A renewed degree-day model to estimate the space heating consumption of low-energy buildings

Case study of Ostarkade
office building in Frankfurt, Germany

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Abstract

A renewed version of the currently-in-use widespread degree-day method is investigated in this master thesis. By reviewing the literature and understanding the degree-day theory it is explicit that using a constant base temperature and analysing a low-energy building on a monthly scale lead to misleading results as it does not take into account specific knowledge of the gain to loss ratio of the building. Therefore this study presents a renewed degree-day method which calculates monthly base temperatures. Through the analysis of the low-energy office building Ostarkade, the space heating consumption estimate is compared with the measurement. It is also compared with two other estimations using constant base temperatures of 12°C and 15°C. The current degree-day method largely under-predicts the space heat consumption in the low-heating season for both base temperatures. The new estimation presents better results in all months of the year and especially in spring and autumn months. The model enables calculating hourly space heating consumptions with a maximum error of 8.8% on monthly total estimates. The model is flexible and allows sensitivity analyses on the input parameters. Also for the first time the impact of the user on the space heating consumption is investigated using the Morris method. The uncertainty analysis has shown that a variation in +/-2°C of the monthly set-point temperature impacts the monthly space heating consumptions up to +10% in colder months. Therefore the calculation of monthly set-point temperatures derived from yearly values need further research. The model also calculates average monthly internal temperatures and average monthly heat gains. This renewed degree-day method presents a basis for future work on monthly base temperature estimates for low-energy buildings. This model offers a new tool to estimate the hourly space heating consumption of low-

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1 Introduction

The increased energy use since 1980 has led to concerns regarding the impact of human activities on the planet. As of the XXIth century the growing awareness of greenhouse gas (GHG) emissions, climate change and the difficulty to supply energy from fossil fuels has stimulated the need to change energy, both the way it is produced as well as the way it is used. Policy responses to these concerns have encouraged strategic plans in all sectors aiming to reduce GHG emissions. In regards to heat production, minimizing energy use has remained especially challenging. According to the International Energy Agency (IEA), stimulating a market for heat is very challenging because both the heat supply and demand varies over time and seasons, due to the weather and local potentials (IEA, Policies for renewable heat 2012). The heat market comprises two end-use sectors, buildings and industry. Buildings represent the largest energy sector in the economy and the largest energy consumer sector worldwide, using around 40% of the total primary energy production. Furthermore, the demand in this sector risks increasing with future population and economic growth. Therefore, ithere is a real need to be attentive to the building sector and to improve its energy performance in order to insure long-term energy security. (International Energy Agency 2013) (International Energy Agency, UNDP 2013).

One of the most significant barriers for achieving building energy efficiency improvements is the lack of knowledge of the factors influencing energy consumption of low-energy buildings

(IEA, Buildings and Communities 2014)

1.1 Heat reduction in buildings: a new emerging sector

As of March 2007, the European Union (EU) Summit set out goals to reduce its emissions by 20% in a cost-effective way as its countries are currently responsible for around 11% of greenhouse gases worldwide. However, it is still unclear how this target will be reached among the 27 individual EU countries and how this reduction will be made through the different energy sectors. Although the power sector has been greatly improved in the last years in terms of installed capacities, the heat sector is still lacking policies in terms of installations and political instruments. (Veit Bürger, Stefan Klinski, Ulrike Lehr, Uwe Leprich, Michael Nast, Mario Ragwitz 2008). For this purpose European countries have adopted different strategies in order to reach improvements in the building sector, as national energy roadmaps in which different targets are set with different regulations and incentives to achieve them. In Denmark, by 2020 all new buildings should use 75% less energy than what is currently asked in regulation compared to 2006. By this time buildings in Germany plan to operate without the use of fossil fuels when in France, all new buildings built after 2012 have to be low-energy buildings and by 2020 all buildings energy-positive. (European Commission 2009). As heat demands and productions are greatly dependent on climates, it is a huge challenge in making common regulations between countries.

According to the IEA report on building energy codes edited in 2013, there are two different ways to address regulations, the prescriptive approach and the performance approach. The former sets minimum energy performance requirements for each component of the building, while the latter asks for a building's overall energy consumption requirement. Using both approaches would ensure a global approach. (International Energy Agency, UNDP 2013). This means that there are different requirements: requirements on the building envelope to reduce heat losses per transmission and ventilation, and requirements on the building's overall design in order to include new features and new technologies to optimise the comfort of users while minimising the energy demand. This is achieved through new features of design, also called bioclimatic architecture. Bioclimatic architecture is based on the principle that the building needs to take the best advantage of its surrounding environment to reduce its energy demand. This is achieved for instance by the orientation of the building to the sun, which allows solar gains to enter the building through windows and provide extra heat during autumn, winter and spring. Meanwhile, the use of shading should minimise over heating during summer and therefore reduce the cooling demand. Also, the use of energy efficient components to better insulate the building envelope allow reducing transmission and ventilation losses. (International Energy Agency, UNDP 2013).

Ensuring a global approach also means that synergies between different people need to be used and knowledge has to be shared. Indeed, people having knowledge about building components are building designers, whereas the overall energy consumption requirement takes into account design specifications about the building but also the heating system of the building. Therefore the energy planner needs as well to be integrated in this approach, as it needs to be a global approach. Indeed, the energy planner has knowledge about the heat sector and knows about heat productions and heat demands. As heat production and heat demand are dependent on climate variations, the energy planner needs a tool to estimate the heat demand of buildings on very short time intervals, as on an hourly basis for instance. The heat demand of the building is defined by the buildings characteristics and therefore by the building designer. Thus energy planners and building designers need to work together to create such a tool which would empower both of them. By sharing knowledge, they could find the optimal combination (or synergy) between energy efficiency and the heating system of the building. Creating tools to estimate the heat demand of low-energy buildings is a challenge considering the fact that low-energy buildings only represent a small share on the market and therefore data and literature are limited. It is likely that if building designers and energy planners, as well as energy engineers and civil engineers work together, the approach would be global and each participant could share and gain knowledge from each other.

1.2 The challenge of low-energy buildings

There is still no global definition for "low-energy buildings" across Europe. This is because although low-energy buildings are a growing market they are still limited: in 2009 there were 20,000 low-energy buildings in Europe of which 17,000 in Germany and Austria only (European Commission 2009). Yet, based on a study conducted by the Concerted Action supporting the Directive on the energy performance of Buildings in 2008, there are 17 different terms used for low-energy buildings such as low-energy house, high performance house, passive house, zero energy house, etc. Low-energy definition varies not only in terms but also in what energy use is included in the definition.

The requirements for a building to be “low-energy” really differ in each country, most of the time they include only space heating consumption but exclude the use of electricity. (European Commission 2009). According to an article written in 2013 about the state of the art on regulations for zero energy-buildings in Europe, quantitative targets could be easily set regarding renewable energy production on buildings for energy used for space heating and cooling and domestic hot water as a percentage or in relation to the building area. However it also says that some studies have shown that improving insulation on a building works better than improving boiler efficiency. (Eleonora Annunziata, Marco Frey, Francesco Rizzi 2013). Natural gas is the main fuel used for heating in the building sector in IEA member countries as gas consumed by buildings represented 58% of total final gas consumption in 2010. (International Energy Agency, UNDP 2013). This also demonstrates the need to provide energy to building by the means of renewable sources.

In regards to the building heat sector, it remains very challenging as both the heat demand and heat production strongly depend on the weather, and they differ in time and location. One of the challenges for new energy efficient buildings is to find the optimal combination between energy efficiency and renewable energy production as they are complementary in order to fit the energy consumption. The challenge is to lower the energy demand on buildings by using efficient building components and supplying the remaining demand from renewable sources. Taking into account weather variations is also a key point. Investors in energy efficiency and renewable heat are largely the same which may induce competition between the two sectors. Nevertheless, synergies also exist as a lower heat demand would make renewable heat affordable. (IEA, Policies for renewable heat 2012). One of the most significant barriers for achieving building energy efficiency improvements is the lack of knowledge of the factors influencing energy consumption of low-energy buildings (IEA, Buildings and Communities 2014). Planners and engineers are not used to new techniques and technologies involved in low-energy buildings which imply extra time and resources during the design and planning phases. Therefore it is necessary to investigate methodologies and tools to simulate the energy use in buildings across Europe and to emphasize the results to provide meaningful advice for better building energy performance. In the light of new tools, various sectors would be involved as building design, energy planning, urban planning, policy making, etc. If all sectors were effectively working together they could get better insight in the performance and implementation of energy-efficient buildings.

1.3 Degree-days, common tool to predict heating consumptions

The degree-day method is one of the most widespread and simple method used to predict heating consumptions. Degree-days are used to model the relation between energy consumption and the external temperature of the building. Degree-days are the summation of temperature differences over time and therefore they can capture both extremity and duration of temperature conditions (CIBSE 2006). The method is easy of use as it only requires the external temperature as an input data. The method has two main applications: (CIBSE 2006)

1) Estimate future energy demand
2) Monitor building energy performance

The first application uses the degree-days to calculate energy estimates. Degree-days are the summation of temperature differences between the exterior temperature of the building and a reference temperature, addressed in the literature as the "base temperature." The rate of heat loss from the building is directly related to this temperature difference, and the method enables to calculate space heating consumptions. (CIBSE 2006). Space heating represents a considerable percentage of the total energy consumption, especially in Nordic and moderate climate zones.

The other application aims to monitor building energy performance. For instance, if one wants to compare heating consumptions of the same building before (t) and after (t+1) the refurbishment of a building, one would compare the measured heating consumptions of the building between t and t+1. However, in order to properly compare the measured consumptions, the impact of the climate need to be removed from the comparison otherwise the calculation would make no sense. This is what is commonly called "climate correction" or "normalisation". If one wants to compare yearly space heat consumptions, then it is possible to use the current degree-day method. However in the case of energy management in buildings, one might want to look at monthly space heating consumptions, for instance to determine when actual energy savings from energy saving measures occur. In this case, if the building has become energy-efficient after the refurbishment, then using the degree-day method would lead to misleading results. The reasons why are detailed below.

The degree-day method is commonly used per a large type of different users, due to the fact that it is really easy of use and that large degree-day database exist online for given locations (Energy Lens 2013). People using the method for estimating future energy demand can be engineers working with architects in the design of buildings, or they can be designers of building control systems, engineers in renewable technologies, power station engineers, etc. People using the method to monitor building energy performance, they can be energy managers, policy makers in local or national government, people working for energy consulting firms or energy utility companies. They can be as well facility managers, energy auditors, or building energy consultants, etc. (Energy Lens 2013).

1.3.1 Problems with the method

"When applied to real-world buildings, common degree-day –based methods suffer from a number of problems that can easily lead to inaccurate, misleading results". (Energy Lens 2013). One of the problems with this method is the definition of the base temperature (Matjaz Prek; Vincenc Butala 2008). In both applications of the method, using the good base temperature is of relative importance as it determines the number of degree-days. The base temperature actually varies according to buildings, and also according to time for the following main reasons: (Energy Lens 2013)

- Buildings are heated to different temperatures
- Average internal heat gains vary from one building to another
- Average solar heat gains, vary through the day but also along the seasons
- Other climate conditions and occupancy pattern vary and has an influence on the base temperature

Therefore it is important to pick the good base temperature which fits the best to the building. As a building's base temperature typically varies throughout the year, even the most appropriate base temperature is usually only an approximation. The problem of the data is also raised in different literature. For instance in the UK, people commonly use the base temperature of 15.5°C because it is a lock-in in culture for a long time: it is known as being 15.5°C and it is the only base temperature for which a large set of data are available (Energy Lens 2013). Also, another source indicates that degree-days are often not used due to lack of availability of data for different time intervals, for different base temperatures and for appropriate weather stations (Layberry 2008). Another source indicated that the accuracy of degree-days was very ambiguous and therefore not helpful to energy managers which need robust tools and clear guidance on their use (AR Day; I Knight; G Dunn; R Gaddas 2003). Typically when the external temperature is very close to the base temperature, degree-days calculations fall apart. The inaccuracy introduced by the use of the wrong base temperature is strongly exaggerated at that time and therefore it is impossible to expect accurate results. (Energy Lens 2013). Also, it is recommended to use a yearly timescale for comparison of weather-normalised data. Finally, the combined effect of the problems leads a general very low accuracy in degree-days calculations, mainly because of the wrong base temperature. Still, even though the method presents large inaccuracies, the degree-day based monitoring and targeting is a central part of many energy management programmes. Therefore, if one wants to use the degree-day method, it is important to understand what cause inaccuracies. *"Otherwise you will frequently find yourself chasing excess consumption that doesn't really exist, and highlighting improvements that haven't really been made."* (Energy Lens 2013).

Among all these difficulties and inaccuracies related to the degree-day method, one can suggests than choosing the appropriate base temperature of the building would lead to accurate results. The equation of the base temperature (Tbase) is given by the following equations. QG are the total heat gains and U' is the overall heat loss coefficient of the building.

Eq. 1-1

$$Tbase = Tin - \frac{QG}{U'}$$

The base temperature of the building is calculated using this equation, assuming that the internal temperature of the building (Tin) is constant and that the gain to loss ratio $\frac{QG}{U'}$ is constant as well. This is discussed further in the section Literature review on degree-days. The degree-day method is working well for normative buildings but when it comes to energy efficient buildings this is not the case anymore. Low energy-buildings have very small heat losses compared to normative buildings and heat gains become a new target of interest. Therefore the gain to loss ratio $\frac{QG}{U'}$ of Eq. 1-1 becomes much higher than it used to be. This needs to be taken into account in the calculation of the base temperature.

In Germany, unsuccessful attempts have been made on reducing the base temperature to account for a higher gain to loss ratio for energy-efficient buildings. The degree-days estimates were still very low accurate. Therefore it is necessary to investigate other options in order to take these new features into account, which leads to the research question.

1.4 Problem Formulation and Research Questions

As previously discussed, the new emerging sector of low-energy buildings raises the problem that building designers, engineers and energy planners have only a limited knowledge of the new techniques and technologies associated with energy efficient buildings. Therefore, what are needed are simple tools to assess the performance of buildings and estimate their space heating consumption. Also, energy managers would be interested by such a tool. To ensure a global approach as indicated by the IEA, energy planners and buildings designers should work together to overcome the challenge of low-energy buildings.

As previously discussed, the current-degree day method is a widespread method which requires simple input data. It is used by different people among sectors around energy and buildings. Typical inaccuracies of the method were presented in the introduction. The main uncertainty in the degree-day method comes to the fact that people are used to calculate degree-days with a base temperature which is not the actual base temperature of the buildings considered. Furthermore, with low-energy buildings, further uncertainties arise from the fact that there is no specific knowledge about how the heat gains affect the space heating consumption along the year. Therefore, if one wants to keep using this method to predict monthly heat consumptions of low-energy buildings, the degree-day method needs to be renewed and adapted to this kind of building. Low-energy buildings present different features than normative buildings which need to be assessed. This leads to the research question:

How can the degree-day method be renewed in order to provide more accurate estimates of the space heating consumption for a low-energy office building?

In order to respond to this research question, the following sub-questions will be answered through different chapters:

1. *What are the defaults of the degree-day method and which improvements can be made to adapt the method to low-energy buildings?*
2. *Which input parameters are influencing the most the space heating consumption?*
3. *What are the main differences in the results of the space heating consumption profile calculated through the renewed degree-day model compared to the current degree-day method?*
4. *How could the model be validated?*
5. *What would be the utility and usage of this renewed degree-day model?*

1.4.1 Aim of the project

This master thesis aims to create a model based on a renewed degree-day method which includes new features of low-energy buildings. The Eq. 1-1 presented in the introduction is investigated to calculate the true base temperature of the building. The model is built using a low-energy office building as a study case, the building Ostarkade. The building is new, energy efficient and located in Frankfurt, Germany. Its full description is available in chapter4. In order to account for variations in climate and building occupancy, the model aims to calculate varying base temperatures along the seasons. The renewed degree-day model should be able to provide a better prediction of the space heating consumption of the low-energy building investigated compared to the one calculated with the current method. The model should allow sensitivity analyses on the input parameters in order to identify the key parameters influencing the space heating consumption.

1.4.2 Delimitations

Different delimitations for the modelling have been made. The analysis is limited to the prediction of the space heating consumption and does not include the months of June, July and August. The study does not investigate the hot water demand. The model does not investigate neither the cooling consumptions. The model only applies to office buildings and therefore does not apply for residential buildings as their space heating consumption differs. However they only differ in the modelling regarding the usage of set-point temperatures and hours of occupancy. The representation of the space heating consumption used in a flat is easier to model than the one used for an intermittent heated building as an office building. Therefore if one wants to use the model to analyse a residential building it would be possible to modify the model and make it work for a residential building. The model only provides the calculation of monthly base temperatures and does not go on a deeper scale as weekly base temperatures or daily base temperatures. However, following the methodology given to construct the model it is possible to calculate weekly base temperatures, daily base temperatures or seasonal base temperatures.

Regarding the data, the analysis was limited to one case study, the building Ostarkade. A small part of the building includes flats, but they were excluded of the analysis. Also the analysis was conducted only during the year 2005 in Frankfurt, Germany. Some of the input data themselves induced delimitations in the analysis: as some were unknown, assumptions had to be made. Therefore this limits somehow the validation of the robustness of the model. The model was compared to the widespread current degree-day method but was not compared to more detailed models.

1.4.3 Definitions

1.4.1.1 Degree-days

Degree-days are a tool that can be used in the assessment and analysis of weather related energy consumption in buildings. Degree-days are essentially the summation of temperature differences over time; the temperature difference is between a reference temperature, also called base temperature, and the external air temperature. The two main uses of degree-days in buildings are to estimate energy consumptions due to space heating and cooling for new build and major refurbishment and for on-going energy monitoring of existing buildings based on historical data. (CIBSE 2006).

1.4.1.2 Base temperature

The base temperature is for buildings a balance point temperature, which means the outdoor temperature at which the heating system does not need to run in order to maintain comfort conditions (CIBSE 2006).

1.4.1.3 Set-point temperature

The set-point temperature is the temperature until which the heating system needs to provide heat in order to maintain certain inside temperature and comfort conditions inside the building.

1.5 Outlines

This section details the outlines of this master thesis.

1.5.1 Methodology

This chapter presents the methodology of this master thesis. It contains information about the literature review, about the data collection and about the methods used for the sensitivity and uncertainty analysis. The chapter also presents the model, the way it was built, its input parameters, assumptions related, and main equations.

1.5.2 Literature review on degree-days

This chapter aims to answer the following question. Literature review was conducted in order to lay the basis for equations used in the modelling.

"What are the defaults of the degree-day method and which improvements can be made to adapt the method to low-energy buildings?"

1.5.3 The renewed degree-day model

This section regroups the description of the building case study and the sensitivity analysis of its input parameter. The way the model was built is described in the methodology in order to assess its reproducibility. The sensitivity analysis is conducted different times: the sensitivity of each key parameter to its related input parameters is tested through the model. The sensitivity of the space heating consumption to all parameters is also investigated, as well as its sensitivity to the key parameters. The sensitivity of the base temperature to the key parameters is also investigated. In the chapter the results of the sensitivity analysis are presented. They aim to answer and partially answer respectively the following sub-questions:

"Which input parameters are influencing the most the space heating consumption? "

"How could the model be validated?"

1.5.4 Results of the analysis

The chapter presents the results of the analysis. It presents the hourly space heating consumption of the building Ostarkade which is compared to other calculated space heating consumptions with a constant base temperature and to the real measured space heating consumption. In this section the key parameters influencing the space heating consumption are investigated in details. The uncertainty of some parameters is also investigated, either because the parameter is uncertain and in order to quantify its uncertainty, either to test the robustness of the model. The chapter aims to answer and partially answer respectively the two following sub-questions:

"What are the main differences in the results of the space heating consumption profile calculated through the renewed degree-day model compared to the current degree-day method?"

"How could the model be validated?"

1.5.5 Discussion

This chapter interprets the results, compares them with the literature, discusses the methodological approach, the choice of the assumptions, etc. The chapter aims to answer and partially answer respectively the two following sub-questions:

"What would be the utility and usage of this renewed degree-day model?"

"How could the model be validated?"

1.5.6 Conclusion

This chapter summarises the conclusions of this master thesis. It also presents further perspectives on this research. It aims to answer the research question stated in the problem formulation which is:

How can the degree-day method be renewed in order to provide more accurate estimates of the space heating consumption for a low-energy office building?

2 Methodology

This section details the methodology followed in this master thesis. Different types of methods were used during the project, as literature review, collection of data, modelling, sensitivity and uncertainty analyses. The main analysis is conducted on a building study case. This chapter presents which type of data was used and how they were collected. This chapter also presents the way that the model was built in details.

2.1 Literature review

A literature review is used during the entire project, especially along the first part in order to conduct a state-of-the-art review about available information regarding the current degree-day method. Literature review was also used to gain specific knowledge about low-energy buildings: their key design feature, their use, the standards and applications. Different documents have been precious help for this project, they are:

- A scientific publication from the Chartered Institution of Building Services Engineers (CIBSE) about the theories and applications of the degree-day method (CIBSE 2006)
- The monitoring report of the reference building Ostarkade provided by the Karlsruhe Institute of Technology (KIT). It was useful to learn about specific data and monitoring of the building. ((fbta) 2006)
- The International Organisation for Standardisation (ISO) norm *"Energy performance of buildings"* has been greatly used to get inspiration about how to model and analyse heat flows in the building. (ISO 2008)
- Two scientific articles about the problems related with the current degree-day method and possibilities for improvements by A.R. Day and T.G. Karayiannis. (A.R. Day; T.G. Karayiannis 1999) (A.R.Day; T.G.Karayiannis 1999)

It needs to be specified that the subject of degree-days used to estimate the energy consumption of low-energy buildings is new and could not explicitly be found in the literature. For this purpose, the chapter 3Literature review on degree-days in this report summarizes the literature review of degree days and problems related to it. This section is mainly based on the sources listed above. Almost all the literature used is in English, but some of it was also in German.

2.2 Building study case

This master thesis is constructed on the basis of a study case, the office building Ostarkade located in Frankfurt, Germany. The building analysed as a study case in this master thesis is presented in chapter 4. The choice of an office building has been made as it is the most wide-spread type of building to be low-energy, as usually investors are rather companies than individuals. Also it was compelling to analyse an office building in the sense to account for intermittency effects. This aspect makes the study case more interesting as only a part of the heat gains can be used as there is no need for heat during the night and week-ends. The aim to work on a building scale is to seek to model the heating consumption of one building as a function of its input parameters. Therefore a change in input parameters will influence the outputs of the model. This study case is analysed with the bottom-up approach, when results on one specific study case can be emphasized. According to a review of modelling techniques on energy end-use consumptions in buildings, bottom-up engineering models are greatly used to investigate new technologies (Lukas G. Swan, V. Ismet Ugursal 2008). This kind of model is precisely required to identify the impact of technologies on low-energy buildings energy consumption. In particular, they can easily be used to quantify the “free” heat gains enabled from new features of design, which now represent a key point in building’s energy consumption. Indeed, the heat gains will be one of the outputs of the model. Also, bottom-up approaches can explicitly address the effect of occupant behaviour, which is usually very hard to define. (Lukas G. Swan, V. Ismet Ugursal 2008). This is also a main advantage of the model. An uncertainty analysis using the model can also be performed to assess the effects of input uncertainty in the Results of the analysis. It means that by changing input data regarding user behaviour, it impacts on the heat consumption can be quantified. Therefore it is interesting to work on a building study case because:

- The influence of the input parameters on the output parameters can easily be assessed by changing the input parameters
- The model calculates monthly mean heat gains, monthly mean internal temperatures and monthly mean base temperatures as output data, and some others.
- The impact of the uncertainty in some input parameters (and especially user behaviour) on the space heating consumption can be quantified

2.3 Data collection and use

The data of the building are provided by the Karlsruhe Institute of Technology (KIT) in Germany. They were in charge of the monitoring of the building in the context of a German project on energy optimized buildings (EnOB: Research for energy-optimised construction s.d.). Therefore they provided a monitoring report of the building and also characteristic data as the heat transfer coefficient, the transmittance value of the windows, building size, volume and usage, etc. In the context of the monitoring they collected and measured data of the building. The relevant data provided which were used in the modelling are the following:

- Heat production data (hourly)
- Space heating consumptions (monthly)
- Outside temperatures (hourly)
- Horizontal solar radiation (hourly)
- Horizontal illumination and illumination on the fourth facades of the building (hourly)

As the building seeks to estimate space heating consumptions, hourly space heat consumption needed to be calculated from the hourly heat production data and monthly space heat consumptions. Indeed, the aim of the analysis was to estimate the space heat consumption (SHcons) of the building. In order to validate the model, the estimated SHcons was compared to the measured SHcons. The hourly heat production data are used to create a distribution file. The production was distributed monthly according to the monthly space heating consumption data. Outside temperatures and solar radiations are necessary for the analysis as they allow estimating the heat losses and the heat gains of the building respectively. Unfortunately, no data were available regarding solar radiation on each façade of the building. Therefore illumination on the five facades (including the horizontal façade) was used to calculate solar radiations on each façade. This is described further in the next sub-section (see Figure 2-2 and Figure 2-3). As monthly heat gains needed to be calculated, only monthly average solar radiation data on each façade of the building were used. This means that if one has monthly average horizontal solar radiation data and knows how to calculate its distribution on the other facades, then it is possible to conduct the analysis using the model. Climate data were available for different years, the year 2005 was chosen for the analysis as it seemed to be the one presenting the most reliable data. As climate data are input data of the model, using for instance climate data of another year would influence the output of the model. Using climate data of a specific year ensured a precise analysis of the building. Therefore, using for instance averaged climate data over twenty years would results in estimated consumptions with less precision. The impact of the climate data on the estimated heat consumption is analysed through an uncertainty analysis.

2.4 Modelling

In order to perform the analysis a model is created using Microsoft Excel. Making a model allows flexibility of the modelling which was the main reason why the analysis was not conducted through any software and why a model had to be created. Also, any software has been found interesting for the analysis, as all software was either too detailed either not enough. Microsoft Excel is user-friendly software, fast, and large help assistance is available online. The model seeks to model a renewed version of the degree-days method. Literature review of the degree-day method and possible ameliorations are presented later. In the literature review, equations given lay the basis of the modelling. The model allows calculating monthly average heat losses and monthly average heat gains of the building based on simplified heat flows of the building. For this purpose the model integrates more detailed input data about the building compared to the current degree-day method which only needs external temperatures.

2.4.1 Input data

The model can be used as a black box. This means that the equations inside can be disregarded and one can look at the output data only by setting the input data. The advantage of the model is that it allows calculating the hourly space heating consumption if data for the hourly outside temperature are accessible. Also, the model allows detailed calculations considering of the detailed input parameters, compared to an analysis which would use the current degree-day method. The model can only be approximate regarding the number of assumptions which need to be made in the input data. Some of the input data can be easily collected as they are defined at the design stage of the building. For the building case study, almost all data of the building were provided by the Karlsruhe Institute of Technology. Some other data are hard to define and can have a large impact on the results, as for instance the impact of the user. In order to see the influence of the main input parameters on the space heating consumption, it is possible to conduct a sensitivity analysis which is also an advantage of the model. The results of the sensitivity analysis are shown in the next chapter. As detailed in Eq. 1-1, the key parameters of the model are the internal temperature, the heat gains and the overall heat loss coefficient. In order to calculate them, different types of data are needed and they are presented in the Table 2-1 below. The external temperature is measured hourly. As it is needed to calculate monthly heat gains, monthly mean solar radiation data are needed. As hourly data were provided, they were averaged over a month. The data regrouped in “characteristics of the building” are known data as they are provided by the Karlsruhe Institute of Technology. The last type of data concerns the use of the building by its occupants, and the most uncertain is the set-point temperature as only the average value over the year is given. However, based on literature it is possible to make some assumptions.

Table 2-1 Input data for the modelling

Climate data	Characteristics of the building	User's behaviour
External temperature (°C)	Volume (m3)	Set-point temperature (°C)
Solar radiation on each façade of the building (W/m²)	Surface area (m²)	Hours of occupancy (hours)
	Size of windows on each façade (m²)	Number of people
	Thermal capacity (J/K)	
	Heating system capacity (kW)	
	Overall heat loss coefficient (W/K)	
	G-value of windows	

2.4.2 Definition of key parameters

2.4.2.1 The overall heat loss coefficient U'

The overall heat loss coefficient is the sum of the heat losses by transmission and heat losses by ventilation. The heat losses by transmission are calculated using the heat transfer coefficient and surface of the building. The ventilation losses are calculated using the air infiltration rate of the building and the volume of the building. As no value was given for the air infiltration rate, a value taken from literature review has been chosen. As it is known that the building has reduced ventilation losses due to an efficient heat recovery system, the value for air infiltration rate was purposely chosen to be low and adapted to energy efficient buildings (International Building Code 2009). Detailed equation of U' is available in Appendix D. The equation used is the one given by the CIBSE (CIBSE 2006).

2.4.2.2 The mean inside temperature of the building Tin

Tin is the monthly internal temperature, it is one key parameter to calculate the monthly base temperature. The average inside temperature of the building is used instead of the traditional set-point temperature in order to account for intermittency effects. Indeed, the average Tin becomes lower than the set-point temperature (Tsp) during the night and during the week-ends when there is no heat demand. Therefore the average inside temperature of the building is slightly lower than the set-point temperatures. The use of the monthly Tin instead of the Tsp with corrections factors is more accurate (A.R. Day; T.G. Karayiannis 1999). The equation used for the monthly average Tin is the one that has been presented by A.R.Day and T.G.Karayiannis (A.R.Day; T.G.Karayiannis 1999). The monthly average Tin is the weighted average of the set-point temperature Tsp during hours of occupancy and of the internal temperatures when hours of non-occupancy. This sum of hours is calculated based on different factors and mainly the time constant of the building which is an indication of how long the building can store the heat into its thermal mass. Therefore, the monthly average Tin greatly depends on the monthly Tsp, the number of hours of occupancy and on the building time constant τ which is given in the Eq. 2-1 below:

Eq. 2-1

$$\tau = \frac{C}{3600 \times U'}, \text{ (ISO 2008) (CIBSE 2006)}$$

- The building time constant (τ) is the rapport between the thermal capacity (C) of the building and its level of insulation (U'). It is given in hours.

The higher the thermal capacity and the better the insulation of the building is, the longer the time constant will be. It represents the time and the ability of the building to store and release the heat, therefore regulating the inside temperature of the building. For instance if the building has a high time constant, then summer comfort will be greater than with a low time constant. This is because the internal temperature will vary less with a high time constant.

- The set-point temperature (Tsp) is the temperature that the heating system aims to reach

This means that if the set-point temperature of the building is for instance set to 21°C, the heating system will run until the inside temperature of the building is 21°C. The set-point temperature (Tsp) is usually defined in the operation of the heating system, but it is also possible that the user can have an impact on it depending on the type of building. According to the monitoring report, the user has the possibility to change the Tsp up to +/- 3C compared to its original set-point ((fbta) 2006). According to a PhD thesis on "control strategies for intelligent facades", the ideal seasonal set-point temperatures for control optimisation along the seasons are 20°C-24°C in winter, 21.5°C-24.5°C in spring and autumn, and 23°C-26°C in summer (Anne Valler; Stine Noe Brandstrup 2012). Varying the set-point temperature along the seasons does not decrease the comfort of the users when it does considerably decrease the space heating consumption (J.F Nicol; M.A Humphreys 2002). Therefore it is likely that it is planned that the set-point temperature of the building, Tsp, is programmed to be lower during the winter and higher close to summer months considering the amount of energy which can be saved. Also, the user regulates the inside temperature of the building regarding his comfort temperature and it is assumed that occupants have a lower comfort temperature in winter compared to summer due to higher temperature differences with the winter outdoor (J.F Nicol; M.A Humphreys 2002). Based on these two assumptions it is likely that the set-point temperature varies along the seasons, with higher set-point temperatures in summer and lower set-point temperatures in summer. The set-point temperatures (Tsp) chosen as input data are in Table 2-2 below.

Table 2-2 Monthly set-point temperatures chosen as input data

Tsp	January	February	March	April	May	Sept.	Oct.	Nov.	Dec.
°C	21.7	22	23	23	23	23.5	23.5	20.8	20.8

2.4.2.3 The heat gains QG

QG represent the heat gains into the building, they are the summation of the internal gains (QG',int) and the solar heat gains (QG',sol). Once the total heat gains to the building are calculated, a utilisation factor is needed to know how much of these heat gains can actually be accounted to offset the heating demand (CIBSE 2006) (ISO 2008).

- The internal gains are calculated based on the occupant density of people in the building.

A study conducted on several office buildings has shown that there is a relationship between occupant density of people and calculated internal gains. Even though gains will be different for type and usage of buildings, they showed that from occupant density internal heat gains can be calculated (see Figure 2-1). (CIBSE 2006). According to Figure 2-1 the lower is the occupant density; the higher are the internal heat gains. This means that on a constant surface in m², more people (and by extrapolation more gains from electronic devices and lights) imply more internal heat gains. Typically, internal gains in office buildings are much higher compared to residential buildings because of electronic equipment and amount of people in the building (Tilmann E. Kuhn 2005). However, another source explains that *"it is often said that the internal gains coming from lighting, the computers and other equipment of offices make the solar gains superfluous in the office buildings. Certain studies indicate that such assertions are exaggerated."* (Elisabeth Gratia; André de Herde 2003) Indeed, selective measurements have shown that internal gains from lamps and equipment function are currently less long than expected. New equipment in most of office buildings is generally turned off during the night which considerably reduces their use. Also, the use of daylight reduces the need for artificial light which reduces internal heat gain from equipment. Therefore using electricity in a more effective way leads to a new insight to consider passive solar heat gains instead of active heat gains from electrical power. (Elisabeth Gratia; André de Herde 2003).

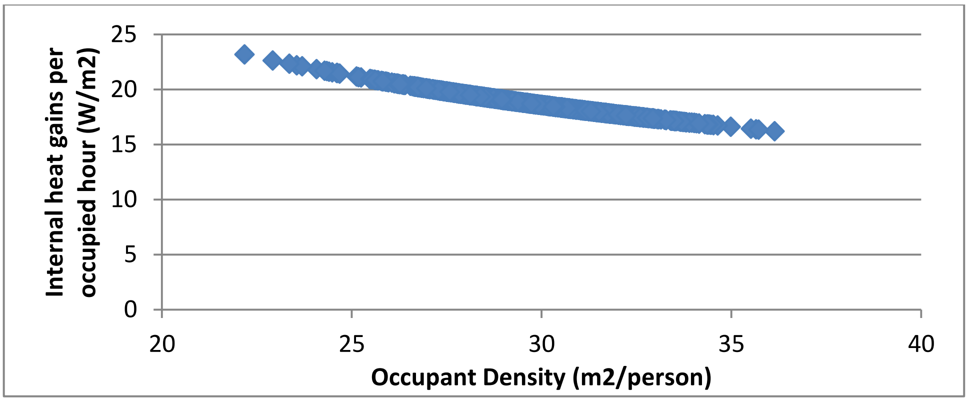

Figure 2-1Relation between occupant density and internal gains per occupied hour

For these reasons, as the building has a high percentage of daylight and probably has energy-efficient equipment, it is likely that the actual internal heat gains of the building are lower than the one calculated in the analysis.

- The solar gains are calculated using data from the solar radiation.

It is necessary to use data of solar radiation on each façade of the building to calculate the solar gains. However, there were no measurement for vertical solar radiation but there were vertical and horizontal measurement for illumination. As can be seen on the Figure 2-2 below, the solar radiation and the illumination on the horizontal façade follow the same curve over the year.

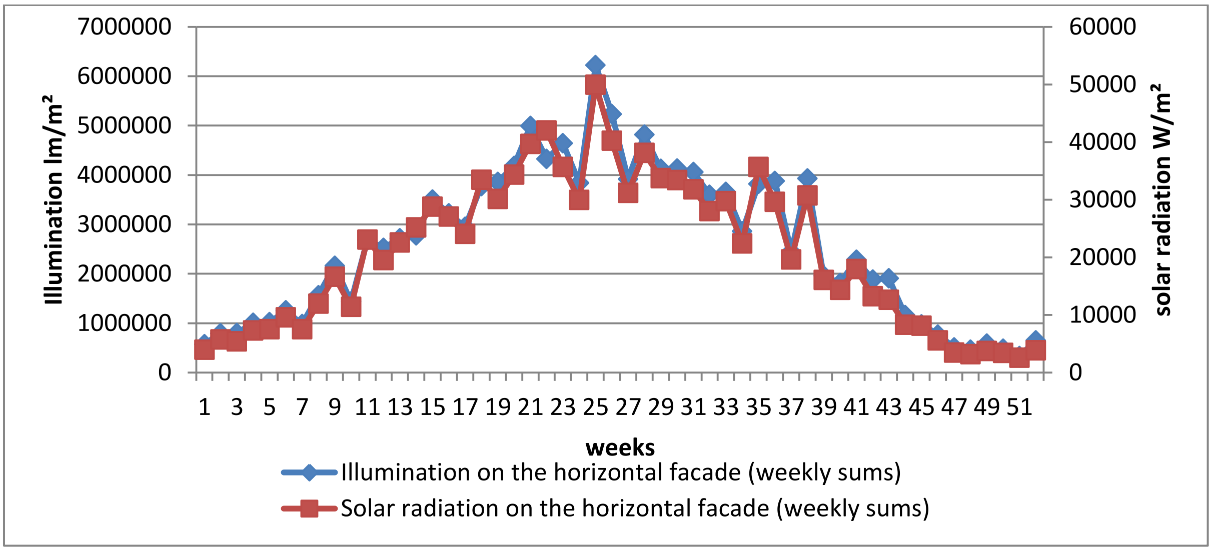

Figure 2-2 Illumination and solar radiation on the horizontal facade (weekly sums)

Therefore a correlation was made between horizontal solar radiation data and illumination data, inspired by a simple model deriving illumination values from solar radiation data (Sokol Dervishi; Ardeshir Mahdavi 2013). Figure 2-3 shows a very good correlation of 0.9 between the horizontal illumination and horizontal solar radiation therefore the accuracy of the method. A correlation is considered as very good if it is superior to 0.9, reasonable if it is close to 0.75 and bad if it is inferior to 0.7 (Lens 2013). In our case, the R^2 is 0.9. Values for solar radiation on each façades can be calculated using values for illumination on each façades and the equation of the linear regression analysis.

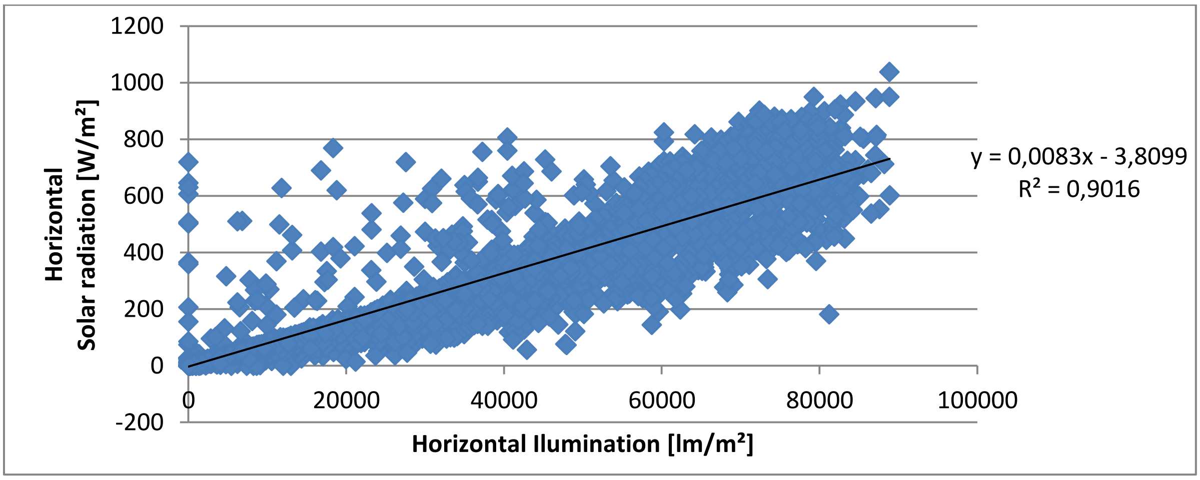

Figure 2-3 Linear regression analysis of the solar radiation and the illumination on the horizontal facade (atrium)

Solar radiations on each façade multiplied per their respective size of windows give the solar radiations in Watts. By multiplying each solar radiation with the g-value of the window, it possible to calculate the total solar gains on each façade. Then the solar gains of each facade are summed together which give the total solar gains. Furthermore, the use of blinds during summer to prevent overheating needs to be considered. As the way the blinds have been used is unknown, some assumptions were made using indications given by the ISO (ISO 2008). The ISO uses a procedure which assumes that when blinds are closed, then the amount of solar radiation received on the window is considerably reduced. The solar radiation received by the window when blinds are closed is reduced between 90% and 65% when external blinds are used (ISO 2008). The building under consideration has external venetian blinds. In the analysis, they are modelled as the following: the solar radiation on each façade except the horizontal façade is reduced per 70% if the solar radiation exceeds 500 W/m² in a given hour. As the atrium (horizontal façade) aims to provide daylight in the building, it is assumed that there are no blinds on the horizontal façade.

The total solar gains are summed with the internal gains. This gives the total uncorrected heat gains Q'G. Q'G is defined in Watts. The internal gains are only accounted during hours of occupation of the building. Detailed equations are given in Appendix D. It is also necessary to use a utilisation factor to assess which part of the heat gains is usable to offset the heat demand.

- The gain utilisation factor η

The utilisation factor is a function of the heat balance ratio ϒ and the time constant of the building τ. This number varies between 0 and 1. The heat balance ratio represents the average monthly uncorrected heat gains (Q'G) divided by the average monthly heat losses (QL). The heat balance ratio is calculated for each month such as the utilisation factor. Full equations are given in Appendix D. The gain utilisation factor is defined independently of the heating system characteristics. It is a measure of overheating (ISO 2008). Indeed, the utilisation factor is necessary because it takes into account the fact that only a part of the heat gains is used to actually decrease the heat demand. The other part of the heat gains would lead to an increase in the inside temperature, above the set-point temperature. This is undesired, and particularly in spring and autumn this would lead to overheating of the building. Therefore only the "desired" part of the heat gains is used, which is calculated with the utilisation factor. In the case of an intermittent heated building as the analysed building, the gain utilisation will be less than for a continuously heated building. This is due to the fact that the absorbed gains into the structure are only remitted into the space when temperatures drop, which occurs at night (CIBSE 2006). So these gains cannot be used to maintain thermal comfort and offset the space heat demand as there is no need for heat by night. This results in a lower utilisation factor than for a residential building for instance. Also by night the difference between outside and inside temperature is higher in intermittent buildings than continuously heated building, which results in greater temperature difference so higher heat losses and longer pre-heat time. In addition as there are no heat gains by night, all the pre-heat need to be supplied by the heating system. This results in a higher heat demand. The monthly gain utilisation factor is calculated following indication of the ISO (ISO 2008). Once each monthly gain utilisation factor (η) is calculated, it is multiplied with each monthly average uncorrected heat gain (Q'G). This results in the usable monthly average heat gains QG. The way that the key parameters and monthly base temperatures are calculated from the input data is shown in the flowchart below on Figure 2-4.

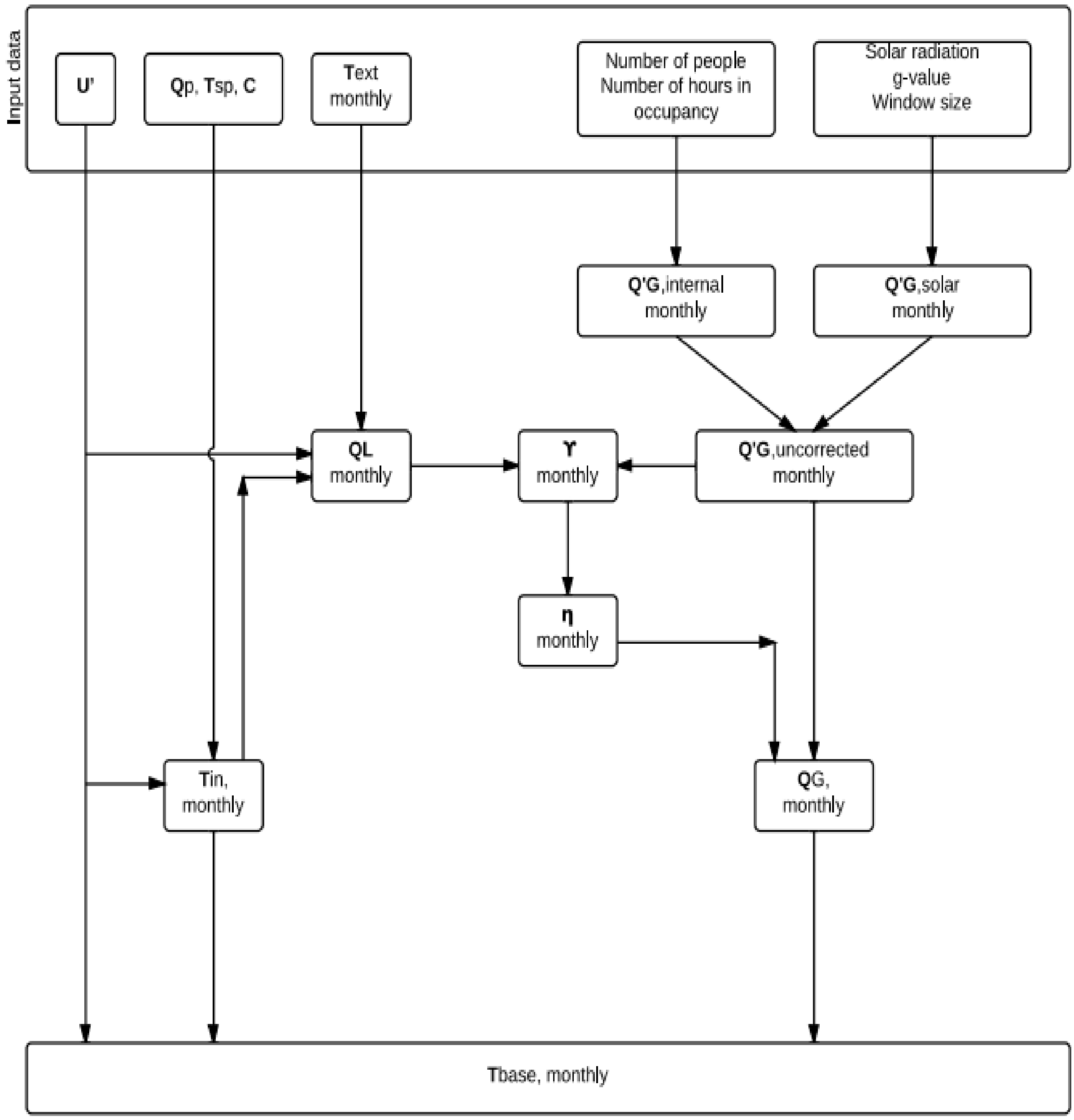

Figure 2-4 Flow chart of the model (from input data to monthly base temperatures)

2.5 Sensitivity analysis

The sensitivity analysis is made in order to know which input parameters influence the most the different output parameters of the model.

"A sensitivity analysis determines the contribution of the individual design variable to the total performance of the design solution". (IEA ECBCS; Per Heiselberg 2010).

Different methods exist to conduct a sensitivity analysis, which are mainly screening methods, local methods or global methods. The method chosen in this project is the Morris method, a screening method which varies one-factor-at-a-time and is referred to this specific method OAT. The method allows the identification and qualitative ranking of the input parameters influencing the most the outputs in the model. The method is found to be suitable for the analysis as it is often used in building simulations. In particular, the method was chosen because it does not require the relation between input and output parameters to be linear. The method is a sample-based method and proceeds as the following: (IEA ECBCS; Per Heiselberg 2010)

- A probability density function (pdf) is assigned to each input parameter of the analysis
- A set of random samples are created following the pdf distribution
- A matrix of input parameters is created and the model generates as much output parameters as there are of input parameters

The method is computationally intensive considering the number of samples analysed. From the sample of output parameters created it is possible to calculate the mean μ and the standard deviation σ. A high averaged mean will result in a large standard deviation and therefore a large sensitivity value, and vice versa (IEA ECBCS; Per Heiselberg 2010). The disadvantage of this method is that it is not linear and therefore does not allow performing an uncertainty analysis as the output does not keep the shape of the pdf. (Hopfe 2009).

2.6 Uncertainty analysis

An uncertainty analysis is made in the results section for two reasons: first to assess the impact of uncertain input parameters, second to assess the impact of possible uncertain input parameters. The difference between the uncertainty analysis and the sensitivity analysis is:

"An uncertainty analysis determines the total uncertainty in model predictions due to imprecisely known input variables, while a sensitivity analysis determines the contribution of the individual input variable to the total uncertainty in model predictions." (IEA ECBCS; Per Heiselberg 2010)

The uncertainty analysis chosen is a local method called "differential analysis". This method was chosen because it seemed to be the only method which does not require extensive calculations. The method, as being a local method, assumes a linear relation between input and output variables. (Macdonald 2002).This fits with the parameters which are chosen for the uncertainty analysis. The parameters chosen are the ones for which it is difficult to assess a number with certainty; they are user-dependent parameters or climate-dependent parameters. The methodology used for the uncertainty analysis was to vary the two extremes of the parameters in order to see the maximum range of influence of the input parameter on the output parameter. Therefore the uncertainty analysis ensures to quantify the effects of certain input parameters uncertainty identified during the analysis on the model output.

3 Literature review on degree-days

This chapter presents a literature review on degree-days. The aim of the chapter is to presents the degree-day theory and equations, identify the problems related with the current degree-day method and identify what could be improved from the current method. This chapter aims to answer the following sub-question

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What are the defaults of the degree-day method and which improvements can be made to adapt the method to low-energy buildings?

3.1 The current degree-day method

Degree-days represent the summation of the difference between the predefined base temperature of the building and the actual outdoor temperature. Monthly degree-days can be calculated as well as daily degree-days or hourly degree-days (degree-hours). The advantage of the method is that it is easy of use and requires only very few input data. Also, the method can calculate degree-hours for a year without being computationally intensive. The main disadvantage is that the method can only be approximate because it is a simplified method. This will be discussed further in the report, especially in the Discussion (CIBSE 2006).

3.1.1 The theory behind the method

There are different methods which can be used to calculate degree-days. The most rigorous, precise and mathematical method among the others is the one used in this report (CIBSE 2006). The Eq. 3-1 to calculate hourly degree-days is given below. Eq. 3-1 to are given by the CIBSE (CIBSE 2006).

Eq. 3-1

$$Hourly\ DD = (Tbase - Text) \qquad if\ (Tbase - Text) > 0$$

From hourly degree-days, daily degree days can be calculated by summing hourly temperature differences and then dividing them by the number of hours of the time frame (24 hours for a day for instance). The formula of daily degree days is given below:

Eq. 3-2

$$Daily\ DD = \frac{\sum_{i=1}^{24}(Tbase - Text,i) \qquad if\ (Tbase - Text,i) > 0}{24}$$

Eq. 3-1 can be used for any kind of time frame, for instance to calculate weekly degree days (sum hourly degree days and divided by 168) or monthly degree days (sum hourly degree days and then divided by 24 times the number of days in that month).

The base temperature (Tbase) is the outside temperature (Text) at which the building does not require any heating. For instance, if the base temperature of a building is set to 12°C, it means that when it is 12°C outside, no mechanical heating is required inside: the heat is provided by other sources. These other sources can be internal gains or solar gains. Internal gains are provided by people and equipment inside of the building when the solar gains are provided by solar radiation through windows and walls. Therefore internal gains are dependent of the occupancy and use of the building when solar gains do depend on climate variations. The heat can also be provided by the structure of the building, because the building has the capacity to store heat into its structure. Therefore the base temperature does depend on:

- Climate conditions (outdoor temperature and solar radiation)
- Use of the building

As the base temperature depends on the use of the building, it is given through two different formulas depending on the kind of building: continuously heated building or building with intermittent heating. It is assumed that for instance a flat is continuously heated when an office building is heated per intermittence. As there is no one inside the building during the week-ends, the building is no heated or less heated. For continuously heated buildings, the base temperature is calculated using the following formula.

Eq. 3-3

$Tbase = Tsp - \frac{QG}{U\prime}$ *Given for continuously heated buildings*

- Tsp is the set-point temperature of the building
- QG are the building heat gains, the summation of solar heat gains and internal heat gains
- U' is the overall heat loss coefficient of the building

Eq. 3-3 assumes that the temperature inside of the building is the set-point temperature. The gain to loss ratio $\frac{QG}{U\prime}$ represents the surplus heat. The heat gains QG need to be divided by the overall heat loss coefficient U' because this coefficient is multiplied by the temperature difference between base and outdoor temperatures to calculate the space heating consumption. This Eq. 3-4 is given below. The problem is that the solar gains vary on a daily and seasonal basis, and also the set-point temperature. This suggests that the base temperature also varies along the year. Also, from the heat gains calculated it has to be distinguished how much of them can actually be used. This will be discussed further in the report in the Discussion.

Regarding intermittent heated buildings (which is the case of office buildings), this equation is slightly different. In the scientific publication "*Identification of the uncertainties in degree-day based energy estimate"* written by A.R.Day and T.G.Karayiannis, it is explained that the use of the set-point temperature in the calculation of the base temperature does not account for intermittent occupancy. It is demonstrated that using mean internal temperatures instead of the set-point temperature for buildings with intermittent occupancy and heating (office buildings) give better results than using traditional correction factors. By using the set-point temperature, one has to use correction factors for when the building is unoccupied, which does not allow flexibility in the modelling. Also, the uncertainty of these corrections factors has not been demonstrated anywhere. A.R.Day and

T.G.Karayiannis have investigated different ways to calculate the base temperature with different time frames. Their analysis has shown that base temperatures calculated with hourly solar gains estimate degree-days with an accuracy of 0.521. Indeed, accounting for hourly solar gains is a misleading hypothesis as it assumes that all the solar gains are instantaneously used to offset the heat demand. This is usually not the case as during the day, a part of the heat gains is actually stored in the thermal capacity of the building structure. They also demonstrated that using parameters with different time frames in the base temperature calculation has also led to a low accuracy. Among the different calculations presented by A.R.Day and T.G.Karayiannis, the monthly base temperature calculated with monthly mean inside temperatures and monthly mean heat gains is the model which presents the best accuracy of 0.975. The formula of this base temperature Eq. 3-4 and the heat demand Eq. 3-5 are given below.

Eq. 3-4

$$Mean\ Tbase = Mean\ Tin - \frac{Mean\ QG}{U\prime} \quad \textit{Given for intermittent heated buildings}$$

Eq. 3-5

$$Heat\ demand = U' \times DD$$

The theory behind the degree-day method and especially behind the base temperature suggests that

- As the set-point temperature is constant for a building but differs from one building to another, the base temperature also differs from one building to another.
- As the overall heat loss coefficient of a building is constant for a building but differs from one building to another, the base temperature also differs from one building to another.
- As the internal gains are constant for a building during hours of occupancy but differs from one building to another, the base temperature also differs from one building to another.
- As the solar gains vary according location, they differ from one building to another. As the solar gains vary according to time of the day and along the seasons, the base temperature also differs according to climate conditions.

3.1.2 What is wrong with the current method

The current degree-day method has been used for almost 80 years in the estimation of energy demand of buildings (A.R. Day; T.G. Karayiannis 1999). The method, based on temperature differences, was working well as it takes the heat losses of the building into account very well as can be seen through Eq. 3-1 to Eq. 3-5. Nevertheless, new buildings, which are low-energy buildings are designed in a way that heat losses are greatly reduced and focus has been put on how to get “free” heat gains. For this purpose, considering a constant base temperature, and thus constant heat gains, leads to wrong results. For normative buildings, as there are not that much heat gains this assumption did not have a high impact on the space heating consumption, but now that heat gains are much more important, it does. Low-energy buildings do account much more on the heat gains and so as well should the method.

Each country has a standard temperature for the base temperature, and standards base temperatures do vary along the countries. One could ask himself what should then be the accurate base temperature for a specific building. As explained in section 3.1.1, the base temperature do actually depends on climate conditions and so it varies according to location. This was also demonstrated by Hitchin, who introduced location dependent correction factors for the base temperature (CIBSE 2006). Also, as explained in section 3.1.1 the base temperature actually directly depends on the heat gains which themselves depend on the solar radiation and on the occupancy of the building. Both of these factors vary throughout the day and over the days, so the base temperature also varies over time. (Lens 2013). From equation Eq. 3-4 it can be seen that the base temperature depends on the heat gains, but also on the overall heat loss coefficient of the building and on the set-point temperature of the building. This latter temperature is the desired inside temperature of the building. Usually in the analyses the set-point temperature is defined as constant, but in fact the user also has a large impact on the set-point temperature. In the case of office buildings, the user probably has less control on the set-point temperature than in a flat with electrical radiators for instance.

Depending on climate variations, construction culture and space heating usage, different countries have adopted different standards for the base temperature: In France and in the US, the base temperature is 18°C, in Denmark it is 17°C. Even though Denmark is a colder country than France and US, this choice of the base temperature may come from the fact that Danish buildings are more energy-efficient and therefore have less heat losses, consequently needing less heat. The lower are the losses and the higher the “free heat gains” are, the lower the base temperature needs to be. As stated in the introduction, Germany, pioneer country in energy efficiency in buildings had developed new standards for the base temperature as can be seen in Table 3-1 below. The differences in these base temperatures try to account for the energy efficiency of the building: the more energy-efficient is the building, the best overall heat loss coefficient it has and the best solar gains it can use. As it can be seen in Table 3-1 below, the most energy-efficient building is the “passive building” with a 10°C base temperature, when the normative building has a theoretical base temperature of 15°C. As stated above, in practice the base temperature is never constant as it varies with time and location.

Table 3-1 Base temperature standards in Germany regarding building’s energy efficiency

	Normative building	Low-energy building	Passive building
Standard Base Temperature (°C)	15	12	10

As the base temperature is in fact constantly changing, using a constant temperature defined by a standard could lead to wrong results, especially when the analysis look at monthly estimates and not only yearly degree-day totals. In fact, this reduction in base temperature assumes that the gain to loss ratio is also constant. For instance if analysing yearly degree-day totals, then the variations in gain to loss ratios would not be visible. However, if one wants to investigate monthly sum of degree-days, it has to consider as well monthly gain to loss ratios in order to account for the real (or more approximate) monthly base temperature of the building.

3.1.3 Further critic from the ISO 13790

The standard norm ISO 13790 regarding the energy performance of buildings gives a step-by-step process in order to calculate building space heating demands (ISO 2008). In the section explaining how to calculate the monthly solar gains, there is a comparison between the ISO method and the degree-day method. The monthly method of the international standards utilises the Eq. 3-6 below for the space heating balance:

Eq. 3-6

$Monthly\ space\ heating\ consumption = U \times \sum(Tsp - Text) - \eta \times Qg$ (ISO 2008)

The main difference between the method used in the ISO standard calculation and the degree-day method is that the ISO standard use temperature differences between the set-point temperature and the outside temperature. This way the temperature difference is much higher as usually the set-point temperature is 21°C.The other critics of the degree-day method by the ISO standard are the following: (ISO 2008)

- Not all the hours are considered into the calculation of the accumulated temperature difference
- There is a distinction between the hours with external temperatures higher or lower than the predefined base temperature
- The internal temperature is defined by a base temperature when it should be the set-point temperature
- The heat gains are not taken into account explicitly (they are already included in the base temperature which is not transparent)

The reduction in temperature difference using a base temperature instead of the real set-point temperature of the building is needed because the utilised heat gains are disregarded into the equation, as it can be seen in Eq. 3-3 and Eq. 3-6. However, the norm ISO argues that the reduction in temperature is made without any specific knowledge of the heat balance ratio (ISO 2008). This confirm what is stated above, there is a need to investigate monthly gain to loss ratios to calculate monthly base temperatures.

3.1.4 Concluding remarks

This chapter has explained that the degree-day method needs to be adapted to low-energy buildings, mainly because the heat gains are not taken into account explicitly in the method. The concept of a constant base temperature leads to wrong results, as it does not include the variations in outdoor temperature neither the variations in solar radiations and internal temperatures. Also, the base temperature differs from one building to another as it depends on the energy efficiency of the building (defined by the overall heat loss coefficient in the Eq. 3-3). This section has answered the following sub-question:

"What are the defaults of the degree-day method and which improvements can be made to adapt the method to low-energy buildings?"

The main defaults of the degree-day method are:

- The concept of a constant base temperature in the degree-day method is wrong
- The heat gains need to be explicitly calculated and integrated into the degree-day equation
- Monthly mean heat gains and monthly mean internal temperatures need to be calculated to calculate monthly mean base temperatures

The improvements which can be made to adapt the method to low-energy building are to include in the model based on the current degree-day method the following points:

- Calculate the space heating consumptions based on a varying monthly base temperature over the year
- Calculate monthly mean base temperatures based on monthly mean heat gains and monthly mean internal temperatures
- Calculate monthly mean heat gains based on calculated monthly mean solar heat gains and monthly mean internal heat gains
- Calculate monthly mean internal temperatures based on hours of occupancy and set-point temperatures

4 New model proposed

In this chapter the new model proposed is presented. The new model is designed to calculate monthly space heat consumptions using the degree-day method. As stated in the introduction, the degree-day method presents the advantage to be easy to use as it is only based on temperature differences between the outside temperature and the base temperature of the building. However, as explained in the problem formulation and through the Literature review on degree-days, the problem with the degree-day approach is that the base temperature is defined as some representative indoor temperature, when it actually depends on the overall heat loss coefficient, on the heat gains and on the internal temperature of the building. The way the model was built is described in the Methodology.

The aim of the model is to calculate monthly average heat gains and monthly average internal temperatures in order to provide monthly base temperatures (see Eq. 4-1) It would also be possible to consider another time frame where one could calculate weekly heat gains and weekly internal temperatures to provide weekly base temperatures. Using monthly base temperatures is also an advantage because data can be collected more easily on a monthly basis. If one wants to calculate daily base temperatures, then daily solar radiations are needed for the calculation and this type of data is very hard to find.

Eq. 4-1

$$Tbase, monthly\ mean = Tin, monthly\ mean - \frac{QG, monthly\ mean}{U'}$$

From Eq. 4-1 the monthly mean inside temperature and the monthly mean heat gains are the key parameters to calculate monthly base temperatures. In this chapter the building reference used for the modelling Ostarkade is first presented, secondly the sensitivity analysis is presented.

4.1 Presentation of the reference building

The building used as reference building for the analysis is a low-energy office building located in Frankfurt, Germany. The building is part of the German project Energy Optimized Building (EnOB, Energieoptimiertes Bauen) supported by the German Federal Ministry of Economics and Technology. The research project monitors and analyses low-energy buildings with efficient energy systems, high technologies and innovative design to allow low primary energy consumption and high occupant's comfort. (EnOB: Research for energy-optimised construction s.d.). The building is named Ostarkade. It optimizes the use of energy for heating, cooling, ventilation and lighting systems. The building is new and was inaugurated in 2002; it was monitored during the years 2004 and 2009 by the Karlsruhe Institute of Technology (KIT).

4.1.1 Building presentation and key features

The building is designed with high architectural features as a glazed atrium in the centre of the building from the 1st to 5th floor, which allows natural lighting and ventilation in summer. The high thermal mass of the building allows passive cooling of the building during the night. In summer, natural ventilation via the atrium cools the exposed concrete slabs. The building is designed to have reduced transmission losses due to strong insulation of the building and a low A to V ratio: the insulation exceeds by 30% the German regulation. Heat recovery systems allow reducing the ventilation losses. Most of the rooms have natural ventilation through windows, only those exposed to excessive noise require mechanical ventilation. Also, and exterior automatic shading system and solar control glass permit to reduce undesirable heat influx from the outside.

The key parameters of the building are available in the table below:

Table 4-1 Key building parameters

Parameter	**Unit**	**Value**
Net floor area	m^2	10.415
Volume	m^3	56.699
Surface area to the volume ratio	%	0.18
Surface of glazing area (total building)		0.22
Ventilation rate (calculated)	1/hour	0.25
Floor	Number of floors	5
Solar shading	Type of shading	Venetian blinds
Occupancy	Number of hours	12
Occupancy	Number of days per week	5
Occupants	Number of occupants	350
Set-point heating temperature	°C	22
Mean outdoor temperature	°C	13.3
Maximum outdoor temperature	°C	35.8
Minimum outdoor temperature	°C	-6.3

The set-point temperature was designed to be 20°C but during the year of monitoring an average inside temperature of 22°C has been recorded so 22°C is used for the analysis as it is the real set-point temperature. In the office rooms, there are radiators for the space heating and so the user can change the inside temperature of +/- 3°C. The comportment of the user is unknown.

The building has a large part of glazing area, with 22% of the envelope of the total building being windows. There is a large part of the windows, especially on the East side of the building. A picture illustrating the building's windows on the South facade is available on Figure 4-1 below.

Figure 4-1 South facade of the building Ostarkade (Google Maps s.d.)

4.1.2 Heat production

The building is designed to be heated using around 90% head produced from renewable energy sources. A wood pellet boiler of 450 kW is used as base load and a gas boiler of 240 kW covers peak loads. When the demand is low, the gas boiler is functioning as it is more efficient than the wood pellet boiler on a low load. There are 40.5 m^2 of solar collectors on top of the building. They are designed in order to provide heat for domestic hot water use in the apartments and in the kitchen of the office building. They also provide heat for the under floor heating in the flats. The heat produced from the collectors can be stored but only used for the flats and the hot water demand. All the heat need for space heating of the building should be provided by the wood pellet and gas boilers. Nevertheless, in the year 2005, year understudied, the monitoring report from the building reveals that the thermal revealed not to be as efficient as expected ((fbta) 2006). As they are supposed to produce heat for the hot water demand, this heat production was, due to a bad monitoring, supplied by the gas boiler during the summer 2005. Indeed the gas boiler was producing heat continuously in order to maintain the heat tank at a certain temperature. The heat production per production unit is shown on the Table 4-2 and Figure 4-2. Moreover, it has been identified that during the summer, pumps for the heating circuit were still running even though the radiators in the offices were turned off. For this reason, on the heat production data, the heat production has to be set to 0 in summer (at least in June, July and August) as there was no space heat consumption.

Table 4-2 Production share per production unit in 2005 ((fbta) 2006)

	Wood Pellet Boiler production	Gas boiler production	Solar thermal collectors production
2005	68%	30%	2%

As can also be seen on Figure 4-2 below, the gas boiler was producing during spring and autumn and not the wood pellet boiler, because the wood pellet is not efficient enough to cover a low load. Because of this the gas boiler had a production share of 30% during the year 2005 as can be seen on Table 4-2 which was much more than expected. As it can be seen on the Figure 4-2 below, during the heating season mostly the wood pellet boiler is producing when during summer, the gas boiler covers the demand which is the hot demand plus additional demand of the pumps running due to bad monitoring.

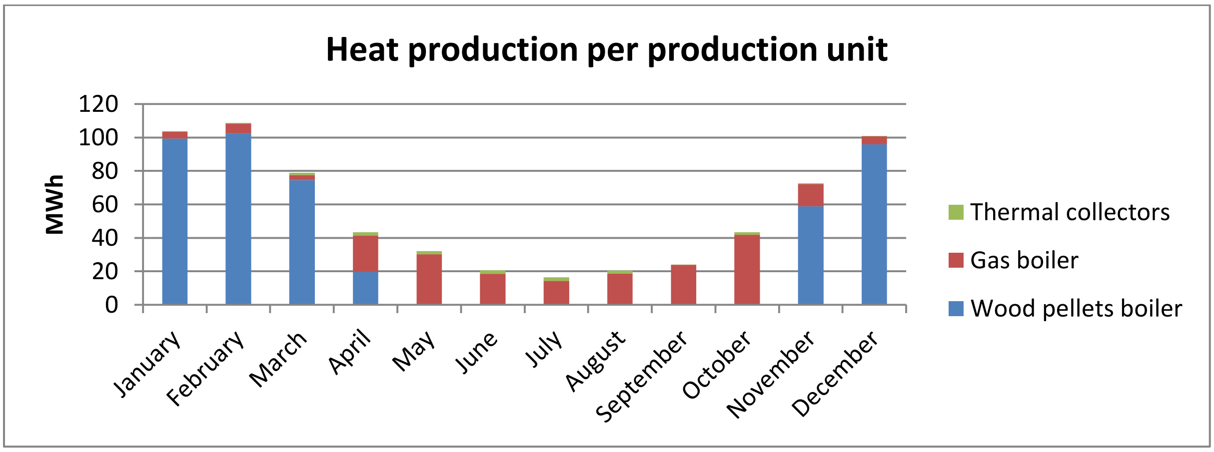


Figure 4-2 Heat production per production unit of the reference building (Frankfurt, 2005)

4.1.3 Heat consumption

Information was found in the monitoring report regarding the heating circuits of the building. Finally the monthly heat consumption is found and divided in three categories:

- Space heating consumption of the office building
- Space heating consumption of the flats
- Hot water demand

The values of heat consumption per use are shown on the Figure 4-3 below. The hot water demand is only a small share compared to the other uses, the space heating for the office building being the most demanding.

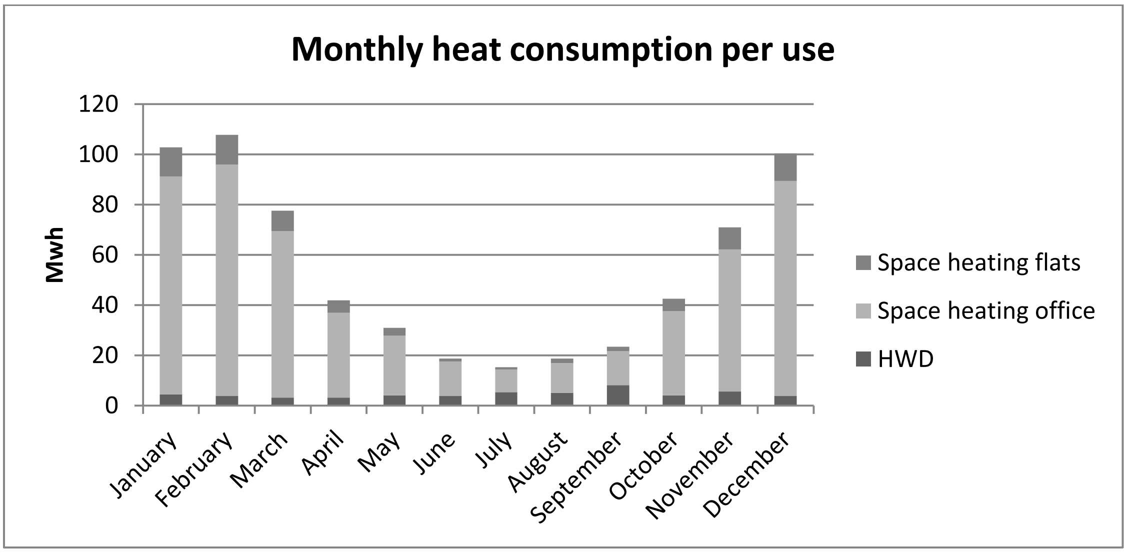


Figure 4-3 Monthly heat consumptions per use of the Ostarkade building (Frankfurt, 2005) ((fbta) 2006)

The daily heat consumption of the building, as can be seen on the Figure 4-4 below, is not linear. There is a peak in the morning at 8am. It can also be seen that the heating starts around 6am in the morning. The total heat consumption is shown on this figure so it can be assumed that the consumption base load by night is for flats use. The heat consumption decreases from 8pm. This is why it is assumed that there are people in the building between 8am and 8pm, so 12 hours or occupancy.

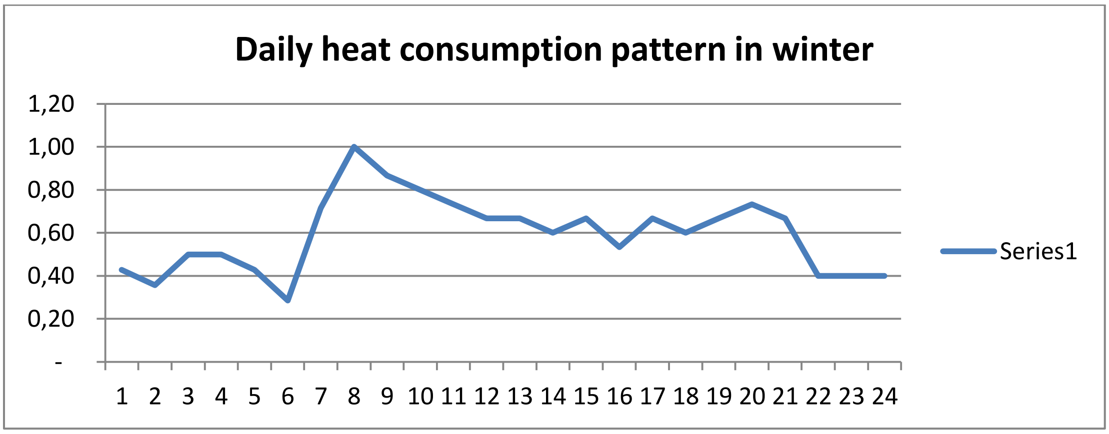


Figure 4-4 Daily heat consumption patter in winter of the Ostarkade building (Frankfurt, 2005)

4.1.4 Climate conditions

The monthly average solar radiation on each façade is shown on the graph below (primary axis) and the monthly average outdoor temperature on the secondary axis. Along this paper several observations and conclusion refer to Figure 4-5.

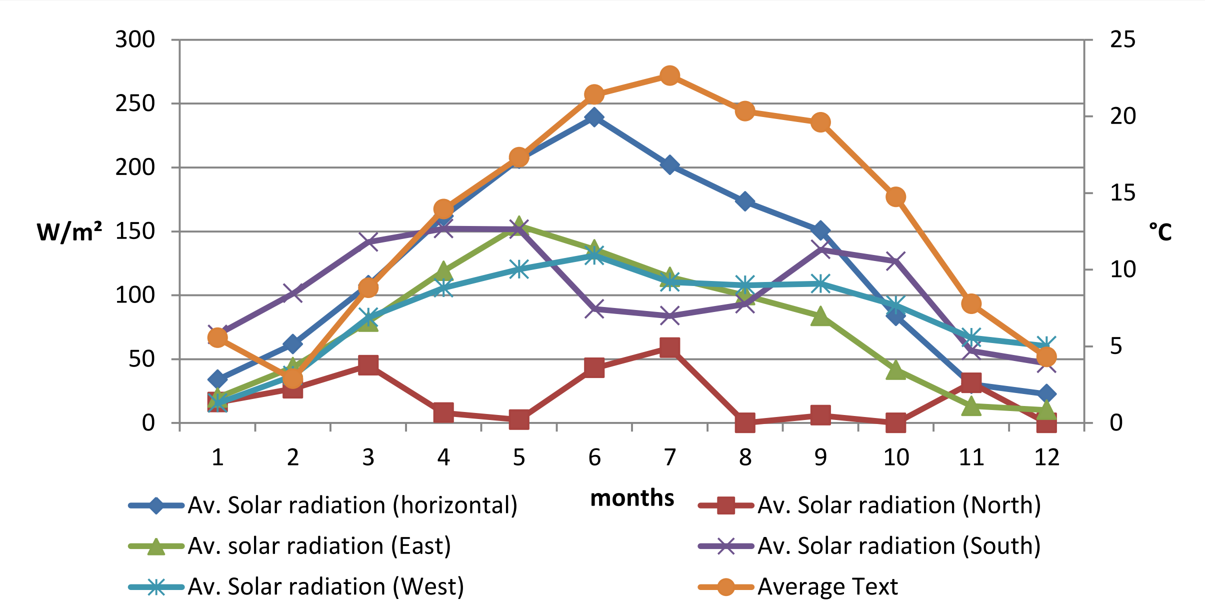


Figure 4-5 Monthly average solar radiations on each facade and monthly average outdoor temperature

Regarding the hourly outdoor temperature, it goes until -6°C in winter and up to 36°C in summer. The yearly outdoor temperature is shown on the Figure 4-6 below. It can be seen that there is a real gap of temperatures at the end and beginning of the winter (around hour 1500 which is the end of February and 7500 which represents mi-November).

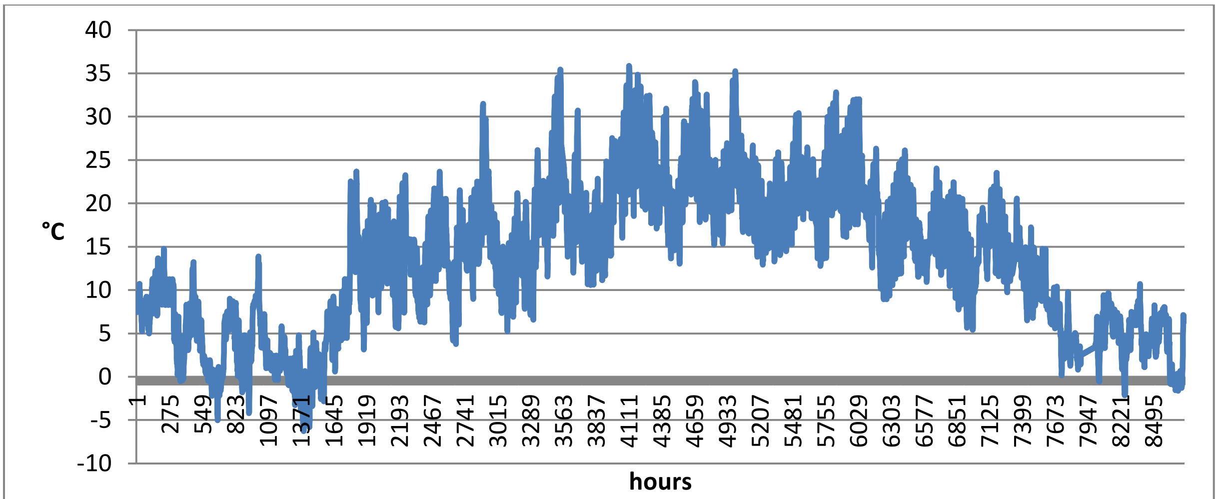
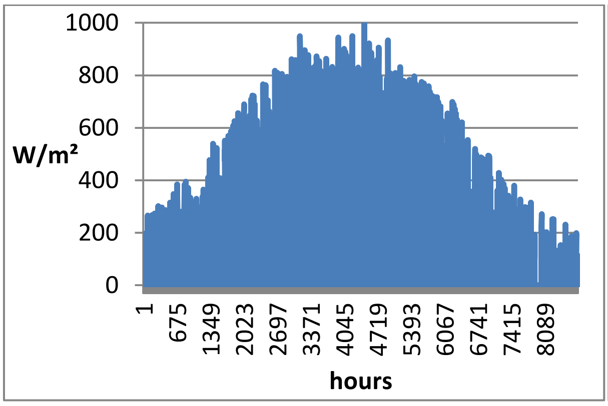


Figure 4-6 Hourly outdoor temperature (Frankfurt, 2005)

Using data of the illumination on each façade, solar radiations on each façade are calculated. This is detailed in the Data collection and use section in the Methodology. The yearly solar radiations, given hourly are shown on the Figure 4-7 to Figure 4-11 below.



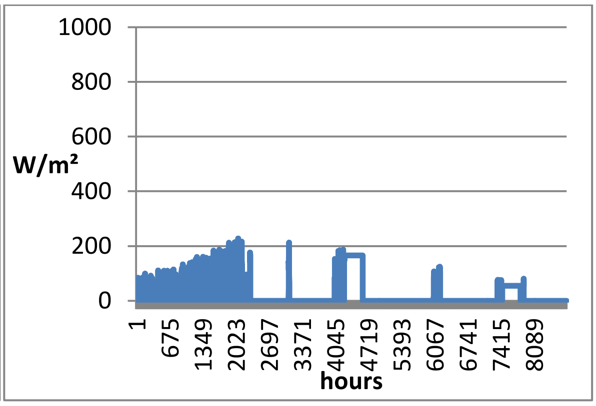
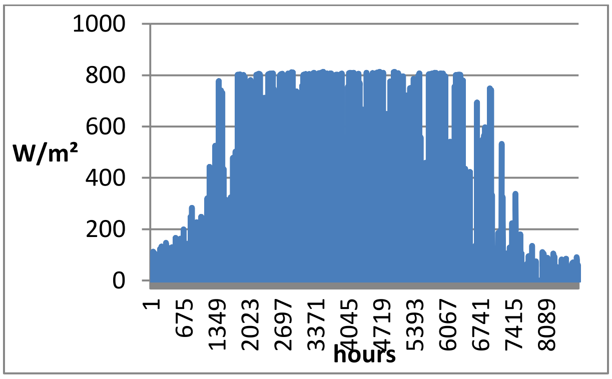


Figure 4-7 Solar radiation on the horizontal facade

Figure 4-8 Solar radiation on the North façade



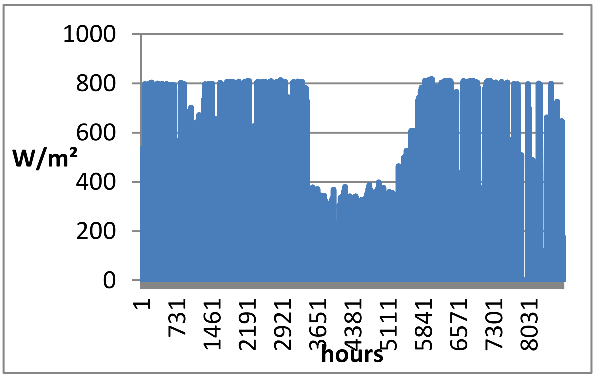


Figure 4-9 Solar radiation on the East façade

Figure 4-10 Solar radiation on the South facade

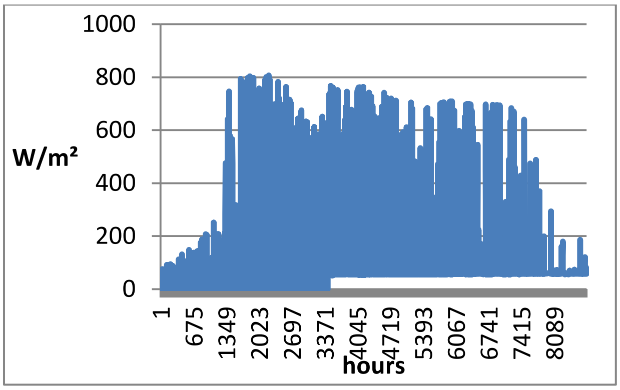


Figure 4-11 Solar radiation on the West façade

These solar radiations are in accordance with what can be expected from solar radiations on building facades on the North hemisphere: On the horizontal façade, the radiation is the highest in summer, as the intensity of the sun, because it can captivates all the sun radiation. On the South façade, the solar radiation is very high during all seasons expect in summer. This is due to the fact that in summer, the sun is higher so the angle between the sun and the façade becomes smaller, which explains why the façade receives less radiation than during other seasons. On the West and East facades, there is a low solar radiation during the winter because days are smaller so there is less time of the solar radiation to reach the facades than during other seasons.

4.2 Sensitivity analysis

In order to answer the following sub-question a sensitivity analysis is conducted on the key parameters of the building.

"Which parameters influence the most the space heating consumption?"

The aim of the sensitivity analysis is to explore the range of variations of the input data. Therefore, if the model calculates accurate monthly space heating consumptions even for the extreme input values, it means that the model can be applicable to other buildings with input data in all the range of variations. However, no data from other buildings were available and therefore future research for this project would be to test the model on buildings with characteristics within the range of parameters defined. Only the impact of the overall heat loss coefficient U' and the thermal capacity C of the building has been demonstrated by A.R.Day and T.G.Karyiannis. Their impact is assessed both on the mean internal temperature and on the final space heating consumption. The impact of the other parameters is assessed by using the Morris method as described in the Methodology. It is possible to investigate and rank the impact of each parameter. Therefore, the sensitivity of the monthly mean inside temperature and the monthly mean heat gains is analysed by different parameters. Finally, the sensitivity of the space heating consumption by the key parameters is also investigated. The parameters are ranked regarding their mean values and standard deviations.

4.2.1 Sensitivity of the inside temperature Tin

The sensitivity of the monthly mean inside temperature relative to variations in C and U'has already been assessed by A.R.Day and T.G.Karayiannis (A.R.Day; T.G.Karayiannis 1999). They have tested the equation on four different buildings, which differ among their thermal mass capacity C and different overall heat loss coefficients U'. The different ranges for the thermal mass capacity C are "heavy weight" ($2.1 \times 10^6 kJ/K$), "medium weight" ($1.9 \times 10^6 kJ/K$) and "light weight" ($1.6 \times 10^6 kJ/K$). According to their research, the equation overestimates the mean inside temperature Tin for heavy weight buildings and underestimates the mean inside Tin for lightweight buildings. The building of the case study has a thermal capacity C of $1.3 \times 10^6 kJ/K$ therefore it is considered as lightweight building. Based on their analysis the model is likely to underestimate the inside temperature of the building Tin. However, they say that the mean inside temperature is of secondary importance and that it would have a lower impact on the energy estimate than the other factors U' and QG (A.R.Day; T.G.Karayiannis 1999). The impact of these variations on the space heating consumption estimate is also investigated. The lightweight and medium weight buildings present results with 95% of accuracy for the estimation of seasonal space heating consumptions compared to actual values, "if all input parameters are known" (A.R.Day; T.G.Karayiannis 1999). Therefore the calculation of the mean inside temperature is validated for lightweight and medium weight buildings. Their research also shows that U' has greater impact on Tin than Qp, the output power of the plant when both of them are analysed for input +/-20% around their mean values. Therefore the effect of variation of U' will be greater than the effect due to a variation in Qp. However, what is missing in their research is the impact of the variation of the set-point temperature Tsp and the number of occupied hours on the inside temperature Tin.

As described earlier the inside temperature Tin also depends on the set-point temperature Tsp and the number of hours occupied. Indeed, the case study building is assumed to have 12 hours of occupancy based on observations but other office buildings might have a higher or lower number of occupancy hours. Also, the set-point temperature Tsp of the building has an average of 22.1°C among the year but as explained earlier it is likely that this temperature has been changing along the year. Depending on the usage of the building, the set-point temperature can also be different among office buildings. Therefore, it is necessary to investigate the impact of these two parameters on the mean inside temperature of the building Tin and on the monthly space heating consumptions estimates. The Morris method allows to compare the parameters influencing the space heating consumption and to rank them according to their standard deviation σ. The higher the standard deviation is, the higher is the sensitivity and therefore the higher is the impact of the input parameter. All parameters influencing the inside temperature Tin are investigated. Their range of variations chosen for the analysis is in the table below.

Table 4-3 Sensitivity of Tin,monthly to Tsp,monthly, Qp, U' and number of occupancy hours

	Tsp (°C)	Occupancy hours	Qp (W)	U’	C
Probability density function	Normal	Normal	Uniform	Uniform	Uniform
Variation	+/- 2°C in each month	+/- 2 hour	+/- 20%	+/-20%	+/-20%
Min	Depending on the month	10	552	9.47	1.04 * 10^6
Mean	Depending on the month	12	690	11.84	1.3 * 10^6
Max	Depending on the month	14	828	14.21	1.56 * 10^6

All parameters are defined to differ of 20% above or under their mean value. This is the case for the output of the heating system Qp, the overall heat loss coefficient U’ and the thermal capacity C (see tablexx). Regarding the set-point temperature a range of +/-2C is chosen and for the occupancy hours +/-2hours. The range of variations is chosen to be large in order to account for the maximum of variations. The results greatly depend on the variations range.

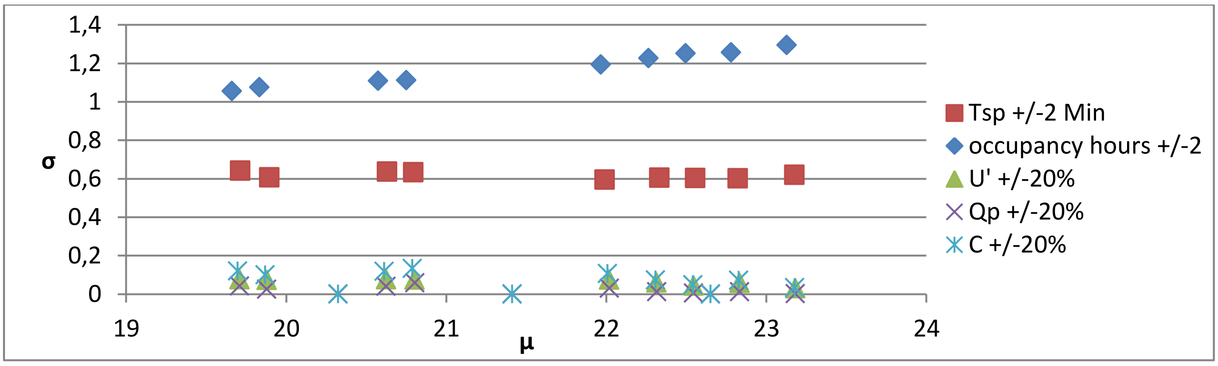


Figure 4-12 Sensitivity of the inside temperature Tin to Tsp, Qp, U' and C

On Figure 4-12 Sensitivity of the inside temperature Tin to Tsp, Qp, U' and C the sensitivity of the inside temperature Tin to the different parameters is shown. The parameters are compared with their standard deviation σ. The analysis shows that the parameter influencing the most the inside temperature is the number of hours occupied. Also, the set-point temperature has a great impact on the inside temperature compared to the other parameters. The overall heat loss coefficient U' has a light impact compared to others. As stated by A.R.Day and T.G.Karayiannis, U' still has a larger impact than the output of the heating system Qp, in all months.

4.2.2 Sensitivity of the heat gains QG

The heat gains are the summation of the internal and solar gains. The occupant density and the number of occupancy hours are the parameters influencing the internal gains whereas the g-value and the size of windows are those affecting the solar heat gains. Therefore the impact of these parameters on the total heat gains is investigated. The range of variation chosen for the parameter is available in Table 4-4 Variation range of the parameters influencing the heat gains QG As for the internal temperature all parameters vary of +/-20% to their mean except the number of occupancy hours which vary of 2hours.

Table 4-4 Variation range of the parameters influencing the heat gains QG

	Occupant density	Occupancy hours	g-value	Size of windows
Probability density function	Normal	Normal	Uniform	Uniform
Variation	+/- 20%	+/- 2 hour	+/- 20%	+/-20%
Min	23.81	10	0.304	Depending on the façade
Mean	29.75	12	0.38	Depending on the façade
Max	35.71	14	0.456	Depending on the facade

The result of the analysis is shown on Figure 4-13 Sensitivity of the (uncorrected) heat gains Q'G to the occupancy hours, occupant density, g-value and windows size below. On the contrary to the inside temperature, the impact of the parameters vary throughout the seasons. Therefore some parameters have a comparable impact to the other depending on the time of the year. In winter, the occupancy hours are the main parameter influencing the heat gains and the occupant density is the second parameter influencing the heat gains in January and December. This might be due to the fact that solar radiations are low during this period and therefore during winter the non-dependent weather parameters are those influencing the most the heat gains. The g-value seems to be the second parameter most influencing the heat gains over the year. They are the second most important parameter in February, March, April, October and November and the most important in May and September. This means that even in cold months, the solar heat gains are an important parameter to offset the heat losses. Regarding the size of the windows, they follow the curve of the g-value but influence less the heat gains.

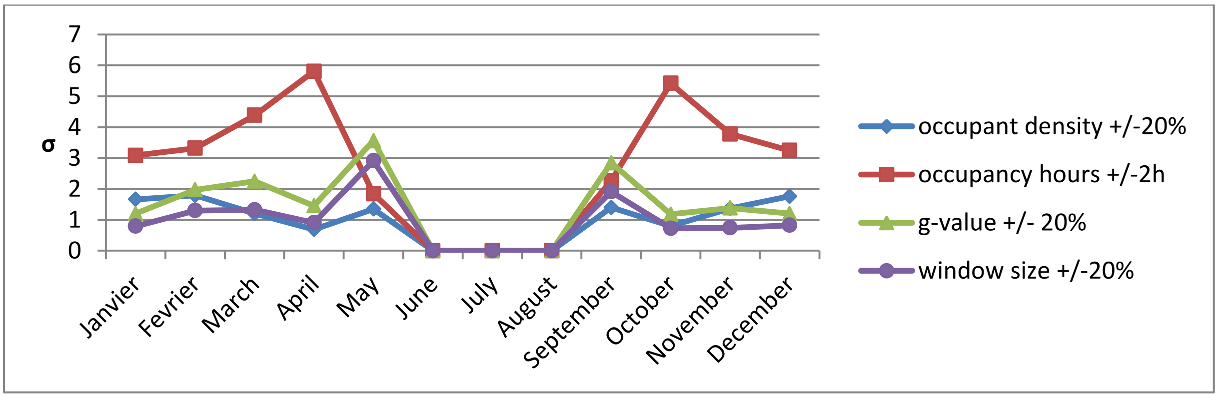


Figure 4-13 Sensitivity of the (uncorrected) heat gains Q'G to the occupancy hours, occupant density, g-value and windows size

4.2.2 Sensitivity of the space heating consumption

The impact of the parameters is also investigated on the monthly space heat consumption. The sensitivity of the space heating consumption to all input parameters is shown on the Figure 4-14 Sensitivity of the space heating consumption to all input parameters below. The parameters vary in their range of variations from **Error! Reference source not found.** and Table 4-4. During the simulation all parameters where varied one at a time.

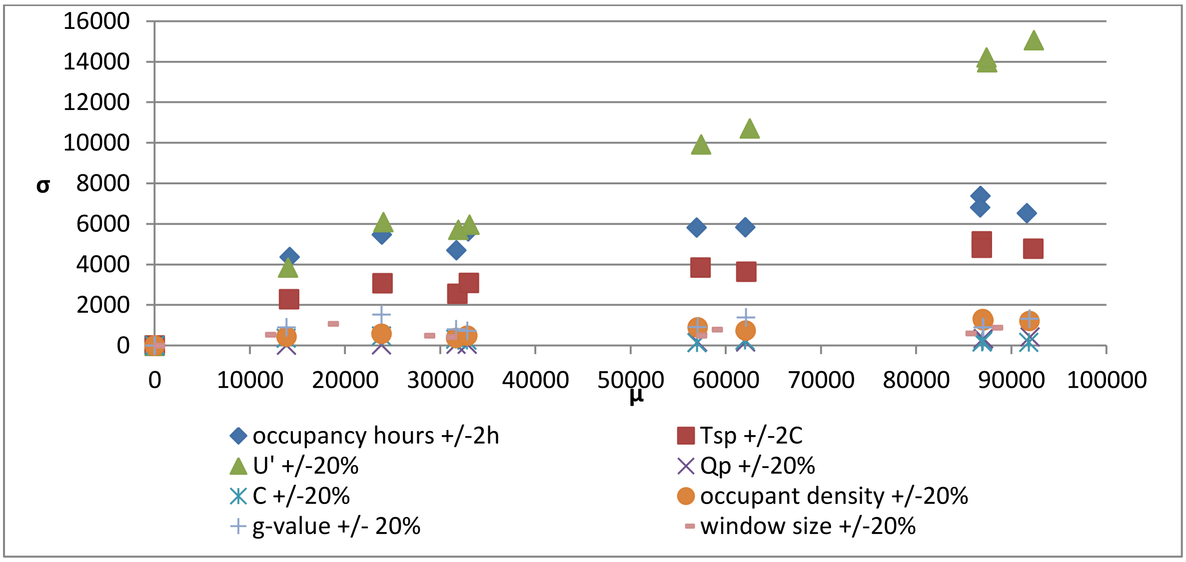


Figure 4-14 Sensitivity of the space heating consumption to all input parameters

Among all parameters the space heat consumption is the most influenced by the overall heat loss coefficient U'. This is particularly the case when mean values of space heat consumptions and standard deviation are high, which probably corresponds to winter months. When the mean and standard deviations values are lower, the overall heat loss coefficient has less influence on the space heat consumption. From Eq. 3-5 this parameter is multiplied to the degree-days to estimate the space heat consumption and therefore it is predictable that it would have a large impact, also because it is a positive number superior to 10. The second parameter influencing the space heating consumption is the number of occupancy hours. In some months (probably months close to summer because mean and standard deviations are low compared to the other), its influence on the space heat consumption is higher than the one of the overall heat loss coefficient. The number of hours occupied already has a great influence on the inside temperature Tin and it also influences the heat gains, therefore it can be expected that it would have a large impact on the space heat consumption. The third most influencing parameter on the space heat consumption is the set-point temperature Tsp. It was expected that this parameter greatly influences the space heat consumption considering the influence it has on the inside temperature (Figure 4-12). The influence on the other parameters, as the g-value and the windows size become more important, compared to the other parameters, when mean and standard deviations values are low. Therefore this probably corresponds to spring or autumn months, when the solar radiation is higher than in winter.

On Figure 4-15 below, the impact of the heat gains, the overall heat loss coefficient and the inside temperature on the space heat consumption is presented. All parameters of the heat gains are simulated in the same time within their respective range of variations. It is the same process for the internal temperature, except the overall heat loss coefficient is not included. The reason it was omitted is that it leads to wrong results when comparing to the impact of the overall heat loss coefficient itself to the space heat consumption. Also, as its impact on the inside temperature is very small, compared to other parameters, it is reasonable to exclude it in this variation.

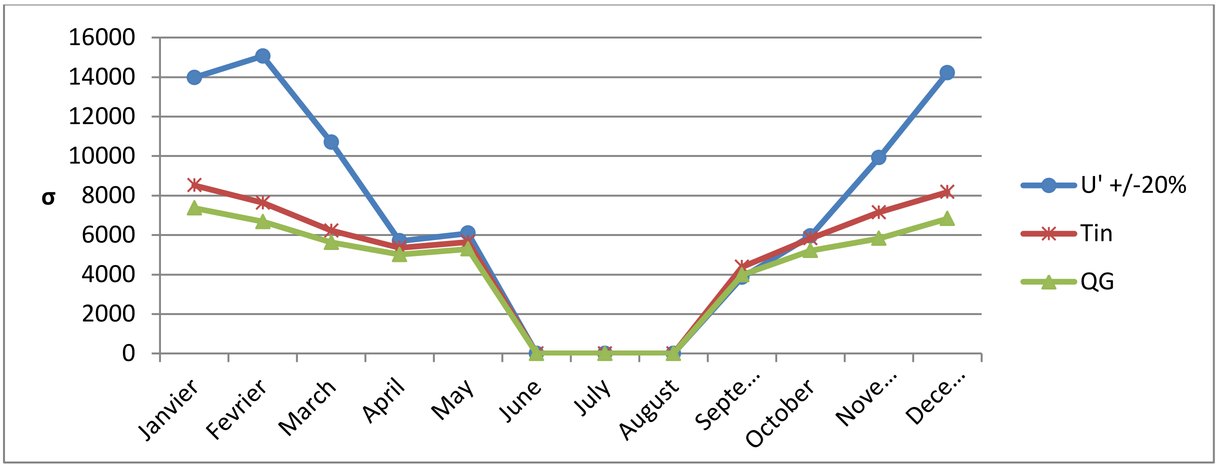


Figure 4-15 Sensitivity of the space heat consumption to the overall heat loss coefficient U', the monthly mean uncorrected heat gains Q'G and the monthly mean internal temperature Tin

On Figure 4-15 it can be seen that the overall heat loss coefficient is the one influencing the most the heat consumption among the other parameters. This is expected with Figure 4-14 However in April, May, September and October its influence among the others decrease and all parameters seem to influence the space heat consumption at a comparable level. As the Tin is an indicator of temperature it is also an indicator of heat losses, and so is the heat loss coefficient. If heat gains are very high during these months, it is possible that the space heat consumption would be very low. During the rest of the year, the mean inside temperature impacts slightly more the space heat consumption than the heat gains. However, according to the work of A.R.Day and T.G.Karayiannis it is possible that the mean inside temperature of this particular building is underestimated, therefore its impact on the space heat consumption could maybe be higher.

4.2.3 Sensitivity of the base temperature

On the Figure 4-16 below the sensitivity of the base temperature is investigated. According to the analysis and within the range of variations of all parameters, it seems that the mean inside temperature influences the most the base temperature among the other parameters, and in all months. The heat gains influence the base temperature almost as most than the inside temperature. The overall heat loss coefficient influences less the base temperature, which is expected as it is applied on Eq. 3-5 after the calculation of the base temperature.

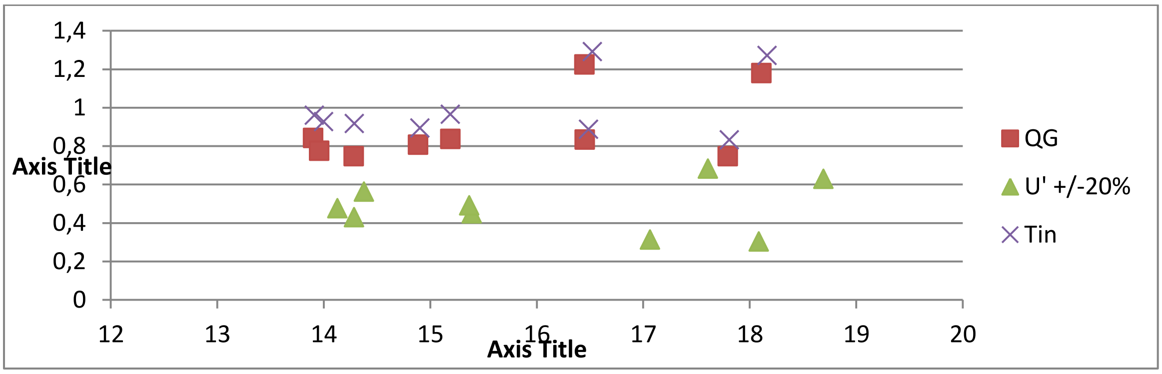


Figure 4-16 Sensitivity of the base temperature Tbase to U', Tin and Q'G

The answer to the sub-question *"What are the parameters influencing the most the space heat consumption?"* the main observations of the chapter are summarised below:

- The overall heat loss coefficient U' is the parameter influencing the most the space heat consumption, in all months of the year except in May. In April, May, September and October, his impact is reduced and almost equivalent to the impact of the heat gains
- The number of occupancy hours has a great impact on the inside temperature and therefore on the space heat consumption
- The g-value greatly influence the total heat gains especially during months with high solar radiations
- The inside temperature and the heat gains influence more the base temperature than the overall heat loss coefficient

5 Results of the analysis

In this chapter the results of the analysis are presented. The main end-result is the hourly space heating consumption calculated through the model of the building considered. Some other output parameters are also presented as the monthly base temperatures, monthly average usable heat gains and monthly average internal temperatures. It is not common in the literature to find calculated heat gains so this output presents a main advantage of the model. Also, calculating different monthly base temperatures has never been presented. The space heating consumption calculated with the model presents better predictions in each month compared to two space heating consumptions calculated with different yearly base temperatures. The predicted SHcons are compared to the measured SHcons in order to evaluate the predictions. The chapter presents values for the key parameters already investigated in Sensitivity analysis. This chapter also presents quantified uncertainties of the most uncertain parameters.

This chapter answers the two following sub-questions. The first sub-question is fully answered in this part through graphics and explanations. The second sub-question is partly answered by comparing the SHcons estimated with the model with the measurement.

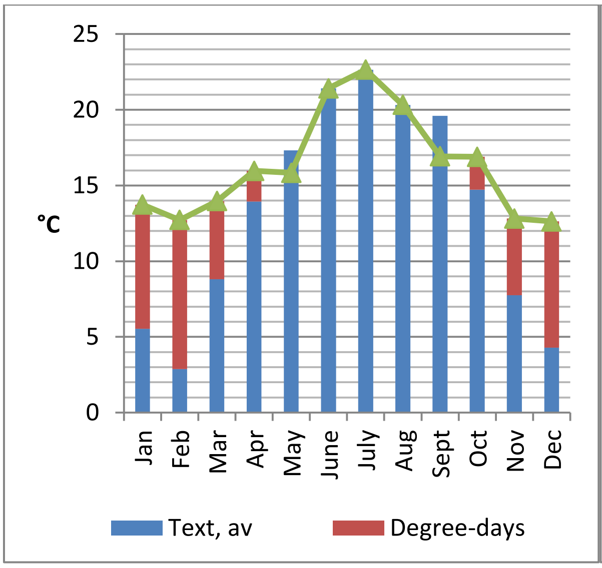
What are the main differences between the space heating consumption calculated with the renewed degree-day method compared to the current degree-day method?

How could the model be validated?

As described earlier, it is possible to conduct the study under different time frame (monthly, weekly, daily). In the analysis monthly base temperatures are used, but the same analysis could have been conducted with a more detailed set of base temperatures, as weekly or daily. It is also possible to calculate seasonal base temperatures using the model.

5.1 Degree-days and base temperature

On the Figure 5-1 and Figure 5-2 below two calculations of the degree-days are presented. Figure 5-1 presents degree-days calculated with the new method when Figure 5-2 presents degree-days calculated with the current method. The former uses base temperatures which vary every month when the latter uses a base temperature of 12°C, as it is the German standard for a low-energy building. The difference between Tbase and Text equals the amount of degree-days. On the figures the degree-days are monthly sums of hourly degree-days. On Figure 5-1 it can be seen that monthly Tbase calculated vary between 14°C and 18°C during the months when heat is required. June, July and August are assumed to be months without heating demand. The lower base temperature calculated is of 14.42°C, in February. In other cold months as January, March, November and December the base temperature is of 15.43°C, 15.40°C, 14.31°C and 14.32°C respectively.



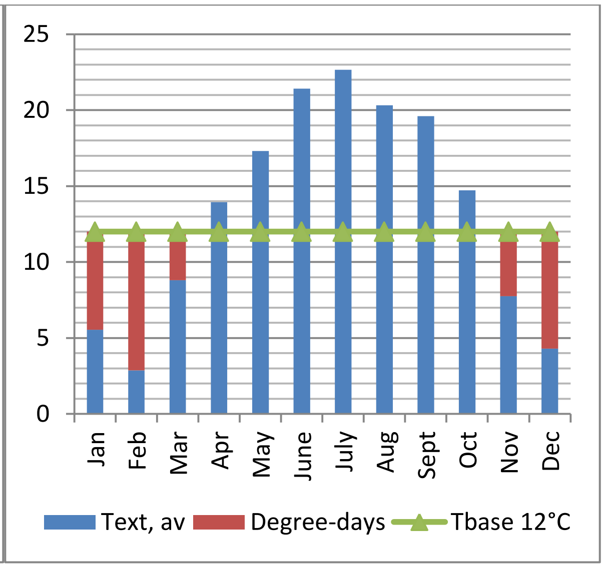


Figure 5-1 (left) Impact of the monthly base temperatures on the degree-days

Figure 5-2 (right) Impact of a base temperature of 12°C on the degree-days

5.2 The space heating consumption

The model permits to calculate the hourly space heating consumption. Different space heating consumptions are presented and compared. They are calculated using Eq. 3-5. They are:

- The actual space heating consumption on Figure 5-3
- The space heating consumption calculated with the degree-day method using monthly base temperatures (renewed method) on Figure 5-6
- The space heating consumption calculated with the degree-day method and a base temperature of 12°C on Figure 5-4
- The space heating consumption calculated with the degree-day method and a base temperature of 15°C on Figure 5-5.

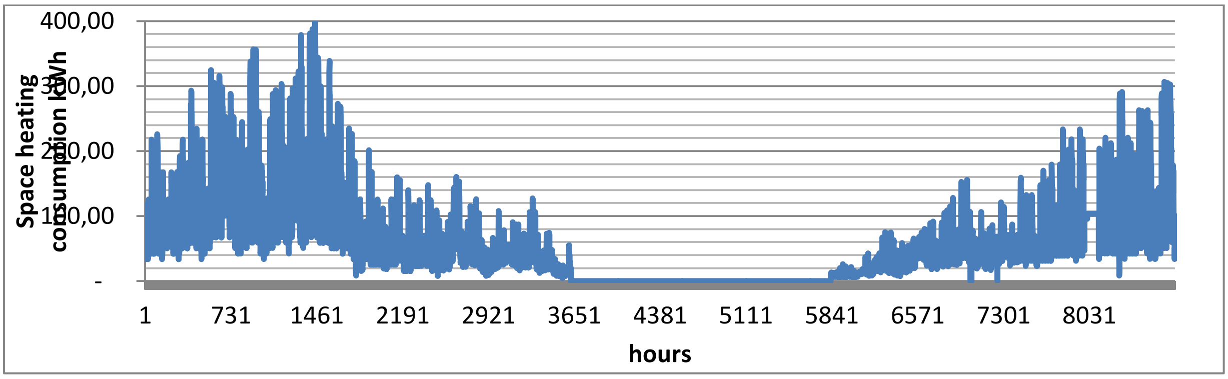


Figure 5-3 Measured hourly space heating consumption

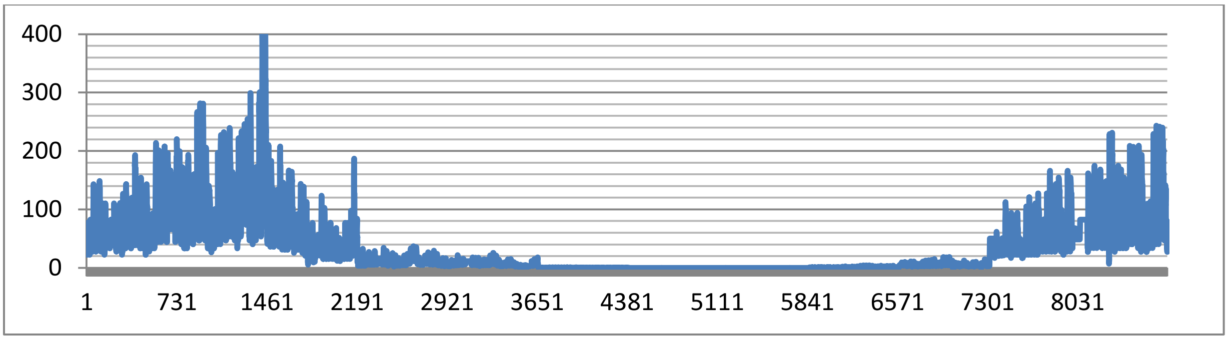


Figure 5-4 Hourly space heating consumption calculated with a base temperature of 12C using a monthly distribution

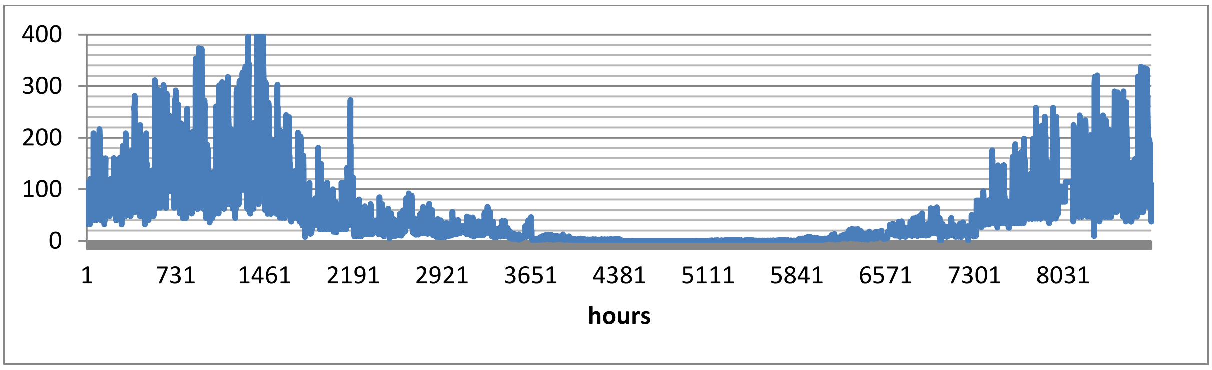


Figure 5-5 Hourly space heating consumption calculated with a base temperature of 15C using a monthly distribution

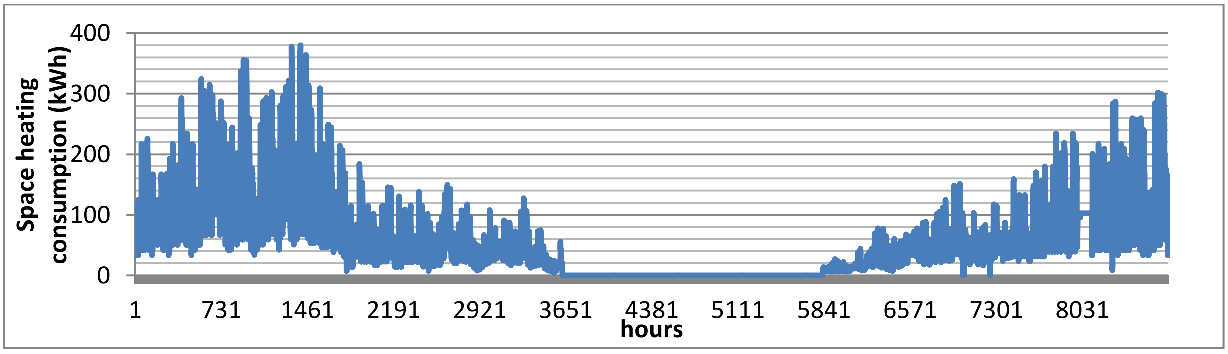


Figure 5-6 Hourly space heating consumption calculated with monthly base temperatures using a monthly distribution

By comparing the figures above the following observations can be made:

- Both space heating consumption (SHcons) presented on Figure 5-4 and Figure 5-5 look discontinued on the yearly basis compared to the measurement (Figure 5-3) and the SHcons calculated with different base temperatures (Figure 5-6). It can be observed that at hour 2191 and around hour 7301, both consumptions respectively grow and decrease suddenly. They also present peak consumptions during winter as around hours 1461 and 2191. Also in winter, they both go up than 500 kWh in some hours when the measured consumption never exceeds 400 kWh per hour.

- Both SHcons presented on Figure 5-4 and Figure 5-5 present shorter heating seasons compared to the measurement. Especially for a base temperature of 12°C, the calculated heat consumption between hours 5841 and 7301 is very low (less than 200 kWh per hour). It seems that the heating season really starts from hour 7301 which corresponds to November. The heat consumption in November and December look quite similar to the measured consumption. However over the year, the SHcons is lower than the measured one. On the contrary the SHcons calculated with a base temperature of 15°C is higher than the measured one in January, February, March, November and December. In the other months the heat consumption is underestimated. This might mean that the real average base temperature of the building is somewhere between 12°C and 15°C.

- The SHcons calculated with different base temperatures is more continuous along the year compared to both SHcons calculated with a constant base temperature. It presents a good prediction of the measured space heat consumption.

The Figure 5-7below presents the four space heating consumption presented above. The consumptions are weekly sums of the hourly space heat consumption.

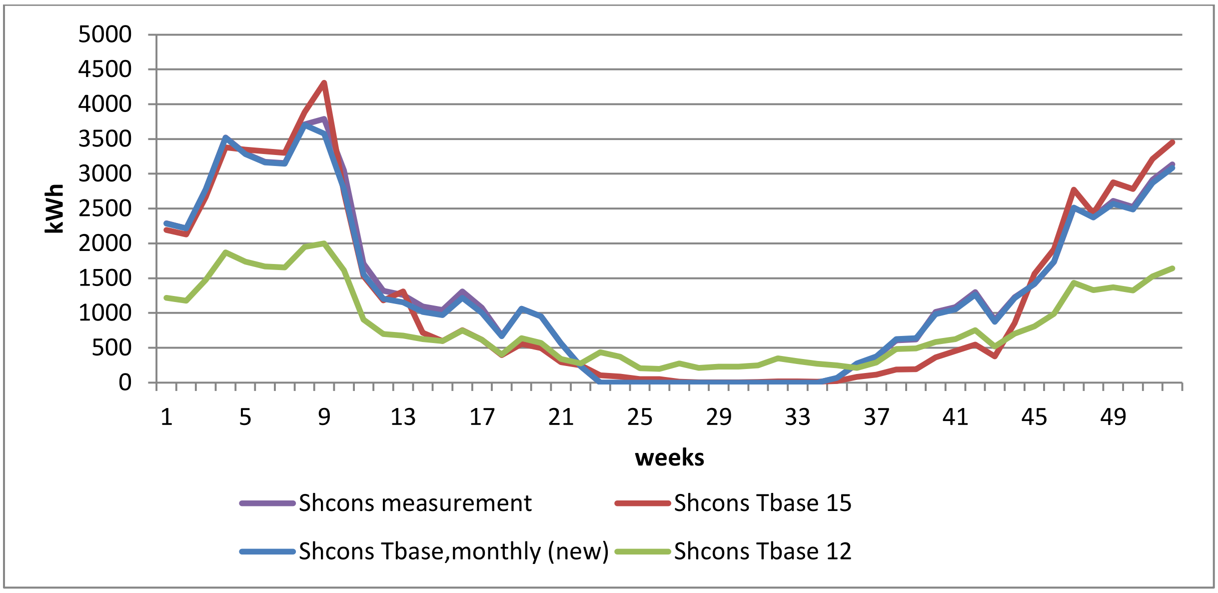


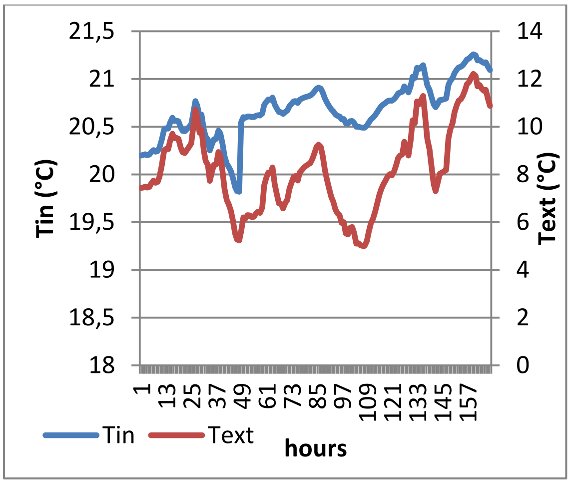
Figure 5-7 Comparison of the calculated space heating consumption with the measured space heating consumption

The observations made are in accordance with what is explained in the Literature review on degree-days. Assuming a constant base temperature without knowledge of the specific gain to loss ratio can lead to misleading results. This is illustrated on Figure 5-4 and Figure 5-5 where the heat consumptions are higher in winter and lower in spring and autumn than the measured consumption.

A reduction in the base temperature, for instance from 15°C to 12°C attempts to account for higher heat gains and less heat losses when a building is more energy efficient. However, on a monthly basis, using constant base temperature without specific knowledge of the monthly heat to losses ratio leads to misleading results. This is well illustrated on Figure 5-4 and Figure 5-5: Both space heating consumptions calculated with constant base temperature overestimate the SHcons in winter and underestimate it in spring and autumn. However, accounting for monthly Tbase with knowledge of monthly gain to losses ratio permits better predictions of the real space heating consumption, as it is shown on Figure 5-6. The model also allows calculating the monthly mean inside temperature and monthly mean heat gains. They are investigated in the next sections.

5.3 The inside temperature

The model allows calculating monthly inside temperatures. The inside temperature depends on many parameters, as described in Methodology. The building time constant is calculated from two constant parameters therefore it is constant. In the analysis, the hours of occupancy are assumed to be constant and that people in the building follow a weekly pattern all along the year. This assumption is discussed in the Discussion. There is no period during which the building is closed. Therefore the only parameter assumed non-constant on which depends the internal temperature is the set-point temperature. The inside temperature of the building during the winter is presented on the Figure 5-8 below. The first two days are Saturday and Sunday, therefore they represent days of non-occupancy. On the Figure 5-8 at hour 49 it can be seen that the inside temperature of the building decreases between the first hour of the week-end (1) and the last (49). From hour 49, the inside temperature 49 it drops from 19°C to 20.2°C in order to pre-heat the building for Monday. This is confirmed on Figure 5-9 where it can be seen that the heat production becomes higher from hour 49. It can also be observed that Tin follows the curve of Text especially during the week-end when the heat production is reduced. The Figure 5-8 also illustrates well the fact that the inside temperature remains higher during hours of occupancy than hours of non-occupancy, even though when the external temperature is not higher.



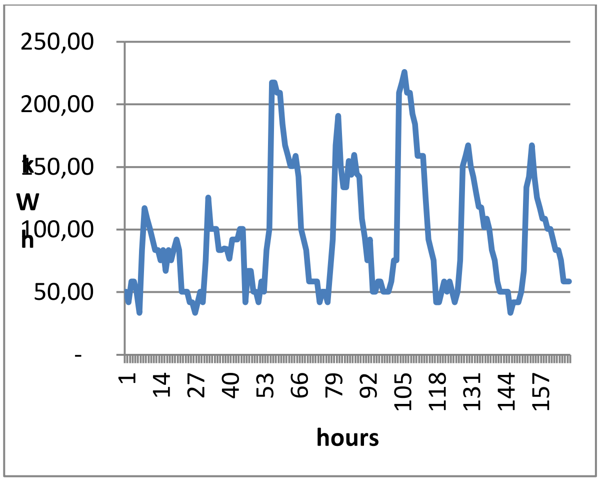


Figure 5-8 Hourly Tin and Text during the 1st week of January

Figure 5-9 Heat production during the 1st week of January

5.3.1 The set-point temperature

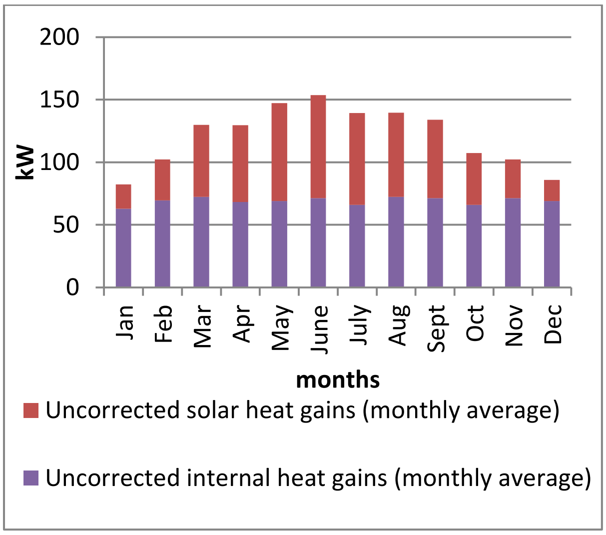
The Sensitivity analysis has demonstrated that the set-point temperature is a key parameter influencing the heat consumption (Figure 4-12 and Figure 4-14).As the set-point temperature defines the temperature until which the heating system needs to provide heat, it really affects the heat production and therefore the space heating consumption. The yearly average of the Tsp is known: it is about 22.1°C. However, the monthly Tsp was unknown. The impact of the uncertain monthly set-point temperatures is investigated in the Uncertainty analysis section. The calculated monthly mean inside temperatures are shown in the Table 5-1 below.

Table 5-1 Monthly mean inside temperature (Tin) compared to monthly set-point temperature (Tsp)

	January	February	March	April	May	Sept.	Oct.	Nov.	Dec.
Tsp (°C)	21.7	22	23	23	23	23.5	23.5	20.8	20.8
Tin (°C)	20.6	20.8	22.0	22.3	22.5	23.2	22.8	19.9	19.7

5.4 The heat gains

The model enables to calculate the monthly mean heat gains (QG). The model first calculates the uncorrected heat gains and the utilisation factor as explained in Definition of key parameters. The uncorrected heat gains (Q'G) and usable heat gains (QG) are shown respectively on the Figure 5-10 and Figure 5-11below. In general, internal gains are higher than solar gains.



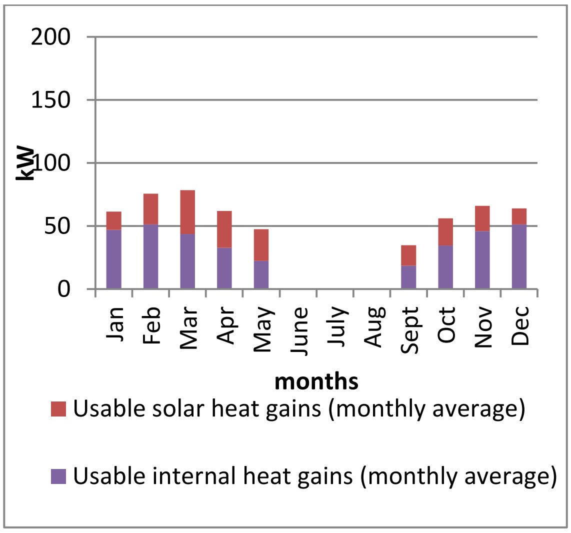


Figure 5-10 Monthly average heat gains uncorrected (Q'G)

Figure 5-11 Monthly average heat gains corrected (QG)

From Figure 5-11 the reduction with the gain utilisation factor is shown. In winter, the heat gains are partially reduced: in January and December, they go down from around 80 kW to around 60 kW. In spring and autumn, the reduction is higher: in March and April, the heat gains go down from around 130 kW to around 60 kW. In September, the reduction is the highest: From 135 kW to 50 kW. This is because the gain utilisation factor is based on the gain to loss ratio. In winter, losses are high and gains are low which results in a low gain to loss ratio. When the gain to loss ratio is low, the gain utilisation factor is high and vice versa. Therefore, the gain utilisation factor is high in winter lower in months close to the summer. This implies that the heat gains can actually be used more during the winter than during the summer. As explained earlier this is to avoid overheating. Also, in spring and autumn the heat demand is lower so less heat gains are needed to offset the heat demand. The values of the calculated monthly gain to losses ratio (ϒ) and monthly gain utilisation factor (η) are given in the Table 5-2 below. In May and September the gain to loss ratio reaches its calculated limit of 1.8902. The ϒlim is calculated according to indications of the ISO (ISO 2008). The Table 5-2 gives indication on the monthly gain to loss ratios. It varies between 0.46 and 1.81 which imply a variation of the gain utilisation factor between 0.39 and 0.75 along the year. These variations are essential for the calculation of the monthly base temperatures. This illustrates the need of knowledge of monthly heat gain to losses ratio if one wants to calculate monthly space heating consumptions of a low-energy building.

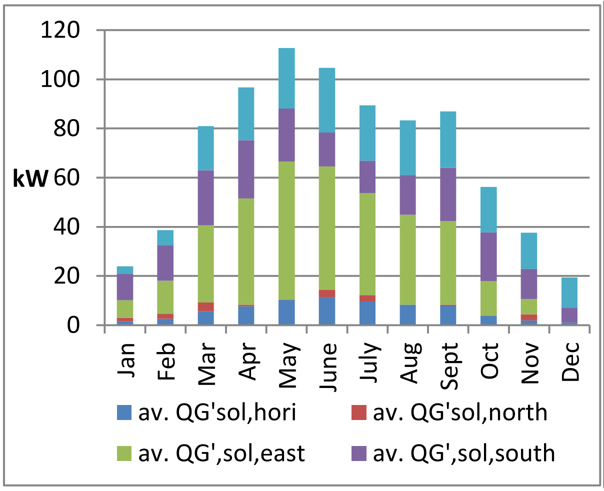
Table 5-2 Monthly gain to loss ratios ϒ and monthly gain utilisation factors η

	January	February	March	April	May	Sept.	Oct.	Nov.	Dec.
ϒ	0.4600	0.4814	0.8295	1.3065	1.8092	1.8092	1.1191	0.7125	0.4701
η	0.7489	0.7390	0.6038	0.4786	0.3909	0.3909	0.5215	0.6441	0.7442

On Figure 5-11 it can be seen that both the uncorrected and usable solar heat gains are the highest in March, April, May and September compared to other months. This is due to high solar radiations on the east and south facades in these months compared to other months (see Figure 4-5). The heat gains on Figure 5-11 are heat gains calculated with the usage of blinds.

5.4.1 The blinds

The usage of the blinds is illustrated on the Figure 5-12 below. It can be seen that the blinds greatly affect the amount of uncorrected solar heat gains. Figure 5-13 represents the solar radiation on each façades for each month without the usage of blinds. Without the usage of blinds, solar heat gains are very high (superior to 150 kW) from May to September. This illustrates the need to use the blinds: with too high solar heat gains the building would be overheated. In October also, the total solar gains without usage of blinds is still high, above 100 kW. In each month, the solar heat gains are reduced, even in January and December. In winter (January, February, November, December), the solar radiations are the strongest on the south façade, as it seems to be the only façade for which the gains are reduced.



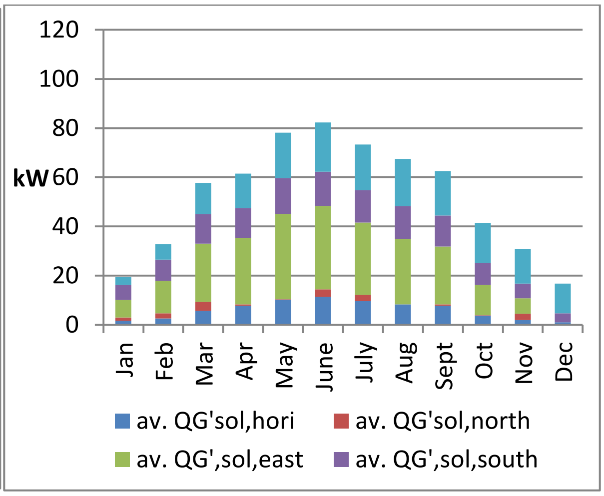


Figure 5-12 (left) Monthly average uncorrected solar heat gains(QG',sol) on each façade without usage of blinds

Figure 5-13 (right) Monthly average uncorrected solar heat gains (Q'G,sol) with usage of blinds

5.5 Heat balance

On the Figure 5-14 below, the heat balance of the building is presented. The usable internal heat gains and usable solar heat gains are summed with the space heat consumption to offset the heat losses. In February and March, the monthly average heat gains are above 70 kW which helps to reduce the need for space heating consumption. In April, May, September and October, the monthly average heat gains are higher than the space heat consumption. In November and December, total heat gains are of 60 kW, representing more than a third of the heat produced per the heating system.

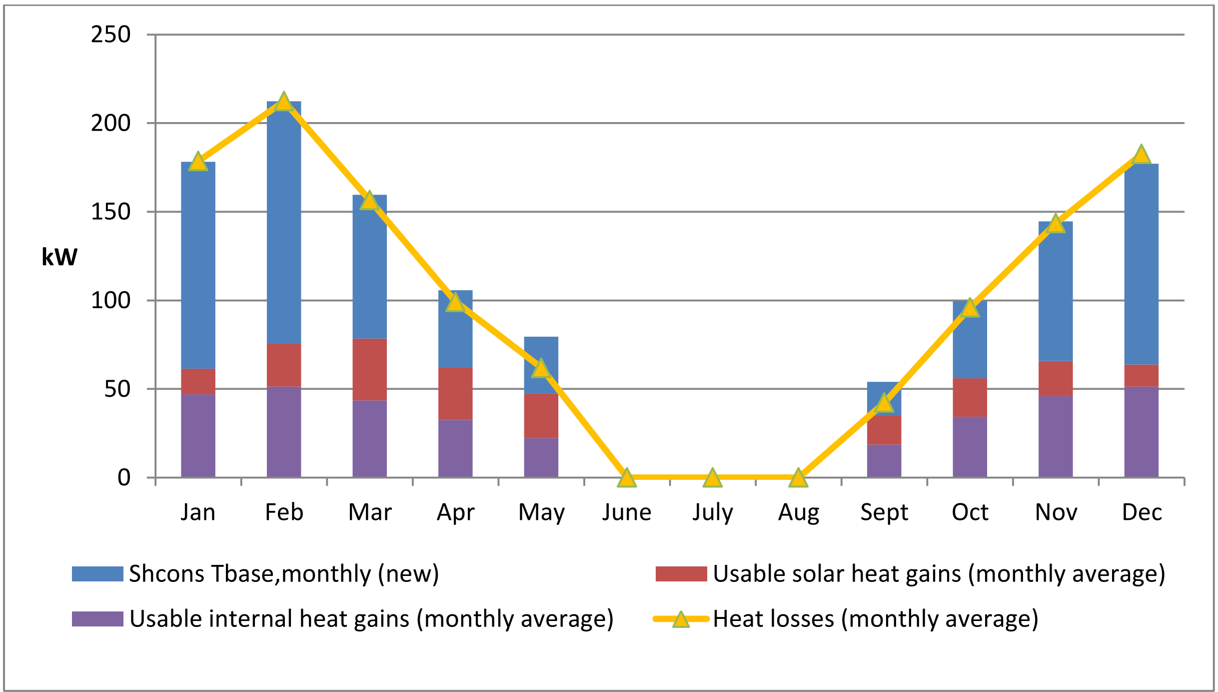


Figure 5-14 Heat balance of the building with the renewed degree-day method

5.6 Uncertainty

Some parameters during the modelling were unknown; therefore their assumption affects the space heat consumption. In order to assess and quantify the effects of the uncertain parameters, an uncertainty analysis is made. Generally, uncertainties can occur from "*unquantifiable information, incomplete information, unobtainable information and partial ignorance*" (Norman Fenton , Wei Wang 2006). In building demand modelling, main uncertainties occur from the occupant behaviour, the operation of the building and the climate (Hopfe, Uncertainty and sensitivity analysis in building performance simulation for decision support and design optimization 2009). In this analysis, the occupant behaviour, as hours of occupancy and occupant density is investigated. The number of hours in occupancy is known from observations. However, often this number is unknown and therefore its related uncertainty is investigated. Also, the control of the occupants on the set-point temperature and on the blinds is investigated. Numbers for occupant behaviour and operation of the building as hours of occupancy or set-point temperatures are defined in standards as the standard

ISO (ISO 2008). However, as demonstrated in the sensitivity analysis, the numbers of hours of occupancy and the set-point temperatures have a high impact on the space heating consumption, compared to the other parameters (Figure 4-14). Therefore it is necessary to quantify the uncertainty related to the results. Also, climate data used in modelling and degree-days calculations are often data averaged over 20 years. Therefore it is important to assess the uncertainty caused by these assumptions. Therefore if the uncertainty of climate data only affects moderately the space heat consumptions, one could use the model with averaged climate data. The parameters investigated in the analysis and their range of variation is presented in the Table 5-3 below. In order to validate the model, it is necessary to test it on other buildings to evaluate its robustness. Indeed, if the model presents acceptable results to estimate the space heating consumption of another building with different features, physical characteristics and type of climate some conclusions can be made regarding the level of uncertainty of the model itself. Nevertheless, due to lack of data the test of the robustness of the model has not been conducted. However, it is possible to evaluate and quantify the effect of the uncertainty. Also, the uncertainty related to variations in climate data is investigated and therefore if the uncertainty is low, it would confirm that using average climate data can be used for the model.

Table 5-3 Uncertain parameters and their range of variation

Parameter	Variation (3σ)	Min (-3σ)	Mean (μ)	Max (+3σ)
Set-point temperature	+/- 2°C		Different for each month	
Blinds		No control	“normal” control	“high” control
Occupancy hours	+/- 2hour	10	12	14
Solar radiation	+/-10%		Data given for 2005	
External temperature	+/-10%		Data given for 2005	

The output parameter investigated is the monthly space heating consumption calculated by the model. The analysis is made with analysing the effect of the uncertain input parameter on the output parameter (SHcons). The analysis investigates the impact of the uncertainty in each month. All input parameters investigated present a linear relation in the calculation of the SHcons. A linear relation between input and output parameters is a requirement in order to conduct this uncertainty analysis (A. Macdonald 2002). The linear relation of all parameters investigated in the study is available in AppendixB. Therefore it is possible to assess quantitative values on the effect of the uncertainty in the input parameter on the SHcons.

5.6.1 The set-point temperature

As already demonstrated in the Sensitivity analysis and the Results of the analysis, the set-point temperature has a great impact on the space heating consumption. The impact of the uncertainty in the set-point temperature is quantified on Figure 5-15.

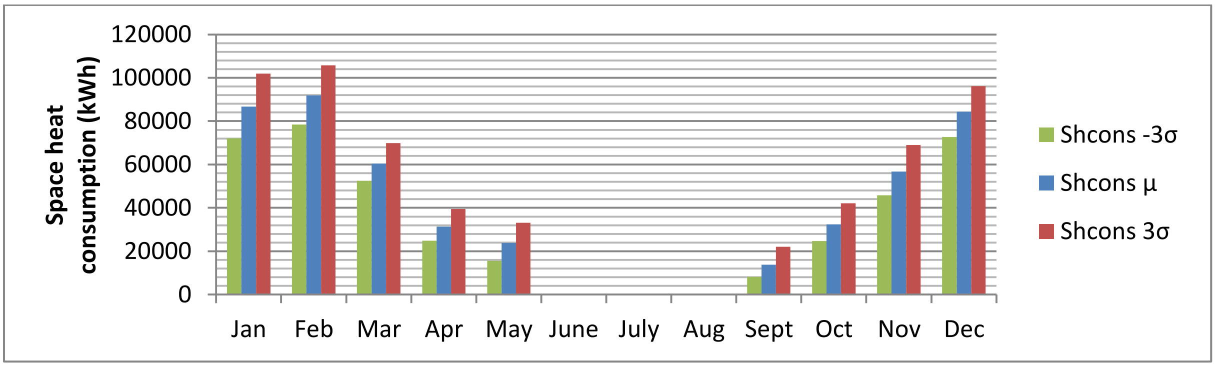


Figure 5-15 Quantitative uncertainty of the set-point temperature (Tsp) on the space heating consumption (Shcons)

The figure demonstrates that the impact of the uncertainty is quite high, especially in January and February when the uncertainty can arise a difference of more than +/- 10,000 kWh with the mean calculated space heat consumption (Shcons). In spring and autumn months, when the heat demand is lower, the impact of the uncertainty is lower.

5.6.2 The blinds

The impact of the user on the blinds is unknown. Therefore it is primordial to identify if this uncertainty is of great influence on the space heating consumption. As it can be seen on the Figure 5-16 below, the uncertainty due to the usage of the blinds is low. When there is no use of the blinds, the space heating consumption is lower than when they are used. However the uncertainty related to the blinds never affects the space heat consumption more than 6,000 kWh. However months when the space heat consumption is low coincide months when solar radiation is high and therefore the usage of the blinds of great importance. May is the month with the highest effects due to the uncertainty, because it is the month with the highest solar radiation. The uncertainty can affect the space heat consumption of 25% in May.

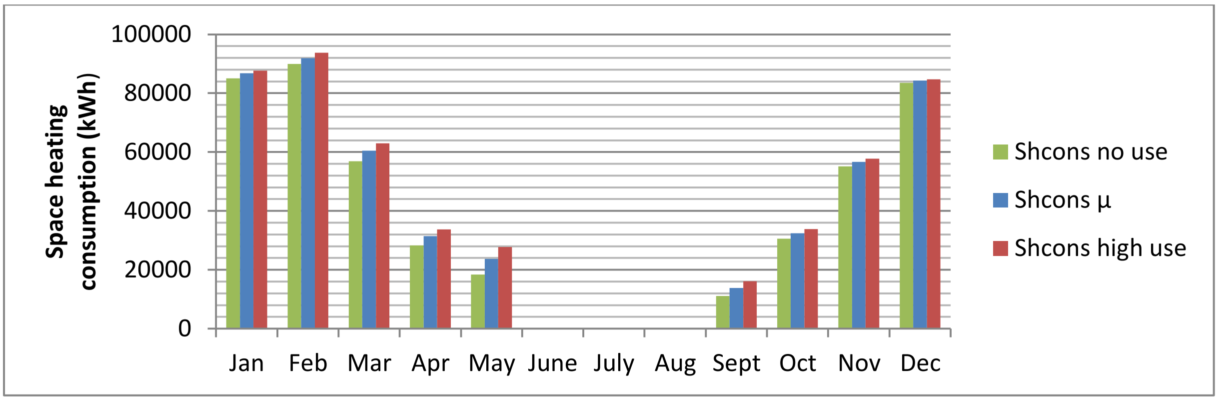


Figure 5-16 Quantitative uncertainty of the blinds on the space heating consumption (Shcons)

5.6.3 The number of hours of occupancy

As demonstrated in the sensitivity analysis, the number of hours of occupancy is one of the most influencing parameter on the heat consumption. When the number of hours of occupancy decreases (-3σ) the space heat consumption increases of around 30 MWh for instance in January. This might be linked to the internal heat gains: when they are no people in the building, the internal gains are drastically reduced. However, this high impact can be explained by two reasons: in the analysis, the internal gains were assumed to be 0 during hours of non-occupancy, when they are actually probably a bit higher. Also, as explained above, internal heat gains as often over-estimated in buildings, and particularly in low-energy buildings, they are probably lower. Therefore it is likely that the impact of the number of hours occupied is actually lower. Considering the building in consideration, the number of hours in occupancy is known therefore it does not impact the results.

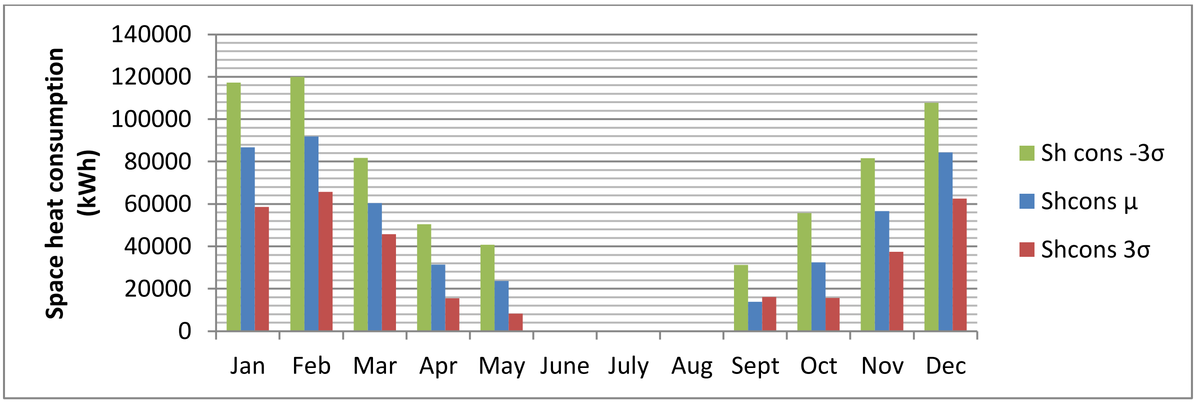


Figure 5-17 Quantitative uncertainty of the number of hours in occupancy on the space heating consumption (Shcons)

5.6.4 The external temperature

As people usually use average values for climate data, the uncertainty related to these data is investigated. When the external temperature is lower of 10%, then the space heat consumption rises of around 5,000 kWh for instance in January. This effect seems quite the same along the months; it is of 6,000 kWh in September. Due to this low impact in uncertainty of the external temperature on the space heat consumption, it can be concluded that using average values for climate data will not induce a large error in the calculation of the space heating consumption. A variation of 10% seems reasonable for climate data.

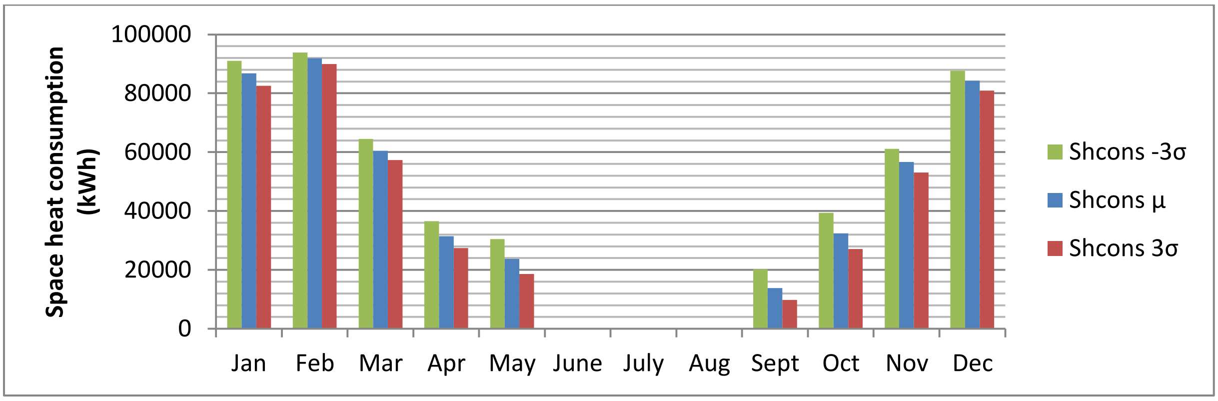


Figure 5-18 Quantitative uncertainty of the exterior temperature Text on the space heating consumption (Shcons)

5.6.5 The solar radiation

As for the external temperatures, the uncertainty related to variations in solar radiation is investigated. The purpose is to evaluate if using average data will induce large errors in the results. As shows Figure 5-19 a variation of 10% of the solar radiation impacts only slightly the results. With 10% of variation in the solar radiation, the space heat consumption is, in all months never affected more than 2,000 kWh. Therefore it can be concluded that using average data for solar radiation values would not induce errors in the results.

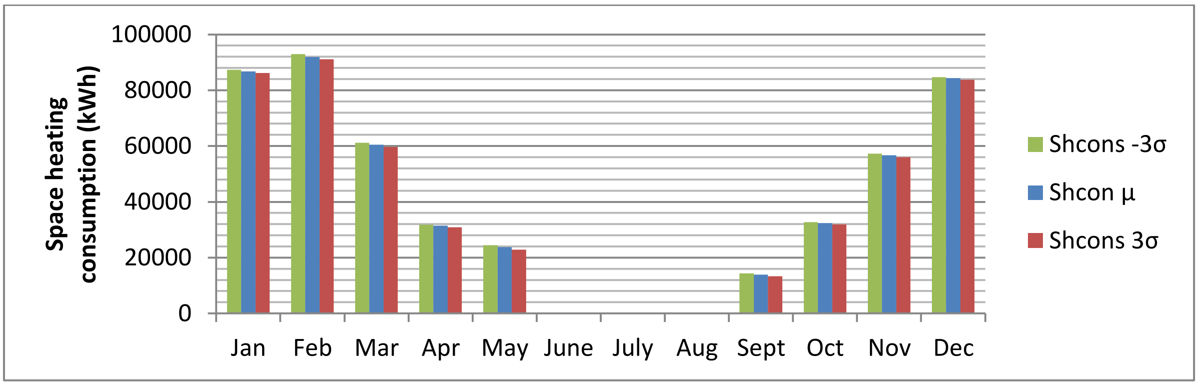


Figure 5-19 Quantitative uncertainty of the solar radiation on the space heating consumption (Shcons)

5.6.6 The base temperature

Finally, the impact of uncertainty in the base temperature is investigated.

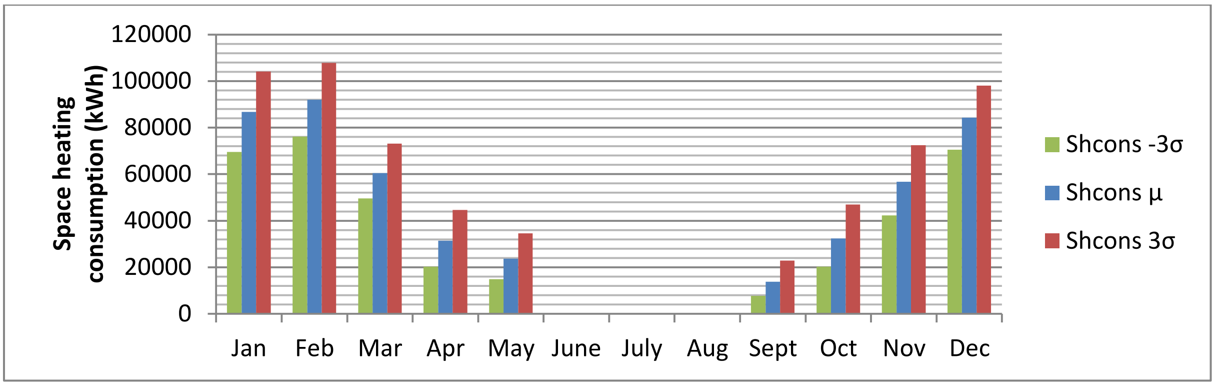


Figure 5-20 Quantitative uncertainty of the base temperature (Tbase) on the space heating consumption (Shcons)

An uncertainty of 2°C in the base temperature leads to high variations of the space heat consumption. As it is shown on Figure 5-20, in January for instance, a 2°C increase of the base temperature would result in a 13,000 kWh of the space heating consumption. In all months of the years the uncertainty is high. Also, the base temperature is only varied +/-2°C to its monthly base temperature, when actually the real base temperature of the building is unknown, and especially its variations among the months. Therefore the uncertainty of the base temperature is actually higher in all months, which would result in an even higher impact on the space heat consumption.

The analysis has quantified the effect of uncertain parameters on the space heating consumption for each month. It has confirmed that uncertain set-point temperatures affect greatly the space heating consumption. Therefore the calculated space heat consumption in the model might have a 10% error in each month due to the uncertainty related to the set-point temperature. Even though the usage of the blinds is unknown, as it is likely that they have been used, the uncertainty in how they have been used is low. Therefore the assumptions made for the usage of the blinds in the modelling are acceptable. Also, as demonstrated in the Sensitivity analysis the number of hours in occupancy strongly affects the space heat consumption. However this impact is probably overestimated. The uncertainty concerning climate data is reasonable and therefore using average climate data for the model is reasonable. The uncertainty in the base temperature is high, and would be even higher than the one shown on Figure 5-20 as the monthly base temperatures are usually completely unknown.

5.7 Error

This chapter has presented space heat consumptions calculated using monthly base temperatures. In order to know how accurate the method is, the error is calculated for each month. The monthly calculated space heat consumption, the actual monthly measured heat consumption and the error associated are presented in the Table 5-4 below. The error is the highest in March and April, being respectively of 8.79% and 6.88%. During cold months, the error in the estimation of the space heat consumption is between 0.13% and 1.56% which is low. The error is higher in spring and winter months. This is due to the fact that degree-day totals have more uncertainty when there are calculated on a shorter time frame. In September for instance, the space heat consumption is very low and therefore the total amount of degree-days errors is low. This give more chances for error to occur. In May, the error is very low. In these calculations, the error of the uncertainty is not taken into account. Especially, it has been shown that the uncertainty of the set-point temperature can impact the space heat consumption around +/-20% in colder months. The error calculated only applies to the chosen values for the set-point temperatures. If they were chosen differently within their interval, the error would be different among the months.

Table 5-4 Error in the estimation of the monthly space heating consumption

	Space heating consumption measured (kWh)	Space heating consumption calculated (kWh)	Error δ (%)
January	86,875	86,766	0.125950608
February	92,188	91,928	0.28148214
March	66,250	60,427	8.789585169
April	33,750	31,427	6.882811128
May	23,750	23,762	0.051435718
September	13,438	13,843	3.020567328
October	33,438	32,414	3.061440703
November	56,563	56,685	0.21619251
December	85,625	84,293	1.555385262

5.8 Conclusion on the results

It has been demonstrated that the space heat consumption calculated with monthly base temperatures give better results than using any constant base temperature. This is particularly obvious on the Figure 5-21 below. It can be seen that for both a base temperature of 12°C and 15°C, spring/autumn consumption is underestimated. With a base temperature between 12°C and 15°C, it might give better predictions for winter months but in March, April, May, September and October it would under estimate the consumption. Therefore using monthly base temperatures can only be better than using a constant base temperature to calculate degree-days.

In order to answer to the sub-question "*What are the main differences between the space heating consumption calculated with the renewed degree-day method compared to the current degree-day method?*" the following answers are given:

- The current degree-day method calculates degree-days with a constant base temperature over the year whereas the renewed degree-day method calculate degree-days with monthly base temperatures
- The renewed method enables to calculate monthly heat gains and monthly mean internal temperature through the model. Therefore it gives insights about the gain to loss ratio and enables to calculate adapted base temperatures for each month
- The renewed degree-day method give better estimates of the space heat consumptions than the current degree-day method, in each month of the year
- The renewed degree-day method estimates continuous space heat consumption along the year which varies along climate variations whereas the current degree-day method estimates discontinuous space heat consumption. The current degree-day method also always underestimates the space heating consumption in spring and autumn months.

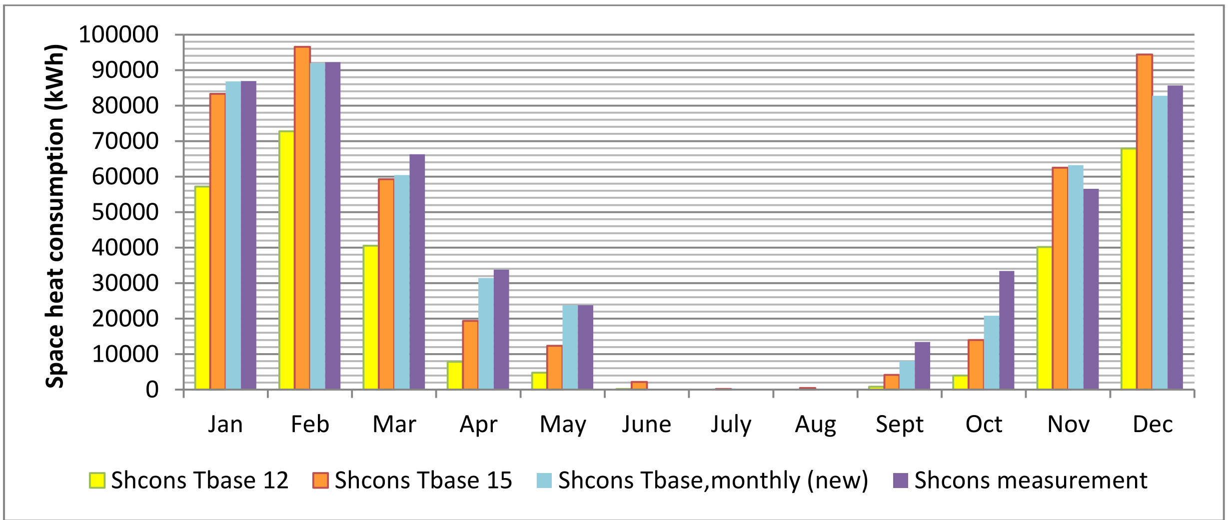


Figure 5-21 Comparison of monthly space heat consumption: measured SHcons, Shcons calculated with a 15°C Tbase, Shcons calculated with a 12°C Tbase, Shcons calculated with monthly Tbase

In order to answer the sub-question *"How could be the model validated?"* the following answers are given:

- The model is validated when comparing the estimated space heat consumption with the actual space heat consumption as it gives good predictions. However the model is only partly validated as it was tested on one building only and therefore it is necessary to test its robustness on other buildings with different characteristics.
- The model is validated as the error compared to the measured space heat consumption is relatively low. The monthly error is between 0.125% and 8.789%. Part of the error is probably due to uncertainties in the monthly set-point temperatures which have a large impact on the heat consumption. Part of the error can also be due to uncertainties in the usage of the blinds, as they have a large impact on the solar heat gains especially in months with high solar radiations.
- The estimation of the mean inside temperature and by extrapolation of the space heat consumption has been tested per A.R.Day and Karayiannis for light weight and medium weight buildings. Therefore the model is validated for this type of building

- The uncertainty related to a variation in 10% in both external temperatures and solar radiations is low. Therefore the model is validated to be used with average climate data.

Other conclusions from the chapter can be made:

- The gain to loss ratio varies among the months and therefore it is necessary to calculate it if one wants to estimate monthly space heat consumptions of a low-energy buildings
- Once the heat gains are corrected, internal gains are higher than solar heat gains. However the internal gains might be overestimated as explained earlier. Also as the real use of the blinds is unknown, the solar heat gains might be higher or lower. The impact of the uncertainty of the blinds is acceptable in cold months but in spring and autumn months the impact of the uncertainty on the space heat consumption becomes higher.
- An uncertainty in the number of hours in occupancy would greatly impact the results. Long occupied hours result in lower space heat consumptions. This is due to the fact that the presence of people generates high internal heat gains. However it is possible that the internal heat gains are overestimated. The number of hours occupied also affects the mean inside temperature as shown in section xxx. This is due to higher internal temperatures when people are in the building than compared to during the night or during the week-ends.
- In May and September more than 50% of the heat demand is offset with the heat gains (see figure 14). In April and October even more than 50% of the heat demand is offset by the heat gains. In March and November also 50% of the heat demand is supplied by the heat gains. March is the month with the highest usable solar heat gains.

6 Discussion

This master thesis has investigated how a renewed degree-day method could predict the space heating consumption of the low-energy building Ostarkade. The hypothesis that using a constant base temperature is wrong has led to the investigation through this paper. This master thesis has emphasised that, using varying monthly base temperatures give more accurate estimations of the space heating consumption instead of using a constant base temperature. For the first time it is demonstrated that monthly base temperatures are of necessary use for low-energy buildings when investigating monthly space heating consumptions. This master thesis has shown that during spring and autumn months using a constant base temperature strongly underestimates the real space heating consumption. Through the calculation of monthly mean heat losses and monthly mean heat gains, specific monthly gain to heat losses ratio have been investigated. Their knowledge has been essential to identify how the total heat gains are utilised to offset the heat demand. Therefore with this gained knowledge it was possible to estimate very accurate space heating consumptions in spring and autumn months. Moreover, the model developed enables to conduct sensitivity analyses on the key parameters influencing the space heating consumption.

6.1.1 Sensitivity of the space heating consumption

The overall heat loss coefficient was identified to be the main parameter influencing the space heating consumption. As can be seen on Figure 4-15 it is strongly influencing in colder months, whereas in April, May, September and October its influence is considerably reduces and becomes equivalent to the other parameters. In September, it was the least influencing parameters on the space heat consumption after the heat gains and the internal temperature. The strong influence of the overall heat loss coefficient on the space heat consumption is in accordance with the literature (Hopfe, Uncertainty and sensitivity analysis in building performance simulation for decision support and design optimization 2009) (IEA ECBCS; Per Heiselberg 2010) (A. Macdonald 2002). However it is the first time that its influence on a monthly basis has been investigated. The Sensitivity analysis had also shown that the monthly set-point temperatures and the number of occupancy hours have a large impact on the inside temperature and on the space heating consumption. Only the impact of different overall heat loss coefficients and heating system capacities has been investigated before (A.R.Day; T.G.Karayiannis 1999). The impact of these parameters showed similar results in the analysis. Furthermore, it is the first time that the impact of the occupant, through the set-point temperatures and number of hours occupied has been investigated. The analysis has shown that the occupant has a much higher influence on the space heating consumption of the building than physical parameters. However the results are definitely very sensitive to their range of variations. The number of hours occupied varied in a +/-2 hours range around the known value and the monthly set-point temperatures in a +/-2°C range around their chosen values for the analysis.

6.1.2 The set-point temperature

The monthly set-point temperatures were arbitrarily chosen based on the assumption that the set-point temperature was changing along the year. Literature on occupant's thermal comfort and possible space heat consumption reductions confirmed the assumption and indicated ranges of variations (J.F Nicol; M.A Humphreys 2002) (Anne Valler; Stine Noe Brandstrup 2012). The impact of this uncertain parameter has been assessed and demonstrates that it has a great influence on the space heating consumption. The error of this uncertainty has not been quantified but its range of influence has been defined: in winter months, with a 2+/-°C variation the space heating consumption can vary of +/-10,000 kWh which represents around 10% of the total space heating consumption in coldest months. Considering its high impact on the space heating consumption, further research need to be addressed to quantify monthly set-point temperatures when only the annual average set-point temperature is known.

6.1.3 The internal temperature

The internal temperatures were calculated as a sum of the set-point temperatures during the occupied hours and the sum of calculated internal temperatures during hours of non-occupancy. This explains why the inside temperature is so sensitive to the number of occupied hours. Aside than on the inside temperature, the number of hours in occupancy was the most influencing factor on the heat gains during colder months. In the analysis, the number of hours occupied was assumed to follow a weekly pattern 12hour/day-5days/week but exceptions occur, for instance when people go in vacations. However, as people usually take vacations during the summer, a reduced amount of internal gains in summer would not impact the heat demand in winter, spring or autumn. Regarding the possibility that vacations were taken during other periods of the year, the absence of people would results in an increase heat demand during this period. No hour for lunch break was taken off the calculation, assuming that most people spend their lunch period inside the building at the canteen and leave lights and equipment on. This was counter-balanced with the assumption that during hours of non-occupancy the internal gains are equal to 0. Also, this assumption will not impact much the usable heat gains, as there is no heat demand during hours of non-occupancy. In the analysis, the hours of occupancy were known and considered to be constant, but in general they are not known and people use values defined in standard, as in the German norm DINV 18599 for instance. The DINV 18599 estimates 11 hours of occupancy for an office building (DIN V 18599 2007). One has to be careful when using standard values, considering the high impact on the space heat consumption of the uncertainty. However in the analysis a variation of +/-2hours of occupancy was considered. Therefore a high variation resulted in a high impact on the space heat consumption.

6.1.4 The heat gains

Regarding the internal heat gains, it is probable that their value has been overestimated. Number of studies has shown that internal gains are much higher in office buildings compared to residential buildings, due to the large amount of people, electronic equipment and lights. But some literature also put in perspective the fact that in low-energy buildings, efficient energy management systems are designed to reduce the building electric consumption. Also the use of daylight reduces the need of electric light. (Elisabeth Gratia; André de Herde 2003). Indeed, a study shown that on a study case of low-energy office buildings in Sweden improvements, in the office equipment can save 10 kWh/m²/year of electricity need, plus an additional 10 kWh/m²/year for improvements in the office lights. This results in decreased internal heat gains. The article concludes that in low-energy offices it is crucial to decrease the internal heat gains when calculating them. (Kajsa Flodberg; Åke Blomsterberg and Marie-Claude Dubois 2012). Therefore the internal gains in low-energy and new buildings are probably lower compared to actual buildings in use. The specific internal gains of low-energy buildings have not been investigated and therefore need further research.

In warmer months of the year, and especially in May and September, the g-value and the windows size were identified to be the most impacting parameters on the heat gains. This is due to the fact that the building has a very large amount of windows on the East façade and also on the South façade, allowing heat gains even in winter. In other months of the year, the size of windows did not have a major influence on the space heating consumption, which is in accordance with the literature (Mari-Louise Perssona; Arne Roosa; Maria Wallb 2005). The g-value was identified to be the second most influencing parameter of the heat gains along the year, which allowed the solar heat gains to be used to offset the heat demand, and especially in February and March (Figure 4-13). Figure 5-14 showed that March is the month with the higher usable solar heat gains (monthly average of 30 kW) compared to other months of the year which confirms the influence of the g-value on the solar gains. In March and October, Figure 5-14 showed that the solar heat gains represent almost 25% of the heat used among the other sources (internal heat gains and space heat consumption). The percentage is the highest in these months because solar radiations are high and external temperatures around 15°C. Therefore the monthly gain to loss ratios in March and October are low enough to allow the use of more than 50% of the heat gains. Regarding the usage of the blinds, some assumptions had to be made. The uncertainty analysis provided a quantitative assessment of this uncertain parameter: in May, if blinds are not used at all, this reduces the monthly space heating consumption of around 30%, and if they are used more than the average, it increases the space heating consumption of around 15% according to Figure 5-16. Therefore the solar gains, due to the impact of the blinds, might be even higher or actually lower in each month, but especially in months with high solar radiations.

6.1.5 Gain to loss ratio and utilisation factor

The calculation of monthly gain to loss ratios and gain utilisation factors was of primordial importance. Their calculation was given in literature, but it was not specified that they needed to be calculated for each month, if monthly space heat consumptions are considered. It was not clear in the literature where if one yearly gain utilisation factor was needed or where if monthly gain utilisation factors were to be used. Only a worked example using monthly utilisation factors was available in the Appendix I of the ISO norm (ISO 2008). The definition given for the utilisation factor in the standard is "*factor reducing the total monthly or seasonal heat gains in the monthly or seasonal calculation, to obtain the resulting reduction of the energy need for heating* (ISO 2008).Therefore, the time frame of the utilisation factor was not considered. Accounting for monthly utilisation factors was necessary to determine for each month the part of heat gains which were to be used. As gain to loss ratios greatly differ depending on the month, it was necessary to derive them such as the utilisation factor for each month. Although results are not shown here, it was important to calculate the factors this way. Consequently this research underlines the need to calculate utilisation factors based on the same time frame than the one considered in the study.

6.1.6 The monthly base temperatures

The monthly base temperatures are low when the monthly space heat consumptions are high and vice versa (Figure 5-1 Figure 5-2). Also, Figure 4-15 suggests that the internal temperature influences the most the space heat consumption among the overall heat loss coefficient and the heat gains. From Table 5-1 Monthly mean inside temperature (Tin) compared to monthly set-point temperature (Tsp), the mean inside temperature follow the curve of the base temperature presented in Figure 5-1This confirms that the gain to loss ratio $\frac{QG}{U\prime}$ in Eq. 1-1 is used to complete the heat needed to maintain comfort between the mean inside temperature and the base temperature.

6.1.7 Accuracy of the model

The robustness of the model has not been tested on more than one building, but the prediction of the monthly space heating consumptions present a maximum error of 8.8% in March, which is the first step to validate the model. The uncertainty of the climate data has been quantified, and has shown that the model could be used by using average climate data for external temperatures and solar radiations. The model is completely transparent, which is a main advantage compared to the current degree-day method. Therefore the model also allows reproducibility. Another advantage is that the model presents flexibility compared to the current degree-day method. As it is more detailed, it is actually possible to calculate the exact monthly base temperature of the building, which should reduce large number of errors.

The current degree-day does not allow this flexibility as the base temperature used is either the country standard, either an assumed constant base temperature for the building. The model also allows using non-standard data, as the number of occupied hours or the set-point temperatures. Indeed, uncertainties can also occur when using a standard as standardised values are not always what happen in the reality. This leads to the main disadvantage of the model is that is presents ambiguous aspects in occupant's behaviour, for instance regarding the choice of the set-point temperature. As it has been assumed that monthly set-point temperatures were used, some consideration should be given to derivate monthly set-point temperature from the yearly average which is actually given, or also given as an indication in standards. Finally, the model is innovative as it presents the calculation of monthly heat gains and monthly base temperatures; they are features which were never investigated before.

6.1.8 Use of the model

As stated earlier, the particularity of the model is that it lies between complex building thermal simulations and the easy-of-use widespread current degree-day method. However, unlike the current degree-day method, the model requires detailed input data about the building's characteristics, the climate and the user. This could be seen as disadvantage, but as the model is user-friendly, it could actually be accessible to different type of people. As stated in the introduction, people want an accurate method to predict their building energy consumption, and sometimes available degree-days data online are not sufficient. Also, the uncertainty of the base temperature of the building enhances large errors in the calculation. Therefore, people might be interested in using a method which calculates a more accurate base temperature for the building. Of course, monthly base temperatures are still average temperatures but their use would give much better predictions than the current method, as it was explained in the Results of the analysis. According to the literature, energy managers, energy auditors, building energy consultants need a robust tool to calculate monthly space heating consumptions. Furthermore, as this type of person is only few educated regarding building design, this type of model might interest them. It is likely that energy managers do not use thermal building simulations, or they would ask for external consultancy. Therefore, providing them a user friendly tool to calculate monthly space heating consumptions could be a good alternative. Moreover, the energy manager of a building has probably access to the input data which are required for the model. The dissemination of this model could also encourage people to use it. Therefore they would gain knowledge about building practices, and which are the small things that can be done to greatly improve occupant's comfort while decreasing the overall energy consumption of the building. For instance, they could get knowledge from the model regarding usage of the blinds and of the set-point temperature. By comparing monthly space heating consumptions from one year to another, one could then see its energy savings. Different type of users, as building energy consultants, or individual people who wants to refurbish their home for instance could also use this renewed model. For instance, building energy consultants might be interested in the calculated monthly heat gains. Regarding individual people, they might want to evaluate how much they can reduce their space heating consumption. What is great is that this kind of people would actually have the detailed set of input data needed for the model. Furthermore, the use of this model could encourage people to provide feedback about the model, which would enhance the robustness of the model as it could be improved based on user experience. Secondly, people could share their data in some kind of community learning and development. As stated in the introduction, what is missing in low-energy building is the lack of knowledge and data. Therefore if people were likely to share their buildings data and associated base temperatures, this could improve the method, the research and the overall knowledge of people considered in the community.

However, some other type of people, as the energy planner, might just want to look at the aggregated demand of buildings and would not look for data of individual buildings. In that case, further work needs to be addressed to extrapolate the results presented in this analysis. If the model could be tested through a lot of different buildings, maybe a patter between the yearly base temperature and monthly base temperatures could be identified. This would enable the direct calculation of monthly base temperature from the yearly base temperature, without the need of the detailed input data. The use of the monthly base temperature to predict hourly space heating consumptions is illustrated in the flow chart Figure 6-1 below.

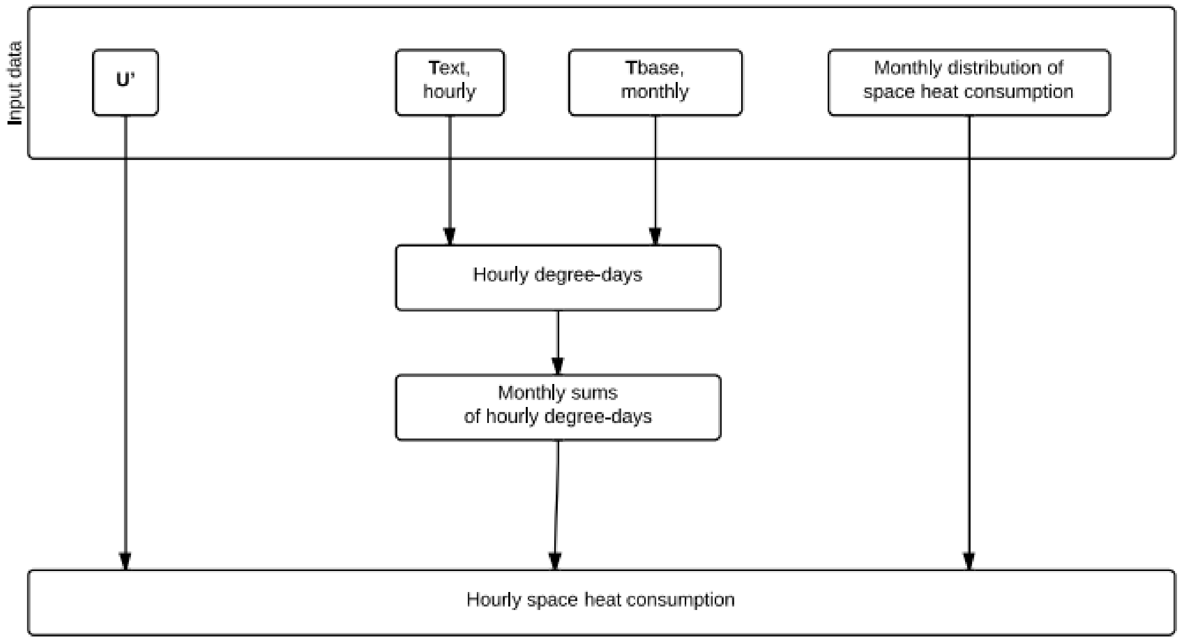


Figure 6-1Flow chart of the hourly space heating consumption calculation from a monthly base temperature and a monthly distribution

The sub-question "*What could be the use of this renewed model?"* was answered in this chapter. As this renewed method presents more accurate results than the current degree-day method, it is assumed than it could interest the same people using the degree-day method. Also, the use of the model could enhance the knowledge of people about low-energy buildings heat flows and practices.

In order to answer the sub-question *"How could the model be validated?"* the robustness of the model needs to be tested on other buildings. The model has already been partially validated when comparing the calculated space heating consumption with monthly base temperatures to the measured space heating consumption. This research is of significant importance as the degree-day method is used by a large number of users in different sectors. Therefore it is important to assess that the current degree-day method lead to misleading results in the case of monthly heat consumption estimates for low-energy buildings and that new methods need to be investigated. This project has pointed out that some factors are determining over the space heating consumption, as the impact of the user.

7 Conclusion

This master thesis has presented a renewed degree-day model. The model calculates monthly base temperatures in order to generate hourly space heating consumption values. It has been demonstrated that the predicted monthly space heating consumption with the renewed method is better than any estimated space heating consumption using a constant base temperature. Indeed, the monthly space heating consumption calculated with a constant base temperature always underestimates the consumption in spring and autumn months. Uncertainties and errors are already high in the degree-day method therefore looking at a monthly scale induces further error in the calculations. With the renewed method, the maximum error on a monthly basis is of 8.8%. The error is inferior to 1% in the coldest months. The large error in the current degree-day method is due to the fact that it does not take into account variations of heat gains during the year. The renewed method allows calculating monthly heat gains and monthly gain to losses ratios.

It is the first time that such results are presented. Even though a relevant numbers of assumptions had to be made, the model presents comparable results to the measured space heating consumption on an hourly basis. Also the model presents main advantages compared to the current method, as it provides interesting output data. One disadvantage is that it requires a large number of input data. Even if typical values can be found in the literature and standards, the uncertainty related to using estimate data greatly affects the estimation of the space heating consumption, especially for the estimation of monthly set-point temperatures.

This first version of a renewed degree-day model has been presented. This renewed model aims to be used by the same people using the current degree-day method. The errors on the monthly scale of the current method for a low-energy building have been presented. As this renewed degree-day model presents better estimations than the current method, further work should be enhanced to improve its robustness and therefore propose a real alternative to the current degree-day method.

8 Appendix A

- Overall heat loss coefficient U'

The volume of the building and air infiltration rate are used to calculate the ventilation losses when the surface area of the building with the heat transfer coefficient represents the transmission losses. The numerical factor 1/3 comes from typical values of density and specific heat of air. By using the formula xx below, the overall heat transfer coefficient is calculated: (CIBSE 2006)

$$U' = \frac{A \times U + \frac{1}{3} \times N \times V}{1000}$$

- Internal heat gains Qint

The internal gains are calculated using the formula below. They are given in Watt. QI represent the internal gains at hours when people actually are in the building. Therefore they need to be added with the solar gains only during the hours of occupancy. OD represents the occupant density in m² per person.

$$Qint = 224{,}97 \times \frac{1}{OD^{0{,}7334}} \times A$$

- Solar heat gains Qsol

To calculate the solar gains, the solar radiation has to be first calculated on every façade. According to the literature review, it is not possible to account for hourly solar gains as it does not give accurate results. Thus the solar radiation can be used on a daily basis, weekly, monthly, or any interval of time which is at least a day. In the model different analyses are performed in order to see which one gives better results. The average (daily, weekly or monthly) solar gain is calculated on each façade with the following formula. It is given in W.

$$Qsr = sr \times Ws$$

Then the total solar gain is calculated, it is the sum of each façade multiplied with the transmittance coefficient of the windows.

$$Qsrtot = (QsrH + QsrN + QsrW + QsrE + QsrS) \times g$$

Input data	**Symbol**	**Unit**
Solar radiation	Sr	W/m²
g-value	g	
Size of windows	Ws	m²

Table 5 Parameters to calculate mean heat gains

- Total heat gains QG

The heat gains represent the sum of the internal gains (only during hours of occupancy) and the solar gains calculated from solar radiation. Therefore the heat gains are calculated with the following formula:

$$Q'G = Qsrtot + Qi \ \times (t3 - t1)/24$$

Q'G represents the uncorrected gain to the space. In order to consider the heat gains that can directly be used to reduce the heat balance a gain utilisation factor has to be applied on this formula to calculate the usable heat gains QG:

$$QG = Q'G \times \ \eta$$

- Heat balance ratio ϒ

$$\Upsilon = \frac{Q'G}{QL}$$

Q'G are the total uncorrected gains to the space during the period considered.

QL is the total heat loss during the period considered

- Gain utilization factor η

The gain utilisation factor η depends on the heat gains, the heat loss of the building and its time constant τ. It is a number between 0 and 1. The equations of η and ϒ are the following:

$$\eta = \frac{1 - \Upsilon\text{^}a}{1 - \ \Upsilon\text{^}(a - 1)}$$

The parameter a is calculated with:

$$a = a0 + \frac{\tau}{\tau 0}$$

The parameters a0 and τ0 are typical parameters defined in standards. For an office building in Germany a0 = 0.8 and τ0 = 70 because it is an intermittent heated building (CIBSE 2006).

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