activated.

Table 8. Control orders

Window control	In order to control the windows and outer blinds, a shutter control is installed. The following window controls are possible: - Open and close an individual window based on room temperature depending on the outside temperature. - Open and close an individual window based on CO2 levels in the room. - Close control of windows based on the measured wind speed outside. - Close control of windows based on rain detection, if available at the weather station.
Blind control	The shadings are also individually controlled from the main distributor of the electrical installation, where the following sun protection controls can be implemented: - Open and close individual sun blinds based on room temperature in combination - with the solar irradiation measured outside - Open the shadings based on the measured wind speed outside. - Open control of individual shadings based on the measured light intensity inside.
Supply ventilation	The supply ventilation is adjusted with motorized constant volume controls, which can be regulated continuously. Two of these volume controls are included in the living room and one in each bedroom. The following functions of the constant volume controls are possible: - Open and close steering based on measured air quality in the room (sequence control with windows)

	- Open and close control based on cooling demand in the room, based on room temperature measurement, in the following order: o Window control o Control supply ventilation (free cooling) o Control for cooling o Control of climate ceilings o Control supply ventilation (active cooling) It can be seen that the priority of the supply ventilation relative to other facilities depends on the operating condition of the mechanical ventilation; passive cooling or active cooling.
Underfloor heating and cooling	Underfloor heating and cooling is centrally regulated based on the outside temperature. Rooms cannot be adjusted separately.
Climate ceiling islands	Climate ceiling islands are placed in every room, two in the living room and one in each bedroom. The climate ceiling islands can be regulated per room. Depending on the season, central heat or cold is available for the climate ceilings. A control valve must be included for each climate ceiling island to regulate it. The climate ceilings are able to perform the following controls: - Open and close control based on the measured room temperature in heating mode - Open and close control based on the measured room temperature in cooling mode.
Centralized air cooling system	A central air cooler is included in the supply ventilation. If actively cooled air is used to maintain the room conditions, this cooling battery will have a fixed air achieve inlet temperature. In the cooled water pipes to the cooling battery, a control valve must be included with which the cooler exit temperature can be controlled. The following controls of the cooling battery must be possible: - Open and close control based on the measured cooler outlet temperature in cooling mode.
Inner garden	The inner garden aims to create an intermediate climate between the indoor and outdoor conditions. The temperature of the inner garden can be influenced by means of the motor-operated window, depending on the outside conditions. The control of the window motors is done from the main distributor of the electrical installation, this controller must be software linked to the hardware in the control cabinet. The following window controls must be possible: - Closing the window to a minimum position in order to be able to buffer solar heat in the inner garden (winter) or maintaining the temperature to an acceptable level in the inner garden during high outside temperatures (summer). - Opening the window to store night coolness in the inner garden (summer) or to store heat in the inner garden during the day (midseason). Here, if the mechanical air supply is active, a minimum opening must be respected.

PCM battery	The PCM battery has a similar construction as that in the inner garden. Night air can be stored by circulating air over the PCM plates with a regeneration fan. By supplying heat to the air stream via a battery connected to the solar boilers of the solar chimney, heat can be stored in the PCM battery. During regeneration, valve sections disconnect the PCM battery from the heat pump's outdoor unit and connect it to the regeneration fan. with the PCM battery, the following controls may be realized: - Charge the PCM battery with night cold by switching on the regeneration fan and controlling the valve sections so that the regeneration fan circulates air over the PCM battery and the heat pump's outdoor unit does not suck in the PCM battery air. - Charging solar heat with a circuit similar to that described above. In addition, the circulation pump on the discharge side of the solar boiler must be switched on in order to be able to supply heat to the airflow over the PCM battery.
Heat pump	The heat pump is equipped with its own control, which can be linked to the hardware in the control cabinet via software. The heat pump must be able to: - Switch off during heating or cooling operations. - Switch on and off. - Setpoint adjustment in cooling and heating operation.
Solar chimney	The solar boilers are equipped with their own control system. Where solar boilers normally stop charging at a high boiler temperature, the solar chimney will already have to switch off the solar boiler at a lower boiler temperature. The following controls must be possible with the solar water heater: - Activating the charging cycle based on a signal from the solar chimney or a sun intensity measurement from the weather station - Terminating the charging cycle if the maximum permissible temperature for the PVT panels is reached, either by setting a set point on / passing it on to the control of the solar boilers or by a separate temperature sensor based on which the supply to the charging pump from the solar water heater is interrupted.

3.3 Variables of interest

The final version of the prototype tries to combine and integrate the most energy efficient solutions together in order to minimise the building consumption, whilst guaranteeing a comfortable living.

Variables that are needed to validate the guideline:

- Data from BMS: produced and consumed energy
- Data from questionnaires: activities, comfort level, etc.

Part V Analysis

1. Data analysis

1.1 Temperature values and user interaction

The competition week started on 14 July at 21:12 and ended on 25 July at 06:00 consisting of two phases: an active and a passive evaluation process. The passive evaluation process started on the 22nd at 00:00 and ended on the 24th at 08:00.

Every morning daily tasks were performed between 8 and 12 am to evaluate the house functionality and the efficiency of the selected appliances, in order to maximize the performance of the house, while complying with the demanding standards of present day society. In order to reproduce the average energy use in a modern home several tasks were realized, such as boiling water and running the oven for an hour, running the washing machine and dishwasher as well as other activities.

WM (washing machine): 193 min, 1.01 KWh (2300 W)
DW (dish washer): 140 min, 1.2 KWh (2400 W)
Cooktop: 60 min, 2.2 KWh (2200 W)
Oven: 60 min, 3.6 KWh (3600 W)

Once the daily tasks were completed, the prototype was open for public tours from 1 pm until 6 pm. On specific days, there were dinner parties organized from 7 pm until 9 pm, where guests from the other pavilions were invited to have dinner in the monitored area of the prototype.

Every day, a planning of the tasks order was made based on the outdoor temperature. The paragraph below shows the schedule for one active day and one passive day.

16.07.2019 – Active evaluation (see **Figure 14**)

- 08:00 WM on
- 08:48 DW turned on
- 10:00 Heat pump off (already in cooling mode), Tlr = 23.8°C and Tbr= 22.8°C, circulation pump ceiling and floor=off
- 11:17 DW done
- 11:18 WM done
- 11:26 Oven turned on, living room shading full down, all three windows opened 100%
- 12:09 cooking hot water

  Every task starts at a different time to reduce the power peak at once and to make use of the solar energy at its fullest. The different peaks per task can be seen in **Figure 13**.

- 17:25 home electronics connected (laptop and screen)
- 18:00 all lights activated, bedroom is quite hot
- 18:05 opening the shading above the window and allowing ventilation to cool down
- 19:30 shower test, DHW (Domestic Hot Water) preheated by boiler solar.

17.07.2019 – Active evaluation

Today's forecast: slightly cloudy after 11:30 until 18:00, 27°C peak at 16:00. A different task time planning has been arranged in order to make use of the sun heat as much as possible.

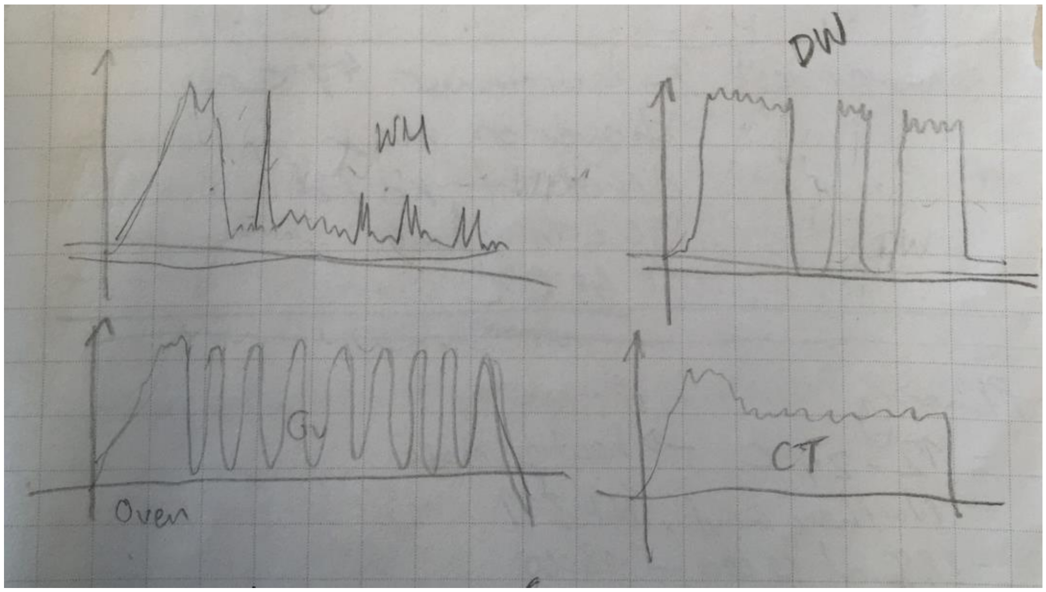

Figure 13. Peak levels of different tasks

22.07.2019 – Passive evaluation

- 08:10 oven test: 60 min, 3.6 KWh (3600 W)
- 08:10 cooking: 60 min, 2.2 KWh (2200 W)
- 09:20 WM: 193 min, 1.01 KWh (2300 W)
- 09:20 DW: 140 min, 1.2 KWh (2400 W)

For the passive days, all activities were executed consecutively, but then as it can be observed in Figure 15, the temperatures were rising quicker. Therefore, windows and doors were opened to ventilate as much heat as possible.

In general, outdoor temperatures varied between 18 degrees at night and max. 35 degrees during the day; however, overnight the house could not be cooled down since the temperature also had to stay between 23 and 25 degrees for full points. An extensive analysis of the scores versus collected data can be found in Appendix E. On the other hand, it was possible to cool down the PCM at night with about 6 hours of ventilation at 1000 m^3 / h. Therefore, for the Passive night cooling at home, each window was open around five cm and the bedroom 1 had the door closed. Interior shades were down halfway the garden was fully open to exterior.

Supply temperature from the PCM to the home was measured at 23.5C with a flow rate of 450 m3 / h. Since the temperature did not needed to be maintained between 1 pm and 7 pm (No scoring during tour visits), the system was sometimes not cooling. The reason is because during the public tours many people were available, almost constantly 6-12 people and even more on peaks (see Appendix E). During this time period several measures were taken such as closing the windows and blinds and pumping water into ceilings and floors. However, the water was generally at room temperature.

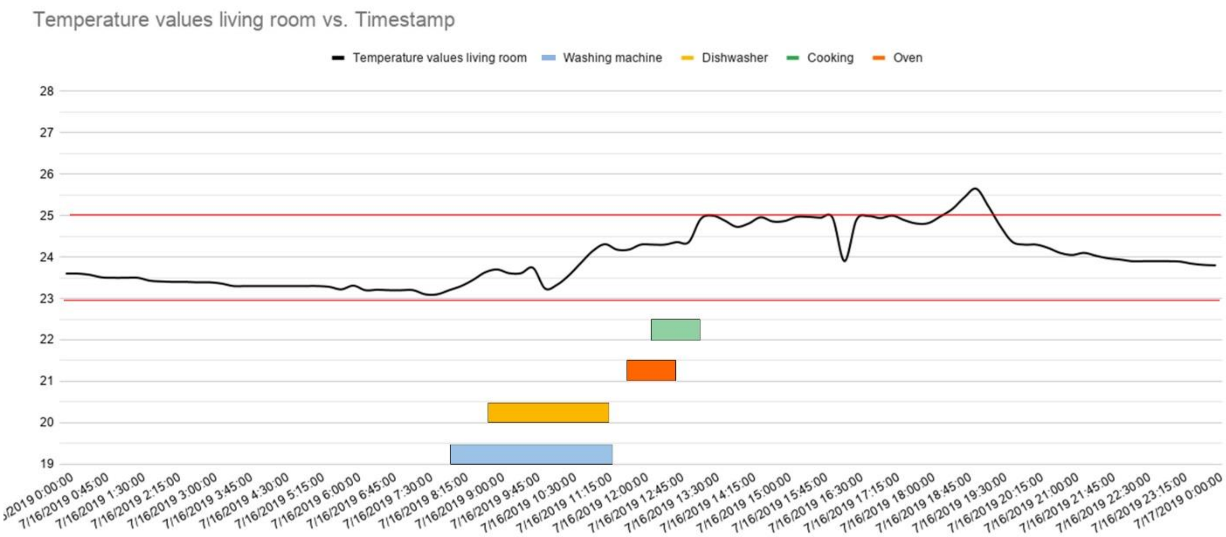

Figure 14. Temperature values living room vs. Timestamp (July 16, 2019)

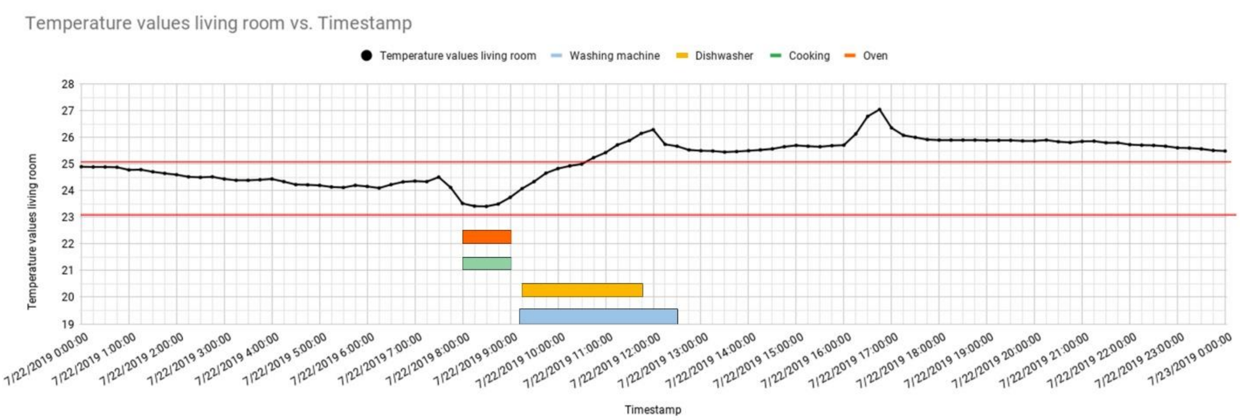

Figure 15. Temperature values living room vs. Timestamp (July 22, 2019)

Table 9. User interaction and temperature values

	Passive control	Active control
Morning: House functioning contest tasks (2 persons in the house)	Temperature rise increases at a fast pace, but still within acceptable conditions	Ideal temperatures
Afternoon: Tour visits (6-12 people)	Temperature level is higher but still ideal; however, sometimes temperature peaks occurred due to high outside temperature level and the amount of people inside.	Ideal temperatures
Night: No occupancy	Ideal temperatures (between 23 and 25 degrees)	-

1.2 Temperature values and user comfort

Person	Time	Actual temperature	Activity	Level of comfort	Age	Gender	Nationality	Health state	Reason
1	16-07-19 21:00	24	Dinner party	3	25	male	Spain	good	-
2	16-07-19 21:00	24	Dinner party	3	21	male	Spain	good	-
3	16-07-19 21:00	24	Dinner party	3	24	male	Hungary	good	-
4	16-07-19 21:00	24	Dinner party	3	21	male	Hungary	good	-
5	16-07-19 21:00	24	Dinner party	3	23	male	Algeria	good	-
6	16-07-19 21:00	24	Dinner party	3	26	female	Algeria	good	-
7	16-07-19 21:00	24	Dinner party	3	25	male	Romania	good	-
8	22-07-19 21:00	26	Dinner party	3	22	female	Romania	good	-
9	22-07-19 21:00	26	Dinner party	3	24	male	Spain	good	-
10	22-07-19 21:00	26	Dinner party	5	27	male	Spain	not good	sick
11	22-07-19 21:00	26	Dinner party	3	22	male	Hungary	good	-
12	22-07-19 21:00	26	Dinner party	3	21	male	Hungary	good	-
13	22-07-19 21:00	26	Dinner party	1	25	female	Belgium	good	Host - cooking
14	22-07-19 21:00	26	Dinner party	2	23	female	Netherlands	good	Host

Figure 16. Evaluated interior thermal comfort by guests

To assess the interior comfort, guests were invited to fill in a short questionnaire after the dinner events on the 16th (active measure day) and 22nd of July (passive measure day). The dinner started around 7 pm and finished around 9 pm. During these two hours, the guests were welcomed by the hosts, received a starter, a main dish and a dessert with drinks. Figure 16 represents the outcomes of the surveys, where the level of comfort has been assessed based on (1) Very Hot, (2) Hot, (3) Comfortable, (4) Cold and (5) Very cold. Fourteen people in total participated. In general, one can say that the interior temperatures were comfortable. However, during the passive day three participants stated differently. The hosts of the event stated to feel very warm. The main reason for this is that they were cooking, using the oven and serving the dinner for the guests. Thus being in constant activity. Additionally at the beginning of the evening, the windows were not open. However, when at a specific moment of the evening the windows were open, one person stated to feel very cold. The main reason only that person was not feeling comfortable was the fact that his health status was not perfect.

1.3 Theoretical versus actual consumption

Table 10. Predicted and actual energy consumption

Predicted energy consumption	Actual energy consumption	
75.73KWh	68.75KWh	Ef (Appliances)*
76.70KWh	64.95KWh	Ev (HVAC + DHW)*
152.43KWh	133.7KWh	Total (Ef + Ev)

*Breakdown: amount of consumption not known for every system individually

Table 10 represents the predicted and actual energy consumption of the prototype for the competition week in Hungary. From the definition of energy performance, the energy performance gap is caused by the NEGATIVE difference between the predicted and actual energy consumption. From the collected data, the following can be extracted: the difference between the predicted and actual energy consumption is POSITIVE. This meaning that there is no energy performance gap. For a more detailed overview of the power meter readings and power balance, see Appendix F.

Energy performance gap = | Predicted energy consumption - Actual energy consumption |

Table 11. Predicted and actual produced energy

Predicted produced energy	Actual produced energy
241.72 KWh	249.64 KWh

With the main goal to give back more than it takes, the current energy strategy of the prototype can be labelled as a zero positive building or self-sufficient building.

Self-sufficient building = | Energy production - Energy consumption |

= | 249.64 KWh – 133.7 KWh|

1.4 Conclusion

By promoting the right ecological solutions and having a conscious user behaviour, such as deciding on certain tasks to do based on the outdoor weather, energy can be consumed efficiently whereas temperatures are kept at a very comfortable level. The MOR Team's proposal for the Rotterdam Europoint Complex is an example of self-sufficient high-rise tower relying solely on renewable energy: High performance, Low energy.

2. Process analysis

2.1 BMS implementation process

In building adaptation, several stakeholders with different backgrounds and disciplines are involved in order to create a holistic design. Often in traditional design processes, an over-the-bench methodology is used, as it is defined in literature, passing over the responsibilities to the next party. However, this way of working does not result very well as stakeholders can have different interests and expectations resulting in conflicts inside one team. Based on their power level, certain stakeholders can influence the project more than others can since they have different set of priorities when the adaptations of the building is being considered (Winch, 2010).

At a certain point, the MOR team decided to restructure its team organization: going from a vertical flow towards a horizontal one. Since the actual hierarchy was giving space for misunderstandings and lack of information sharing, the new structure was able to keep everyone on the same track. Everyone strived for the same mission and vision. Weekly formal and informal meetings were happening, such as board meetings, team meetings, committee meetings, contest champions meeting and team building activities to keep up the team spirit.

Table 12. Drivers and barriers in BMS implementation

Drivers	Project	Same mission and vision (Energy efficient and circular built environment)
	Process	New work environment and organization (Integrated and interdisciplinary)
Barriers	Process	Different interest and expectations
		Different set of priorities
		Lack of knowledge in some aspects
		Decision making problems
		No team spirit
		Lack of information sharing, transparency and trust
	Project (BMS implementation)	Privacy constrains
		Data security

Having an interdisciplinary team advanced the achievement towards an integrated and holistic design. However, the decision-making procedures went not always as smooth as possible. For the BMS implementation process, the engineering committee mainly gave decisions. Additionally, other committees were giving inputs about budget, time, design of the prototype and feasibility. Albeit as Table 12 demonstrates, several barriers were hindering. In order to implement BMS in an efficient way, these barriers had to be overcome. Most of the actors still had a difference in interest. Thus focusing more in their own field. In addition, since BMS implementation is a quite recent process, knowledge in certain aspects was lacking. These problems could only be solved through recognition of stakeholder's interests and priorities, and by helping each other to grow and improve for the sake of the project's success.

Moreover, during the decision-making process of choosing the right smart applications, barriers such as privacy concerns and data security arose. By doing multi-criteria analysis based on the objectives of every involved committee the best possible outcome could be achieved for the MOR case.

2.2 Conclusion

In order to achieve a successful project, it is crucial that every involved stakeholder is transparent about information. Working in an effective way means recognition of stakeholder's interests and priorities that will lead to share information and accept to be flexible in the organization for the sake of the project's success. This recognition of different interests and trust could be achieved thanks to two main aspects. The first important facet was the transition from the sequential model to the parallel interaction, which changed the shape of the design process drastically. The different parties started to have meaningful interactions where everyone had the same understanding about the project's mission and goal besides their own individual goals. Every stakeholder started to strive to pick up the best possible available technique to accomplish the shared goal. However, during the BMS implementation several barriers still had to be overcome, such as decision-making problems due to different set of priorities and lack of knowledge in certain aspects. For example, the process to decide on the HVAC was very complex and difficult. Information was being awaited from the Building Physics committee in order to understand how it works and what kind of sensors could be connected and placed. Then, instead of just waiting for information to be passed over, which then leads to time constraints, taking action to find out the solutions yourself is remarkable. Inside one team, members should complement each other but also challenge each other. This brings to the second important aspect: role adaptability. Leadership is a process where it is essential to get to know what you are good at, what others are good at, to listen and communicate with each other and to be able to reflect on the process. This means that inside one project, a person can be a follower while leading, but can also oppose or stand in a bystander position when needed in order to give the best input as possible to the team.

Part VI Research Findings, Conclusion and Discussion

1. Research findings

This master thesis focusses on an approach that can help to solve the presented paradox by doing further research, which afterwards elaborates upon the implementation of Building Management System (BMS) requirements in order to add value to the energy performance of retrofitted residential buildings. By defining objectives and sub-questions, the research goal of this thesis has been made more specific in order to understand the integration of the BMS requirements. The paragraphs below conclude by giving a brief review of the research sub-questions.

♦ *What are the influential factors related to energy consumption?*

In order to achieve the energy efficiency targets, it is key to understand and strengthen knowledge regarding the robust prediction of total energy usage in buildings, which will later on enable the assessment of energy-saving measures, policies and techniques. The basis to achieve efficiency in energy consumption is understanding the factors that contribute to this energy consumption. In his book Energy: Management, Supply and Conservation, Dr Clive Beggs (2002) stated that energy is being wasted due to different reasons, such as poorly designed buildings and installations, inadequate control systems, inefficient control settings, poor maintenance and irresponsible use of equipment. Additionally, scientific research has proven that the building's energy consumption is mainly influenced by factors that can be separated into 6 different categories; (1) climate, (2) building envelope and other characteristics, (3) building equipment, (4) operation and maintenance, (5) indoor environmental conditions and (6) occupant behaviour (Yan et al., 2015).

While significant progress in the first five focus areas has been achieved, occupant behaviour in buildings still leads to an excessive energy consumption due to their stochastic, diverse and complex nature. According to Bluyssen (2009), the end-users' prerequisites for being able to adjust building systems and components refers to the interaction with the building in order to improve the Indoor Environment Quality (IEQ), which is described by environmental factors such as indoor air quality, thermal comfort, acoustical quality and visual or lighting quality. The main drivers behind energy-related occupant behaviour include the inhabitants' desire to look for pleasant conditions and satisfaction within their environment (Peng et al., 2012). "If a change occurs, such as to produce discomfort, people react in ways to restore their comfort" (Nicol & Humphreys, 2002). For example, an occupant may adjust the thermostat or open the window to enhance their comfort. Several personal factors, such as (1) demographic variables, (2) states and traits, (3) lifestyle and health status, and (4) genetics, event and exposures, can influence a person to respond in a certain way (Bluyssen, 2013).

- *How should the project be organised with respect to these influential factors in order to achieve energy performance?*

Based on the literature findings, several parameters are proposed to enhance the energy efficiency of the existing building stock. However, in order to achieve the preferred outcome, an optimum organization structure is needed since it can influence the whole design process and outcome. The MOR team started the competition with a traditional organization structure, where information about the design is being transferred in sequence. This vertical flow of information resulted in a lack of communication since different committees were working on separated islands and were not making use of a central model in a shared program. This shows that in order to achieve the shared goals and to be able to create a holistic design, the organization needed to be restructured. By having an integrated design process, every committee started to work more closely to accomplish the common goal. This enhanced the current approach by introducing a better understanding of the spatial quality, diversity and the interactions between the involved stakeholders for the design. The several weekly meetings in different combinations resulted in a structured communication and information sharing amongst the stakeholders. Through an iterative design process, the design was reviewed simultaneously with every stakeholder's input contributing to a holistic design outcome, which achieves energy performance in the built environment. Additionally, problems must be solved with user-centred design, which is at the heart of a holistic approach. It can be concluded that interdisciplinary and integrated cooperation is central to the approach of this research.

- *What are the drivers and barriers for project managers for the BMS implementation to optimize the energy performance of retrofitted residential buildings?*

Having an interdisciplinary team advanced the achievement towards an integrated and holistic design. Every stakeholder had a clear overview of the process and the upper goal that needed to be achieved. However, several barriers, such as different interest and expectations, different set of priorities, decision-making problems and lack of information sharing and transparency, had to be overcome in order to implement the BMS requirements. Therefore, during the whole process it is essential to get to know what you are good at, what others are good at, to listen and communicate with each other and to be able to reflect on the process. These problems could only be solved through recognition of stakeholder's interests and priorities, and by helping each other to grow and improve for the sake of the project's success. While at the same time, managers are required to acknowledge a mind shift (taking responsibility for sustainable development), a paradigm shift (having a holistic perspective on managing change) and a scope shift (managing social, environmental and economic impact) in order to make buildings healthy and comfortable while improving the energy efficiency of retrofitted buildings.

2. Main conclusion

Answer to main research question:

- *How to integrate the BMS requirements to optimize the energy performance and user satisfaction in retrofitted residential buildings?*

The main design criteria for the use of an integrated building management system is to serve mainly the end-user for comfort, domestic hot water, energy savings and safety purposes while creating awareness for future behaviour changes. On the one hand, the system controller aims at achieving a balance between People, Planet and Prosperity based on the collected data. While on the other hand, with the used strategy the intention is to understand how to close the energy performance gap, to understand the gap between simulated and measured data and finally to get input for predictive maintenance for the building use.

This integration of the BMS requirements consists of mainly three parts: (1) defining smart conceptual design, (2) defining the technology needed and (3) looking for product providers.

The first step in the BMS implementation process is to understand what is crucial to improve the daily life of the end-users. The smart applications aim to add value to the building and urban environment disciplines, whereas the wider goal is to achieve resiliency and climate adaptation. The main reason for choosing a smart building management system is to improve the energy efficiency while keeping the comfort level and satisfaction of the building users high. Therefore, integration of the end-users during the design process is crucial in order to obtain an integral smart application design. In the broader picture, the smart application system can be divided into 7 different main topics: well-being, behaviour, energy, operational performance, circularity, security and outdoor climate.

In contemplation of reaching the goals set for the conceptual design in part one, the next step is to define the technology needed. This part consists of several phases. First, a general overview of the building systems are described in order to gain knowledge on the possible collection of data that is necessary to make the smart application happen. Afterwards, to determine the type of the required sensors; the building systems are split in different control categories based on the six categories of ISSO69. Finally, the last step in the sensor design strategy is situating the specific locations of the sensors on the electrical, mechanical and architectural schemes.

Once all the decisions are made based on what services are needed, it is time to look for product providers. However, before contacting any supplier, it is recommended to first define boundary conditions and constraints (e.g. wired-wireless) and to find solutions that are not controlled by only one manufacturer. Afterwards, all the wishes, available systems and implementation typologies are discussed with the suppliers. This process will be an iteration of several steps until the final preferred outcome is obtained through a multi-criteria analysis

To conclude, it is important to have an integrated design approach, purposeful design and interdisciplinary team to contribute to a sustainable, flexible, adaptive, affordable and future-proof built environment. Additionally, problems must be solved with user-centred design, which is at the heart of a holistic approach.

3. Discussion

3.1 Discussion of design and process

Design:

The operational phase of a building is dominated by one main actor: the user. The user behaviour can influence the final performance of the house. This is why informing the user on how to reduce consumption can considerably enhance the energy efficiency. Therefore, this research contributed to the existing body of literature regarding energy efficient retrofitting in the built environment to fill out the gap between the calculated energy consumption and actual energy consumption. From architecture and engineering, to efficiency, impact and awareness and then to information management, research into new technologies is needed in order to foster an efficient way of using resources.

BMS is the central model of the project, which provides feedback on how changes might influence the multiple components of the building, such as structure, envelope, architectural spaces, thermal performance and energy consumption. Therefore, besides updating the built environment to comply with the climate agreements, the users and the building need to be in constant transparent ecosystem to foster energy practices that reduce the energy consumption. End-users can start making unconsciously better decisions based on the environment they occupy.

Additionally, based on the analysis of the data obtained through the sensors, it is visible that there is a clear connection between the temperature's fluctuations, energy consumption and the committed activities. So, by promoting the right ecological solutions and having a conscious user behaviour, such as deciding on certain tasks to do based on the outdoor weather, energy can be consumed efficiently whereas temperatures are kept at a very comfortable level. The BMS provides for an interaction between the end-user and the building in order to improve the indoor environment quality based on the user's needs and wishes.

Moreover, the social, economic and environmental dynamics of the composition of this project is a primary driver for holistic innovation towards sustainability. Next to passive solutions, advanced technologies are applied to ensure energy sufficiency. For example, the winter garden is a well-thought design that captures a meaningful interaction between retrofitting, energy efficiency and comfort. In this buffer zone, the vegetation that cools down the incoming air regulates also the moisture content and filters the pollutants. Additionally, the high-uncovered ceilings of the existing load-bearing structure allow both hot air to rise and be cooled down by the concrete's thermal mass. At night, the building uses night flushing to cool down the whole mass for the next day. By integrating PCM's into the green walls and combining it with the air intake of the HVAC system, it is also possible to gain free cooling through thermal energy storage. Whereas, the presence of a green wall inside a buffer space increases the feeling of well-being, reduces stress, boost productivity and gives a pleasant climate during summer time.

However, it should be noted that one building would not make a change; it should start from the city level, whereas landscaping and additional storage options can foster the improvement. Additionally, policies must be more ambitious and triggering to adapt itself towards future needs. Fostering resilient practices to reduce energy consumption in the built environment. Thus, in order to envision a future-proof built environment that gives back to its surroundings more than it takes away from it, we should all collaborate together to turn the inefficient building stock into energy sufficient buildings. What are you going to do for this?

Process:

In the beginning, there was a strong focus on the architectural concept and not much importance was given to the other committees such as engineering. However, if a more agile (and scrum) way of working was reached since the beginning, a better collaboration could have had improved the decision-making processes throughout the whole project and could have add value to the process.

3.2 Research limitations

Multiple other factors led to the success of the MOR project holistic outcome, but since these factors are out of the scope, they are not mentioned here in this thesis. Additionally, it should be noted that since every case is unique, the steps for BMS implementation can differ and are not a strict rule of prescriptive steps.

The MOR project achieved a strategic approach towards energy sufficient building design that focusses on adding value to the environment, economy and end-users. Whereas, the MOR-design is able to face extreme climate due to its main adaptability concept. On the other hand, comfort is complex and is a cultural construct. Therefore, no 'one-size-fits-all' approach applies to housing retrofit. Different delivery models are required, including public sector, community-led and market-based and thus one prototype design cannot be generalized for the whole world. However, the MOR prototype is a project that can be taken as a good example with strong design values and a process that can bring order to the chaotic nature to the existing practice.

3.3 Further recommendations

Due to time limitations, tests have only been done during the competition days, which were Hungarian summer conditions. However, to obtain more realistic results about the energy consumption, user behaviour and comfort level, it is recommended to have tests while someone is actually living in the prototype throughout the year. Afterwards, a post occupancy evaluation can be achieved to understand the evaluation of the whole design better.

Moreover, the prototype is still open for further improvements and updates based on the available technologies in the market. Due to time, knowledge and money constraints during the project, not every possible technology could be integrated. Therefore, it can be advised to implement Machine Learning systems and self-learning algorithms besides BMS. A data-driven architectural design can be the next step for this project. Since every person is different and behave differently, the building could not only measure the data and give feedback, but also learn the behaviours of its users.

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Appendix

Appendix A. End-user Journey map

Actor	Young professional/Student
Scope	A day (activities)

Journey Map 24 hours (1 day) Appartment scale

	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	23:00
Activity?	Sleep Mode								Waking up and getting ready for work: showering, having breakfast, ...	Working hours									Coming back home from work: start cooking, eating, relaxing, etc and then go to sleep				
What do we want?	Temperature,Good air quality,Security								Good temperature, Good air quality, Availability of electricity and domestic heat water	Security (Smart doorbell for comfort). Efficient use of energy. Smart appliances working i.e. washing machine, dryer.									Water supply, eelctricity, good temperature, good air quality, good lighting, safety				

	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	23:00
Activity?	Sleep Mode								Waking up and getting ready for work: showering, having breakfast, ...	Working at home, preparing lunch, having a friend over									Cooking, eating, relaxing, etc and then go to sleep				
What do we want?	Temperature,Good air quality,Security								Good temperature, Good air quality, Availability of electricity and domestic heat water	Water supply, eelctricity, good temperature, good air quality, good lighting, safety									Water supply, eelctricity, good temperature, good air quality, good lighting, safety				

Building scale		
Activity?	Connecting different neighbours through communal spaces such as kitchen, library,... Shared services such as; laundry, car- and bike-sharing, food sharing	Which are the annoying things that should be improved during these activities?
What do we want?	Security of the Building, Efficient maintenance, Detection of the growth of the foodcrop inside the building, application to connect to community	Which services/products can we offer to improve the previous annoying things?

Neighborhood scale		
Activity?	Improving energy consumption. Assets optimization. Doing daily activities such as groceries, going to work etc.	Which are the annoying things that should be improved during these activities?
What do we want?	Sharing energy assets (Blockchain),"Microgrid", in which it integrates a distributed generation with storage systems. Finding car spots closeby	Which services/products can we offer to improve the previous annoying things?

Appendix B. General Overview of the systems and measurements to control

Lighting	• Eindoor (lux) sensors • Shading control • Fixtures (artificial light) control • Manual input (colour, intensity, on/off)
Domestic Hot Water	• Solar chimney • Solar chimney pump control • Heat pump control (hot water) • Water heater
Other water	• Black water pump • VOD pump measurement • Greywater pump control • Green wall watering
Electronics	• Power draw measurement (whole house) • Power draw per module • Power draw per ceiling module • Circuit control • Electrical Sockets
Ventilation	• Chilled ceilings • Chilled floor • Remaining cooling load (active cooling) • Mechanical cooling • Mechanical post-cooling • Supply duct • CO2 measurements per room and VOC • RH in bathroom • T indoor • T garden

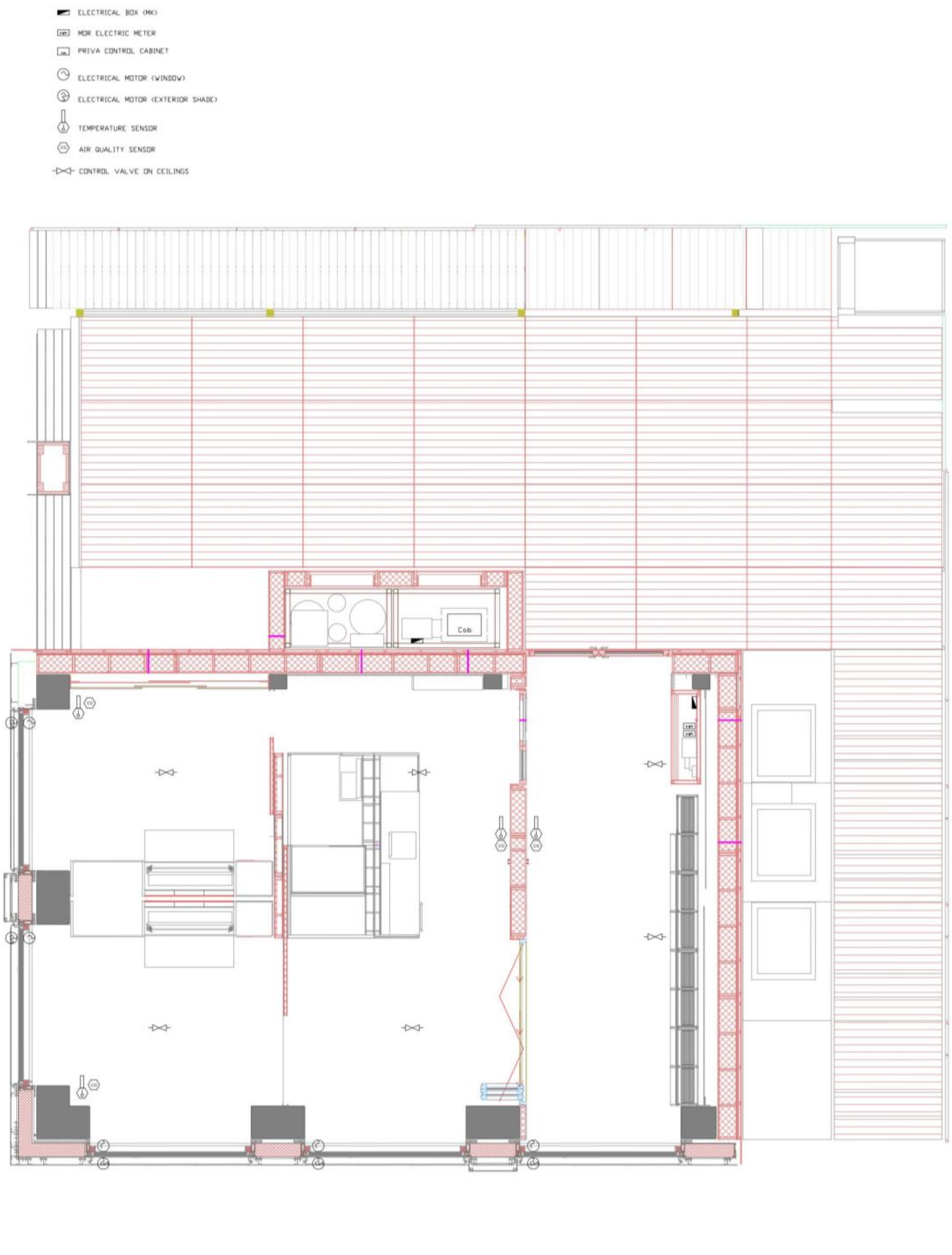
	• T outside • Valve control • T precooling-preheating • T supply • T extract (before HE) • Bypass control HE • Bypass control green wall • Green wall PCM bypass • Garden window control • Room window control • Garden grilles control • Garden door open-closed measured
Heating-cooling	• T outdoor (measure) • T indoor per room (measure) • Solar radiation façade (measure) • Presence detection • Manual control measurements • Heating-cooling setting of ceilings • Air cooling-heating

Appendix C. Defined sensors

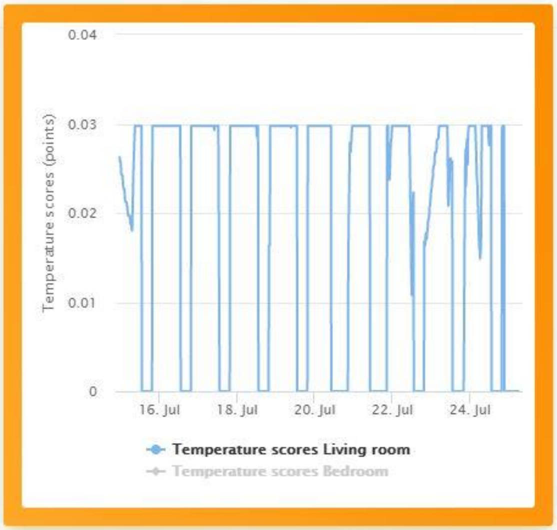
Category	***What***	***Why***
Security	Video Doorbell	For security when you are away and comfort
	Window	For security during night ventilation
	Technical security	shortcuts, overheating equipment's, etc.
Well-being	Moisture and water leak sensors	Prevent water leakages and health problems due to moisture level inside
	Inside temperature sensors	Check inside temperature
	Relative humidity sensors	Check humidity level
	CO2 sensors	Check air quality
	VOC and other pollutants sensors	Check air quality
	Inside light quality	Check inside light quality
	Motion sensor	To detect the presence of the occupants
Outdoor Climate	Outside climate sensors	Check external temperature
	Outside air quality	Check external air quality
	Outside light quality	Check external light quality
Energy	Blind control (Shading motor)	to reduce unwanted incoming light and to slow down undesired heating
	Window open-close control (Window motor)	To control indoor air quality and temperature - natural ventilation
	Light control	Reduce energy consumption - light motion sensor for corridors - Lighting should be DC (energy stored in battery)

	Energy consumption control	To reduce energy consumption as much as possible - for example, smart use of sockets etc.
	DHW: Solar Chimney, Water tank	To detect the temperature of the water
	Chilled ceilings and floor	To heat up or cool down the inside temperature
	Smart plugs	Energy metering
	Indoor surface temperature	To predict heating demand
	Victron energy	Colour Control Panel: monitor the amount of energy stored in the battery etc., how the dc system should save as much as energy or how to use the energy, etc. configuration modes
	Heat pump	To control the production of heat
Behaviour	Decreasing function spaces	To influence people's behaviour: Laundry (varying prices à decreases machines number)
	Shared vehicles	Promoting sustainable vehicles use (bicycles) by gaining points (money to in another service of the building)
	Social activities	To reduce waste from the food growth and energy (app advertising food seasonal production and cooking together)
Circularity	Water efficiency	rain water, grey water depuration, screaming water tap or red water
	Material passport	Recycle materials and detect their lifetime - owner - etc
Operational Performance	Predictive maintenance	For effective and efficient maintenance
	Demand-supply prediction	Forecast energy demand and produce accordingly
	Predictive energy control	Forecast energy demand and produce accordingly

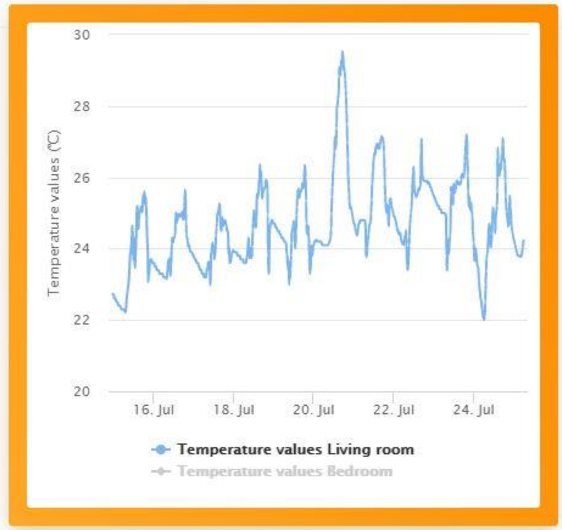
Appendix D. Location of sensors



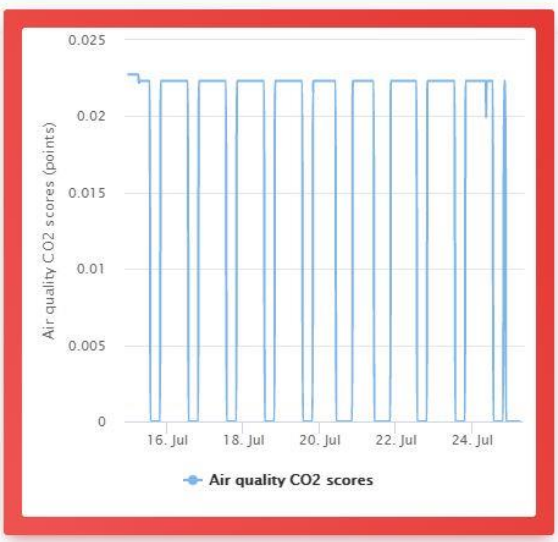
Appendix E. Contest 9 House functioning scores (SDE, 2019)



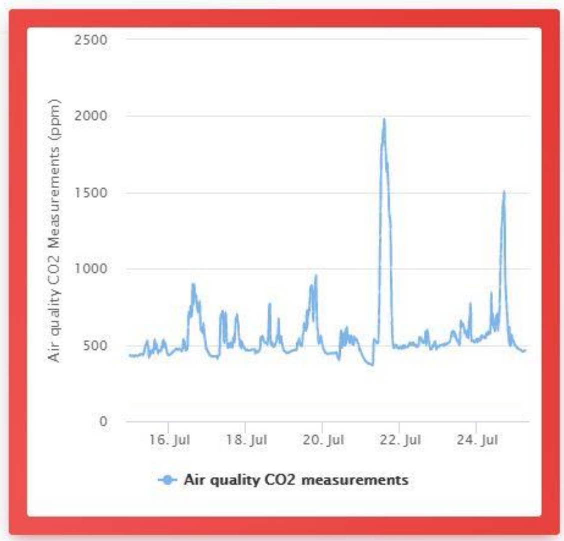
Temperature scores per time period



Temperature measurements per time period

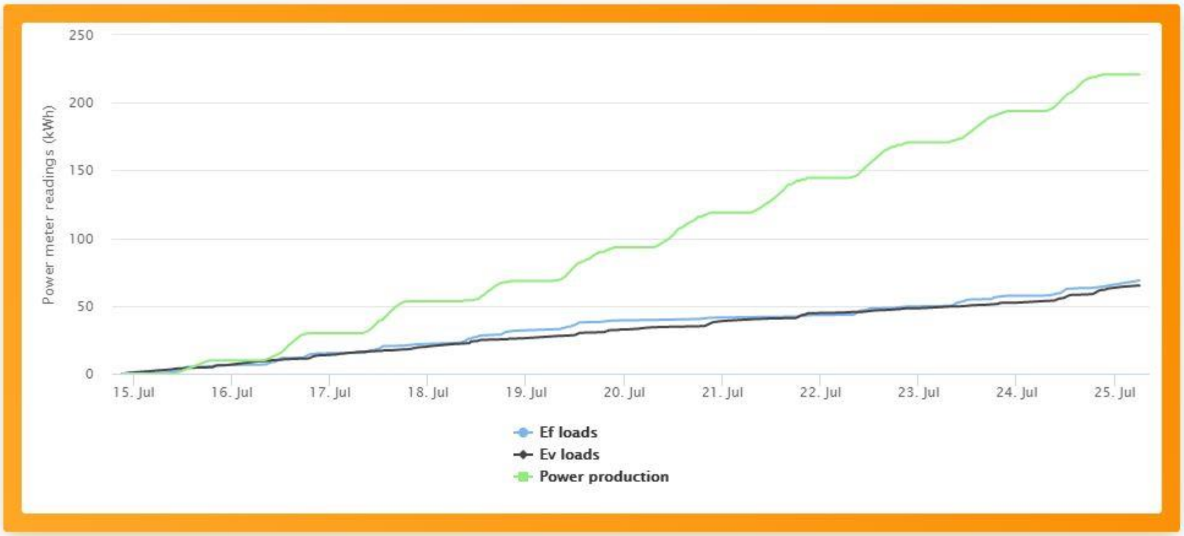


Air quality CO2 scores per time period

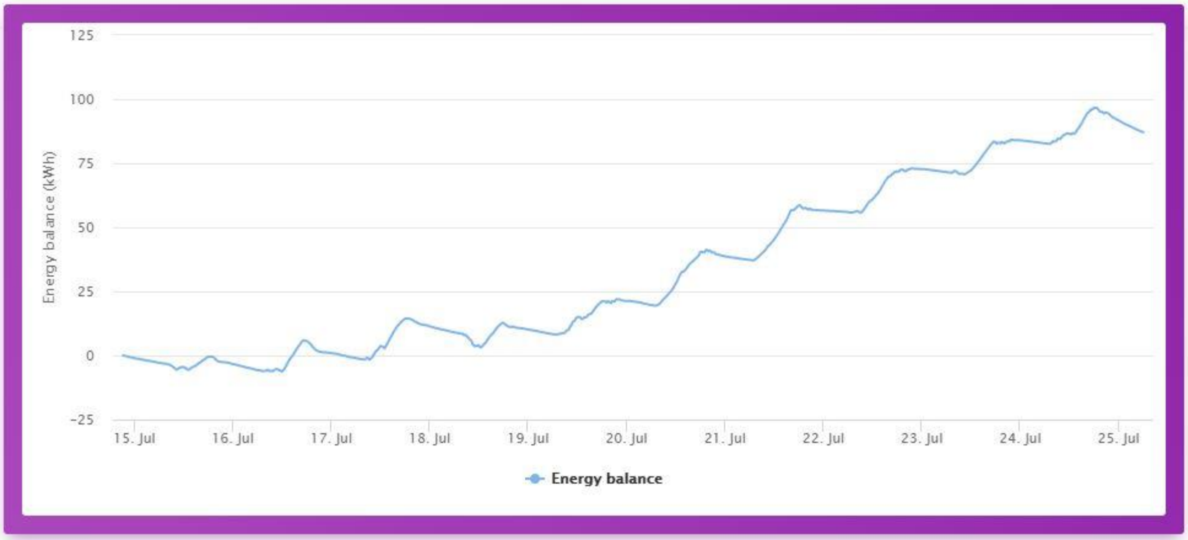


Air quality CO2 measurements per time period

Appendix F. Contest 10 Energy balance scores (SDE, 2019)



Power meter readings over time



Power balance over time ($E_{generated}-(E_f+E_v)$)