Bachelor Thesis

Future sustainable terraced houses in Cardiff

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Colophon

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Preface

With this report I present my research about the evaluation of methods to reduce energy use and maintain future comfort for existing houses in Cardiff. This research is done for my Bachelor Thesis. During this research I was staying in Cardiff, Wales, for three months where I got to know the British culture and different other cultures from all over the world.
This research focuses on the improvement of existing residential buildings in Cardiff by simulating the future energy use and comfort in terms of Joule and uncomfortable hours, respectively. I have been interested in this subject a long time and so I hope to get a first introduction about sustainability in the building sector.

Collecting data about the future climate and characteristics of buildings in Cardiff forms the base for the simulation of energy use and comfort. This is done by literature studies and house investigation. But the focus of this research is to analyse and evaluate different changes in building characteristics. During the research I learnd to simulate by EnergyPlus, an often used simulation program in the sustainability sector and write a report and paper by LaTex which is a program often used by researchers to document their results. For this I got a great support of my colleagues from the research office and I would like to thank them all for their help.

Especially I would like to thank my supervisors Mr. Entrop from University of Twente and Mr. Mourshed from Cardiff University for their critics and support they gave during the research. Firstly, I appreciate the support of Mr. Entrop during the planning and organisation of this research. Secondly, I am thankful for the help of Mr. Mourshed concerning simulations and accomplishment of this research.

Finally I would like to thank my parents because they always support me and made it possible to accomplish my Bachelor study in two different countries.

Karin Ernst
August 2014

Abstract

There are many studies done about energy usage and comfort in residential buildings and it is often concluded that the comfort will decrease due to the climate change. The climate change will lead to amongst others a global warming of the atmosphere, melting of ice caps and rising of sea level. In the UK the increase of temperature and precipitation are the greatest changes. For Cardiff a higher outside temperature and solar radiation are essential changes, because they might increase the interior temperature in buildings and therefore decrease the comfort. The effect of the climate change on the comfort and energy use of buildings will vary by region and by the type of houses. Heavyweighted houses are not strongly influenced, because they have a greater heat capacity. So the inside temperature does not vary as quick as the outside temperature and the changes of inside temperature over day and in the night will be less.

For the municipality in Cardiff it is interesting how the comfort and energy use in houses of Cardiff will change and what methods will help to reduce the energy use whilst maintaining today′s comfort. This aim leads to the following research question: *How should the design of houses in Cardiff be due to the changed climate in 2030, 2050 and 2080?* The found methods help to avoid the adaptation of ad-hoc mechanical installations which increase the emission of greenhouse gases and therefore this study is giving a first print of how the future climate will affect the comfort and energy use of commonly built houses in Cardiff and which sustainable methods are more efficient than others.

First of all, literature studies will give the description of future weather and help to create a building standard that represents the recently built terraced houses in Cardiff. The weather in Cardiff will change to a warmer outside temperature and a stronger solar radiation. Next to these two developments, the wind speed, precipitation and other natural factors are expected to change, but in this research the focus lies only on outside temperature and solar radiation. The temperature is increasing continuously from 16°C to 21°C in summer, but the solar radiation appears to increase inconsistently (from 1187 kJ/m^2 to 1274 kJ/m^2). It is expected that the higher temperature and solar radiation will heat up the building and therefore the comfort will decrease. But this effect on buildings in Cardiff will be discussed later by doing the simulation.

The building standard is a terraced house with two bedrooms, kitchen, living room, entrance hall, bathroom, toilet and an attic, where a working couple is living. So the couple is leaving in the morning at 7pm for work and they will return at 6pm. The evenings and at the weekends the couple will stay at home most of the time. A gas central heating is installed so that a defined inside temperature can be maintained. But the gas central heating does not only regulate the temperature to maintain comfort, natural ventilation should also help by cooling down the inside temperature.

After collecting all these data a model can be created. Using the simulation program EnergyPlus the comfort in terms of uncomfortable hours is examined as well as the energy use in terms of heating, cooling and total energy usage. Therefore the weather data in .epw format, created by the project PROMETHEUS, and a standard building model is uploaded. Based on the simulation of the standard building model it appears that the future energy use will be reduced in summer about 75% and in winter about 28%. This means that the total energy use will decrease from 68 793 MJ to 4374 MJ in summer season until the end of the century. This result is contrary compared to studies made earlier, but this difference can occur due to different methods used, locations, climate and models. Nevertheless, eight different changes in design and construction are examined: improvement of the insulation, change

of the wall window ratio (WWR) and adaptation of shading devices. The insulation is improved, by adding two insulation layers to the exterior wall so that a double cavity wall is created. Concerning the roof, the insulation layer is extended and the windows are changed from double glazed to triple glazed ones. The WWR is changed in two ways. Firstly, it is increased from 0.12 to 0.19 and secondly, it is reduced to 0.06. For the third solution overhangs are adapted above each window. In a last model a balcony on the first floor is installed additionally to the overhangs. From the analysis it appears that the lower WWR is the most efficient one compared to the others, because it reduces the energy use about five times more than the majority of solutions. This is why less solar radiation is entering the rooms. Windows are the exterior surfaces with the highest heat conductivity and if the window surface is decreased, the surface with a better insulation is increased. Therefore the building will loose less heat. The second most efficient solution is to increase the WWR. This is not as efficient as reducing it, because a greater WWR will let more solar radiation enter the building, but on the other hand it also leads to a greater ventilation. Redevelopping the whole external surface, so that it reaches the building regulation of 2013, is efficient, but not as much as changing the WWR. But retrofitting the entire exterior surface is the most efficient concerning redevelopping. This is logic, because in case wherein only the windows is retrofitted, the house would still loose heat by the wall and the roof. Thus it can be seen that the building regulations reduces energy usage and therefore it is good to update the regulation regularly. Adapting shading devices is not recommended solution because the comfort decreases slightly and the energy use is increasing. But these results and recommendation are especially for Cardiff and it would be different if the research is done for another city or another building type.

Contents

List of abbreviations

IPCC	International Panel of Climate Change
UKCP09	United Kingdom Climate Projection from 2009
TRY	Test Reference Year
DSY	Design Summer Year
WWR	Window Wall Ratio
ACH	Air Change per hour
SAP	"The Government's standard Assessment Procedure for Energy Rating of Dwelligns"
PPD	Predicted percent dissatisfied
ACM	Adaptive comfort model
AAS	ASHRAE standard 55
EAS	European Standard BS EN 12521:2007
IDF	Input Data File
HVAC	Heating, Ventilation and Air Conditioning

Chapter 1

Introduction

The climate change has become an important issue for civil engineers, politicians and other scientists in the last years. Climate change will affect the way of living, because the outside temperature and solar radiation is expected to increase in the next century and this can lead to the fact that buildings will heat up more [1]. Hence, the cooling energy is expected to increase by 122% and the heating energy can decrease by 40% [2], however there are some opinions that the reduction in heating energy and the increase of cooling energy will compensate each other [3]. But this is strongly dependent on the region [4–6]. Besides the regional varieties, the impact of climate change on energy use and comfort depends on the type of building [5]. For example larger buildings have a lower heat loss than smaller ones and modern buildings (post-1990) will heat up more than older buildings (pre-1990) because of the cavity wall construction of the older ones [7]. Hence, especially in new buildings the higher interior temperature is expected to decrease the comfort of living. This might become a crucial problem which can be solved by adapting mechanical ventilation but that will lead to a greater CO_2 emission. It appears that the emission will be doubled by 2030 [8] for the reason of mechanical systems. Therefore, other solutions than installing ad-hoc mechanical ventilation need to be found. Examples are the reduction of glazing area which will achieve a decrease of cooling energy of 31% or a reduction of the U-factor[1] which is expected to save 8% of the cooling load [10]. For this reason the effect of climate change on recently built houses in Cardiff needs to be investigated to find solutions to maintain today′s comfort, reduce the energy use and avoid a greater emission of greenhouse gasses like CO_2 in the future.

1.1 Framework

Before starting this research the scope needs to be defined. Studies about energy use and comfort are done for many different buildings, environments and climate, but this research is focused on typical residential buildings in Cardiff. So in the following different parameters are outlined to give the limits of the research.

Firstly the parameters concerning the climate change, which affect the energy use and comfort, are limited to the outside temperature and the solar radiation. This is due to the fact that the climate change is a very complex process and it is too difficult to take every parameter into the simulation. Furthermore, the future climate predictions will be limited to the next century because predictions about later in the future will be too uncertain. Due to the lifetime of buildings, which is fifty years, the houses will be modified by renovation at the end of the century or they will be demolished. To predict future climate, different scenarios will be predicted; a high, medium and low scenario. Only the medium scenario will be analysed due to the fact that it is rated as the most likey scenario. Next to this, the highest scenario is supposed to be too optimistic because of the fact that former high scenario predictions suggested a higher temperature for today than it really is [11].

Secondly there are five different characteristics influencing the energy use [12] which are the environ-

[1] The U-factor is the overall thermal transmittance coefficient [9]

mental characteristics, occupational characteristics, building characteristcs, system characteristics and appliances. All these five characteristics are needed to describe the building, but only building characteristics will be changed during the analysis of effective methods. Occupational characteristics are assumed to be a constant parameter so they are neglected. During the analysis and environmental characteristics will be neglected because they are too complex to model. Next to this, system characteristics and appliances are neglected due to the fact that the research is not about renewabel energy sources or the efficient usage of fossil fuels which are two aspects of "Trias Energetica" [13]. If these two aspects of sustainable energy use were focused on then the system characteristics and appliances should be analysed, but the focus lies on reducing energy use, which is the third aspect of "Trias Energetica", and therefore reducing the energy consumption. Furthermore systems and appliances have a general lifetime of about ten to fifteen years which means that every ten or fifteen years the appliance or system will be updated or replaced [14]. About ten years ago the lifetime was rated about five years longer than in these days [15] which shows clearly that the lifetime is continuously decreasing. So there is no point to analyse todays systems and how they will work in about hundred years, because during the next century it will be expected that the system will be updated and improved for several times. This is why this research is only focused on the building characteristics which concern the building fabric and its design.
As earlier explained especially recently built houses are expected to heat up, thus the research will be focused on houses built in the last ten years. Globally there are four types of residential dwellings: apartments, terraced houses, semi-detached houses and detached houses. The commonly building type will be investigated during the research.
Next to this the geographical framework is limited to the capital city of Wales, Cardiff. Thus the results of this research can only be transferred to other cases outside of Cardiff, which have similar circumstances.
The future is always unsure, so no one knows whether new materials will be developed or existing materials will not be available any more. Also the development of technologies and innovation are very quick. But these two uncertainties are not taken into account.
Finally the economic and politic changes are neglected. The politics and economy can have a great influence on innovation of the sustainability of buildings, by giving subsidies, changing the directive.

1.2 Problem statement and objective

The problem which is discussed in this research is only indirectly a problem of the municipality of Cardiff, because the community will be facing the problem of an increasing energy use and a deteriorating comfort and not the municipality itself. But the municipality represents the public, so their problem is that it is not known how building fabrics should be to maintain today′s comfort in the future without increasing energy use and CO_2 emission. Thus the objective is to evaluate the efficiency of methods of construction and building design to decrease the energy use of recently built houses and to maintain today′s comfort in Cardiff in the next century by using energy use simulation. This objective will lead to the following research question:
How should the design of houses in Cardiff be due to the changed climate in 2030, 2050 and 2080?
To answer this research question two steps need to be done. Firstly the degree of the impact on the houses in Cardiff needs to be investigated to develop solutions for Cardiff which work efficiently (second step) to reduce the energy use and maintain todays comfort, but which are not over-dimensioned. For the first part of research the future climate will be investigated by analysing the future weather files developed

in the project PROMETHEUS, a project started by the University of Exeter (UK). To understand the future climate the underlying method to create these future weather files will be examined by a literature study. So the first question to answer is *"How will the climate change in Wales?"* and the results of this literature study are presented in the second chapter (§2).
The second underlying question is *"What are the characteristics of the common type of houses in Cardiff built in the last ten years?"*. This question can be answered by literature studies and by an investigation of different recently built houses. For information of these houses the agency selling them will be contacted and a viewing is arranged. All information about the houses can be read in chapter three (§3).
The criteria of efficient methods are the future energy use and the comfort. Energy use is a quantitative criterion and can be easily compared to today′s energy use, but the comfort is a subjective criterion. Thus a definition of comfort needs to be clear. This definition will be based on the ASHRAE standard 55 because this standard is based on the adaptive comfort model which is often used for comfort definition of residential buildings. After all these literature studies, different simulations are done. These will give answer on the third question *"What is the energy use and comfort of typical houses in Cardiff today and in the future?"*. The answer of this question can be found in chapter four (§4).
Finally the changes in building fabric and design can be evaluated due to their efficiency to reduce energy use and maintain today′s comfort by simulating the house adapted with the new component or system in all four moments (§5). By answering the fourth question *"What is the effect of methods to maintain the future energy use and comfort?"* a ranking of efficient methods can be developed.

Chapter 2

Climate Change

To understand the impact of climate change on comfort and interior temperature better, the climate change is examined and the first question of research can be answered: "How will the climate change in Wales?" Climate change belongs to the environmental characteristics of a building which are surrounding buildings, surrounding vegetations, infrastructure, air temperature, gound temperature, solar irradiance, wind velocity, precipitation and humidity [12]. Air temperature and the solar radiation are influencing the interior temperature most and for this reason it is important to find out more about climate change, how it works and what the effects for Cardiff are. In the following chapter the literature study about climate change will be presented. Climate change is a very complex process between human activities and the nature. For this reason there are many different effects on different parameters of the nature like wind, temperature, sea level, sunshine and the atmosphere. This complex process can be simplified as seen in Figure 2.1.

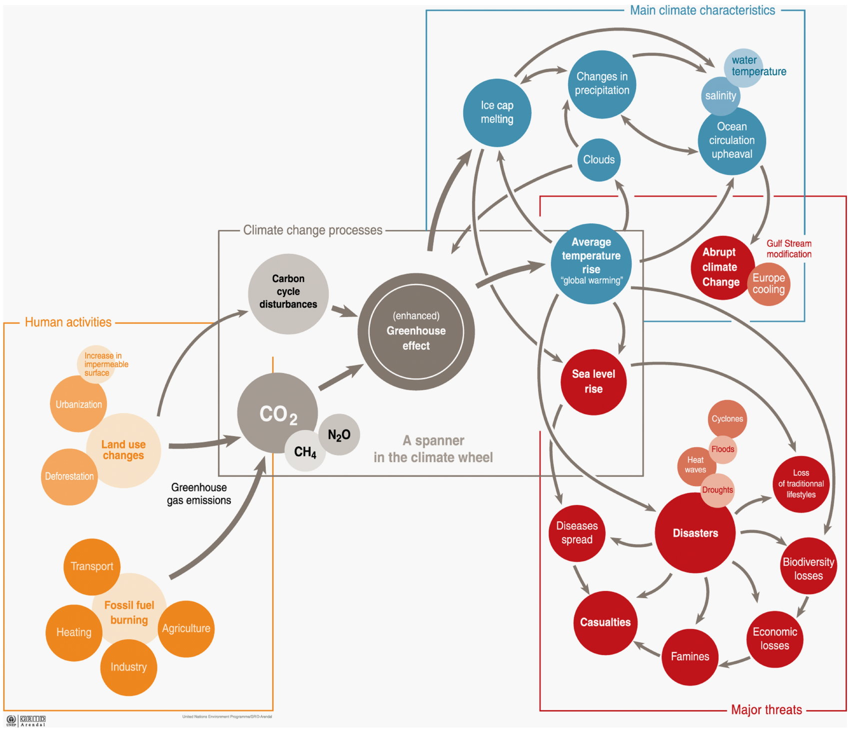


Figure 2.1: Simplified process of climate change

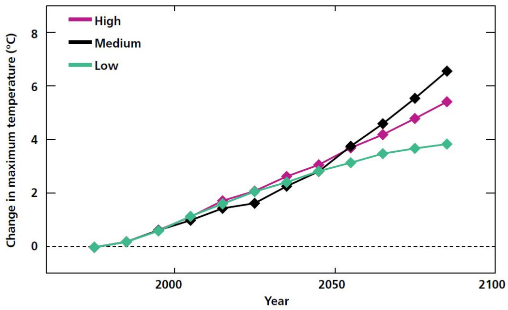
In the figure only human activities are shown as reasons for this process, but it is also caused by natural substances and processes [16], for example the greenhouse gases (CO_2, CH_4, N_2O and Halocarbons) which can be produced anthropogenicly due to the emission of fabrics or cars, or due to chemical reactions in the atmosphere. Nevertheless, the environment will change. Many circles can be seen in the figure whereof the most are vicious circles. For example the greenhouse effect, caused by greenhouse gases, lets the average temperature rise, which leads to more clouds and that in turn causes more emissions and greenhouse gases in the atmosphere. The complexity of this process can be seen for example in the relation between average temperature, ice melting and sealevel rising. Whereas the average temperature is influencing the sea level rise directly, it also melts the ice caps and therefore influences the rise of the sea level indirectly. As seen in the figure these changes have a significant effect on humans and the economy. Diseases, floods and economic losses are major threats. There are many other effects but in this research the focus lies on the effect on comfort and energy use in buildings. So it is important to find out how the climate will change in the world, the UK and especially in Cardiff.

2.1 Global climate change

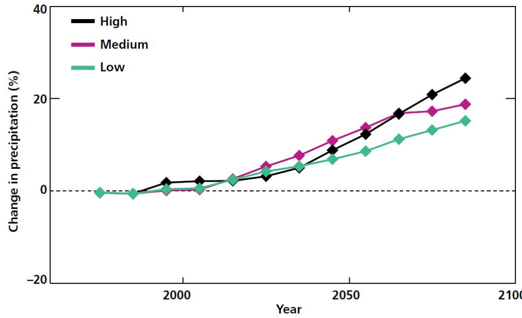
Global climate change concerns changes of climate and therefore of weather from all over the world. It has been found out that the atmosphere has been warming up since 1850 and it will continue. The warming of the atmosphere and the ocean leads to sea level rising of 0.19 m in the period from 1901-2010 [16]. The surface and ocean appears to heat up with a linear trend of 0.78°C which is the average of the period 1850-1900 and 2003-2012 [16]. An increasing temperature of the ocean and land surface can make a contribution to the heating of air temperature. In the last 25 years, this increase of air temperature was about 0.2°C per decade and the increase of temperature will continue in the next years with 2.8°C based on the A1B SRES emission scenario of IPCC [11]. But the warming of the ocean is not only affecting the air temperature, but also the ocean circulation. Due to the fact that the heat will not penetrate from the surface of the ocean into the deep, changes of global water cycles are expected to occur and they may not be uniform [16]. That means that the contrast between wet and dry seasons and regions will increase. It is expected that this process cant be stopped. Even if the emission of greenhouse gases will be stopped during the next century, it will take a long time until the climate will be stabilized.

2.2 Climate change in UK

Based on this global climate change different future scenarios for the UK are created by the United Kingdom Climate Impact Program (UKCIP). The last published projection is from 2009 (UKCP09) which projects future climate in the UK for all decades from today until the end of the century. These projections are based on three future scenarios: low, medium and high ones which all have the baseline of thirty years from 1961-1990, called the 1970s. The analysis of the baseline describes an increase of 1°C temperature in the thirty years and this is where the three different scenarios are relied on. For all these three scenarios it appears that in southern England the mean temperature will increase from 2.2°C to 6.8°C in 2080 [17]. This change of 4.2°C as well as all the other data is referring to the medium scenario. The mean daily temperature will increase in southern England more than in northern Britain: In the south it will increase from 2.2°C to 9.5°C in 2080 which is a change of 5.4°C. In northern Britain the change is only 2.8°C (from 1°C to 5°C) But not only the summer will be warmer, the temperature in winter will also increase: Depending on the location, the increase will be from 0.7°C to 2.7°C or from 1.3°C to 4.4°C. The change in mean daily maximum temperature is presented in Figure 2.2a wherein it is clearly seen that the temperature will increase more according to the highest scenario and less according to the lowest scenario.



(a) Change in maximum temperature



(b) Change in precipitation

Figure 2.2: Future scenarios of change in temperature

Like the temperature, the precipitation (in %) will also increase (Figure 2.2b). Depending on the location in the UK, there is no big change in the annual precipitation, but concerning the precipitation in winter, it will increase from +9% to +70% at the western side of the UK. In the Scottish highlands the precipitation will even increase from -11 to +7%. The precipitation in winter is expected to increase from -65 to -6% in southern England and in northern Scotland the change will be nearly zero.

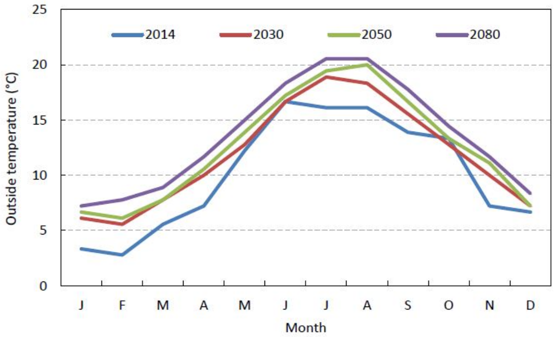
2.3 Climate change in Cardiff

UKCP09 provides not only data for the whole UK, but also more detailed data for different locations like Cardiff. It needs to be noticed that the data for all different climate scenarios and different locations are weather data. Weather is defined as a "momentary state of the atmosperic environment at a certain location" [18] and so the climate is "the integration time of weather conditions" [18]. This means that the climate changes over years. However the weather changes during the year.

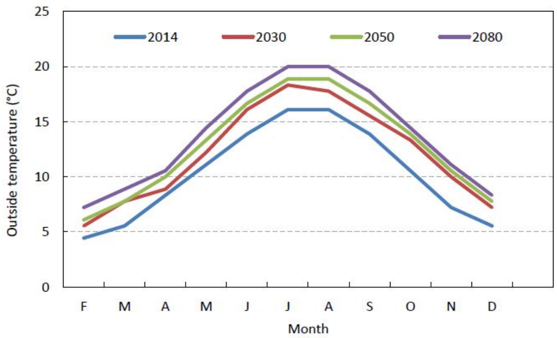
The climate scenarios and therefore the future weather data used in this research are the United Kingdom Climate Projection from 2009 (UKCP09) by the United Kingdom Climate Impact Program (UKCIP) which are converted into EnergyPlus compatible files by the Universtiy of Exeter, started the project PROMETHEUS to modify the future weather data from UKCP09. For this projection the next century is split into three periods: the 2030s, 2050s and 2080s. All of these periods last thirty years and that means that the 2030s stands for the years 2020-2049, the 2050s contains the period of 2040-2069 and 2080s stands for 2070-2099 [17]. So there are three scenarios and all of them are described with three periods. To create special weather data for Cardiff, the whole UK is split into 5 km grid boxes. This is done by a weather generator which interpolates locally measured weather data.

Additionally, different probabilities are added to each scenario because none of these scenarios have a relative probability neither can be assumend that they are even probable. This is done by adding five different percentiles like 10%, 33%, 50%, 66% and 90% whereof 10% can be defined as a projection which is very likely to be greater, 90% is very likely to be less and 50% is defined as the central estimate [17]. So there are three scenarios with each 5 different probabilities and therefore there are 15 different scenarios. For all of these 15 scenarios a 'Test Reference Year' (TRY) and a 'Design Summer Year' (DSY) is created to analyse future energy use and overheating risk of buildings, respectively. Thus 15 different scenarios with each two different defined years leads to 30 different sets of future weather data. All these weather data are converted into .epw files so that they are compatible with EnergyPlus and therefore suitable for this research. The last step in creating these weather data is the validation. The created weather data based on UKCP09 were compared to the weather data based on UKCP02, the projections made in 2002.

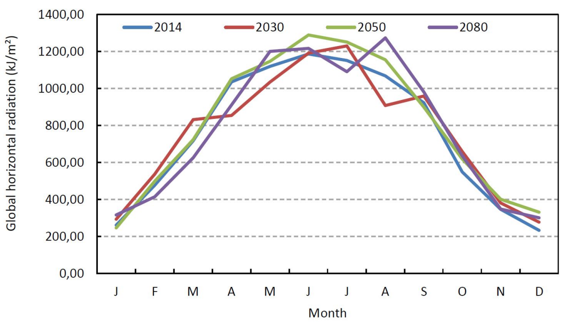
This is done by simulating a recently built house and using a thermal model. For more information about creating these scenarios are added in Appendix I.
To get an idea about what the climate will be, given different scenarios, percentiles and design years, three different comparisons are done for the future temperature and global horizontal radiation. Firstly, the two design years, TRY and DSY, are compared based on the data files of the medium scenario and its 50th percentile for every four moments in time (today, 2030, 2050 and 2080) [19], because this is the scenario used during the simulation. Secondly, to analyse the difference between the percentiles, only the 10th, 50th and 90th percentile of DSY of the medium scenario are compared for 2030, 2050 and 2080 [19]. This is why it appears that the DSY is always about 1°C higher than the TRY and the DSY will be enough to get an idea about the difference of the percentiles. At last the highest and medium scenario will be compared to each other to get an idea about how great the difference is. For this the DSY of the 10th, 50th and 90th percentile of the highest and medium scenario are compared [19]. In the following, the results of these comparisons and the effect on the temperature and solar radiation will be described.
Based on the examination of the weather files, it appears that the temperature increases over the years for each season continuously so that the average temperature of a month based on DSY in summer and winter will be expected to increase from 16°C and 3°C to 21°C and 7°C in 2080 [19]. But in case of TRY the summer and winter temperature will only increase to 20°C and 7°C, respectively [19]. Furthermore, it can be seen that the the DSY is generally 1°C higher than TRY, especially in the summer [19] and the difference between the 10th, 50th and 90th percentile can vary between 1°C to 3°C. It appears that the temperature of the 90th percentile is higher than the one of the 10th or 50th percentile [19] and this difference will even increase in the future which means that there is nearly no difference between the scenarios in 2030 but in 2080 the difference is expected to be 1°C [19].
Like the temperature, the solar radiation will increase but not as continuously as the increase of temperature. Comparing the radiation of TRY and DSY it seems that for both design years it will hardly change in the future winter but in the summer season the radiation will continuously increase except of June 2030 for the TRY [19]. However, the increase for TRY is continuous in the future, for DSY the future radiation will be higher or lower than today′s variation without any pattern; radiation in 2030 will be lower, in 2050 higher and in 2080 lower than in 2050, but still higher than today [19]. The same inconsistent development can be seen in the comparison of the radiation of the highest and medium scenario. Even if the 90th percentile is generally higher than the 10th percentile [19] it can occur that the 10th percentile of the medium scenario has a higher radiation than the 50th percentile of the high scenario [19]. Again there is no pattern observable, but in all comparisons it appears that the difference in percentiles, scenarios or future moments is greater in the summer season than in the winter season. Nevertheless, the radiation for the DSY will increase to $1318\,\mathrm{kJ/m^2}$ or even $1386\,\mathrm{kJ/m^2}$ under the 10th or 90th percentile of the medium scenario, respectfully, compared to today′s radiation of $1187\,\mathrm{kJ/m^2}$.
All these differences can also be seen in the analysis of the most likely scenario which is the medium scenario with a propability of 50%. Due to the fact that the comfort and the energy use will be considered, both design years will be taken into account. So the DSY and TRY of the medium scenario with a probability of 50% are regarded. Because of the focus on temperature and solar radiation, Figure 2.3 shows only the development of these two environmental characteristics. But in the weather data file all other characteristics of weather like the wind speed, wind direction, humidity, etc. are integrated, too.



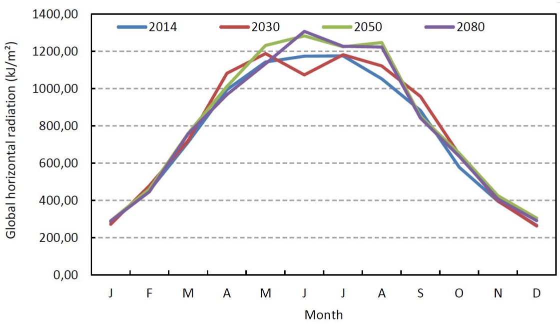
(a) Change of temperature based on DSY



(b) Change of temperature based on TRY



(c) Change of solar radiation based on DSY



(d) Change of solar radiation based on TRY

Figure 2.3: Change in temperature and global horizontal radiation in the next century

From the monthly fluctuation presented in Figure 2.3a and 2.3b it can be deduced that the temperature in summer is about five times as high as in summer. That means that the temperature in winter will be about 3-4°C and in summer it is about 20-21°C. Concerning the future development the temperature is increasing continuously. Based on DSY the temperature is expected to increase from 16°C to 21°C in the summer season of 2080 and in winter from 3°C to 7°C till the end of the century. So the change in summer (5°C) will be slightly greater than in winter (4°C). According to the TRY there is a similar development but it is continuously about 1°C lower than the DSY. The solar radiation changes between summer and winter from a maximum in the summer of 1273 kJ/m^2 to a minimum in the winter of 233 kJ/m^2. This difference of approximately 1000 kJ/m^2 was expected. Concerning the solar radiation, the development is not as continuous as expected. In Figure 2.3c it can be seen that the maximum summer radiation increases from 1187 kJ/m^2 to 1274 kJ/m^2 in 2080. This is an increase of 86 kJ/m^2 based on DSY and it is lower than the increase of 131 kJ/m^2 based on TRY. So there is a significant difference between DSY and TRY in summer season, but the development of solar radiation in winter throughout the next century is very small. Concerning DSY the radiation increases from 233 kJ/m^2 to 300 kJ/m^2 and based on TRY it increases from 266 kJ/m^2 to 289 kJ/m^2. These differences are unsignificantly small compared to the changes in summer.

2.4 Conclusion: Future climate in Cardiff

The future climate scenarios are created by UKCIP and called UKCP09 because they were predicted in 2009. These predictions are split in three scenarios whereof only the medium scenario will be used for the simulation due to reasons explained in the framework (§1.1). The projections of UKCP09 are converted by the project PROMETHEUS into .epw files which are compatible with EnergyPlus, the simulation

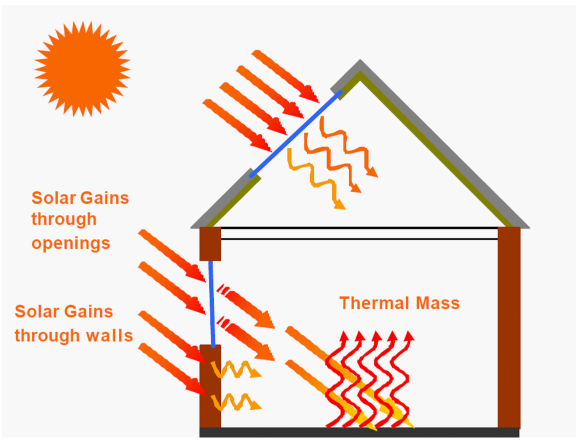
program used in this research. Therefore four steps are necessary. Firstly, interpolating weather data to create a 5 km grid network to predict future weather more locally. Then, two design years are added which enables EnergyPlus to simulate energy use and comfort. Additionally, five different percentiles are implemented to add a propability to each scenario. So there are three scenarios with each five percentiles and again each two design years. These thirty different future scenarios are converted into .epw files which are tested. Using a simulation of a recently built house and the converted weather data from UKCO09 and UKCP02 the created model is validated.
The thirty different future scenarios will give different results and future developments of temperature and radiation. This can be seen by comparing different scenarios: The highest scenario will lead to higher temperature just like the 90th percentile increases more than the 10th percentile. Between the DSY and TRY there is a continuous difference of 1°C over the whole year and the DSY will always lead to a higher temperature than the TRY which seems logic, because the DSY is modelled to simulate the overheating risk of buildings. In contrast to the temperature the radiation does not have a clear development. For some months in the year the increase of global radiation can be higher in the medium scenario (10th percentile) than in the highest scenario (50th percentile) and also the comparison of the different percentiles does not follow a pattern. But for all comparisons it seems that the solar radiation will change more in the summer than in the winter. This is because the solar radiation in the summer is higher than in the winter and so the difference will be higher in the summer.
Based on this scenario the mean daily temperature in the UK will increase about 4.2°C and the mean daily maximum summer temperature will increase about 5.4°C until the end of the next century. Not only the temperature will increase, but also the solar radiation will increase from 1187 kJ/m^2 to 1273 kJ/m^2 given the DSY of the medium scenario with the 50th percentile. These values can vary depending on the location, like the values of radiation. For this reason the mean temperature in Cardiff is expected to increase from 16°C to 21°C in summer and from 3°C to 7°C in the winter. The solar radiation will increase slightly, but the increase is so small that the solar radiation can be regarded as unchanged. Contrarily, it will increase in summer about 131 kJ/m^2 which is a significant increase that might effect the interior temperature.
Thus, the question "How will the climate change in the next century?" can be answered clearly. The mean temperature increases about 5°C all over the year, but the radiation will be unchanged in winter, and in summer it will increase about 100 kJ/m^2.

Chapter 3

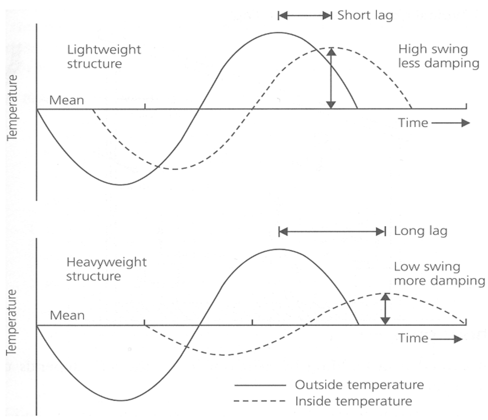
Commonly built houses in Cardiff

After the analysis of future weather scenarios the second question can be examined. The second question *"What are the characteristics of the common type of houses in Cardiff built in the last ten years?"* deals with the characteristics of the commonly built house of the last ten years and it will be answered in this chapter.

The climate is not the only variable that influences energy use and comfort. Heating of rooms happens due to the heat transfer from outside to inside or the other way around. Heat transfer can occur due to three processes: conduction, convection and radiation [20]. Solar radiation can enter the building directly through windows as it is seen in Figure 3.1a and therefore heat up the interior space. But the solar radiation can also heat up the exterior surfaces and subsequently the heat will be transferred to the inside by conduction. Due to the outside temperature the exterior surfaces can heat up or cool down and again by conduction the inside temperature will be influenced.



(a) Heat transfer due to radiation



(b) Lightweight and heavyweight building structure

Figure 3.1: Principles of heat transfer

But the heat transfer through conduction is not only depended on the environmental characteristics, but also on heat capacity of the materials the exterior wall is made of. A lightweight building structure has mostly a low heat capacity and therefore the inside temperature can change quickly depending on the outside temperature (see Figure 3.1b). In contrast, a heavyweight building structure will not change the inside temperature so quickly and it will swing less. So the layout, the construction and other building characteristics are very important to collect.

3.1 Building characteristics

Based on surveys, articles and a visual inspection, information about different building characteristics is collected. It is already defined that the buildings should not be older than ten years. Based on this criterion more information are investigated. The investigation starts with the type of house, the interior layout and the construction. In the following chapters system characteristics and occupational characteristics are defined.

Type of building

To collect the data about the type of commonly built houses in Cardiff, the national survey '2011 Census' from Cardiff gives global information about housing, households and the population. '2011 Census' is the recently done survey in the United Kingdom which was carried out on 27th March of 2011 in Welsh, England, Scotland and Northern Ireland by the Office for National Statistics (ONS) and was published on 23 November of 2012. The "Key & Quick Statistics Profile Cardiffs & Wales" contains information about 'Who we are', 'How we live' and 'What we do'. The total amount of dwellings in Cardiff is 148,093 dwellings [21] and the majority of dwellings are terraced houses: 45,020 dwellings (30.4%) of all houses are terraced houses (encluding end-terraced houses), 42,651 dwellings (28.8%) are semi-detached houses, 40429 dwellings (27.3%) are flats, maisonette or apartments, 19,993 dwellings (13.5%) are detached houses or bungalows and 148 dwellings (0.1%) are Caravans or other mobile or temporary structure [21]. Terraced houses are defined as identical houses which share two walls with the neighbour houses, they are also called row house or townhouse. Only the end house of the row has just one shared side wall and has often another layout compared with the mid-terraced houses [22]. Next to the type of the house, '2011 Census' gives information about the average number of rooms per household (5.4 rooms) and bedrooms (2.8 rooms) [21]. To sum up, the type of commonly built houses in Cardiff in the last ten years is a three bedroom terraced house with in total five rooms built.

Building design

Concerning the building design information about the interior layout is investigated as well as the window design. The interior layout is examined by developing a standard for recently built terraced houses. This standard is based on ten different houses which conform to the earlier described type. It appears that two out of ten recently built terraced houses have two floors, but eight terraced houses have three levels: On the ground floor there is the entrance hall, a WC, the kitchen and the living room. On the first floor there are two bedrooms and a bathroom and on the last floor there is the masterbedroom with an ensuite. Figure 3.2 shows the interior layout, the front- and back view and the dimensions (in m) of the rooms. The total floorarea, the room area and, in brackets, the volume of rooms is given in Table 3.1. The volume is calculated based on the hight of the storeys which is 2.20m. The dimensions of the front door, interior doors, windows, and the french door to the garden are shown in Tabel 3.2.

Figure 3.2: Technical drawings of commonly terraced house with dimensions in m

Table 3.1: Roomsizes and floorarea in m^2 and the volume of the rooms in brackets in m^3

Room	Size (m x m)	Area m^2	Volume m^3
Ground floor			
Kitchen	3.07 x 2.30	7.06	15.53
Livingroom	3.94 x 4.40	17.35	38.17
Entrance hall	1.10 x 3.07	3.38	7.44
Toilet	1.00 x 2.00	2.00	4.40
Staircase	1.00 x 2.15	2.15	5.61
Storage	0.85 x 0.85	0.72	1.59
First floor			
Bathroom	2.10 x 2.00	4.20	9.24
Bedroom 2	2.30 x 3.30	15.31	33.68
Bedroom 3	1.71 x 4.40	7.59	16.70
Landing & staircase	2.10 x 2.55	4.51	9.92
Storage	0.90 x 0.90	0.81	1.78
Second floor			
Ensuite	1.50 x 1.50	2.25	3.34
Bedroom 1	4.46 x 4.40	19.64	36.91
Staircase	1.00 x 3.85	3.85	4.62

Table 3.2: Size, surface and amount of installed elements like doors and windows

Element	width (m)	hight (m)	surface (m^2)]	amount of elements	totale surface (m^2)
exterior door	0.90	2.00	1.8	1	1.80
interior door	0.70	2.00	1.4	8	11.20
small window	0.80	1.00	0.80	5	4.80
big window	0.80	1.30	1.04	1	1.04
french door	0.70	2.00	1.40	2	2.80
window beside french door	0.30	1.50	0.45	2	0.90

The sum of total window surface (S_{win}) is $9.54\,m^2$ which leads to the assumption that the Window Wall Ratio (WWR) is equal to 0.12 due to the whole exterior surface (S_{wall}), exlusive the sidewalls, of $80.5\,m^2$ (see equation 3.1 to 3.3). Furthermore, it appears that the window surface in the north direction is $6.1\,\mathrm{m}^2$ and in the south direction it is $2.64\,\mathrm{m}^2$. So the surface in north direction is nearly twice as big as the one in south direction. The south direction is the front view of the building, because the front door is in direction of south-west (see Figure 3.3).

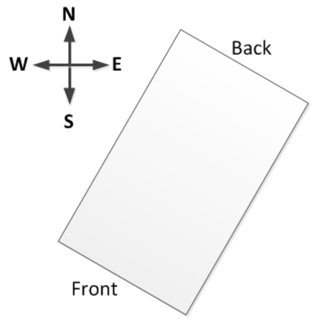


Figure 3.3: Orientation of building

$$
\begin{aligned}
S_{win} &= 2 * D_f + 2 * W_f + 5 * W_s + 1 * W_b \\
&= 2 * 0.7 * 2 + 2 * 0.3 * 1.5 + 5 * 0.8 * 1 + 1 * 0.8 * 1.3 \\
&= 9.54\,[\mathrm{m}^2]
\end{aligned}
\tag{3.1}
$$

$$
\begin{aligned}
S_{wall} &= 2 * S_{front} + 2 * S_{roof} \\
&= 2 * (4.4 * (2.2 + 2.2)) + 2 * (4.4 * 4.74) \\
&= 80.5\,[\mathrm{m}^2]
\end{aligned}
\tag{3.2}
$$

$$
\begin{aligned}
WWR &= \frac{S_{win}}{S_{wall}} \\
&= \frac{9.54}{80.5} \\
&= 0.12\,[-]
\end{aligned}
\tag{3.3}
$$

D_f = Frenchdoor
W_f = Window next frenchdoor
W_s = Small windows
W_b = Big windows
S_{front} = Exterior wall surface
S_{roof} = Exterior roof surface

The house shown in Figure 3.2 represents the commonly built terraced house in the last ten years and is located in the housing area Radyr, but not every house looks exactly like this. Due to the investigation it appears that only four out of ten houses have a seperate dining room, an integrated garage at the ground floor, but no seperate toilet. Three houses have a cloakroom and a utility room and it appears that in one of ten houses is a conservatory. Eight houses have an ensuite and one out of ten houses has two ensuites. But all the houses have commonly three bedrooms, a kitchen, a lounge and a bathroom. From the inventory of the layout it results that nine of ten houses have a pitched roof whereof six houses use the room under the roof as a loft and only three have bedrooms directly under the roof. At last it appears that none of the houses has adapted shading devices, neither dynamic nor static ones. A static device is for example a balcony and a dynamic one is for example a blinder. Concluding, the standard building model is mainly designed like the presented house, but the second floor is changed to an attic and the windows are changed to common garret windows so that it is representative for all recently built houses.

Construction

Concerning the construction of this house assumptions are made based on different architectural journals and the building regulation of 2010: The exterior walls are cavity walls whereof the cavity is filled with mineral wool for a better insulation [7, 23–25]. According to the building regulation from 2010 exterior walls should have a minimum resistivity of 0.3 W/m^{2}K [26]. The U-value is the overall thermal transmittance coefficient [9] and the lower the U-value, the better the thermal insulation. This value is calculated as seen in formula (3.4) [27]. For this the total resistivity is needed which is the sum of the resistivity of each layer (3.6), thus the ability of the material of that layer to resist a heat flow, needs to be calculated like in formula (3.6) which can be derived from the conductivity of the material, the property of the material to conduct heat given in different standards [27].

$$U = \frac{1}{R_{total}} \tag{3.4}$$

$$R_{total} = \sum R \tag{3.5}$$

$$R = \frac{d}{\lambda} \tag{3.6}$$

U = U-value
R_{total} = total wall resistivity
R = resistivity of layer
d = thickness of layer
λ = conductivity of layer

The most efficient design of external walls would be a double cavity wall construction [24], but due to the assumption that not all houses conform to the highest sustainable standard, the standard terraced house has a common cavity wall. Thus the exterior wall looks like presented in Figure 3.4 having a resistivity of 0.271 W/m^{2}K and its dimensions can be found in Table 3.3.

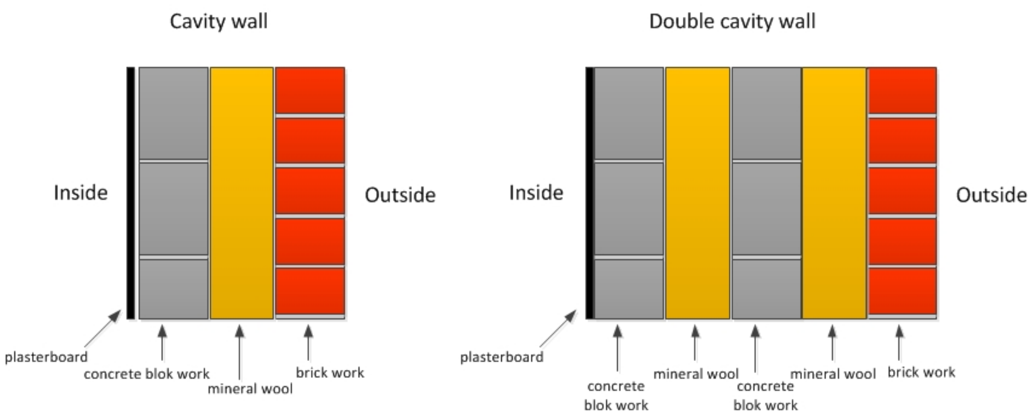


Figure 3.4: Exterior wall constructions

Table 3.3: Construction of singel cavity wall

Layer	Material	Thickness [m]	conductivity [W/mK]
external surface			
layer 1	brickwork	0.100	0.75
layer 2	mineral wool	0.150	0.042
layer 3	concrete blokwork	0.150	0.15
layer 4	plasterboard	0.013	0.5
internal surface			

Based on a visual inspection and discussion with an agent on May 9, 2014, the interior walls are simple plasterboard walls and the interior floors appear to be based on joints with a gypsum board as a ceiling, and a timberplank covered with a carpet as the floor of the next level. Due to the discussion with the agent the floor is a solid concrete floor with an insulation layer above because otherwise there will be an uneven heat flow pattern which means that the heat loss in the centre will be smaller than at the edges of the building [25]. The second floor is a loft where a bathroom and the masterroom are located, so the insulation seems to be in the roof and not on the ceiling of the first floor, otherwise the bedroom will not be insulated. The roof insulation consists of a 0.25 m thick insulation layer of mineral wool so that the actual resistivity of the roof is 0.192 W/m^{2}K. Based on the inventory about the standard house all the nine windows whereof one is a garret window (at the landing of the second floor) and the french door leading into the garden are double glazed so that they have a resistivity of 1.957 W/m^{2}K to comply the building regulation.

3.2 System characteristics

Concerning the system characteristics, the ventilation and the heating system should be discussed. The ventilation system has a great influence on the comfort and the heating system influences the energy use.

Ventilation system

About the systems of the house, there is no mechanical ventilation adapted so the ventilation occurs only due to natural ventilation. This can happen due to opening of windows or small outlets in bathroom and toilet. ASHRAE standard 55 defines the minimum needed AirChange Rate per hour (ACH) for different rooms like 0.15 L/s per square meter floor or 3.5 L/s per person [28]. In case of the terraced house it is more suitable to calculate the ACH based on the definition per square meter floor. The minimal needed ACH per room of the terraced house are seen in Table 3.4.

Table 3.4: AirChange Rate per hour for rooms in the terraced house

Room	ACH
Kitchen	1.06
Toilet	0.30
Livingroom	2.64
Entrance hall	0.51
Bedroom 2	2.22
Bedroom 3	1.14
Bathroom	0.63
Landing & Stairs	0.68
Bedroom 1	2.95
Ensuite	0.34

Next to the required ventilation there will always be an unwanted air infiltration. No building can be build air-tight so that there are no gaps where air can come through, but it seems that the air-tightness of UK dwellings generally increases between pre-1994 to post-2006 [29]. However, it is proven that the average air-tightness of post-2006 new build UK dwellings is $5.97 m^3/(hm^2)$ at 50Pa [29]. For this study the infiltration will be calculated by the program, because it will be influenced by the location, climate conditions and construction method of the building [29].

Heating system

The heating system has two main functions which are the heating of rooms and the supply for tapwater. For this reason a gas central heating is installed with a boiler in the kitchen. The boiler regulates the heating system and the use of hot tap water. The hot water tank will be installed in one of the upper storeys so that the delivery of hot water from the tank to the bathroom or kitchen can occur due to gravity. But the hot water will not only be used as tap water, the radiatior will also need the hot water, too. Based on the total floor area the total hot water usage for tapwater is expected to be 7.11GJ/year [30]. The total energy use for heating rooms and tapwater will be analysed in the simulation. The gas central heating will be simulated by an "Ideal Load system" and therefore no more details are necessary, but this will be explained later in the chapter 'Simulation setup' (§4.2).

3.3 Occupational characteristics

The '2011 Census' contains not only information about the building type, but also about the household. Based on this survey it is known that the average household is 2.3 persons [21] which leads to the assumption that a couple is living in the terraced house or a little family with a child. From this point of view the occupancy patron can be defined as a working couple which leaves at 7am for work, comes back at 6pm in the evening and in the weekend they will mostly stay at home. One of the bedrooms will be an office room and the other room a spared bedroom [31]. Furthermore, it is known that in most of these terraced houses lives the owner (59.1%) himself [21] which makes the retrofitting more easy, because they do not need the accordance of their renter. Based on "The Government's standard Assessment Procedure for Energy Rating of Dwellligns" (SAP) and the total floor area the internal heat gain is 528W [30].

3.4 Conclusion: Standard residential dwelling for simulation model

Based on the investigation of ten new build houses in Cardiff the second question of research can be answered (*"What are the characteristics of the common type of houses in Cardiff built in the last ten years?"*). The following characteristics of a commonly built house in Cardiff are combined in a standard model which will be used as the standard of simulation analysis. The standard house is a three level terraced house with three bedrooms oriented with the front door in south-west. One house of the investigation fits the best to the standard investigated interior layout and with little changes it is representative for all recently built houses. On the ground level there is the living area containing an entrance hall, a kitchen, a toilet and a living room. The second floor is the private area with one bedroom, spare room and a bathroom and on the third floor, directly under the pitched roof, an attic is integrated.

Next to the layout the construction is examined which leads to the assumption that the standard exterior walls are brick cavity walls, composed of a brick layer, a cavity insultated with material wool, a concrete block layer and a gypsum plasterbord on the inside. The interior wall is uninsulated and contains two gypsum plasterboards with a wooden framework forming an air gap between the gypsum layers. The ground floor contains a solid concrete layer with an overlying mineral wool insulation framed with wooden joints whereof a wooden floor lies which is covert with a carpet layer. The ceiling is a light construction of a gypsum board under wooden joints which carry wood shingles and these shingles are covered with carpet. The insulation of the roof can be integrated in the roof itself or at the ceiling of the second floor. This decision depends on the use of the attic. For this case it is chosen to integrate the insulation in the roof, thus the construction of the roof contains a layer of slate, then a roof membrane to hold against the rain which covers the mineral wool. The insulation is overcast with a wooden layer and this is covered by a gypsum layer.

At last all glazing surfaces are double glazed and contain 0.1% of the whole exterior surface (WWR is equal to 0.1). More information about thickness, resistivity and conductivity can be found in §3.1. The occupancy is very important for the energy use of the building, but it will not be examined further. Thus the occupancy patron will be constant and describes a working couple which leaves the house in the morning at 7am an comes back at 6pm. At the weekend they are staying at home most of the time. Concerning the installed systems the standard house will be ventilated in a natural way by opening windows and doors and due to the infiltration. Furthermore, it will be heated by the gas central heating. This means the hot tapwater and the heat water for the refrigerator will be heated in the water tank upstairs by gas.

Chapter 4

Comfort and Energy use - today and in the future

After the detailed literature studies and investigation of the future climate and the house characteristics, the third question of the study which was about the future energy use and comfort in the standard terraced house of the last ten years can be answered: *"What is the energy use and comfort of typical houses in Cardiff today and in the future?"*. By simulating the common recently built house in Cardiff with different moments in the time components of building fabrics or systems can be evaluated. In the following chapter the criteria and the simulation setup are discussed and subsequently the results are presented concerning the energy use and comfort of the standard building model. Herefrom it can be concluded how serious the problem will be.

4.1 Definition of criteria

The criteria for evaluating different components of building fabrics or ventilation systems are the energy use and thermal comfort. In the following both criteria are explained.

Energy use

The energy use is a quantitative criterion with the unit Joule (J) and so the future energy use can be easily compared with today′s energy use. The aim of the research is to reduce the energy use, thus the limit will be today′s usage. This limit is not known yet, but after the first simulation of the standard building model, the limit will be defined.

Comfort

Thermal comfort is defined by "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation" and it depends on different parameters: the metabolic rate, clothing insulation, air temperature, radiant temperature, air speed and humidity [32]. It needs to be noticed that air temperature is not the same as radiant temperature. Air temperature is the average temperature of the air surrounding a person and the radiant temperature deals with the amount of thermal radiation between an occupant and a black uniform enclosure. It is a single value for the entire body [32].
A thermal comfort zone defines that condition of an acceptable thermal environment and is limited with an upper and lower benchmark temperature. The benchmark temperature can be defined in two ways which are both detected by the predicted percent dissatisfied (PPD): On the one hand, there is the adaptive comfort, which is related to the outdoor temperature and the change in activity and clothing level and thus it changes during the year. On the other hand, there is a deterministic temperature with a fixed activity and clothing level [33]. In the case of the terraced house, the adaptive comfort model (ACM) is more suitable, because in contrast to office buildings the occupants can adapt their environment by

opening windows or change the clothes [34].
The criteria concerning the ACM are defined in the ASHRAE standard 55 (AAS) and the European Standard BS EN 12521:2007 (EAS). These two standards are different regarding the definition of the thermal comfort zone which is caused by a different sample of groups or buildings and a different formulation used to create the standard [34]. Thus, the upper limit of the EAS is 0.8-1.0°C higher than the AAS which leads to a different result concerning the saved energy consumption [34], because a building compliant with EAS can save energy due to the fact that a higher comfort level is allowed and therefore less heating energy will be used. On the other hand, the same building compliant with AAS will not save energy [34]. Furthermore, the EAS can accomplish the cooling energy savings quicker than the AAS [34]. Both of the two methods of the ACM have advantages and disadvantages, thus non of the methods will be wrong or right. For this purpose the AAS is chosen because many researchers refer to it during their studies [35–38].
Based on AAS (2010) and the ASHREA Handbook - Fundamentals (2013) [28] the comfort temperature (t_{oc}) is dependent on the outside temperature (t_{out}) as it is defined in the model of Humphreys and Nicols (1998). Based on this model and today′s climate, today′s comfort can be determined by filling in the average outdoor temperature, given as the dry bulb temperature, in the equation (4.1). The result can be seen in Figure 4.1 and more detailed in Table 4.1 where the upper and lower thermal comfort level are introduced.

$$t_{oc} = 24.2 + 0.43(t_{out} - 22) * e^{(\frac{t_{out}-22}{24\sqrt{2}})^2} \tag{4.1}$$

$$t_{upper} = t_{out} + 2.5 \tag{4.2}$$

$$t_{low} = t_{out} - 2.2 \tag{4.3}$$

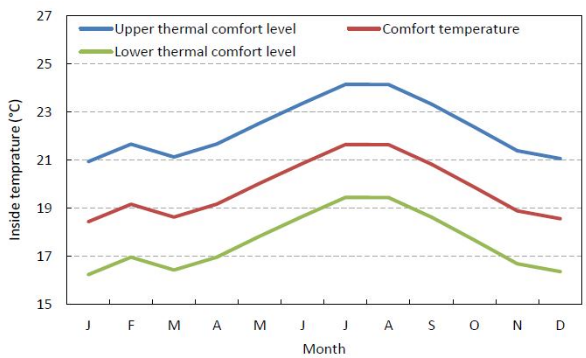


Figure 4.1: Comfort zone of residential buildings conform the adaptive comfort model

This thermal zone is defined based on 90% thermal acceptability, which means that 90% of the occupants are satisfied with their thermal environment and the upper and lower thermal comfort level can be calculated by equations (4.2) and (4.3), respectively.

Table 4.1: Thermal comfort zone defined by AAS and based on ACM

Thermal comfort zone			
Month	Comfort temperature (in °C)	Upper thermal comfort level (in °C)	Lower thermal comfort leven (in °C)
January	18	21	16
February	19	22	17
March	19	21	16
Mei	20	23	18
June	21	23	19
July	22	24	19
August	22	24	19
September	21	23	19
October	20	22	18
November	19	21	17
December	19	21	16

The output of the simulation will be the amount of uncomfortable hours and by an increase or decrease of this amount of hours the improvement or decrease of comfort can be measured. But it needs to be noticed that the amount of uncomfortable hours is a theoretical value and not necessarily the actual discomfort people feel, because the people will adapt to their environment and so it can happen that even if a temperature is slightly above the thermal comfort limit, it can still be comfortable.

4.2 Simulation Setup

For the simulation there are two important input data files required. Firstly, the future climate scenario is needed and because of the project PROMETHEUS, no future weather data files need to be created. So the required file can be loaded by EnergyPlus. For simulating the impact of climate change, the weather files of medium scenario (50th percentile) containing the TRY and DSY are chosen so that the impact can be investigated for the enegy use and the overheating risk.
Secondly, the information about the commonly built houses in the last ten years needs to be modified in an Input Data file (IDF). This is done by sketching the house in the plugin OpenStudioModel (OSM) of the program GoogleSketchUp 8 where all information about the layout is exported to an IDF. Information about materials, construction, occupancy and appliances is added later manually by writing a model code. In the following the details of the standard building model are discussed.

Building model

The IDF file contains all information about the general simulation and concerning the building like its construction, used materials and layout, schedules for occupancy, lighting, etc. and finally the heating system. The building′s location is conform to the latitude and longitude of Cardiff, namely 51 30’ 0”N / 3 12’ 0”W [39] and as earlier said its direction is south-west which means that the building′s north is turned 45 clockwise comparing to the true north. Due to the fact that the house is built in a housing area outside of Cardiff the terrain can be described as suburbs. This is all important information needed for the general environment and subsequently the simulation details are given. The simulation runs a whole year and the timesteps are defined to one hour. It is possible to simulate per ten minutes, thirty minutes or more hours but the interval should be chosen not too small, because the simulation will take unnecessarily long, but on the other hand, the interval should not be too big, otherwise the simulation will be too inaccurate. The following example shows how the data is introduced in the model.

```
Building,
Standard terraced house,           !- Name
45,                                !- North Axis deg
Suburbs,                           !- Terrain
0.003,                             !- Loads Convergence Tolerance Value
0.02,                              !- Temperature Convergence Tolerance
                                   Value deltaC
MinimalShadowing,                  !- Solar Distribution
30,                                !- Maximum Number of Warmup Days
6;                                 !- Minimum Number of Warmup Days
```

After the simulation characteristics the properties of used materials, like thickness, conductivity, roughness, etc. are introduced and the different layers of constructions are described. The example below shows the code which is needed to insert data about material and construction.

```
Material,
Solid concrete,                    !- Name
MediumRough,                       !- Roughness
1.500,                             !- Thickness m
0.960557739836122,                 !- Conductivity W/m-K
1361.56938678661,                  !- Density kg/m3
1073.79105882353,                  !- Specific Heat J/kg-K
0.9,                               !- Thermal Absorptance
0.7,                               !- Solar Absorptance
0.7;                               !- Visible Absorptance
```

```
Construction,
Exterior Wall,                           !- Name
Brick - Fired Clay - 4 in.  - 110        !- Outside Layer
lb/ft3,
Mineral Fiber Batt Insulation - 3 1/2    !- Layer 1
in.,
Concrete Block - 6 in.  - 85 lb/ft3 -    !- Layer 2
Solid Grouted,
G05 25mm wood,                           !- Layer 3
1/2IN Gypsum;                            !- Layer 4
```

The next step of modelling is creating zones and surfaces. One zone has special characteristics concerning the water and heating system, the ventilation or occupancy. Thus, all rooms are a different zone which leads to a total amount of ten zones (entrance hall, toilet, kitchen, living room, stairs, landing, bedroom, spare room, bathroom and attic). For every zone the surfaces are added by defining the coordinates of the edges as it is seen in the next example. This example describes the entrance hall as a zone and its exterior wall. Furthermore, every surface of a zone has an outside condition which needs to be chacarterised so that the program can simulate the heat flow. The shared walls (the east and west one) are modelled as a common exterior wall with the common outside condition except for the influence of sun and wind, but the north and south exterior walls are sun and wind exposed. Every internal surface of a zone, like interior walls and ceilings, have on their outside another zone, for example the west wall of the spare room borders the bathroom and the landing, so the part adjoining the bathroom has on its other side the zone "Bathroom" and the rest of the west wall has the zone "Landing" as outside object. Generally, there is a minimum of six surfaces belonging to a room; the floor, the ceiling or roof and a wall in direction of north, east, west and south.

```
Zone,
Entrance hall,                      !- Name
,                                   !- Direction of Relative North deg
2.65680034521833,                   !- X Origin m
4.36674402938247,                   !- Y Origin m
0,                                  !- Z Origin m
,                                   !- Type
,                                   !- Multiplier
,                                   !- Ceiling Height m
,                                   !- Volume m3
,                                   !- Floor Area m2
,                                   !- Zone Inside Convection Algorithm
;                                   !- Zone Outside Convection Algorithm
```

```
BuildingSurface:Detailed,
Entrance hall:South,                !- Name
Wall,                               !- Surface Type
Exterior Wall,                      !- Construction Name
Entrance hall,                      !- Zone Name
Outdoors,                           !- Outside Boundary Condition Object
SunExposed,                         !- Sun Exposure
WindExposed,                        !- Wind Exposure
,                                   !- View Factor to Ground
,                                   !- Number of Vertices
0, -3, 2.286,                       !- X,Y,Z Vertex 1 m
0, -3, 0,                           !- X,Y,Z Vertex 2 m
1, -3, 0,                           !- X,Y,Z Vertex 3 m
1, -3, 2.286;                       !- X,Y,Z Vertex 4 m
```

In addition to construction details the schedules are added to the IDF which describe the occupancy, lighting, heating, activity and clothing patron. The occupancy patron was explained earlier (see chapter 3.3) and the lighting and heating schedules are related to the occupancy one. The occupancy schedule is different for weekdays and weekends and for the kitchen, bedroom, bathroom, spare room and living room seperately and for the toilet, landing, stairs and entrance hall there is one uniform schedule, because these rooms are often shortly used. In case of the landing, stairs and entrance hall, these are used only to get to another room and the toilet is less used, because there is also a bathroom upstairs. But it needs to be noticed that only the kitchen, bathroom, bedroom living room and spare room are heated rooms since they are more often used. More details about the occupancy schedule for each room can be found in Appendix II. The house will not only be heated by outside temperature and solar radiation, but also due to internal gains like the heat of people, lighting and equipment. Based on SAP there is a general value of internal heat gain due to equipment and lighting over the whole year, so there are no detailed schedules necessary except for the one which schedules the heat gain of people. This is basically depending on the activity schedule. A last schedule is added about the ventilation. The schedule 'KITCHEN OCCUPANCY' is an example and all the other schedules are described like this one.

```
Schedule:Compact,
KITCHEN OCCUPANCY,                   !- Name
Fraction,                            !- Schedule Type Limits Name
Through:  12/31,                     !- Field 1
For:  WeekDays,                      !- Field 2
Until:  8:00, 0.00,                  !- Field 3
Until:  10:00, 1.00,                 !- Field 4
Until:  18:00, 0.0,                  !- Field 5
Until:  20:00, 1.0,                  !- Field 6
Until:  22:00, 0.5,                  !- Field 7
Until:  24:00, 0.00,                 !- Field 8
For:  AllOtherDays,                  !- Field 9
Until:  9:00, 0.00,                  !- Field 11
Until:  13:00, 0.5,                  !- Field 12
Until:  15:00, 0.0,                  !- Field 13
Until:  18:00, 0.5,                  !- Field 14
Until:  20:00, 1.0,                  !- Field 15
Until:  23:00, 0.50,                 !- Field 16
Until:  24:00, 0.00;                 !- Field 17
```

Due to the fact that only natural ventilation is used caused by opening the windows, the ventilation will work at weekdays in the morning and for the rest of the day it will be zero, because all people are gone and they would not leave the windows open, but at weekends the ventilation is accepted nearly over the whole day. In contrast to the ventilation the infiltration will appear continuously for the whole day, but it is only a small fraction of the ventilation. The amount of ventilation and infiltration will be calculated by the simulation program because the 'Airflow Network' is installed. 'Airflow Network' enables the simulation to calculate multizone airflows based on outside temperature, humidity and therefore the difference in air pressure. For this reason no further information about infiltration needs to be defined.

In total, the 'Airflow Network' consists of three different codes which are necessary for each zone. The following model code is an example for the 'Airflow Network' in the kitchen.

```
AirflowNetwork:SimulationControl,
House AirflowNetwork,               !- Name?
MultizoneWithoutDistribution,       !- AirflowNetwork Control
SurfaceAverageCalculation,          !- Wind Pressure Coefficient Type
,                                   !- AirflowNetwork Wind Pressure
                                    Coefficient Array Name
,                                   !- Height Selection for Local Wind
                                    Pressure Calculation
LOWRISE,                            !- Building Type
500,                                !- Maximum Number of Iterations
                                    dimensionless
ZeroNodePressures,                  !- Initialization Type
1.0E-04,                            !- Relative Airflow Convergence
                                    Tolerance dimensionless
1.0E-06,                            !- Absolute Airflow Convergence
                                    Tolerance kg/s
-0.5,                               !- Convergence Acceleration Limit
                                    dimensionless
45,                                 !- Azimuth Angle of Long Axis of
                                    Building deg
1.0;                                !- Ratio of Building Width Along
                                    Short Axis to Width Along Long Axis
```

```
AirflowNetwork:MultiZone:Zone,
Kitchen,                              !- Zone Name
ASHRAE55Adaptive,                     !- Ventilation Control Mode
,                                     !- Ventilation Control Zone
                                      Temperature Setpoint Schedule Name
0.0,                                  !- Minimum Venting Open Factor
                                      dimensionless
,                                     !- Indoor and Outdoor Temperature
                                      Difference Lower Limit For Maximum
                                      Venting Open Factor deltaC
,                                     !- Indoor and Outdoor Temperature
                                      Difference Upper Limit for Minimun
                                      Venting Open Factor deltaC
,                                     !- Indoor and Outdoor Enthalpy
                                      Difference Lower Limit For Maximum
                                      Venting Open Factor deltaJ/kg
,                                     !- Indoor and Outdoor Enthalpy
                                      Difference Upper Limit for Minimun
                                      Venting Open Factor deltaJ/kg
VEN-SCHED;                            !- Venting Availability Schedule Name
```

```
AirflowNetwork:MultiZone:Surface,
Kitchen:North,                        !- Surface Name
ZoneLeak,                             !- Leakage Component Name
,                                     !- External Node Name
0.5;                                  !- Window/Door Opening Factor, or
                                      Crack Factor dimensionless
```

Furthermore, the heating system will be defined by the 'Ideal Loads Air System' The aim of this research is not to find a more sustainable heating system and so the 'Ideal Loads Air System' of EnergyPlus is used which provides the house with the amount of heat that would be necessary to hold the inside temperature. Thus, the HVAC system does not need to be specified further [40]. Via zone controls, zone equipment configurations and the ideal loads system components the temperature in the kitchen, living room, bedroom, bathroom and spare room can be regulated. Actually, six different codes are necessary, but the one in the example below is the most important.

```
ZoneHVAC:IdealLoadsAirSystem,
Kitchen Ideal Loads,          !- Name
,                             !- Availability Schedule Name
Kitchen INLETS,               !- Zone Supply Air Node Name
,                             !- Zone Exhaust Air Node Name
50,                           !- Maximum Heating Supply Air Temperature
                              C
13,                           !- Minimum Cooling Supply Air Temperature
                              C
0.015,                        !- Maximum Heating Supply Air Humidity
                              Ratio kgWater/kgDryAir
0.009,                        !- Minimum Cooling Supply Air Humidity
                              Ratio kgWater/kgDryAir
NoLimit,                      !- Heating Limit
autosize,                     !- Maximum Heating Air Flow Rate m3/s
,                             !- Maximum Sensible Heating Capacity W
NoLimit,                      !- Cooling Limit
autosize,                     !- Maximum Cooling Air Flow Rate m3/s
,                             !- Maximum Total Cooling Capacity W
,                             !- Heating Availability Schedule Name
,                             !- Cooling Availability Schedule Name
ConstantSupplyHumidityRatio,  !- Dehumidification Control Type
,                             !- Cooling Sensible Heat Ratio
                              dimensionless
ConstantSupplyHumidityRatio,  !- Humidification Control Type
,                             !- Design Specification Outdoor Air Object
                              Name
,                             !- Outdoor Air Inlet Node Name
,                             !- Demand Controlled Ventilation Type
,                             !- Outdoor Air Economizer Type
,                             !- Heat Recovery Type
,                             !- Sensible Heat Recovery Effectiveness
                              dimensionless
;                             !- Latent Heat Recovery Effectiveness
                              dimensionless
```

Finally, the output needs to be defined. During the analysis the change in the energy use and comfort over the year will be examined and therefore monthly data is needed which are the monthly heating and cooling energy and the amount of dicomfortable hours based on ASHRAE standard 55.

```
Output:Variable,*,Zone Ideal Loads Zone Total     !- HVAC Sum [J]
Heating Energy,monthly;
Output:Variable,*,Zone Ideal Loads Zone Total     !- HVAC Sum [J]
Cooling Energy,monthly;
Output:Variable,*,Zone Air Temperature,monthly;   !- HVAC Average [C]
Output:Variable,*,Zone Thermal Comfort ASHRAE     !- Zone Sum [hr]
55 Simple Model Summer or Winter Clothes Not
Comfortable Time,monthly;
```

As it is done with every created model, the model is tested by analysing different outputs. In this case the relation between infiltration rate and the difference of inside and outside temperature is examined as well as the relation between heating energy and outside temperature. Both relations show clear fluctuations like day-night differences, weekdays and weekends, and summer and winter. So the model is accepted to work properly.

4.3 Simulation

The building model and the .epw files are forming the basic input for the simulation program EnergyPlus. EnergyPlus is a simulation program to model energy and water usage which is often used by engineers, architects and researchers to optimize the building design to decrease the energy and water use [41]. This means that it is suitable for energy and comfort analysis because it calculates the heating and cooling load which is needed to maintain thermal comfort. EnergyPlus is based on the simulation programs BLAST (Building load analysis and system thermodynamics) and DOE-2 which were created and often used in the 1970s and 1980s [42]. In the last thirty years these programs were not suitable anymore because the standard has been changed and the old programs were not able to handle feedback information from the HVAC system. So the old model codes and systems are refreshed to create EnergyPlus which has the best capabilities of BLAST and DOE-2 and much more advantages. For example, it is more easy for developers to add new modules and features and on the other hand, it is more easy for the users than the previous simulation programs. The input files are easy to maintain and expand, because EnergyPlus uses common ACSII input files. Another advantage concerning the input files is that they are available for 1250 locations worldwide on the website of the U.S. department of Energy. The advantage which makes it often used is that the program and the weather data are available for free. The only two disadvantages are the absence of a graphical interface and that the user surface could be more user-friendly [42]. Nevertheless, it is an ideal simulation program, because it is not necessary to be an expert to simulate energy use [43]. Due to the beneficial modularity it is possible that the researcher can work on modules without interfering with other modules. Therefore, the researcher is able to model a building without knowledge of the entire program structure. Developers of EnergyPlus even aim to make the simulation program as simple as possible, so that simulation codes and algorithms and therefore the different models are separated. For this reason the investment of modelling and simulating is minimized, but the impact on energy researches is maximized [43]. All the advantages of not knowing the entire program structure in detail do not prevent the necessity to know how the program works globally. Figure 4.2 gives a global idea of how the program is working. The third-party user interface is a separate program that offers the user a simpler user surface than the one of EnergyPlus. For example the program GoogleSketchUp can be used on the one hand to introduce the building characteristics, upload weather files. On the other hand, it is also a tool to present the display in graphs or tables. Based on this third-party user interface the Input Data Files (IDF) are created which are necessary for the simulation. The IDF are described using the code FORTRAN90 so that data can also be introduced manually.

In the figure it is presented as the blue box above the Simulation Manager. The core of the simulation program consists of three components: a simulation manager, a heat and mass balance simulation module and a building system simulation model. These three components form the basic needs for the simulation. The heat and mass balance simulation and the building system simulation are interacting so that one of the simulations can use the feeback of the other to create more realistic simulation outputs. The simulation manager is needed for the subroutines, so that all simulation steps are done in the right order. These simulation steps are actually called flags and the first flag is always the WarmupFlag [44]. This WarmupFlag is necessary because the entire simulation is based on loads simulation and therefore inaccuracies are not accepted. So the program checks first whether the simulation is balanced and then the simulation of energy use can start. The eight boxes at the side of the red one present different kinds of modules. For this research the Airflow Network is used, for example, but as seen in the figure more modules can be added to make the model more accurate. Finally, the program calculates the desired results and via a third-party-user interface the results can be presented in graphs or tables. In this research Excel and GoogleSketchUp are used as the third-party user interface. GoogleSketchUp helped to introduce building data, but it cannot be used for the output, because the versions of programs were not matching. So Excel is used to show the results in tables and graphs.

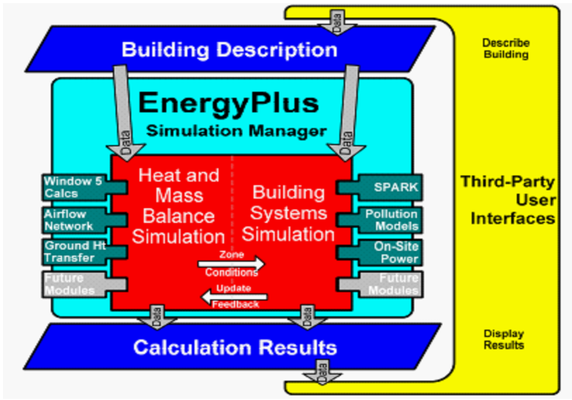


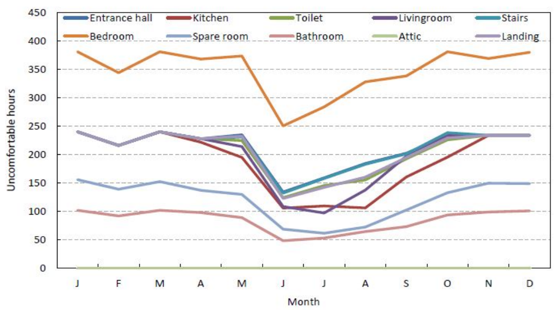
Figure 4.2: Simulation structure of EnergyPlus

4.4 Future energy use and comfort

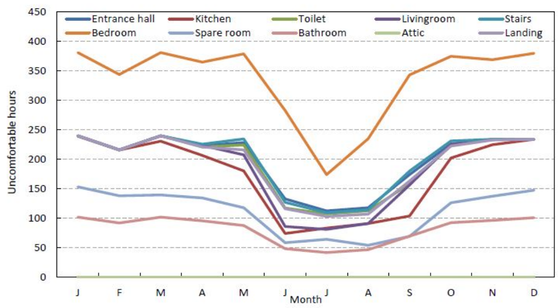
The first simulations are based on the standard building model and the four moments in time. As in the chapter about climate change in Cardiff (§2.3) explained, the DSY is created to analyse the overheating risk and the TRY is used widely for simulating the energy use. This is why the results about heating and cooling energy and the discomfortable hours are based on TRY and DSY, respectively. In generally, there are four different variables examined. Concerning the thermal comfort, the amount of uncomfortable hours is analysed and to examine the energy use, the cooling, heating and total energy use will be examined. In the following the results of simulating the standard building model are presented.

Thermal comfort

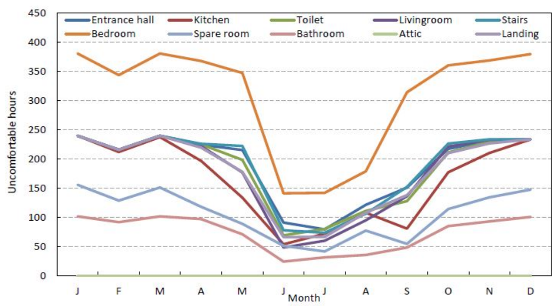
The thermal comfort is measured by the amount of uncomfortable hours as it is seen in Figure 4.3 and it appears that most of the rooms have the same comfort, because the amount of uncomfortable hours are nearly the same. That means in winter season there is no change in the amount of hours and in summer season the change will be up to thirty hours in 2014 as it is seen in Figure 4.3a. The bathroom, spare room and bedroom have a significant better or worse comfort. The bedroom for example has less comfort, because the amount of uncomfortable hours is about one and a half times higher than the majority of rooms. On the other hand, the bathroom and the spare room are the most comfortable rooms, because they only have about the half of uncomfortable hours than the other rooms. The factor of the differences will be the same throughout the year, so that the difference in the actual amount of uncomfortable hours is greater in winter due to the greater amount of uncomfortable hours. Generally, there are less uncomfortable hours in summer and therefore the difference in hours is less than in the winter: in summer the majority of rooms has about a hundred to 150 uncomfortable hours and in winter there will be around 200-2050 uncomfortable hours. Nevertheless, it appears that during the whole year and in every room there will be uncomfortable hours even if the interior temperature is controlled by the heating and cooling system.



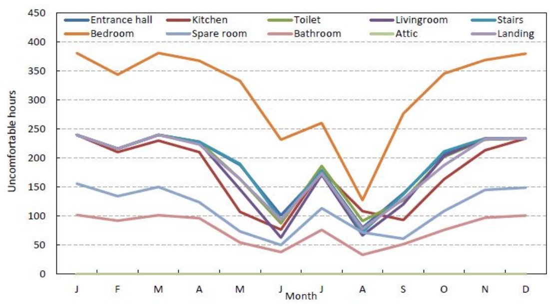
(a) Comfort in 2014



(b) Comfort in 2030



(c) Comfort in 2050



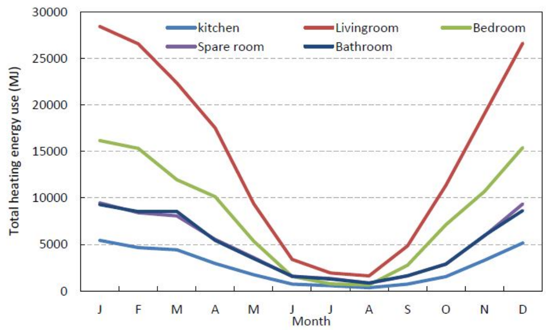
(d) Comfort 2080

Figure 4.3: Change in uncomfortable hours of standard building model

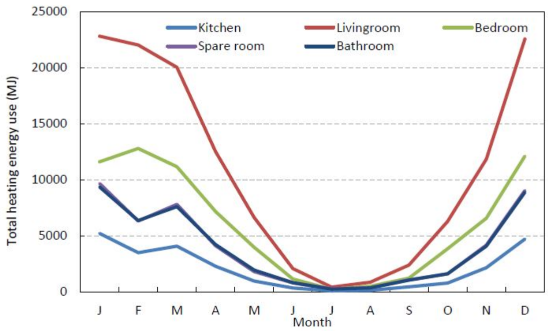
In the future the ranking of most uncomfortable or comfortable rooms will be the same seen in Figure 4.3b, 4.3c, 4.3d, but the amount of hours during the year will change. Even if in winter season there is no difference at all, in summer season the comfort will improve, because the trough of uncomfortable hours is decreasing from about 130 to eighty hours. The trough itself will also change, because in 2014 it is in June (see Figure 4.3a) and in 2080 it is in August (see Figure 4.3d). The last special appearance is the peak developing in July until 2080 which is not as high as the winter level of uncomfortable hours, but it is a great change compared to the summer level of hours. Until 2005 there is one trough, but thirty years later there will be two troughs, before and after the peak in July.

Energy use

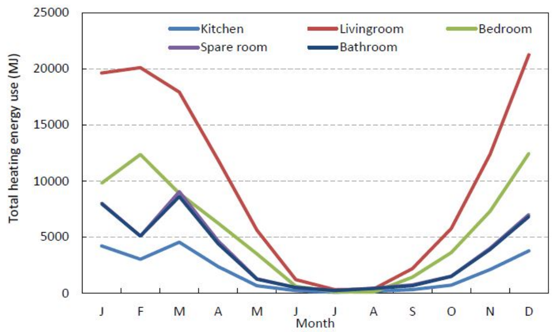
The criterion for energy use is split into heating, cooling and total energy use to get a better understanding about the usage. In Figure 4.4 it appears that the heating energy use is much higher in winter than in summer, so that for example the heating energy use in the livin groom during the winter in 2014 is 28 417 MJ and in summer it is only 1635 MJ (see Figure 4.4a). But in the kitchen the heating energy use in winter will only be 5449 MJ and in summer 362 MJ. In general, it seems that the rooms at the north side of the building will need more heating energy throughout the year than the rooms at the south. From the analysis it appears that heating energy use will be necessary throughout the year even if in summer cooling energy is necessary. The maximum of total heating energy in winter and summer will decrease about 28% and 95%, respectively, so that the maximum in 2080 is 49 554 MJ in winter and 350 MJ in summer (see Figure 4.4d).



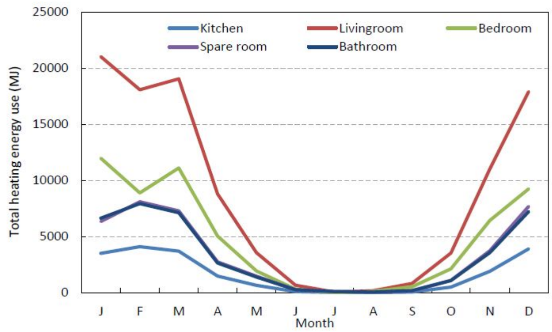
(a) Heating energy use in 2014



(b) Heating energy use in 2030



(c) Heating energy use in 2050

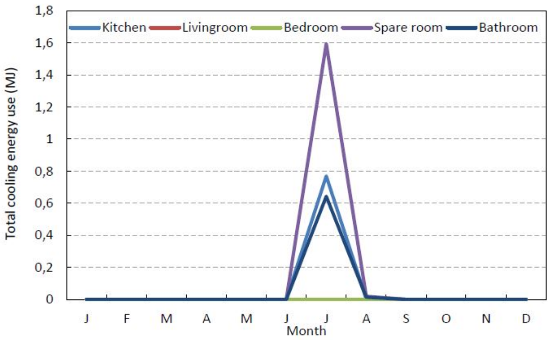


(d) Heating energy use in 2080

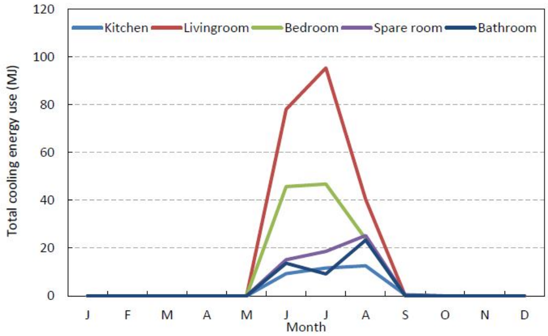
Figure 4.4: Change in heating energy use of standard building model per room

In contrast to the continuously occuring heating energy the cooling energy will only occur in summer and it will be only a small fraction of heating energy. In 2014 the total cooling energy use reaches a maximum of 3 MJ (see Figure 4.5a) and the maximum increases until 2080 to 783 MJ (see Figure 4.5d), but both are only less than 1.5% of the maximum total heating energy use (see Figure 4.5). So even if the cooling energy use in summer will be reduced to zero, it will nearly have no effect on the total energy use. Nevertheless, it appears that nowadays only the rooms at the south side will need cooling energy but in the future there will be also energy necessary to cool down the rooms at the north side whereof the living room will need the most cooling energy. This may be caused by the increasing outside temperature and therefore also the north oriented rooms will heat up. This increase of total cooling energy use happens in two great steps. Firstly, the energy use increases about 180 MJ until 2030 (see Figure 4.5b) and will stay the same until 2050 (see Figure 4.5c), but in the last thirty years of the century the energy use will increase about 300 MJ and the peak increases about 600 MJ (see Figure 4.5d). The last change is concerning the range of time when cooling energy use is demanded which will increase between 2014 and

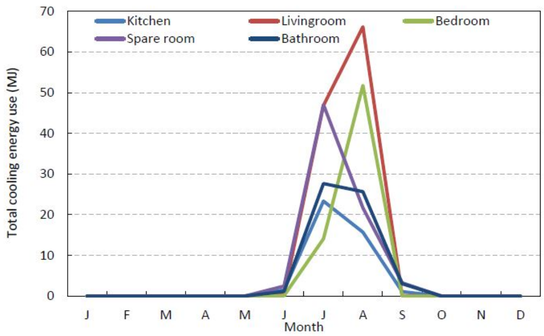
2080. Nowadays cooling energy is only demanded during July, but in 2080 the range of use increases to three months, June to August.



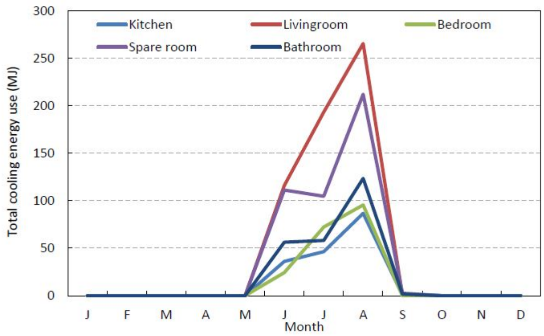
(a) Cooling energy use in 2014



(b) Cooling energy use in 2030



(c) Cooling energy use in 2050



(d) Cooling energy use in 2080

Figure 4.5: Change in cooling energy use of standard building model per room

As earlier said, the cooling energy use is a very small fraction compared to heating energy use. That is why the change in heating energy use is dominant and will mainly influence the total energy use. Only in future summers the heating energy use is so small that the cooling energy use is higher. So the cooling energy use is mainly influencing the total energy use in summer. In detail the total usage in 2014 will be about 68 793 MJ and 4374 MJ in winter and in summer, respectively, and it will decrease to an energy use of 49 554 MJ in winter 2080 and 825 MJ in summer.

4.5 Impact of climate change on energy use and comfort

The results described above are caused by different reasons, but all of them can be explained by the change of radiation and temperature.

Thermal comfort

Concerning the thermal comfort it appears that during the whole year and in every room there will be uncomfortable hours even if the temperature is regulated by the heating system. This is why the temperature is not the only factor influencing the comfort. As earlier said, the activity level, clothing, wind speed and other factors will influence the comfort and therefore the amount of uncomfortable hours will never be zero. Furthermore, it appears that the bedroom the most uncomfortable room which can be explained due to the activity in that room. People are very sensible for the temperature during sleep.

If the temperature is slightly too warm or too cold the comfort will decrease. On the other hand, the bathroom and spare room are next to the kitchen the most comfortable hours because these have the least window surface of all rooms. So the rooms will be not strongly heated by the radiation. They are still more comfortable than the rooms without windows due to the ventilation and heating system. Bathroom, spare room and kitchen can be ventilated and they are heated by the central heating.
Concerning the difference between rooms, it appears that in winter there is a smaller difference than in summer. This is why in winter there is only the temperature affecting the interior comfort, because the solar radiation is very low. In contrast to the winter, there will be stronger radiation in summer. The temperature around the whole house is the same so that the temperature cannot cause a great difference in comfort. But due to the solar radiation, which is stronger on the south side, the rooms at the north side are less comfortable than at the south side. Thus, the rooms will heat up more or less, depending on their size, window surface and location.
For the future development it appears that rooms will be more comfortable. This is caused by the climate change. A stronger radiation and a higher outside temperature are expected to increase the interior temperature. For this reason these two criteria are not the cause of the increased comfort. So other criteria of climate change like the wind direction or humidity might cause this development.

Energy use

For the energy use it appears that in winter more heating energy is required because the outside temperature is cooler than in summer and therefore the the building is cooling down more in winter. Generally, it seems that the rooms at the north side will be heated more than rooms at the south, due to the fact that the rooms at the south are more heated by solar radiation than in the north. But for all rooms heating will be necessary throughout the year because heating energy is not only used to heat up the inside temperature, but also to supply the house with heat tap water. So even if the heating is not necessary, there will always be a demand for heat tap water. In the future the maximum heating energy is less decreasing in winter than in summer since solar radiation is increasing in summer about three times more than in winter.
Contrary to heating energy use cooling energy use only occurs in summer because then the outside temperature is so high that the rooms might heat up. This will never be the case in winter, because there the outside temperature is already cool. Like the heating energy use there is a difference in cooling energy for rooms at the north side or south side: Nowadays only the south side is cooled since radiation is at the south side much stronger, but in the future even north side rooms need cooling energy. This is due to the increase of the outside temperature so that even the north rooms need cooling. The future increase of cooling energy use occurs in two steps which is caused by the inconsistent development of solar radiation.

This analysis shows that more cooling is necessary, because of the increasing radiation and temperature. But this can be prevented by three different changes of building characteristcs: a smaller Wall-window-ratio (WWR) and adapted shadow devices are expected to prevent that less radiation can enter the building. Due to the increased temperature better insulation might be a solution. An extra layer of insulation also increases the heat capacity and so the interior temperature will not change very quickly due to outside temperature. Additionally, a better insulation also reduces heating energy use in winter season. The smaller WWR might help to reduce the cooling energy use, but a greater WWR might lead to a greater ventilation so that the inside temperature might cool down and therefore the comfort improves. But on the other hand, a greater WWR also allows more radiation to enter and therefore the cooling effect might be negligible.

4.6 Conclusion: Comfort and Energy use - today and in the future

To simulate today′s and future energy use of the building standard, a standard buidling model is created which is a simplified version of the terraced house presented in chapter three (§3). This standard building model has an attic instead of a third bedroom and the ensuite at the second floor, the storages are neglected and the roof windows are changed to common garret windows. Before the first simulation is done, the criteria are defined. Comfort will be described as the amount of uncomfortable hours and is based on the adaptive comfort model defined in ASHRAE 2010. The limit of energy use is set by today′s energy use, because the aim is to reduce the usage. So the standard building model is uploaded together with the weather data from PROMETHEUS in EnergyPlus and the output is the comfort in terms of uncomfortable hours and the energy use in terms of heating, cooling and total energy use.
With this model and the criteria the third question (*"What is the energy use and comfort of typical houses in Cardiff today and in the future?"*) can be answered in the analysis of the results: From the simulation it appears that the comfort is higher in winter than in summer season since the higher radiation and temperature in summer are heating the building more than it can be cooled down. In the future the comfort will improve throughout the year which is not only caused by increasing solar radiation and temperature. Other characteristics of climate change might cause this effect. Concerning the heating energy use, it is likewise the comfort higher in winter and lower in summer, but there will always be heating energy requested. This is due to the fact that the heating energy is used for heating the tap water and so there will be heating energy use in summer even if cooling energy use is needed. In contrast to the cooling energy use the heating energy use will decrease in the future about 28% in winter season and 75% in summer season. The cooling energy use will only occur in summer months, but in the future it is required more often: in 2014 only in July cooling energy will be used but in 2080 it is also required in June and August. This increase is caused by the greater radiation and higher temperature in the future. In spite of the increase of total cooling energy use from 3 MJ in 2014 to 783 MJ in 2080, it will always be a small fraction of heating energy and so the heating energy will mainly dominate the total energy use. Only in the future summer the heating energy will be reduced so far, that the cooling energy use will dominate the total usage. To sum up, the development of comfort and energy use is contrary to recent studies but this can be caused by the use of different methods, locations, climate and models in the recent studies. For this research it is interesting to analyse the a smaller WWR or add shadow devices, because the greater solar radiation decreases comfort and increases cooling energy use. A better insulation can help to decrease the interior temperature so that the building will not heat up due to a higher outside temperature. This is expected to decrease cooling energy use in summer and heating energy use in winter.

Chapter 5

Methods and technologies

After analysing the future problems of thermal comfort and energy use in the preceding chapter, the different solutions which might help to reduce heating and cooling energy can be examined. The results, the evaluation and a final ranking will be presented in the following chapter. Therefore the last question of this research can be answered (*"What is the effect of methods to maintain the future energy use and comfort?"*). In the preceding chapter three solutions are suggested: a better insulation, change of WWR and adapting shading devices. Based on these methods eight different models are created. Firstly, the insulation will be improved. The effect is examined for retrofitting only wall, roof or windows and finally the combination of all three retrofitting solutions. Secondly, the surface of windows will be changed to a greater WWR and to a smaller one. Finally, elements to increase the shadowing of the building will be adapted. In this model common overhangs are adapted to the building standard and in another model a terrace for the first floor is additionally to the overhangs installed. These solutions are analysed seperately and will be presented in the order from the inside to outside of the building.

5.1 Improved insulation

The initial insulation is based on the minimum U-value required in the building regulation 2010. But in the last years the regulation has changed and more sustainable elements are developed, like Low-E windows (windows with a very low emissivity) or a double cavity wall. The new resistivity values are based on building regulation of 2013 [45] and as it is seen in Table 5.1 there is a clear increase.

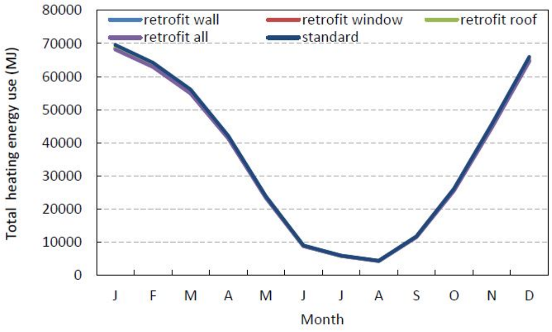
Table 5.1: Solutions concerning retrofitting the external surfaces

Retrofitting of external surfaces				
External surface	Retrofitting method		Retrofitting method	
	Before	After	Before	After
Wall	single cavity wall	double cavity wall	0.271	0.155
Roof	insulation layer of 0.25 m	insulation layer of 0.35 m	0.192	0.139
Window	double glazed window	E-low window	1.957	0.832

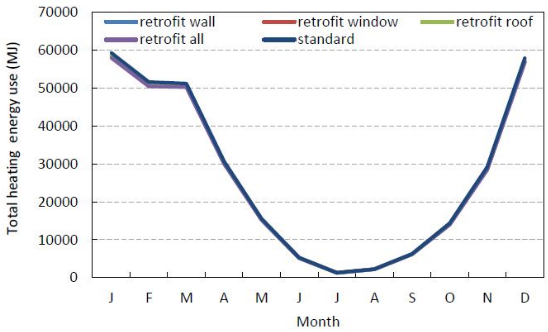
There are four models created wherein wall, window and roof are redeveloped individually and as a combination. The individual analyse of each external surface will show which of the three improvements is the best, in case not everything can be improved. In detail the redevelopment means that the exterior walls become double cavity walls, so that between the insulation layer and the brick layer another insulation and concrete block layer are added (see Table 5.2). The roof construction is not changed basically, because only the thickness of insulation layer is increased from 0.15 m to 0.35 m. At last the windows resistivity is increasing due to the fact that triple glazed windows are used.

Table 5.2: Construction of double cavity wall

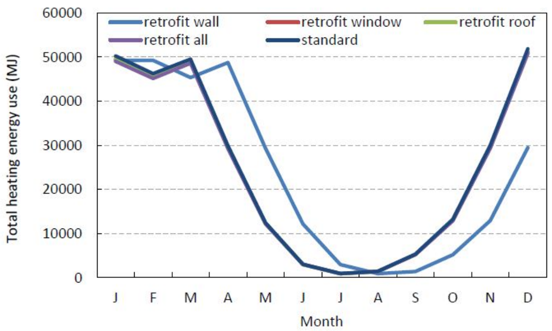
Layer	Material	Thickness [m]
external surface		
layer 1	brickwork	0.100
layer 2	mineral wool	0.140
layer 3	blokwork	0.150
layer 4	mineral wool	0.140
layer 5	blokwork	0.150
layer 6	plasterboard	0.013
internal surface		



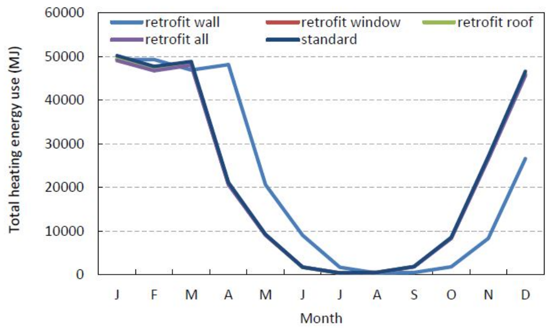
(a) Heating energy use in 2014



(b) Heating energy use in 2030



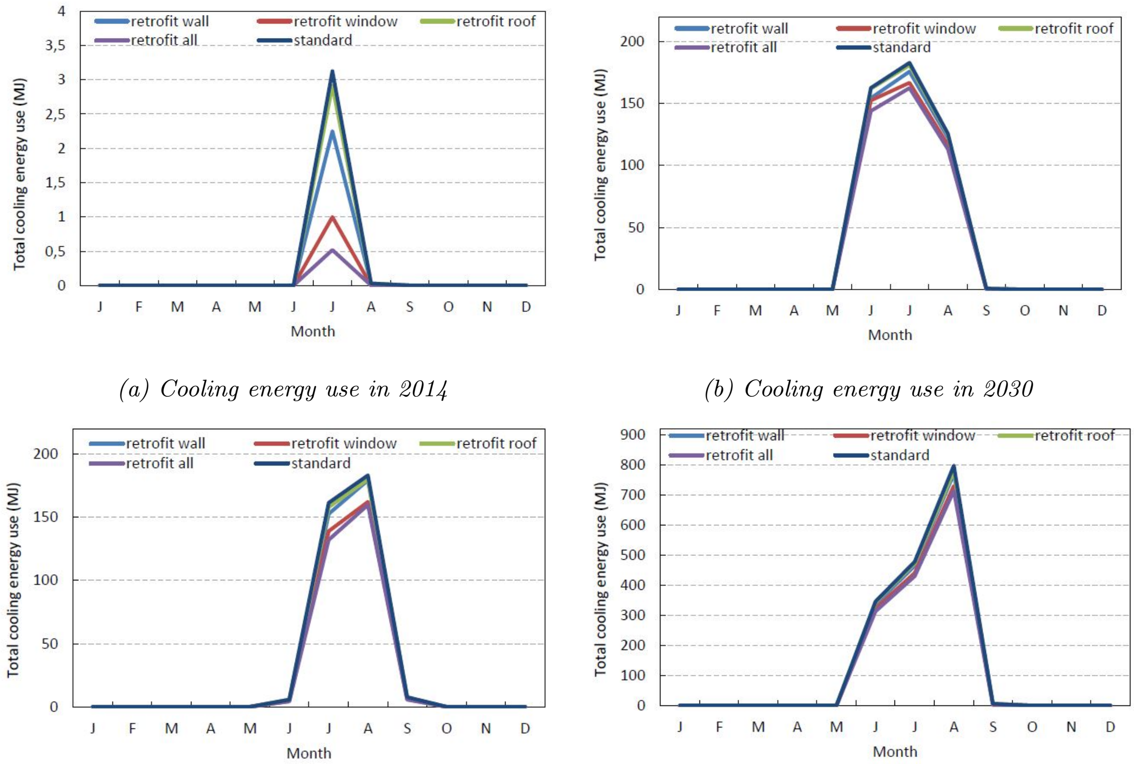
(c) Heating energy use in 2050



(d) Heating energy use in 2080

Figure 5.1: Change in total heating energy use due to the improvement of insulation

The simulation shows that there is nearly no change in the amount of uncomfortable hours and therefore the comfort is unsignificantly changing independent whether external surfaces are retrofitted individually or in combination. Just as the thermal comfort there will be in near future unsignificant decrease of heating energy use as it is seen in Figure 5.1. Retrofitting all external surfaces, only window or only the roof will decrease the heating energy use about 2-10% in winter and up to 92% in summer of 2014. The redevelopment of walls will save at least heating energy use (2-3%). After 2050 the patron will change because retrofitting only the wall will shift the graph about one month so that the heating energy use will be higher from May to August and lower in the rest of the year (Figure 5.1c). Concerning the other retroffiting methods it appears that they will not decrease the heating energy use as much as in 2014. At all future moments the decrease will be maximal 3%.



(a) Cooling energy use in 2014

(b) Cooling energy use in 2030

(c) Cooling energy use in 2050

(d) Cooling energy use in 2080

Figure 5.2: Change in total cooling energy use due to the improvement of insulation

Concerning the cooling energy it seems that every method will decrease the energy use, but more or less effective. Generally, the decrease is the greatest for retrofitting all external surfaces or only the roof. The other two individual possibilities have no significant effect on reducing the usage. The maximum of cooling energy can be decreased by retrofitting everything for about 12% in the future. After retrofitting all, the redevelopping of walls will be the most effective, than changing windows and retrofitting the roof is the least effective method to reduce cooling energy use. But even if there is a significant decrease of cooling energy use it will not affect the total energy use, because even the maximum decrease in 2080 of 83 MJ will be a minor fraction (15%) of the heating energy use in the same month of summer 2080 which is about 482 MJ. So the total energy use follows again mainly the development of the heating energy use.

5.2 Change Window surface

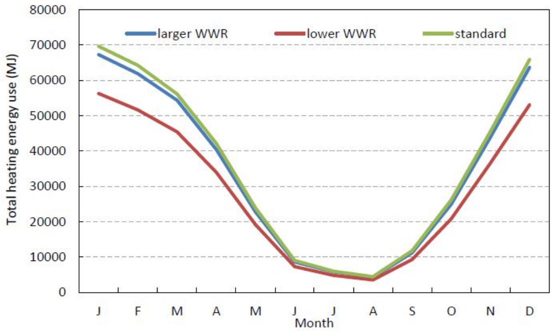
The next two models concern the change of the window surface. This leads to a greater or smaller amount of solar radiation entering the rooms which means that it will heat up more or less, respectively and therefore the heating and cooling energy can increase or decrease. But not only the energy use will be directly influenced, by increasing the surface of windows, more ventilation can occur and for this reason the rooms can cool down. Another side effect is the entering of more light, which will reduce the usage of artificial light.

On the one hand the window surface is increased from a WWR of 0.1 to 0.19 which means in detail that the window surface is increased to 15.3 m^2. By minimizing the window surface to 4.85 m^2 the WWR decreases to 0.06. In both cases the windows on the south and north side are increased or decreased equally. The detailed changes of windows by increased and decreased WWR is seen in Table 5.3

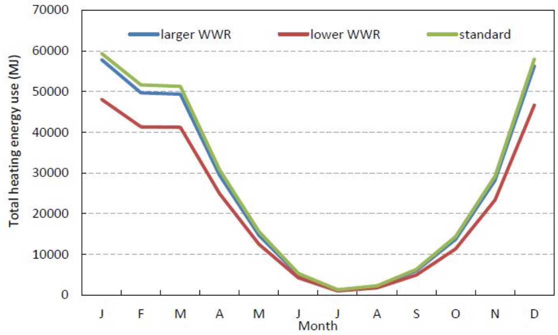
Table 5.3: Change of window dimensions of different WWR

Room		WWR is 0.1	WWR is 0.19	WWR is 0.06
Kitchen		1.0m x 0.8m	1.0m x 1.6m	1.0m x 0.8m
Livingroom	Window 1	1.5m x 0.3m	1.5m x 0.5m	1.0m x 0.8m
Livingroom	Window 2	1.5m x 0.3m	1.5m x 0.5m	–
Livingroom	Frenchdoor 1	2.0m x 0.7m	2.0m x 0.7m	2.0m x 0.7m
Livingroom	Frenchdoor 1	2.0m x 0.7m	2.0m x 0.7m	–
Bathroom		1.0m x 0.8m	1.0m x 1.0m	0.5m x 0.5m
Spare room		1.3m x 0.8m	1.3m x 1.0m	1.0m x 0.8m
Bedroom	Window 1	1.0m x 0.8m	1.0m x 3.6m	1.0m x 0.8m
Bedroom	Window 2	1.0m x 0.8m	–	–
Attic	window north	1.0m x 0.8m	1.5m x 1.0m	–
Attic	window south	1.0m x 0.8m	1.5m x 1.0m	–
Total		9.54 m^2	15.3m^2	4.85m^2

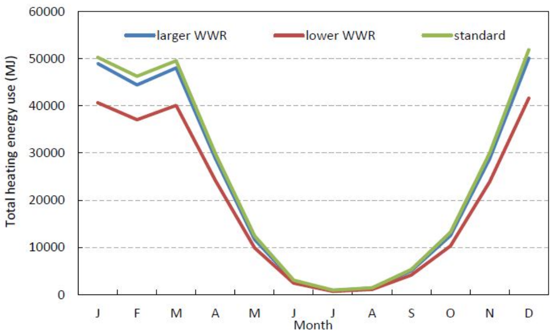
The simulation shows that the higher WWR has no significant effect on the comfort, but when the amount of uncomfortable hours is changing slightly, it will decrease. Only the kitchen shows a definitive improved comfort due to a decreased amount of discomfortable hours. Likewise the larger WWR, the lower WWR will show no significant changes. But in rooms wherein the amount of uncomfortable hours changes slightly, it increases and thus the comfort decreases.



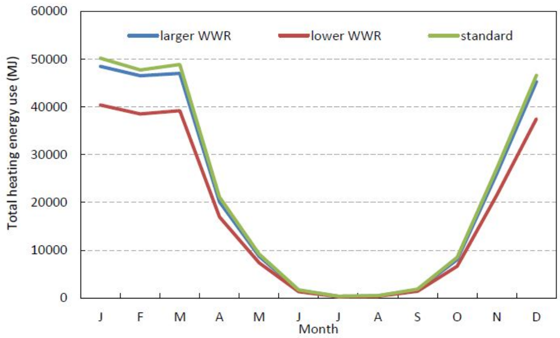
(a) Heating energy use in 2014



(b) Heating energy use in 2030



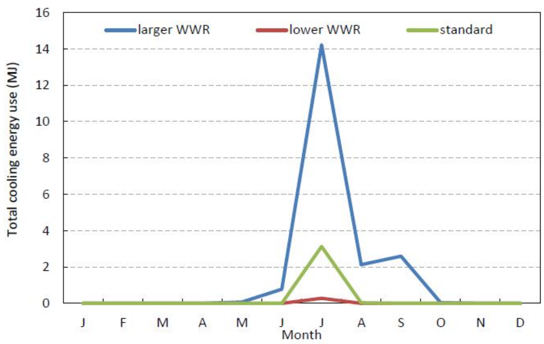
(c) Heating energy use in 2050



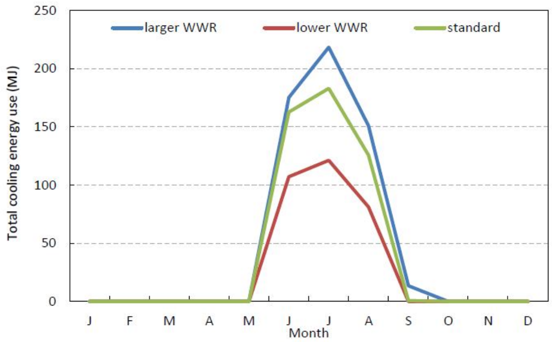
(d) Heating energy use in 2080

Figure 5.3: Change in total heating energy use due to a larger and lower WWR

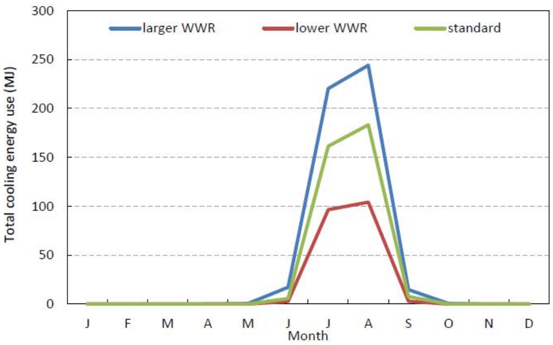
Concerning the heating energy use, a greater and smaller WWR lead to a decrease, but the decrease of a lower WWR is about five times geater than the one of a larger WWR (Figure 5.3). This is why less solar radiation is entering the room due to a lower WWR and so the rooms will not heat up a lot. In detail it means that a larger WWR decreases the heating energy use about 4% and a lower WWR will reduce the energy use in winter season about 20%. These changes are equal to a reduction to 56 229 MJ in 2014 and at the end of the century to 40 384 MJ with a lower WWR and in case of the larger WWR the enegry use will only decrease to 67 253 MJ in 2014 and in future of 48 474 MJ. In the future there is no change in decreasing rate, so even in 2080 it is a decrease of 4% and 20%. Next to the difference between the WWR, the simulation shows that there is a greater decrease in winter than in summer season, because in summer there is already less heating energy used.



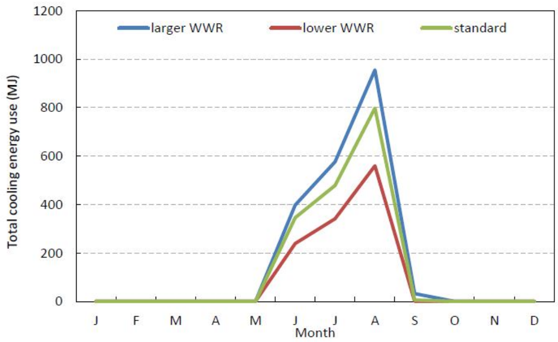
(a) Cooling energy use in 2014



(b) Cooling energy use in 2030



(c) Cooling energy use in 2050



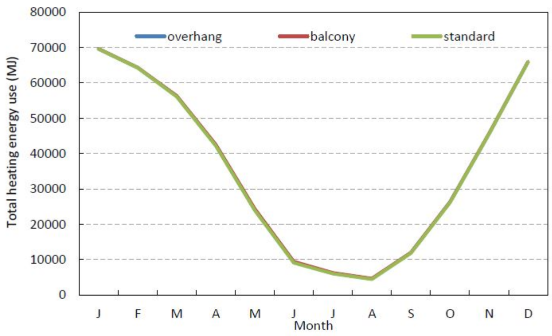
(d) Cooling energy use in 2080

Figure 5.4: Change in total cooling energy use due to a larger and lower WWR

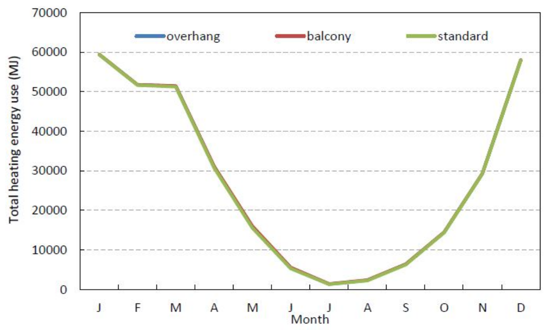
In contrast to the effect on heating energy use, the lower WWR will decrease the cooling energy use and the larger WWR will increase it (Figure 5.4). In the future the decrease of a lower WWR is generally greater than the increase of the larger WWR so that in 2080 the total cooling energy will have a maximum of 955 MJ (158% increase) and the lower WWR will decrease the maximum to 559 MJ (30% decrease).

5.3 Shading device

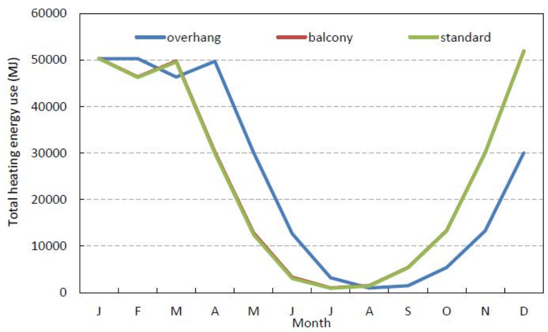
To increase the shadowing overhangs of a half meter width are installed directly above each window. The roof windows have no shadowing, because the room is not often used and so it is not important whether the attic is too heat or too cool. Furthermore, heat will raise up, so it is not expected that rooms in ground and first floor will be heat up due to a heat attic. In the model wherein the terrace is additionally adapted, the overhang above the windows in the living room is increased to 4.5 m by 3 m so that it covers the whole width of the house.



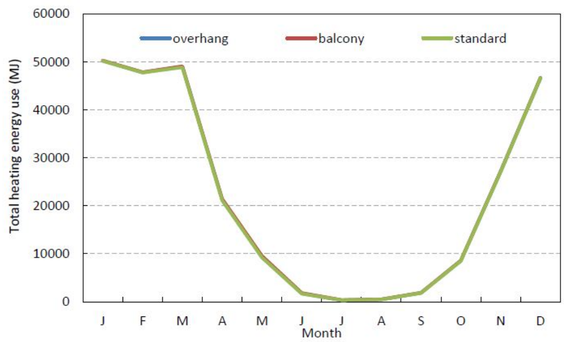
(a) Heating energy use in 2014



(b) Heating energy use in 2030



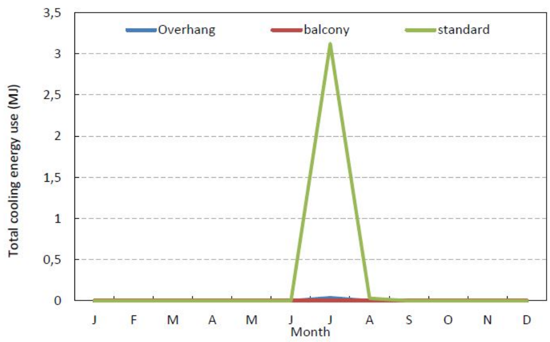
(c) Heating energy use in 2050



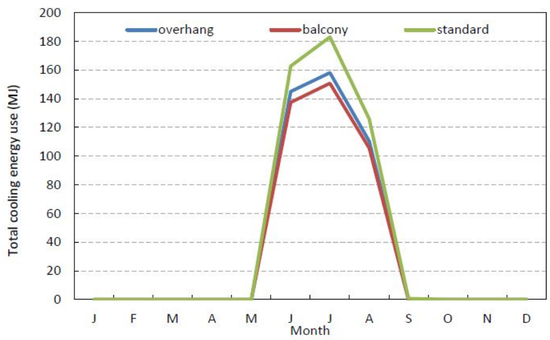
(d) Heating energy use in 2080

Figure 5.5: Change in total heating energy use due to adapted overhang or additionally a balcony

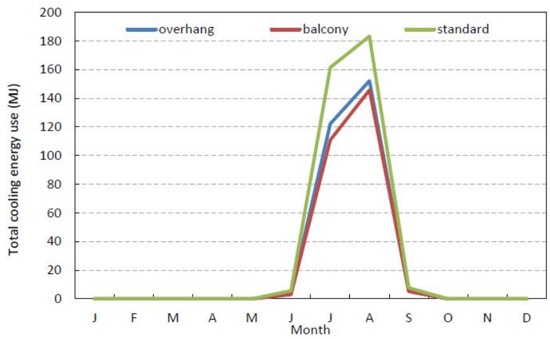
The simulation shows for both models no significant changes concerning the amount of uncomfortable hours and therefore the comfort. Only nowadays in the living room the simulation shows an increase of uncomfortable hours for both models. Just as the comfort, the heating energy use shows no significant changes (Figure 5.5), except of the years around 2050. After April of these years, the development of heating energy use with adapted overhang will be occur a month later than it will occur with the balcony and the standard model as it is seen in Figure 5.5c. Generally, there is no significant change to see in the graph, because the changes are in 2014 maximal 4% compared to the building standard model and in the future the change will top out to 10% in 2080 which is equally to the difference of 395 MJ and 39 MJ, respectively. This difference also shows that the increase heating energy caused by adapted balcony is twice as big as the increase caused by adapting only overhang. Nevertheless, these little changes will not significantly change the total energy use, so there is also no improvement or decrease shown.
In the case of cooling energy use there is a decrease caused both models, but it appears that the balcony model will decrease the cooling energy use slightly more so that the today′s usage became zero and in the future the usage will decrease about 31% to 402 MJ in July 2050 (see Figure 5.6c). As in Figure 5.6d seen the cooling energy will slightly increase again in 2080, but there is still a decrease of 15% comparing to the standard model. Since the difference between overhang and balcony is maximal 1% which is equal to a difference in energy use of 12 MJ, there is no significant difference. Generally the decrease is greater in near future than at the end of the century, because the nowadays decrease is about 99%, in 2030 27% and later it will only be 15%. Nevertheless, the change in decrease of cooling energy use in future will not significantly effect the total energy use, but it can be seen that the decrease of energy use is greater in summer than in winter. This is caused even much by the decrease of cooling energy use than the fact that the heating energy use will reduce in summer more than in winter. Concerning the total energy



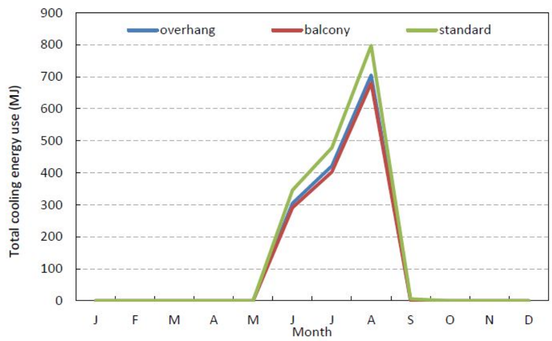
(a) Cooling energy use in 2014



(b) Cooling energy use in 2030



(c) Cooling energy use in 2050



(d) Cooling energy use in 2080

Figure 5.6: Change in total cooling energy use due to adapted overhang or additionally a balcony

use it appears that the balcony will increase the usage twice as much as the overhang only just like the heating energy use.

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5.4 Evaluation of methods

To evaluate whether a method is efficient or not, it is often used to compare the saved costs of energy use with the costs for the implementation of the element. But this study is focused on the reduction of energy use and not on the financial aspects and therefore the methods are evaluated in its efficiency comparing to the other methods.
The first group of solutions concerns the insulation of exterior surfaces. Based on the results it appears that only a fully retrofitted exterior surface, which includes an improvement of thermal resistivity of wall, window and roof, will lead to a significant reduction of total energy use. This is expected, because it would not be efficient if the wall is redeveloped to the current building regulation whereas the roof and windows have a low thermal resistivity. In that case the house will keep loosing heat via window and roof and the energy use will still be high. By comparing the individual redevelopments of different external surfaces it appears that retrofitting the windows is less efficient than the wall, but more efficient than the roof. Retrofitting windows is less efficient than the wall due to the fact that the wall surface is much greater than the windwo surface. Furthermore, retroffiting the wall leads to a greater insulation than the one of windows and therefore the heat transfer is decreased more than in case of retrofitting windows. Redeveloping the roof has the slightest effect because the attic is unused and not heated. So

the heating system would not react if the attic is extreemly heaten up or cooled down. Concerning the comfort it appears that the comfort is unsignificantly changing.

Based on the results it can be noticed that a smaller WWR is more efficient than the larger WWR concerning reduction of energy use and maintaining the comfort. This is due to the fact that a smaller WWR will prevent a greater heating of rooms by reducing the solar radiation which enters the rooms. Furthermore, the thermal resistivity of windows is the smallest of all external surfaces and by reducing the surface with lowest thermal resistivity, the heat losses will be smaller. Concerning the comfort, there is no change since the heating system compensates the effect of increased and decreased heating due to radiation.

The solution to adapt shadowing it appears that neither the overhang nor the balcony is efficient in reducing energy use. It was expected that the balcony should reduce cooling energy more than only overhang, because it can provide much more shadowing. But it appears that the balcony even increases the energy use whereas overhangs will not lead to any major change. This study is focused on the impact of solar radiation on interior climate and energy use and thus the balcony is simulated as a great shadowing device. So properties of balcony like heat storage or others are not simulated and so the actual impact of a balcony can vary from the results.

Concerning the comfort there are no major changes due to a changed WWR or an improved insulation. This is why the heating system can compensate the changes causing by a different heat transfer. A smaller WWR and the improved insulation reduces cooling energy which means that less energy is necessary not to exceed the maximum comfortable temperature. A greater WWR would lead to a higher rate of entering radiation and therefore more cooling energy is necessary.

To sum up, it can be concluded that the reduction of WWR to 0.6 is clearly the most efficient. The larger WWR, the different methods of retrofitting and the overhang are close to each other but a slightly difference about 100 MJ-1000 MJ shows that a larger WWR is more efficient than retrofitting which is more efficient than adapting overhangs. The balcony will be not rate as being efficient because it increases energy use and decreases comfort. These conclusion are summarized in Table 5.4 wherein an overview of the ranking is given.

Table 5.4: Ranking of methods to reduce energy use and maintain comfort

Ranking of methods	
1	Decrease WWR
2	Increase WWR
3	Retrofit all external surfaces
4	Retrofit external walls
5	Retrofit windows
6	Retrofit roof
7	Adapt overhang
8	Adapt balcony

5.5 Conclusion: Methods and technologies

Based on the analysis of the enery use and comfort of the buidling standard model three main solutions are developed: improve the insulation of external surfaces, change the WWR and add shading. The first method is retrofitting the insulation property of external surfaces. The results of these simulations show no significant reduction of heating energy, but a decrease in cooling energy use. The decrease of cooling energy use can be explained by the lower heat transfer. That means the building looses less heat and so less cooling energy is necessary. Generally, it appears that retrofitting all surfaces decreases the energy use most and depending on heating and cooling energy use the wall and windows can reduce the energy use as the second best. The simulations of a larger and lower WWR, which is 0.19 and 0.06, respectively, show that a larger WWR will not lead to major changes concerning the thermal comfort, but small changes denote a decrease of comfort. The heating energy use will slightly decrease due to a larger WWR and the cooling energy will increase about 4% caused by the greater amount of radiation entering the building. The lower WWR also leads to no significant changes in comfort, but it denotes a slightly improve of comfort in some rooms. Concerning the energy use, it will decrease the heating and cooling energy use so that the total energy use will decrease about 17% in 2014 and it will raise to a decrease of 20% in 2080. This effect is caused due to the fact that less radiation can enter the building and therefore the buidling will not heat up. Furthermore, the surface with the greatest heat transfer is reduced and so the building is loosing less heat.

The results of simulating the models with adapted shading devices show no significant change concerning the comfort and the heating energy use. But due to the balcony the heating energy and therefore the total energy use increases twice as much as due to the overhang. Due to the balcony and overhang less radiation enters the room, but the absence of radiation is so great that extra heating energy is necessary to maintain the comfort. Only the cooling energy use will decrease about 15-30%, but this is only a small fraction of heating energy use, so the decrease will not be shown in the total energy use.

Chapter 6

Discussion

The examination of future energy use and comfort of the building standard model shows that the total energy use will decrease and the comfort improves. These are developments which are not conform the results of the literature study. But the earlier studies, referred in the literature review, are done for other regions in UK so that the result should not be necessarily the same than the conclusion for Cardiff. Furthermore, earlier studies handle different methods and criteria and they are mostly done for offices and apartments and not for terraced houses.

The concluded ranking is not actually a definitive one because there are many uncertainties influencing this result. The energy use and comfort depend strongly on the weather, people, and appliances which are the greatest uncertainty factors. Concerning the weather it is already said that there are three different scenarios with five different percentiles to describe its probability. For this research the scenario is chosen which is rated as the most likely, but there is no garantuee that the weather will change like this. To handle this uncertainty more research can be done to analyse the effect of these methods for different scenarios. By examine the change in impact on energy use and comfort due to different scenarios the uncertainty can be better handled.

The people form the second major uncertainty. The people′s behavior, occupancy and consciousness of sustainable living are difficult to predict and so only assumptions can be made. For this uncertainty the influence of people′s behaviour should be more analysed, because in case the behavior has a great impact on energy use and comfort, the uncertainty becames even more important.

Finally, the appliances are very uncertain, because the appliances are in a continuous development. These uncertainty is difficult to research, because it cannot be predicted how the technology will develop and no one will know how far it will be at the end of the century. Concluding there are many uncertainties influencing these result and so the ranking cannot be seen as a strikt rule about which method is better. Under difference circumstances the ranking can be changed, especially because the results of the majority of methods are close and only differ about 100 MJ-1000 MJ. But further research is not only recommended to handle uncertanties, but also to understand the effect of solutions better. Concerning the WWR the window surface can be changed differently, for example by increasing window surface at the south side and reducing it on the north side. The shadow devices can also be simulated differently. In this research the heat capacity of a balcony or overhang is neglected, but that might have significant effect on energy use and comfort. Concluding, the simulation model can be extended so that solutions can be modelled more detailed or more environmental parameters can be added.

Chapter 7

Conclusion

During the literature study it appears that the climate change in Cardiff leads to an increase of temperature and solar radiation. The temperature will increase all over the year, but the solar radiation will not continuously increase. The future solar radiation may be higher or lower in summer, but a clearly trend of increase is seen. These weather data are provided by the project PROMETHEUS, started by the University of Exeter. These are the same weather data used for the simulation. But for simulating the energy use and comfort the building model needs to be created. Therefore the layout, building construction and occupancy of the building standard are modeled in an IDF file. The standard has three levels wherein a working couple is living and its constructions are designed conform the building regulation 2010. The simulation shows the amount of uncomfortable hours, heating, cooling and total energy use so that the development of comfort and energy use can be examined to find suitable solutions. It seems that the total energy use is decreasing as well as the uncomfortable hours which means an improved comfort. In summer the heating energy use becomes nearly zero but in winter it will be still high. Thus three types of solution are considered. Firstly the change of WWR is examined to reduce the heating energy use. Therefore, two models are created, one with a larger WWR (0.19) and one with a lower (0.06) whereof the lower WWR reduces the total energy use five times as much as the larger WWR. Concerning the comfort there are no significant changes. Secondly the adaptation of shadow devices are analysed by adding overhangs in one model and in another model a great balcony is added. From this simulation it appears that the overhang decreases the heating energy use, but has no changes on the amount of uncomfortable hours. Contrarily, the balcony even leads to an increased energy use and the comfort in living room and spare room will be decreased. The last method concerns the insulation capacity of external surfaces and therefore four different models are created; retrofitting wall, window, roof and a combination of all three. The results show that the complete retrofitting is the most efficient compared to other redevelopments. Retrofitting the roof is actually the less efficient of this group of solutions and redeveloping the walls is slightly better than only retrofitting the windows. A global comparison of these eight examined methods leads to a ranking seen in Table 5.4 wherein the lower WWR is the most efficient and the balcony the least. But this ranking is only valid under this special circumstances and regarding the different kinds of uncertainties. The development of weather, people and appliances are the greatest uncertainties whereof the first two uncertainties can be handeld better by doing more research. Only the development of appliances is difficult to handle because the development of technology is so fast and goes even faster so that it is not possible how it will be changed until the end of the century. Nevertheless, it can be recommended to have a lower WWR and improve the thermal properties of exterior surfaces, so that it is always accomplished to the current building regulation.

Chapter 8

Recommendation

Based on the analysis it can be recommended to the public of Cardiff that they should retrofit their building in case the building does not conform to the last building directive. The directive from 2010 is a former standard, so retrofitting the house on the standard of directive from 2013 is recommended. Furthermore, different studies are recommended to do. As mentioned in the disucssion, research about the impact of occupancies on energy use is helpful to minimize uncertainties in studies of modelling energy use. This is a research field that can be extended. For simulation studies in the future it is important to get more knowlegde how different the impact of the weather on energy use and comfort is. Therefore, it is recommended to do more research like this one, but not only focused on one scenario. Instead of that all, scenarios should be examined.

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Appendix

I. Methodology of creating EnergyPlus data files

To create future weather data files compatible with EnergyPlus, four main steps need to be done (see Figure 8.1). These method is based on the report of Eames et. al. [11] as it is not otherwise denoted. Firstly the daily climate variations needs to be investigated to provide daily and hourly weather data for the historic years in a spacial resolution of 5km grid boxes. Hence, the projection for local places can be made. Secondly, the TRY and DSY are created and the five different percentiles are added to the projections. Thirdly, the weather files need to be converted in .epw files which are finally evaluated by modelling the impact of future climate on a standard new built house and compare it to the projection of UKCP02, predicted in 2002.

Run UKCP09 weather generator

The weather generator is a tool to develop daily or hourly weather data by using mathematical and statistical relationships between different variables. This is done by analysing hundred observed samples of future weather in the 30 years between 1961 and 1990. These patrons will help to predict future weather data. Furthermore, information about climate change are given on a 25 km grid, but due to interpolation the spatial resolution can be increased to 5 km grid based on local observations. Hence, more detailed local prediction is possible. The output parameters of running the weather generator are precipitation, dry bulb temperature, partial vapour pressure, relative humidity, sunshine fraction, total radiation and potential evapotranspiration.

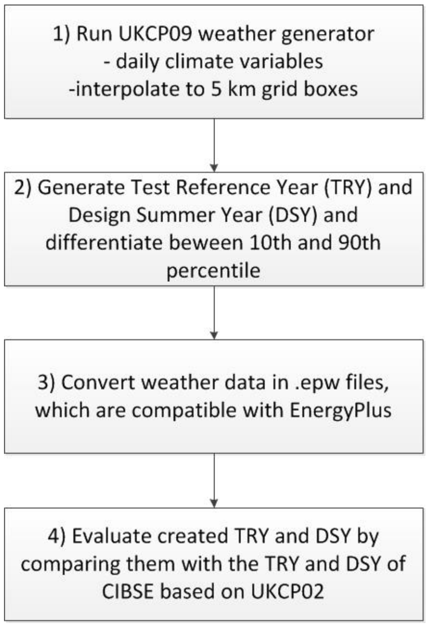


Figure 8.1: Four step model to create future weather data files compatible with EnergyPlus

Generate TRY and DSY and add probability

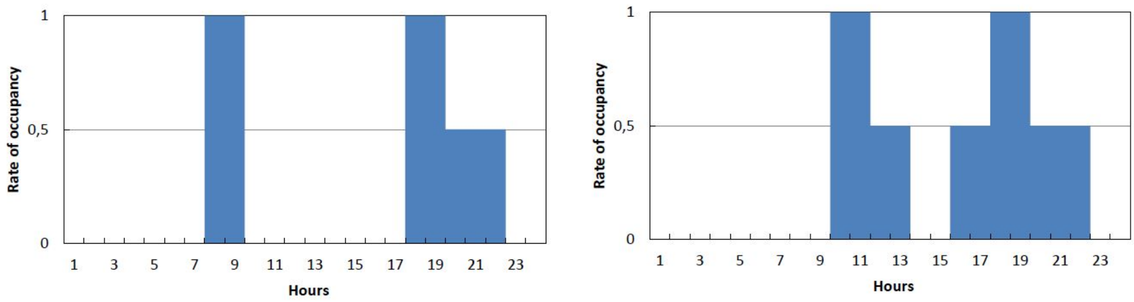
As earlier said both design years will be examined and so it is important to know how they are created. TRY is created by calculating the typical month of 12 seperate months in 22 years of data, namely from 1983-2004. The cumulative distribution function (DCF) of the daily mean value of the three parameters dry bulb temperature, global solar horizontal irradiation and wind speed is used to define the most average months. These results are compared via the statistic of Finkelstein-Schafer (FS), that means that the lowest value of the statistic will be the typical month (best goodness of fit). Thus the TRY is not always a realistic year in contrast to the DSY, but it gives a "good indication of a longterm average energy consumption" [46]. However, the DSY is created on a simpler way. The mean temperature in the period of April to September in the years from 1983-2004 is calculated and the year with the third warmest summer periode is the DSY.

Subsequently the five different percentiles are added which help to maintain the climate trend and to prohibit a inconsistent weather signal over the year because the scenario of an increasing temperature about 2°C in a year gives no information about the monthly change of temperature. Hence, an increase of 2°C can occur on the one hand when a slightly increase of temperature appears in all month and on the other hand when six months are cold and the second half year has an extremely higher temperature than before. This can lead to problems when the overheating risk is examined and so the probability is necessary. The five different percentiles are calculated by ranking the hundred TRY and hundred DSY from the lowest to the highest and subsequently the percentiles are selected. This proces is repeated for each month to create a probabilistic TRY or a probabilistic extreme weather year. Finally, the months are combined to a composite year by the method of Levermore [47], like the 50th percentile of January, 50th percentile of February, etc. will form together the 50th percentile year.

Converting weather data files and evaluate the created TRY and DSY

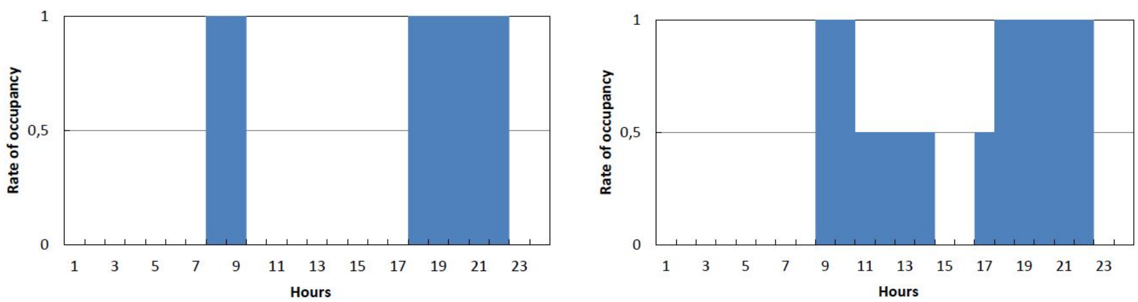
This step is not longer done by the UKCIP but by the University of Exeter which started the project PROMETHEUS to convert the weather data into .epw files. There are no further information given how the conversion works, but it is necessary to check the created future weather files by comparing the created future TRYs and DSYs with the TRY and DSY from CIBSE via simulations of a typical new built house and using a thermal model. The TRY and DSY from CIBSE are different, because they are based on UKCP02, future weather prediction made in 2002, and therefore have another period of years as baseline. This simulation is not done using EnergyPlus, but the industry standard dynamic thermal modelling program (IES) and are performed for Edingburgh, London and Manchester for all five percentiles of TRY and DSY and for the time periods 2050s and 2080s. The result of this comparison is that the future TRY of CIBSE and the created one are generally similar to each other except of some differences which can be explained due to the different baseline.

II. Occupancy rate



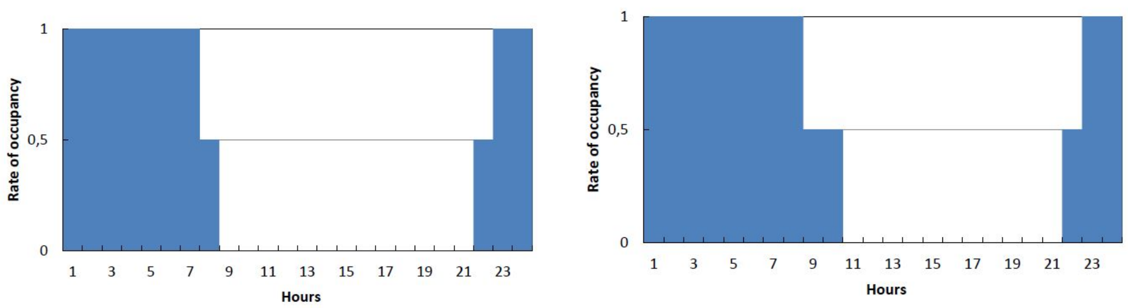
(a) During the week *(b) At the weekend*

Figure 8.2: Occupancy schedule for kitchen



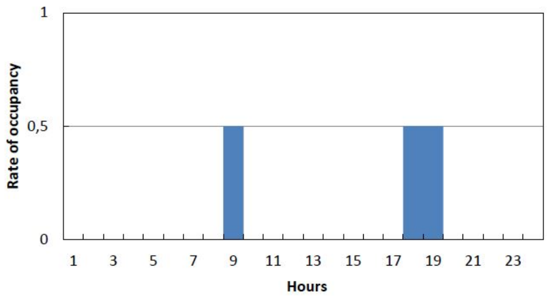
(a) During the week *(b) Occupancy schedule for livingroom at the weekend*

Figure 8.3: Occupancy schedule for living room

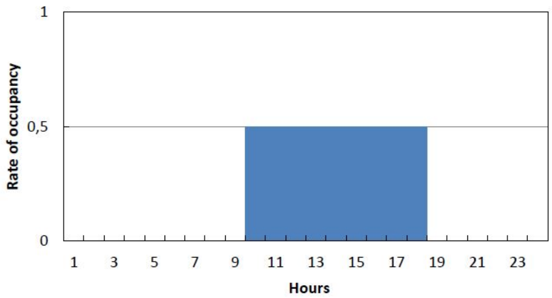


(a) During the week *(b) At the weekend*

Figure 8.4: Occupancy schedule for bedroom

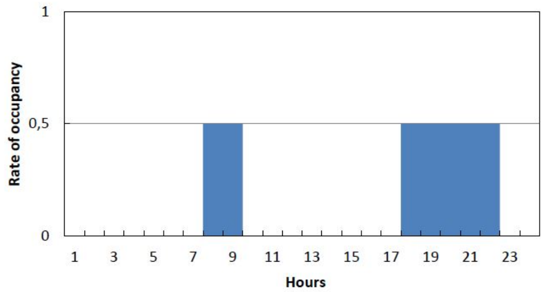


(a) During the week

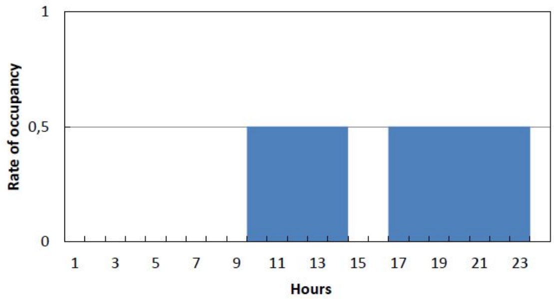


(b) At the weekend

Figure 8.5: Occupancy schedule for spare room

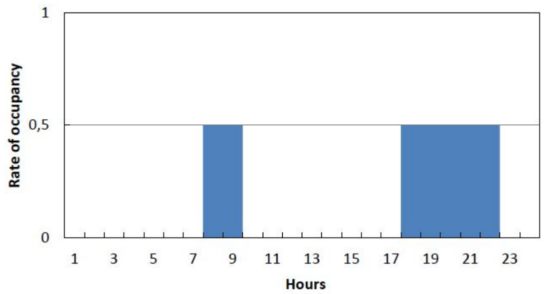


(a) During the week

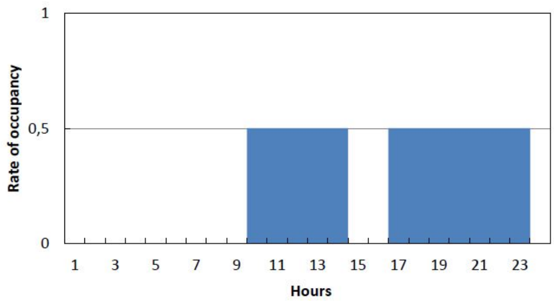


(b) At the weekend

Figure 8.6: Occupancy schedule for bathroom



(a) During the week



(b) At the weekend

Figure 8.7: Occupancy schedule for toilet, entrance hall, stairs and landing