Technical University of Denmark

Master Thesis

Evaluation of Building Renovation for Social Housing in Denmark - An experimental and numerical study

A thesis presented for the degree of
Master in Civil Engineering

Author: Christina Sommer Thomsen
Supervisor: Carsten Rode
Assistant supervisor: Hagar Elarga

Department of Civil Engineering
Technical University of Denmark
Denmark
21st of June, 2018

Declaration of Authorship

I, Christina Sommer Thomsen, hereby declare that this thesis is my own work composed by me except where stated otherwise. This thesis has not previously been presented to an examination board nor has it previously been published. Any use of any other authors work in any form is properly acknowledged.

Christina Sommer Thomsen, s113809
Technical University of Denmark

Acknowledgements

First and foremost I would like to thank Hagar Elarga for being an amazing guide and support and for pushing and encouraging me when I needed it; I could not have wished for a better co-supervisor. Secondly this thesis might not have been possible if it was not for the REBUS project; thank You for putting renovation on the agenda in the construction industry.

My boyfriend and all four of my parents for their eternal support, cheer, encouragement and love. It means more than You know. My beloved friends and family for their support and understanding of my absence and forgetfulness.
It takes a village. ♡

Abstract

The aim of this thesis was to investigate the influences of the gap between expected and actual energy performance of renovated buildings in Denmark. This was done by collecting needed measured data for four apartments which were a part of a major renovation project. The needed data included indoor temperatures, electrical consumption, weather data (temperature, relative humidity and solar radiation) and infiltration rates. The collected data was cleaned and had been through an outlier detection process to reassure correct and accurate input files for the numerical model.
During one of the site visits it was noticed that one of the renovated apartments had a strong, cold draft from the entrance door. This was investigated by the use of a thermographic camera and by carrying out a Blowerdoor test. This revealed an infiltration equal to the infiltration rate of the non-renovated, and that there was a severe cold bridge at the joint of the facade and ceiling, due to poorly execution.
The software used to compile and simulate the numerical models is TRNSYS, which is a dynamic simulation program using a black box approach. Three models for each apartment is compiled: a Reference, a Non-detailed and a Detailed case. However, for the fourth apartment only a Reference and a Non-detailed case is considered, as the results of the Non-detailed model simulation compared to the measured heating consumption is considered non reliable. The Reference model cases are based on the Danish Building Regulations and are though to approximately imitate the calculation tool BE15, which is used in the Danish building industry to assure a building complies with the Danish Building Regulations and other legislation. The Non-detailed model cases are based on the collected measurements without taking occupancy behaviour into account. The Detailed model cases are developed from the Non-detailed adding schedules for the lights and adjusting the amount of electrical devices.
The heating consumption of the model cases are then compared with the measured heating consumption, which is evaluated by applying the root-mean-square deviation. The RMSD reveals that the Detailed model cases are in better agreement with the measured heating consumption than the Reference model cases. The heating consumptions of the models are analysed and it is shown that for this project two influences of the energy performance are found; occupant behaviour and construction default.
It is finally concluded that pre-measurements over a period of time could be a good solution in comprehending the need for renovation, the state of the construction and to overall reduce the gap between expected and actual energy performance of a building.

Introduction

We have reached a point in Denmark where many buildings need renovation e.g. buildings built in and before the 1960s. As a result of this and the increased focus on building energy efficiency, renovation of buildings is now the largest part of the building sector [1]. Several engineering companies, universities, social housing associations etc. have thus partnered up with the purpose of improving building renovation and formed the project REBUS - Renovating Buildings Sustainably. Their aim is to ensure energy-reducing, cost-effective, resource-efficient and reliable renovation solutions [2]. They have many projects in progress aiming to produce new and better solutions to the challenges of renovation as we know it today.
One of the challenges when renovating is the discrepancy of the expected, modelled energy performance before renovation and the actual energy performance after a renovation. The aim is to have more realistic and compliant models before the renovation of a building and thus ensure a good indoor climate.

One of the things REBUS-project wants to implement is involvement of the user, which is coherent with the future of a *Smart City*. There are currently only few commercial measurement instruments on the market usable for such a project as this. In this project several measurement instruments will be used to measure indoor temperature, CO2-level, RH, electricity usage and heating consumption. All the collected data will in this project be used to design and verify the numerical models. The buildings used for this study are already undergoing a large scale renovation process which has almost reached its halfway point at the start of this thesis. Thus, giving the possibility to collect measurements for both un-renovated and renovated apartments. The building industry in Denmark uses first and foremost the software BE15 as this is an quick way to ensure a building complies with the Danish law [3]. For dynamic simulations of building performance a variety of software is applicable, and each company has its own preference. The numerical models in this project will be developed using TRNSYS. This software is not that widespread in Denmark, however it is highly applicable for different types of dynamic simulations, especially the simulations needed for this thesis. In the end it should be possible to analyse how to assure a more accurate performance model and pin point the challenges as to why the models currently are not complying with the actual performance.

Contents

Also included are all model files; .zip-folder for online hand-in and USB for printed hand-in.

List of Figures

List of Tables

Chapter 1

Literature Review

1.1 Numerical modelling on residential buildings

Development of proper energy models is necessary to estimate or predict energy consumption in any building. Methodologies to estimate building energy consumption varies from pure regression to very complex models of particular components and systems [6] [7] [8] [9] [10] [11].
L. La Fleur et al. [12] investigated in 2016 the numerical predictions and evaluation of energy use and indoor climate for a Swedish social housing building from 1961 before and after renovation. They used field measurements as input in IDA ICE. Their investigation showed that the BES model was able to predict the indoor thermal environment and energy use with reasonable accuracy. They concluded that field measurements are essential in the ability to construct a realistic model, and that user behaviour can have a significant impact on the energy-saving potential.
G. Salvalai [13] performed a parameter estimation study of a water-to-water heat pump using IDA ICE in 2011, as ground source heat pumps was offered one of the most energy efficient technologies in providing heating and cooling. The IDA ICE model was validated using experimental data. It was concluded that if the input parameters are well known, the simulated steady-state operation of heat-pump was found to correspond closely with the experimental operation.
In 2017 A. Cacabelos et al. [14] researched a calibration methodology that divides a building into different sub-models and calibrates them separately to obtain an accurate model. Using TRNSYS and GenOpt a public library was simulated and calibrated, and the results showed a really good agreement in the energy consumption and the temperatures from the different zones of the building. Furthermore, it achieved better results than with a global calibration with an improvement of Mean Bias Error and Coefficient of Variation of the Root Mean Square Error of approximately 50%.
D. S. Østergaard et al. [15] did a study in 2016 on how assumptions in the modelling of heat emissions from existing hydraulic radiators affects the heating system return temperature in a building simulation model. IDA ICE was used for modelling and simulations. The study showed that the detail level and assumptions in a simulation model have a large impact on the results. They concluded that a detailed building simulation model can provide a good estimate of the actual heating system operation, provided that actual radiators and realistiv indoor temperatures are taken into account in the model.
C. H. Lozinsky et al.[16] investigated the building infiltration rates as it is one of the most uncertain parameters among multi-unit residential building energy model inputs. They conducted component infiltration rate tests at two multi-unit residential buildings to develop component-weighted infiltration rates. They compared these inputs with single building-level infiltration rates in whole-building energy models. They concluded that the component-weighted allowed for the incorporation of building-specific measurements, which helped reduce parameter uncertainty during model calibration. The separation of the infiltration rate by component can help the modelling of energy retrofits that specifically target building infiltration.

1.2 Social housing in Denmark and renovation methods

K. E. Thomsen et al. [17] [18] have done a case study in 2015 as a part of the Danish participation in IEA EBC Annex 56 "Cost Effective Energy and Carbon Emissions Optimization in Building Renovation". A residential multi-storey building from the late 1960's was refurbished and it was concluded that the renovation resulted in significant energy savings, as the measured energy consumption for heating and domestic hot water was reduced by 31%. Furthermore, the electricity demand for ventilation went up but the electricity production from the photovoltaic system covers approximately 60% of this increase.
M. Jradi et al. [19] performed a study in 2017 of four buildings in Denmark, which were considered for energy renovation analysis and assessment with the aim to enhance their energy performance. They came up with two renovation packages: one improving the equipment of the building (e.g. LED lights and heating circulation pump) and one improving the envelope of the building and its energy supply system. It was concluded that package number one resulted in an energy saving of 27.7% with a payback period of less than four years and average CO_2 emissions reduction of 5.1 t/year in the four buildings. Package number two had an average energy saving of around 50% with a payback period of 11 years.
In 2012 M. Morelli et al. [20] did a case study of a multi-family building from 1896, demonstrating the ability of retrofitting the building to be a "nearly-zero" energy building. Three types of measures where investigated on a test apartment: installation of interior insulation, retrofitting the windows and installing a decentralised mechanical ventilation with heat recovery. The results showed a reduction of the theoretical energy use of 68% which was within the frame of new buildings in Denmark, but in order to obtain a "nearly-zero" energy building it is necessary to use renewable energy sources.

1.3 Integrated Wireless Technology

E. Sirombo et al. [21] demonstrated in 2017 the capability of a building monitoring system (BMS) to provide feedback data used to address the ongoing management issues of multi-family buildings in social housing including the understanding of user behaviour among other. They made use of a case study approach on a large environmentally friendly social housing intervention consisting of 323 flats which had a BMS installed. After the first year of occupancy they concluded that the installation of the BMS compensate the extra-cost of the construction due, which can be approximated to 0.5% of the total construction cost. Furthermore, the real estate fund involved was interested in embedding building performance monitoring as a standard practice.
M. W. Ahmad et al. [22] present a comprehensive review in 2016 on metering and sensing technologies for buildings. It is presented that choosing a proper metering and monitoring solution depends on various factors (e.g. accuracy and cost) and that one of the biggest challenges is the protection of metering data against unauthorised access as the privacy of the transferred data is important to both clients and service providers. They conclude that building energy metering and indoor environmental technologies has advanced in recent years, and will continue to advance due to the developments in information and communication technologies.
S. Noye et al. [23] investigated the potential of wireless sensor networks technology to provide additional temporary data to extend the scope of building commissioning. The used monitoring kit highlighted that buildings are used different than expected and that the sensing data can help fill in the gaps without intensive investigative work or interruption of the users of the building. They conclude that despite different technical limitations (e.g. interoperability between wireless device manufacturers) the market for wireless sensor network in buildings are expected to grow as the potential benefits have been recognised despite the limitations. Nguyen and Aiello [24] and Zhaoand Magoules [11] have advised that future research should focus on developing efficient

and effective performance monitoring system for promotion of energy awareness in buildings to enable building users to become aware of the energy performance in real-time, facilitating more effective business decisions based on accurate and timely information.
Klingensmith et al. [25] proposed a distributed energy monitoring system focusing on the IT infrastructure using wireless senor networks (WSNs), proposing a flexible solution to be easily extended. Another strategy for occupancy estimation using a WSN based on temperature, humidity, light readings and audio levels is presented by Khan et al.[26]. Collected data are initially analysed by using a set of statistical classifiers, then context information on room occupancy schedules and resource usages is integrated into the model. Results of this first analysis step are further forwarded to a new classification level that provides a fine-grained occupancy estimation and delivers it to support decision making processes.

1.4 Data analysis

Wireless technologies allow for a non-intrusive instrumentation of spaces for short or long periods of time in existing buildings, and it is common to produce large amounts of data; to be able to effectively handle them, it is necessary to face a number of challenges, such as the selection of a sampling strategy, the necessity or not to clean data and correct errors, the summarising and aggregation strategies (Bolchini et al.)[27]. Some researchers have discussed the data mining solutions, where the quality of collected data plays a relevant role.
Ahmed et al. [28] have presented an analysis of building environmental data, involving also buildings' physical features and climate conditions. The analysis referenced to a university building and aims at effectively predicting rooms schedule by optimising energy usage and users comfort. Balac et al. [29] proposed a large scale analytically platform for real-time energy management within a university campus smart grid system. A multi-variate predictive technique is employed to discover anomalous performance behaviour; more over the collected data is further analysed.

ASHRAE [30] has provided guidelines to determine which is the information the user is interested in (e.g. users' comfort), what data should be collected (e.g. indoor temperature and humidity) and with what frequency (e.g. once per hour). Indeed the reference provides a lot of information, mainly adopted in North America, according to regulations. However, it focuses primarily on the definition of the data to be collected rather than the classification, characterisation and documentation of the adopted choices. Moreover, no guidelines are provided for the manipulation of data (e.g. data cleaning, outlier detection, etc.) that is eventually necessary based on the final campaign goal.

Chapter 2

Concept

As a part of the REBUS project it has been made possible to investigate the indoor climate and energy consumption performance at an ongoing urban renewal project in Aalborg Øst of both non-renovated and renovated apartments. In this chapter the reader will be presented to the basics in heat transfer in buildings and the instruments used for the experimental part of this project: the measuring of different data. Furthermore, the site and buildings will be presented together with the selected cases.

2.1 Heat transfer in buildings

The first law of the thermodynamics states that energy can not be created nor destroyed. The conservation of energy is thus expressed by Equation 2.1.

$$E_{stored} = \sum E_{in} - \sum E_{out} \tag{2.1}$$

As energy is not created nor destroyed, it can transform between different forms. As the energy transforms, more and more is wasted as the energy transfer increases the entropy, thus the efficiency will never be 100 percent. The second law of thermodynamics is thus that thermodynamic processes are irreversible, which is expressed in Equation 2.2.

$$\Delta S_{universe} = \Delta S_{system} + \Delta S_{surroundings} \geq 0 \tag{2.2}$$

Heat transfer through a building envelope depends on several factors: the temperature on each side of the surface, the surface area, the travelling distance of the heat i.e. the thickness of the layer(s) and last but no less important are the surface/material characteristics. Furthermore, the direction of the heat transfer is of course always from warm to cold, but the actual direction is often simplified to be perpendicular to a surface, while in reality the heat travels in all directions for every point of the layer. The heat transfer is also often simplified calculated in steady state, while in reality a building envelope performs dynamically as the interior and exterior conditions change.

The heat transfer through a building envelope is categorised through conduction, convection and radiation as seen in Figure 2.1. The three modes are shortly explained in the following.

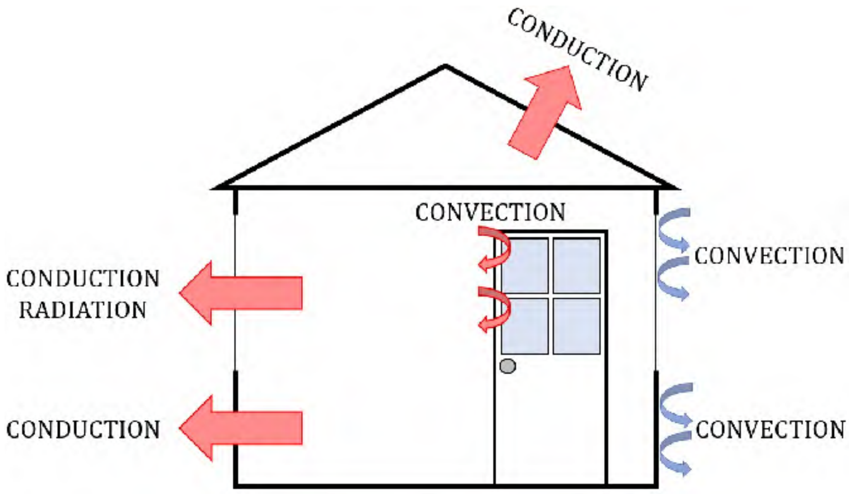


Figure 2.1: Heat transfer modes through a building envelope

Conduction

Conduction is heat transfer between two particles in direct contact, this be in both solids, liquids and gasses. The heat transfer is highly influenced by the temperature differences on either side of the layer as well as the thickness of the layer. On the way to achieve equilibrium the energy travels from warm to cold. The heat transfers through conduction through walls, roofs, floors and the glazing of windows, and is calculated using Equation 2.3 (Fourier's law). This equation can only be used for steady state conditions for a one-dimensional flow, while Equation 2.4 is used for dynamic/transient conditions.

$$Q_{cond} = A \cdot \lambda \cdot \frac{T_1 - T_2}{d} \tag{2.3}$$

$$Q_{cond} = V \cdot \rho \cdot c \cdot \frac{\delta T}{\delta t} \tag{2.4}$$

Convection

Heat transfer through convection is the transfer of heat by the movement of a fluid past a surface. This can either be natural (by buoyancy forces) or forced (by external means), and furthermore either laminar (orderly, layered flow) or turbulent (chaotic flow). The building envelope is influenced by heat transfer through convection through cracks in the envelope as well as on the walls and the windows. The heat transfer through convection is calculated using Equation 2.5.

$$Q_{conv} = A \cdot h_{conv} \cdot (T_1 - T_2) \tag{2.5}$$

Radiation

The radiative heat transfer is mainly through the windows of a building envelope, but has an influence on the walls and roof as well depending on the material. Heat transfer through radiation is by electromagnetic waves. The higher the temperature of an object, the more radiation it gives off and the shorter the wave length. Solar radiation is short waved and is stored in the building envelope and re-emitted as long waved (thermal) radiation. The short waved (solar) radiation which passes through the windows and heats up indoor surfaces are not able to pass back through the window, as it is transformed into long wave (thermal) radiation. This is also known as the *Green house effect*. The characteristics of the surface in terms of absorptivity

(α), reflectivity (ρ), transmitivity (τ) and emissivity (ε) all affect how the surface response to the radiation. The emitted radiation of one body reaches another body, e.g. a window, and a fraction of this radiation is thus absorbed, reflected and transmitted. If the surface is opaque, e.g. a wall, none of the radiation will be transmitted, whereas if the surface is transparent, e.g. a window, some of the radiation will be transmitted. The emissivity of a black body equals 1 and is thus seen as an ideal thermal radiator, while any other body has an emissivity of $0 < \varepsilon < 1$. Building materials are commonly seen as grey bodies with an emissivity of 0.9.
The heat transfer through radiation is determined using the simplified Equation 2.6.

$$Q_{rad} = A_1 \cdot h_{rad} \cdot (T_1 - T_2) \tag{2.6}$$

where

$$h_{rad} = \varepsilon \cdot \sigma \cdot \left(T_1^2 + T_2^2\right)(T_1 + T_2) \tag{2.7}$$

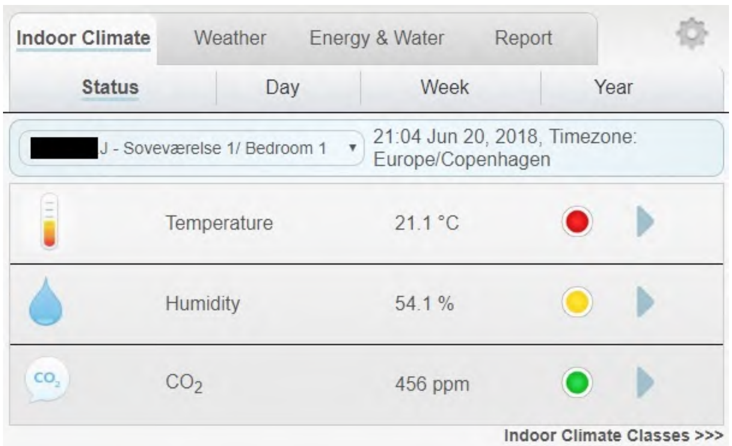
2.2 Measurements

Up until recently measuring was seen to be only for researchers and involves many invasive instruments taking up a lot of space. The world today is slowly developing towards the concept of Smart City to improve the quality of life of the citizens by for instance measuring the pollution in the cities with small sensors connected to the internet as they have done in Copenhagen [31]. To continue in this stream of development it was important to chose measuring instruments as non-invasive as possible to present the benefits of the concept to the occupants, while presenting the opportunity of user involvement.

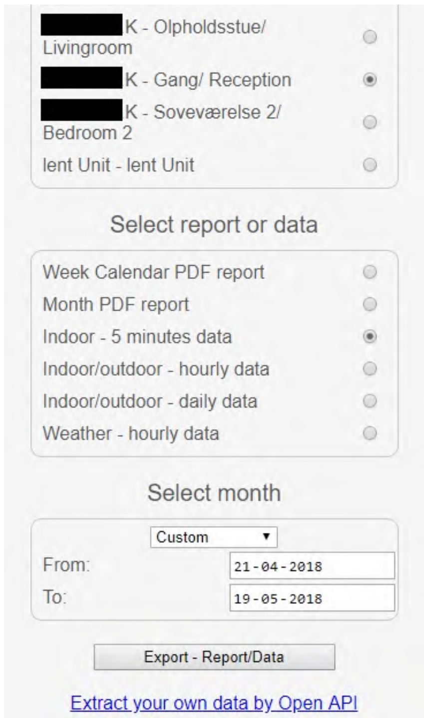
2.2.1 IC-Meter

The Indoor Climate-Meter is a Scandinavian product as the concept is developed in Denmark while the production is located in Sweden [32]. The product is a combination of a measurement instrument, a server and an app/website in which all data can be accessed from anywhere with internet. The instrument measures temperature, relative humidity, CO2-level and dB-level with a 5-minute interval. At the same time the system gathers information on the weather situation via the Norwegian Meteorological Institute *Yr* [32]. The thought is to have a simple system for the user, the resident, where the measured and cloud-collected data is for the user to decide if they would only like to use it for them selves to be aware of their indoor climate. The collected data could also be shared with companies in order to e.g. improve the building or Universities for educational use or research.
The instrument itself measures 145x70x25mm and has an operation range of $-20°$C-80°C within the RH range of 0-95%. It requires a micro-sim card as it has to communicate online with the data cloud, and as it is not wireless it needs to be plugged into a power supply. The sensors have an average error of $\pm$30ppm [33], $\pm$0.3°C and $\pm$2% [34] for CO2-, temperature- and humidity measurements respectively.
The online site of IC-meter is fairly easy to navigate in. It is possible to check the latest data of a unit as seen in Figure 2.3a as well as generate a full report of the data set of a unit for a selected time period as seen in Figure 2.3b.

Figure 2.2: IC-meter set up in the Familyroom of Renovated Apartment 2



(a) Main page interface



(b) Generating data report

Figure 2.3: IC-meter online site interface

2.2.2 Wireless Sensor Tag System

The company behind the system is a California based company called Cao Gadgets LLC and both Wireless Sensor Tags, KumoSensor and Kumostat are trademarks hereof [4]. All three trademarks work together and are a part of the Wireless Sensor Tag System. There are different types of tags/sensors to use with the system depending on the information one wants to extract. All tags/sensors are wireless connected to the Ethernet Tag Manager (Figure 2.5d) which is the link to get all the data stored in the cloud storage, why it requires internet access. For this project the following products are used.

(a) Wireless Sensor Tag at Bathroom

(b) Reed Kumo Sensor at Familyroom

Figure 2.4: Wireless Sensor Tag system at Renovated Apartment 2

Wireless Sensor Tag

The Wireless Sensor Tag is an angle based motion sensor which logs open/close of doors, windows or the like. Furthermore, it logs temperature and humidity in the surrounding air with an error of ±0.02°C and ±1% respectively. The operation range of temperature is −40°C-85°C within the RH range of 0-95%. The tag is placed in its initial angle and from here on any other angle is considered for the door or window to be open. It has a battery life lasting up to seven years depending on usage and a wireless range of up to 210m in line of sight to the Ethernet Tag Manager. The tag itself measures 41x41x8.5mm and is seen in Figure 2.5a.

PIR KumoSensor

The IR-sensor detects motion in a 102x92° viewing angle. Furthermore it measures the temperature and humidity with the error of ±0.02 °C and ±1% respectively. The operation range of temperature is −40°C-85°C within the RH range of 0-95%. The battery lasts an average of two years and the sensor has a wireless range of 120m in a line of sight to the Ethernet Tag Manager. The PIR-sensor measures 69x27x15mm and is seen in Figure 2.5b.

Reed KumoSensor

The Reed sensor consists of two pieces: the sensor itself and a matching magnet piece. By placing the at the edge of a door/window adjacent to each other it will register when the door/window is open/closed. Furthermore it measures the temperature and humidity with the error of ±0.02 °C and ±1% respectively. The operation range of temperature is −40°C-85°C within the RH range of 0-95%. The battery lasts an average of three years and the sensor has a wireless range of 210m in a line of sight to the Ethernet Tag Manager. The Reed-sensor measures 69x27x15mm and is seen in Figure 2.5c.

(a) Wireless Tag

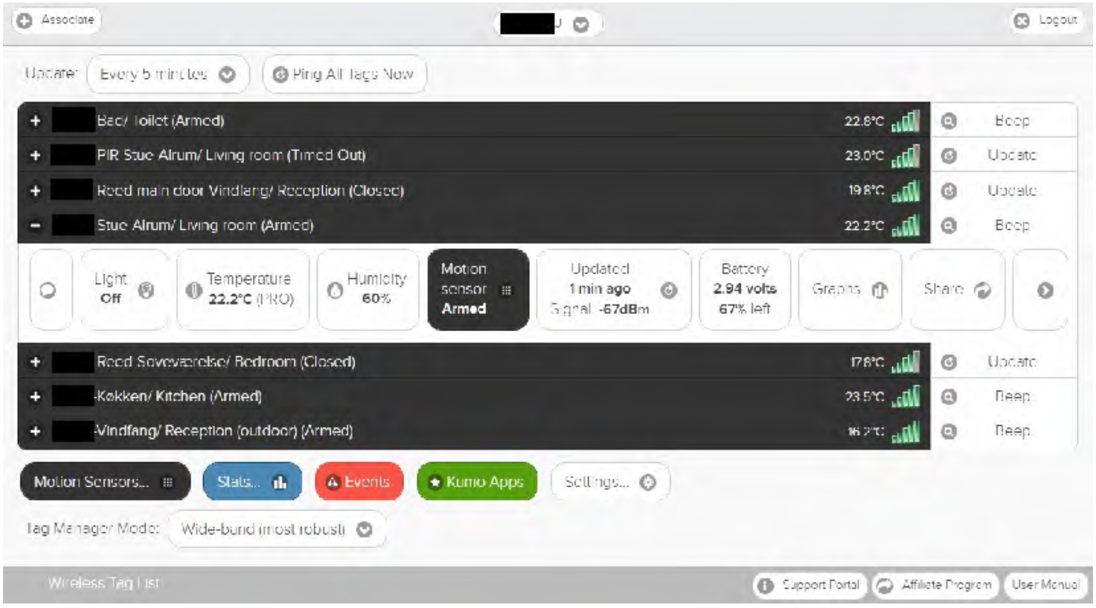
(b) PIR KumoSensor

(c) Reed KumoSensor

(d) Ethernet Tag Manager

Figure 2.5: The sensors used from the Wireless Sensor Tag System [4]

In Figure 2.6 the online site of Wireless Tag is shown. Figure 2.6a is the main page where the latest measurement is shown along with how long ago it was measured. Figure 2.6b is the online graph generator where it is possible to generate a data report containing all the measured data for a unit within a selected time period.



(a) Wireless Tag online site interface

(b) Wireless Tag online graph and data report generator

Figure 2.6: Wireless Sensor Tag system at Renovated Apartment 2

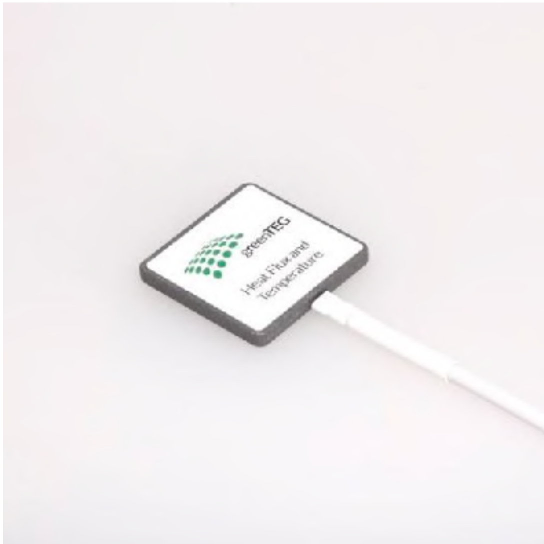
2.2.3 gO Measurement System

The gO Measurement System is developed by the Swiss company greenTEG AG [35] and is rather new as it became available on the market in the autumn of 2017. The system can be used for both measuring U-value, humidity, temperature, building moisture and dew point temperature on wall surface. The system consists of a gateway (Figure 2.7a), a sensor node (Figure 2.7b) and different sensor applications (e.g. Figure 2.7c and 2.7d). The gateway is connected to the internet via a global module and sends the measurements to a cloud, and receives the measurements from the sensor nodes via LoRaSC radio link.

(a) Gateway

(b) Sensor node

(c) Digital ambient air temperature sensor



(d) Combined heat flux and surface temperature sensor

Figure 2.7: The gO Measurement System combination used in this project [5]

Sensor nodes are put on a wall on both sides with the chosen sensor applications. The nodes generate voltage which is proportional to the heat passing through the surface, and this is then converted into the heat flux. For this project a digital ambient air temperature sensor and a combined heat flux and surface temperature sensor is used. Figure 2.8 shows the setup for measuring the U-value of the facade walls of Non-renovated Apartment 2.

Figure 2.8: gO Measurement System setup at Non-renovated Apartment 2

2.2.4 Smappee

Smappee provides user-friendly energy monitors and have a hand full of different products for different uses. The company was founded in Belgium 2012 [36] as the founder saw a need for the consumer to be able to control his/her own energy consumption, instead of just accepting the complicated energy bills a consumer receive from the energy company. As the first in the world Smappee tracks the energy consumption on appliance level, and via the website or app the user can name the different appliances Smappee has identified and see the consumption real-time. Their main product is the *Smappee Energy* which detects power consumption including the standby power consumption. The monitor is to be connected directly at the users fuse box and to a wifi signal. Figure 2.9 shows the installed *Smappee Energy* monitor at the fuse box of Non-renovated Apartment 1 and 2. The online site of Smappee as seen in Figure 2.10 is simple and easy to navigate around.

Figure 2.9: Smappee installed at Non-renovated Apartment 1

(a) Interface of Smappee online

(b) Smappee online graph

Figure 2.10: Interface and graph of Smappees online site

2.3 Case studies

The buildings investigated in this project are located in Aalborg Øst as a part of the residential area *Kildeparken*. Aalborg Øst was earlier considered a deprived area [37], but the plan of the construction of a new super hospital led to an urban renewal of the entire area including Kildeparken.

Kildeparken includes three areas: Fyrkildevej, Ravnkildevej and Blåkildevej as seen in Figure 2.11. At the start of this thesis the renovation of Blåkildevej had finished, the renovation of Ravnkildevej was ongoing and the renovation of Fyrkildevej had just begun.

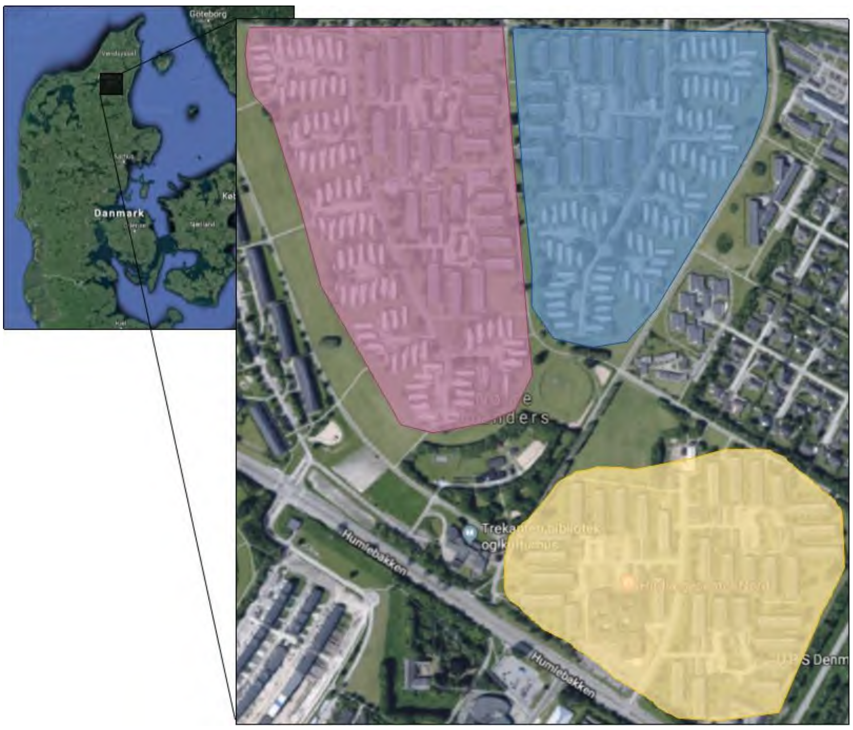


Figure 2.11: Blåkildevej (red), Ravnkildevej (blue) and Fyrkildevej (yellow).

2.3.1 Non-renovated building

The buildings of Kildeparken were typical 1960's buildings built with simple concrete elements. The structure of the original construction is seen in Appendix A. The U-values of the construction parts seen in Table 2.1 are from measurements performed for a continuous three days with the earlier mentioned gO System.

Table 2.1: U-values of non-renovated construction

Construction part	U-value [W/m^2K]
Deck to basement/terrain	Not available
Deck to basement/terrain in bathrooms	Not available
Facade	1.30
Gable	1.30
Roof	Not available
Windows	2.60

2.3.2 Renovated building

Some of the buildings in Kildeparken are undergoing a total reconstruction and others only a renovation where they keep the new floor plan as close to the original as possible. Blåkildevej is assumed to have had the same original floor plan as Fyrkildevej. The new construction structure of the buildings in Blåkildevej are seen in Appendix B [38] and the U-values of the constructions parts are seen in Table 2.2. All insulation used for the new structures is Class 37.

Table 2.2: U-values of renovated construction

Construction part	U-value [W/m^2K]
Deck to basement/terrain	0.46 (basement) 0.48 (terrain)
Deck to basement/terrain in bathrooms	1.66 (basement) 0.5 (terrain)
Facade	0.12
Facade at balconies	0.18
Gable and corner at balconies	0.20
Roof	0.13
Windows	0.70-1.00 Chosen average 0.85

2.4 Selected cases

Prior to this thesis three non-renovated apartments had been selected for research and the instruments had been set up in the two occupied apartments. The third apartment was vacant. The instruments in the vacant apartment were set up at the 12th of February 2018.
As the renovation of Blåkildevej had finished some time before the start of this thesis the renovated apartments were to be chosen in this area. The residents had the opportunity to volunteer and the project ended up with three different apartments to use for measuring. The instruments were set up at the 12th of February 2018.
From the six available apartments four is selected for this thesis and described in the following.

Non-renovated 1

This is a two bedroom apartment of 83m^2 located at the first floor. The apartment is occupied by one retired person, who is using one of the bedrooms as storage and often has open windows as the occupant prefers a cooler indoor environment.

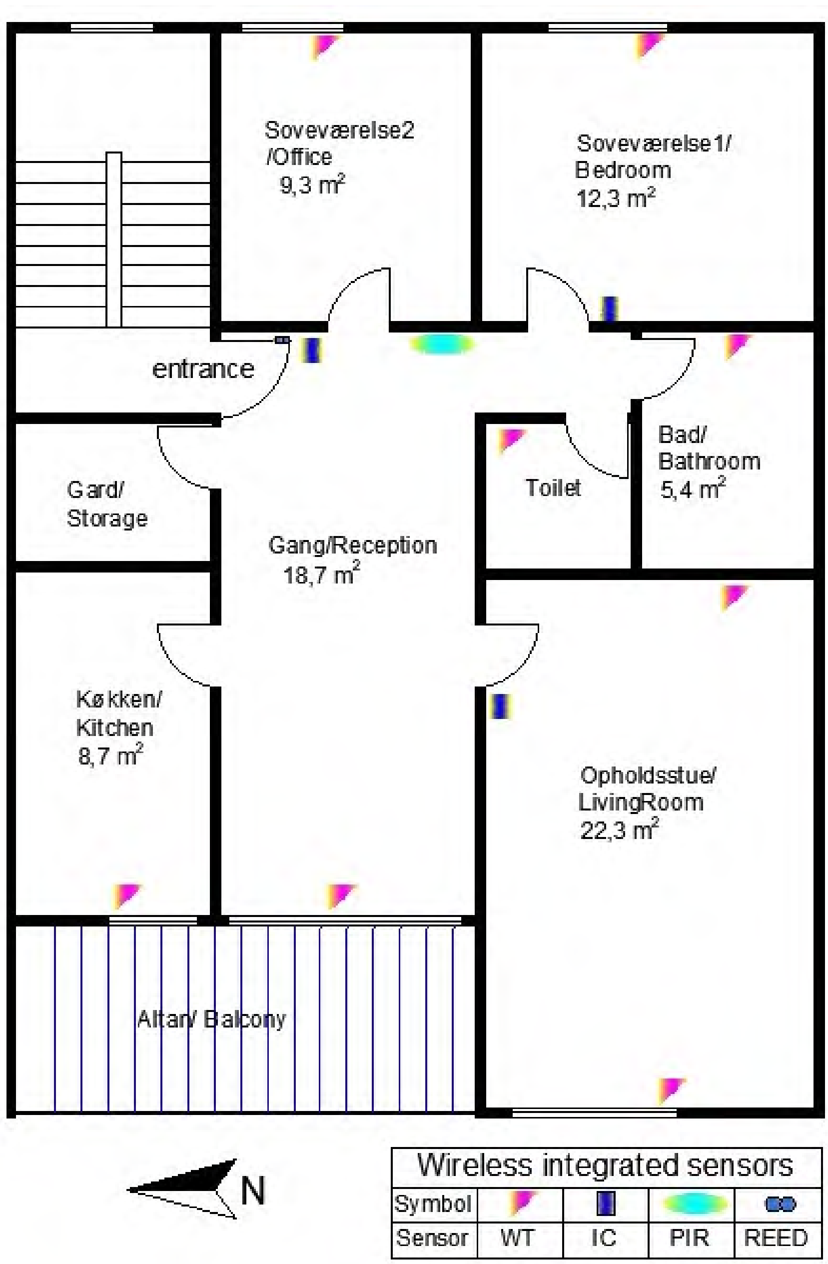


Figure 2.12: Floorplan of Non-renovated Apartment 1

Non-renovated 2

This is a three bedroom apartment of $90m^2$ located at the ground floor. It is occupied by a home-bound couple and two of their three children. Bedroom 2 and 3 are used as bedrooms while Bedroom 1 is mainly used for storage. They mainly use the Reception and often have guests.

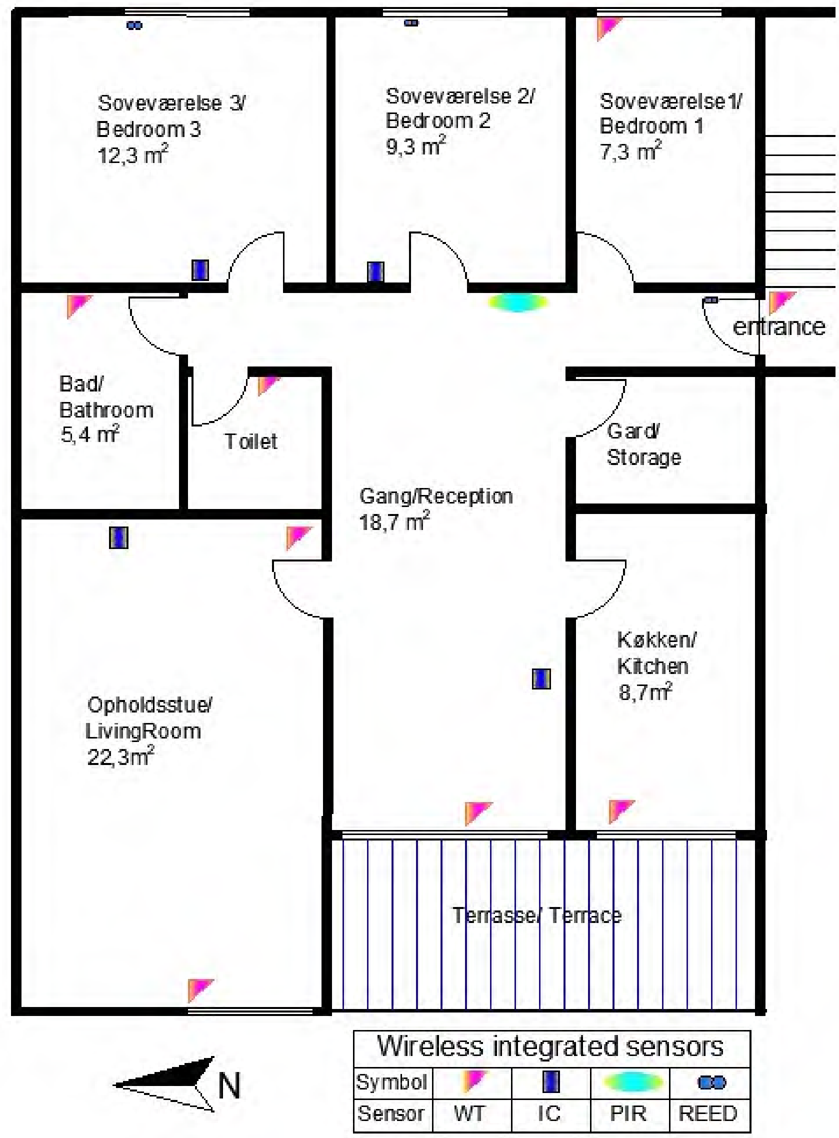


Figure 2.13: Floorplan of Non-renovated Apartment 2

Renovated 1

This is a one bedroom apartment of $55m^2$ located at the ground floor and is occupied by a retired couple and their dog, cat and birds. They have turned off the heating in their entrance as they felt a strong draft from the front door, and thus keeps the door between the entrance and livingroom closed at all times.

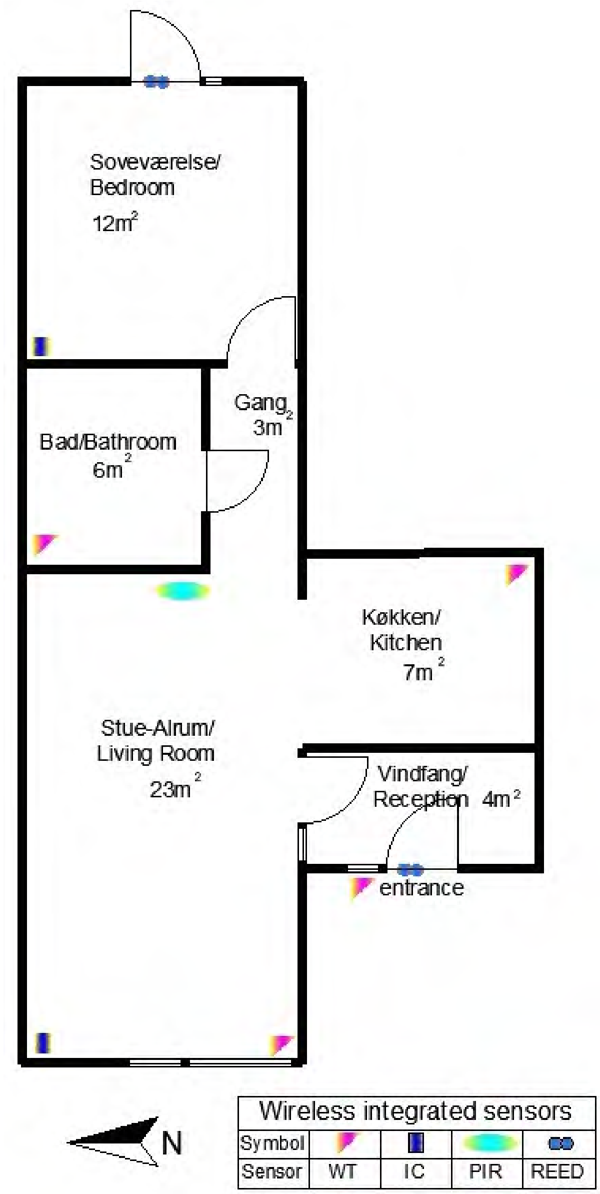


Figure 2.14: Floorplan of Renovated Apartment 1

Renovated 2

This is a three bedroom apartment of 93m^2 located at the first floor occupied by one retired person and temporarily the adult son. The tenant prefers sleeping with the window open in the bedroom.

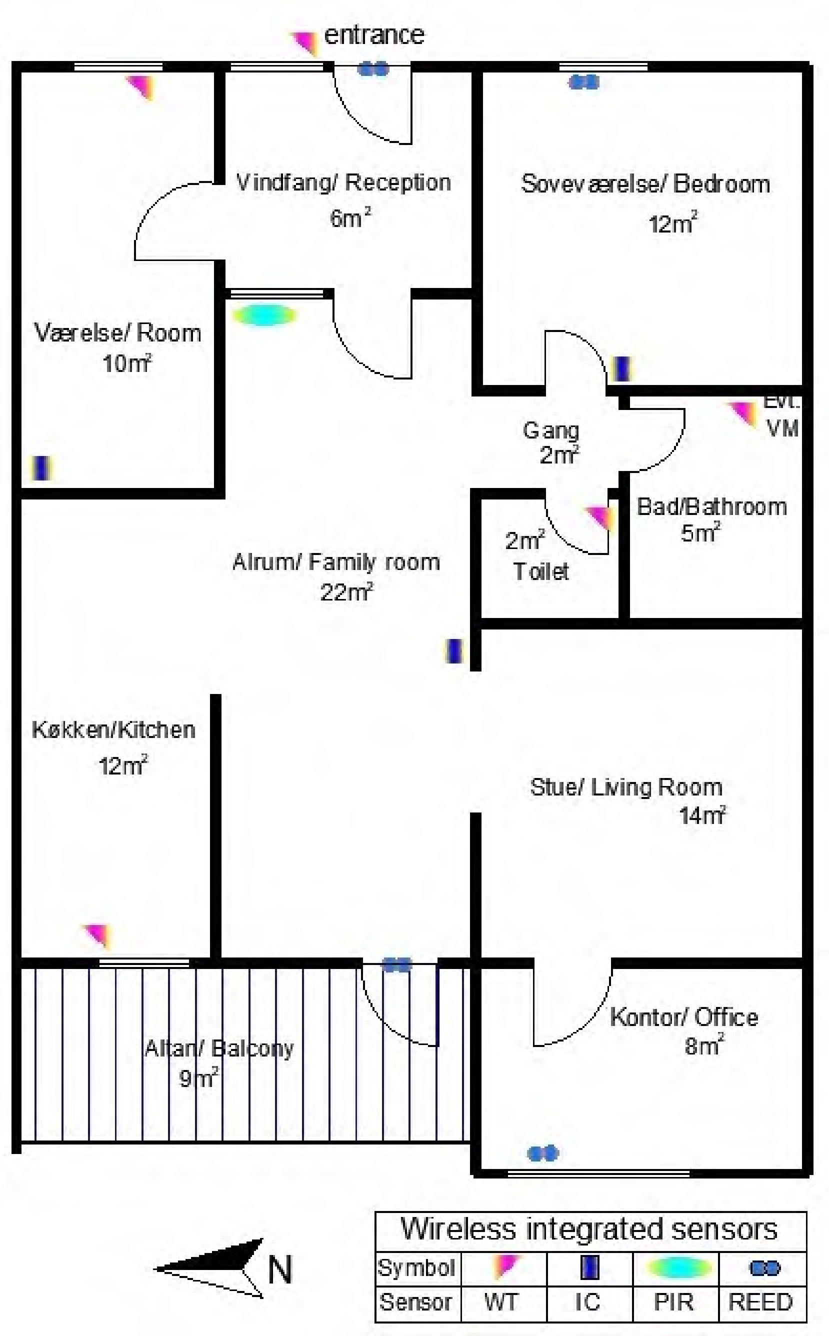


Figure 2.15: Floorplan of Renovated Apartment 2

Chapter 3

Methodology

In order to achieve a validated numerical model, sufficient accurate input data is needed. For the current project some parameters such as the indoor temperatures of the apartments and usage of electrical appliances were measured implementing the non-invasive technology as described in section 3.2. Theses data were implemented in a dynamic simulation model developed in TRNSYS. Later, the predicted heating consumption were compared to actual measured data from the four case studies. In this chapter, data analysis and model description will be clarified thoroughly.

3.1 Lab level instrument accuracy checking

A lab level test had been carried out at a climatic chamber at DTU as shown in Figure 3.1 to check the accuracy of the wireless sensors. This phase is briefly illustrated at the present thesis, since it is not a part of the scope of the thesis. By setting up the IC-meters and Wireless Tags in a climatic chamber with high infiltration from outside, the CO_2-level of the IC-meter is calibrated as the outdoor CO_2 content is about 400PPM which is the assumed CO_2 calibration level by the manufacture [32].

Figure 3.1: The instrument setup in the climatic chamber

3.2 Data processing

3.2.1 Weather

As the apartments are located in Aalborg the input data for the weather should be nearby, as there is a significant enough difference from the climatic data measured e.g. in Copenhagen. The weather data was thus provided by Aalborg Universitys Department of Civil Engineering in cooperation with Davis [39] (http://www.vejrradar.dk/weatherstation/TMV23/) and is measured at the weather station Thomas Manns Vej in Aalborg fairly close to the site. The data needed for the numerical model was the dry bulb temperature, the relative humidity and the total solar radiation.
It is possible to download data for either the past 48 hours, the past week or the full archive. The full archive provides data back from September 2017 up till the current date. The data is divided into a folder for each year, then a folder for each month and the measured data is then provided in a file for each day. The time step of the measurements is for each minute, but as TRNSYS will need to have the same time steps for all input data, the weather input was then to be decreased to match the five minute interval of the measured indoor temperatures. On several occasions the registration of the temperature, relative humidity or solar radiation was missing, setting back the process of setting up the input files due to the search of these errors, as TRNSYS would abort a simulation if there was no value to be read. An example of the climate input file is found in Appendix C.

3.2.2 Indoor temperatures

The instruments were installed on November 14 2017 at the non-renovated apartments prior to the start of the present thesis, whereas the instruments in the renovated apartments were installed at the 12th of February 2018. As Wireless Tags are supplied with power through batteries they were in risk of running out of power, why some of the previously installed units were replaced or had batteries changed in the start of 2018.
In order to make it easier to analyse the collected data and have a clear view of the quality and consistency of the measurements, the collected data was categorised by time intervals and sensor type for each apartment as seen in Table 3.1. The goal was to have 12 measurements per hour which corresponds to a measurement every five minutes. In the table it is clarified that the IC-meter measurements all comply with the goal of 12 measurements per hour with a margin of error of maximum 0.5%, whereas the measurements from the Wireless Tag-system is fairly inconsistent in the measuring interval. The grey cells indicate an incomplete month of measurements, the green values indicate a number of measurements with a margin of error of 5% from the goal of 12 measurements per hour and the green cells indicate which data set is used as inputs to the models.

As there are no measurements in the renovated apartments for January and the first half of February those months are excluded. Furthermore, there are too many incomplete measurements of rooms for April and thus this months is excluded too, leaving March and the second half of February. At first just the second half of February (14th-27th) was chosen as the simulation period, but it was discovered that the measured heating consumption had missing data within this time frame for some of the four apartments. Therefore, the final time period which was found to be with the smallest amount of errors and inconsistencies start the 21st of February to 6th of March giving a period of two full weeks.

Table 3.1: Total and hourly number of measurements for each Wireless Tag and IC-meter

			January		February		March		April	
			Meas.	/hour	Meas.	/hour	Meas.	/hour	Meas.	/hour
Renovated 1	Wireless Tag	Bedroom					4234	5.69	4111	5.71
		Kitchen					4240	5.70	4113	5.71
		Kitchen new					*8480*	*11.40*	*8226*	*11.43*
		Entrance					4218	5.67	4311	5.99
		Entrance new					*8436*	*11.34*	*8622*	*11.98*
		Livingroom					4239	5.70	4136	5.74
	IC-meter	Bedroom					8916	11.98	8631	11.99
		Kitchen			No measurements available					
		Entrance			No measurements available					
		Livingroom					8916	11.98	8632	11.99
Renovated 2	Wireless Tag	Bedroom			*Using measurements from IC-meter*					
		Room					10189	13.69	10253	14.24
		Office					8879	11.93	8546	11.87
		Kitchen					9343	12.56	9101	12.64
		Entrance					8629	11.60	8392	11.66
		Familyroom					8390	11.28	8148	11.32
		Livingroom			No measurements available					
	IC-meter	Bedroom					8913	11.98	8629	11.98
		Room					8914	11.98		
		Office			No measurements available					
		Kitchen			No measurements available					
		Entrance			No measurements available					
		Familyroom					8916	11.98	8629	11.98
		Livingroom			No measurements available - Using Familyroom					
Non-renovated 1	Wireless Tag	Bedroom 1	8066	10.84	7284	10.84	8065	10.84	7949	11.04
		Bedroom 2	9074	12.20	8251	12.28	9056	12.17	8991	12.49
		Kitchen	8758	11.77	7930	11.80	8846	11.89	9836	13.66
		Reception	8602	11.56	7723	11.49	8577	11.53	8781	12.20
		Livingroom	8803	11.83	7949	11.83	8826	11.86	8798	12.22
	IC-meter	Bedroom 1	8928	12.00	8061	12.00	8916	11.98	8639	12.00
		Bedroom 2	No measurements available							
		Kitchen	No measurements available							
		Reception	8929	12.00	8059	11.99	8916	11.98	8639	12.00
		Livingroom	8928	12.00	8061	12.00	8916	11.98	8638	12.00
Non-renovated 2	Wireless Tag	Bedroom 1	10674	14.35	10731	15.97				
		Bedroom 2	*Using measurements from IC-meter*							
		Bedroom 3	9041	12.15	8167	12.15	8784	11.81	8324	11.56
		Kitchen	9666	12.99	9265	13.79				
		Reception	*Using measurements from IC-meter*							
		Livingroom	9112	12.25	8552	12.73	9104	12.24		
	IC-meter	Bedroom 1	No measurements available							
		Bedroom 2	8927	12.00	8052	11.98	8911	11.98	8598	11.94
		Bedroom 3	8929	12.00						
		Kitchen	No measurements available							
		Reception	8928	12.00	8063	12.00	8915	11.98	8639	12.00
		Livingroom	8884	11.94	8061	12.00			8639	12.00

At the Renovated Apartment 1 it is seen that the Wireless Tag measurements are done for each 10 minute and thus only approximately six measurements per hour. As an IC-meter was only installed in the Bedroom and Livingroom it was necessary to duplicate each measurement in the Kitchen and Entrance, and thus assume that the temperature does not change significantly within 10 minutes.

At Non-renovated Apartment 2 Bedroom 3 the temperatures measured by the IC-meter were approximately 4°C higher than the temperatures measured by the Wireless Tag as the latter was placed near the window and the former opposite of the window. The Wireless Tag in Bedroom 1 was placed near the window as well. Because of the noticeable difference the approximate of 4°C was added to the measurements of Bedroom 1 and 3. Furthermore, it is indicated that the measurements of March for Bedroom 1 and Kitchen in Non-renovated Apartment 2 is incomplete, but the measurements are available until the 6th of March at 21:39 and 21st of March at 12:15 respectively. For Bedroom 1 the data from the night before is thus used, as the difference was insignificant.
An example of a temperature input file is found in Appendix D.

3.2.3 Electrical consumption

The electrical consumption measured through Smappee is used to define an average hourly consumption to use as input for the numerical model. The total used data is seen in Appendix E and the calculated average used as input is seen in Table 3.2. As Smappee distinguishes between the "always on"-consumption (e.g. refrigerator) and the total consumption, the "always on"-consumption is thus subtracted to get the "actual" consumption. By taking the average of the consumption, the occupants behaviour/schedule is taken into account and is thus "implemented".

Table 3.2: Average measured electrical consumption of apartments

	Average hourly electrical consumption [kJ/hr]
Ren_1	608.42
Ren_2	771.86
Non-ren_1	55.29
Non-ren_2	1210.55

3.3 Infiltration

3.3.1 Blowerdoor test

It was important to evaluate the infiltration air flow rate for the non-renovated apartments to comprehend the influence on the overall energy balance. A Blowerdoor-test managed by COWI A/S [40] was carried out for the Non-renovated Apartment 1 where a ventilator unit is attached in the entrance door of the apartment. The ventilator then forms a pressure difference of 50Pa both as positive and negative pressure. The results are seen in Table 3.3 [40].
During the site visit to the Renovated Apartment 1, a strong cold draft was noticed at the apartment between the external door and door frame in the reception, which was the motive to investigate the reason behind it. A Blowerdoor-test was carried out for this apartment and the results shown in Table 3.3 indicated that the infiltration rate for this renovated apartment was more or less equal to the non-renovated apartment.

Table 3.3: Infiltration rates from Blowerdoor-test

Apartment	Infiltration rate [l/s m^2]
Non-renovated 1	0.2
Renovated 1, Entrance	0.71
Renovated 1, w/out Entrance	0.19

3.3.2 Exhaust ventilation flow rates

The exhaust ventilation rates of the exhausts in toilet, bathroom and kitchen are measured in two non-renovated apartments. The measured ventilation rates are shown in Table 3.4.

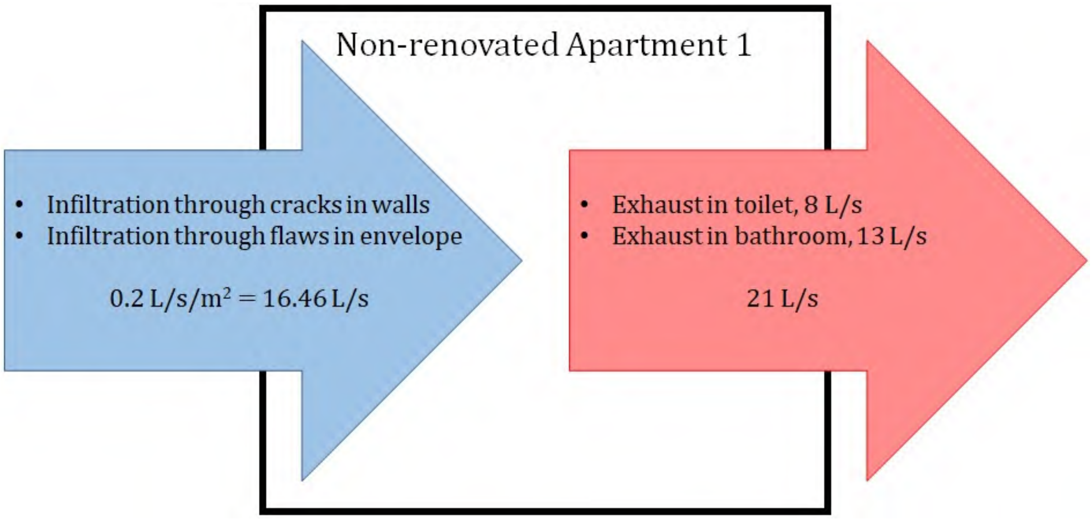
Table 3.4: Measured ventilation rates

Apartment	Room	Ventilation rate [l/s]
Non-renovated 2 (ground floor)	Toilet	5
	Bathroom	9
	Kitchen hood	30
Non-renovated 1 (first floor)	Toilet	8
	Bathroom	13
	Kitchen hood	65

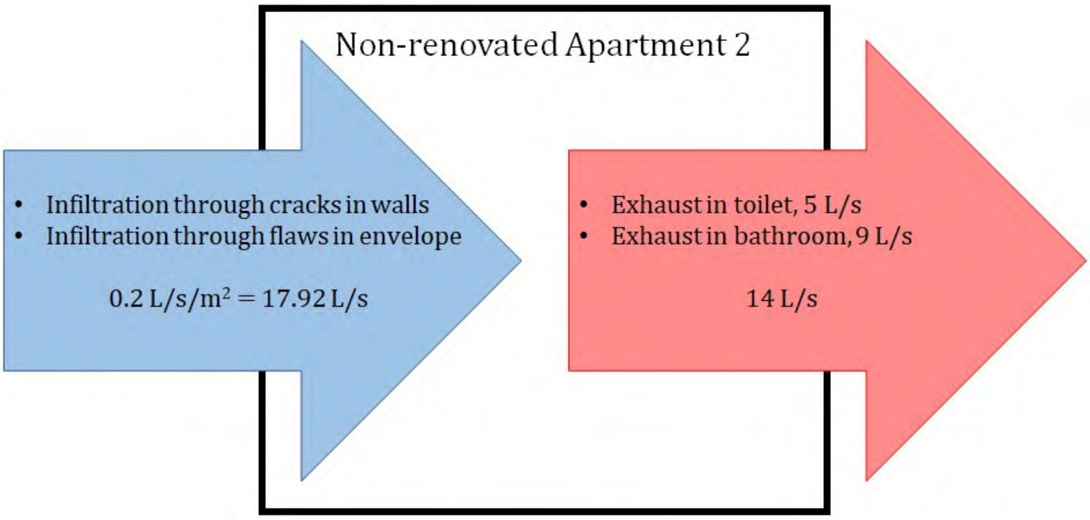
The exhaust ventilation in the bathroom and toilet are running at all times, while the kitchen hood is controlled by the occupants and is usually only used when the occupants are cooking, why the latter is not implemented in the models.
In the renovated apartments the old exhaust systems are replaced with a new exhaust system. The exhaust ventilation rates measured at the non-renovated apartments were implemented at numerical models of the renovated apartments as well, differentiating between ground and first floor.

3.3.3 Air balances

In order to implement the correct infiltration rate in the numerical models, air balances are done for each apartment. Tables of the calculated air balances are found in Appendix F for the Reference case model and Appendix G for the Non-detailed and Detailed case models. As the Blowerdoor-test revealed an unusually high infiltration rate for a renovated building, the maximum allowed infiltration rate of $1 l/s/m^2$ at a pressure difference of 50Pa according to the Danish Building Regulations 2018 §263.1 [41] is used for Renovated Apartment 2. Figure 3.2-3.3 illustrates the air balances used for the Non-detailed and Detailed model cases. The difference between the total exhaust and the total infiltration is added as extra infiltration in bathroom.

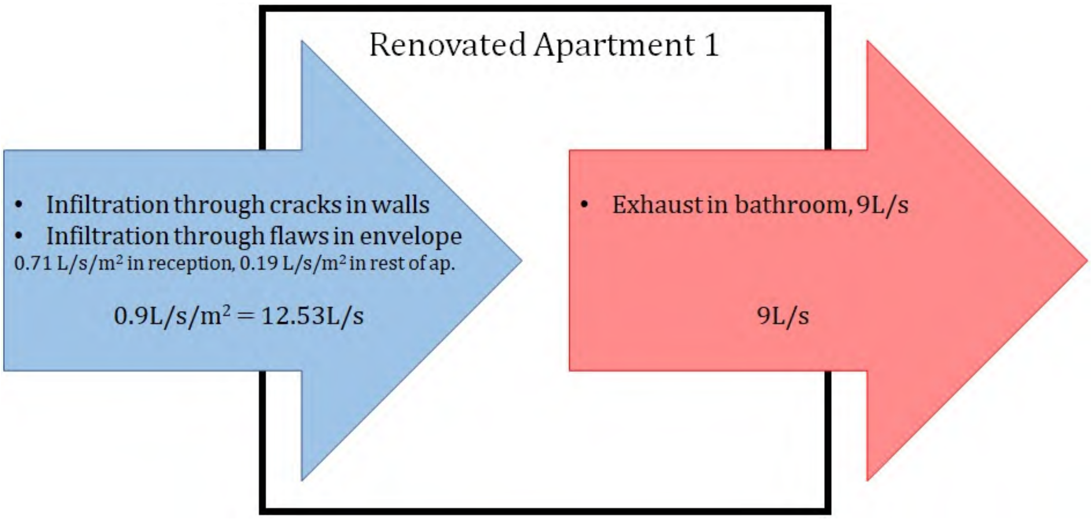


(a) Non-renovated Apartment 1

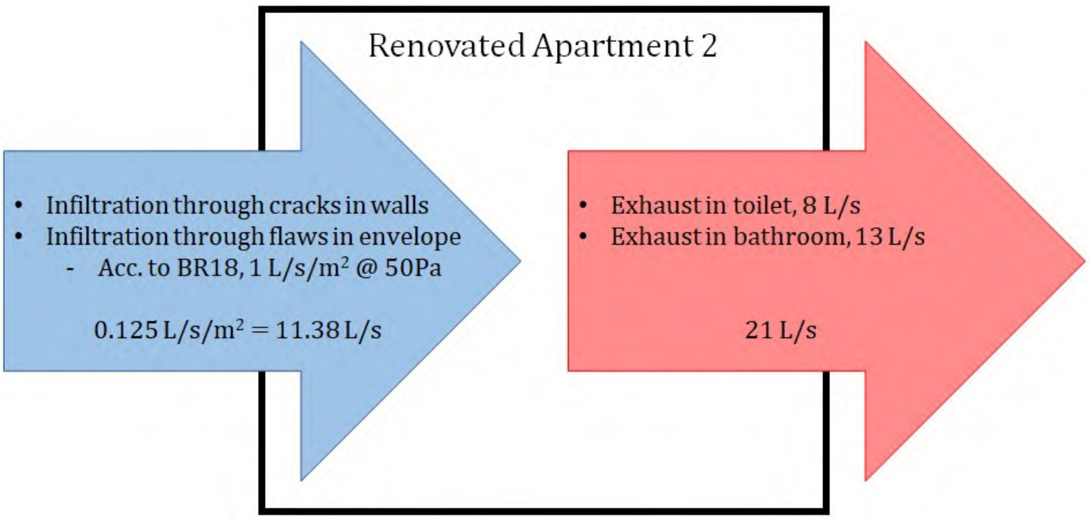


(b) Non-renovated Apartment 2

Figure 3.2: Air balance for the non-renovated apartments



(a) Renovated Apartment 1

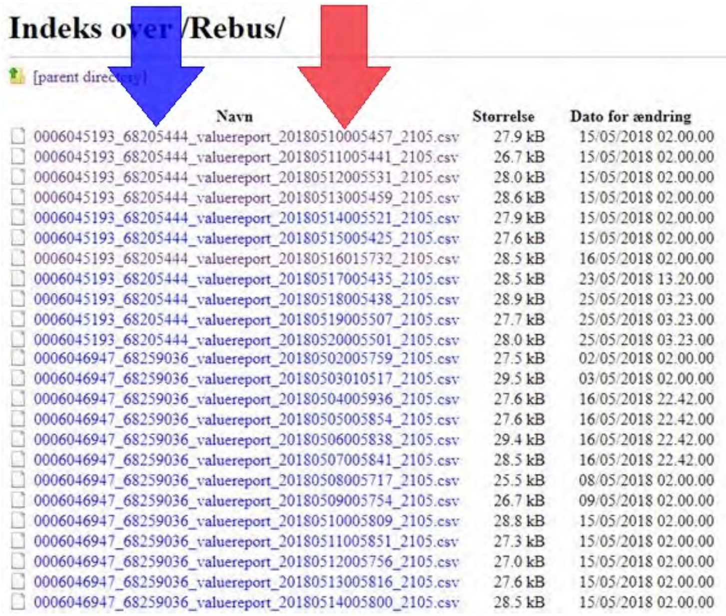


(b) Renovated Apartment 2

Figure 3.3: Air balance for the renovated apartments

3.3.4 Measured heating consumption

The measured heating consumption is provided as an online archive by Ista (ftp://80.161.191.118/). Each apartment has an ID (blue arrow in Figure 3.4) and a file is generated for each day (red arrow in Figure 3.4). The files contain data of the volume flow, flow and return temperature, energy etc., while the only needed data for this project is the power/heating consumption. The provided time steps vary from one measurement per hour to one measurement every 30, 15 or five minutes with no real consistency, furthermore registrations of one or sometimes more data sets are missing throughout numerous of the files.


Indeks over /Rebus/

[parent directory]

Navn	Størrelse	Dato for ændring
0006045193_68205444_valuereport_20180510005457_2105.csv	27.9 kB	15/05/2018 02.00.00
0006045193_68205444_valuereport_20180511005441_2105.csv	26.7 kB	15/05/2018 02.00.00
0006045193_68205444_valuereport_20180512005531_2105.csv	28.0 kB	15/05/2018 02.00.00
0006045193_68205444_valuereport_20180513005459_2105.csv	28.6 kB	15/05/2018 02.00.00
0006045193_68205444_valuereport_20180514005521_2105.csv	27.9 kB	15/05/2018 02.00.00
0006045193_68205444_valuereport_20180515005425_2105.csv	27.6 kB	15/05/2018 02.00.00
0006045193_68205444_valuereport_20180516015732_2105.csv	28.5 kB	16/05/2018 02.00.00
0006045193_68205444_valuereport_20180517005435_2105.csv	28.5 kB	23/05/2018 13.20.00
0006045193_68205444_valuereport_20180518005438_2105.csv	28.9 kB	25/05/2018 03.23.00
0006045193_68205444_valuereport_20180519005507_2105.csv	27.7 kB	25/05/2018 03.23.00
0006045193_68205444_valuereport_20180520005501_2105.csv	28.0 kB	25/05/2018 03.23.00
0006046947_68259036_valuereport_20180502005759_2105.csv	27.5 kB	02/05/2018 02.00.00
0006046947_68259036_valuereport_20180503010517_2105.csv	29.5 kB	03/05/2018 02.00.00
0006046947_68259036_valuereport_20180504005936_2105.csv	27.6 kB	16/05/2018 22.42.00
0006046947_68259036_valuereport_20180505005854_2105.csv	27.6 kB	16/05/2018 22.42.00
0006046947_68259036_valuereport_20180506005838_2105.csv	29.4 kB	16/05/2018 22.42.00
0006046947_68259036_valuereport_20180507005841_2105.csv	28.5 kB	16/05/2018 22.42.00
0006046947_68259036_valuereport_20180508005717_2105.csv	25.5 kB	08/05/2018 02.00.00
0006046947_68259036_valuereport_20180509005754_2105.csv	26.7 kB	09/05/2018 02.00.00
0006046947_68259036_valuereport_20180510005809_2105.csv	28.8 kB	15/05/2018 02.00.00
0006046947_68259036_valuereport_20180511005851_2105.csv	27.3 kB	15/05/2018 02.00.00
0006046947_68259036_valuereport_20180512005756_2105.csv	27.0 kB	15/05/2018 02.00.00
0006046947_68259036_valuereport_20180513005816_2105.csv	27.6 kB	15/05/2018 02.00.00
0006046947_68259036_valuereport_20180514005800_2105.csv	28.5 kB	15/05/2018 02.00.00

Figure 3.4: Online archive of measured heating consumption files

3.4 TRNSYS

Transient Systems Simulation program (TRNSYS) is a dynamic simulation program used to simulate the behaviour of transient systems: thermal and electrical energy simulation including multi-zone buildings. The software was developed at the University of Wisonsin and the University of Colorado and became commercially available in 1975. It uses a modular, "black box" approach as the different components (*types*) read input and give one or several outputs without the user being able to know the exact process of the component. The main part of the software, Simulation Studio, is where the model is set up by connecting the components, and input/output, graphically. The interface TRNBuild is used to set up detailed multi-zone buildings.

For each apartment three models are compiled: a Reference, a Non-detailed and a Detailed case. The boundary conditions for the Reference cases are based on the Danish Building Regulations while the Non-detailed and Detailed cases are based in the previously described collected data. The three types of model cases and their input are clarified in the following.

3.4.1 Models

All models are set up using the same template. The input files are carefully done in Excel and converted to .txt file format, examples of the input files are seen in Appendix C and D. The model is set up to have data for every five minutes, thus all input have to be in this format, otherwise the software will crash. The output will be in five minute intervals as well. Figure 3.5 shows the setup in TRNSYS Simulation Studio and the used types are explained in the following.

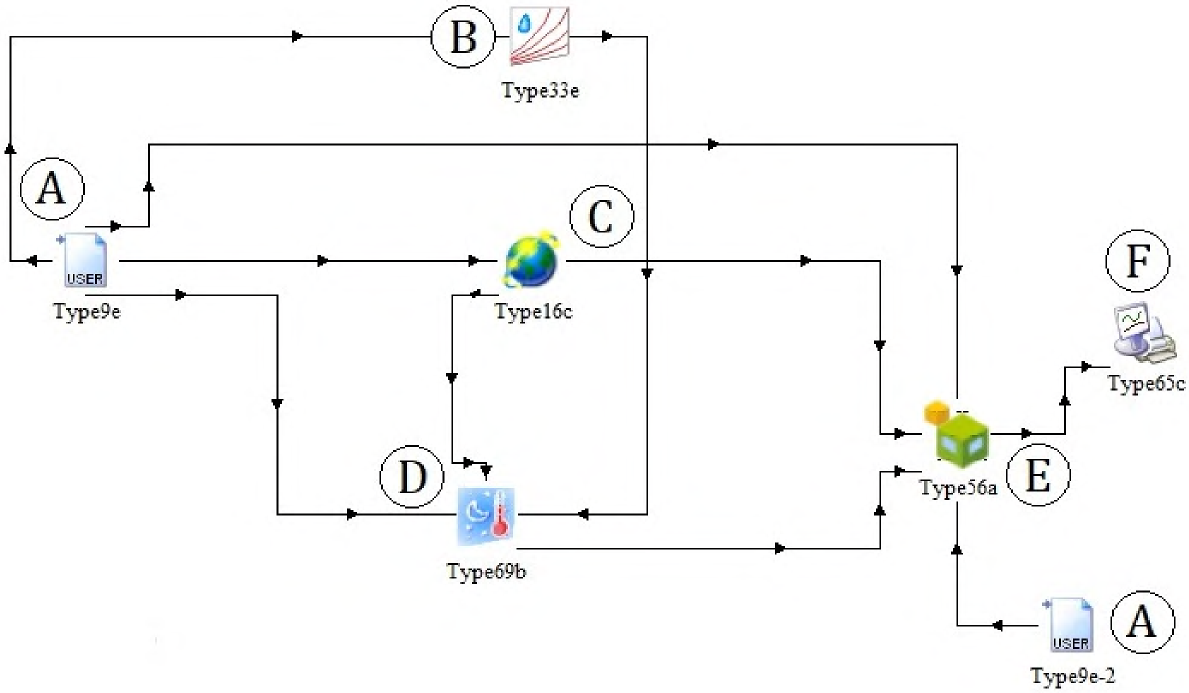


Figure 3.5: TRNSYS Simulation Studio setup

Key legend of Figure 3.5

A - Type9e

Type 9 are data readers for generic data files. The one on the far left is reading the climate data file and providing three outputs: ambient temperature, relative humidity and horizontal radiation. The one on the far right is reading the input files and provides the temperature for each heated zone in the building.

B - Type33e

Type 33 are using the Psychrometrics to convert inputs to the wanted outputs within the Psychrometric ranges. Here it is used to find the *dew point temperature* from the dry bulb temperature (ambient temperature from Type9e to the far left) and the relative humidity.

C - Type16c

Type 16 are using the Psychrometrics to find the radiation on a number of surfaces. The letter defines what is known, thus *c* is where the temperature and humidity is known. From Type9e on the far left it is provided with the the ambient temperature, relative humidity and the horizontal radiation. It then provides the following outputs: diffuse horizontal radiation, solar zenit angle, solar azimut angle and the incidence angle, total radiation and beam radiation of the chosen surfaces (North, South, East, West and horizontal).

D - Type69b

Type 69b is used to calculate the fictive sky temperature based on the dew point temperature from Type33e, the ambient temperature from Type9e on the far left and the horizontal beam an diffuse radiation from Type16c.

E - Type56a

Type 56 are multi-zone buildings where *a* is with a standard output file. This type attaches the building to the simulation. It is provided with the diffuse horizontal radiation, solar zenit angle, solar azimut angle and the incidence angle, total radiation and beam radiation of North, South, East, West and horizontal from Type16c, the fictive sky temperature from Type69b and the ambient temperature and relative humidity from Type9e on the far left. Furthermore it is provided with the temperatures of the heated zones from Type9e on the far right.
In the building file it is chosen which output is wanted. As it is the heating consumption which is to be compared, this is chosen as the output.

F - Type65c

Type 65 are the types that generates an actual output. *c* is for an online plotter with a file but without standard units. In here the results are defined to a file, for this project an .xls-file is used. This type is provided with the heating consumption generated in from the building structure in Type56a.

The types are connected with the definition of output/input of the connected types. The connections are defined as seen in

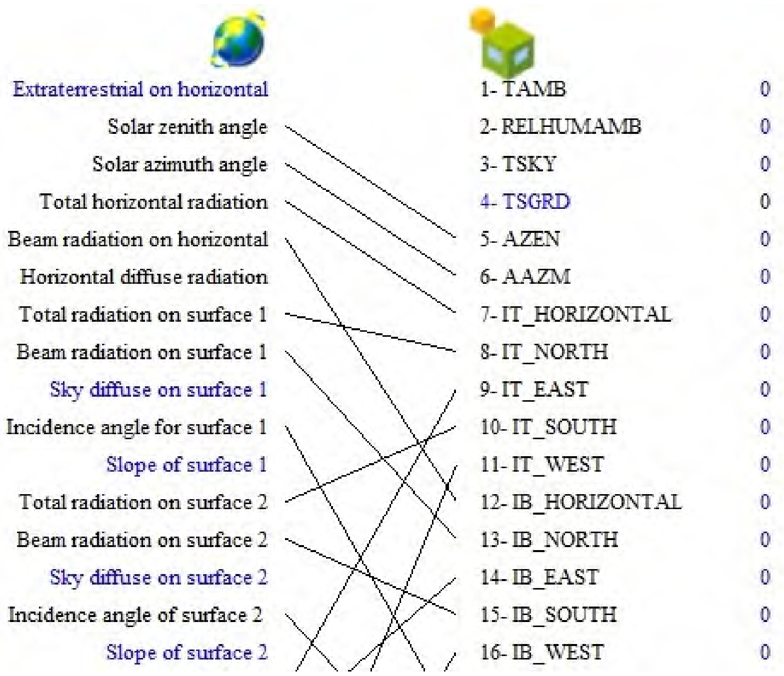


Figure 3.6: Definition of connection between Type16c and Type56a

To evaluate the influence of light schedules on the overall energy consumption, the modelling included a

Reference model case

In order to get an approval for constructing a building calculations are executed using the calculation programme BE15 (the newest version is BE18) due to Danish law, as it ensures that a building complies with the Danish Building Regulations (BR18) and other relevant legislation. The software generates a document which is then used as an official approval.
The Reference model is set up using the same boundary conditions as BE15. All inputs are thus

from the Danish Building Regulations of 2018. The standard design values used for the models are seen in Table 3.5.
According to BR18 §263.1 [41]:

> [...] the volume flow through flaws in the building envelope in new buildings heated to minimum 15°C must not exceed 1l/s/m^2 heated floor area at a difference in pressure of 50Pa.

Through a quick calculation this equals to 1.44 ACH at normal pressure. According to BR18 §443.3 and §443.4 [41]:

> [...] the evacuation [*of the range hood over the cooker in the kitchen*] should be adjustable to minimum 20l/s.
>
> Evacuations from bathrooms and toilet rooms in residential units should be adjustable to minimum 15l/s. In toilet rooms without bath/shower and sculleries, evacuation should be adjustable to minimum 10l/s.

The indoor and outdoor design temperature of 20° and -12° respectively are used, as these are the used temperatures in the software BE18. The constant indoor temperature is only applied in rooms with a heating device, thus excluding the toilets and storage-rooms. BE18 also states that the appliance load should be minimum 210W and maximum 840W. Using the minimum appliance load equals 756kJ/hr. The lighting of 10W/m^2 is ON at all times for every room in the apartments.

Table 3.5: Values used in Reference models

Parameter	Value
Indoor temperature	20 °C
Outdoor temperature	-12 °C
Infiltration rate	1l/s/m^2 @ 50Pa
Evacuation rate, bathrooms	15l/s
Evacuation rate, toilets	10l/s
Appliances	min. 210W
Light	10W/m^2

Non-detailed model case

The Non-detailed model is set up with a minimum of details using the collected data as input for indoor temperature and climate input. The lights of 10W/m^2 are kept constant not taking the occupant behaviour into account, though there is no light in the entrances, bathrooms, toilets or storage-rooms, as these are rooms occupants rarely spend longer periods of time in. An electrical device of 140W is added to livingrooms to indicate the presence of a tv-screen. Occupants are all set to be *seated at rest* with a total heat gain rate of 100W. An electrical appliance of the average measured electrical consumption is added in the kitchens. All boundary conditions are seen in Table 3.6. The temperatures of the Entrance of Renovated Apartment 1, the Bedroom of Renovated Apartment 2, the Office, Bedroom and Bathroom for Non-renovated Apartment 1 and the Bedroom 1, Bedroom 3 and Kitchen for Non-renovated Apartment 2 are all quite low, why the temperatures are set as cooling, as TRNSYS otherwise is not capable to comprehend the temperature being this low. However, the temperatures of Bedroom 1 and 3 of Non-renovated Apartment 2 is also set as heating in order to achieve the correct temperature.

Table 3.6: Boundary conditions for the Non-detailed model cases

		Occupant	Electrical device 140W	Light $10W/m^2$	Appliance [kJ/hr]	Infiltration [h^{-1}]	Meas. temp.
Renovated 1	Entrance					1.0224	✓
	Kitchen			✓	608.42	0	✓
	Livingroom	✓	✓	✓		0.3473	✓
	Bathroom						✓
	Bedroom	✓		✓		0.2128	✓
Renovated 2	Entrance					0.18	✓
	Room			✓		0.18	✓
	Familyroom	✓		✓		0.18	✓
	Kitchen			✓	771.86	0.18	✓
	Bedroom	✓		✓		0.18	✓
	Bathroom					0.2952	✓
	Toilet					0.18	-
	Livingroom		✓	✓		0.18	✓
	Office			✓		0.18	✓
Non-renovated 1	Reception			✓		0.288	✓
	Office			✓		0.288	✓
	Bedroom	✓		✓		0.288	✓
	Bathroom					1.49	✓
	Toilet					0.288	-
	Livingroom		✓	✓		0.288	✓
	Kitchen			✓	55.29	0.288	✓
	Storage					0.288	-
Non-renovated 2	Reception	✓		✓		0.288	✓
	Bedroom 2	✓		✓		0.288	✓
	Bedroom 1	✓		✓		0.288	✓
	Bathroom					0.288	✓
	Toilet					0.288	-
	Livingroom	✓	✓	✓		0.288	✓
	Kitchen			✓	1210.55	0.288	✓
	Storage					0.288	-
	Bedroom 1			✓		0.288	✓

Detailed model case

The Detailed model case is somewhat the same as the Non-detailed model case, only schedules are added for lighting and the number of electrical devices have been re-evaluated. The latter was due to the site visits as they had shown that for the Renovated Apartment 2 there is a stationary pc in the Room which is always ON, while in the Non-renovated Apartment 2 the children often use their laptops and gaming console in the Reception. An electrical device is thus added in these rooms. Table 3.7 shows the boundary conditions of the Detailed models while the schedules are found in Appendix H.

Table 3.7: Model definition for Schedule-model

		Occupant	Electrical device 140W	Light 10W/m^2	Appliance [kJ/hr]	Infiltration [h^{-1}]	Meas. temp.
Renovated 1	Entrance					1.0224	✓
	Kitchen			Schedule	608.42	0	✓
	Livingroom	✓	✓	Schedule		0.3473	✓
	Bathroom						✓
	Bedroom	✓				0.2128	✓
Renovated 2	Entrance					0.18	✓
	Room		✓	Schedule		0.18	✓
	Familyroom	✓		Schedule		0.18	✓
	Kitchen			Schedule	771.86	0.18	✓
	Bedroom	✓		Schedule		0.18	✓
	Bathroom			Schedule		0.2952	✓
	Toilet					0.18	-
	Livingroom		✓	Schedule		0.18	✓
	Office					0.18	✓
Non-renovated 1	Reception			✓		0.288	✓
	Office			✓		0.288	✓
	Bedroom	✓		✓		0.288	✓
	Bathroom					1.49	✓
	Toilet					0.288	-
	Livingroom		✓	✓		0.288	✓
	Kitchen			✓	55.29	0.288	✓
	Storage					0.288	-
Non-renovated 2	Reception	✓	✓	✓		0.288	✓
	Bedroom 2	✓		✓		0.288	✓
	Bedroom 1	✓		✓		0.288	✓
	Bathroom			Schedule		0.288	✓
	Toilet					0.288	-
	Livingroom	✓	✓	✓		0.288	✓
	Kitchen			✓	1210.55	0.288	✓
	Storage					0.288	-
	Bedroom 1					0.288	✓

Four apartments have been modelled in TRNSYS. For three out of four apartments three parametric cases were considered: a Reference case, a Non-detailed case and a Detailed case. However, for Non-renovated Apartment 1 only two parametric cases were considered: a reference case and a non-detailed case. This was due to the results of the Non-detailed model simulation compared to the measured heating consumption was non reliable. Accordingly, it was agreed to only consider the Non-detailed case.

Chapter 4

Results

4.1 Numerical models validation

The validation of the models is based on the root-mean-square deviation (or -error), RMSD, as this value is used to measure the difference between a group of values e.g. sample values. The RMSD is the sample standard deviation of differences between predicted and observed values, in this case between simulated and measured values. It is thus an efficient method evaluate the validation of the simulated models. The RMSD is calculated using Equation 4.1, while Table 4.1 shows the RMDS for all four apartments and the different simulations performed in TRNSYS. The unit of the RMSD is in this case W/m^2 as it is the unit of the compared values.

$$RMSD = \sqrt{\frac{\sum_{t=1}^{n} \left(x_{1,t} - x_{2,t}\right)^2}{n}} \tag{4.1}$$

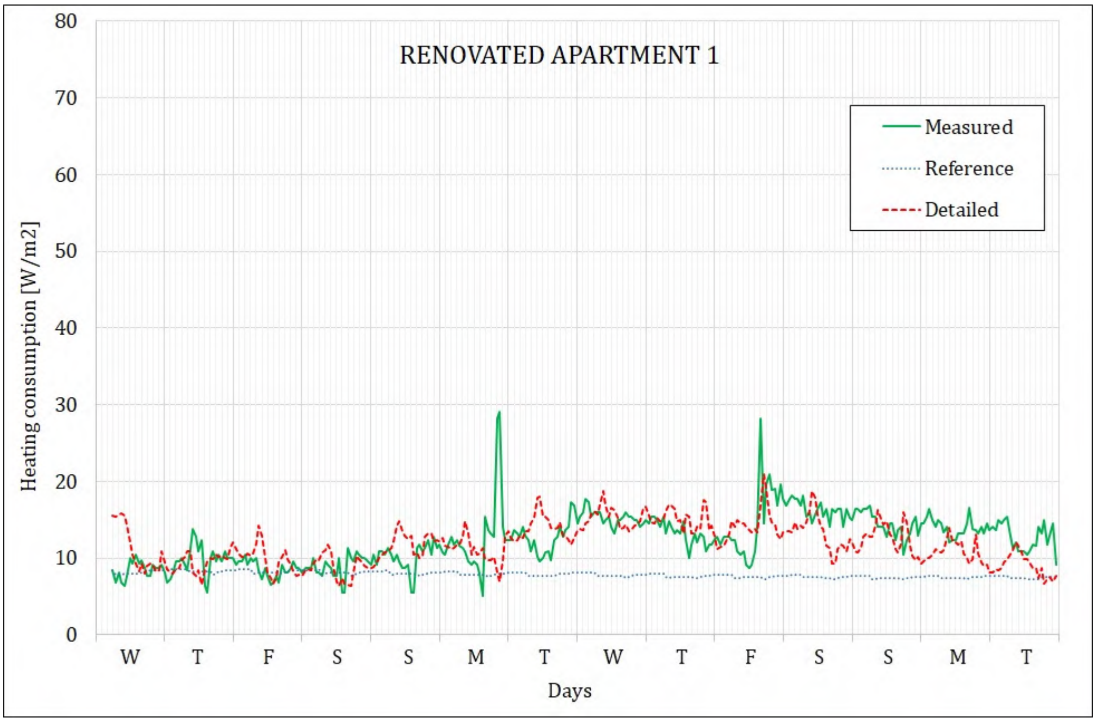
where $x_{1,t}$ = measured value
$x_{2,t}$ = simulated value
n = number of values

It is seen in Table 4.1 that the RMSD is low for all three simulations for Renovated Apartment 1 and 2, while there is a significant difference for the two non-renovated apartments between the Reference models and the Non-detailed/Detailed models. For the Non-renovated Apartment 1 there is not simulated a model with a schedule as this turned out to be an extreme case with unusually low heating consumption, temperatures and electrical consumption which will be discussed in section 4.2.1.

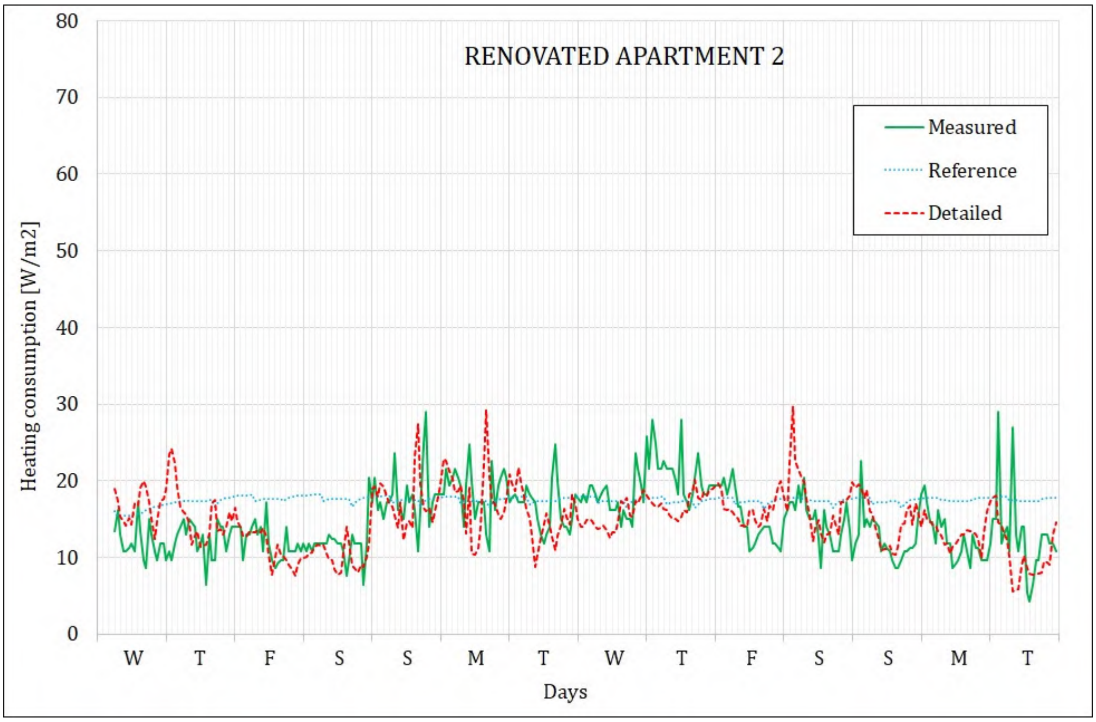
Table 4.1: RMSD for the four apartments simulated in TRNSYS

Apartment	RMSD Reference [W/m^2]	RMSD Non-detailed [W/m^2]	RMSD Detailed [W/m^2]
Renovated 1	5.74	6.97	3.70
Renovated 2	4.92	6.32	4.60
Non-renovated 1	57.06	27.51	-
Non-renovated 2	18.52	8.54	8.42

The heating consumption of the models are seen as graphs for each apartment in Figure 4.1 and 4.2.



(a) Renovated apartment 1



(b) Renovated apartment 2

Figure 4.1: Comparison of heating consumption for renovated apartments

For the Renovated Apartment 1, Figure 4.1a illustrates that the Detailed and Measured consumptions are in good agreement. The peaks in the Measured consumption may be due to the opening of windows. The consumption is rather stable with a range of around 7 to 20W/m^2 disregarding the two peaks at the first Monday evening and the second Friday afternoon.
As shown in Figure 4.1a the Reference consumption is constant, due to the constant boundary

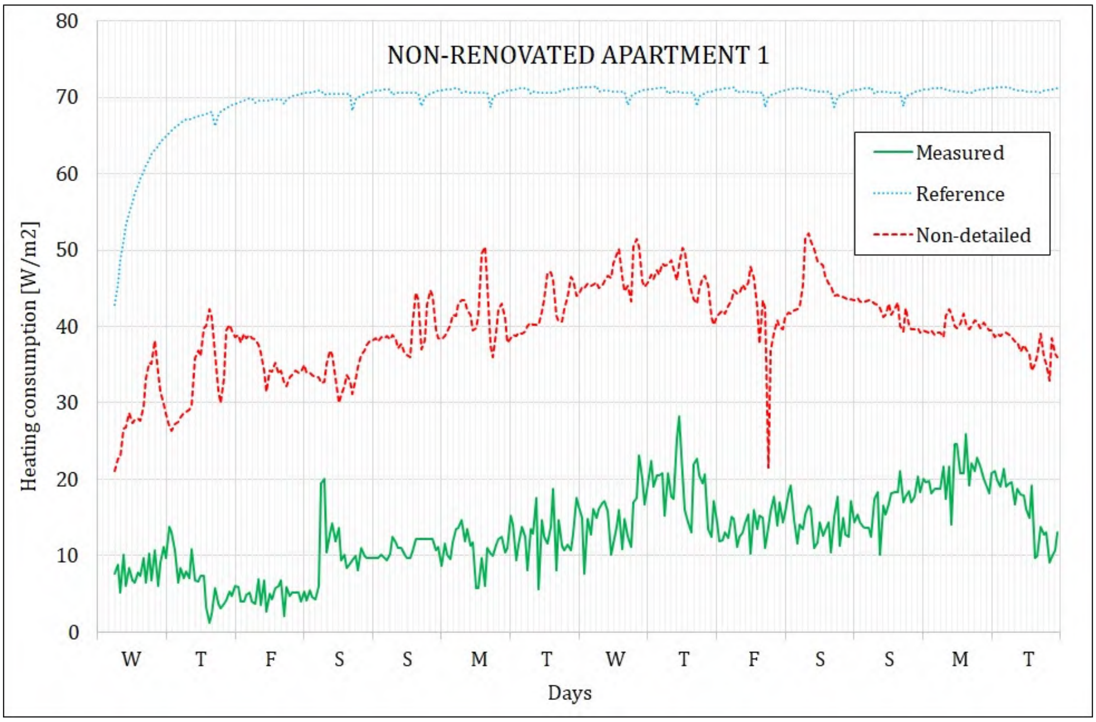
conditions. The Reference case is lower than both the Measured and Detailed profiles, which indicates the effect of the unusually high infiltration as described in section 3.3.
Figure 4.1b illustrates that the overall heating consumption for the Renovated Apartment 2 is within the range of around 10 to 25W/m^2. The Detailed and Measured consumption are in good agreement, while the Reference consumption is slightly above the average of the Measured and Scheduled profiles.
The Measured consumption in the Renovated Apartment 2 varies more than the Measured in Renovated Apartment 1. Furthermore, the Reference consumption is almost 10W/m^2 higher in the Renovated Apartment 2 than Renovated Apartment 1. This is due to the location of the apartments as Renovated 1 is located at the ground floor while Renovated 2 is located at the first floor with exposed roof.

Figure 4.2a clarifies that the Reference heating consumption for the Non-renovated Apartment 1 is around 70W/m^2 being the highest of all four cases. This is first and foremost due to the only 5cm of insulation in the exterior walls of the non-renovated building. Furthermore, the occupant is only one person while there are two or more occupants in the other apartments. Even though the electrical consumption was unusually low, the simulation was held at constant gains with no schedules as adding schedules would increase the need for heating. It was thus evaluated that the Non-Renovated Apartment 1 is an extreme case, as mentioned earlier. This is also seen from the RMSD for both the Reference and Non-detalied model cases as they are significantly higher than the other three apartments. The Measured consumption varies between 4-23W/m^2.
Figure 4.2b shows that the Measured and Detailed heating consumption for the Non-renovated Apartment 2 are in good agreement which was also expressed from the low RMSD in Table 4.1. The Reference heating consumption is around 40W/m^2 which is significantly higher than the Measured and Detailed prifles varying from 13-36W/m^2. The Detailed consumption has several peaks which does not comply with the Measured profile. This will be discussed in section 4.2.1

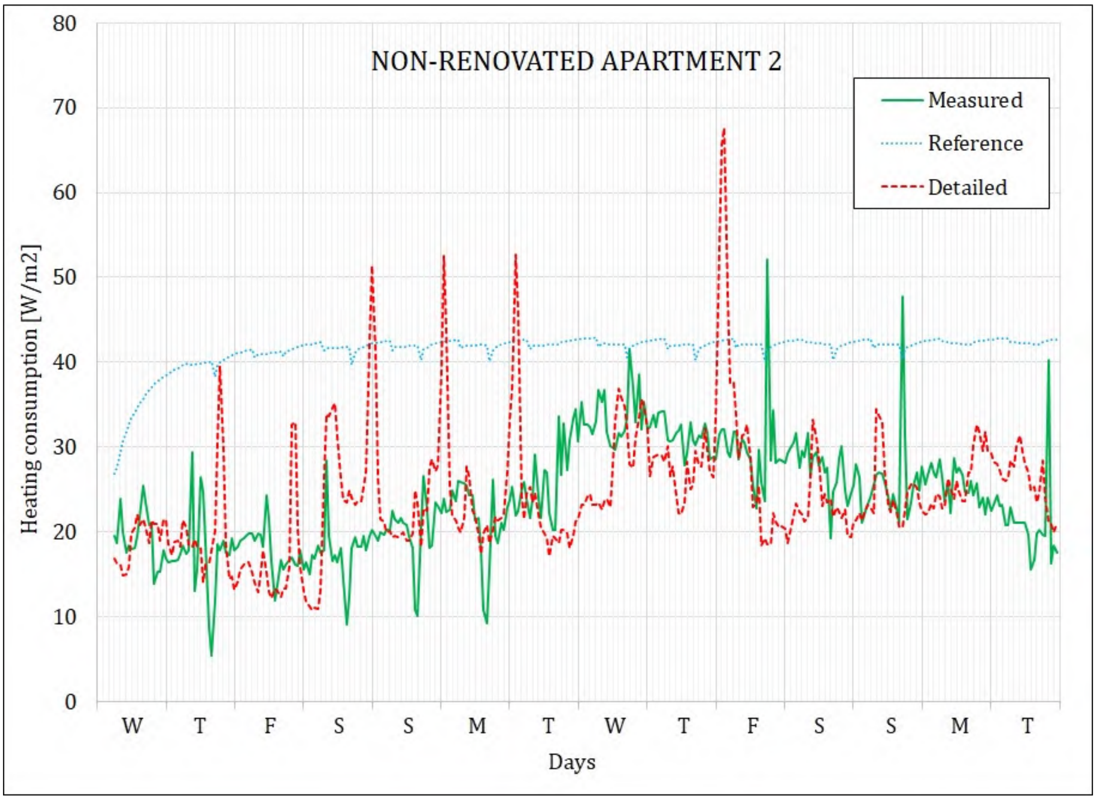
To evaluate the effect of the renovation hence the added insulation layers amongst other, the variance of the Measured heating consumption is calculated, and the results are shown in Table 4.2. From the non-renovated to renovated there is shown an decrease in the variance, which indicates that the improvement of the heat transfer and storage due to the lower heat transfer coefficient is behaving as required.

Table 4.2: Variance of measured heating consumption

	Variance
Renovated 1	12.06
Renovated 2	17.91
Non-renovated 1	27.32
Non-renovated 2	41.46



(a) Non-renovated apartment 1

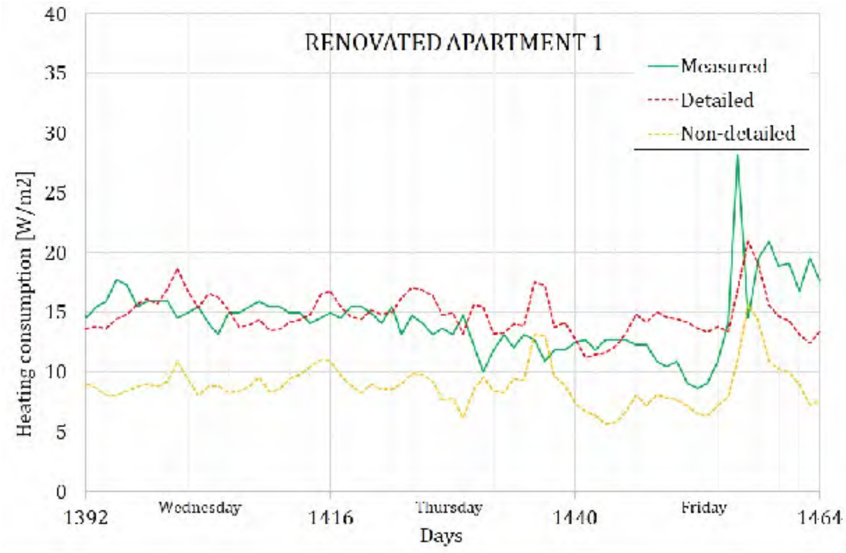


(b) Non-renovated apartment 2

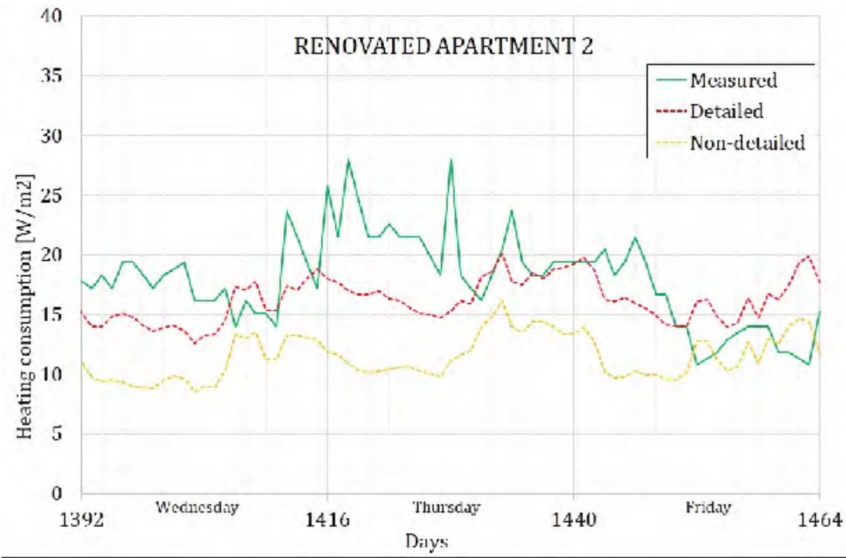
Figure 4.2: Comparison of heating consumption for non-renovated apartments

In order to evaluate the influence of the applied scheduled lighting and re-evaluation of electrical devices, the Non-detailed and Detailed model cases for the renovated apartments are compared. Figure 4.3a shows the Measured, Detailed and Non-detailed profiles of heating consumption for

Renovated Apartment 1 for three days of the simulated 14 days. The implementing of scheduled light and extra electrical devices increase the consumption with around $5W/m^2$ which equals around 50% of the Non-detailed consumption, resulting in a higher agreement to the Measured profile. The Non-detailed had more lighting but one less device, and this combination had reduced the need for heating as a significant part of this was covered by the thermal heat gain from the lighting.
For the Renovated Apartment 2, Figure 4.3b illustrates that implementing of scheduled light and the extra electrical device increases the heating consumption by a little less than $5W/m^2$ as well. The overall increase is not as much as for the Renovated Apartment 1, though it is very close.



(a) Graph comparing influence of schedule for Renovated Apartment 1



(b) Graph comparing influence of schedule for Renovated Apartment 2

Figure 4.3: Comparison of Non-detailed and Detailed profiles for Renovated Apartment 1 and 2

4.2 Performance gap influential

Several reasons exist which influence the increase of the gap between the actual and predicted energy performance. However, in this study only two reasons were analysed: the occupant behaviour and construction defaults.

4.2.1 Occupant behaviour

The Non-renovated Apartment 2 had peaks in the Scheduled heating consumption which was not in agreement with the Measured heating consumption, indicating a heat gain from other than the heating system. Comparing the Scheduled heating consumption with the temperature of the Livingroom reveals that there in fact is a temperature increase.

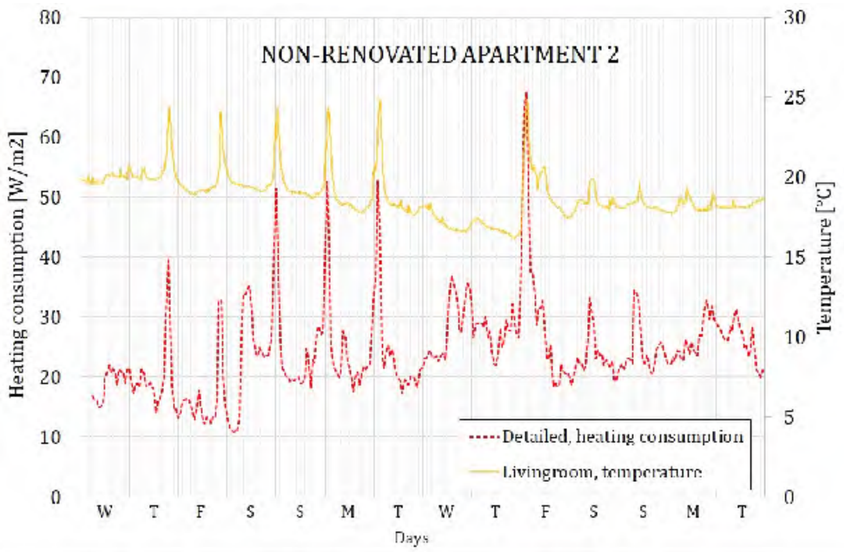


Figure 4.4: Graph of temperature and heating consumption for Non-renovated Apartment 2

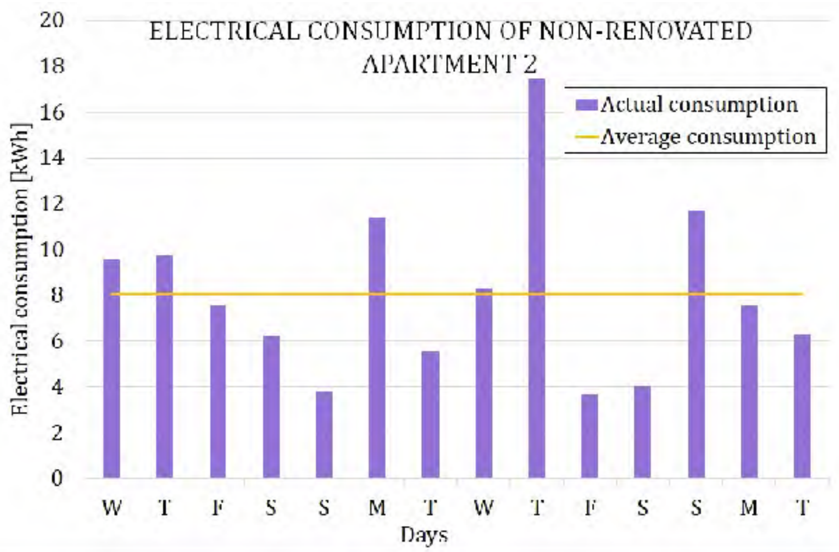
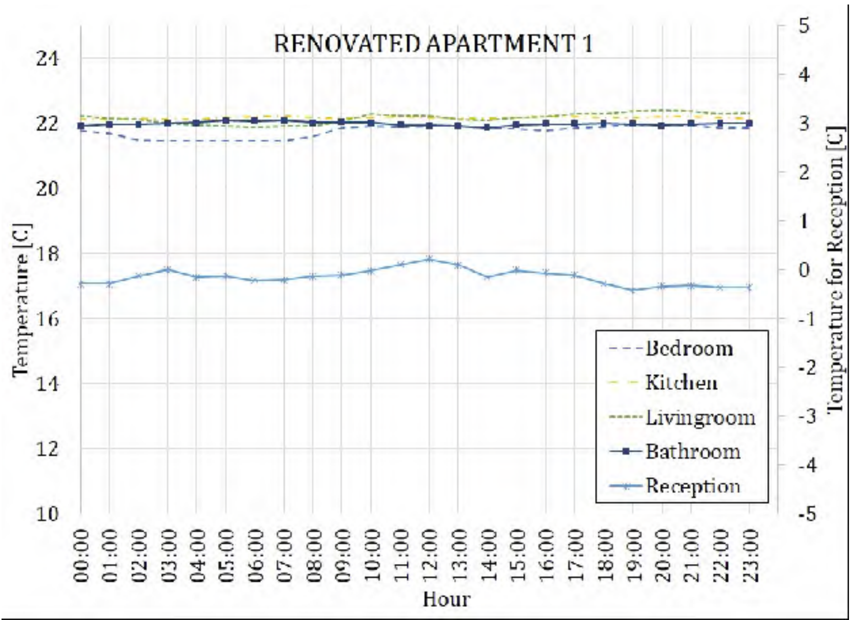


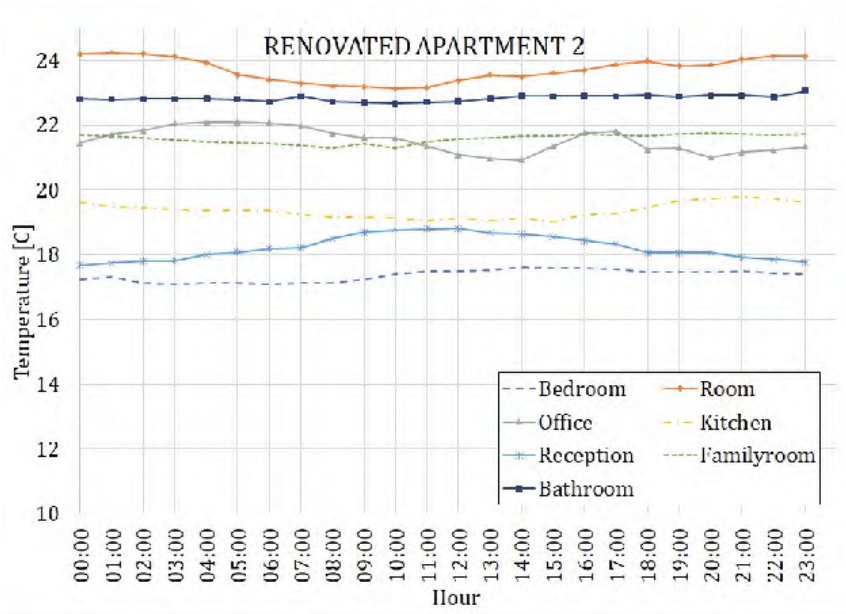
Figure 4.5: Graph of electrical consumption for Non-renovated Apartment 2

The electrical consumption as seen in Figure 4.5 does not ultimately indicate an increased temperature from thermal radiation of electrical appliances apart from the second Thursday. This day the electrical consumption is double as much as the average used for the simulations. The other peaks in the Scheduled heating consumption might then be from an increase of occupants, and knowing that the occupants often have guests amplifies this assumption.

An Average Day of temperatures have been compiled for each room on each apartment. Based on all the measured temperatures of the simulated two weeks an average was compiled for each hour of the day. The results are seen as graphs in Figure 4.6-4.7, which illustrates a significant difference in how the occupants prefers their indoor climate. The placement of the sensor of course has an influence, but this is equalised as described in section 3.2.2.



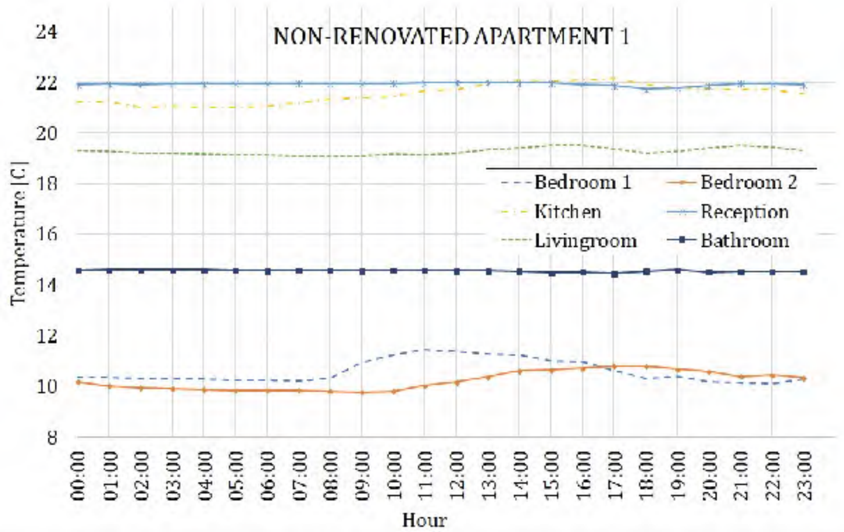
(a) Renovated Apartment 1



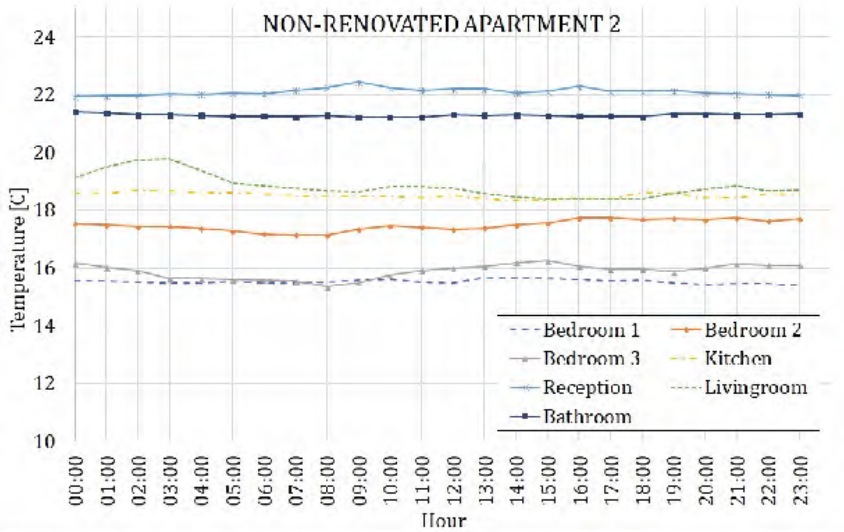
(b) Renovated Apartment 2

Figure 4.6: Average day of temperatures for renovated apartments

The Renovated Apartment 1, Figure 4.6a, has an almost constant temperature of 22°C in all rooms except the Entrance. The Entrance is extremely cold, constantly around 0°C, which was investigated as mentioned in section 3.3.1. The cause of this will be discussed in section 4.2.2. Figure 4.6b shows that the occupants of Renovated Apartment 2 prefers different bedrooms temperatures as Room is occupied by the tenants adult child. The child prefers a warm climate while the tenant prefers a cooler bedroom.



(a) Non-renovated Apartment 1



(b) Non-renovated Apartment 2

Figure 4.7: Average day of temperatures for non-renovated apartments

Generally Figure 4.6b, 4.7a and 4.7b show that they all prefer a cooler bedroom, though the bedrooms of Non-renovated Apartment 1 are unusually cold. Non-renovated Apartment 1 in Figure 4.7a is generally colder in almost every room: the Reception, Livingroom and Kitchen have temperatures between 19 to 22°C while the bathroom is held at 15°C and the two bedrooms are held around 11°C. This indicates that the occupant has turned off the heating completely in the three last mentioned rooms.

4.2.2 Construction default

As mentioned the Entrance of Renovated Apartment 1 is extremely cold, constantly around 0°C. The investigation of this as mentioned in section 3.3.1 found that the infiltration was extremely high. Figure 4.8 reveals that the joint between ceiling/deck and facade construction is poorly executed, resulting in a temperature down to 13°C. The Wireless Tag sensor was placed by the door where a strong draft from between the door and doorframe was noticed as mentioned in section 3.3.1. Figure 4.9 shows a compliance between the outdoor temperature and the measured indoor temperature of the Entrance, indicating that the leak at the door has a great influence of the temperature in the Entrance. These two issues present the large influence of the craftsmen constructing the buildings, mistakes in construction instructions/design as well as the used materials. If a construction has defaults the performance of the building after renovation as well as in new buildings will be highly affected. If the craftsmen miss something, the entrepreneur uses a different construction material than what was designed or if there is a mistake in the construction instructions/design, the building will perform differently and maybe not at all as intended.

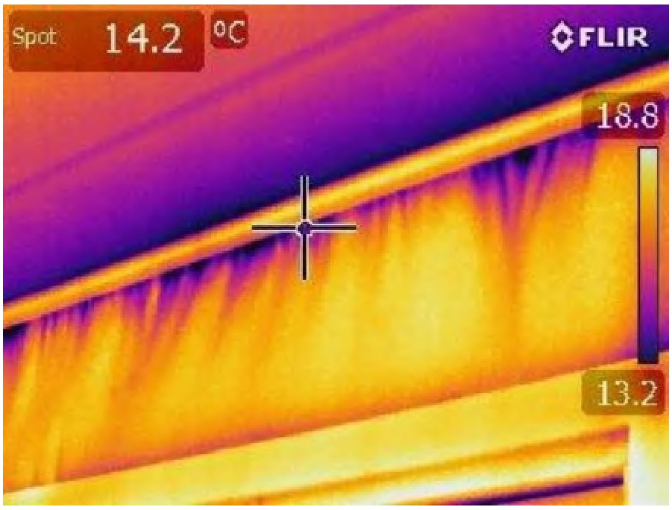


Figure 4.8: Thermographic photo of joint at facade/ceiling at Renovated Apartment 1 Entrance

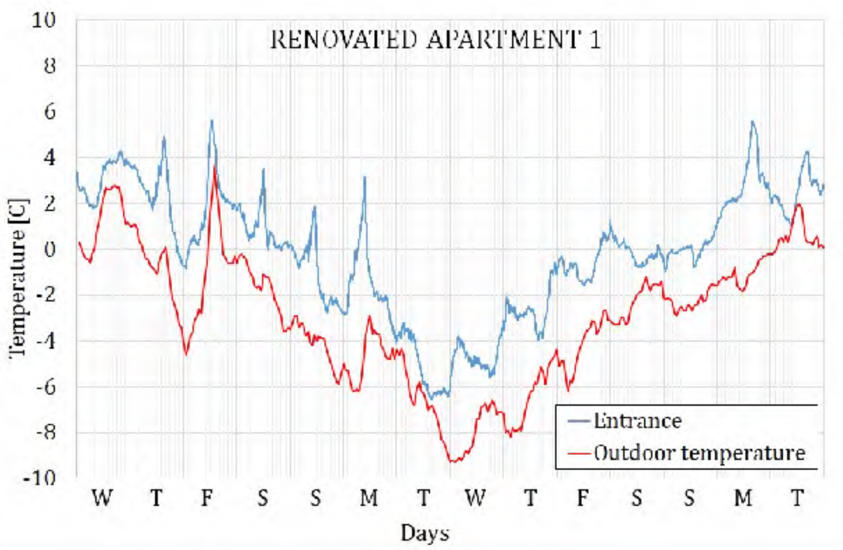


Figure 4.9: Graph comparing outdoor and Entrance temperature at Renovated Apartment 1

Chapter 5

Conclusion

In this study, dynamic simulation models were developed and validated by measurements with a basic objective of reducing the gap between predicted and actual energy.
Data analysis in the present study has consumed a lot of time in data cleaning and outlier detection process, especially for Wireless Tags sensors. On the other hand, the IC-meter was highly consistent in measurements.
The IC-meter is preferred when analysing data compared to Wireless Tag system due to the latter inconsistency in time steps and its battery life of about five months for high data resolution. On the other hand, the prices of the Wireless Tag system is cheaper than IC-meter and the system is easy to install.
Generally the wireless sensor technology, including both the IC-meter and Wireless Tag system, is considered a promising solution, as it is applicable even when the researcher/user is located far from the site of the measurements. The location of the site of this project was in Aalborg and all the collecting and analysis of the data was done in Lyngby, more than 200km distance in a straight line.
The occupant behaviour is of great influence for the heating consumption and the overall energy performance. Construction defaults are not expected and thus often not checked adequately prior to construction. This project illustrated that this too is of great influence of the overall energy performance.
It is finally concluded that pre-measurements over the period of two weeks to one month could be a good solution in comprehending the need for renovation, the state of the construction and to overall reduce the gap between expected and actual energy performance of a building.

Bibliography

[1] Dansk Byggeri. Dansk Byggeri: Renovering er nu det vigtigste marked, 2016.

[2] REBUS. REBUS website, 2015.

[3] Statens Byggeforskningsinstitut; Aalborg Universitet København. BE18 website.

[4] CAO Gadgets LLC. Wireless Sensor Tags website.

[5] greenTEG AG. gO Measurement-System, datablad. 2017.

[6] Nelson Fumo, Pedro Mago, and Rogelio Luck. Methodology to estimate building energy consumption using EnergyPlus Benchmark Models. *Energy and Buildings*, 42(12):2331–2337, 2010.

[7] Ivan Korolija, Yi Zhang, Ljiljana Marjanovic-Halburd, and Victor I. Hanby. Regression models for predicting UK office building energy consumption from heating and cooling demands. *Energy and Buildings*, 59:214–227, 2013.

[8] M. Kavgic, A. Mavrogianni, D. Mumovic, A. Summerfield, Z. Stevanovic, and M. Djurovic-Petrovic. A review of bottom-up building stock models for energy consumption in the residential sector. *Building and Environment*, 45(7):1683–1697, 2010.

[9] A. S. Ahmad, M. Y. Hassan, M. P. Abdullah, H. A. Rahman, F. Hussin, H. Abdullah, and R. Saidur. A review on applications of ANN and SVM for building electrical energy consumption forecasting. *Renewable and Sustainable Energy Reviews*, 33:102–109, 2014.

[10] Hai Xiang Zhao and Frédéric Magoulès. A review on the prediction of building energy consumption. *Renewable and Sustainable Energy Reviews*, 16(6):3586–3592, 2012.

[11] Pekka Tuominen, Riikka Holopainen, Lari Eskola, Juha Jokisalo, and Miimu Airaksinen. Calculation method and tool for assessing energy consumption in the building stock. *Building and Environment*, 75:153–160, 2014.

[12] L. La Fleur, B. Moshfegh, and P. Rohdin. Measured and predicted energy use and indoor climate before and after a major renovation of an apartment building in Sweden. *Energy and Buildings*, 2017.

[13] G. Salvalai. Implementation and validation of simplified heat pump model in IDA-ICE energy simulation environment. *Energy and Buildings*, 2012.

[14] A. Cacabelos, P. Eguía, L. Febrero, and E. Granada. Development of a new multi-stage building energy model calibration methodology and validation in a public library. *Energy and Buildings*, 2017.

[15] D. S. Stergaard and S. Svendsen. Case study of low-temperature heating in an existing single-family house - A test of methods for simulation of heating system temperatures. *Energy and Buildings*, 2016.

[16] C. H. Lozinsky and M. F. Touchie. Improving energy model calibration of multi-unit residential buildings through component air in fi ltration testing. *Building and Environment*, 2018.

[17] K. E. Thomsen, J. Rose, O. Morck, S. Ø. Jensen, and I. Østergaard. Energy consumption in an old residential building before and after deep energy renovation. *Energy Procedia*, 2015.

[18] K. E. Thomsen, J. Rose, O. Mørck, S. Ø. Jensen, I. Østergaard, H. N. Knudsen, and N. C. Bergsøe. Energy consumption and indoor climate in a residential building before and after comprehensive energy retrofitting. *Energy and Buildings*, 2016.

[19] M. Jradi, C. T. Veje, and B. N. Jørgensen. A dynamic energy performance-driven approach for assessment of buildings energy Renovation—Danish case studies. *Energy and Buildings*, 2017.

[20] M. Morelli, L. Rønby, S. E. Mikkelsen, M. G. Minzari, T. Kildemoes, and H. M. Tommerup. Energy retrofitting of a typical old Danish multi-family building to a "nearly-zero" energy building based on experiences from a test apartment. *Energy and Buildings*, 2012.

[21] E. Sirombo, M. Filippi, A. Catalano, and A. Sica. Building monitoring system in a large social housing intervention in Northern Italy. *Energy Procedia*, 2017.

[22] M. W. Ahmad, M. Mourshed, D. Mundow, M. Sisinni, and Y. Rezgui. Building energy metering and environmental monitoring - A state-of-the-art review and directions for future research. *Energy and Buildings*, 2016.

[23] S. Noye, R. North, and D. Fisk. A wireless sensor network prototype for post-occupancy troubleshooting of building systems. *Automation in Construction*, 2018.

[24] Tuan Anh Nguyen and Marco Aiello. Energy intelligent buildings based on user activity: A survey. *Energy and Buildings*, 56:244–257, 2013.

[25] Neil; Klingensmith, Dale; Willis, and Suman Banerjee. A Distributed Energy Monitoring and Analytics Platform and its Use Cases, In Proc. *ACM Workshop Embedded Systems For Energy-Efficient Buildings*, pages 1–8, 2013.

[26] Aftab; Khan, James; Nicholson, Sebastian; Mellor, Daniel; Jackson, Karim; Ladha, Cassim; Ladha, Jon; Hand, Joseph; Clarke, Patrick; Olivier, and Thomas Plötz. Occupancy Monitoring Using Environmental & Context Sensors and a Hierarchical Analysis Framework. *BuildSys@ SenSys*, pages 90–99, 2014.

[27] Cristiana Bolchini, Angela Geronazzo, and Elisa Quintarelli. Smart buildings: A monitoring and data analysis methodological framework. *Building and Environment*, 121:93–105, 2017.

[28] Ammar Ahmed, Nicholas E. Korres, Joern Ploennigs, Haithum Elhadi, and Karsten Menzel. Mining building performance data for energy-efficient operation. *Advanced Engineering Informatics*, 25(2):341–354, 2011.

[29] Natasha; Balac, Tamara; Sipes, Nicole; Wolter, Kenneth; Nunes, Bob; Sinkovits, and Homa Karimabadi. Large Scale Predictive Analytics for Real-time Energy Management, In proc. *IEEE Int. Conf. Big Data*, pages 657–664, 2013.

[30] ASHRAE. ASHRAE, Performance Measurement Protocols for Commercial Buildings. 2010.

[31] W. Meyer. Hvad er en Smart City?, 2017.

[32] IC-Meter. Official website, 2018.

[33] SenseAir Product Specification. SenseAir S8.

[34] Sensirion. SHT21 Datasheet. 2011.

[35] greenTEG AG. greenTEG website, 2018.

[36] Smappee. Smappee Website, 2018.

[37] Himmerland Boligforening. Private investorer går ind i Kildeparken i det østlige Aalborg, 2016.

[38] Ingeniørfirmaet Viggo Madsen A/S. Notat vedr. energitiltag i kildeparken - blokke, 2015.

[39] Department of Civil Engineering - Aalborg University and Davis. Online Weather Observations - Thomas Manns Vej 23.

[40] COWI. Tekniske test i Kildeparken, Aalborg. 2018.

[41] Ministry of Transport Building and Housing. Executive order on building regulations 2018 (BR18). 2018.

Appendix A

Structure of Un-renovated construction

Construction part	**Structure**	**U-value [W/m^{2}K]**
Deck to basement/terrain	Parquet Insulation (50mm) Concrete (100mm)	Not available
Deck to basement/terrain in bathrooms	Terrazzo Concrete (100mm)	Not available
Facade	Concrete (85mm) Insulation (50mm) Concrete (75mm)	1.30
Gable	Concrete (150mm) Insulation (50mm) Concrete (75mm)	1.30
Roof	Concrete (175mm) Insulation (200mm) Construction of trusses w. corrugated sheets	Not available
Windows	Plastic windows	2.60

Appendix B

Structure of Renovated construction

Construction part	**Structure**	**U-value [W/m^{2}K]**
Deck to basement/terrain	Parquet Insulation (50mm) Concrete (100mm)	0.46 (basement) 0.48 (terrain)
Deck to basement/terrain in bathrooms	Tiles Concrete w. floor heating Polystyrene (20mm) Concrete (100mm)	1.66 (basement) 0.5 (terrain)
Facade	Gypsum (26mm) Insulation between posts (95mm) Insulation between studs (265mm) Wind barrier (15mm) Cladding	0.12
Facade at balconies	Gypsum (26mm) Insulation between posts (45mm) Insulation between studs (195mm) Wind barrier (15mm) Cladding	0.18
Gable and corner at balconies	Original concrete (150/80mm) Original insulation (50mm) Original concrete (75mm) Insulation (40mm) Insulation between studs (195mm) Wind barrier, board (9mm) Cladding	0.20
Roof	Original concrete (175mm) Original insulation (200mm) Insulation (150m) Original construction of trusses w. corrugated sheets	0.13
Windows	Protec 3-layered wood/aluminum windows	0.70-1.00 Chosen average 0.85

Appendix C

Example of climate input file, 36 of 4033 data sets

Temp	RH	Solar	Hours
0.3	90	0	1224.00
0.3	90	0	1224.08
0.4	90	0	1224.17
0.4	90	0	1224.25
0.4	90	0	1224.33
0.4	90	0	1224.42
0.4	90	0	1224.50
0.4	90	0	1224.58
0.4	90	0	1224.67
0.4	90	0	1224.75
0.4	90	0	1224.83
0.3	90	0	1224.92
0.3	90	0	1225.00
0.3	90	0	1225.08
0.3	90	0	1225.17
0.3	90	0	1225.25
0.2	90	0	1225.33
0.2	90	0	1225.42
0.1	90	0	1225.50
0.1	90	0	1225.58
-0.1	90	0	1225.67
0	90	0	1225.75
0.1	90	0	1225.83
0.1	90	0	1225.92
0	90	0	1226.00
0	90	0	1226.08
0.1	90	0	1226.17
0.1	91	0	1226.25
0.2	91	0	1226.33
0.1	90	0	1226.42
0.1	90	0	1226.50
0	90	0	1226.58
0	91	0	1226.67
0	91	0	1226.75
-0.1	91	0	1226.83
-0.1	90	0	1226.92

Appendix D

Example of temperature input file, 33 of 4033 data sets

Bedroom 1	Bedroom 2	Bedroom 3	Kitchen	Reception	Livingroom	Bathroom
17.19	19.03	18.72	19.16	22.84	19.86	21.93
17.19	18.96	18.73	19.15	22.91	19.86	21.93
17.18	18.92	18.73	19.14	22.89	19.85	21.92
17.18	18.85	18.73	19.15	22.87	19.85	21.92
17.18	18.79	18.74	19.13	22.86	19.84	21.94
17.19	18.75	18.74	19.16	22.85	19.84	21.97
17.18	18.73	18.77	19.15	22.85	19.83	21.97
17.18	18.73	18.81	19.16	22.85	19.82	21.95
17.19	18.70	18.83	19.17	22.84	19.82	21.93
17.18	18.67	18.85	19.17	22.83	19.82	21.90
17.17	18.65	18.85	19.16	22.83	19.82	21.89
17.18	18.63	18.86	19.15	22.82	19.83	21.85
17.17	18.58	18.87	19.15	22.82	19.81	21.87
17.17	18.55	18.88	19.14	22.84	19.80	21.84
17.18	18.53	18.88	19.14	22.83	19.80	21.83
17.18	18.52	18.91	19.13	22.84	19.80	21.82
17.17	18.50	18.89	19.13	22.85	19.80	21.80
17.17	18.49	18.89	19.13	22.85	19.78	21.78
17.17	18.46	18.91	19.12	22.85	19.78	21.78
17.16	18.45	18.91	19.12	22.84	19.78	21.77
17.16	18.44	18.92	19.11	22.83	19.77	21.77
17.15	18.42	18.91	19.11	22.71	19.77	21.76
17.14	18.40	18.89	19.11	22.63	19.76	21.75
17.15	18.39	18.93	19.11	22.63	19.77	21.75
17.16	18.37	18.91	19.10	22.59	19.76	21.74
17.12	18.37	18.91	19.10	22.63	19.76	21.74
17.14	18.35	18.91	19.10	22.66	19.77	21.73
17.14	18.34	18.92	19.09	22.67	19.77	21.72
17.12	18.31	18.93	19.08	22.66	19.76	21.72
17.12	18.30	18.92	19.09	22.56	19.76	21.72
17.14	18.28	18.93	19.10	22.52	19.75	21.69
17.12	18.27	18.96	19.10	22.47	19.75	21.69
17.12	18.25	18.91	19.10	22.64	19.74	21.69

Appendix E

Electrical consumption from Smappee

	Renovated Apartment 1				Renovated Apartment 2			
	Always on	Cons.	Actual cons.	Actual cons.	Always on	Cons.	Actual cons.	Actual cons.
Date	kWh	kWh	kWh	kJ/hr	kWh	kWh	kWh	kJ/hr
21-feb	1.05	3.22	2.17	325.50	1.40	7.85	6.45	967.50
22-feb	0.92	5.87	4.95	742.05	1.39	6.02	4.63	694.50
23-feb	0.74	4.26	3.52	527.40	1.36	3.36	2.00	300.00
24-feb	0.75	3.71	2.96	444.45	1.34	2.98	1.64	246.00
25-feb	0.74	3.80	3.06	458.40	1.33	7.38	6.05	907.50
26-feb	0.74	6.74	6.00	899.40	1.22	6.59	5.37	805.50
27-feb	0.74	4.32	3.58	536.40	1.25	7.03	5.78	867.00
28-feb	0.76	5.49	4.73	709.50	1.37	5.40	4.03	604.50
01-mar	0.77	5.57	4.80	720.30	1.39	5.94	4.55	682.50
02-mar	0.77	4.71	3.94	591.30	1.42	6.69	5.27	790.50
03-mar	0.77	5.23	4.46	669.30	1.43	9.91	8.48	1272.00
04-mar	0.77	5.02	4.25	637.80	1.41	7.26	5.85	877.50
05-mar	0.77	5.40	4.63	694.80	1.39	7.34	5.95	892.50
06-mar	0.77	4.51	3.74	561.30	1.14	7.13	5.99	898.50
				608.42				**771.86**
	Un-renovated Apartment 1				**Un-renovated Apartment 2**			
	Always on	Cons.	Actual cons.	Actual cons.	Always on	Cons.	Actual cons.	Actual cons.
Date	kWh	kWh	kWh	kJ/hr	kWh	kWh	kWh	kJ/hr
21-feb	0.00	0.08	0.08	11.97	0.38	9.99	9.61	1441.50
22-feb	0.00	0.06	0.06	9.29	0.38	10.15	9.77	1464.90
23-feb	0.00	0.25	0.25	37.56	0.42	7.96	7.54	1130.40
24-feb	0.00	0.40	0.40	59.70	0.73	6.95	6.22	932.40
25-feb	0.12	0.36	0.24	53.78	1.14	4.96	3.82	573.00
26-feb	0.31	0.39	0.08	59.01	0.41	11.84	11.43	1714.35
27-feb	0.28	0.42	0.14	63.59	0.37	5.90	5.53	829.05
28-feb	0.24	0.64	0.40	95.61	0.36	8.68	8.32	1248.00
01-mar	0.27	0.47	0.20	71.07	0.38	17.86	17.48	2622.15
02-mar	0.29	0.47	0.18	71.04	0.39	4.08	3.69	553.50
03-mar	0.26	0.36	0.10	53.88	1.11	5.12	4.01	601.50
04-mar	0.26	0.38	0.12	57.60	1.39	13.12	11.73	1759.50
05-mar	0.24	0.42	0.18	63.39	0.65	8.21	7.56	1133.70
06-mar	0.24	0.44	0.20	66.56	0.35	6.64	6.29	943.80
				55.29				**1210.55**

Appendix F

Air Balance for ref-model

		Volume	Area	Infiltration	Airflow IN	Airflow OUT	Diff.	Model IN	Coupling			
		m3	m2	l/s/m2	l/s	l/s	l/s	h-1	kg/h			
Ren_1	Reception	10	4		0.5			0.1800	2.16	to livingroom		
	Kitchen	17.5	7		0.875			0.1800				
	Livingroom	65	26	0.125	3.25		8.125	0.1800	17.82	to bathroom		
	Bathroom	15	6		0.75	15		2.1300				
	Bedroom	30	12		1.5			0.1800	9.72	to bathroom		
Ren_2	Reception	15	6		0.75			0.1800				
	Room	25	10		1.25			0.1800				
	Familyroom	55	22		2.75			0.1800	11.88	to bathroom and kitchen		
	Kitchen	30	12		1.5			0.1800			Bathroom	3.494
	Bedroom	30	12	0.125	1.5		13.625	0.1800			Kitchen	8.386
	Bathroom	12.5	5		0.625	15		4.1040				
	Toilet	5	2		0.25	10		0.1800				
	Livingroom	35	14		1.75			0.1800				
	Office	20	8		1			0.1800				
Non-ren_1	Reception	46.75	18.7		2.3375			0.1800	10.098	to bathroom and kitchen		
	Office	23.25	9.3		1.1625			0.1800			Bathroom	3.867
	Bedroom	30.75	12.3		1.5375			0.1800			Kitchen	6.231
	Bathroom	13.5	5.4	0.125	0.675	15	14.713	4.1033				
	Toilet	5	2		0.25	10		0.1800				
	Livingroom	55.75	22.3		2.7875			0.1800				
	Kitchen	21.75	8.7		1.0875			0.1800				
	Storage-room	9	3.6		0.45			0.1800				
Non-ren_2	Reception	46.75	18.7		2.3375			0.1800	10.098	to bathroom and kitchen		
	Bedroom 2	23.25	9.3		1.1625			0.1800			Bathroom	3.867
	Bedroom 3	30.75	12.3		1.5375			0.1800			Kitchen	6.231
	Bathroom	13.5	5.4		0.675	15		3.8600				
	Toilet	5	2	0.125	0.25	10	13.800	0.1800				
	Livingroom	55.75	22.3		2.7875			0.1800				
	Kitchen	21.75	8.7		1.0875			0.1800				
	Storage-room	9	3.6		0.45			0.1800				
	Bedroom 1	18.25	7.3		0.9125			0.1800				

Appendix G

Air Balance for model

		Volume	Area	Infiltration	Airflow IN	Airflow OUT	Diff.	Model IN	Coupling			
		m3	m2	l/s/m2	l/s	l/s	l/s	h-1	kg/h			
Ren_1	Reception	10	4	0.71	2.84		-3.530	1.0224	12.269	to livingroom		
	Kitchen	17.5	7	0.19	1.33							
	Livingroom	65	26		4.94			0.3473	27.086	to bathroom		
	Bathroom	15	6		1.14	9						
	Bedroom	30	12		2.28			0.2128	14.774	to bathroom		
Ren_2	Reception	15	6	0.125	0.75		9.625	0.1800				
	Room	25	10		1.25			0.1800				
	Familyroom	55	22		2.75			0.1800	11.88	to bathroom and kitchen		
	Kitchen	30	12		1.5			0.1800			Bathroom	3.494
	Bedroom	30	12		1.5			0.1800			Kitchen	8.386
	Bathroom	12.5	5		0.625	13		2.9520				
	Toilet	5	2		0.25	8		0.1800				
	Livingroom	35	14		1.75			0.1800				
	Office	20	8		1			0.1800				
Non-ren_1	Reception	46.75	18.7	0.2	3.74		4.540	0.2880	16.1568	to bathroom and kitchen		
	Office	23.25	9.3		1.86			0.2880			Bathroom	6.188
	Bedroom	30.75	12.3		2.46			0.2880			Kitchen	9.969
	Bathroom	13.5	5.4		1.08	13		1.4987				
	Toilet	5	2		0.4	8		0.2880				
	Livingroom	55.75	22.3		4.46			0.2880				
	Kitchen	21.75	8.7		1.74			0.2880				
	Storage-room	9	3.6		0.72			0.2880				
Non-ren_2	Reception	46.75	18.7	0.2	3.74		-3.920	0.2880	16.1568	to bathroom and kitchen		
	Bedroom 2	23.25	9.3		1.86			0.2880			Bathroom	6.188
	Bedroom 3	30.75	12.3		2.46			0.2880			Kitchen	9.969
	Bathroom	13.5	5.4		1.08	9		0.2880				
	Toilet	5	2		0.4	5		0.2880				
	Livingroom	55.75	22.3		4.46			0.2880				
	Kitchen	21.75	8.7		1.74			0.2880				
	Storage-room	9	3.6		0.72			0.2880				
	Bedroom 1	18.25	7.3		1.46			0.2880				

Appendix H

Lighting schedules for Detailed model cases

		Occupants		Devices		Light		Appliances	
		Amount	Schedule	Amount	Schedule	Amount	Schedule (ON)	Amount	Schedule
Ren_1	Entrance								
	Kitchen					10W/m2	17-19	608.42	At all times
	Livingroom	1	At all times	140W	At all times	10W/m2	15-23		
	Bathroom								
	Bedroom	1	At all times						
Ren_2	Entrance					10W/m2	06-08		
	Room			140W	At all times	10W/m2	06-08		
	Familyroom	1	At all times			10W/m2	08-22		
	Kitchen					10W/m2	06-08 + 12-14 + 17-22	771.86	At all times
	Bedroom	1	At all times			10W/m2	06-08 + 21-23		
	Bathroom					10W/m2	06-08 + 21-23		
	Toilet								
	Livingroom			140W	At all times	10W/m2	17-23		
	Office								
Non-ren_1	Reception					10W/m2			
	Office					10W/m2			
	Bedroom	1	At all times			10W/m2			
	Bathroom								
	Toilet								
	Livingroom			140W	At all times	10W/m2			
	Kitchen					10W/m2		28.31	At all times
	Storage-room								
Non-ren_2	Reception	1	At all times	140W	At all times	10W/m2			
	Bedroom 2	1	At all times			10W/m2			
	Bedroom 3	1	At all times			10W/m2			
	Bathroom					10W/m2	07-09 + 22-23		
	Toilet								
	Livingroom	1	At all times	140W	At all times	10W/m2			
	Kitchen					10W/m2		1210.55	At all times
	Storage-room								
	Bedroom 1								