Design Patterns of Ventilatively Cooled Buildings in Denmark
Simple Predesign Tool for Estimation of VC Potential

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June 2015

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Title:
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Project period:
IE, autumn semester 2014 - summer 2015
01-09-2014 to 10-06-2015

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Editions: 5
Number of pages: 172
Completed: 10-06-2015

Preface

This Master thesis is a documentation of the study concerning ventilatively cooled buildings in Denmark and simple ventilative cooling estimation tools for the predesign phase. The time frame of the project lasted from September 2014 to June 2015, and it was written by two civil engineering students in the Master of Science Programme at the faculty of Indoor Environmental and Energy Engineering at Aalborg University.

At the end of this project all references are listed in a bibliography. Harvard method is used for source citation. Sources are divided in books, articles, websites and reports. Books are referred as follows: author, title, ISBN-number, edition, publisher, year. Articles/reports: author, title, edition, date, year. Websites: author, title, URL-address, year, date of use. Tables and figures without source reference are self-made. If a source reference is located before the full stop it refers to the concerned sentence, otherwise it is referring to the previous section, if it is located after the full stop.

The report consist of a main part and appendix. The main report includes the main theory and results, whereas more detailed information is presented in the appendix. Therefore, the two parts should be read together. An Appendix CD containing building descriptions, BSim simulations and excel calculations from VC potential tools is attached to the report. In the Appendix CD the different files are organised under different folders depending on different subjects.

The project group would like to express there gratitude to the supervisors:

- Per Kvols Heiselberg
- Jérôme Le Dréau

Dainis Dabols   Kasper Dalgaard Jensen

Abstract

It is expected that on-going tendency of improving building insulation together with global warming and increasing in heat island effect in urban environments will lead to considerable increase in building cooling demand in the future. An efficient solution to minimise the room overheating and reduce the need for mechanical cooling is utilisation of direct ventilative cooling. This master thesis is conducted to observe the general design patterns of ventilatively cooled buildings in Denmark and to investigate the possibility of generating a reliable estimation of ventilative cooling (VC) potential during the predesign phase by the use of simple design tools.

To determine the characteristic design patterns of ventilatively cooled buildings in Denmark, a database of buildings using VC is created. Parameters, which are of high importance when designing VC systems, are observed for each building case. Both, new and renovated buildings with VC are analysed to see which special architectural and ventilation system design elements are used.

In order to facilitate the implementation of VC in newly designed as well as renovated buildings, two simple VC potential tools are analysed. These VC potential tools are intended to be used in decision making process during the building predesign phase. The first one is EURAC VC potential tool which is based on a steady-state VC potential calculation method originally introduced by NIST [J. Emmerich et al., 2011]. Another tool, which is developed by this project group, is based on 5R1C-model using dynamic heat balance calculation. The two VC potential tools are tested on selected case study building, Aarhus municipality office building. Calculation results are verified by BSim model. Afterwards, the VC potential tool based on 5R1C-model is subjected to a variety of different input conditions to analyse its robustness.

It was observed that the original EURAC VC potential tool tends to underestimate the VC potential whereas the modified version of this tool noticeably overestimates the VC potential. Therefore, it can be argued that steady-state methodology with constant heat loads and ignorance of effect from building thermal mass cannot generate reliable estimation of VC potential.

In contrast, the 5R1C-model has proven to yield a reliable estimation of VC potential. The results in all variations (control strategy, thermal mass, ACR, NTV) of the case study office are always in a good correlation with the results from the BSim simulations. It also revealed that 5R1C-model slightly underestimates the number of overheating hours. The reason for that could be the simple approach of dealing with the thermal mass in 5R1C-model.The investigation of robustness shows that the deviation in overheating hours between the 5R1C-model and BSim has a tendency to decrease with the increase in heat loads. Thus, one may argue that VC potential tool based on 5R1C-model is able to generate reliable prediction of VC potential in office buildings of different size and complexity.

Resumé

Det forventes, at den igangværende tendens, omhandlende forbedring af bygningers isolering, global opvarmning og stigning i "heat island" effekten i bymæssige områder, vil forhøje behovet for køling af bygninger i fremtiden. Brugen af direkte ventilative cooling (VC) er en effektiv løsning til at minimere overophedning, samt reducere behovet for mekanisk ventilation. Dette afgangsprojekt har til formål at finde generelle design mønstre for bygninger kølet med VC i Danmark, samt undersøge om det er muligt at estimere et realistisk potentiale for VC i løbet af den tidlige designfase, vha. simple design værktøjer.

For at kunne karakterisere generelle design mønstre for bygninger kølet med VC i Danmark, er der lavet en database bestående af bygninger med VC. Ud fra denne database er forskellige parametre med høj betydning for VC observeret. Både nye og renoveret bygninger er analyseret for at finde frem til de forskellige arkitektoniske design og ventilations elementer, der har en betydning for de enkelte løsninger.

For at kunne fremme brugen af VC i nye og renoveret bygninger, er to forskellige estimeringsværktøjer analyseret. Disse VC estimerings værktøjer er tiltænkt at blive brugt i den tidlige beslutningsfase. Det første værktøj er EURAC VC potential tool, introduceret af NIST [J. Emmerich et al., 2011], som er baseret på steady-state beregninger. Det andet værktøj, som er udviklet af denne projektgruppe, er baseret på en 5R1C-model ved brug af dynamiske varmebalance beregninger. De to værktøjer er afprøvet på en testbygning, Aarhus Kommunes nye kontorbyggeri. Resultaterne er verificeret vha. BSim. Efterfølgende er værktøjet, som er baseret på 5R1C-model, afprøvet med forskellige inputs for at undersøge dens robusthed.

Det originale EURAC VC potential tool underestimere potentialet for VC, mens den modificeret udgave overestimere. Det kan derfor konkluderes, at steady-state metoden, med konstant belastning samt manglende påvirkning fra termisk masse, ikke kan give en troværdig estimering af potentialet for VC. Derimod er det observeret, at det udviklet værktøj giver en troværdig estimering af potentialet for VC. Resultaterne er under forskellige forhold altid i god overensstemmelse med resultaterne fra BSim. Dog ses det, at 5R1C-modellen underestimere antallet af timer med overophedning ift. BSim. Dette skyldes højst sandsynligt den simple måde at håndtere bygningens termiske masse på i beregningen. Undersøgelse af metodens robustheden viste, at forskellen i resultaterne minimeres, når belastningerne stiger. Det kan dog siges, at VC værktøjet baseret på 5R1C-modellen, kan give troværdige estimeringer af potentialet for VC i kontorbygninger af forskellige størrelser og kompleksiteter.

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Introduction 1

Energy consumption in residential and tertiary buildings accounts for 41 % of all use in the EU [Aalborg University, 2014]. It is used to cover building needs for heating, cooling and ventilation, as well as for hot water production, room lighting and appliances. Even though space heating forms the largest part of the energy use, it is expected that its share in total building energy consumption will decrease, see figure 1.1. This is due to improvements in building insulation as a result of increased requirements regarding heat loss and infiltration rate through building envelope. Improved building insulation together with global warming and increasing in heat island effect in urban environments will lead to increase in building cooling demand in the future [Medved, 2014]. For some European countries the cooling need has been investigated and a steady growth until 2030 is expected. This tendency is also presented in figure 1.1.

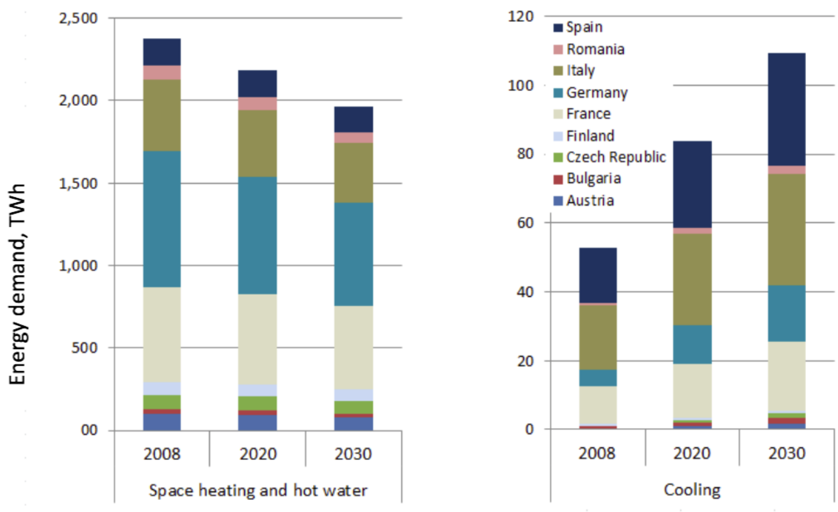

Figure 1.1. Expected evolution of cooling, heating and spaceheating in 9 EU countries from 2008 to 2030. [Kranzl et al., 2014]

According to [Adnot J, 2003] offices and trade spaces form the main part in cooled floor area, which indicates that these buildings are of great interest when focusing on decreasing energy used for cooling.

Studies of climate cooling potential have concluded that building overheating during the summer is very likely to occur also in Northern Europe [Artmann et al., 2007]. This can especially be seen in well insulated buildings with substantial amount of glazing exposed to direct solar radiation, which leads to room overheating during the summer and sometimes even during the transitional seasons. Therefore, the role for energy efficient cooling solutions is increasing in today's architecture.

One of the simplest and widely used passive cooling technique of buildings is ventilative cooling i.e. buildings cooled with cold outdoor air. This principle can be utilised by running natural ventilation when the outdoor temperature is lower than the one inside the building. However, ventilation inlet air temperature must not be too low to avoid the risks of cold draft and moisture condensation. Generally, the highest internal and solar heat gains, as well as the outdoor temperatures occur during the day. In cases when the outdoor air temperature reaches or exceeds the indoor air temperature, direct ventilative cooling during the day is not possible. In such situations night time ventilation may be considered as a cooling solution as the outdoor air temperature is at its lowest during the night which means that high cooling effect may be obtained. Furthermore, an increased air change rate (ACR) can be applied, due to no limitation on comfort during unoccupied periods.

Numerous researchers have been analysing the effect from different parameters on performance and effectiveness of ventilative cooling (VC) and night time ventilation (NTV) with regards to building indoor climate. The parameters that are considered to be the most important are: outdoor climate, ventilation air change rate, building thermal mass and internal heat gains. Few researchers also considered the effect of heat transfer coefficient [Artmann et al., 2007] and the duration of NTV [Finn et al., 2007].

Study of ventilative cooling strategy by E. Gratia et al. [Gratia et al., 2004] revealed that the energy consumption for cooling might be reduced by around 30 % by efficient application of VC. S. Schiavon and A. K. Melikov [Schiavona and K. Melikov, 2008] found that increased ventilation rates contribute to decrease in cooling needs between 17 % and 48 % and reduce the required maximum cooling power by 10 % to 28 %. It was also argued by Yun et al. [Young Yuna et al., 2008] that occupants can still receive direct ventilative cooling by opening the windows even though the ambient temperature exceeds the indoor temperature. Furthermore, it has been demonstrated by measurements in Field's shopping center (Copenhagen, Denmark) that the use of natural cooling decreased the number of hours when operative temperature is above 28 °C by around 70 % and saves 60 % of the energy used for cooling [T. Tranholm et al.].

Nevertheless, there are some challenges in ensuring optimal design and performance of VC in buildings, especially, if it is driven by natural driving forces.

The application of ventilative cooling has some limitations with regards to building design. Requirements for the indoor climate such as stable thermal and atmospheric conditions together with avoiding draft set limitations to a ventilative cooling systems. Another limitation of this technique is high dependence on outdoor weather conditions, like time dependence and limited cooling potential in cold ambient air, or extreme weather conditions (wind, precipitation).

In order to have efficient ventilative cooling in buildings it is essential to estimate the VC potential already during the early design phase. This knowledge would be large asset for the designer in decision making process, as well as generate the predesign values for natural ventilation system. For this reason a simple calculation tool evaluating the potential of VC might be useful. The estimation of VC potential would also enhance the usage of natural NTV in buildings.

The aim of this master thesis is to create a database of buildings using VC in Denmark. This is done to investigate which parameters are of high importance in design of VC systems. Both new and renovated buildings with VC will be analysed to see which special architectural and ventilation

system design elements are used.
Afterwards, the evaluation and optimisation of VC potential tools, used during the building predesign phase, is performed. The two VC potential methods to be used are: VC potential tool introduced by NIST [J. Emmerich et al., 2011] and further developed by EURAC research Institute for Renewable Energy and a 5R1C-model based on the dynamic heat balance of the building/room. The chosen VC potential calculation tools will then be applied to selected case study. The results calculated by VC potential tools will be compared to the ones obtained from BSim building indoor climate simulation program.

1.1 Thesis Statement

Decreasing the energy consumption in both old and new buildings will be required in the future. Because of an increase in requirements that especially minimised the need for heating, more focus is put on avoiding overheating and reducing energy used for cooling by implementation of low energy initiatives for example ventilative cooling. Therefore, the following will be investigated:

- *What are the general design patterns related to ventilative cooling in Denmark, and what should be taken into account when designing buildings with ventilative cooling?*

- *Is it possible to generate a reliable estimation of ventilative cooling potential during the predesign phase by use of simple design tool?*

Part I

Ventilative Cooling

Concurrently with an increasing focus on decreasing the heat consumption in new and also already existing buildings, energy efficient techniques to secure acceptable indoor temperature have appeared. One of these used techniques is ventilative cooling. Ventilative cooling refers to the use of natural or mechanical ventilation strategies to cool down indoor spaces by using the outdoor air. By the use of ventilative cooling it is possible to secure a good thermal comfort and simultaneously reduce the amount of energy required for space cooling. Increased ventilation flow rates and night time ventilation are the most commonly used ventilative cooling techniques, but other options must be considered as well.

To get an impression of how ventilative cooling has been implemented in Danish buildings, state-of-the-art investigation is performed and results are compiled in a database. This information together with VC theory overview are used to find some general design patterns related to ventilative cooling.

Climate in Denmark 2

Ventilative cooling in buildings is always influenced by the outdoor conditions. The outdoor temperature together with wind direction and speed are the main driving forces of natural cooling, which is also described in section 4.1 on page 15, *Ventilation Principles*. To estimate the ventilative cooling potential in Denmark, the outdoor conditions have to be analysed.

In this project the new design reference year (DRY) weather data for Denmark (2001 - 2010) are used to estimate the ventilative cooling potential. [SBi, b]

2.1 Outdoor Temperature

At first, the external temperature is analysed within and outside working hours. Working hours are assumed to be from 08.00 - 17.00. Due to presence or absence of the users it is interesting to look at both periods because different criteria as for example indoor temperature and indoor air velocity are present. Therefore, the average monthly temperature along with the maximum and minimum hourly and daily temperature are found within and outside working hours. These are shown in figures 2.1 and 2.2 on the next page.

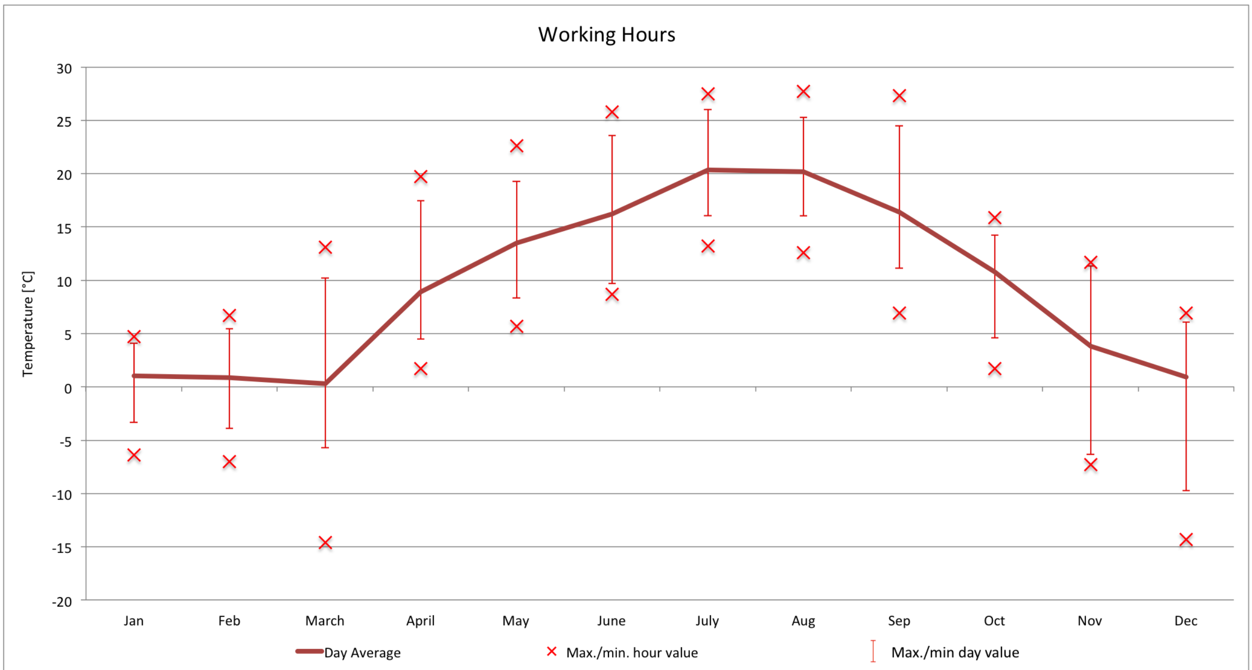

Figure 2.1. External air temperature within working hours.

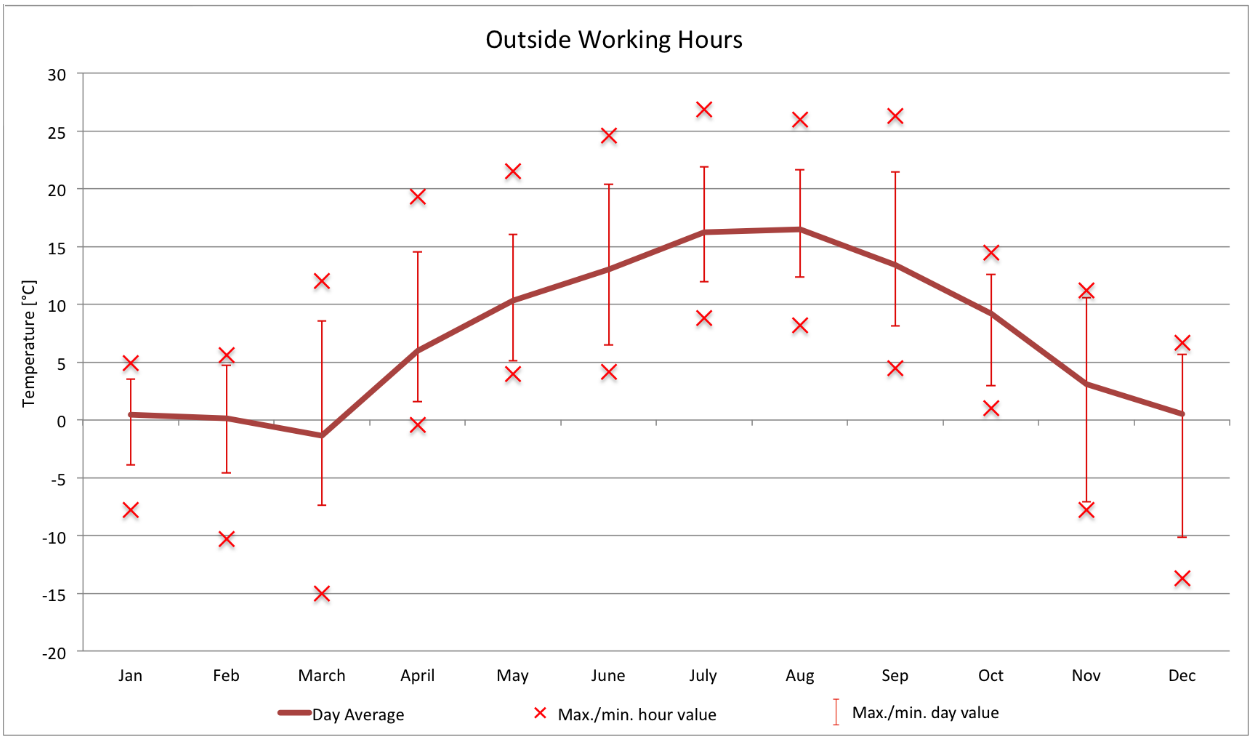

Figure 2.2. External air temperature outside working hours.

To analyse the potential for ventilative cooling in Denmark the comfort temperature for the cooling season is essential. It is found to be 24.5 °C ± 1.5 °C for a category B building [Dansk Standard, 2001]. In the summer period, where the need for cooling often is the highest, the outdoor temperature exceeds the indoor comfort temperature in certain periods. This will give a too high inlet temperature for the ventilative cooling, and the air will therefore not be useful for the cooling aspect in these periods. However, the average monthly temperature does not exceed the comfort temperature, and thereby encourage the potential for ventilative cooling in proportion to temperature.

Additionally, the graph at figure 2.2 for temperature outside working hours shows that the outdoor temperature is lower than the indoor temperature set point, and thereby enhances the opportunity for night time ventilation. As there are no users inside the building, it can be ventilated with cool outdoor air to remove the heat stored in the building fabrics.

Apart from the internal temperature, ventilation is used to secure a good indoor air quality all year around. If natural ventilation is used for this purpose, ventilation air preheating is crucial not to create discomfort for the users. Since this report deals with the ventilative cooling potential and not with air quality this aspect is not analysed further on.

2.2 Wind Conditions

Wind direction, speed and frequency at given times need to be known to get the best utilisation of the ventilative cooling for a building. Wind roses, which illustrate the wind direction, speed and frequency of a given time period, are used for this purpose. First, the wind for a entire year is analysed, and illustrated in figure 2.3.

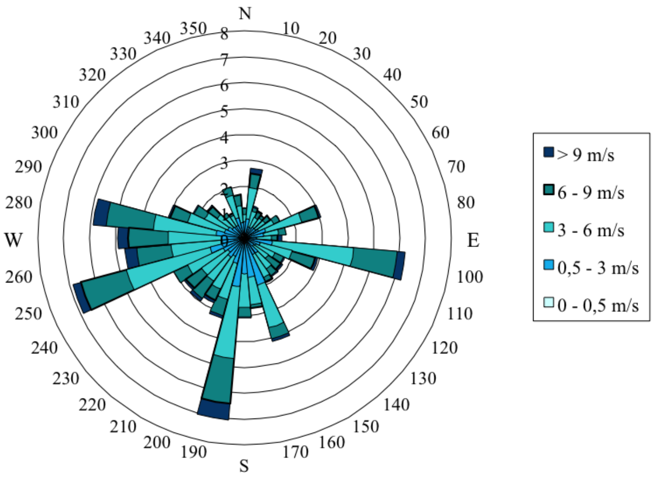

Figure 2.3. The wind rose for a whole year illustrate the wind distribution.

The wind rose above shows that the wind is mainly distributed from east, west and south, which means that the placement of openings for ventilation in a building is not limited only by certain direction.
As indicated in the previous part about external temperature this report only deals with ventilative cooling aspect. This means that the cooling season is of greater interest for this project. Consequently, wind roses for days with external temperature between 20 °C and 25 °C are made, which can be characterised as normal summer days (decided by the project group). This is done for both inside and outside working hours and illustrated on figure 2.4.

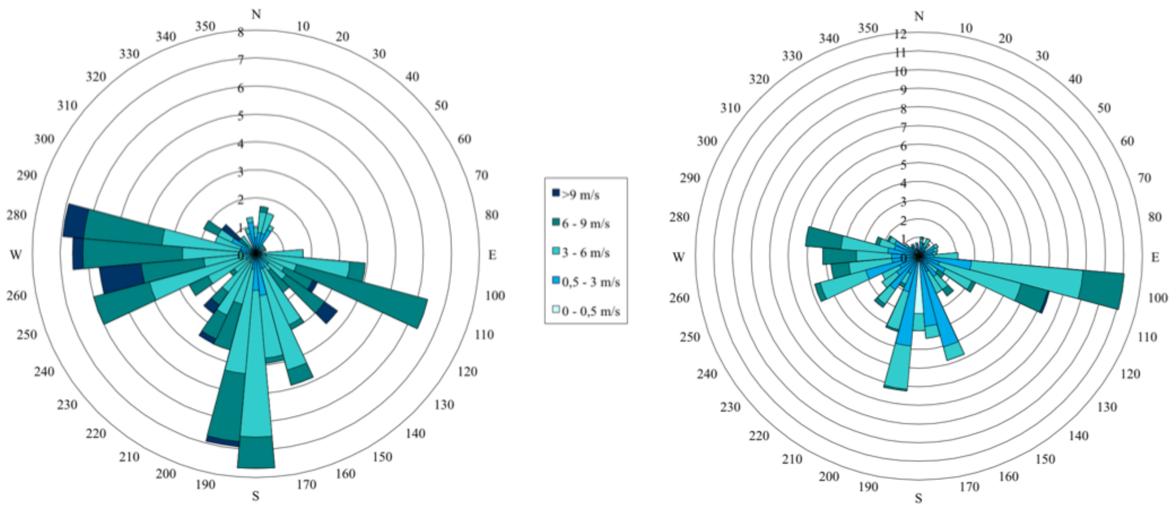

Figure 2.4. The wind roses show the wind distribution for days with a temperature between 20 °C and 25 °C (61 days). The rose to the left shows the distribution of the wind within working hours (534 hours) and the rose on the right is outside working hours (947 hours).

Wind from east, west and south directions is with the most frequent within the working hours. However, it is different outside working hours, where the wind from west and south has decreased, and the prevailing wind direction is from east. This is an important fact if night time ventilation is used in a building. In summer days, it might get too hot during the day for effective ventilative cooling, and thereby night time ventilation becomes an important tool to secure a good indoor temperature during the working hours.

The difference between day and night temperature is one of the factors for making ventilative cooling possible by night time ventilation. As the temperature graphs show, differences between inside and outside working hours occur. This, together with an average temperature in the cooling season below the comfort temperature, and a windy climate, indicates that there is a large ventilative cooling potential in Denmark.

3 Ventilative Cooling Cases in Denmark

A database with information about ventilative cooling application in Denmark is collected, to get an idea of some characteristic patterns and solutions related to site, building form, morphology, envelope etc. This work is done to get knowledge about what has been done so far and understand how to enhance the use of ventilative cooling in buildings.

This part is made in cooperation with *IEA EBC Annex 62 Ventilative Cooling*, which is a newly commenced project from 2013, intended to develop new design methods and compliance tools related to predicting, evaluating and eliminating the cooling need and the risk of overheating in buildings. Furthermore, it aims to develop new and attractive energy efficient ventilative cooling solutions. [EBC]

Materials for the building analysis are provided by previous studies from *Aalborg University*, the engineering company *WindowMaster A/S*, which has expertise within indoor climate, and materials found on the internet.

The following section presents the overview of analysed buildings with ventilative cooling in Denmark. Buildings are categorised based on building type, location and ventilation principles.

3.1 Overview of Analysed Cases in Denmark

This section gives a quick overview of different cases analysed in this project. Buildings with natural VC in Denmark included in the database together with the information regarding building type and ventilation principles are listed in table 3.1 on the next page.

#	Building name	Type	Single	Cross	Stack	Mechanical	Hybrid 1	Hybrid 2
1	B&O Headquarters	off			**x**			x
2	Green Lighthouse	edu			**x**	x	x	
3	Home for Life	res			**x**	x	x	
4	NCC Headqaurter	off			**x**	x		
5	Spirehuset	edu		x	**x**	x	x	
6	KBH. Universitet, KUA1	edu	x	x	**x**	x		x
7	KBH. Energi	off		x	**x**	x		
8	Solhuset	edu			**x**		x	
9	Albertslund Rådhus	off	**x**	x	x	x		x
10	A2SEA/Promecon	off		x	**x**	x		
11	Ballerup Kommune	off	**x**	x		x		x
12	City 2	shop		x	**x**	x	x	
13	Beierholm Væveri	off			**x**	x		
14	DSV	off			**x**	x	x	
15	DNU	hos			**x**	x		
16	DR Byen	off		x	**x**	x	x	
17	DTU 324	edu	x		**x**	x	x	
18	Aarhus Kommune	off	**x**			x	x	
19	Industriens Hus	off			**x**	x		x
20	GASP	hos	x	x	x	x	x	
21	Dyssegårdsskolen	edu	x	**x**	x	x	x	
22	Kontorbygning	off	x	**x**		x		x
23	Field's	shop		x	**x**	x	x	
24	Grønvangsskolen	edu		x	**x**		x	x
25	Søndersøskolen	edu	**x**	x	x			x
26	Pakhus	off			**x**			x
27	Kragelundsskolen	edu	**x**			x	x	x
28	Scion DTU, Pyramid	off			**x**			
29	Vandflyverhangaren	edu			**x**	x		
30	Retten Frederiksberg	off	x		**x**			x
31	Lynetten	oth			**x**			
32	Tornbjerg Børnecenter	edu	**x**		x	x		x
33	Ørestad Gymnasium	edu			**x**			
34	Elefanthus	oth			**x**	x	x	
35	Ved Stranden	off	**x**	x				x
36	BRF-Kredit	off			**x**	x		
37	E. Phil & Son Headquarters	off			**x**	x		x
38	WindowMaster Office	off			**x**	x		

Table 3.1. Overview of the analysed cases. The red cross symbolises the main ventilation principle. Hybrid 1 means natural ventilation during the summer and mechanical with heat recovery during winter. Hybrid 2 means natural ventilation with fan assistance.

Detailed building descriptions that are made for the Annex 62, can be found in the Appendix CD under *Building Descriptions* together with an excel spreadsheet (*Annex 62 - Buildings*), which contains more detailed information about the buildings.

If we look at the types of the reviewed buildings it can be seen that more than half (53 %) of the reviewed buildings are offices. The second largest group (29 %) is formed by educational buildings. The rest (18 %) are shopping centers (2 cases), hospitals (2 cases), residential (1 case) and other (2 cases) types of buildings. This is illustrated on figure 3.1.

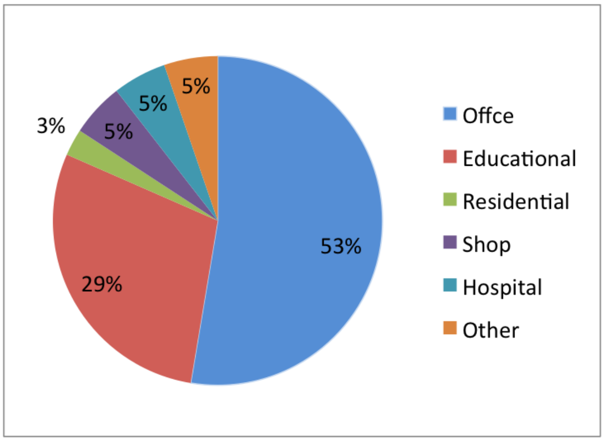

Figure 3.1. Building types.

Moreover, office and educational buildings have almost analogical indoor climate requirements and occupational profile. Since offices, schools and shopping centers are typically unoccupied during the night, there is a large VC potential by NTV in these buildings.

Building locations in terms of urbanisation and geographical regions are shown in figure 3.2 and 3.3.

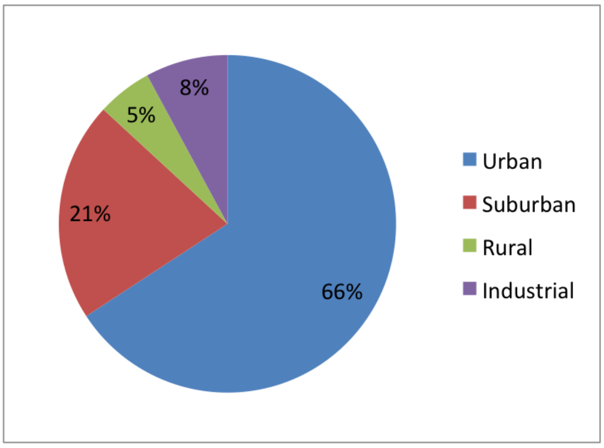

Figure 3.2. Site location of the reviewed buildings.

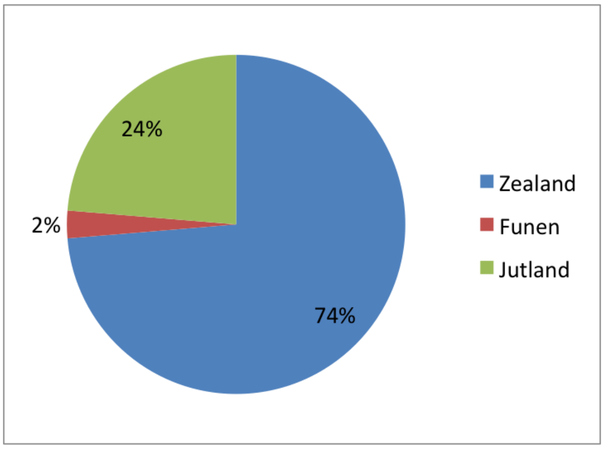

Figure 3.3. Region of the reviewed buildings.

Most of the reviewed building sites are located in urban (66 %) and suburban (21 %) areas. If we look on how the buildings are spread out geographically, it can be seen that most of them are located in Zealand. 79 % of the reviewed buildings are constructed or renovated during the last 10 years. Natural ventilation is implemented during the renovation in 32 % of the reviewed buildings, whereas it has been originally designed in the rest 68 % of the buildings.

Windows/skylights/doors are used as an airflow guiding ventilation components in all analysed buildings. Dampers/flaps/lowers, as well as special effect vents are used in 10 % of cases. Atrium is the most widely used airflow enhancing ventilation component. This solution is used in 55 % of the reviewed buildings. It is mostly used in office and educational buildings.

The main natural ventilation principles applied in reviewed buildings are shown in figure 3.4.

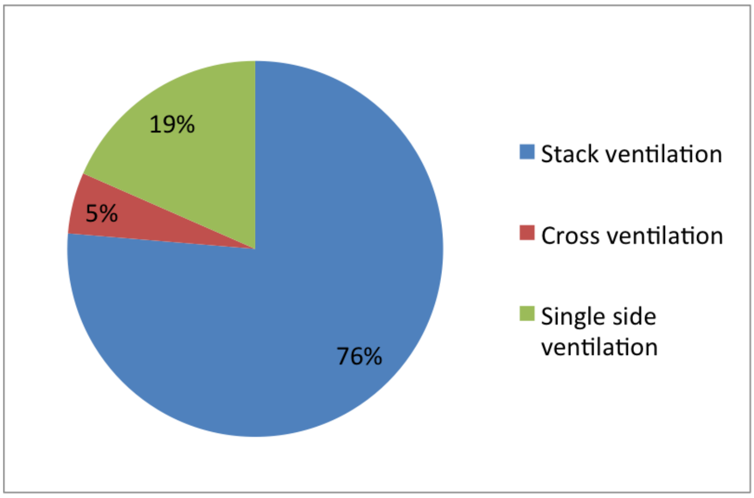

Figure 3.4. Main natural ventilation principles in reviewed buildings.

It was also observed that 95 % of the buildings are ventilated by more than one ventilation principle. Hybrid ventilation is used in 86 % of the buildings included in the database. 39 % of the reviewed buildings are using fan assisted natural ventilation, while a combination of natural ventilation (during the summer) and mechanical ventilation (during the winter) is used in 34 %. The number of buildings using hybrid ventilation might actually be higher as there was no complete information regarding the ventilation type and control strategy in all the buildings.

Important Parts for Ventilative Cooling 4

To observe general design patterns of ventilative cooling literature studies are performed. The most general observations are explained together with their influence on ventilative cooling. Examples from the analysed cases presented in previous chapter are used to illustrate ventilative cooling use in Danish buildings. Further description of all the presented examples can be found in Appendix CD under *Building Descriptions*.

Following ventilative cooling design parts that will be described are:

- Ventilation principles
- Night time ventilation
- Site design
- Building form and envelope
- Internal layout of the building
- Natural ventilation system components
- Control of ventilative cooling

4.1 Ventilation Principles

Different ventilation types are applicable when talking about ventilative cooling of a building. The different ventilation types are:

- Natural ventilation
- Mechanical ventilation
- Hybrid ventilation

The natural ventilation contains of three different principles: Single sided, cross and stack ventilation, which are mainly driven by the outdoor conditions. In situations where ventilative cooling is not efficient enough a mechanical ventilation can be added to the system, thereby forming a hybrid ventilation system. Despite high energy consumption, in many cases only mechanical systems are used for ventilative cooling. These systems are much more predictable and easier to control than naturally driven systems. The different kinds of ventilation principles in proportion to ventilative cooling are described in the following sections.

The descriptions of ventilation principles are based on the literature *Design of Natural and Hybrid Ventilation* [Heiselberg, 2006].

4.1.1 Natural Ventilation

The three natural ventilation principles are described in the following part.

Single Sided Ventilation
Single sided ventilation is characterised by only having openings in one external wall. If only one opening is located in the room, it will work as inlet and outlet located on bottom and top of the window. If several vertically placed openings are located in a room at the same wall, the one at the bottom works as inlet and the one at the top is used as outlet due to thermal buoyancy. Thermal buoyancy together with wind are the main driving forces in winter whereas wind turbulence drives this type of ventilation in summer. The principle of single sided ventilation with one opening in the external wall is illustrated on figure 4.1.

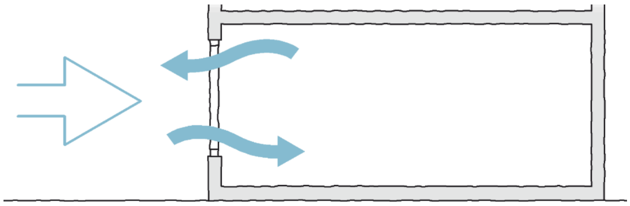

Figure 4.1. Principle of single sided ventilation. [SBi, 2008] - modified

The main advantage of single sided ventilation in proportion to ventilative cooling is that it is well suited for cellular plans, and therefore, does not need complex inner planning solutions, like atrium, stacks, internal vents, etc. If there is a possibility of placing a ventilation opening in the external wall, single sided ventilation principle can be used in the room. Moreover, this type of ventilation is not subjected to pollution coming from other rooms. Because openings are only located in one external wall, the maximum possible ACR is limited. This is lower than for other ventilation principles.

Cross Ventilation
By locating the openings at different facades of the building, cross ventilation can be implemented. Openings at two opposite walls or two adjacent walls can create an air stream through the zone. Wind induced pressure is the main driving force of cross ventilation. Compared with single sided ventilation, cross ventilation provides a larger air change rate. However, it also has more demands for the envelope and morphology of the building to create the desired air flow. Cross ventilation principle is illustrated on figure 4.2.

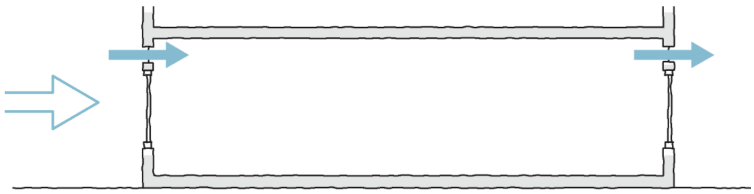

Figure 4.2. Principle of cross ventilation. [SBi, 2008] - modified

Stack Ventilation

Thermal buoyancy is the main driving force of the stack ventilation, which means that it can operate when there is no wind. The principle is to use the openings in the lower levels as inlet for the fresh cold air. The air gets heated inside the building, thus becoming lighter and is rising upwards, where it leaves the building through the openings at the top. The air is driven by the hydrostatic pressure difference, and the principle is illustrated on figure 4.3.

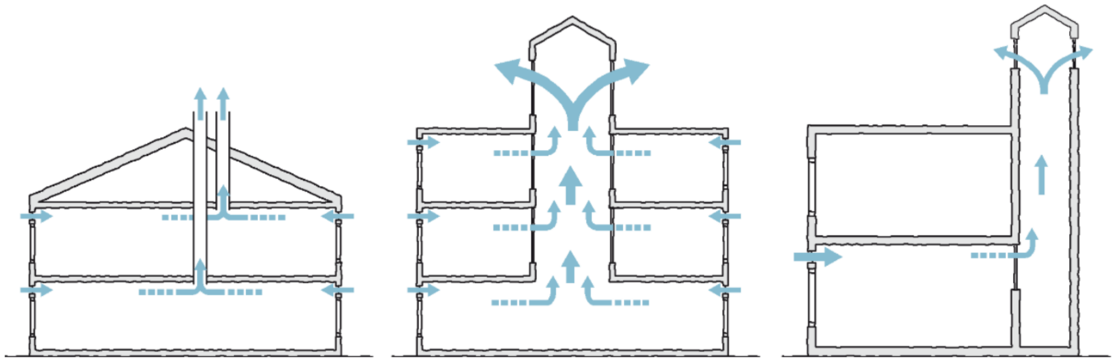

Figure 4.3. Principle of stack ventilation. [SBi, 2008]

The main disadvantage of stack ventilation is that it requires a complex building layout. The demands for envelope and morphology of the building are higher than for the other types of ventilation principles. Openings have to be located at different heights, and the morphology has to contain an atrium, chimneys etc. to secure that the stack effect is formed.

4.1.2 Mechanical Ventilation

Contrary to natural ventilation, mechanical ventilation is driven by electrical fans. This means that energy have to be added to the system before the ventilation system works. Mechanical ventilation systems can consist only of exhaust systems, or of system that contains both inlets and outlets. The advantage of mechanical compared to natural is that it can provide a higher driving thrust and thereby is less sensitive to the outdoor conditions than a natural ventilation system. A system containing both inlet and exhaust is characterised as a balanced system. [SBi, 2008] A mechanical ventilation unit can consist of several components; ventilators, filters, heating and cooling coils, humidifier, dehumidifier and heat exchanger. All have an influence on how the system is running, and secure that the needed airflow with the desired temperature and humidity is injected into the rooms. [Dansk Standard, 2005]

Mechanical ventilation is preferred in spaces that require high air change rates and/or are used periodically (group rooms, meeting rooms or conference rooms). Sometimes it is not possible to have natural ventilation due to high hygienic requirements (operation rooms in hospitals). In other cases mechanical ventilation is used in rooms that have poor natural ventilation potential due to specific building architecture or morphology.

4.1.3 Hybrid Ventilation

In some cases the air change rate achieved by natural ventilation is not efficient enough to secure a satisfactory thermal comfort. In these situations a hybrid ventilation could be the optimal solution. Hybrid ventilation can be divided into three main types [Heiselberg, 2006]:

- Natural and mechanical ventilation
- Fan assisted natural ventilation
- Stack and wind supported mechanical ventilation

Natural and Mechanical Ventilation
This principle of hybrid ventilation is based on two independent ventilation systems. One of the two systems is used in some periods and the other system for other. For example, mechanical ventilation is used during occupied hours and natural ventilation is used as night time ventilation.

Fan Assisted Natural Ventilation
In situations where natural ventilation cannot cover the ventilation needs, a mechanical fan can be added to the system, and thereby increase the ACR. This means that the advantages of natural ventilation (free cooling) are used as much as possible.

Stack and Wind Supported Mechanical Ventilation
The last principle consists of a mechanical ventilation system, which uses the natural driving forces to the maximum. This ventilation system solution can be used for systems with small pressure losses. Thereby, natural forces create significant part of the pressure required to overcome the total pressure drop of the ventilation system.

By using hybrid ventilation for ventilative cooling it is possible to utilise natural ventilation as much as possible and secure an acceptable indoor thermal climate.

4.2 Night Time Ventilation

Typically, night time ventilation is used to lower the cooling needs of a building. In some cases it can act as the only cooling strategy. The main purpose of night time ventilation is to remove the heat that is trapped inside the building during the daytime. Night ventilation influences the indoor climate in following ways:

- Lowers the indoor temperature peaks.
- Lowers the mean indoor temperatures during the working hours, especially in the beginning of the day.
- Lowers the temperatures of building elements (slabs, walls, etc.).
- Increases a time lag between the maximum outdoor and indoor temperatures.

[Santamouris and Wouters, 2006]

This passive cooling strategy is performed by circulating low-temperature ambient air through the building during the night. Cool outdoor air flows through the building, thus increasing the convective heat transfer between the ventilation air and the building elements. As a result, the heat from the building structures is transferred to ventilation air, which is then discharged into atmosphere, which may be considered as a heat sink. Night time ventilation can be run as long as a certain temperature difference between indoor and outdoor air is present. For example, cooling process continues until a predefined lowest room temperature set point is reached. As a result, building structure is cooled down before the temperature starts to rise again during the following occupation hours. The precooled building elements perform like a heat sink during the day. To maximize the cooling effect obtained during the night, the windows must be kept closed during the day, when the outdoor temperature is higher than the one inside the building.

The main prerequisite for effective performance of the night cooling is a high diurnal temperature difference of around 15-20 °C [Heiselberg, 2006]. Moreover, night time ventilation has the highest sufficiency in hot and dry climates [Lechner, 2001]. The ambient temperature must not be too low (below dew point of the building structures) as it can lead to the formation of condensation inside the building.

Another important parameter is the thermal mass of the building. The higher the thermal mass, the more heat can be accumulated. This means that in heavy thermal mass buildings, the indoor temperature will increase slower as it would do in lightweight buildings. Consequently, the period when indoor temperature is within the acceptable range would increase, thus decreasing the operation time or even eliminating the need for mechanical cooling. In order to obtain high night cooling efficiency, heavy elements of the building should be exposed to the ventilation airflow. The efficiency of the nighttime ventilation would become considerably lower, if the heavy elements are covered with insulation (for example suspended ceilings), furniture and other obstacles. To increase the efficiency of the night ventilation, the ventilation ACR must be higher then the one required for comfort. It is recommended to increase the ACR for the night ventilation to 4-6 h^{-1} [Heiselberg, 2006]. Heavy, closed, well insulated and shaded buildings that use night cooling strategy can reach 35-45 % temperature drop, if compared with the outdoor temperature [Heiselberg, 2006].

Therefore, it can be concluded that following parameters influences night ventilation:

- Outdoor air temperature
- Ventilation ACR and airflow pattern inside the building
- Heat transfer efficiency between the ventilation air and buildings constructions
- Heat storage capacity of the building elements

4.3 Site Design

During the design phase of a building it is not always possible to choose the desirable location. Often the location of the building is decided in advance. This means that the cooling potential of the site has to be investigated to optimise the performance of ventilative cooling.

Proper site design can facilitate the effectiveness of the natural ventilation, thus enhancing the natural cooling effect. The following aspects must be taken into account when working on site design for the naturally cooled building:

- Air flow pattern created by building surroundings (topography, neighbouring buildings).
- Microclimate conditions, such as external air temperature and prevailing wind direction, sun path and irradiation.
- Airflow paths containing dust particles or other pollutants should be avoided.

Site design includes several aspects, like building location, orientation, form and layout, and landscaping around the building. The influence of these parameters is described in the following sections.

4.3.1 Building Location and Layout

Wind driven ventilation is the most common and simple form of natural cooling. Wind is an air movement caused by the pressure gradient between two locations. The air moves from the location with higher pressure towards the one with lower pressure. The site should be selected according to specific climatic conditions (microclimate) around the building and the building use (residential, office, industrial). It is also important to identify the location of pollution sources and their position to the prevailing wind direction, as the pollution can be carried along with wind in large distances. The natural cooling potential is higher in sites that are freely exposed to wind.

Country Sites

In country sites, local wind speed and direction around the building are largely influenced by the site topography. In sites located nearby hills and mountains, diurnal mountain and valley breezes can be utilised in building ventilation, which is illustrated on figure 4.4.

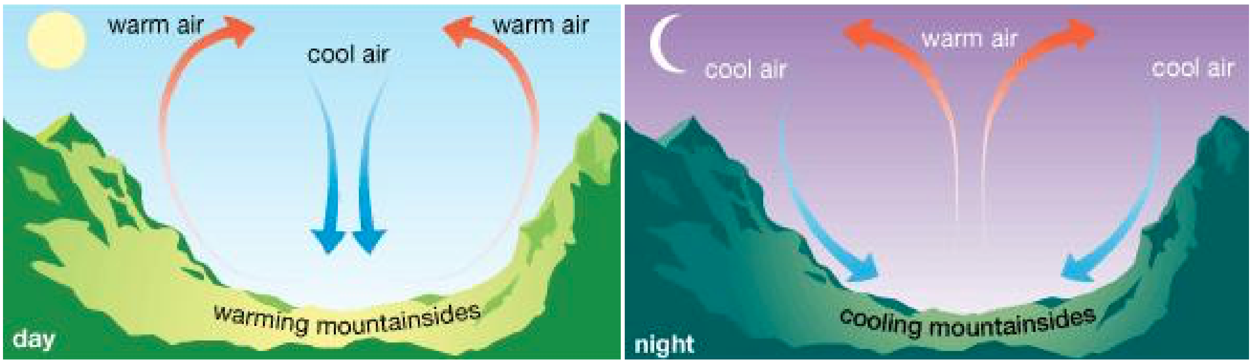

Figure 4.4. Alley and mountain breeze at day and night. [Encyclopædia Britannica, a]

The most favourable location of the building in mountain and hill sites is in the middle of the slope. In order to maximise the natural cooling potential, the building must be placed along the contour lines of the slope so that the smallest section of the building is cross-ventilated by the mild slope winds. If the building is located down in the valley, it will be exposed to valley winds that are colder and damper. If the building is placed on the ridge of the mountain, it will be exposed to high wind velocities.

In sites located close to the large open water surfaces (sea, lake, river), similar but reverse diurnal wind patterns occur. This is illustrated on figure 4.5.

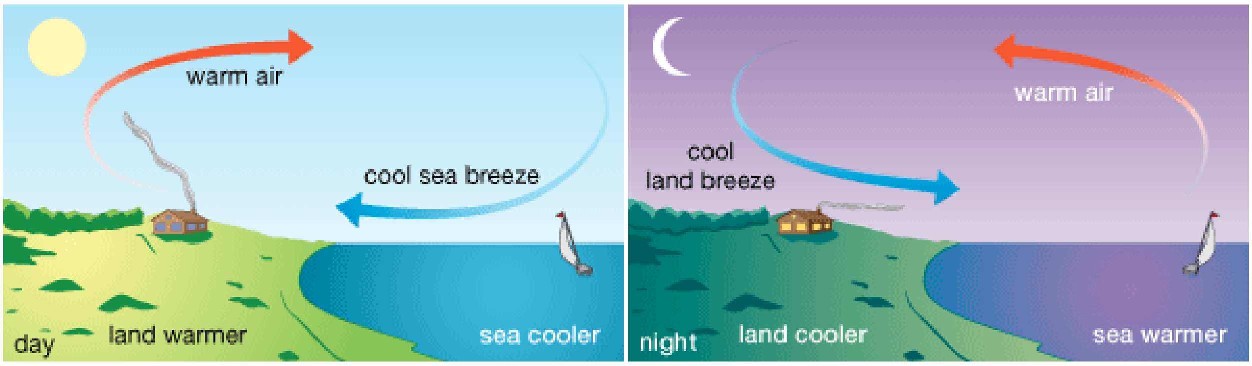

Figure 4.5. Sea and land breeze. [Encyclopædia Britannica, b]

Water surfaces cool down the ambient temperature based on convection process between the ambient air and water surface, and during the evaporation process (latent heat). In this kind of sites it is recommended to place the building along the coastline of the water. Thus the building could be cooled by the use of cross-ventilation driven by either sea breeze during the day or land breeze at night. It is important to notice that constraints regarding the possibility of floods and environmental protection aspects should be taken into consideration when placing the building near large water surfaces.

In Denmark the influence from the described mountain and alley breeze is not very significant because the country is very flat. However, it is different with the sea and land breeze, which can be utilised near small lakes and the coastline around Denmark. *Pakhuset* at Langelinie in Copenhagen is an example of such a case, where the cooling effect from the water has been used. The main part of the openings for natural ventilation are facing the sea, and the effect from the sea breeze is utilised by both day and night time ventilation. A picture of the office building is shown in figure 4.6, where all the small openings can be seen.

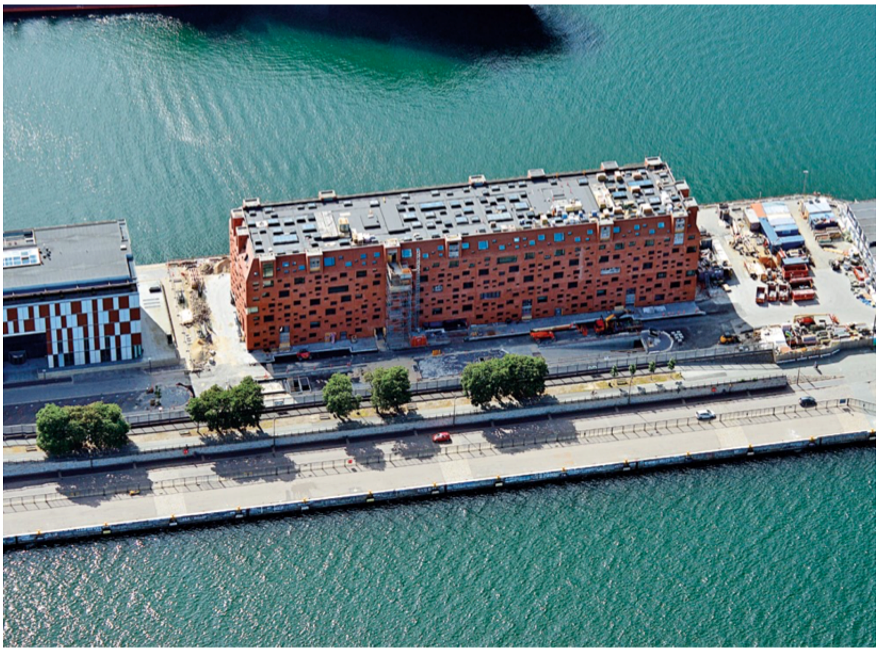

Figure 4.6. The office building *Pakhuset* at Langelinie in Copenhagen, which utilises the sea breeze for natural ventilation. [WindowMaster, b]

Another example is the hydroplane hangar, which is located in a more urban area, but with a facade that is freely exposed to a small lake. This building has been renovated and ventilative cooling is implemented. The site of the building was taken into account, when the design of the ventilative cooling system was made. Openings, that are used as air inlets, are facing the small lake, which increases the air velocity because of no obstacles for the wind, and also makes use of the sea breeze from the lake. This building is shown on figure 4.7 on the next page.

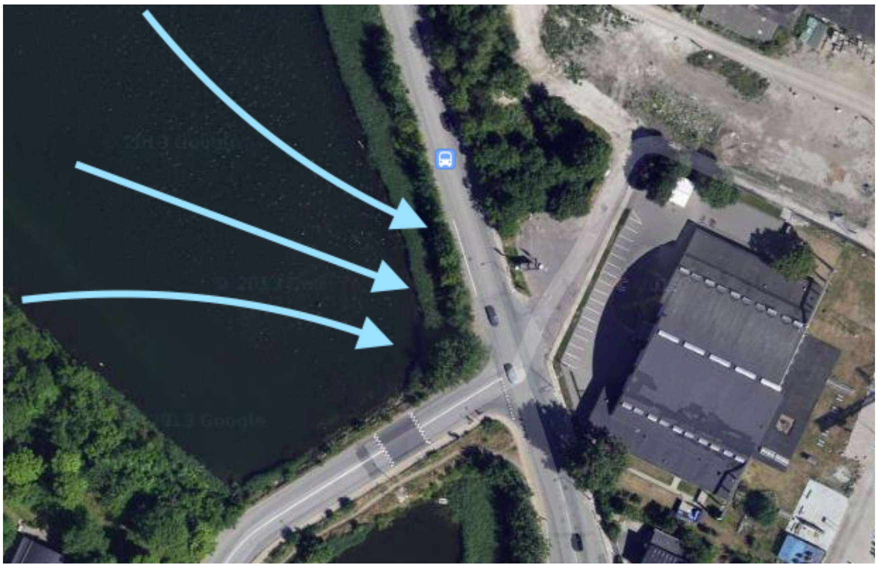

Figure 4.7. Renovated hydroplane hangar to a office building, which uses ventilative cooling with inlets located in the facade to the sea. [Google] - modified

In cases where a building is not located close to the coast or a lake, other initiatives can be used. This includes man-made solutions as for example a pond. This kind of solution is used in the ventilative cooled building *Beirsholms weaving mill* located in a suburban area in Kolding. In this case a small man-made lake is placed close to the building. The wind is guided by other buildings over the open water, and thereby is the cooling effect from the water is utilised. This is illustrated on figure 4.8.

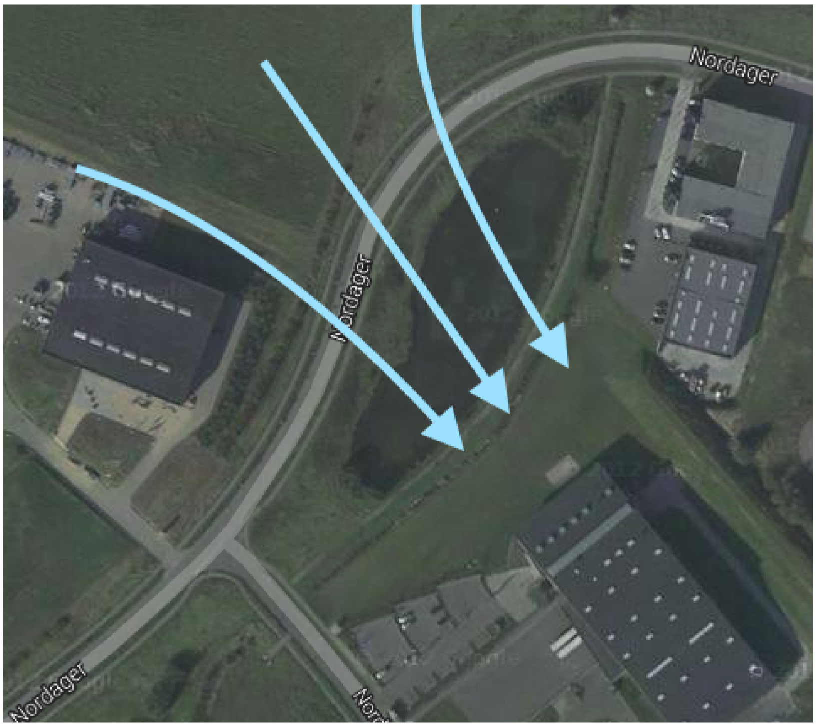

Figure 4.8. New building which utilises the cooling effect from a man-made pond near the building. [Google] - modified

Urban Sites

Buildings in urban sites considerably change the existing wind pattern because of increased roughness to the free flow of the air. Because of the friction created by the buildings, the average wind speed in urban sites is lower and has higher turbulence in comparing with rural areas. Moreover, the wind pattern in urban areas has higher local air velocities due to tunnel and venturi effects created by building and structure displacement in urban areas. The height of the building together with the distance between them are two of the most important parameters affecting the wind pattern. In urban sites, the building should be placed in a certain distance from its surrounding buildings, which is larger than the wake they create. Therefore, it is crucial to make sure that the building is not sheltered from wind by other buildings already at the building design phase. Wind exposure design is especially important during the summer periods when the ventilative cooling strategy is utilised. Wake regions around the buildings can be minimised if the buildings are placed in a certain manner, which is illustrated on figure 4.9.

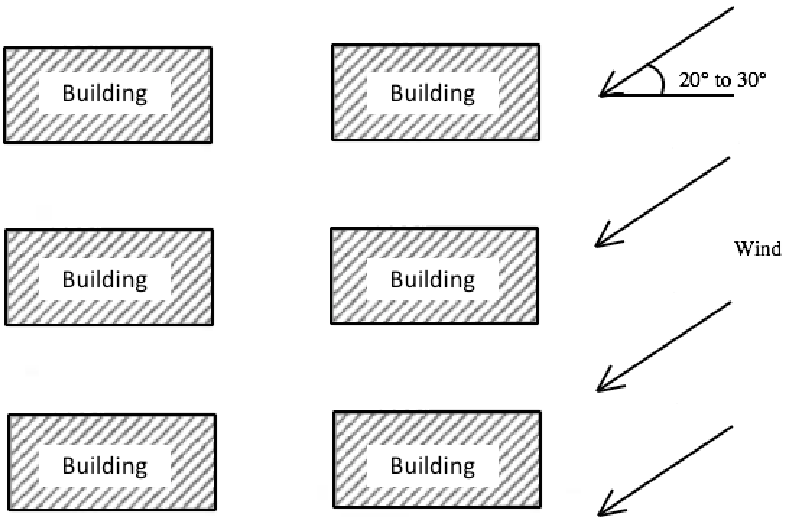

Figure 4.9. Optimum building layout in urban sites in proportion to wind. [Santamouris and Asimakopoulos, 1997] - modified

The most favorable layout of buildings in the urban area is when the buildings are orientated at 20° to 30° angle regarding to the prevailing wind direction. This building layout ensures that each building will experience wind pressure difference across the opposite facades, thus increasing the potential of natural ventilation. To ensure good ventilation conditions, the distance between tall buildings must be larger than between low buildings. If, according to constraints in actual site configuration, it is not possible to place the building so that it is freely exposed to summer wind, then it must be placed with respect to neighbouring buildings in the upwind direction so that the longitudinal axis of it is perpendicular to the dominating wind direction during summer.

Urban site microclimate, ventilation conditions, as well as local air temperature are largely affected by the urban density. In highly dense urban areas the phenomenon of "heat island" has been observed [Howard, 1818]. According to [Dictionary.com] "heat island" is an urban area with a higher average temperature than its rural surroundings due to the greater absorption, retention and generation of heat by structures, as well as other human activities. This phenomenon is mainly affected by the density of the urban area [Santamouris and Asimakopoulos, 1997]. The diurnal surface and air temperature variations in downtown, suburban and rural areas are illustrated in figure 4.10.

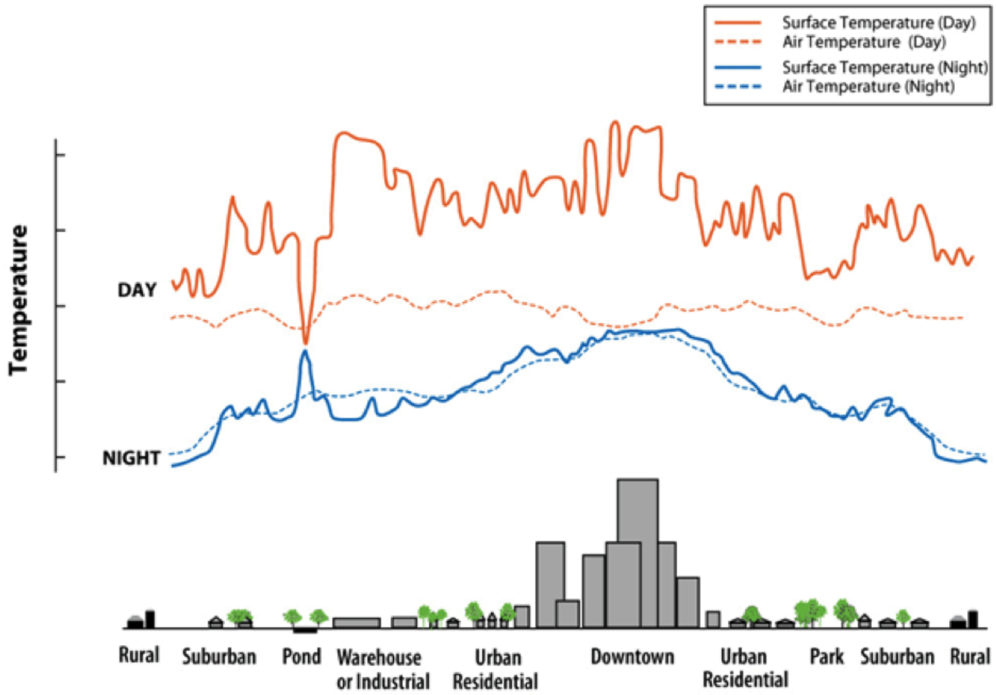

Figure 4.10. Urban heat island. [EPA - United States Environmental Protection Agency]

As it can be seen in the picture above the air temperature (dashed orange line) during the day is about the same in all areas. Surface temperatures (solid orange line) during the daytime are increasing along with the increase in urban density. The lowest surface temperature during the daytime is at the pond, while the highest ones occur in the industrial area and downtown. It can also be noticed that due to presence of solar radiation, surface temperature is higher than air temperature during the day, whereas surface and air temperatures (blue lines) during the night are about the same. Ventilative cooling potential is lower in sites located within urban heat island rather than the ones at the countryside because of the higher surface and air temperatures during the night.

Because of the wind sheltering due to wake from other buildings and the "heat island" phenomena, it can be concluded that the higher the urban density the poorer the natural ventilation conditions for the building are.

"Heat island" phenomena and wind sheltering effect from other buildings can also have a considerable influence on building VC potential in Denmark. It was observed that 25 out of 38 or 66 % of buildings included in ventilatively cooled building database are located in urban area.

Landscaping
Landscaping can be applied as an effective strategy for guiding the wind around the buildings. Landscape design that is beneficial to natural ventilation mainly depends on the vegetation type and layout. In general, vegetation improves the microclimate by decreasing the air and surface temperatures around the buildings. This vegetation affects the air movement around the buildings by sheltering, deflecting or funnelling the local wind flow. Due to water evapotranspiration through leaves and shading effect, plants can be used as a passive cooling source. Proper landscape design can reduce the building cooling costs by 15 - 35 % [Santamouris and Asimakopoulos, 1997]. The

energy need for cooling can be even more decreased down to 50 % by increasing the vegetation cover near the building by 10 - 30 % [Santamouris and Asimakopoulos, 1997]. In addition, vegetation improves the air quality by absorbing the carbon dioxide and emitting the oxygen, as well as reducing the external noise level. Proper placement of trees and bushes around the building can facilitate the air movement through it thus improving the natural cooling. By planting the trees or shrubs in rows it is possible to guide the wind on to the building, or on the contrary, shelter the building from direct wind exposure. The examples of wind funnelling can be seen in figure 4.11.

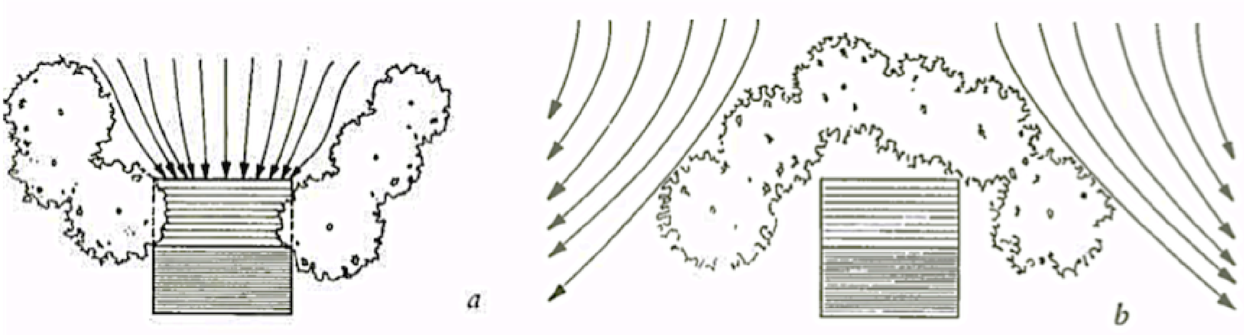

Figure 4.11. Guiding of the wind towards (a) or away (b) from the building. [Allard, 1998]

Decreasing the distance between the building and windbreaks will result in airflow acceleration around the sides of the building due to venturi effect, which is illustrated on figure 4.12. Zones where the airflow acceleration occurs have high negative pressure (high suction effect). This means that these zones are best suited for placement of the ventilation outlet openings.

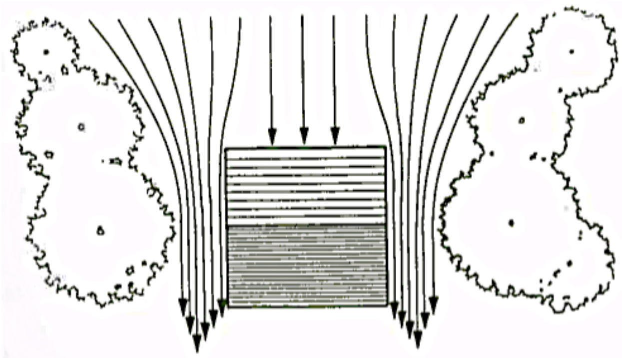

Figure 4.12. Acceleration of the airflow with windbreaks. [Allard, 1998]

When designing the tree and bush plantings around the building, different parameters are important to consider. These are the area of wake, the cross-sectional airflow pattern through the building that is created by vegetation shape and distance from the building and the proportion of the vegetation canopy and stem. This is illustrated on figure 4.13 on the next page.

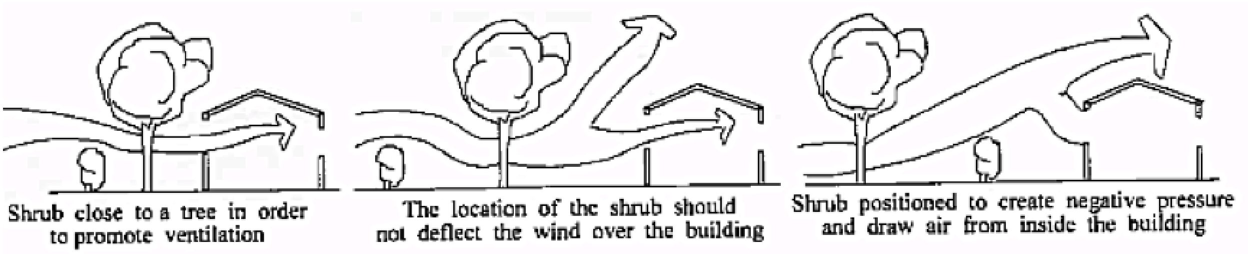

Figure 4.13. The effect of vegetative plantings on the wind pattern through the building. [Santamouris and Asimakopoulos, 1997]

To guide the airflow through the building interior, the distance between the windbreaks and the building should be no more than 1 to 1.5 times the building height [Santamouris and Asimakopoulos, 1997]. In cases when it is preferred to protect the building from undesirable airflows by guiding the airflow over it, windbreaks can be used. To obtain the highest wind sheltering effect, the distance between the windbreaks and the building should be 1.5 to 5 times the height of the windbreak [Allard, 1998].

4.4 Building Form and Envelope

Ventilative cooling is influenced by outdoor conditions as well as the internal layout of the building. Therefore, the impact of the building form and envelope, as well as internal layout on the airflow distribution within the building should be evaluated already during the building predesign phase. The heat storage capacity of the building is approximately related to its volume, whereas the exposed surface (envelope) area is related to the speed with which the building heats up or cools down. Thereby the rate at which building heats up during the daytime and cools down during the night time is linked to rate of building volume to envelope area. This means that building with high volume to surface ratio will heat up slower than the one with low volume to surface ratio. Thus, preferred form of the building with ventilative cooling is the one with low envelope area, especially the solar exposure area, and large internal volume. Optimal form of naturally ventilated building is elongated and placed perpendicular to the dominant wind direction [Santamouris and Asimakopoulos, 1997]. This shape of the building is preferred as natural room ventilation effectiveness is limited to the building depth. In order to facilitate the performance of cross ventilation, thus improving the ventilative cooling effectiveness, the cross-section area along the prevalent wind direction during the summertime should be as small as possible. Furthermore, the difference between the building length and depth should not be large. Large length to depth ratio would result in low value of wind pressure in the central part and of negative pressure areas around the edges of the windward facade.

The effective ventilation depth of the single side ventilated rooms is up to 2 times the room height and up to 5 times the room height if the cross ventilation is used, see figure 4.14 on the facing page. For example, if the room height is 3 m, the maximum effective ventilation depth would be 6 m for rooms with single side ventilation and 15 m for rooms with cross ventilation.

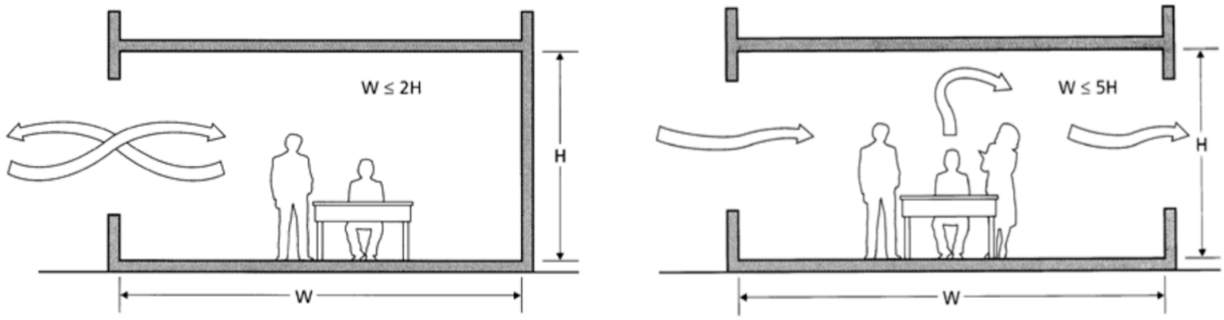

Figure 4.14. Effective ventilation depth in single sided and cross ventilation. [CIBSE, 2005]

Buildings utilising stack ventilation principle have maximum ventilation depth of up to 15 m from each side of the stack, if the room height is 3 m. This means that stack-ventilation in as must-have solution for large, deep or squared buildings.

Increase in the building height while keeping the original length and depth will increase the depth of the downwind wake on the leeward side of the building. It can also be mentioned, that the local wind speed increases with the height. This means that wind-driven ventilation strategies can be beneficial to rooms located in top part of the building. The increase in height facilitates formation of the stack-effect between the lower and upper parts of the building. Therefore the optimal ventilation principle for rooms located at the lower part of the high-rise buildings is stack ventilation.

Flat roofs, single sloped roofs with a pitch of op to 15° and single sloped roofs facing downwind are subjected to having a negative pressure (suction) over the surface regardless of the wind direction, see figure 4.15. These types of roofs can be used for placing the ventilation outlets. For double sloped roofs with tilt angle below 21°, both slopes will also have a negative pressure no matter the wind direction. For the tilt angle above 21°, the slope on the windward side of the building will have a positive pressure, whereas the slope on the leeward side of the building will have a negative pressure, see figure 4.15.

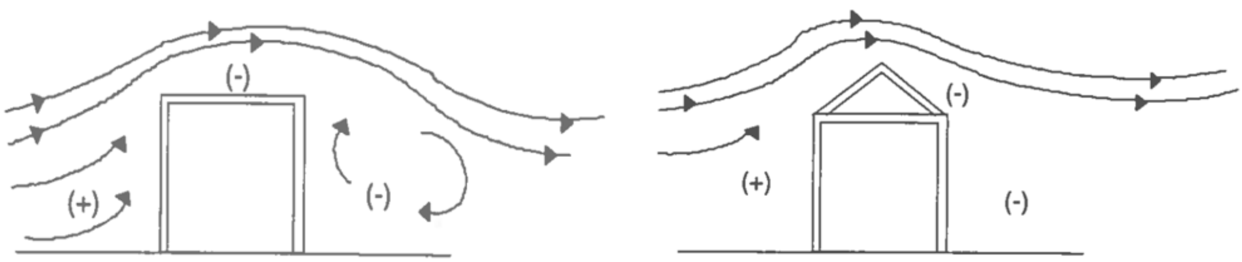

Figure 4.15. Wind pressure around a building with flat roof (left) or double sloped roof (right). [Santamouris and Asimakopoulos, 1997]

Since all buildings with ventilative cooling analysed within this project have natural or hybrid ventilation, the form of the building is of great importance. When looking through the analysed buildings, a common pattern is observed. In many cases a building form that is beneficial to natural ventilation has been used. Typical examples following this design approach are *B&O headquarters* and *Aarhus municipality*, which both are long, not deep and have rectangular shape. Ventilation inlet openings are placed along the facades, while the outlets are located at the roof

(B&O headquarter) or at the opposite facade (Aarhus municipality). Another noticeable aspect is that both buildings have a flat roof, which means that, disregarding the wind direction, there will always be negative pressure on the roof plane. This phenomenon is utilised in B&O headquarters building by placing ventilation outlets on the roof. The buildings are shown on figure 4.16 and 4.17.

Figure 4.16. External view of B&O headquarters. [Open Building]

Figure 4.17. External view of Aarhus municipality building. [WindowMaster, b]

In cases when the building function and/or specific site layout takes precedence over the ventilation design, the building form is not always beneficial for ventilative cooling. This can be seen when looking, for example, at deep squared buildings. These buildings are hard to ventilate by the use of single-sided or cross-ventilation because of limited ventilating depth. Typically, unfavorable building shapes for natural cooling are used in large office buildings, shopping malls. An example of large deep building is Field's shopping mall in Copenhagen, see figure 4.18.

Figure 4.18. Top view of the Field's shopping mall. [Travel Team Image]

The picture shows that Field's building has almost a quadratic form. This means that it is almost impossible to have efficient ventilative cooling with natural ventilation without implementation of additional architectural elements enhancing natural ventilation. In this case the openable skylights were implemented in the hallways, thus improving the potential of the natural cooling by utilising a stack-effect.

Another type of buildings, that was observed when working on the building descriptions, are buildings with complex geometry. In these buildings irregular air pressure distribution due to corrugated building envelope appears. As a result, even slight changes in wind direction and speed might turn the inlet openings into outlets because of the wake regions created by the corrugation of the building envelope. It was observed that some smaller educational buildings have unfavorably corrugated envelope, but favorable internal planning. Typical example of building with corrugated envelope is the the kindergarten *Spirehuset* located in Hirtshals, and shown in figure 4.19 and 4.20.

Figure 4.19. External view of Spirehuset. [WindowMaster, b]

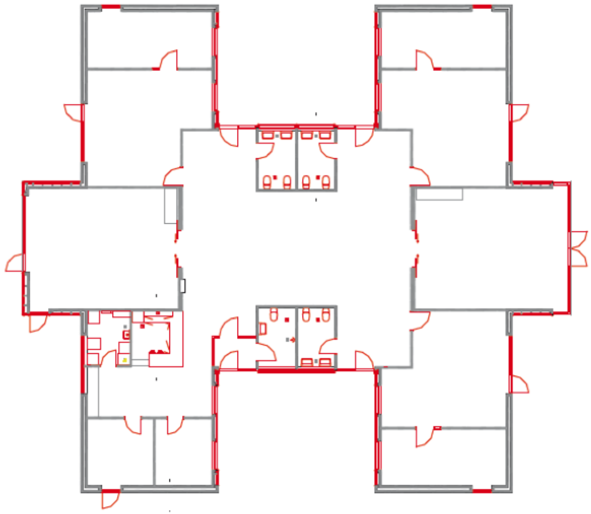

Figure 4.20. Floor plan of Spirehuset. The red lines in the envelope represent the openings. [WindowMaster, b]

Due to the complex geometry difficulties in ventilating the inner rooms appear. In this case it is solved by having skylight openings and utilising the stack-effect.

A typical solution for the natural ventilation for buildings with either deep squared plan and/or corrugated envelope is the use of stack-effect by implementation of atria, stack ducts in the middle of the building or openable skylights in the roof construction. Therefore, it can be concluded that buildings which have unfavourable form for natural cooling can be improved by adding some architectural elements that facilitate the performance of natural cooling by the use of stack-effect.

4.5 Internal Layout of the Building

In situations where buildings have unfavourable form for ventilative cooling, the morphology can be designed to improve the possibility of using natural ventilation. The morphology has a big influence on which ventilation strategy of the natural ventilation should be used to ensure optimum performance of the system. Internal layout of the building affects the ventilation airflow pattern inside it. In general, rooms with higher pollution potential (e.g. kitchens and bathrooms) should be positioned along the leeward side of the building to avoid the pollution transfer to less polluted rooms (offices, meeting rooms, etc.).

The most advantageous horizontal layout for the natural ventilation is open plan design. This type of internal layout is especially beneficial for the spaces ventilated by cross ventilation. However, cellular planning is often preferred due to practical needs. Partitions in cellular layout should be placed so that they do not restrict the airflow through spaces. To do that, the area of partitions perpendicular to the airflow direction should be as small as possible. Moreover, placement of the partitions should be designed to guide the internal airflows through the building. As a rule of thumb, partition walls are placed so that larger spaces are formed on the leeward side of the building, see figure 4.21.

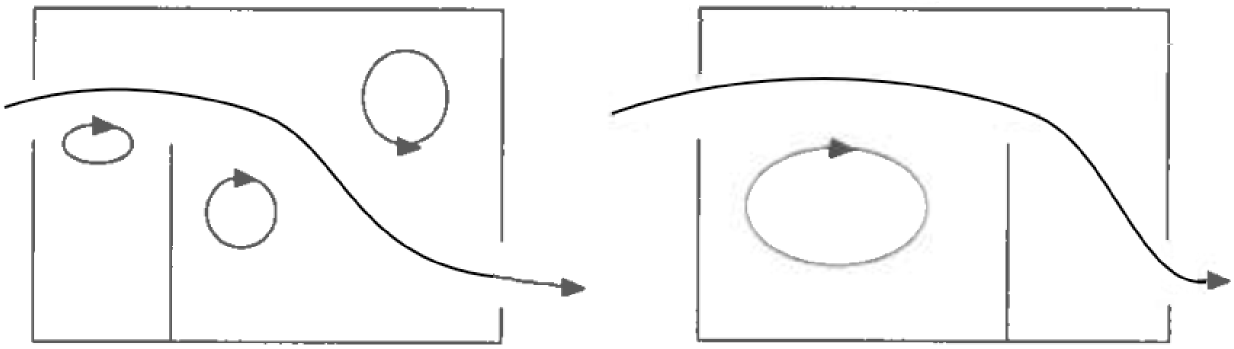

Figure 4.21. Example of bad (left) and good (right) partition design for natural ventilation. The pictures are from a top view. [Santamouris and Asimakopoulos, 1997]

Single-loaded corridor plans are better than double-loaded corridor plans for utilisation of cross ventilation because the airflow is facing a lower resistance when passing through the building. This is illustrated on figure 4.22.

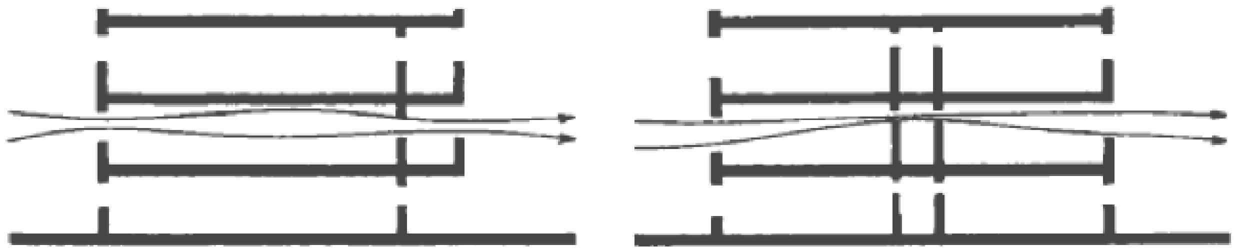

Figure 4.22. Cross ventilation in single-loaded (left) and double-loaded (right) corridors. [Lechner, 2001]

Cross ventilation in double-loaded plans can be improved either by keeping the doors to the corridor open, or by installation of openable windows above the corridor doors (transoms). However, disturbance from noise have to be considered.

Another way of improving the ventilation conditions in double-loaded corridor plans is combining the cross ventilation through corridor windows with stack ventilation through roof windows (single-storey buildings) or ventilation shafts (multi-storey buildings).

This kind of solution was used in *Frederiksberg courthouse*, where an atrium is located in middle of the building bringing the daylight into the building and serving as a stack for natural ventilation. Offices and hallways situated around the atrium are naturally ventilated. This is illustrated on figure 4.23 on the facing page.

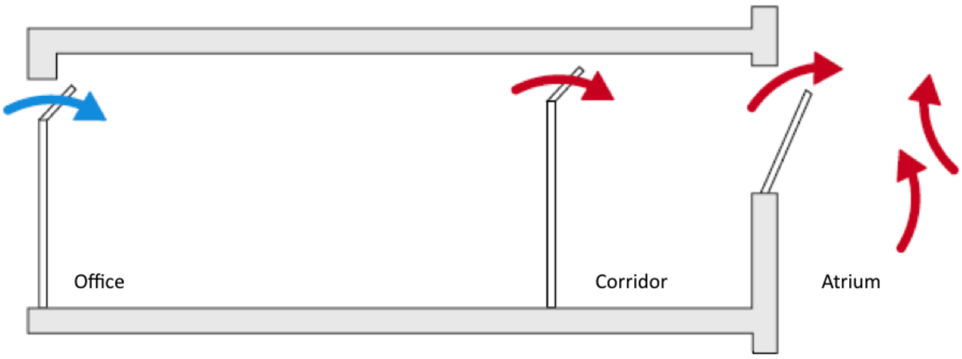

Figure 4.23. Sketch of ventilation airflow path in Frederiksberg courthouse. [WindowMaster, b]

Natural ventilation is ensured by automatically controlled vertical windows, interior windows/flaps and vertical skylights. The primary natural ventilation principle is stack ventilation. The air is supplied via the facade windows and is distributed around the office, and then is passed to the atrium via interior flaps. The flaps are located in the walls between the office/hallway and hallway/atrium. In atrium, the ventilation air rises and leaves the building through skylights at the top of the atrium.

In reality, there are rooms ventilated by single sided ventilation. This is not the most beneficial solution either for ensuring good indoor air quality, or efficient ventilative cooling. However, there are some simple initiatives to improve the ventilation effectiveness. This could be done by proper window placement and by appropriate use of wing walls, see figure 4.24.

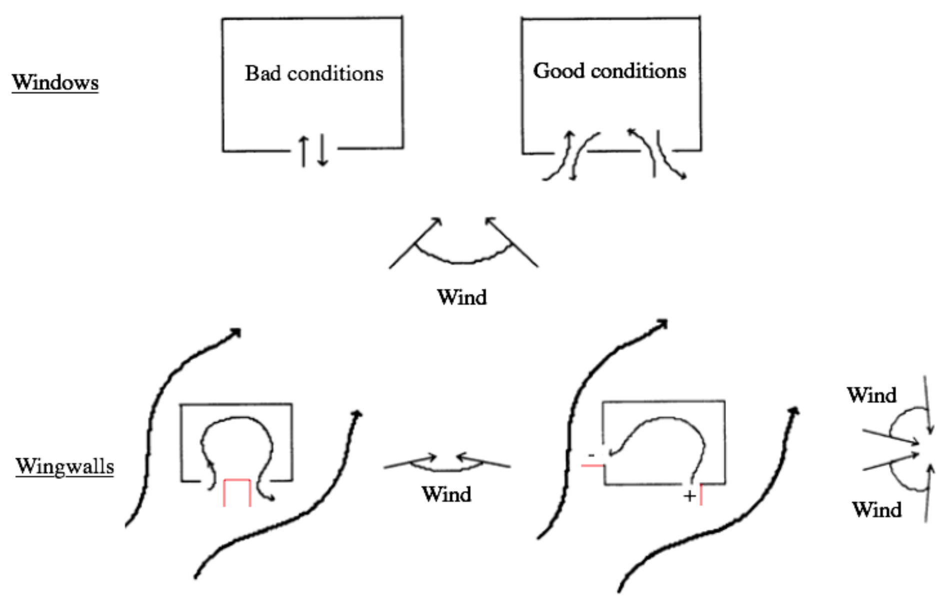

Figure 4.24. Improvement of single side ventilation by opening location and wing wall implementation. The red lines indicates a wing wall. [Heiselberg, 2006]

The vertical air movement in distribution of internal spaces in multi-storey building is mainly governed by stack-effect. In multi-storey buildings the warm, contaminated air is removed from the buildings through atriums, staircases or ventilation shafts. It is important to notice that the outlet openings should always be placed on the leeward side of the building. Outlet openings should be elevated above roof level to eliminate the situations, when the polluted air escapes the building through ventilation openings on the top floor. This can be done by making sure that the neutral plane is above the ventilation inlet openings on the top floor. This is illustrated in figure 4.25

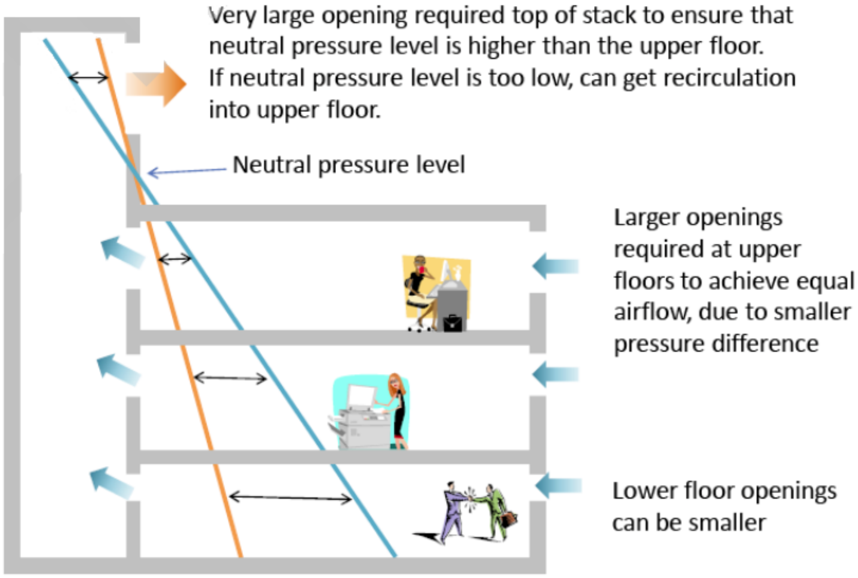

Figure 4.25. Stack ventilation design principle. [Heiselberg, 2006]

Through the analysis of the buildings, some patterns were observed. In cases where buildings have a bad form, an atrium is often located in the middle of the building. This is done to secure the distribution of fresh air throughout the entire building. When the building contains an atrium, stack ventilation becomes the main ventilation principle.

Two different kinds of office plans are used in the analysed office buildings. These are open and cellular plans. In a cellular office plan the opportunity for different ventilation strategies is limited. Single sided ventilation is mainly used, which also have the lowest potential of the ventilative cooling. Cellular offices are difficult to ventilate with other principles because of disturbance from other parts of the building. For example, noise from the rest of the building if another opening is opened to a hallway or alike. The noise level in open plan offices is higher than the one in cellular offices. However, it is not that critical. Stack ventilation principle can be applied to open plan office, if an atrium is located nearby the open plan office area. Apart from stack ventilation, cross ventilation can be used in some cases. When a building consists of large open plan offices, instead of small cellular office plans, several external walls are located in the same room, which makes it possible to have openings in different directions, thus increasing the ventilative cooling possibility.

An example of a building with an adverse form (squared), but a good morphology to enhance ventilative cooling is the office building owned by DSV in Zealand. In this case the open plan office areas are placed around an atrium, which is located in the middle of the building. A picture of the building interior is shown in figure 4.26 on the next page.

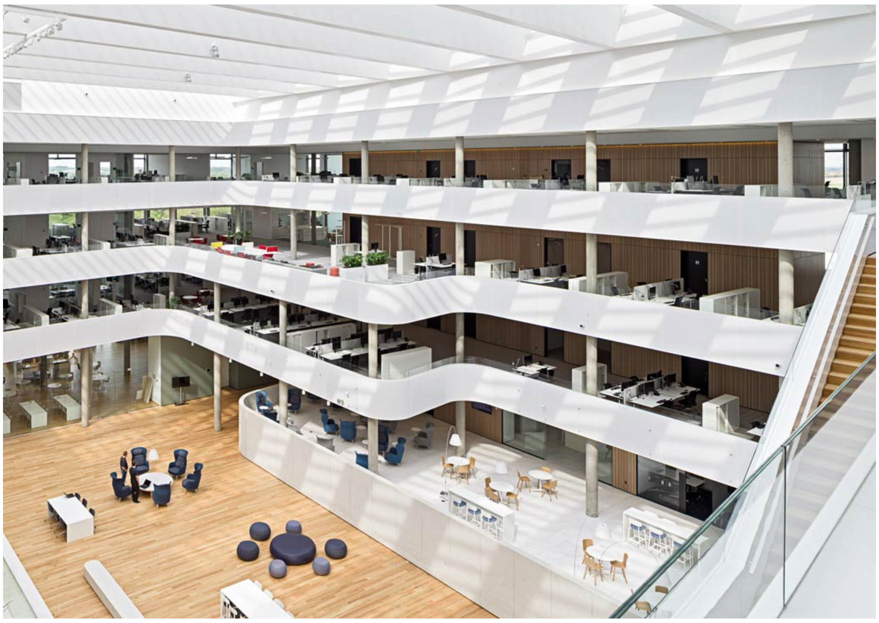

Figure 4.26. Example of a good morphology for ventilative cooling, which contains open plan offices and an atrium. [PLH Arkitekter A/S]

In this case the advantage of the morphology is utilised and stack ventilation cools down the building.

In cases where ventilative cooling is implemented in an existing building, some difficulties related to morphology occur. In many old buildings cellular office planning is used, and the possibility of changing the morphology is low. This means that single sided ventilation is almost the only solution in these cases. The old renovated office building, *Ved Stranden*, in Copenhagen is a typical example of this situation. An external view of the building and a sketch of the ventilation principle are illustrated on figure 4.27 and 4.28.

Figure 4.27. The south facade of the preserved building in Copenhagen. [Erasmus and Partnere]

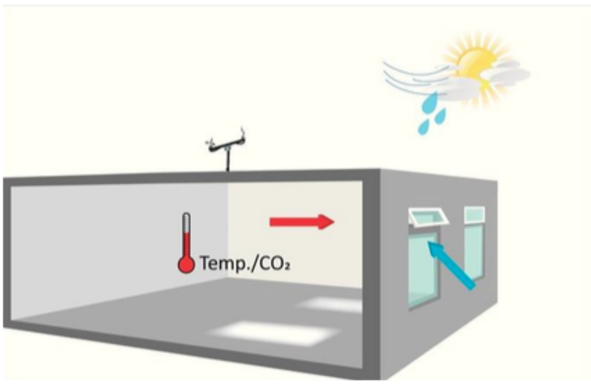

Figure 4.28. Sketch of the ventilation principle. [WindowMaster, b]

The main principle in this case is single sided ventilation, and cross ventilation appears when the door to the hallway is open. To avoid the noise from the hallway, single sided ventilation is the main ventilation principle.

4.6 Natural Ventilation System Components

It is not only building form, site and envelope, which have an influence on ventilative cooling. The natural system components also have an influence on the performance of the ventilation system. Key components of natural ventilation system are described in the following sections.

4.6.1 Windows

The most widely used devices to control the natural ventilation are the operable windows. Windows equipped with electrically driven mechanical actuators together with different kinds of sensors are used for automated natural ventilation control. The advantage of openable windows is the ability of providing high air change rates (ACR) due to large opening area. Thus, windows can be used to remove large contamination in short periods of time. However, windows are not well suited for ensuring low, continuous ACR and have poor protection against precipitation, dust, and insects. Openable windows also have a poor protection against external noise pollution. Windows are traditionally divided as:

- **Side-hung casement windows** rotate around vertical axis on one side of the window. This window type has large opening area, but lacks the protection against precipitation. Well suited for manually controlled short term airing (pulse ventilation).

- **Hinged windows** rotate around horizontal (top or bottom) axis on one side of the window. These windows have smaller opening area than side-hung casement windows; however, this type of windows is the most widely used type in automated natural ventilation systems as it provides some protection against precipitation and can be adapted to provide low ACR.

- **Pivot-hung windows** rotate around vertical or horizontal pivoting axis located in the middle of the window. Horizontal pivot-hanged windows have good stack ventilation potential. This type of windows is often used in spaces ventilated by single side ventilation principle. Drawbacks of these windows are subjected to have problems with air tightness and high risk of autorotation in case with high wind.

- **Sash windows** can be opened by sliding one sash over another in either horizontal or vertical direction. These windows provide good control of airflow rate. However, they are hard to open or close due to wedging of sash sliding elements.

- **Roof windows/skylights** are manly used for discharging the polluted air from the building using the stack-effect. This type of windows is especially low protection against precipitation.

The different types of windows are illustrated in figure 4.29 on the next page.

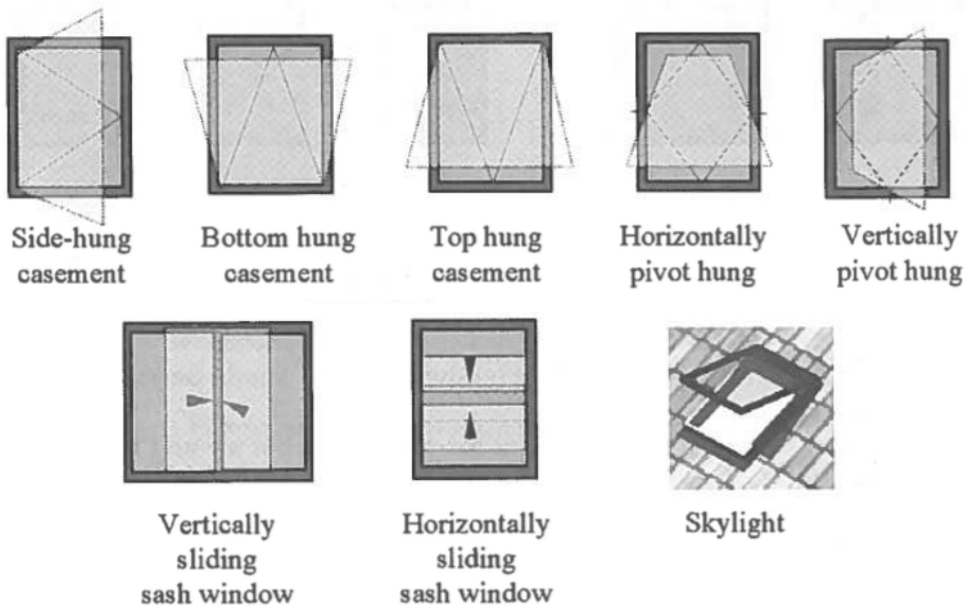

Figure 4.29. Window types. [Ghiaus and Allard, 2005] - modified

Even though a building has an optimum envelope in proportion to ventilative cooling, a non optimal placement of the openings may induce uncomfortable indoor conditions. Since window is the most common device for natural ventilation, a special attention needs to be paid to this system component.

Correct positioning of windows in the building envelope is very important. Security, feasible amount of air, user behavior and draft are all parameters that have to be taken into account, when the location of the hinged openings has to be decided. Openings, used for night time ventilation, should not be located near the ground to reduce the risk of burglary. High amount of air might be required to cover the cooling demand, which can be a problem in urban environment, where buildings stand close together and the microclimate is distorted. In such cases openings, located at a higher level, often are necessary. Problems with users mostly arise when kids are involved. An unwanted interference by opening or closing the window openings have an influence on the system and, in some cases, the entire building. For example, if the ventilation principle is stack ventilation, window position (opened/closed) can change the location of the neutral plane. This means that openings should be placed out of reach of kids or other persons that could influence the system in a negative way. By placing the openings at the top of each room (near the ceiling) the interference from kids is solved and some issues with draft are minimised. The velocity decreases before reaching the occupied zone, where the users are present, and thereby discomfort is prevented.

Apart from the window openings placed in the facades, roof windows/skylights are used in some cases. These openings are mostly used together with the facade windows, and thereby serve as outlets for stack ventilation. Roof windows are protected against burglary, are difficult for kids to influence and ensure good daylight conditions in internal spaces.

Spirehuset is a good example of how the openings should be placed when kids are involved. The hinged openings are placed at the top of the window sections. This secures that no interference from the users arise, and entails low velocity of the incoming air, when it reaches the occupied zone. The building and the top placed openings are illustrated in figure 4.30 and 4.31.

Figure 4.30. Spirehuset in Hirtshals with openings located in the top. [Erasmus and Partnere]

Figure 4.31. Close view of the opening. [Erasmus and Partnere]

In some cases the design of natural ventilation is restricted, often in renovation cases, and the already existing envelope must be used. This is the case *Ved Stranden* building in Copenhagen. The existing external side-hung casement windows are preserved. An internal bottom hinged window leads the air upwards and thereby ensures that the air doesn't reach the occupied zone with a too high velocity and thereby cause discomfort. The building and its openings are illustrated in figure 4.32 and 4.33.

Figure 4.32. The south facade of the preserved building in Copenhagen. [Erasmus and Partnere]

Figure 4.33. Close view of the opening. [WindowMaster, b]

Besides the two above-mentioned cases, *Søndersøskolen* in Værløse is a good example of optimal location of the openings. The rooms to the facade have openings located just above the large window sections. These openings are made as top-hinged windows and let the air enter the room close to the ceiling. This approach is convergent with *Spirehuset*, but the advantage for this building turns up when we look closer to the inner rooms. The height of the inner rooms is increased, which makes it possible to place a series of windows just above the outer rooms on the facade. Thereby, ventilative cooling is used in the entire building. The openings in outer and inner rooms are shown in figure 4.34.

Figure 4.34. The hinged windows for the outer rooms are placed above the large window sections in the facade. The openings for the inner rooms are the roof windows together with the series of openings just below. [WindowMaster, b]

4.6.2 Ventilation Louvers and Vents

The use of automated *louvers* is beneficial to natural cooling as they enhance the supply of large airflows as well as protected the building from rain, insects and burglary. Unlike windows, louvers do not serve as a considerable source of daylight as they have restricted view to the outdoors. On the other hand, louvers act like solar shading that hinders the indoor temperature rise due to penetration of direct solar radiation inside the building. A louver is shown at figure 4.35.

Figure 4.35. Adjustable ventilation louvers. [Renotalk]

Vents are typically used as air inlets. Though, in some cases they are also used as outlets. Similar to louvers, vents protect indoor spaces from penetration of precipitation, dust and insects, and sometimes provide sound proofing. According to regulation possibilities vents can be divided into non-adjustable, hand controlled, or self-adjusting.

Self-adjusting vents are used to ensure stable airflow into the building. The most common self-adjusting vent type is *pressure-controlled* vents. These vents provide approximately the same airflow by changing their permeability according to indoor and outdoor pressure difference. Distinction between low pressure (1-5 Pa) and high pressure (10-20 Pa) vents can be made. Another type of self-regulating vents is *humidity-controlled* vents that operated according to relative air humidity difference between indoor and outdoor. These vents are used in spaces where humidity is an issue (bathrooms, washing rooms, different production facilities, etc.). In cold climates where the thermal buoyancy is the main driving force of the natural ventilation, *temperature-controlled* vents can be used. These vents change the air permeability according to temperature difference between indoors and outdoors; the larger the temperature difference, the larger the resistance to the airflow (pressure drop). Lately, *pollutant-controlled* vents have appeared on the market. These vents are a part of the demand controlled ventilation system. Pollutant-controlled vents are electronically controlled vents that are coupled with a sensor monitoring the pollution level in the room. The air permeability is changed due to pollution level in the room. Typically, CO_2 level in the room is used as a pollution indicator. This type of vents can be applied in spaces with high pollution load (meeting rooms, classrooms, conference halls, underground parking lots). The main disadvantages of pollutant-controlled vents are relatively high price and pollution level reading accuracy.

An example of the use of special effected vents was observed in *A2SEA* office building in Fredericia. A location between a motorway and a railway required some innovative solutions for ventilative cooling by natural ventilation without having any noise issues. The solution with sound insulated openings as illustrated in figure 4.36 and 4.37.

Figure 4.36. External view of the sound insulated opening. [WindowMaster, b]

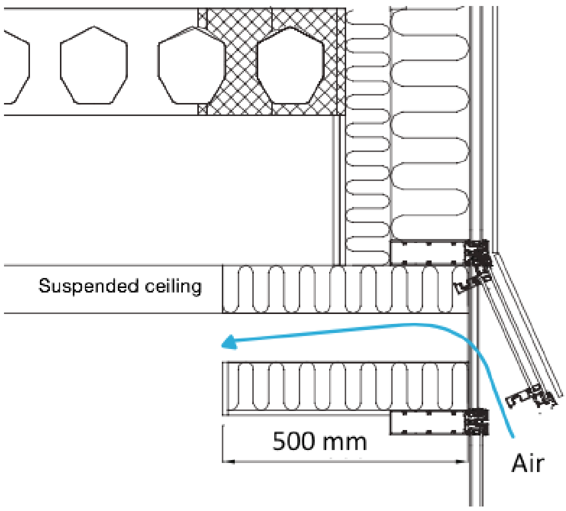

Figure 4.37. Detailed drawing of the insulated opening in the facade. [WindowMaster, b]

The insulated openings entail that the building can be ventilated by outdoor air without disturbance from external noise from the motorway and railway.

4.6.3 Stack Ducts/Chimneys

Stack effect in buildings can be increased by the use of stack ducts. The stack ducts can be divided according to installation way; single duct, shunt duct and individual ducts, see figure 4.38.

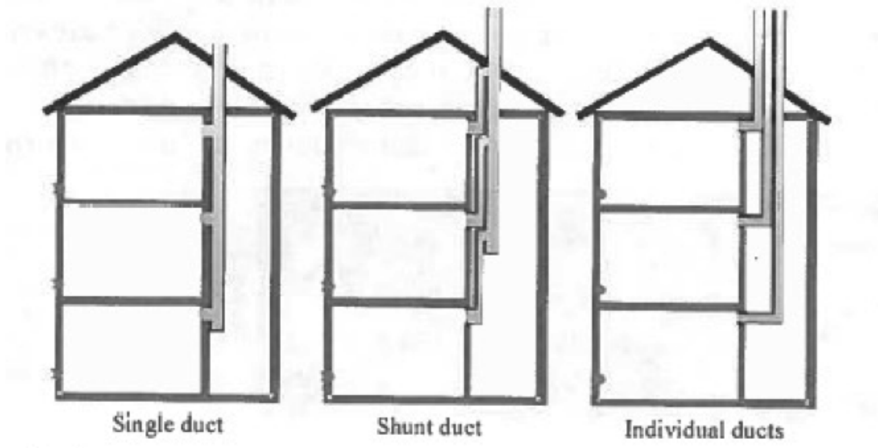

Figure 4.38. Stack duct types. [Ghiaus and Allard, 2005]

Despite being the simplest and cheapest, single duct installations should be avoided due to high risk of pollution and odor spread between the floors. Individual ducts are not affected by this problem, but this is the most expensive solution and takes a lot of space. Shunt ducts are considered to be the compromise solution eliminating pollution propagation and having reasonable implementation costs.

4.6.4 Roof Ventilators

In order to increase the airflow through ventilation chimneys, venturi effect is used. Venturi effect occurs when the fluid, following through a pipe, is drawn through a constricted part of the pipe, thus resulting in pressure decrease and velocity increase. Venturi ventilators use this underpressure effect to increase the suction in the stack duct. Venturi ventilators are placed above the roof on top of the stack duct. Besides enhancing the airflow, venturi ventilators protect the stack duct against rain and snow. An example of a venturi ventilator is shown on figure 4.39

Figure 4.39. Venturi ventilator. [Master Services]

There are many different types of roof ventilators, starting from simple covers on top of the chimney and continuing with more sophisticated solutions, like venturi ventilators, wind turbines, wind deflectors, etc. Relative ventilation effectiveness for some of the most widely used roof ventilators is shown in figure 4.40.

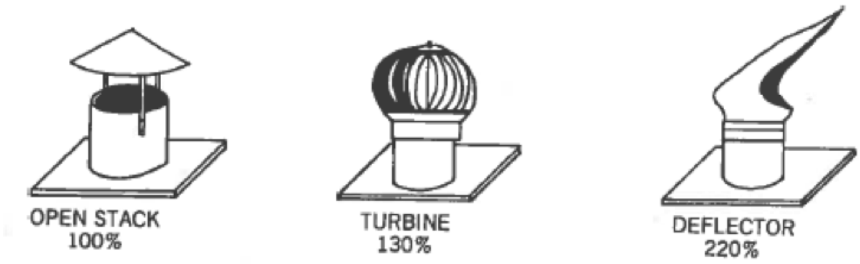

Figure 4.40. Relative efficiency of different roof ventilators. [Lechner, 2001]

The performance of open stack with cover and roof turbines is not affected by wind direction, whereas the effectiveness of the wind scoops (deflectors) is linked to the wind direction (if they are not able to rotate according to wind direction). However, the efficiency of wind scoops and wind ventilators in no wind conditions is lower than the one for the open stack due to airflow resistance.

4.6.5 Wind Towers

Wind towers are traditionally used in Arabic architecture. These devices capture the high velocity winds high above the ground level and then channel it down the windward shaft into the ventilated spaces. Sometimes, ventilative cooling effect is enhanced by evaporative elements inside the tower, thus making use of evaporative cooling as well. Cooler and denser supply air replaces the warmer and lighter room air, thus forcing it upwards where it is drawn into the exhaust shaft located at the leeward side of the wind tower. Wind scoops are the modern interpretation of traditional wind towers, see figure 4.41. Motorised four-way dampers inside the wind scoop unit are used to control the air supply and extraction depending on required ACR with regards to the local wind speed and direction. Wind scoops are driven either by natural forces only, or a combination of natural forces and low pressure electrical fan.

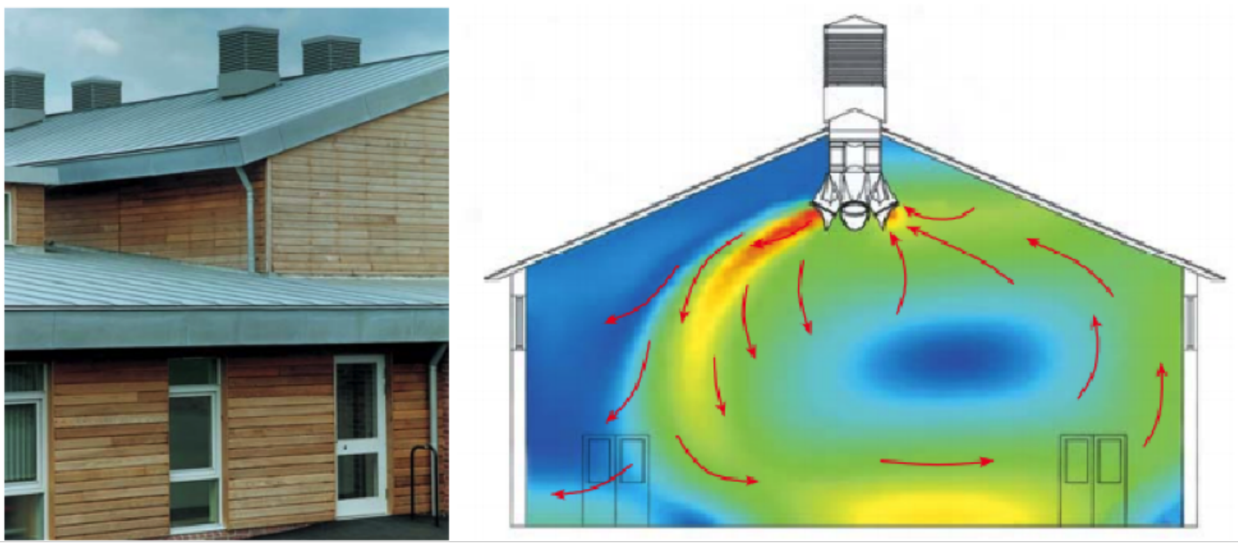

Figure 4.41. Wind scoops on the roof (left) and their operative principle (right). [Passivent]

4.7 Control of Ventilative Cooling

To obtain and maintain a satisfactory indoor climate with a low energy consumption, the optimum control of the system have to be chosen. The need for ventilation for the user comfort and health point of view, together with the maximum use of the free cooling potential from natural and mechanical ventilation have to be balanced. Different sensors, set points and control strategies all have an influence on the ventilative cooling of a building. Some of these are presented in the following sections.

4.7.1 Generic Control Strategies

The chosen control strategy will have an influence on the performance of the ventilation system. More and more advanced strategies have been developed. New strategies are controlling more than only the ventilative cooling part. Combinations of controlling cooling, heating, lighting, solar blinds etc. to secure a satisfactory result are now used in new and renovated buildings. [WindowMaster, a]

The main reason for having a complex system, which controls all system in a building, is to eliminate the system "cannibalism" and make sure that resources are used in the most efficient way.

Following criteria have to be fulfilled before it can be said the system is running as it should:

- Sufficient amount of fresh air is provided. This is generally a winter design requirement, and will not be analysed further on in this project.

- Sufficient ACR is provided to remove the heat gains and maintain an acceptable indoor temperature.
- Even distribution of airflow is ensured to avoid areas of under or over-cooling.
- Draught and discomfort for the users is avoided.
- Disturbance from other system components is avoided. (For example, if the solar shading blinds are down, they might disturb the air entering the room through the window).

Even though most of the new systems have become more complex and advanced, manual control, together with the opportunity to overrun the system, is still very important for the users. Investigation of the effect from user control have shown, that an internal temperature of 24 °C in a building with full automatic control gets the same level of complaints as a fully user controlled building with an internal temperature of 27 °C. This means that it is preferable to have the user control as an opportunity. The exception could be public buildings, where the performance of the system might be seriously distorted by non-authorised persons. [A. J., 1996] Another way of dividing the control strategies based on user interference with the ventilation system is:

- Only user
- User + Automatic control based on sensors
- Only Automatic control based on sensors

By each step the control strategy is increasing in complexity. If only sensors control the system, some advanced technologies have to be used to ensure that the system runs optimally and fulfill the requirements. In some cases could *Only user* be a reasonable solution, for example in small offices. But, in cases where a higher number of users' needs have to be fulfilled and in buildings with night time ventilation, automatic control must be used.

The controller reacts on the data from internal and external sensors according to the chosen set points. CO_2 and temperature sensors are for example placed in different internal zones to measure the indoor climate, which sends information to the controller, which decides if anything should be changed. The internal temperature sensors are a reliable and inexpensive investment, whereas CO_2 sensors are more unstable and expensive. Besides the indoor sensors, external sensors providing information regarding the outdoor conditions are necessary. Weather station measuring wind speed and direction, rain and humidity are added in many cases to ensure satisfactory performance of natural ventilation, which is very dependent on the outdoor conditions. Wind direction and speed gives information about which openings to open to get most out of the ventilative natural cooling, and when to close the openings due to unfavourable weather conditions. In some cases the choice of control strategy is influenced by safety issues, which can produce limitations to the system. This is especially present for floors in a building near the ground, where it is possible for unwanted persons to enter the building.

The new and advanced strategies are using CFD (Computational Fluid Dynamics) to model the wind pressure around a building. This can reduce the time spent trying to tune the parameters for each set of windows, and thereby make sure that correct ventilations rates are provided depending on external weather conditions. [WindowMaster, a]

4.7.2 VC Control Strategies

If it is decided to use automatic control, relevant control strategy must be selected. Many different opportunities are present. Some of the most widely used for VC buildings are explained in the following sections.

Temperature and CO_2 Control
The internal temperature and CO_2 concentration (mostly in winter) are the parameters, which determine the position of the openings. The indoor temperature and CO_2 concentration are compared with their setpoints, and the position of the openings are decided on the basis of the deviation from the set points. This simple control strategy has eventually been improved to account for the outdoor conditions as well. The pressure around the building is varying because of the wind speed and direction, rain intensity and external temperature, which means that the necessary opening areas are varying for each facade. These changes are taken into account in the optimised temperature and CO_2 control strategy. [A. J., 1996]

Pre-cooling Control Strategy
If night time ventilation should be implemented to cool down the building, a pre-cooling control strategy must be used. At first pre-cooling strategy is measuring the number of hours, when the internal temperature is above the internal temperature set point in the occupation period. If the internal temperature has been higher than the set point temperature for more than 3 degree hours, and the internal temperature is above the external, pre-cooling of the building begins. The pre-cooling stops, when the same number of hours of cooling is equal to the number of hours of daytime heat gains. This means that this control strategy is based on a energy balance estimation for the building. The same amount of energy, which is added during the day, is removed during the night.

In situations when mechanical ventilation is available, a calculation of how late the supply and extract fans should start is made to secure that pre-cooling can be completed.

In situations when night time ventilation is not completed, the time to stop the cooling is difficult to set because of the thermal mass of the building. An exposed slab still have a temperature around 20-23 °C after a full night of cooling. This means that even though the temperature of the air inside is decreased, the building construction heats up the internal air immediately after night time ventilation stops.

In these cases an opportunity is to stop the pre-cooling at the right time, so the building can manage to warm the air to the set point. The other opportunity is to extend the pre-cooling, and then heat the building in a short period before the users arrive. The advantage of the last opportunity is more stored heat from the building material is removed, which can be utilised the next day. [A. J., 1996] A graphical illustration of the control strategy is shown in figure 4.42.

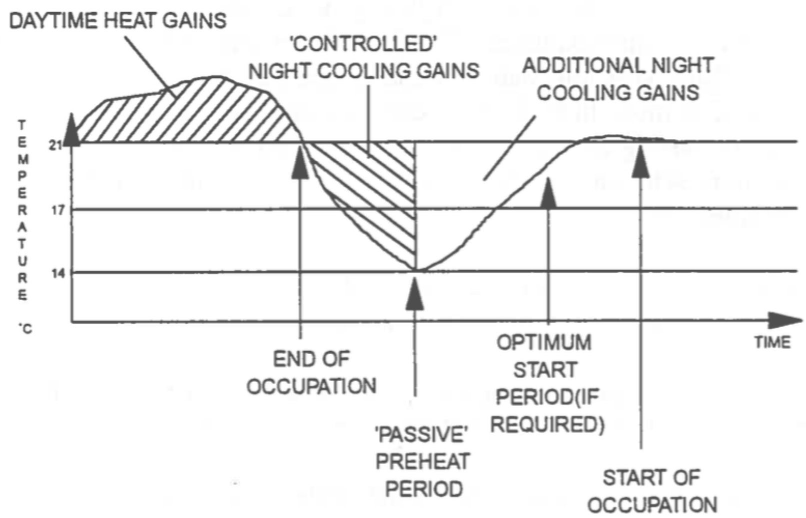

Figure 4.42. Graphical illustration of the first precooling control strategy. [A. J., 1996]

The first hatched area above 21 °C is the measured number of hours, where the internal temperature has exceeded the internal set point temperature. When the users leave the building, the "controlled" night cooling gains starts, until the same amount of heat, as the one measured during the day, has been removed. Afterwards, additional night gains begins, so the internal temperature reaches the desired indoor temperature before the start of occupation period. This cycle is repeated day by day.

Another way to use precooling control strategy is to utilise the maximum effect of thermal capacity in the building. This strategy allows the night time ventilation to run, when the mean indoor temperature between 12.00 - 17.00 is above the precooling set point (18 °C), and the internal temperature is higher than the external. The night time ventilation runs until the internal air temperature drops to for example 14 °C. Subsequent the increase in temperature occurs, because of heat gains from the building fabric and furniture. When a temperature of 17 °C is reached, the night time cooling starts again. This process continues until the preheat period is reached. The preheat period is the time period to heat up the internal air to the passive heating set point (19 °C) before the users arrive. In cases where this set point can not be reached, heating starts. This precooling strategy is based on a set point control. It does not take into account the energy balance calculation as the previously mentioned control strategy, but uses the cooling and heating set points for the building to control the system. The control strategy is graphically illustrated on figure 4.43 on the following page.

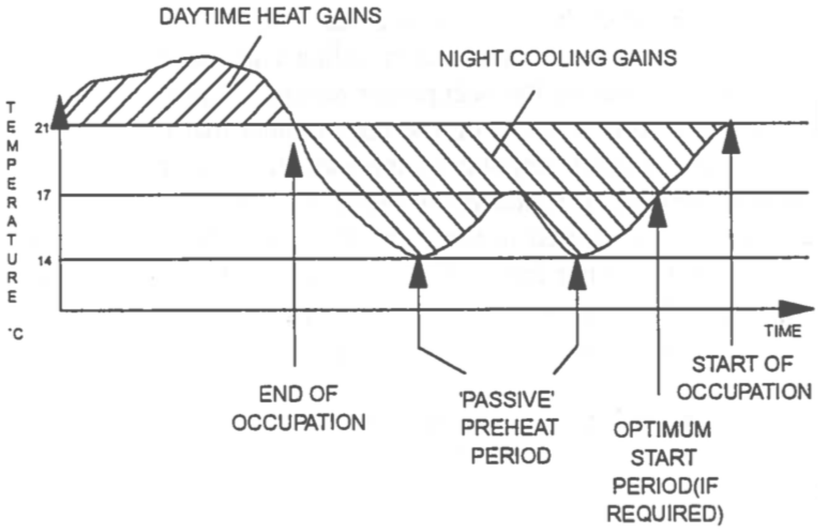

Figure 4.43. Graphical illustration of the second precooling control strategy. [A. J., 1996]

In this case the area of the first hatched area is not important. More important is the fact, that the mean temperature has been above the pre-cooling set point, and the internal temperature is higher than the external, so night cooling can take place. The time period where the night cooling runs is shown by the second hatched area. The indoor temperature is cooled down to 14 °C in this case, where it stops until the temperature reaches 17 °C again. This continues until the passive preheat period is reached and the passive heating set point at 19 °C can be reached before the users arrive.

Both precooling control strategies are taking the outdoor conditions into account, as described for the temperature and CO_2 control strategy.

From the analysed buildings, it is observed that NV Advance^{TM} from WindowMaster is the most widely used stand-alone control system of natural ventilation. NV Advance^{TM} ensures precise positioning of the windows according to ventilation need and outdoor weather conditions. The building is divided into different control zones. Each zone is individually controlled and monitored by centralised server-PC, which is also used for logging the readings from sensors and actuator positions. The system example with natural ventilation control is shown in figure 4.44.

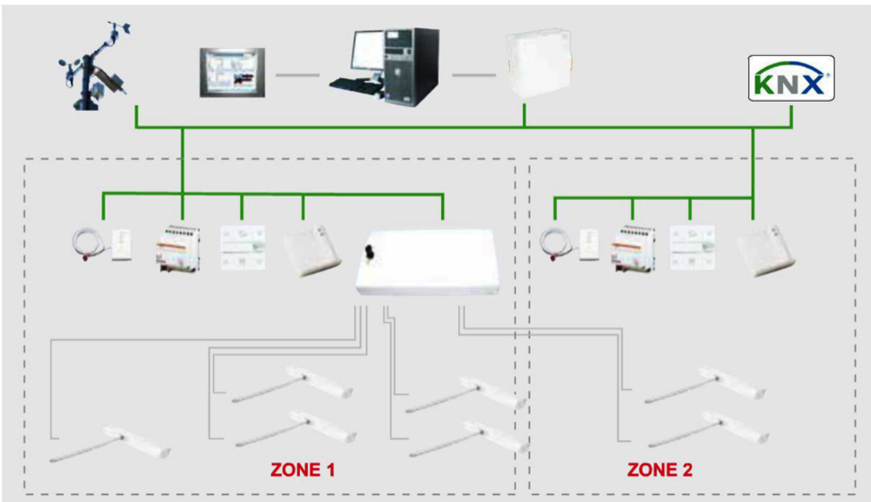

Figure 4.44. NV Advance^{TM} natural ventilation control. [WindowMaster, a]

The unique feature of this control system is the pre-programming of the controller based on performing CFD analysis of the building and its surroundings. This is done by creating a calculation model of a building and its surroundings, and then running the CFD simulation for 16 different wind directions. As a result, wind pressure coefficients for each particular ventilation opening (window) are obtained for each wind speed and direction. This allows finding the perfect opening angle for each window in all weather conditions. Another unique feature of the NV Advance^{TM} control system is the MotorLink^{TM} chain actuators that are operated by MotorController. This technology allows the synchronisation of multiple actuators on a facade, as well as individual precise control of each actuator.

The system also contains multiple sensors that are used for continuous monitoring of indoor climate and outdoor weather conditions. Indoor sensors are used for on-going measurements of temperature and CO_2 level, whereas outdoor conditions (wind speed and direction, precipitation and solar radiation) are measured by weather station located on the rooftop. NV Advance^{TM} ensures that the indoor climate is kept within the desired comfort range. This is done by adjusting the position of ventilation openings based on combing the information from CFD analysis with the actual indoor and outdoor climate measurements, and feedback from the openings.

Additionally, by connecting more sensors and actuators to the NV Advance^{TM} controller, it is possible to control smoke management, heating, lighting and solar shading systems of the building. NV Advance^{TM} can also be used in buildings with hybrid ventilation systems as it can be coupled with control of mechanical ventilation. [WindowMaster, a]

5 General Design Patterns of Ventilatively Cooled Buildings

Through the analysis of different ventilative cooled buildings in Denmark it becomes evident, that a lot of parameters have to be taken into account to design an optimal ventilative cooling system. Building location, form, envelope, morphology etc. all have an influence of how efficient the cooling system is, and a lot of them set limitations to the opportunities to the building design. Naturally cooled buildings must be designed in such a way that natural driving forces of ventilation systems are enhanced if ventilative cooling should be the main cooling system. The influence from all these parameters requires individual approach in designing ventilative cooling system for each case. It means that it is difficult to apply one standard solution for all cases.

The general design patterns are obtained in investigating office and educational buildings, as these two types of buildings form the majority of observed buildings. These buildings are characterised with high heat loads during the day, because the highest solar loads coincide with with highest internal heat loads (people and equipment) during occupation hours. Moreover, these buildings have high NTV cooling potential as they are typically unoccupied during the night. This means that the room can be ventilated with increased ACRs, and there are lower requirements regarding thermal comfort. It is important to notice that a minimum inlet temperature must be specified in order to avoid moisture condensation issues.

The state-of-the-art investigation showed the utilisation of building site location is preferable, when ventilative cooling is designed. Utilising of the open landscape and sea breeze together with man-made solution to improve the opportunity for ventilative cooling are important to use. In new projects, where open landscapes or area with water are nearby, this is easy to utilise. In case of renovation the opportunity to change or use the surroundings is limited. In urban sites it is important to analyse the impact on wind conditions cause by nearby buildings. Neighbouring buildings might change the wind directions or even shelter the building from direct wind exposure and thereby the decrease the VC potential.

An analysis of the site is always necessary to figure out the optimal location of the openings in the building for ventilative cooling. Furthermore, the location of ventilation openings is affected by the chosen ventilation principle. In the observed buildings it was noticed that ventilation inlet openings are located close to the ceiling. This is done to minimise the risk of draft and user interaction with the ventilation system. To increase the user satisfaction with the indoor climate, manual control possibility is available in most of the buildings. The exception is kindergartens and some public buildings where unauthorised users might disturb the performance of ventilation system.

Furthermore, the form and morphology needs to be considered when working on the design of new buildings that are designed for ventilative cooling. Buildings with rectangular multi-story form are desired for implementing ventilative cooling. In many cases, especially big quadric-formed buildings, an atrium is located in the middle. An atrium provides the possibility of ventilative cooling with different ventilation principles and a good daylight together with open spaces for the users. In recent projects it is observed that open plan office type is widely used, as the performance of ventilative cooling is more stable due to less resistance in airflow paths. Furthermore open planning allows to use multiple ventilation principles. Cellular offices are more present in the renovation cases, which set limits on choice of ventilation principle.

Depending on particular building, different ventilation principles are feasible. Stack ventilation is mainly used as the main ventilation principle in new projects, whereas single sided and cross ventilation are more used in renovation projects. Depending on which ventilation principle is chosen, the openings for inlet and outlet have to be placed in appropriate way. It can also be seen that hybrid ventilation principle is widely used in ventilatively cooled buildings in Denmark. This ventilation principle secures a stable performance of the ventilation system in all weather conditions.

Case Study - Aarhus Municipality 6

In order to estimate the VC potential by different tools in the next part of the project, a study case is selected. This building is chosen on the basis of the analysed buildings with ventilative cooling in Denmark for the *IEA EBC Annex 62 Ventilative Cooling* project. All the analysed cases can be seen in table 3.1 on page 12, or in the building descriptions in the Appendix CD under *Building Descriptions*.

A number of criteria were determined by the project group to decide which low-energy building to work with. First of all, the building should be relatively new and meet the requirements of Danish building regulations. Thereby, a low energy use is secured together with good indoor climate, which still are important factors when we talk about ventilative cooling. Furthermore, there is an opportunity that ventilative cooling has already been taken into account during the design phase, thus resulting in optimal, well-functioning HVAC system at the end. To simplify the further work and obtain trustworthy results, a simple building geometry is desired. To reduce the uncertainties caused by the simplification of building geometry, a rectangular or quadric multi-storey building is preferred. The reason why it could be interesting to work with a multi-story building is the investigation of differences in indoor climate between different floors.

Finally, it is desired to work on a case, where WindowMaster has implemented a ventilation system, which is controlled by so far the most advanced natural ventilation control system (NV Advance^{TM}). The NV Advance^{TM} control system logs data, which means that the historical data regarding the system performance and energy use, as well as the indoor climate parameters such as indoor air temperature, relative humidity and the CO_2 concentration at a certain time are logged, so no indoor climate measurements are required. However, the extraction of these data involves getting a sanction from WindowMaster and the building owner. The data will be used for validation of a BSim model.

The building that attracted our attention while working on the description of naturally cooled buildings was the Aarhus municipality building. It attracted our attention because it is the first zero energy office building in Denmark. Besides having well insulated envelope by the use of progressive vacuum-insulation materials, it also produces electricity and heat by the use of solar energy. It has been commissioned in 2012 so it can be considered as relatively new building. Moreover, since it has been occupied for the last two years, the data from building management system (BMS) are available. It is a multi-storey building with relatively simple geometry and internal layout which means that accurate building model in the simulation program can be made. The challenge in modelling of this particular building would be the implementation of various HVAC systems in the simulation as the building is equipped with numerous energy production systems. More detailed description of Aarhus municipality building is presented in the following sections.

6.1 Aarhus Municipality

The new office building of Aarhus Kommune at Grøndalsvej in Viby near Aarhus is the first zero energy office building in Denmark. It was decided that the new building for *Center for Environment and Energy* together with a division for *Social Relationship and Employment*, should consume 50 % less energy than buildings under category *Low Energy 2015*. This building category allows the energy use for heating, cooling, ventilation, domestic hot water and lightning below: (41+1000/A) [$kWh/m^2.per.year$], where A is the heated floor area. This drastic reduction of building energy demand resulted in a zero energy office building made by the contractor *E. Phil & Søn*. It is characterised as a demonstration project, to show that it is possible to build a functional zero energy office building. [Aarhus Kommune] The building is shown on figure 6.1

Figure 6.1. External view of the office building. [Schmidt/Hammer/Lassen architects]

Form, Envelope and Layout
The new building is an independent complex consisting of two parallel three-storey rectangular buildings with a total floor area of 6286 m^2. New building segments are interconnected by three tower buildings, see figure 6.2 on the facing page, consisting of elevators, floors, toilets and technical rooms.

The total share of the glazed facades is 38 %. High amount of glass often leads to problems with a too high transmission losses (U-value), but in this case, by the use of a special vacuum insulation and energy-efficient windows, the U-value of the facades below 0.9 was obtained. The building load bearing function is ensured by reinforced concrete framework. By the use of polyurethane thermo-panels with increased insulating properties (U-value of 0.023 $W/m^2 \cdot K$) it was possible to reduce the overall thickness of the external walls. Outer layer of the facades is covered with green glazed facade plates made of recycled glass, which forms the architectural appearance of the building, see figure 6.3 on the next page

Figure 6.2. External view of the space between the buildings (courtyard). The part to the right is the tower that connects the different buildings. [Schmidt/Hammer/Lassen architects]

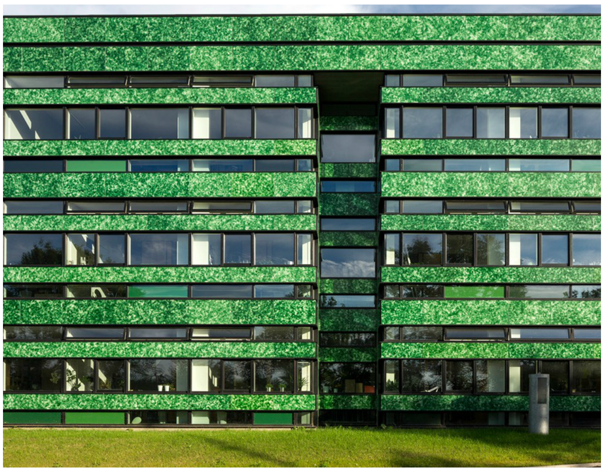

Figure 6.3. Green glazed facade in Aarhus. [Schmidt/Hammer/Lassen architects]

The internal layout of the building is designed as a cellular plan office with internal walls made of tempered laminated glass together will small areas with open offices for 3-4 persons. The walls appear as uncut surfaces in the long corridors, and secure a good daylight in all parts of the building. Special transparent sound insulation H-connectors placed between the glazed wall elements are used to minimise the disturbance coming from the corridors. The internal glazed walls and a typical office are shown on figures 6.4 and 6.5.

Figure 6.4. Internal corridors.

Figure 6.5. One person office.

Building Systems

During the design process of a zero energy building a lot of sustainable energy systems have to be added and integrated into the building, which can also be observed in the new office building. First of all, total annual electricity consumption of the building is covered by $1100\,\mathrm{m}^2$ solar cells placed on the rooftop. In addition, $420\,\mathrm{m}^2$ of solar thermal collectors are used to generate the hot water to run absorption cooling during the summer and to heat up water (heating and domestic hot water). Ventilative cooling with both mechanical and natural techniques (hybrid) are applied to cool down the building. The absorption cooling principle is used to secure an acceptable indoor temperature when the outdoor temperature is too high to apply natural cooling strategy. Natural single sided ventilation is the main ventilation principle. Cross ventilation is used in some cases, and appears when the office doors along both sides of the central corridor are open. Night time ventilation is used when the ventilation during the day is not efficient enough to secure a desired thermal conditions. Rain water is used for flushing the toilets and outdoor sprinkling.

Ventilative cooling is controlled by NV Advance$^{\mathrm{TM}}$ control system from WindowMaster that is integrated into the BMS system of the building. The system is controlled on the basis of measured data of the internal and external temperature, indoor humidity and CO_2-level, precipitation, wind speed and direction. By continuously analysing the input data, the controller sends signals to linear chain actuators to open or close the ventilation openings. To pre-calibrate the controller a CFD-analysis of 16 different wind directions for the building was made by WindowMaster to obtain the wind pressure coefficients (C_p) on each opening with regard to different wind directions. This wind analysis was required to make sure that each particular window is opened at the optimum position according to actual wind speed and direction. Besides this advanced automatic control system, it is also possible for the users to control the systems manually for different zones using a simple user-friendly interface at their computers. The user can set a desired indoor temperature, which means that different set points can be used for each office. The users can also control the external solar shading, which also has a huge influence on the daylight level in the office. The top band windows, which are opened automatically in proportion to the indoor temperature and CO_2-level, are regulated by BMS by changing the opening area.

6.2 Initial Case - 3 Person Office

The case study, which will be used for evaluation of the VC potential tools, is a 3 person office. This kind of office is common for the building in Aarhus, and is thereby interesting to look at. Furthermore, the internal heat loads are high because of the high number of people and electrical equipment, which often results in high cooling demand during the summertime. Different sizes of a 3 person office can be found in the building, but the office with internal volume at $78.2\,\mathrm{m}^3$ and with internal dimension $2.8\,\mathrm{m} \times 3.99\,\mathrm{m} \times 7\,\mathrm{m}$ (height $\times$ width $\times$ depth) is used for the calculation. Three persons occupy the office from 08.00 - 17.00 except during the weekends. During the summer vacation (week 26-35) only two person is occupying the office.

The desired indoor temperature comfort zone is 20-26 °C. This means that heating set point ($T_{i,hsp}$) is 20 °C and the cooling set pint ($T_{i,csp}$) is 26 °C respectively. The exact values used for the loads (people, equipment and sun) are taken from the results from the BSim model, which is described and used later on in chapter 10 on page 77, *BSim Simulations for Validation of VC Tools*.

The minimum ACR is calculated by [Dansk Standard, 2007]:

$$\dot{m}_{min} = 3\,\text{pr} \cdot 7\,\text{l/s/person} + 27.93\,\text{m}^2 \cdot 0.7\,\text{l/s/m}^2$$
$$= 40.55\,\text{l/s} = 1.9\,\text{h}^{-1}$$

The maximum ACR for natural ventilation is set to $76.03\,\text{l/s} = 3.5\,\text{h}^{-1}$, according to the information about the existing ventilation system in the building [Grontmij, 2011].

Construction elements

In table 6.1 the different construction elements and their properties for the 3 person office are presented.

Construction element	Material	e $[mm]$	c_p $[kJ/kg.K]$	ρ $[kg/m^3]$	λ $[W/m.K]$
Opaque partition walls	Plasterboard	25	1	881	0.2
	Insulation	50	0.8	16	0.039
	Plasterboard	25	1	881	0.2
Transparent partition walls	Glass panels	10	0.9	2600	0.8
Slab	Plasterboard	10	1	881	0.2
	Concrete	160	0.8	2385	1.6
	Carpet	5	1.8	283	0.06
Facade	Glass wool	50	0.8	16	0.039
	Glass wool	40	0.8	25	0.039
	Glass wool	50	0.8	16	0.039
Roof	Plasterboard	14	1	881	0.2
	Stone wool	50	0.8	32	0.039
	Airspace	450	0.1	500	3.75
	Concrete	270	0.8	2400	2.1
	Stone wool	450	0.8	100	0.04
	Bitumen felt	1	1	1700	0.5

Table 6.1. Construction elements and material parameters.

Windows

Two different window types are used in the office. One type is used for the upper and middle band in the facade and another for the lower band. The parameters for the windows are presented in table 6.2.

Glazing characteristics	Upper and middle band	Lower band
g-value [-]	0.49	0.15
Light transmittance coefficient [-]	0.71	0.26
U-value $[\text{W/m}^2 \cdot \text{K}]$	0.64	0.64

Table 6.2. Glazing data.

This initial case will be used for estimation of VC potential by different simple tools in the following part.

Part II

Simple Predesign Tools for VC Potential

In this part two simple VC potential estimation tools are presented and analysed - EURAC VC potential tool and 5R1C-model. These tools are meant to be used in estimating the VC potential of naturally ventilated buildings during the preliminary design phase. Aarhus municipality's new office building is selected from the previously made naturally cooled building database to serve as a study case, which is then used in initial testing and validation process of the tools. Simulations by BSim are used to investigate the reliability of the estimated VC potential by the two tools. Finally, the results from the VC potential tools and BSim are compared and one VC potential tool is selected for further investigation and robustness analysis.

EURAC - Ventilative Cooling Potential Tool 7

This tool is based on the climate suitability analysis technique originally introduced by [J. Emmerich et al., 2011] and further developed by [Belleri, Annamaria (EURAC)]. It is intended to be used during the early design phase to get the first estimate of the potential for ventilative cooling. The potential of VC is evaluated by taking into consideration the information regarding internal heat loads and local climate conditions. It calculates the ventilation rate needed to offset the internal heat loads by means of direct ventilative cooling, as well as assess the potential of VC in cases when direct ventilative cooling is not able to remove the heat loads during the day.

7.1 Theory

The theory behind this tool is based on establishing an energy balance of the building, which is considered to be a single-zone where the temperature inside is equally distributed. The energy balance of dynamic single-zone model can be calculated as follows

$$K \cdot T_i + M \cdot \frac{dT_i}{dt} = E \tag{7.1}$$

$$K = \sum U \cdot A + \dot{m} \cdot c_p \tag{7.2}$$

$$E = K \cdot T_e + q_{in+s} \tag{7.3}$$

Where:

K	Combined conductive and ventilative heat transfer coefficient [W/K]
E	System excitation [W]
T_e	Outdoor air temperature [K]
T_i	Indoor air temperature [K]
q_{in+s}	Indoor heat loads plus solar heat loads [W/m^2]
M	Internal thermal mass [J/K]
$\sum U \cdot A$	Thermal conductance of the building envelope [W/K]
$\dot{m}$	Mass flow rate of ventilation air [kg/s]
c_p	Specific heat capacity [J/kg $\cdot$ K]

In case when internal thermal mass (M) is insignificant and thereby can be neglected or the indoor air temperature (T_i) is relatively constant, the heat accumulation term in equation 7.1 on the preceding page becomes so small that it can be neglected. Under this assumption the building's response to change in thermal loads can be simplified to steady-state case as follows:

$$K \cdot T_i = E \tag{7.4}$$

This steady-state formulation is the basis for approximation of the ventilative cooling potential for certain building in specific climate. This formulation is further expanded with the concept of heating balance point temperature of the external air at which the total internal heat loads are removed from the building by means of conductive and ventilative heat losses.

$$K(T_{i,hsp} - T_{o,hbp}) = q_{in+s} \tag{7.5}$$

Where:

$T_{i,hsp}$	Internal heating set point [K]
$T_{o,hbp}$	Heating balance point temperature [K]

By solving equation 7.5 for $T_{o,hbp}$ and expanding it by defining the value of K as in equation 7.2 on the preceding page:

$$T_{o,hbp} = T_{i,hsp} - \frac{q_{in+s}}{\dot{m}_{min} \cdot c_p + \sum U \cdot A} \tag{7.6}$$

Where:

$\dot{m}_{min}$	Minimum required mass flow rate [kg/s]

The minimum required mass flow rate is determined based on the requirements found in the indoor air quality standards. [Dansk Standard, 2007]

7.2 Tool Description

The heating balance point temperature $T_{o,hbp}$ represents the balance between heating and cooling. In order to ensure that the indoor temperature does not drop below the internal heating set point ($T_{i,hsp}$), the building needs to be heated when the outdoor air dry bulb temperature ($T_{o,db}$) drops below $T_{o,hbp}$. In periods when $T_{o,db}$ is larger than $T_{o,hbp}$ direct ventilative cooling can be applied to offset the internal heat loads so that the indoor air temperature does not exceed the cooling set point temperature ($T_{i,csp}$). If $T_{o,db}$ rises above the $T_{i,csp}$, direct ventilative cooling is no longer useful to maintain the indoor thermal comfort and the application of NTV has to be considered.

Based on the hourly values of climatic data at defined site location the tool splits the total number of hours per year into following groups:

- **VC mode [0] - Ventilative cooling not required** when the outdoor dry bulb temperature is lower than the heating balance point temperature.

  $T_{o,db} < T_{o,hbp} \rightarrow \dot{m} = 0$

  It is assumed that heating is needed during this period and mechanical ventilation with heat recovery is used instead of natural ventilation.

- **VC mode [1] - Ventilative cooling with minimum ACR** when the outdoor dry bulb temperature lies in between the heating set point temperature and the comfort zone. The comfort zone is defined as the difference between the internal cooling and heating set point temperatures ($T_{i,csp} - T_{i,hsp}$).

  $T_{o,hbp} \leq T_{o,db} < T_{o,hbp} + (T_{i,csp} - T_{i,hsp})$

  In addition, the outdoor dew point temperature must be higher than 17 °C (or 65 % RH) to avoid moisture related problems.

  $T_{o,dp} > 17\,°C$

  Under this condition the mechanical ventilation with heat recovery is replaced with natural ventilation at minimum required ventilation rate for atmospheric comfort that is specified in standards [Dansk Standard, 2007].

  $\dot{m} = \dot{m}_{min}$

- **VC mode [2] - Ventilative cooling with increased ACR** when the outdoor dry bulb temperature is within the range of comfort zone temperatures.

  $T_{o,hbp} + (T_{i,csp} - T_{i,hsp}) \leq T_{o,db} \leq T_{i,csp}$

  The outdoor dew point temperature must be higher than 17 °C (or 65 % RH) to avoid moisture related problems.

  $T_{o,dp} > 17\,°C$

  The ventilation rate required to maintain the indoor air temperature within the comfort zone is calculated as follows:

  $$\dot{m} = \frac{q_{in+s}}{c_p \cdot (T_{i,csp} - T_{o,db})}$$

- **VC mode [3] - Ventilative cooling is not useful** when the outdoor dry bulb temperature is larger than the cooling set point temperature or dew point temperature is below 17 °C (or 65 % RH).

  $T_{o,dp} > T_{i,csp}$ or $T_{o,dp} < 17\,°C$

  Under this condition the direct ventilation is not useful and night time ventilation potential during the following night is considered instead.

  $$NCP = \frac{H \cdot \rho \cdot c_p \cdot (T_{i,csp,night} - T_{o,db})}{3600}$$

Where:

NCP	Night time cooling potential $[\mathrm{W/m^2 \cdot ach}]$
H	Floor height [m]
ρ	Density $[\mathrm{kg/m^3}]$
$T_{i,csp,night}$	Cooling set point temperature at night [K]

5R1C-model 8

Another way of calculating the potential of ventilative cooling in the early design phase is the calculation of dynamic heat balance for the chosen room or building. This is the main idea of the 5R1C-model. The following part describes how to set up the equations to calculate the heat balance of the room [Steen-Thøde et al., 2001].
The heat capacity of a building is an important parameter to consider when the heat balances are evaluated under dynamic conditions. This is the main difference of the 5R1C-model in comparing to previously described calculation approach used by the *EURAC VC potential tool*. The heat capacity evens out large variations of the indoor temperature under varying heat loads, and is therefore an important part of the heat balance. This means that added energy must be equal to the losses and energy accumulated in building structures. The dynamic heat balance can be used to calculate the varying indoor temperature as a result of varying outdoor and indoor conditions. These temperatures can be used for estimation of VC potential.

8.1 Theory

The main idea of the heat balance is to calculate the amount of heat that enters and leaves the room. By taking some small assumptions it becomes possible to simplify the calculation, and thereby make this method easier to apply. However, to get realistic and reasonable results, the calculation must not be simplified too much. The main indoor thermal climate parameter is the room temperature, which is calculated based on the indoor air and surface temperatures. These temperatures, must be calculated several times under dynamic conditions. This means that three different heat balances can be set up. One for the indoor air, one for indoor surfaces and one for thin layers in the wall, ceiling and floor where the accumulative layer is located. Temperature in the accumulative layer for each construction element, T_m, is assumed to be the same, which also is valid for the internal surface temperatures, T_{si}. This gives three heat balances with three unknown temperatures:

- Internal air temperature, T_{air}
- Internal surface temperature, T_{si}
- Accumulative layers temperature, T_m

An illustration of the calculation principles is shown in figure 8.1 on the next page. The different parameters seen in the figure are described in the following.

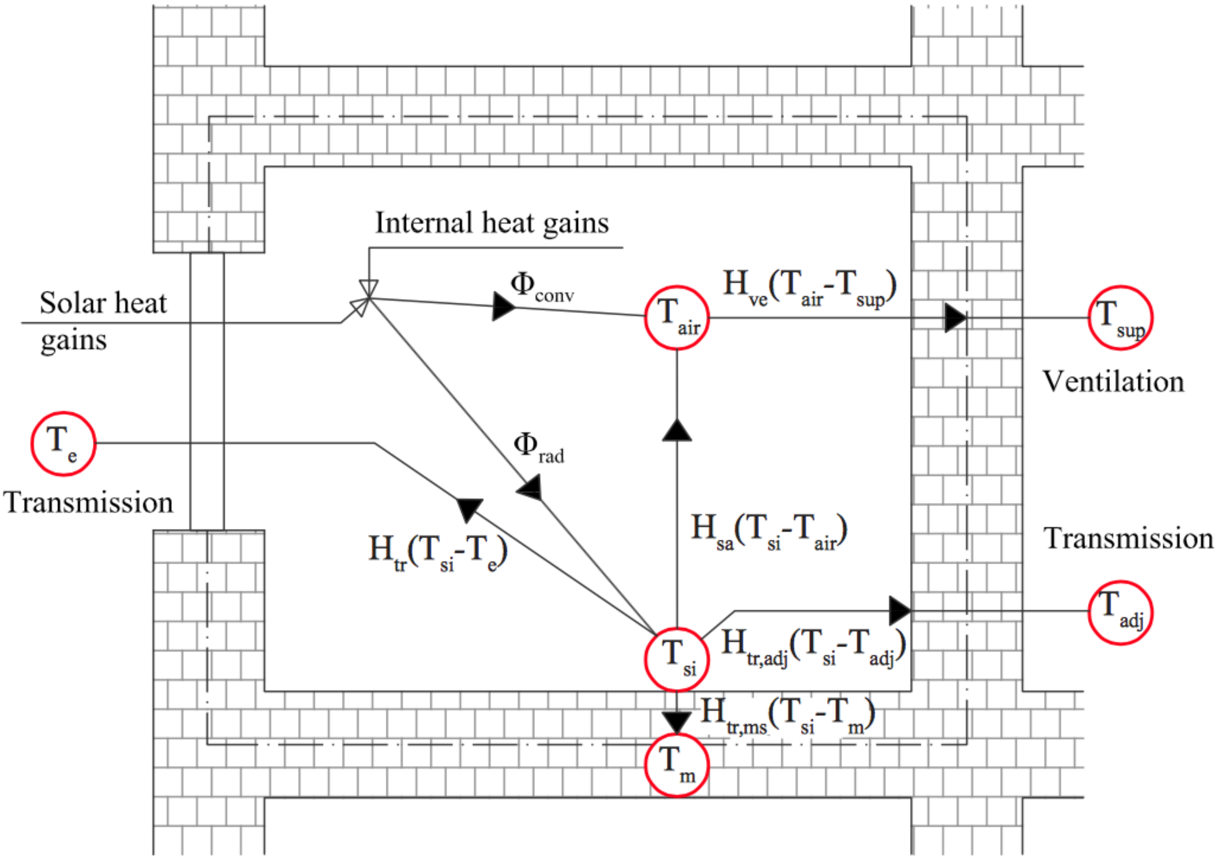

Figure 8.1. Simple sketch of the calculation method. [Steen-Thøde et al., 2001] - modified

Room Air Heat Balance

The heat balance for indoor air consists of added convective heat loads, ventilation loss due to different internal and external temperatures and heat transfer between room air and internal surfaces. This can be expressed by following equation:

$$\Phi_{conv} + H_{sa} \cdot (T_{si} - T_{air}) = H_{ve} \cdot (T_{air} - T_{sup}) \tag{8.1}$$

Where:

Φ_{conv}	Convective heat loads [W]
H_{sa}	Specific heat transfer between room air and internal surfaces [W/°C]
H_{ve}	Specific heat loss by ventilation [W/°C]
T_{si}	Internal surface temperature [°C]
T_{air}	Internal air temperature [°C]
T_{sup}	Supply/external air temperature [°C]

Φ_{conv} is equal to one half of the internal heat loads, which are varying during the day. This is the sum of heat gains from people and equipment.

H_{sa} is different for the horizontal and vertical surfaces depending on the convective transition number, α. The value of α is 3.3 W/m$^2 \cdot ^\circ$ C for vertical and 2.3 W/m$^2 \cdot ^\circ$ C for horizontal surfaces.

It is calculated by the following equation.

$$H_{sa} = \Sigma \alpha \cdot A$$

Where:

α	Convective transition number [W/m$^2 \cdot^\circ$ C]
A	The area of each construction element (wall, roof and ceiling) [m^2]

H_{ve} is dependent on the amount of ventilation both natural and mechanical. The specific heat loss by ventilation is calculated by:

$$H_{ve} = \dot{m} \cdot c_p$$

Where:

$\dot{m}$	Mass flow rate of ventilation air [kg/s]
c_p	Specific heat capacity [kJ/kg $\cdot^\circ$ C]

Surface Heat Balance

In this situation the surface heat balance consists of the radiative heat gains, losses from the surfaces to the other rooms and to the outdoor, together with heat losses to the indoor air and to the accumulative layer. This can be expressed by following equation:

$$\Phi_{rad} = H_{tr} \cdot (T_{si} - T_e) + H_{tr,adj} \cdot (T_{si} - T_{adj}) + H_{sa} \cdot (T_{si} - T_{air}) + H_{tr,ms} \cdot (T_{si} - T_m) \quad (8.2)$$

Where:

Φ_{rad}	Radiative heat loads [W]
H_{tr}	Specific heat loss by transmission through building envelope [W/°C]
$H_{tr,adj}$	Specific heat loss by transmission to adjacent rooms [W/°C]
$H_{tr,ms}$	Specific heat loss between internal surface and thermal mass [W/°C]
T_e	External air temperature [°C]
T_{adj}	Adjacent room temperature [°C]
T_m	Thermal mass temperature [°C]

Φ_{rad} is equal to half of the internal heat loads and the total amount of heat from the sun, which enters the room.

H_{tr} and $H_{tr,adj}$ are calculated by the same equation, but each is dependent on its own U-value.

$$H_{tr,adj} = H_{tr} = \Sigma U \cdot A$$

Where:

U	Heat transmission coefficient for each construction element [W/m$^2 \cdot^\circ$ C]

In this case it is assumed that there are no transmission losses to the adjacent rooms. Since only one room will be looked at a time, and it is presumed that the adjacent rooms have the same room temperature.

The accumulative layer is placed in a thin layer in the construction. $H_{tr,ms}$ is found using the same procedure as for the loss to the adjacent rooms and outdoor.

$$H_{tr,ms} = \Sigma U_a \cdot A$$

Where:

U_a	Heat transmission coefficient from the surface to the accumulative layer [W/m$^2 \cdot ^\circ$ C]

Accumulative Layer Heat Balance

The last heat balance is for the accumulative layer. In this case the heat capacity of the thermal mass of the room is taken into account. The heat balance becomes:

$$H_{tr,ms} \cdot (T_{si} - T_m) = S \cdot \frac{dT_m}{d\tau} \tag{8.3}$$

Where:

S	Thermal heat capacity of the room [kJ/kg $\cdot^\circ$ C]
τ	Time step [h]

Only layers between the surface and the accumulative layer are taken into account, when calculating the total heat capacity of a construction element. In general, only the inner 0.1 m for heavy construction materials should be used, and 0.05 m for light construction materials. S is calculated as follows:

$$S = c \cdot \rho \cdot A \cdot e$$

Where:

c	Heat capacity [kJ/kg $\cdot^\circ$ C]
ρ	Density [kg/m^3]
e	Thickness [m]

As mentioned in the beginning, the three unknowns are temperature in accumulative layer (T_m), suface temperature (T_{si}) and internal air temperature (T_{air}). The way to calculate these unknown temperatures is illustrated in figure 8.2 on the facing page. This figure is basically a simplification of figure 8.1 on page 62.

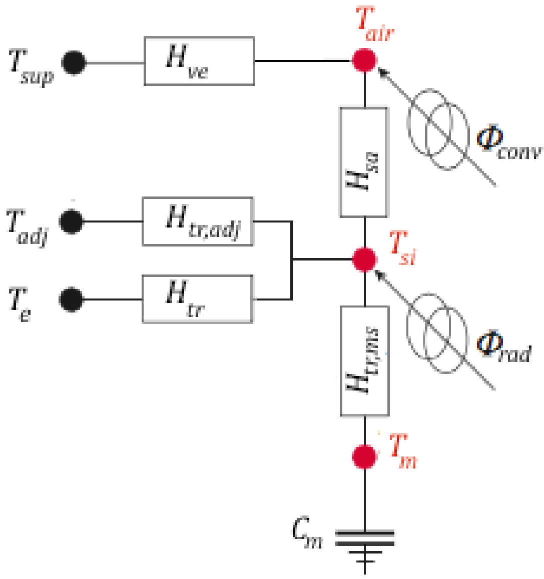

Figure 8.2. 5R1C-scheme for heat balances calculations.

At first, the temperature in the accumulative layer (T_m^n) is calculated. This is possible if the temperatures from the previous time step are known (T_{air}^{-1} and T_{si}^{-1}). When the temperature of the accumulative layer is known, it is possible to calculate the surface temperature (T_{si}^n). The transmission loss from surface to accumulative layer ($H_{tr,ms}$) must be included together with transmission losses to outdoor and adjacent rooms (H_{tr}, $H_{tr,adj}$). Furthermore radiative heat loads are also used for this calculation. Finally, the internal air temperature, T_{air}^n can be calculated. Transmission loss due to ventilation (H_{ve}^{n-1}), transmission loss between surface and air (H_{sa}) and convective heat loads must be included. C_m illustrates the thermal mass of the building/room (capacitance). This calculation will be done for each time step to find the internal air temperature during the entire year.

The three energy balances are:

$$\Phi_{conv} + H_{sa} \cdot (T_{si} - T_{air}) = H_{ve} \cdot (T_{air} - T_{sup})$$

$$\Phi_{rad} = H_{tr} \cdot (T_{si} - T_e) + H_{tr,adj} \cdot (T_{si} - T_{adj}) + H_{sa} \cdot (T_{si} - T_{air}) + H_{tr,ms} \cdot (T_{si} - (T_m)$$

$$H_{tr,ms} \cdot (T_{si} - T_m) = S \cdot \frac{dt_a}{d\tau}$$

These three equations can be rearranged, so that the unknowns can be calculated.

$$T_m^n = a_1 \cdot T_m^{n-1} + a_2 \cdot T_{si}^{n-1} \tag{8.4}$$

$$T_{si}^n = b_1 \cdot T_m^n + b_2 \cdot T_{adj}^n + b_3 \cdot T_e^n + b_4 \cdot T_{sup}^n + b_5 \cdot \Phi_{conv} + b_6 \cdot \Phi_{rad} \tag{8.5}$$

$$T_{air}^n = c_1 \cdot T_{si}^n + c_2 \cdot T_{sup}^n + c_3 \cdot \Phi_{conv} \tag{8.6}$$

Where:

$$a_1 = 1 - \frac{H_{tr,ms} \cdot \delta\tau}{S}$$
$$a_2 = 1 - a_1$$
$$b_1 = \frac{H_{tr,ms}}{H_{tr,ms} + H_{tr,adj} + H_{tr} + \frac{H_{sa} \cdot H_{ve}}{H_{sa} + H_{ve}}}$$
$$b_2 = b_1 \cdot \frac{H_{adj}}{H_{tr,ms}}$$
$$b_3 = b_1 \cdot \frac{H_{tr}}{H_{tr,ms}}$$
$$b_4 = 1 - b_1 - b_2 - b_3$$
$$b_5 = b_1 \cdot \frac{c_1}{H_{tr,ms}}$$
$$b_6 = b_1 \cdot \frac{1}{H_{tr,ms}}$$
$$c_1 = \frac{H_{sa}}{H_{sa} + H_{ve}}$$
$$c_2 = 1 - c_1$$
$$c_3 = c_1 \cdot \frac{1}{H_{sa}}$$

At first, different room constants ($H_{tr,ms}, H_{ve}, H_{sa}, H_e$ and S) are calculated, and the time constant, $\delta\tau$, is determined, to solve the equations above. a_2 must be less than 0.1 to ensure accuracy of the calculation. Subsequently, a timetable with all the varying input parameters ($\Phi_{conv}, \Phi_{rad}, T_e, T_{sup}$ and T_{adj}) is set up. The external air is used as supply air in the calculation, which means that $T_e = T_{sup}$. T_{adj} is not taken into account, because of the assumption that there is no heat transfer between the different rooms because of equal temperature. Finally, the initial values for the unknown temperatures are set to a realistic value and T_m, T_{si} and T_{air} can be calculated for each time step.

To calculate the ventilation loss (H_{ve}) the needed airflow must be calculated. By the use of the three heat balances and changing one of the unknowns (T_m, T_{si} and m_{needed}) it becomes possible to calculate the needed airflow. The earlier unknown (T_{air}) is set to the cooling set points (26 °C):

$$\begin{aligned}
&m_{calc} = \\
&-(S \cdot (H_{tr,ms} \cdot \Phi_{conv} + H_{sa} \cdot \Phi_{rad} + H_{sa} \cdot \Phi_{conv} + H_{tr} \cdot \Phi_{conv} - H_{tr,ms} \cdot H_{sa} \cdot T_{air} \\
&- H_{sa} \cdot H_{tr} \cdot T_{air} + H_{sa} \cdot H_{tr} \cdot T_e + H_{tr,ms} \cdot H_{sa} \cdot T_m^{n-1}) \\
&- (H_{tr,ms})^2 \cdot H_{sa} \cdot \tau \cdot T_m^{n-1} + (H_{tr,ms})^2 \cdot H_{sa} \cdot \tau \cdot T_{si}^{n-1})/ \\
&(S \cdot (H_{tr,ms} \cdot c_p \cdot T_e + H_{sa} \cdot c_p \cdot T_e + H_{tr} \cdot c_p \cdot T_e - H_{tr,ms} \cdot c_p \cdot T_{air} \\
&- H_{sa} \cdot c_p \cdot T_{air} - H_{tr} \cdot c_p \cdot T_{air}))
\end{aligned} \tag{8.7}$$

This calculated airflow will be used in calculation of the heat balances.

When the temperature variation during the year is calculated, it becomes possible, through different criteria, to investigate the potential for ventilative cooling. The following section gives a description of the tool made on behalf of these energy balances, to estimate the potential for ventilative cooling.

8.2 Tool Description

On the basis of theory described in the previous section and by application of VC mode selection principle from EURAC VC potential tool, a new VC potential tool is developed by the project group of this master thesis.

When the internal air temperature is calculated for each hour, the cooling potential can be estimated. However, at first a number of heat losses and loads have to be determined depending on the building/room. These parameters are listed in table 8.1.

Parameter		Unit
Heat capacity of the room	S	[kJ/kg $\cdot$° C]
Specific heat transfer between room air and internal surfaces	H_{sa}	[W/°C]
Specific heat loss by ventilation	H_{ve}	[W/°C]
Specific heat loss by transmission to outdoor	H_{tr}	[W/°C]
Specific heat loss by transmission to adjacent room	$H_{tr,adj}$	[W/°C]
Specific heat loss between internal surface and thermal mass	H_{ms}	[W/°C]
Convective heat gain	Φ_{conv}	[W]
Radiative heat gain	Φ_{rad}	[W]

Table 8.1. Input parameters

The calculations of all parameters are described in the previous section. Furthermore, the minimum and maximum ACR have to be defined to make sure that no unrealistic values are used later on in the calculations.

Desired indoor temperature comfort zone range is set to 20-26 °C. [Dansk Standard, 2001] This means that heating set point ($T_{i,hsp}$) is 20 °C and the cooling set point ($T_{i,csp}$) is 26 °C respectively.

The control strategy used in the 5R1C-model is illustrated in the flowchart in figure 8.3.

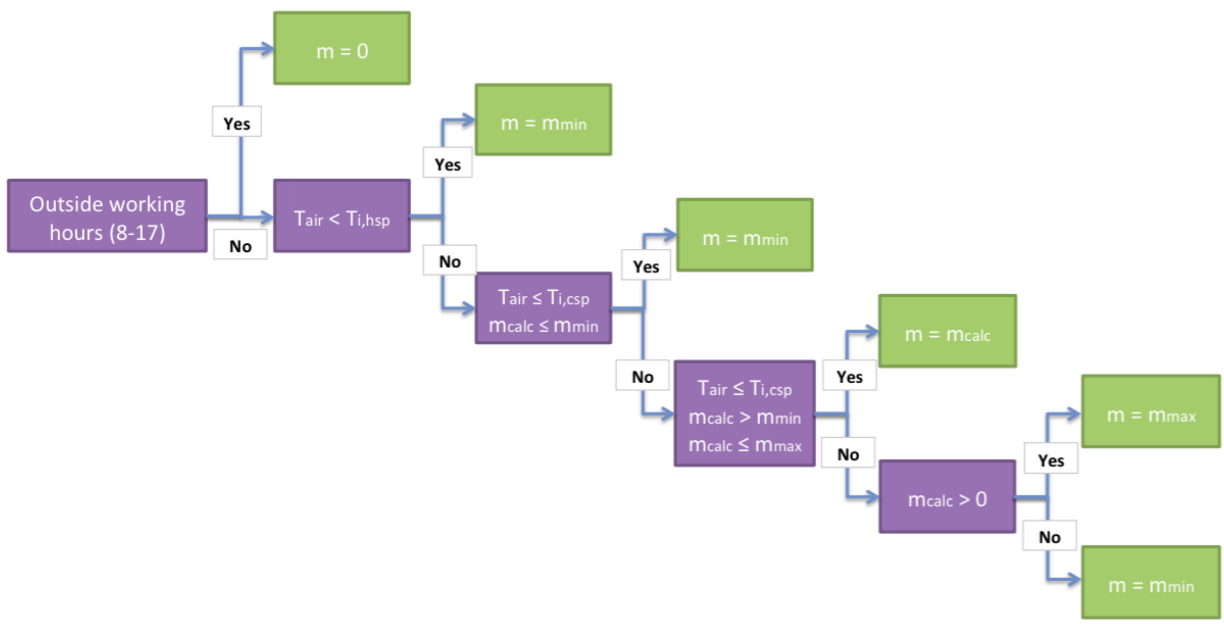

Figure 8.3. Control strategy 1.

First of all, ventilation is added for the calculation the entire year inside working hours. When T_{air} is below $T_{i,hsp}$ the room is ventilated with the minimum ACR for atmospheric comfort. This gives low internal air temperatures during the heating season because no heat recovery is implemented. This means that indoor temperatures below the heating set point indicates that heating is needed. It must be noticed that heating is not implemented in this calculation tool. When the internal air temperature is within the comfort zone and the calculated ACR is lower than the minimum ACR for atmospheric comfort, the minimum ACR is applied. In cases when the needed ACR is between the minimum and maximum ACR, the needed ACR is used. When the needed ACR exceeds the maximum ACR of the system, the maximum ACR will be used. When the calculated ACR is negative (external temperature is higher than $T_{i,csp}$), the room is ventilated with minimum ACR to maintain atmospheric comfort.

From May till September an ACR, which is equal to the infiltration ($0.046\,\mathrm{h}^{-1}$), is added during the night to secure that indoor temperature decrease. Furthermore, the VC system is enabled 2 hours before the occupation hours to decrease the temperature before the users arrive. During the heating season VC is not used during the night.

One of the criteria to ensure accurate results is a low time step of the calculation. Guidelines from literature states that coefficient $a_2 < 0.1$ [Steen-Thøde et al., 2001].

Based on calculated internal air temperature, each hour is divided between four VC modes to define the VC potential. The classification of VC modes is illustrated in figure 8.4.

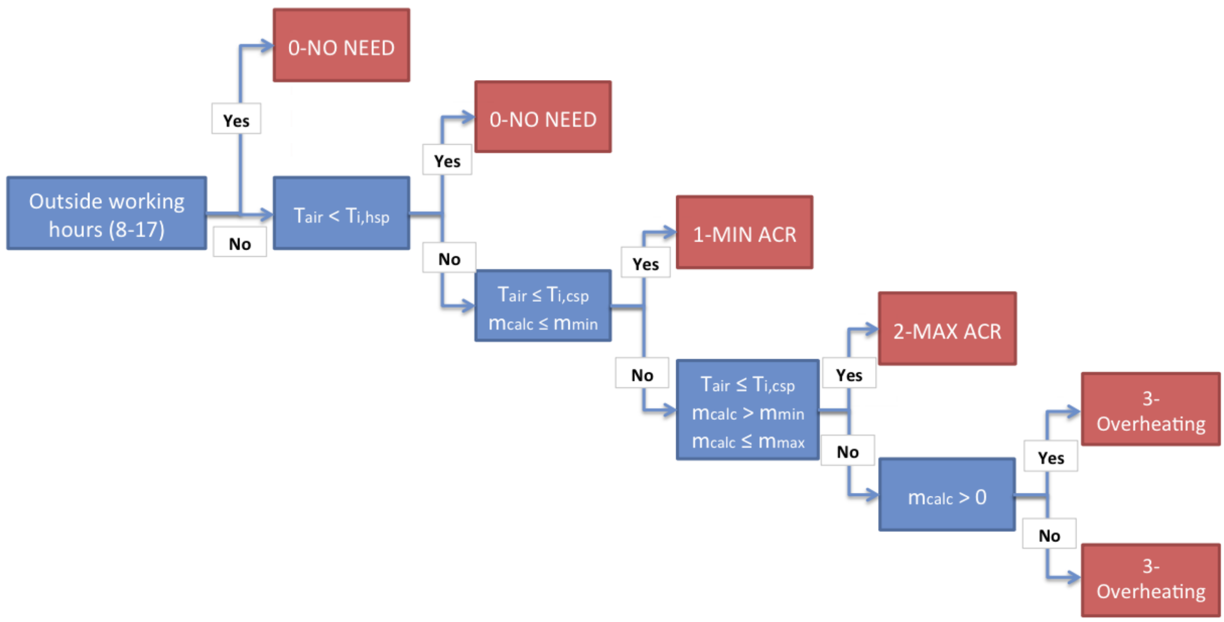

Figure 8.4. VC mode selection for control strategy 1.

- **VC mode [0] - No Need** (VC is not neded - mechanical ventilation with heat recovery)
- **VC mode [1] - Min ACR** (direct VC with ventilation rate maintained at the minimum)
- **VC mode [2] - Max ACR** (direct VC is useful)
- **VC mode [3] - Overheating** (direct VC is not useful; night time ventilation is considered)

Operative Temperature
When analysing the thermal comfort, it is preferable to look at the room temperature as a function of the operative temperature. In most cases the operative temperature is calculated as the mean air and radiant temperature. The room temperature sensor is one of the key components in controlling the VC system, and thereby an important part of heating and cooling systems. To obtain the best thermal comfort, the room thermostat should react in proportion to the operative temperature, which is the same temperature the users feel. Investigation of different sensors (type, color, etc.) shows that it is difficult to measure the precise operative temperature and thereby is it difficult to make sure that the system ensures the desired operative temperature [Simone et al., 2007].

In the 5R1C-model the surface temperature is assumed to be the same for all surfaces.

On the basis of this, it is decided to use the internal air temperature T_{air} in the investigation of the cooling potential. Therefore, internal air temperature will be used for further investigation.

Validation of BSim Model with BMS Data 9

The idea is to use BSim for validation of the two presented VC potential tools. Before this validation can be performed, the simulation tool has to be validated as well. This can be done by analysing the BMS data from selected case study, *Aarhus Municipality* and comparing it to results from BSim. By looking at the measured indoor temperatures, it was noticed that the most acute overheating problems occur on south side top floor of the building. Therefore, it was decided to develop a BSim model for this type of office. The geometry and input parameters are presented in Appendix C. The BSim model is named *Original* and can be found in the Appendix CD under *BSim models*.

Since data regarding external temperatures were not logged during some periods and BMS system did not measure the solar radiation, it was decided to use the new Danish DRY weather file for the BSim simulations. Therefore, it is expected that BSim simulation results will slightly differ from the ones extracted from the BMS. This is because the BMS data are a result of actual weather condition measurements at the building site during the last year (01.02.20014-31.01.2015), whereas the outdoor conditions in BSim are sampled based on the new Danish DRY weather file.

First of all, the data from BMS are analysed. To match with the initial BSim model only 3 person offices located on the top floor of the Aarhus municipality building are observed. In order to detect if there are any problems with overheating, the number of hours when indoor air temperature is above 26 °C and 27 °C is extracted from BMS data.

The results for top floor south side 3 person offices are listed in table 9.1.

Location	Zone	> 26 °C	> 27 °C
North	306	1	0
	307	1	0
	308	2	0
South	327	5	0
	328	24	3
	359	76	8
	360	66	19
	363	56	14

Table 9.1. Hours above 26 °C and 27 °C for the different 3 persons offices on top floor.

To find the overheating periods, the indoor temperatures from March till October are plotted, see 9.1. This is done for the control zone 360 and 363 were the most number of hours above 27 °C are measured.

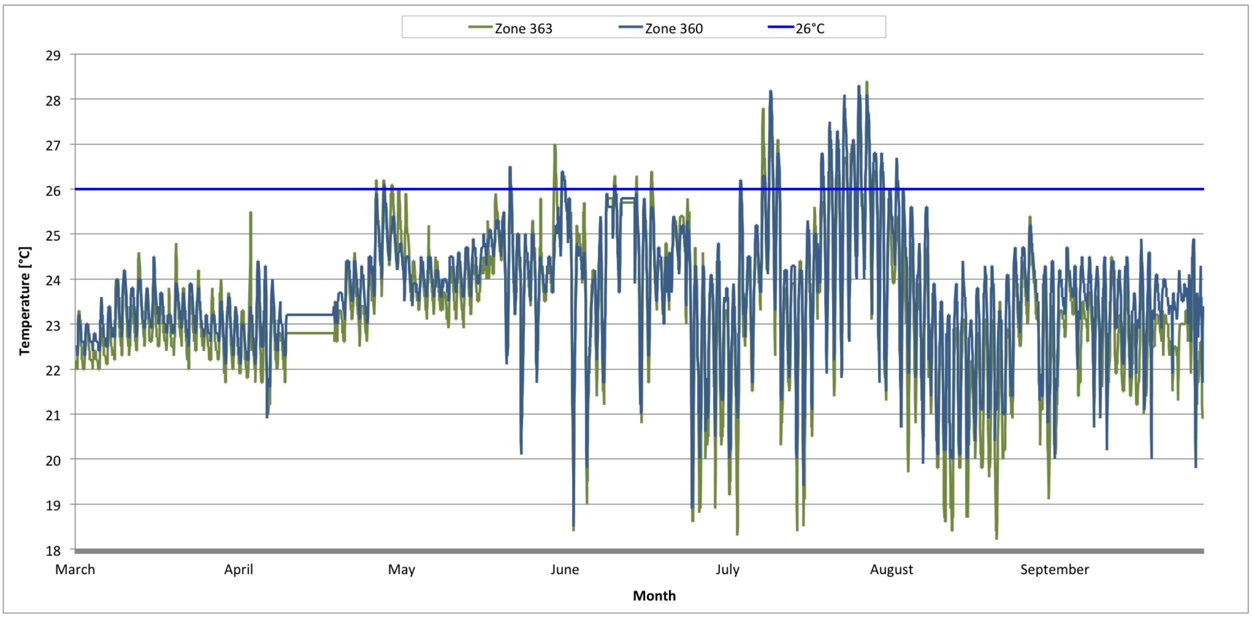

Figure 9.1. Indoor temperatures from March to October in WM zone 360 and 363.

Graph shows that overheating mainly occurred during the summer season (June and July). It was also observed that large part of the overheating period corresponds with the summer holidays (week 26 to 34).

The month where issues with room overheating occurred the most, is July, see figure 9.2.

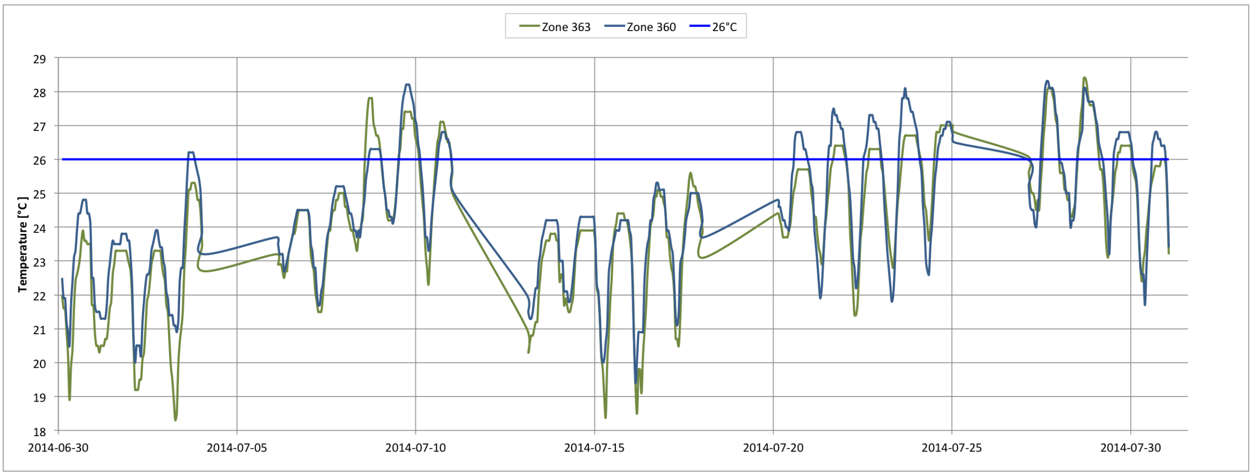

Figure 9.2. Indoor temperatures in July in south facing 3 person offices located on the top floor.

Indoor temperatures above 26 °C were observed during 12 out of the 23 working days. The highest indoor temperature of 28.4 °C was measured in WM zone 363 on the 29.07.2014 at 13:00. Typically, night cooling lowers the room temperature by 4 - 5 °C below the cooling set point. NTV it is stopped few hours before the occupation period starts and the heat stored in the building fabrics is then used to raise the room temperature up to the comfort zone.

For further analysis of thermal conditions in the selected room, a histogram with cumulative frequency graph is created. As the main focus of this project is on natural cooling, it was decided that it is more interesting to look at the room temperatures within working hours inside the cooling season (May - September). The results for WM zone 360, which has the highest amount of hours above 27 °C, are illustrated in figure 9.3.

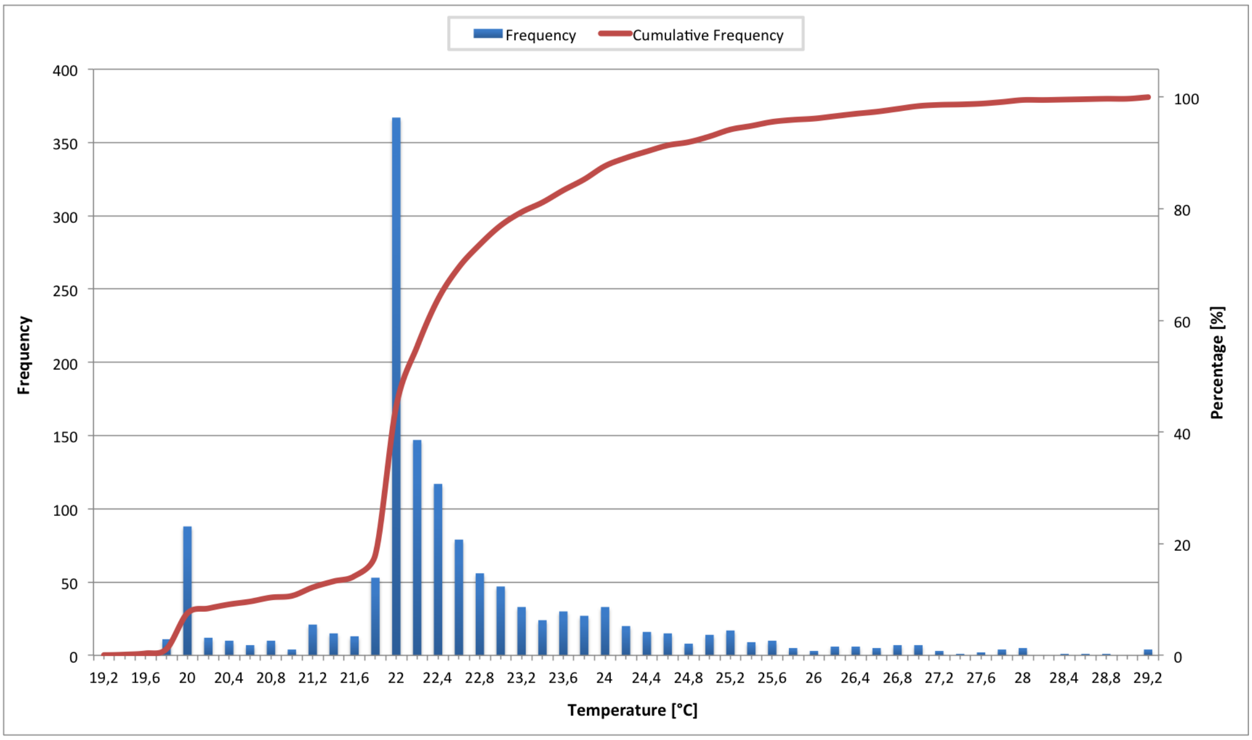

Figure 9.3. Indoor temperature histogram for zone 360 based on BMS data.

It can be seen from the figure above that the temperature of 22 °C occurs most frequently. This temperature is within the thermal comfort range in both (heating and cooling) seasons. It was also observed that room temperature is under 26 °C for 96 % and under 27 °C for 98 % of the time. This indicates that this room is not subjected to acute overheating.

The most critical situation was measured on the 28.07.2014 when the temperature in WM zones 360 and 363 was higher than the upper limit of the comfort range (26 °C) during most of the working hours. This is shown in figure 9.4 on the next page.

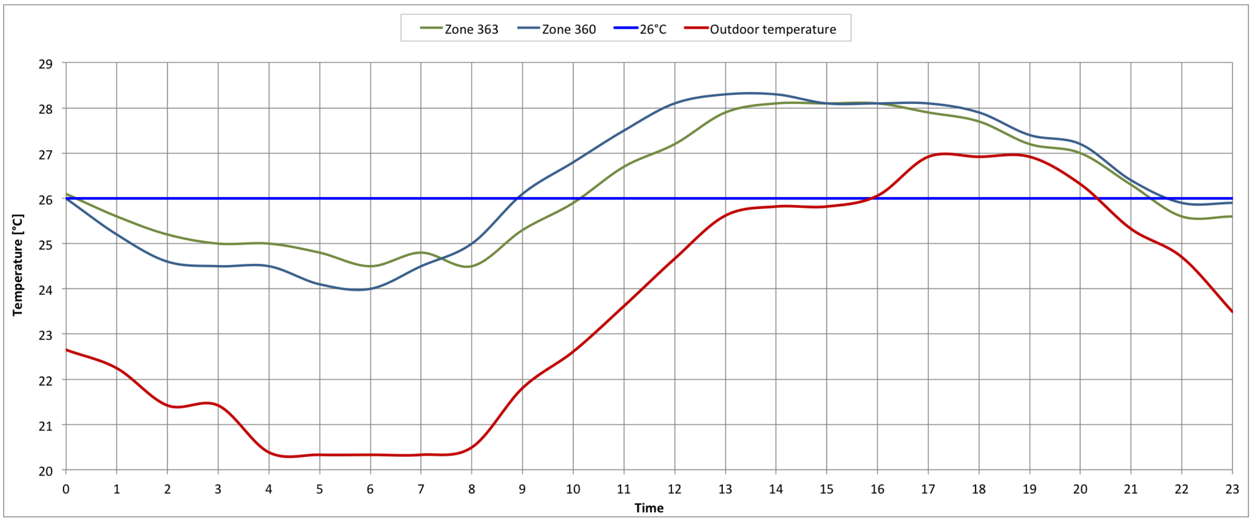

Figure 9.4. Indoor temperatures in 28^{th} of July from BMS data.

It can be seen in the graph above that the indoor temperature does not drop below 24 °C during the night. This is because of relatively high outdoor temperature during the night (20.4 °C) and the fact that the ventilation ACR is limited (maximum of $3.5\,\mathrm{h}^{-1}$) due to utilisation of single sided ventilation. The maximum possible ACR could be increased if cross ventilation was utilised.

The distribution of operating modes of the ventilation system for WM zones 360 and 363 is illustrated in figure 9.5.

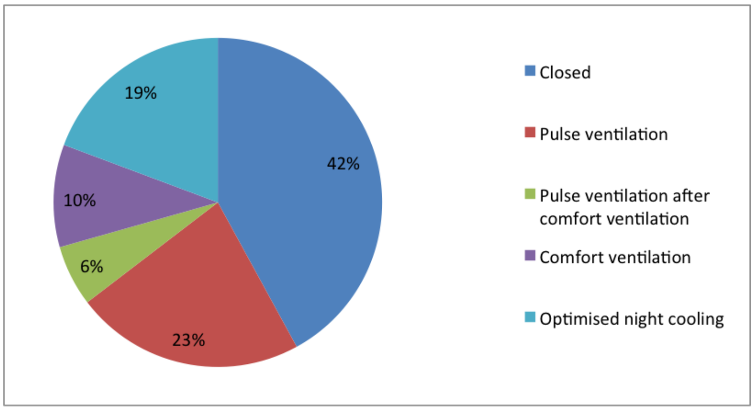

Figure 9.5. Annual distribution of ventilation modes (WM zones 359/360/363).

NTV plays an important role in cooling of the rooms as it is active 19 % of the time. It can also be seen that natural pulse ventilation is used 29 % of the time. In order to save the energy the ventilation is inactive 42 % of the time.

It can be observed in table 9.1 on page 71 that the most acute overheating problems occur in 3 person offices located the south side on the top floor. Zone 360 was selected for comparison with the BSim model. Description of the BSim model can be found in Appendix C on page 143. This room was chosen because it experienced the highest number of hours when the indoor temperature was above 27 °C and decent amount hours with indoor temperature above 26 °C. The comparison of hours above 26 °C and 27 °C of BSim simulation and BMS data are shown in figure 9.6.

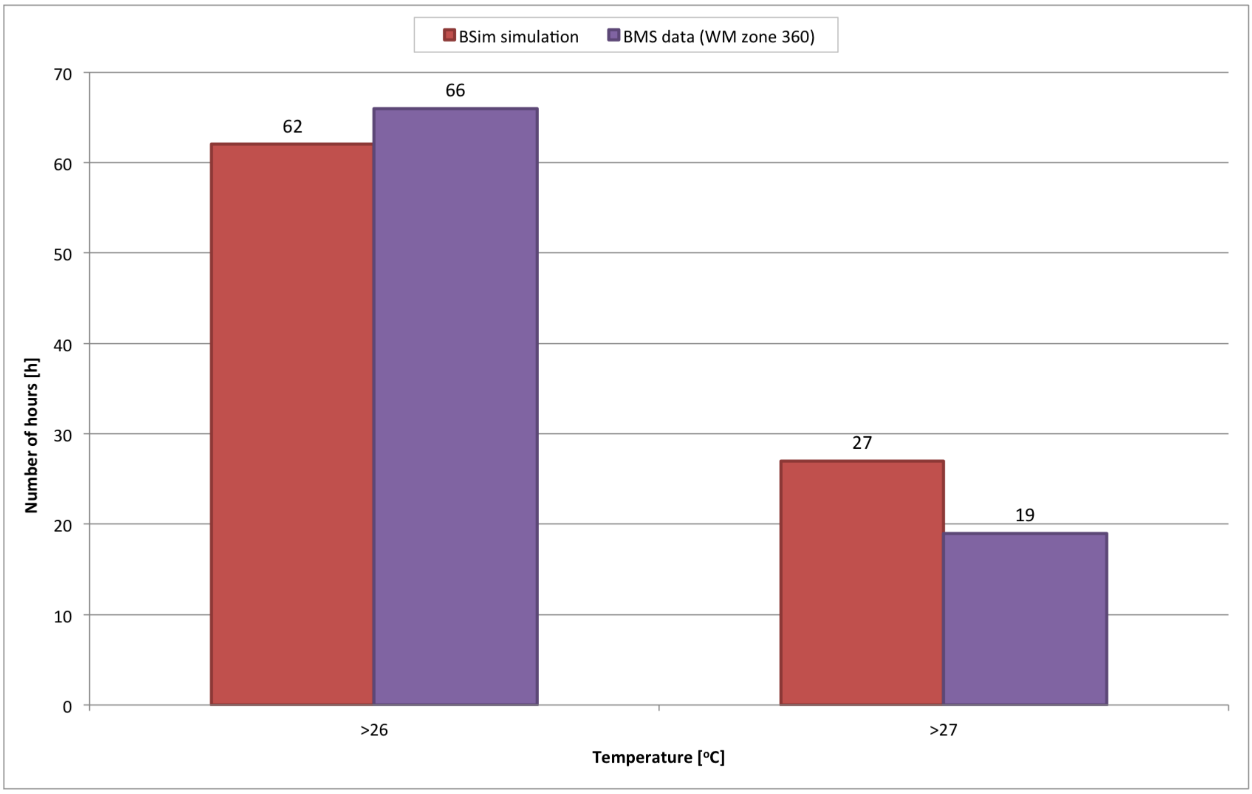

Figure 9.6. Overheating hours in 3 person office.

It can be seen that the results from the BSim simulation well coincide with the BMS data. The number of hours when temperature in the room exceeds 26 °C calculated by BSim is very close to the real measurements, whereas the number of hours above 27 °C is overestimated (42 % more than registered by BMS). The main reason for this deviation could be the difference in outdoor weather conditions, as well as the difference in internal heat loads (people, equipment) and manual window and solar shading operation by the user. Unfortunately it was not possible to obtain detailed information regarding manual operation of windows and solar blinds.

Finally, the number of hours when NTV is used is extracted from BSim. When looking at the results from BSim, it is assumed that NTV is active during the time periods outside working hours when the value of venting is not zero. The use of NTV was obtained from the BMS data. The results for NTV duration are listed in table 9.2.

	BSim simulation	BMS data
Duration of the NTV	2041 hours	1664 hours
Proportion of NTV within the total hours	23.3 %	19 %

Table 9.2. Duration of the NTV.

The results from figure 9.6 and table 9.2 indicate that the BSim simulation is fairly close to the measured BMS data. Therefore, it can be concluded that BSim is trustworthy and may be used in further validation process of the VC potential tools.

10 BSim Simulation for Validation of VC Tools

As it was observed in previous chapter, the results from the BSim simulation for the 3 person office were nearly the same as measured by BMS. Therefore, BSim will be used for validation of the two VC potential tools. However, before it is possible to use BSim for validation, some modifications need to be added to the original BSim model used in previous chapter.

The geometry, building materials and heat loads are not changed. The main changes occur in the different HVAC systems. Simple control strategy from VC potential tool has to be implemented in BSim to compare the results. This entails that some of the systems in BSim will be used in a different way. Cooling and heating (also heat recovery of ventilation air) is disabled, and set points which fit with the control strategy are added to *Ventilation* input.

During heating season (when $T_{air} < 20\,^{\circ}\mathrm{C}$) the minimum ACR in working hours is secured through *Infiltration* in BSim. This is also valid for the low ACR outside working hours in the hot summer months, which also is mentioned in section 8.2 on page 67, *Tool Description* for the 5R1C-model. *Infiltration* is chosen due to the possibility of having a constant ventilation rate, and it is easy to check that it is running as preferred.

Inside working hours the needed ACR is applied through *Ventilation* in BSim. Normally natural ventilation is added as *Venting*, but to make it easier to control and secure that at least the minimum during working hours is maintained, *Ventilation* is used instead. *Ventilation* is controlled by VAV in BSim. It means that the system can regulate by itself, and only use the needed ACR, which is the same principle as in the 5R1C-model. In cases when the needed ACR is higher than the maximum, the maximum is used. It means that the internal air temperature increases, and thereby exceeds the cooling set point. This is the same strategy that is used in simple VC potential tools.

After running the BSim simulation, the estimation of VC potential can be made by looking at the output data of *Air change rate* and *Indoor air temperature*.

The output data for *Ventilation* and *Infiltration* can be checked to make sure that the system is running as it should, and thereby follows the same principle as earlier described tools.

The exact input parameters for the BSim model can be found in Appendix C on page 143, *BSim Descriptions*. The BSim model can be found in the Appendix CD under *Initial Case*. This BSim model will be used to validate the estimated VC potential from the different tools.

Comparison of VC Potential Tools for Case Study 11

In following sections the VC potential calculated by the EURAC VC potential tool and 5R1C-model are presented. The VC potential is calculated for the initial case, a 3 person office, as described in section 6.2 on page 52, *Initial Case - 3 Person Office* . The results are analysed and then compared to the modified BSim model, which was described in the previous chapter.

The three calculation tools (EURAC VC potential tool, 5R1C-model and BSim), used for investigation of the VC potential in case study building, are given a color code. The colors used in presentation of the results for each calculation tool are shown in table 11.1.

Method	Color
EURAC VC potential tool	
5R1C-model	
BSim simulation	

Table 11.1. Color codes.

The results of the original calculation are highlighted with plain color, whereas the results for different variations of the calculations are highlighted with different patterns (still keeping the color code of the tool).

The idea about the EURAC VC potential tool and 5R1C-model is to make an universal and useful preliminary design tool. In this case we are working with an office building, which means that a lot is different in proportion to a residential or other types of buildings (occupation hours, heat loads, control strategies etc.). Consequently, the results inside working hours are the most interesting in terms of user satisfaction. This is because all the hours when the system is not running are set to VC mode [0] (no need) outside working hours and thereby might lead to wrong interpretation of the results. Therefore, only results inside working hours are presented. For further interest results for all hours can be found in Appendix A on page 135.

The calculation, on which the results are based on, can be found in the Appendix CD. Calculation example for each VC tool can be found in Appendix A, *EURAC VC Potential Tool* and Appendix B, *5R1C-model*.

11.1 Original EURAC VC Potential Tool

In this part the results from the original EURAC VC potential tool will be presented. EURAC VC potential tool will be applied to the 3 person office located on the top floor in the south side of the case study building. This room was chosen as it is more likely to be subjected to overheating than rooms located in lower floors. This means that this room will experience a high need for VC and possibly NTV. Internal heating and cooling set point temperatures are 20 °C and 26 °C respectively

For detailed information regarding input parameters and VC potential calculation process look in the excel spreadsheet *EURAC - original* in the Appendix CD, or see the calculation example in Appendix A.

On figure 11.1 graphical interpretation of VC hour distribution for every month inside working hours is illustrated based on the results from original EURAC VC potential tool. The exact monthly values of VC modes are presented in table 11.2 on the facing page.

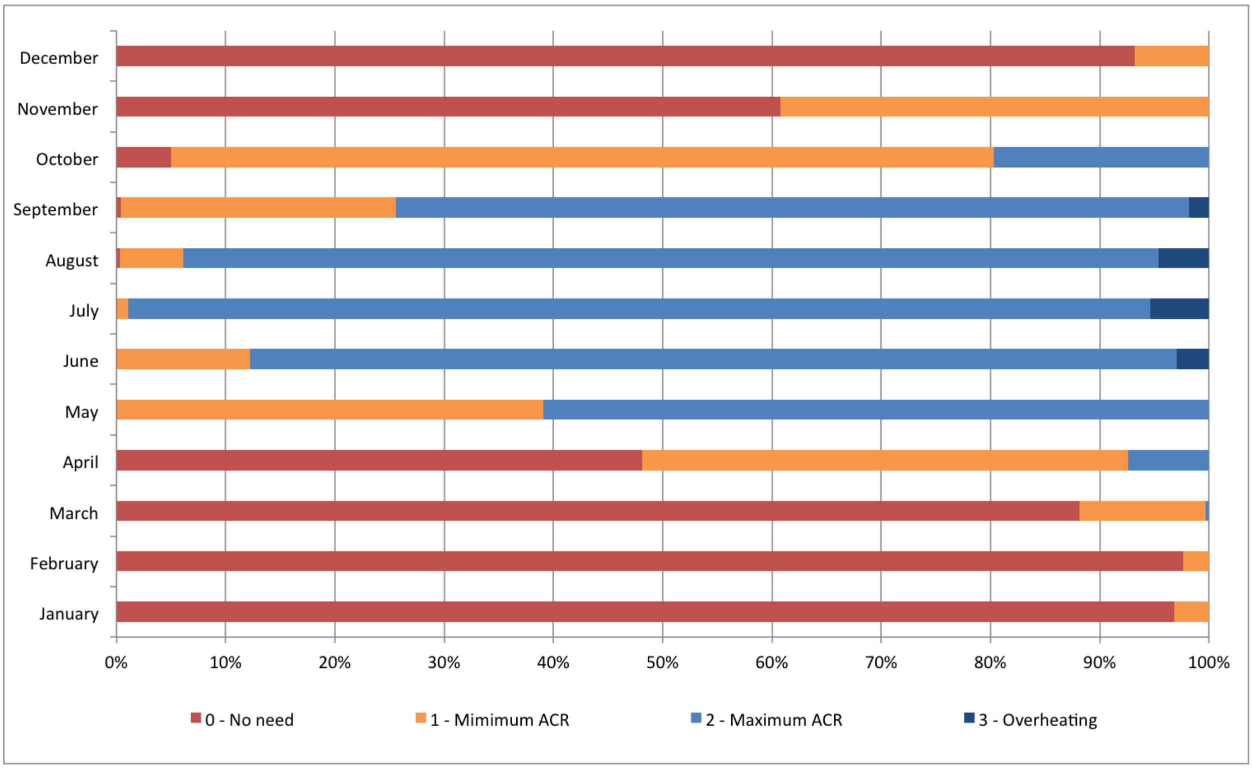

Figure 11.1. VC hours from original EURAC VC potential tool. (Working hours)

Month	0 No need	1 $m_{min} = 1.9\,h^{-1}$	2 $m_{max} = 3.5\,h^{-1}$	3 Overheating
January	270	9	0	0
February	246	6	0	0
March	246	32	1	0
April	130	120	20	0
May	0	109	170	0
June	0	33	229	8
July	0	3	261	15
August	1	16	249	13
September	1	68	196	5
October	14	210	55	0
November	164	106	0	0
December	260	19	0	0
Total	1332	731	1181	41

Table 11.2. VC hour distribution from the original EURAC VC potential tool. (Working hours)

The graph shows that overheating occurs mainly during the hot summer months (June, July, August) and September. Furthermore, no heating is needed during these months, together with May, which is realistic. When designing the ventilation system, special attention need to be paid to heat recovery system as ventilating with cold outdoor air create draft and lead to user dissatisfaction.

Because EURAC VC potential tool has many simplifications, it is interesting to investigate if the results are realistic before any further comparison with the 5R1C-model. This is done by comparing it with the modified BSim simulation, presented in chapter 10 on page 77, *BSim Simulations.*

To get insight of how the distribution of VC hours in the original EURAC VC potential tool looks compared to BSim, a graphical VC hour distribution is presented in figure 11.2 and 11.3.

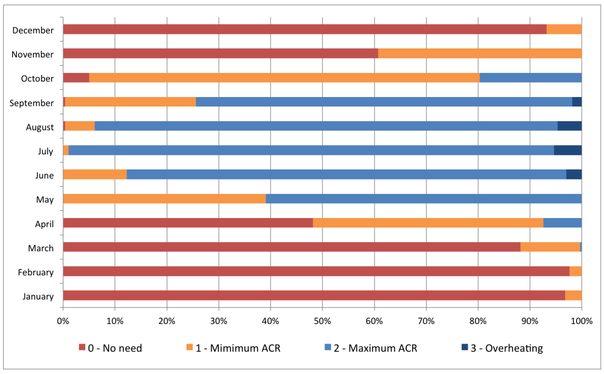

Figure 11.2. EURAC VC potential tool. (Initial case)

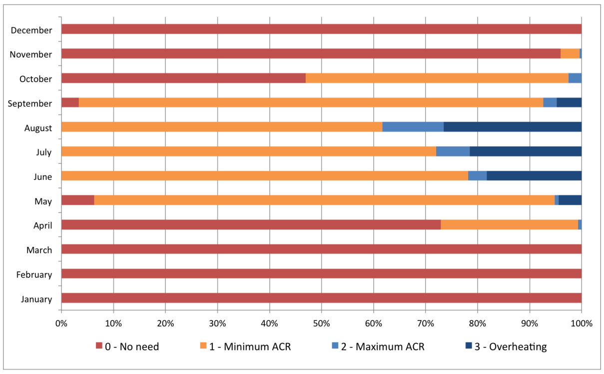

Figure 11.3. BSim simulation. (Initial case)

A huge difference in VC mode [2] appears. BSim estimates much lower need for VC mode [2] (direct cooling with increased ACR). Moreover, the efficiency of VC with minimum ACR is much higher in BSim. Lastly, the graphs show a large discrepancy between the estimated VC mode [3] (overheating hours).

The total annual distribution of VC modes from EURAC VC potential tool and BSim simulation is presented in figure 11.4.

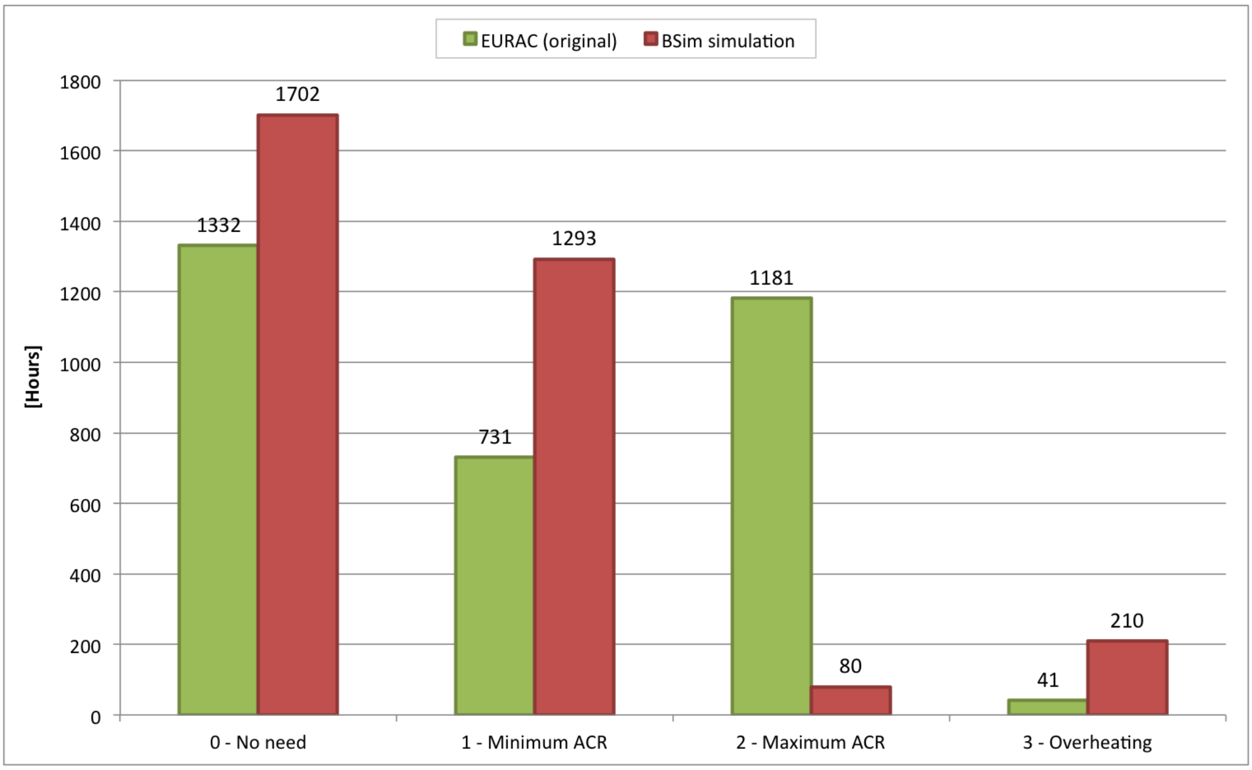

Figure 11.4. Comparison of original EURAC VC potential tool and BSim simulation. (Working hours)

The results presented in figure 11.4 for inside working hours show that BSim calculates a higher number of hours in all cases apart from when the maximum ACR is efficient.

Large discrepancy appeared in the results of the overheating hours. The number of hours when overheating appears is 5 times larger in BSim simulation which highlights some issues with the EURAC VC potential tool. High number of hours when the maximum ACR is efficient for the EURAC VC potential tool could be caused by the fact that it is calculating separately for each hour. The cooling effect from the previously calculated ACR is not taken into account. The EURAC VC potential tool is underestimating the number of hours when overheating appears compared to BSim. Thereby, there is a chance that the designer would make a wrong decision by not knowing that there is a potential issue with overheating.

Due to these variations and mismatches, some modifications should be implemented in the tool. These modifications are mentioned in the beginning of the following section and continues with the analysis of the new results from the modified EURAC VC potential tool.

11.2 Modified EURAC VC Potential Tool

During the working process some issues with the EURAC VC potential tool revealed. First of all, as it was already mentioned in tool description, this calculation method does not take into consideration the thermal mass of the building. This simplification might not have a large impact on the results if the building is light. According to data from VC buildings analysis in Denmark, buildings are typically classified as medium or heavy thermal mass, which means that some part of the internal heat gains during the day is accumulated and released later during the night. This means that building fabric performs like a heat sink during the day, thus reducing the internal temperatures and the need for cooling.

Secondly, the tool is using one constant value of internal and solar heat loads. This approach causes some uncertainties as heat loads vary with time. The maximum value of solar heat loads is reached during the middle of the day, whereas there are no heat loads due to the solar radiation during the night. The internal heat loads from people and equipment also vary. In office buildings internal heat gains are assumed to be non zero during working hours and zero during unoccupied periods.

Lastly, it is observed that this tool is based on steady-state calculation methodology. For example, the tool does not "see" that the indoor temperature has been decreased below the cooling set point during the previous hour due to direct VC and there is no need for high ventilation rates during the next hour. In such situation the tool keeps on calculating high ventilation rates just because the outdoor temperature is in a certain range. In situations when the outdoor temperature is close to the cooling set point unrealistically high ventilation rates (up to $135\,\mathrm{h}^{-1}$) were calculated, because of no limitations on for the the maximum ACR.

In order to solve some of the previously mentioned drawbacks of this calculation tool, some modifications were made. The issue with building thermal mass consideration was not solved as it would vastly change the calculation method.

At first, internal and solar heat loads were changed. Instead of having one constant value for the total internal heat loads, varying internal and solar heat loads were implemented into structure of the EURAC VC potential tool. The values for internal heat loads from persons and equipment were obtained from the initial BSim model witch is described in Appendix C on page 143.

It is assumed that the building is occupied every day from 08:00 to 17:00 (also during the weekends). Some changes are added during the summer holidays, when the internal heat load is decreased. In periods outside working hours there are no internal heat loads either from people or equipment.

Because of implementation of varying heat loads, the heating balance point temperature of the outdoor air is now varying i.e. it is changing throughout the day depending on changes in internal heat loads. This modification allows having a realistic internal heat load pattern, thus leading to more trustworthy results.

Second modification that was made to the original calculation tool is different approach of the evaluation of periods when VC mode [3] is utilised. As it was mentioned in previous chapter, there are some moments during the summer season when unrealistically high ventilation rates ($\dot{m}_{calc}$) were calculated under VC mode [2]. To make the distribution of hours with VC more realistic, VC mode [2] was supplemented with maximum possible ventilation rate ($\dot{m}_{max}$), thus saying that direct VC is useful when:

$$T_{o,hbp} + (T_{i,csp} - T_{i,hsp}) \le T_{o,db} \le T_{i,csp}$$
$$T_{o,dp} > 17\,^{\circ}\mathrm{C}$$

, and when the value of the calculated ventilation rate is within:

$$\dot{m}_{min} < \dot{m}_{calc} \le \dot{m}_{max}$$

In situations when $\dot{m}_{calc} > \dot{m}_{max}$ it is assumed that direct VC is not useful and overheating appears (VC mode [3]). For the initial case (3 person office) it was assumed that the maximum ventilation rate $\dot{m}_{max} = 76.03\,\mathrm{l/s}$ (or $ACR_{max} = 3.5\,\mathrm{h}^{-1}$).

Calculation Results

Graphical interpretation of VC hour distribution for every month for the modified EURAC VC potential tool is summed up in figure 11.5. The exact monthly values of VC modes are presented in table 11.3 on the next page. The complete calculation can be found in Appendix CD under *Case Study*.

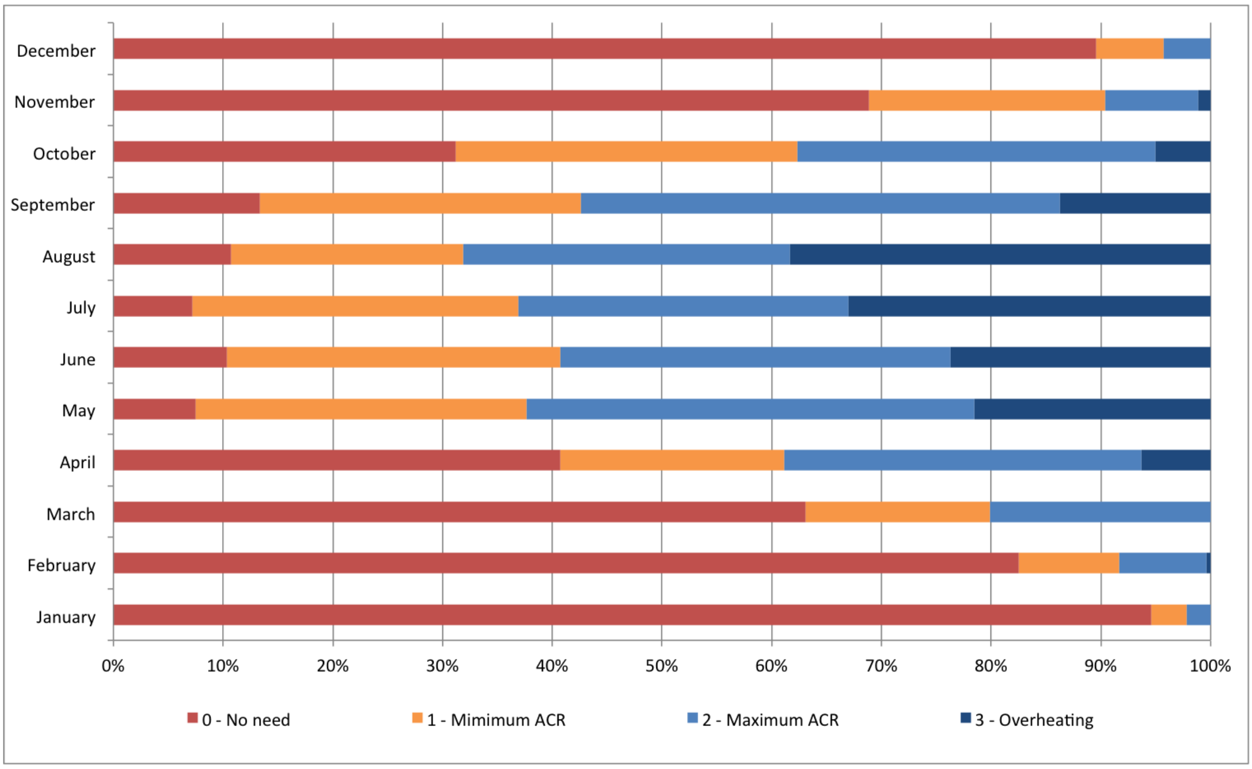

Figure 11.5. VC hours from modified EURAC VC potential tool. (Working hours)

Month	0 No need	1 $m_{min} = 1.9\,h^{-1}$	2 $m_{max} = 3.5\,h^{-1}$	3 Overheating
January	264	9	6	0
February	208	23	20	1
March	176	47	56	0
April	110	55	88	17
May	21	84	114	60
June	28	82	96	64
July	20	83	84	92
August	30	59	83	107
September	36	79	118	37
October	87	87	91	14
November	186	58	23	3
December	250	17	12	0
Total	1406	683	791	395

Table 11.3. VC hour distribution from the modified EURAC VC potential tool. (Working hours)

Both the figure and table indicates that heating is required during the entire year. The amount of hours, when VC mode [1] (min. ACR) and VC mode [2] (max. ACR) are applied are almost equal. One thing which indicates some issues with the tool is that overheating appears during February and November. This is unusual for building located in Denmark.

The modifications entails a difference in distribution of VC hours. This is easy to see in figure 11.6 and 11.7, which shows the results for the modified and original EURAC VC potential tools.

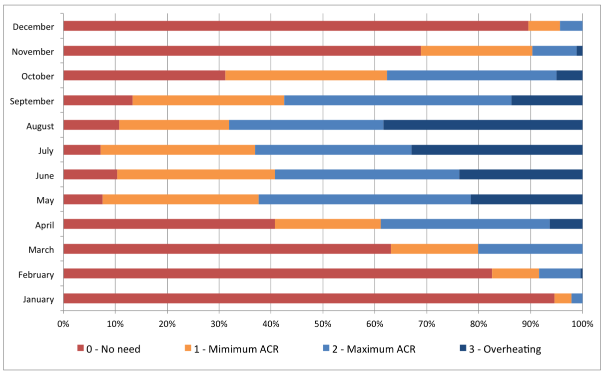

Figure 11.6. Modified EURAC VC potential tool. (Initial case)

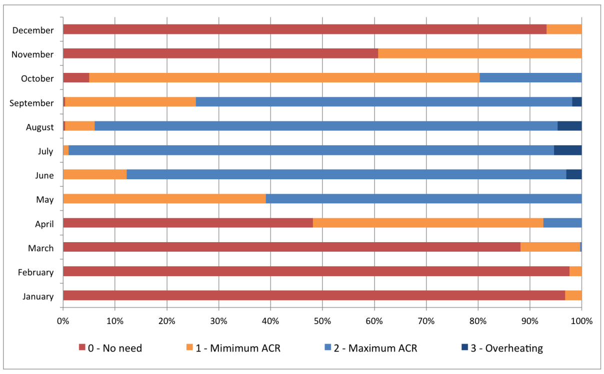

Figure 11.7. Original EURAC VC potential tool. (Initial case)

The number of months where overheating appears has increased in comparing with the results from the original tool. This is caused by the fact that the average heat loads is replaced by varying heat loads that results in higher peak temperatures inside the room. Furthermore, figure 11.6 shows that heating is needed during the entire year. This heating demand could be explained by the fact that the outdoor dry bulb temperature drops below the heating balance temperature as there are almost no heat loads during the early morning that would compensate for the decrease in outdoor temperature. The heating set point is 20 °C, and it seems to be unrealistic that the indoor temperature during the summer gets below the heating set point, especially during the working hours. Furthermore, the heat accumulation is not taken into account in this calculation method.

The total annual distribution of VC modes for both EURAC VC potential tools and BSim simulation is presented in figure 11.8.

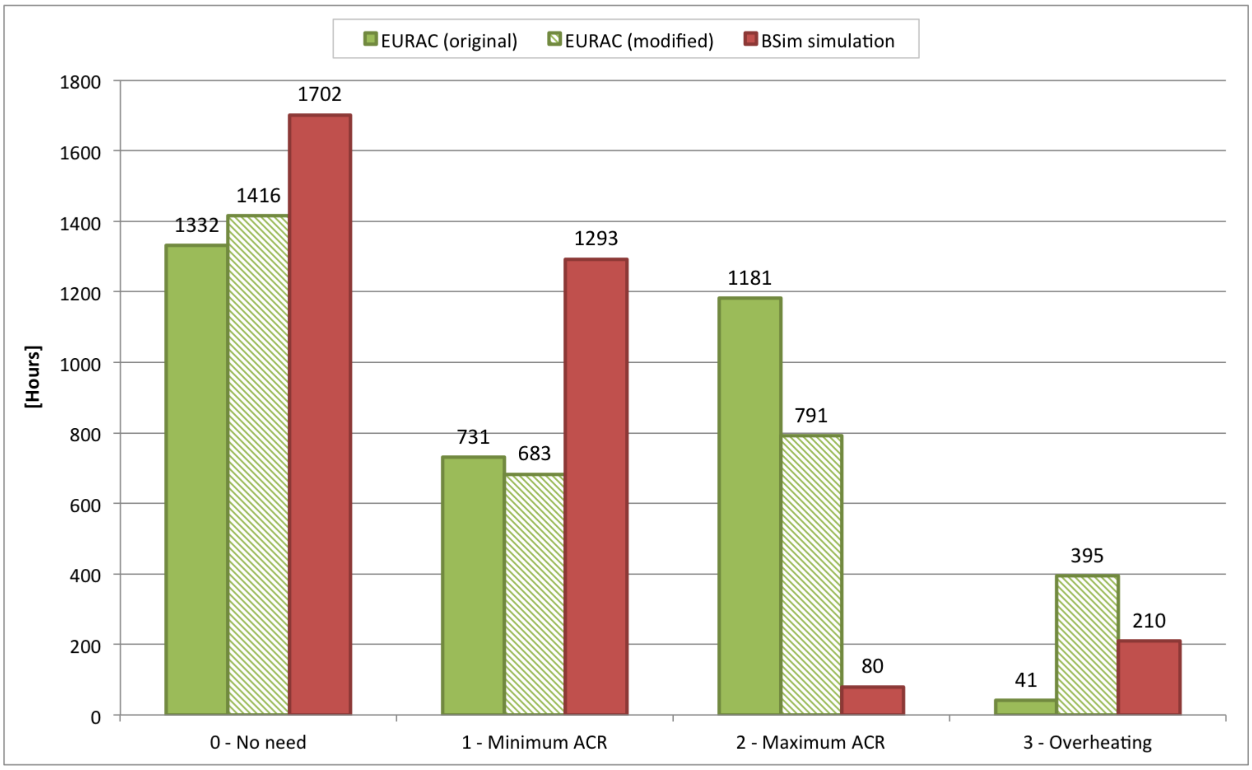

Figure 11.8. Comparison of both EURAC VC potential tool and BSim simulation. (Working hours)

The modified EURAC VC potential tool is overestimating the overheating hours if compared to BSim. This means that the designer will be aware of overheating issues, which was not the case for the original EURAC VC potential tool. However, the tool is in this case estimating much higher number of overheating hours than BSim.

Even though max ACR was limited in modified EURAC VC potential tool, it was observed that large discrepancy between estimated hours of VC mode [2] is still present.

The results from the two EURAC VC potential tools will be compared with the 5R1C-model later in section 11.4 on page 96, *Comparison of VC Potential Tools*.

11.3 5R1C-model

In this section the 5R1C-model is applied for the case study, 3 person office. Indoor temperature comfort zone is assumed to be in the range of 20 °C and 26 °C. During the cooling season (May - September) an ACR that is equal to the infiltration rate (0.046 h^{-1} - [Grontmij, 2011]) is implemented during the night to make sure that the indoor temperature is decreasing during the night.

The calculation used for this section can be found in the Appendix CD under *Case Study*.

VC hour distribution inside working hours during each month is illustrated in figure 11.9 and presented in table 11.4 on the next page.

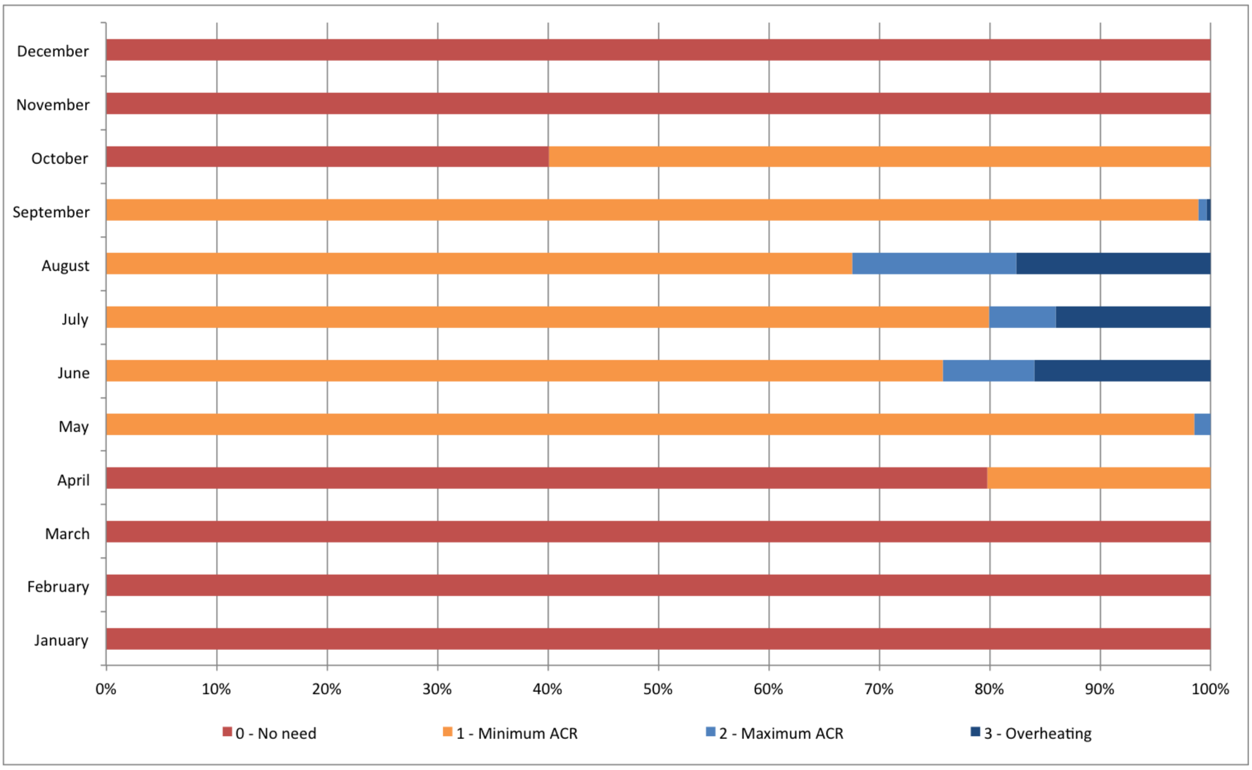

Figure 11.9. VC hours from 5R1C-model. (Working hours)

Month	0 No need	1 $m_{min} = 1.9\,h^{-1}$	2 $m_{max} = 3.5\,h^{-1}$	3 Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	215.5	54.5	0	0
May	0	275	4	0
June	0	204.5	22.5	43
July	0	223	17	39
August	0	188.5	41.5	49
September	0	267	2	1
October	112	167	0	0
November	270	0	0	0
December	279	0	0	0
Total	1686.5	1379.5	87	132

Table 11.4. VC hour distribution from 5R1C-model. (Working hours)

As the results show, overheating appears only during the summer months (June, July and August), which is realistic. Furthermore, no direct VC is needed during the winter months. VC mode [2] is only applied for 87 hours. This might be induced by relatively small difference between minimum and maximum ACR. The minimum ACR is efficient for most of the cooling season because of relatively high cooling setpoint (26 °C). The heating season lasts from October till May, which means that there is no need for heating during the summer months. Results also indicate that direct VC with minimum ACR has a large potential (it is used 42 % of the time inside working hours).

Overheating (VC mode [3]) appears for 132 hours a year inside working hours.

The differences in distribution of VC hours between the 5R1C-model and BSim can be seen in figures 11.10 and 11.11.

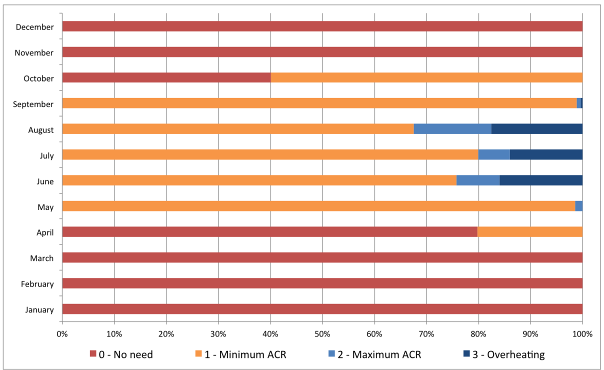

Figure 11.10. 5R1C-model. (Initial case)

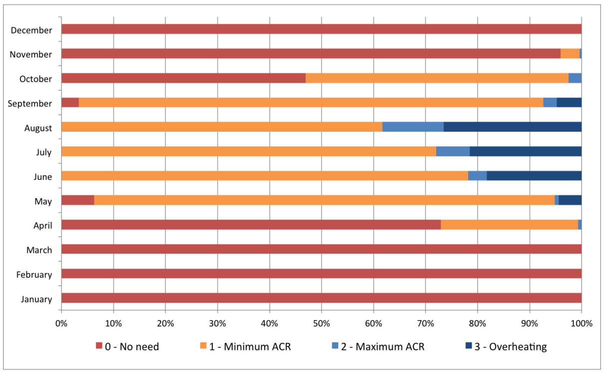

Figure 11.11. BSim simulation. (Initial case)

The two graphs show that there is a good correlation between the results in 5R1C-model and BSim simulation. The cooling season for both methods is basically the same. The only difference is that BSim calculates a small need for cooling during the transient season.

The total annual distribution of VC modes for 5R1C-model and BSim simulation is presented in figure 11.12.

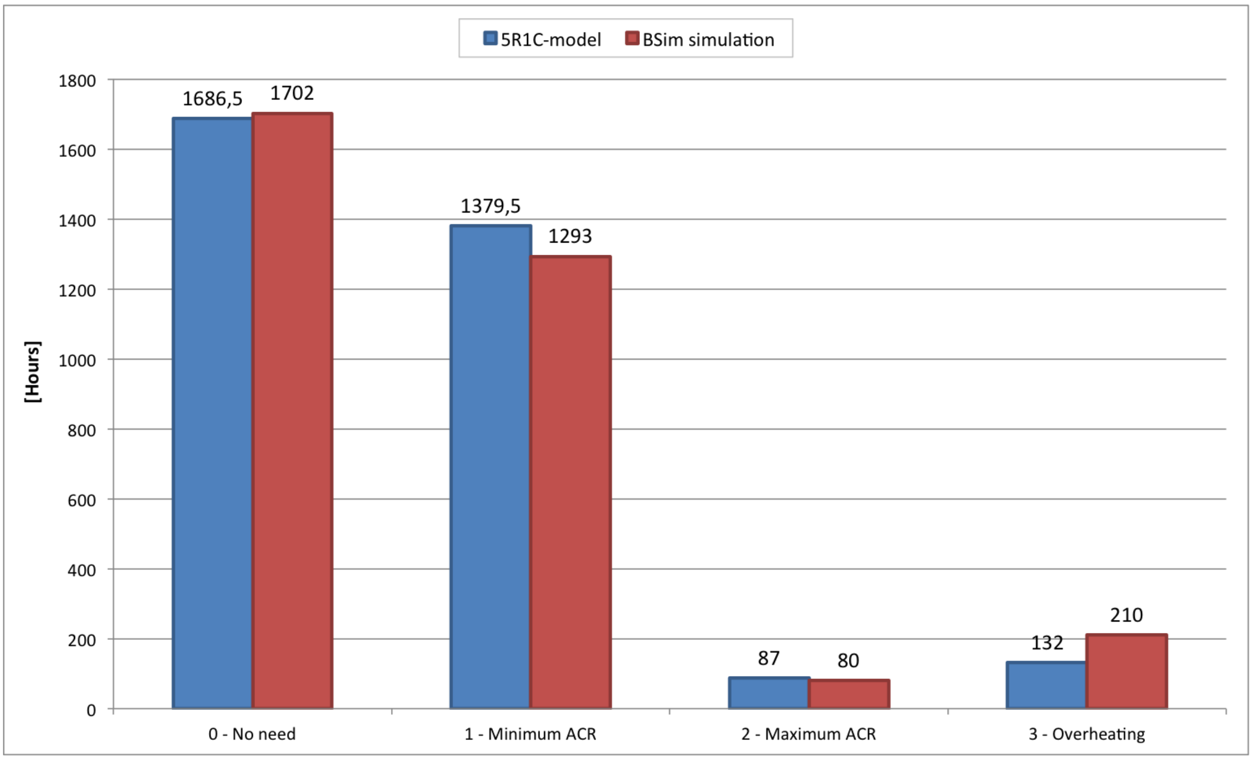

Figure 11.12. Comparison of results from 5R1C-model and BSim. (Working hours)

The biggest difference between the two tools appears in calculated hours of overheating. The 5R1C-model underestimates the overheating issue, which in some cases might mislead the designer when considering the option of NTV for the building. The rest of the results are almost similar in the two tools.

The final comparison of 5R1C-model with the two EURAC VC potential tools is presented later in section 11.4 on page 96, *Comparison of VC Potential Tools.*

11.3.1 Impact from Simplifications

As the 5R1C-model is a simple design tool some simplifications compared to the reality and more advanced methods are present. Especially the fact that no heating is implemented and the simple estimation of thermal mass are the most distinctive simplifications. The impact from these simplifications are investigated and presented in the following.

Heating

As already mentioned, the 5R1C-model does not account for room heating. As a result, some unrealistically low indoor temperatures outside cooling season occur. This simplification might have an impact on ventilative cooling potential during some months in the transient season. Yearly profile of daily average indoor air temperatures inside working hours is illustrated in figure 11.13 on the next page.

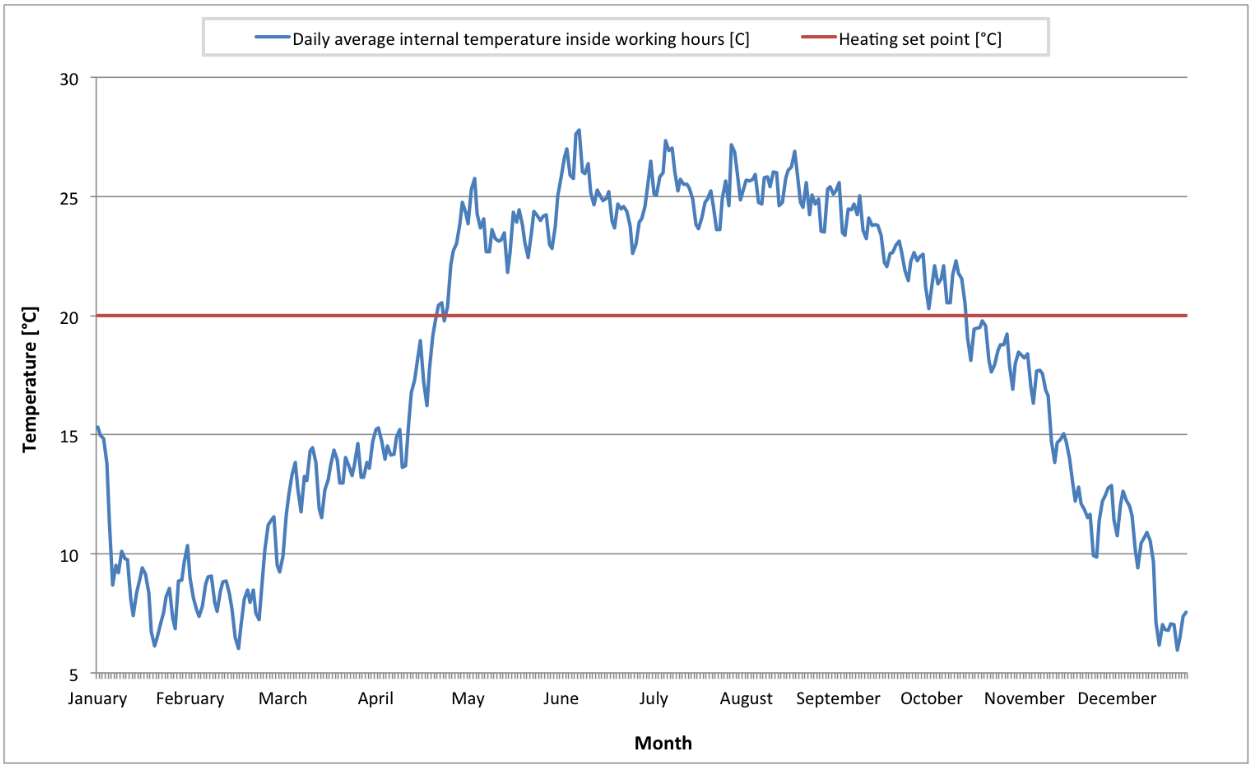

Figure 11.13. Daily average internal air temperature inside working hours over a year for the 5R1C-model.

The duration of heating season might increase if heating is added. For example, there might arise a need for cooling in April and/or October (or some other months during the transient season). If heating is implemented, the internal temperature would be fluctuating around the heating set point. Whereas, if there is no heating the internal temperature would decrease as shown in figure 11.13. In this case much more energy is needed before the internal temperature reaches the cooling set point.

On the basis of this, heating is implemented in the BSim model to investigate if it leads to considerable difference in distribution of VC modes. It is chosen to use BSim because the heating possibility is already embedded. A heating system with maximum power of 71 W/m^2 was enabled in the BSim model from October - April.

The changes of VC hours for VC mode [2] and [3] are used as indicators in investigation of the impact from adding the heating. VC mode [1] can not be considered as reliable indicator to estimate the impact from heating on VC potential during cooling season. This VC mode includes both ventilation for health and for cooling (thermal comfort). Whenever the temperature exceeds 20 °C the room is ventilated with minimum ACR, and it is hard to distinguish whether it is used for health or thermal comfort.

The results are presented in figure 11.14, 11.15 and table 11.5 on the next page for both with and without heating.

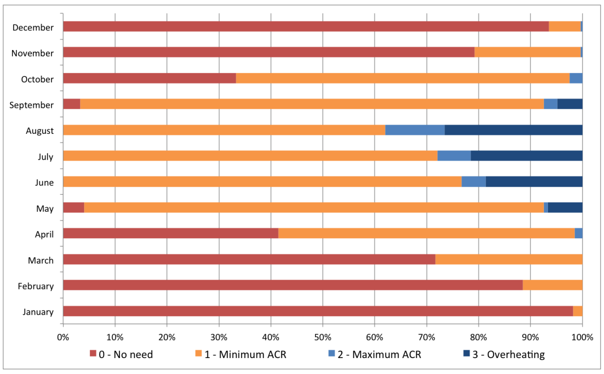

Figure 11.14. Heating (BSim simulation).

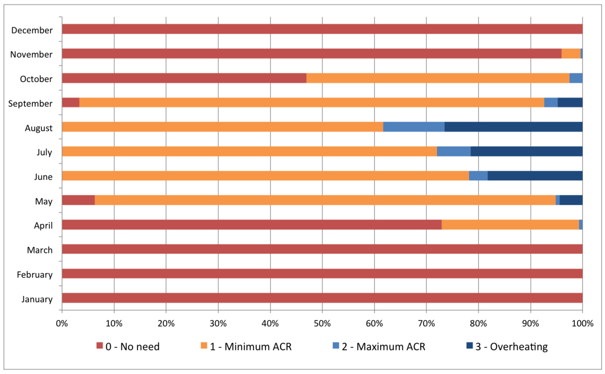

Figure 11.15. No heating (BSim simulation).

Month	**0** No need	**1** $m_{min} = 1.9\,\mathrm{h}^{-1}$	**2** $m_{max} = 3.5\,\mathrm{h}^{-1}$	**3** Overheating
January	274 (279)	5 (0)	0 (0)	0 (0)
February	223 (252)	29 (0)	0 (0)	0 (0)
March	200 (279)	79 (0)	0 (0)	0 (0)
April	112 (197)	154 (71)	4 (2)	0 (0)
May	11 (17)	239 (239)	2 (2)	18 (12)
June	0 (0)	214 (218)	13 (10)	52 (51)
July	0 (0)	201 (201)	18 (18)	60 (60)
August	0 (0)	173 (172)	32 (33)	74 (74)
September	9 (9)	241 (241)	7 (7)	13 (13)
October	93 (131)	179 (141)	9 (7)	0 (0)
November	214 (259)	55 (10)	1 (1)	0 (0)
December	261 (279)	17 (0)	1 (0)	0 (0)

Table 11.5. VC hour distribution with and without heating. The values in brackets represent the initial case without heating. (Working hours)

In the BSim model a heating system is enabled from October - April with a heating setpoint at 19 °C. The comfort zone is from 20 °C - 26 °C, which normally would lead to having an internal heating set point at 20 °C. Heating set point was lowered to avoid situations when heating and VC mode [1] are running at the same time. Lowered heating set point reduces the amount of hours for VC mode [1] outside cooling season, thus giving a more realistic representation of VC need. However, the amount hours when heating is needed will still be high as the temperatures below 20 °C will be counted as VC mode [0].

The table shows that, even though the heating set point is lowered, differences for VC mode [1] appear, especially in heating season (October - April). As mentioned earlier, VC mode [1] is activated when the indoor temperature exceeds 20 °C. During the heating season there might be periods during the day, when the indoor air temperature slightly exceeds this temperature. It means that the room is ventilated with outdoor air with minimum ACR even though there is no need for direct VC as the room temperature most likely would not exceed the cooling set point (26 °C). This happens even though the heating set point was lowered in the BSim model.

Table 11.5 shows that the hours for VC mode [2] and [3] are almost equal in both cases (with or without heating). These VC modes can be considered as indicators of cooling need. For VC mode [2] a small increase in VC hours appear for April, June and October. After implementation of heating the hours for VC mode [3] are almost the same. The largest difference in overheating hours (6 hours) appear in May. However, no heating is used in May, which means that the implementation of heating in April entails a slight increase in overheating in May because of higher initial internal air temperature.

For a better overview the results from the previous table are summarised and presented in figure 11.16.

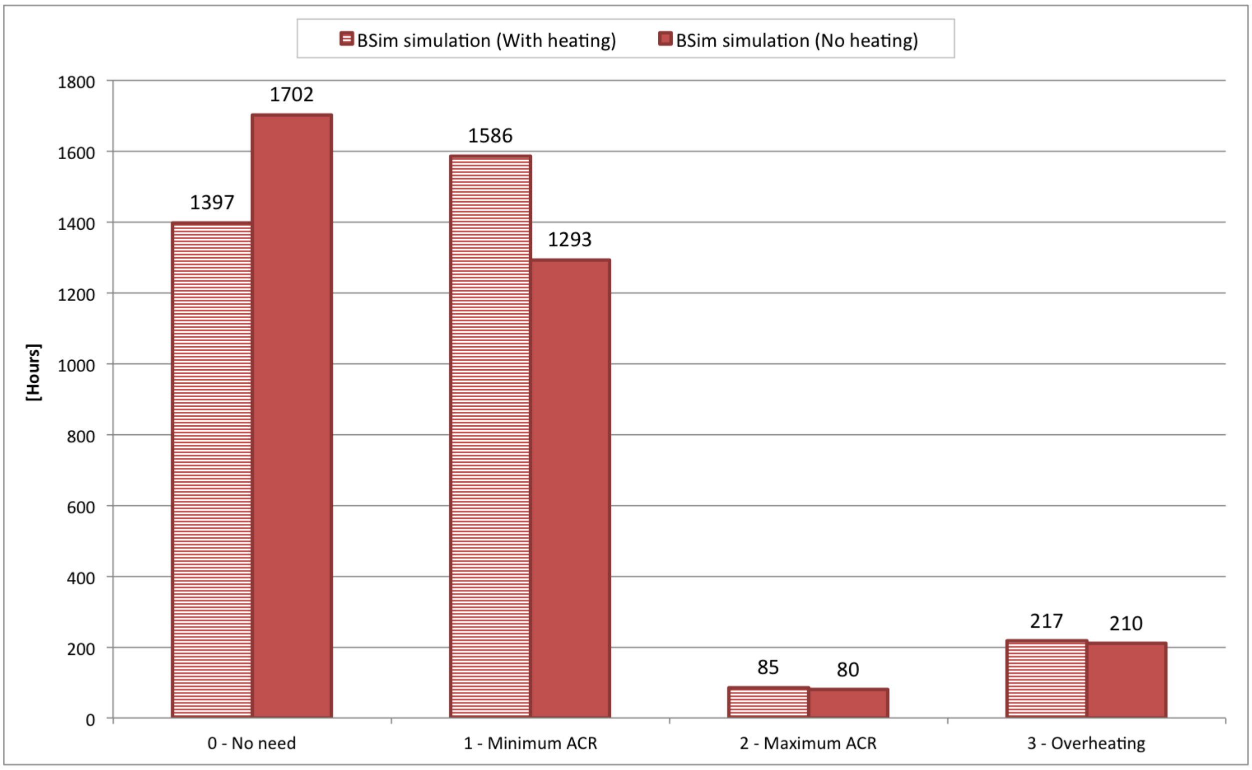

Figure 11.16. Total VC hour distribution with and without heating. (Working hours)

It can be seen that the calculated number of hours with overheating resulted in a difference of 7 hours between the two BSim simulations. Moreover, only a difference of 5 hours is calculated for VC mode [2].

The largest difference in VC hours appear outside the cooling season. If the results differed even more, it would most likely be because of changes in the transient and cold months and not because of differences in summer months. Since the main focus in this project is on the VC potential during the cooling season, the results from May - September are of most interest. Thereby, it can be concluded that heating system does not have a considerable impact on ventilative cooling potential as overheating most likely occur during the summer and not during the transient or winter months. Therefore, heating will not be implemented in the 5R1C-model.

Estimation of Heat Capacity

In 5R1C-model a rather simple approach for estimating the thermal mass is used. As mentioned earlier, accumulative layer is placed 0.1 m in for heavy constructions and 0.05 m in for light constructions. The order of construction layers is not taken into account, which in some cases can estimate a misleading thermal mass of the construction elements. For example, in cases with carpets, insulation, suspended ceilings etc., which reduce the possibility to accumulate energy in underlying materials. This issue is not taken into account when calculating the amount of thermal mass in 5R1C-model.

To investigate if this simplification has a considerable influence on the potential of ventilative cooling and VC hour distribution, a more advanced method to calculate the thermal mass is tried. This method is based on heat conduction in components composed of several parallel, plane and homogeneous layers. Furthermore, it is a calculation under regular sinusoidal conditions and one-dimensional heat flow [European standard, 2007]. Because the main focus in this project is on ventilative cooling, further description of the tool is abstained.

Calculation of the thermal mass is made for already described initial case, and also for a case with increased thermal mass when the internal walls are made of concrete instead of the materials presented in table 6.1 on page 53. The new thermal mass estimated by the advanced method is then implemented in calculation of VC potential in the 5R1C-model. The different calculated thermal masses for the original and advanced model for both cases are presented in table 11.6

Case	**Method**	**Thermal mass** $[Wh/K \cdot m^2]$
Case study	Simplified	63
	Advanced	59
Increased thermal mass	Simplified	98
	Advanced	92

Table 11.6. Estimated thermal mass.

As the table shows, a small differences between the estimated thermal masses appears. In figure 11.17, 11.18 and table 11.7 on the following page the results for the VC distributions are presented for the case study with the two different thermal masses.

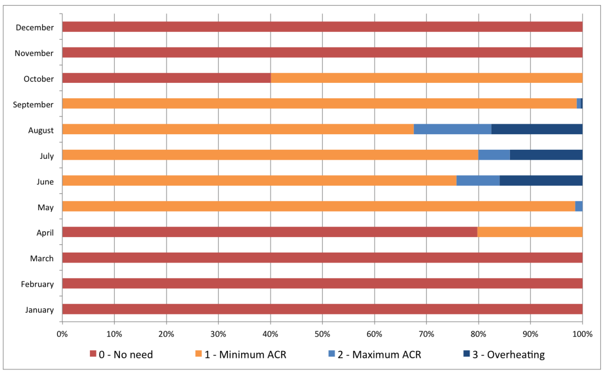

Figure 11.17. Simple method. (5R1C-model)

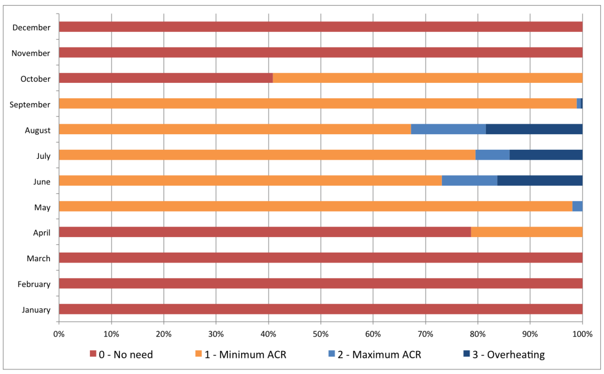

Figure 11.18. Advanced method. (5R1C-model)

	Case study			
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,\mathrm{h}^{-1}$	$m_{max} = 3.5\,\mathrm{h}^{-1}$	Overheating
January	279 (279)	0 (0)	0 (0)	0 (0)
February	252 (252)	0 (0)	0 (0)	0 (0)
March	279 (279)	0 (0)	0 (0)	0 (0)
April	212,5 (215.5)	57.5 (54.5)	0 (0)	0 (0)
May	0 (0)	273.5 (275)	5.5 (4)	0 (0)
June	0 (0)	197.5 (204.5)	28.5 (22.5)	44 (43)
July	0 (0)	222 (223)	18 (17)	39 (39)
August	0 (0)	187.5 (188.5)	40 (41.5)	51.5 (49)
September	0 (0)	267 (267)	2 (2)	1 (1)
October	114 (112)	165 (167)	0 (0)	0 (0)
November	270 (270)	0 (0)	0 (0)	0 (0)
December	279 (279)	0 (0)	0 (0)	0 (0)

Table 11.7. VC hour distribution with simplified and advanced calculation of thermal mass. The values in brackets represent the initial case with the simple method. (Working hours)

By quick glance at the figures no difference appears. It is only possible to see some small changes, when looking at the exact values for VC hour distribution in the table. However, it is difficult to get the total overview of what is the impact from simplified method of thermal mass calculation.

The results for incresed thermal mass (interwall wall made of concrete) are presented in figure 11.19, 11.20 and table 11.8 on the next page

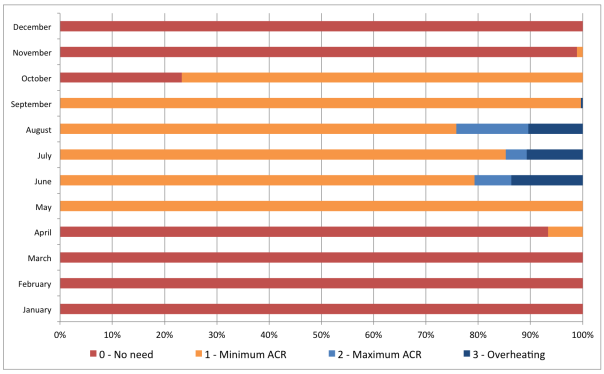

Figure 11.19. Simple method with increased thermal mass (5R1C-model)

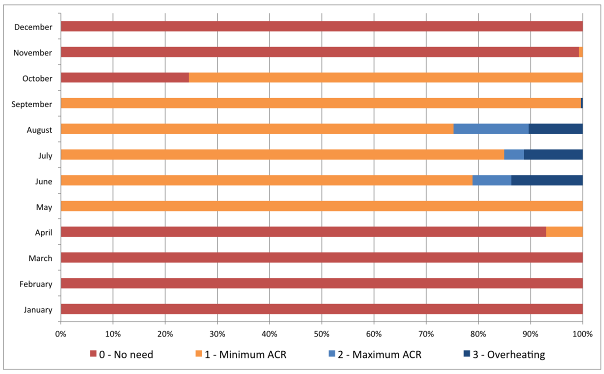

Figure 11.20. Advanced method with increased thermal mass (5R1C-model)

Increased thermal mass				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279 (279)	0 (0)	0 (0)	0 (0)
February	252 (252)	0 (0)	0 (0)	0 (0)
March	279 (279)	0 (0)	0 (0)	0 (0)
April	251 (252)	19 (18)	0 (0)	0 (0)
May	0 (0)	279 (279)	0 (0)	0 (0)
June	0 (0)	213 (214)	20 (19)	37 (37)
July	0 (0)	237 (238)	10.5 (11)	31.5 (30)
August	0 (0)	210 (211.5)	40 (38.5)	29 (29)
September	0 (0)	269 (269)	0 (0)	1 (1)
October	68.5 (65)	210.5 (214)	0 (0)	0 (0)
November	268 (267)	2 (3)	0 (0)	0 (0)
December	279 (279)	0 (0)	0 (0)	0 (0)

Table 11.8. VC hour distribution with simplified and advanced calculation of thermal mass (with increased thermal mass). The values in brackets present the initial case with the simple method. (Working hours)

Almost no changes as for the initial case appear, and it is still difficult to get the total overview. The results for the case study and with increased thermal mass are summarised and presented in figure 11.21.

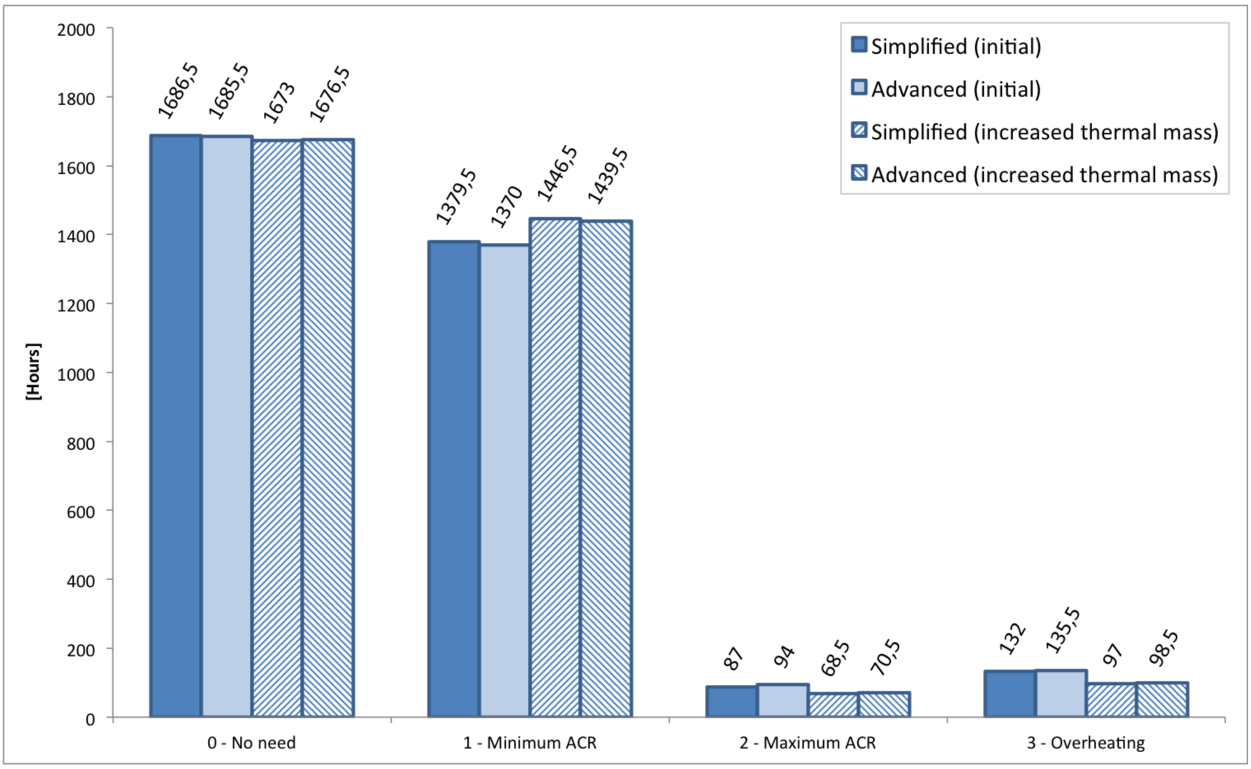

Figure 11.21. Comparison of methods to estimate the thermal mass for two different cases. (Working hours)

The figure shows that even though the two methods estimate the thermal mass slightly different, the impact on the VC distribution is negligible. The number of overheating hours have only changed by few hours in both cases. This is also valid for the rest of VC modes. These changes are so small that they would not effect the decision regarding VC system design. On the basis of this and assuming that the 5R1C-model should be a simple tool, it is decided to continue using the original simplified thermal mass calculation method.

11.4 Comparison of VC Potential Tools

In this chapter the results obtained from the two different variations of EURAC VC potential tools and 5R1C-model, as well as the modified BSim model are summarised and compared. The results are compiled in table 11.9 and illustrated in figure 11.22.

Calculation tool	**0** No need	**1** $m_{min} = 1.9\,h^{-1}$	**2** $m_{max} = 3.5\,h^{-1}$	**3** Overheating
EURAC (original)	1332	731	1881	41
EURAC (modified)	1416	683	398	395
5R1C-model	1686.5	1379.5	87	132
BSim	1702	1293	80	210

Table 11.9. Comparison of results for VC potential tools. (Working hours)

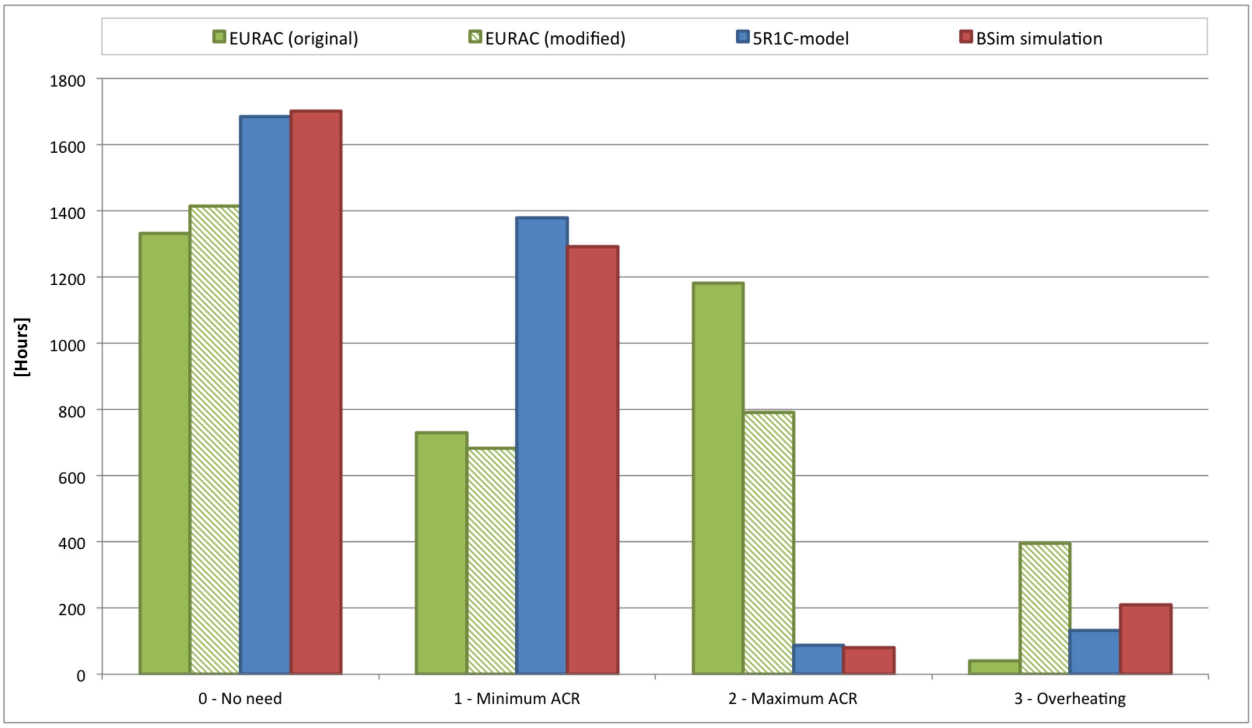

Figure 11.22. Comparison of results from VC potential tools. (Working hours)

If the original EURAC VC potential tool is compared to the results from BSim model, it can be seen that it underestimates the number of hours with overheating. In contrast, the modified EURAC VC potential tool overestimates the potential for VC mode [3]. It can be seen in the graph that there is no correlation between the results from both variations of EURAC VC potential tool and BSim. The largest differences occur in estimation of VC mode [2] ($1.9\,\mathrm{h}^{-1} \leq \dot{m}_{calc} \leq 3.5\,\mathrm{h}^{-1}$) and VC mode [3] (Overheating). The difference between the original EURAC VC potential tool and the BSim simulation is most likely caused by following factors:

- Thermal mass of the building is not taken into account.
- Internal and solar heat loads do not vary during the day.
- Steady-state methodology. No straight correlation between the previous and current time step of the calculation. For example, the tool does not account for the cooling effect from increased ventilation rates during the previous time step.

Even though varying internal and solar heat loads were implemented and maximum possible ventilation rate for VC was specified in modified EURAC VC potential tool, the results did not yield the expected improvement. This could indicate that some of the unchanged mentioned factors might be the source for observed discrepancy between the EURAC VC potential tool and other calculation methods (5R1C-model and BSim).

The results from 5R1C-model well coincide with the results from the BSim simulation. The VC potential for VC mode [0], [1] and [2] is nearly the same for the 5R1C-model and the BSim simulation. Only discrepancy for VC mode [3] appears.

One of the reasons for this discrepancy in the results between 5R1C-model and BSim is different approach in handling the thermal mass. The 5R1C-model is handling the thermal mass in a simple way. The accumulative layer is placed in a thin layer in the construction elements and only takes the inner part into account. It means that the accumulated heat in outer thermal mass is not taken into account. In reality (and BSim) the internal temperature is also affected by the outer part of the thermal mass. The increase in temperature of the external part due to solar radiation would decrease the transmission loss. BSim calculates a detailed temperature distribution throughout the entire construction elements due to higher discretisation and because the impact from outer thermal mass is taken into account. This entails more precise results.

Furthermore, only one temperature for internal surfaces T_{si} and one for the thermal mass T_m is used in 5R1C-model, whereas BSim calculates surface temperatures separately for each construction element.

After evaluation of the results from all previously described tools it was decided to stop further optimisation of EURAC VC potential tool and put focus on further analysis of 5R1C-model.

Part III

Robustness Analysis of 5R1C-model

Even though the VC potential, estimated by the 5R1C-model, was close to BSim for the case study, the potential for using the tool in the predesign phase is not established. The robustness of the tool must be tested, which is done by calculating the potential for VC under different conditions in the following part - for example changing thermal mass and applying simple NTV strategy.

At the end of this part, discussion of the discovered results in the entire report is made to get a clear review of the obtained information from the ventilative cooled building database, and discuss if the used VC potential tools are useful in the predesign phase.

12 Robustness of 5R1C-model

Even though the results from the 5R1C-model are close to BSim, more analysis and investigation have to be performed before the method can be safely used in predesign phase. It could just be a coincidence, that the results from the previous chapter fits fairly good to the BSim simulation. The robustness of the 5R1C-model will be tested by subjecting the tool to different conditions.

The robustness will be checked by:

- Implementing another control strategy
- Increasing the maximum ACR
- Increasing the thermal mass of building fabrics
- Implementation of simple NTV strategy
- Changing the room type
- Subjecting the room to another climate
- Changing heat loads

By applying these changes, it becomes possible to see if there are any limitations in application of 5R1C-model.

All variations of the excel calculations and BSim models used for the results presented in the following sections can be found in the Appendix CD under *Robustness* and *BSim Models*.

Monthly distribution of VC modes for the different cases in this chapter are presented in Appendix D. The results in the following are based on these values.

12.1 Control Strategy 2

In the initial case a very simple control strategy was used to estimate the VC potential. To investigate was is the impact from another control strategy on the results from the 5R1C-model a more complex control strategy is now implemented. Furthermore, it is interesting to see, if the 5R1C-model still estimates a trustworthy VC hour distribution compared to BSim. The control strategy 2 is illustrated in figure 12.1 on the following page.

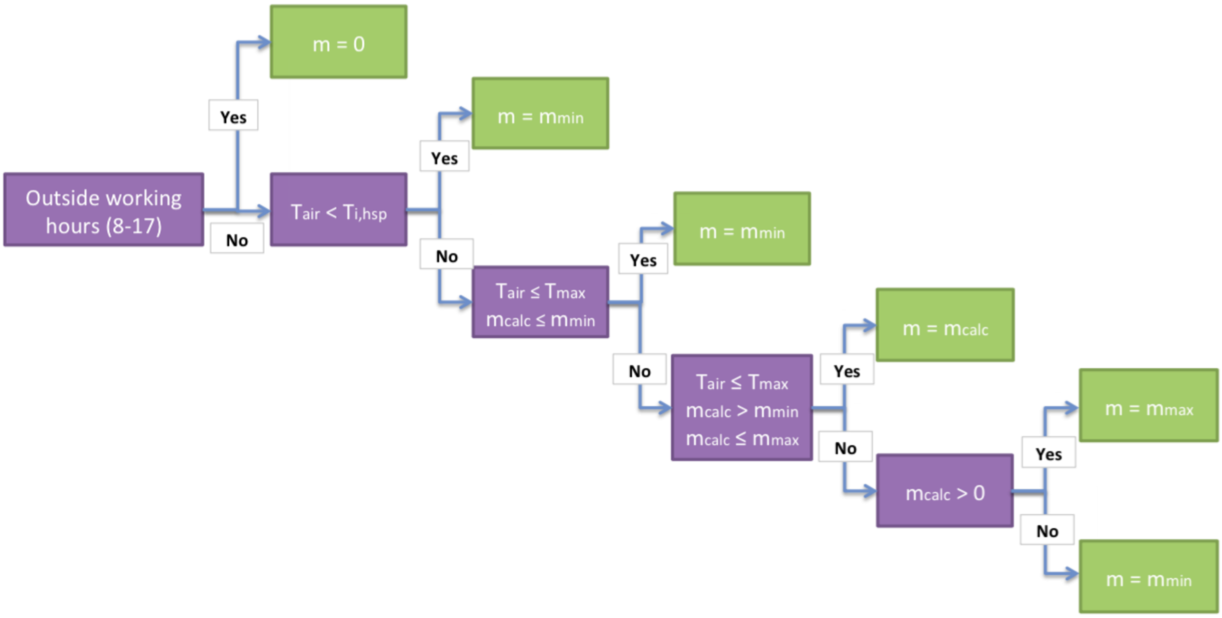

Figure 12.1. Control strategy 2.

The main difference between control strategy 1 and 2 is in cooling set points, which are 26 °C and 24.5 °C respectively. This means that the system with control strategy 2 will try to cool the room down to 24.5 °C. At the same time, the use of direct VC (VC mode [2]) will be prolonged until the indoor temperature reaches the upper limit of the comfort zone (26 °C). The acceptable temperature comfort zone is maintained the same as was in control strategy 1 (20-26 °C). New control variable (T_{max}) representing the maximum acceptable indoor air temperature is introduced in control strategy 2. The selection algorithm of VC modes used for control strategy 2 is presented in figure 12.2.

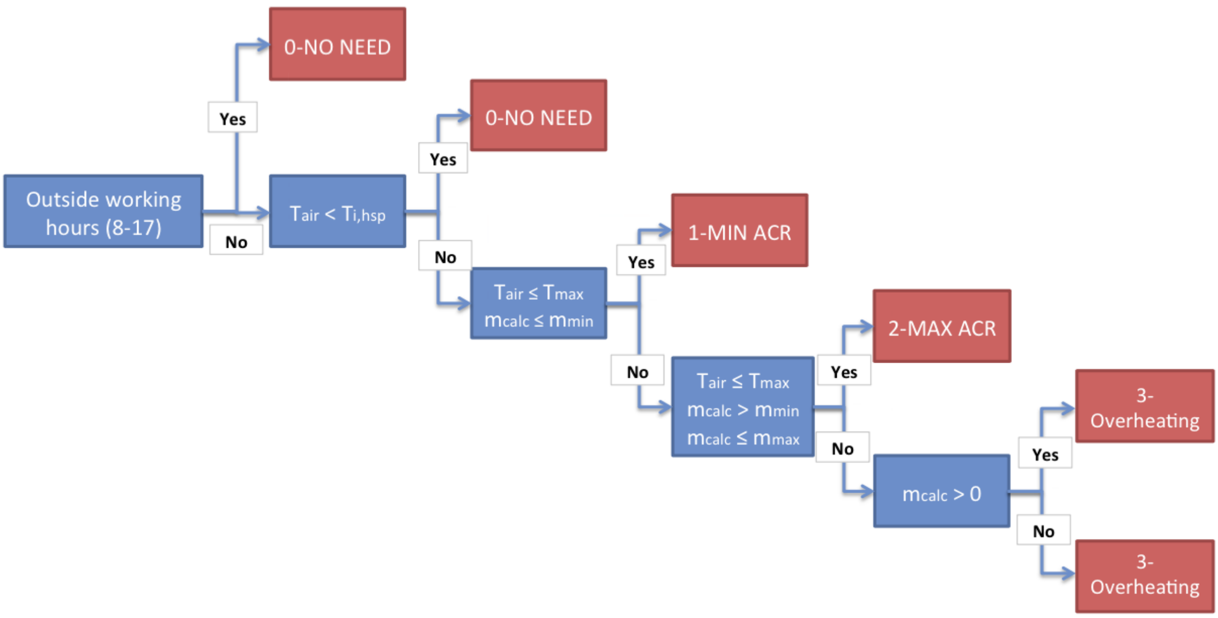

Figure 12.2. VC mode selection for control strategy 2.

Control strategy 2 is implemented in the 5R1C-model. The results are compared to the initial case with control strategy 1 from the 5R1C-model and presented in figure 12.3 and 12.4.

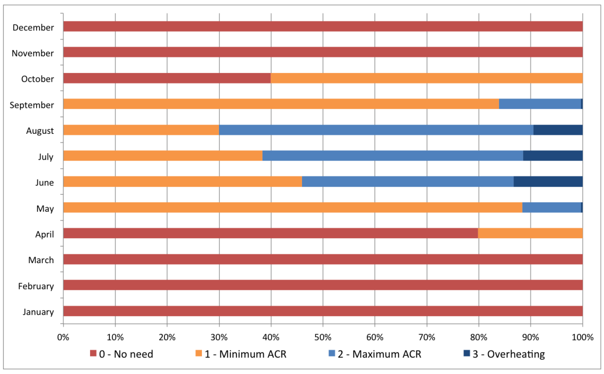

Figure 12.3. Control strategy 2. (5R1C-model)

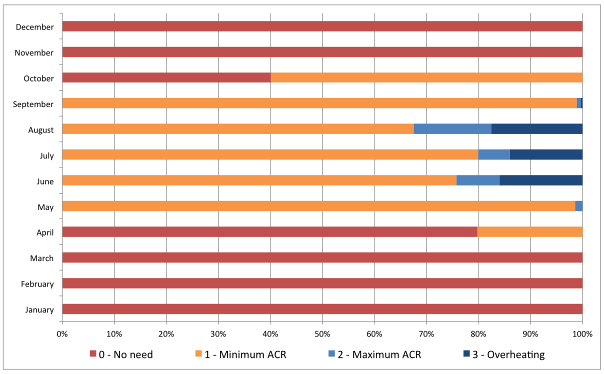

Figure 12.4. Control strategy 1. (5R1C-model)

It can be seen in the figures above that the heating need is the same for both control strategies. The differences appear in distrbution of the VC hours between VC mode [1], [2] and [3]. VC mode [2] (maximum ACR) is used much more then for control strategy 1. Furthermore, there is a notable decrease in overheating hours for control strategy 2.

Control strategy 2 is also implemented in BSim and the total annual VC hours for both BSim and 5R1C-model are summarised in figure 12.5.

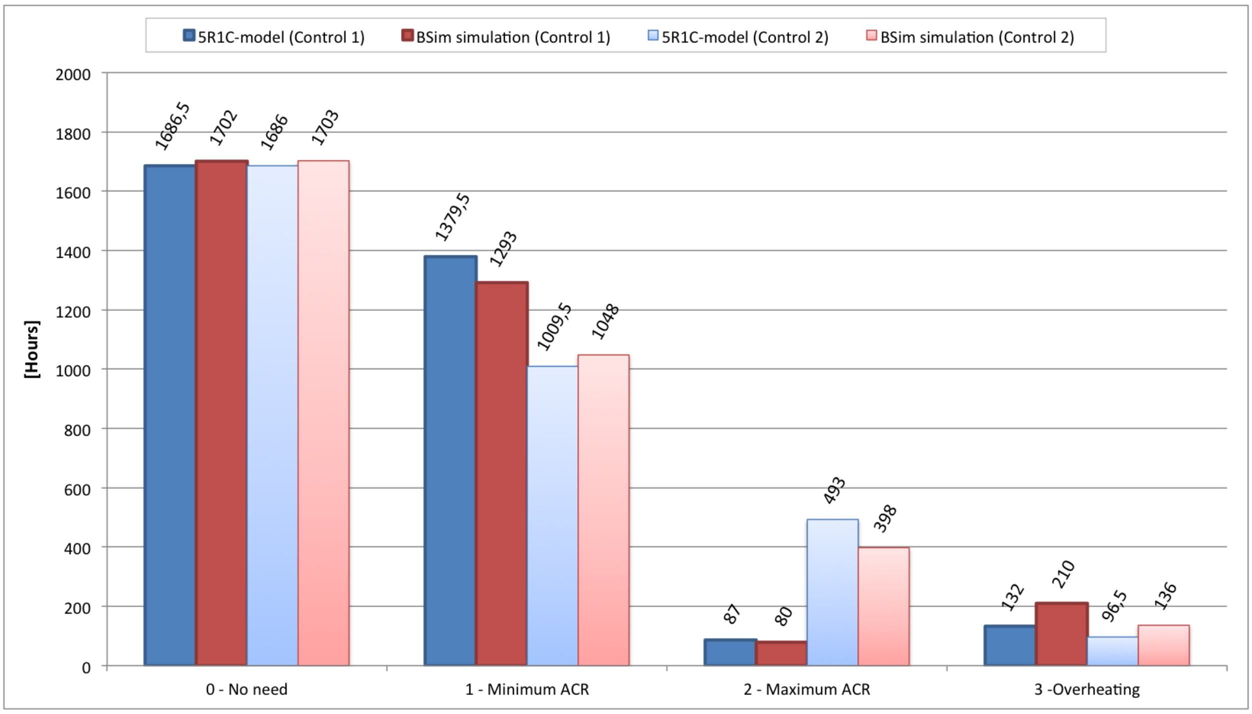

Figure 12.5. Distribution of VC hours for 5R1C-model and BSim with control strategy 1 and 2. (Working hours).

The results show that VC hours, calculated by 5R1C-model, are in good correlation with BSim for both control strategies. The distribution of VC hours has changed because of different temperature set points. However, the results from BSim and 5R1C-model follow the same tendencies for both control strategies.

In comparing with control strategy 1, the number of hours when VC mode [1] is active has decreased by one fourth, whereas it has increased by more than 5 times in VC mode [2]. For VC mode [3] the hours have decreased by around one third. The main reason for these changes in VC hour distribution is lowered cooling set point. Thus, direct VC is used more than it was in the control strategy 1.

If compared to control strategy 1, considerable part of the VC hours is formed by direct VC with increased ACR (VC mode [2]). This means that the occupants will be subjected to higher air velocities (higher draft risk), which may cause some dissatisfaction with the indoor climate in the building.

It can be concluded that implementation of control strategy 2 in 5R1C-model and BSim yielded trustworthy results and led to a decrease in overheating hours.

12.2 Maximum ACR

For the initial case study a maximum ACR of $3.5\,\mathrm{h}^{-1}$ was used. This value is chosen based on knowledge about the natural ventilation potential in the room using single sided ventilation [Grontmij, 2011]. Higher maximum ACR effects the distribution of VC modes in the 5R1C-model, in particular, the time when it switches from VC mode [2] to VC mode [3]. In order to investigate the effect from increased ACR on the VC hour distribution and does the 5R1C-model still generate trustworthy results, maximum possible ACR in initial 3 person office is increased from $3.5\,\mathrm{h}^{-1}$ to $5\,\mathrm{h}^{-1}$ and $10\,\mathrm{h}^{-1}$.

The results from 5R1C-model showing monthly distribution of VC hours for original and increased ACR are presented in figure 12.6, 12.7 and 12.8.

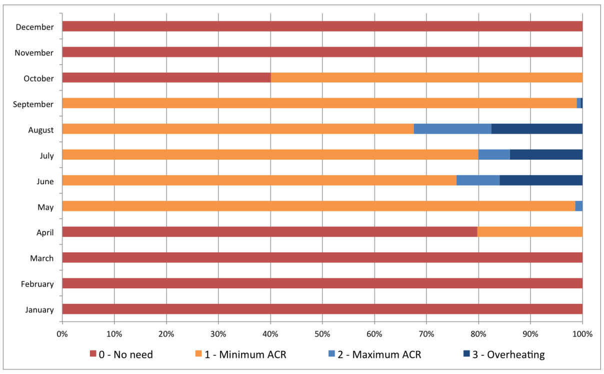

Figure 12.6. ACR = $3.5\,\mathrm{h}^{-1}$. (5R1C-model)

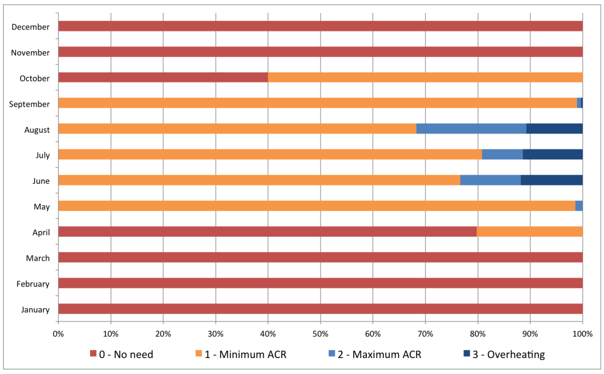

Figure 12.7. ACR = $5\,\mathrm{h}^{-1}$. (5R1C-model)

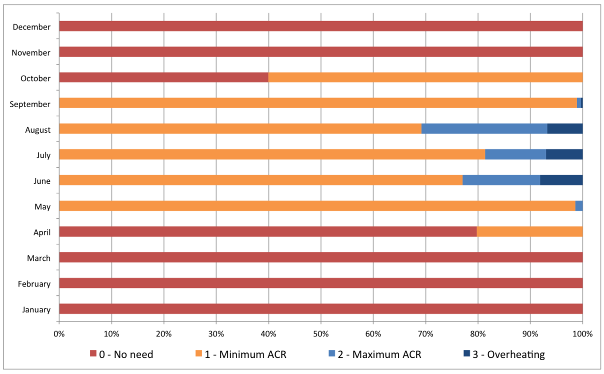

Figure 12.8. ACR = $10\,\mathrm{h}^{-1}$. (5R1C-model)

It can be observed that the increase in maximum ACR will not have an impact on the heating need. This is because the VC mode [2] (room ventilation with increased ACR) only occur in periods when the indoor temperature exceeds the cooling set point (26 °C) which is considerably higher than heating set point (20 °C). Changes in VC hour distribution mainly occur in cooling season. Another pattern that can be observed is the decrease in overheating hours after each increase in maximum ACR is implemented.

To get a better perspective of changes in VC potential and to validate the results, the same implementation with increased ACR is made in BSim. The annual VC hour distribution from 5R1C-model and BSim simulation for each increase in maximum ACR are compared in figure 12.9 on the next page.

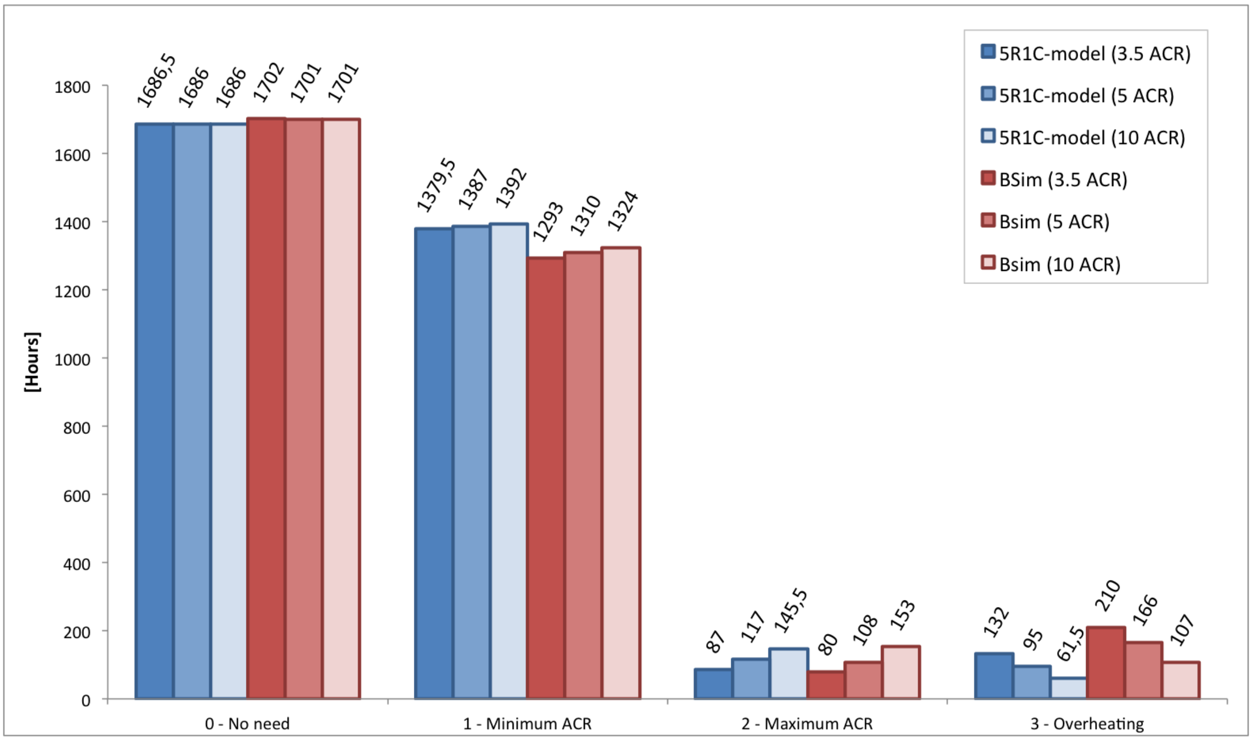

Figure 12.9. Total VC hour distribution in cases with increased ACR. (Working hours)

It can be seen in graph that the results from 5R1C-model and BSim follow the the same tendency after increasing the maximum ACR. The number of hours when VC mode [2] is activated has increased in both calculation methods as increased ACRs have a higher cooling effect. Due to higher cooling effect from the VC mode [2], around 50 % reduction in number of overheating hours (VC mode [3]) can be observed. Moreover, higher maximum ACR lowered the indoor air temperature and prolonged the periods when ventilation with minimum ACR is efficient. To observe the effect of increased ACR on thermal comfort, the mean indoor air temperatures during summer months inside working hours are compared.

	$3.5\,h^{-1}$		$5\,h^{-1}$		$10\,h^{-1}$	
	5R1C	BSim	5R1C	BSim	5R1C	BSim
$T_{i,mean}$ - Working hours	25.24	24.18	25.20	24.07	25.25	23.95

Table 12.1. Average Indoor air temperature in summer months inside working hours.

In table 12.1 it can be seen that the indoor air temperature estimated by BSim is around 1 °C lower than the one calculated by 5R1C-model. However, both calculation methods resulted in minor decrease in indoor air temperature if the maximum ACR is increased. Finally, it can be concluded that higher maximum ACR will lead to increase in the VC potential, thus reducing the number of overheating hours. Furthermore, the changes in VC hour distribution are similar to BSim.

12.3 Thermal Mass

In the 5R1C-model a simple approach to deal with the calculated thermal mass is used. The analysed initial case, 3 person office, can be categorised as *Light building* [SBi, a], because of large amount of glazing and suspended ceiling. The load bearing construction is made of concrete. However, it is not exposed, and thereby the effect of the thermal mass from the concrete is low. Total thermal mass of the 3 person office is $63\,\mathrm{Wh/K\cdot m^2}$.

As the results for the initial case showed, a difference between the 5R1C-model and BSim appears. To investigate the robustness of the method, and see the effect from the thermal mass, a variation of thermal mass for the 3 person office is made. The 5R1C-model uses simplified approach of dealing with thermal mass which could be one of the reasons for discrepancy in the results in comparing with BSim.

The investigation is made in three different steps. In each step the thermal mass is increased, and new calculations with the 5R1C-model and BSim are made.

The increase of thermal mass for the 3 person office is divided into following steps:

- **Step 1** - Internal glass wall adjacent to the corridor is changed to a wall made of concrete. Total thermal mass of the room becomes $82\,\mathrm{Wh/K\cdot m^2}$.
- **Step 2** - Two internal walls to the adjacent rooms are changed to walls made of concrete. The changes made in Step 1 are still maintained. Total thermal mass of the room becomes $98\,\mathrm{Wh/K\cdot m^2}$.
- **Step 3** - Ceiling is changed to freely exposed concrete. The changes made in Step 1 and Step 2 are still maintained. Total thermal mass of the room becomes $137\,\mathrm{Wh/K\cdot m^2}$.

The new structure of mentioned construction elements is presented in Appendix E.

At first, the impact from increased thermal mass is presented in figures 12.10, 12.11, 12.12 and 12.13 on the next page. The graphs show the monthly distribution for each step of changed thermal mass.

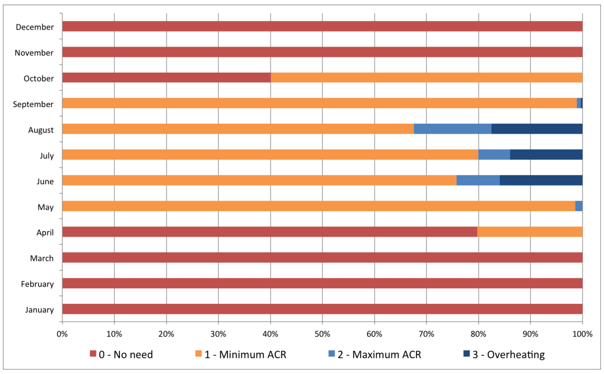

Figure 12.10. 63 Wh/K · m^2. (5R1C-model)

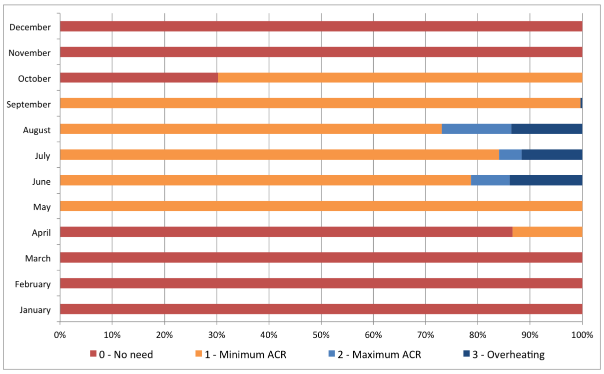

Figure 12.11. 81 Wh/K · m^2. (5R1C-model)

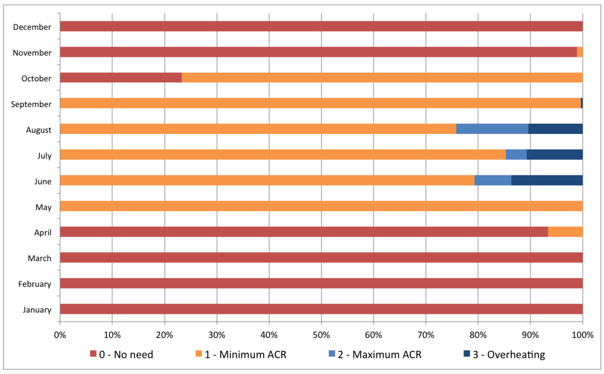

Figure 12.12. 98 Wh/K · m^2. (5R1C-model)

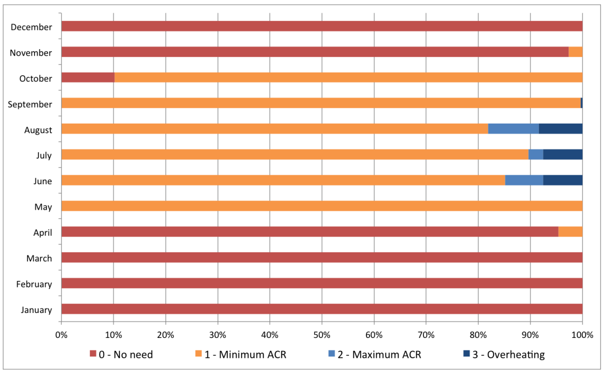

Figure 12.13. 137 Wh/K · m^2. (5R1C-model)

The need for cooling with maximum ACR and hours of overheating decrease by each step. The differences become clear when looking at the results for the initial case (figure 12.10) and step 3 (figure 12.13).

During April the need for heating increases by each step. Furthermore, the opposite tendency appears in October. By each step the need for heating decreases. The amount of decrease in heating need in October is higher than the increase in April, which means that a decrease in overall heating demand for the 5R1C-model appears after increase of thermal mass.

In figure 12.14 and 12.15 on the facing page annual distribution of VC hours is presented for both 5R1C-model and BSim. As mentioned before, the amount of thermal mass is increased by each step, and thereby we end up with a heavy building/room instead of the light as it was initially.

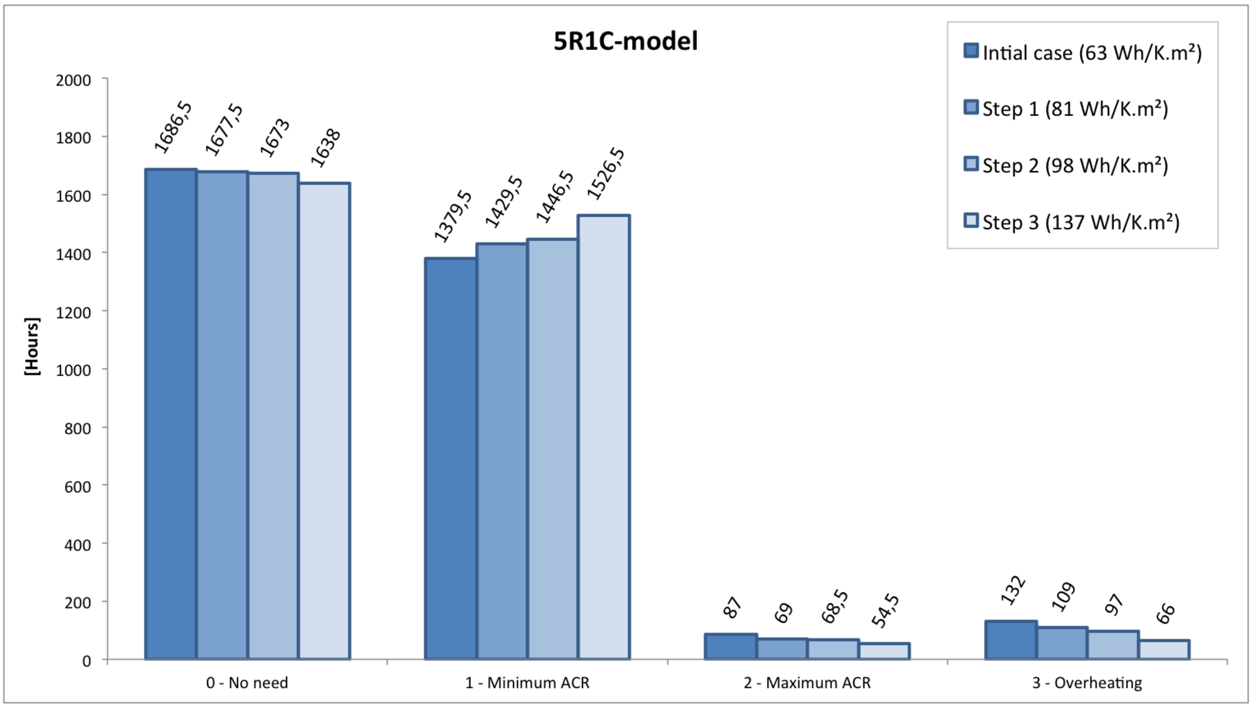

Figure 12.14. VC hour distribution after increasing thermal mass in 5R1C-model. (Working hours)

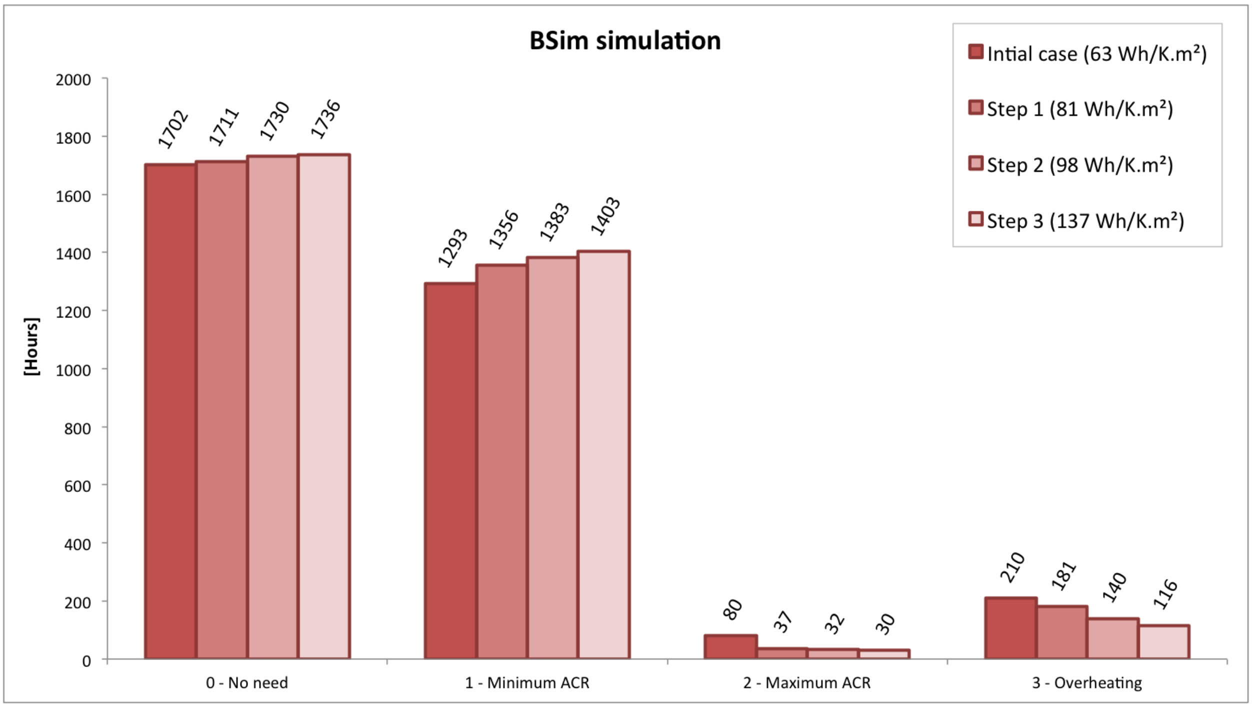

Figure 12.15. VC hour distribution after increasing thermal mass in BSim. (Working hours)

If VC mode [2] and [3] are observed the same pattern can be seen in both calculation methods. The amount of VC hours is decreasing for each mode when the thermal mass is increased. Even though only a low ACR (infiltration) is added during the night, a decrease in overheating hours appear. Increased heat capacity of the room entails that more energy has to be added before the internal air temperature exceeds the cooling set point. Part of the added energy is accumulated in the construction elements which delays the increase in internal air temperature. Since critical internal air temperatures are delayed due to increased thermal mass, ventilating with minimum ACR becomes more efficient.

For VC mode [0] opposite tendency appear for the 5R1C-model and BSim simulation. Furthermore, increase in thermal mass entails a reduction in the heating need in autumn because of thermal inertia from the accumulated heat. These tendencies can be observed when looking at the internal air temperatures for both methods (see calculations on Appendix CD). It was also observed that both methods have nearly the same cooling need in April. However, VC mode [0] is activated much earlier in BSim than for 5R1C-model after the summer. This indicates that BSim is more sensitive to changes in outdoor air temperatures or that the effect from thermal mass is overestimated in the 5R1C-model. It can also be observed in figure 12.16, which shows the calculated internal air temperature for 10^{th}, 11^{th} and 12^{th} of July for step 1.

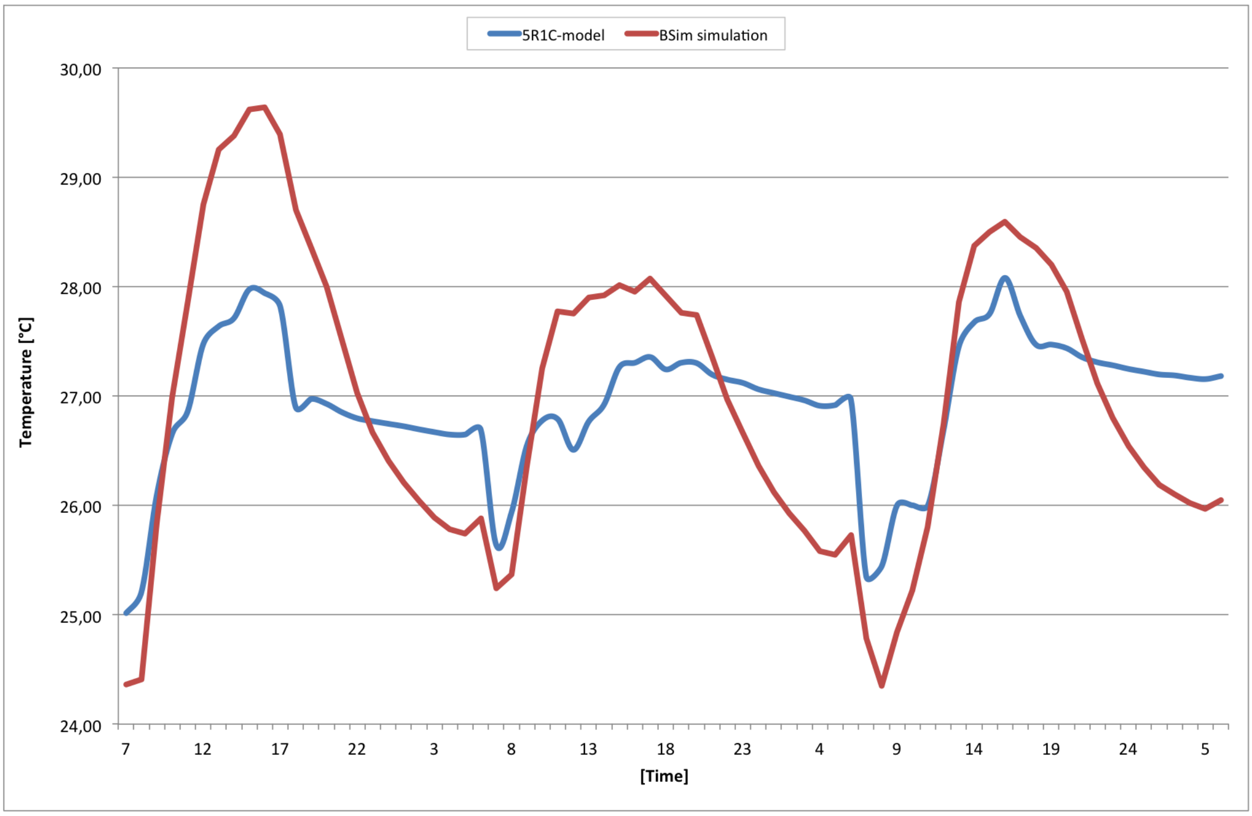

Figure 12.16. Indoor air temperature profiles from the 5R1C-model and BSim simulation. The results are for Step 1 ($81\,\mathrm{Wh/K \cdot m^2}$).

A much more fluctuating temperature appears in BSim, which is the reason for the discrepancy in VC mode [0]. In comparing with BSim, the heating need in 5R1C-model is lower in autumn due to larger effect from thermal inertia. This leads to decrease in VC mode [0]. This is not valid for BSim, which switches to heating much quicker and therefore an increase in VC mode [0] appears.

To see if the same divergence in the results for overheating hours appear for each step of increased thermal mass, VC hours for VC mode [3] are graphically presented in figure 12.17 on the facing page.

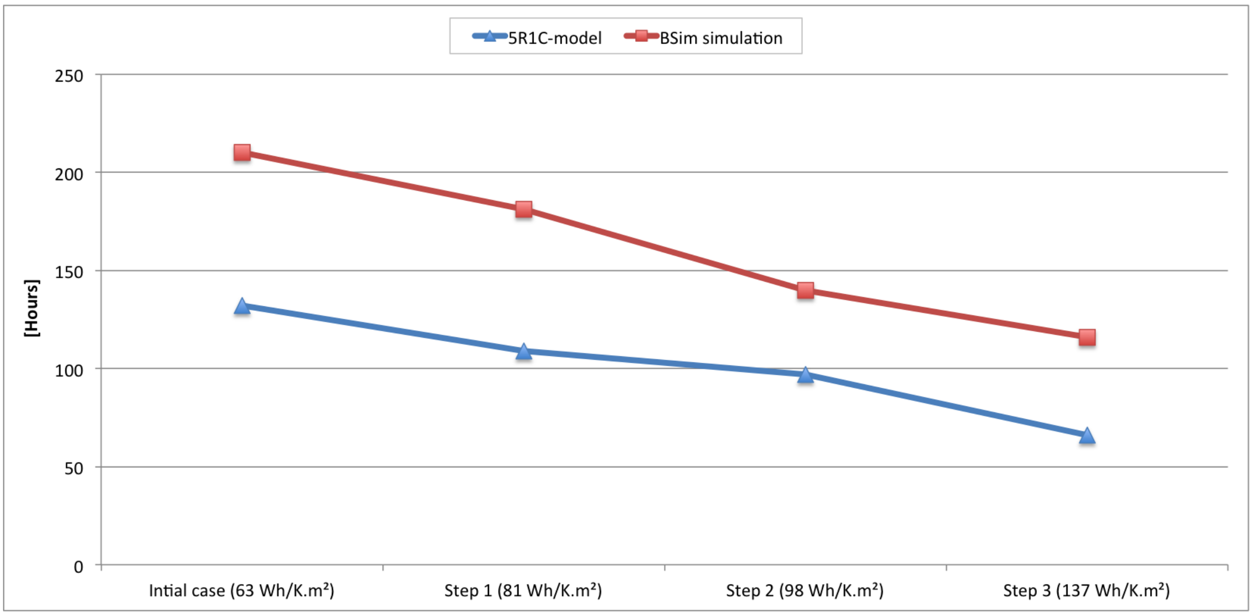

Figure 12.17. Decrease in hours for VC mode [3] by increasing the thermal mass.

The figure shows that the results from the two methods follow the same tendency. This indicates that the 5R1C-model overestimates the effect from thermal mass and thereby estimates more stable and lower indoor air temperatures. Even though the thermal mass is changed, the hours for VC mode [3] changed with the same gradient in both methods. Therefore, one may argue that the approach with only one capacitance and thereby only one temperature for the thermal mass entails a small discrepancy between the results.

12.4 Simplified NTV

So far the VC potential was estimated by the use of natural ventilation during the occupation hours. To see the effect on VC hour distribution from implementation of NTV and to check if the 5R1C-model still generates reliable results, a simple NTV strategy will be introduced and integrated into the 5R1C-model.

This cooling strategy is based on having the room ventilated with constant ACR using the outdoor air in periods when ventilation system is inactive (17:00 till 06:00). At first, the minimum ACR of 1.9 h^{-1} will be used for NTV. Moreover, the NTV is activated only during the summer months (June, July and August). This is because it was previously determined by 5R1C-model that there is a need for NTV (VC mode [3]) only during these three months (see table 11.4 on page 88).

The monthly VC hour distribution is presented in figure 12.18 and 12.19 on the following page for 5R1C-model with and without NTV.

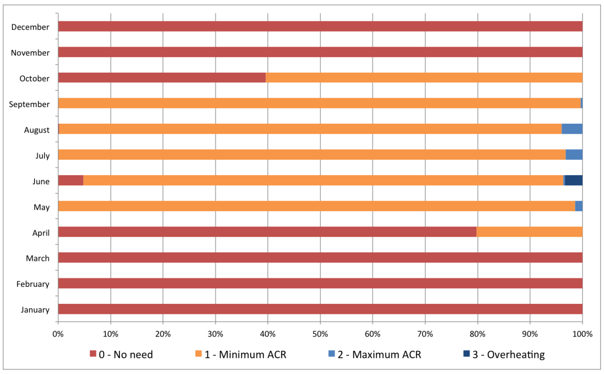

Figure 12.18. With NTV. (5R1C-model)

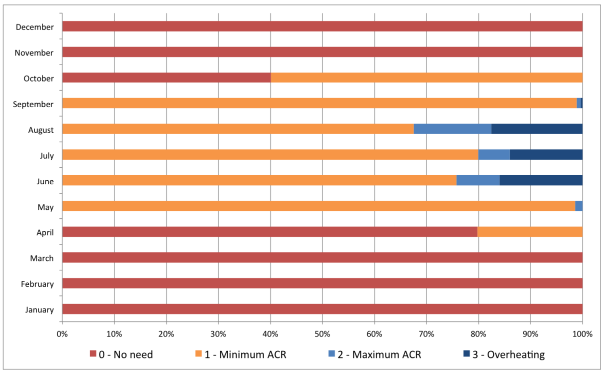

Figure 12.19. No NTV. (5R1C-model)

Most of the hours with overheating are gone after implementation of NTV. The need for heating looks unchanged except for June, where a small increase appear after implementation of NTV. These hours appears after a night with low external temperatures before a weekend, where no internal heat loads appear. To investigate if the control strategy with NTV gives trustworthy results, same NTV strategy is implemented in the initial BSim model for the case study.

Results for initial 3 person office with control strategy 1 using NTV from the 5R1C-model and BSim are shown in figure 12.20.

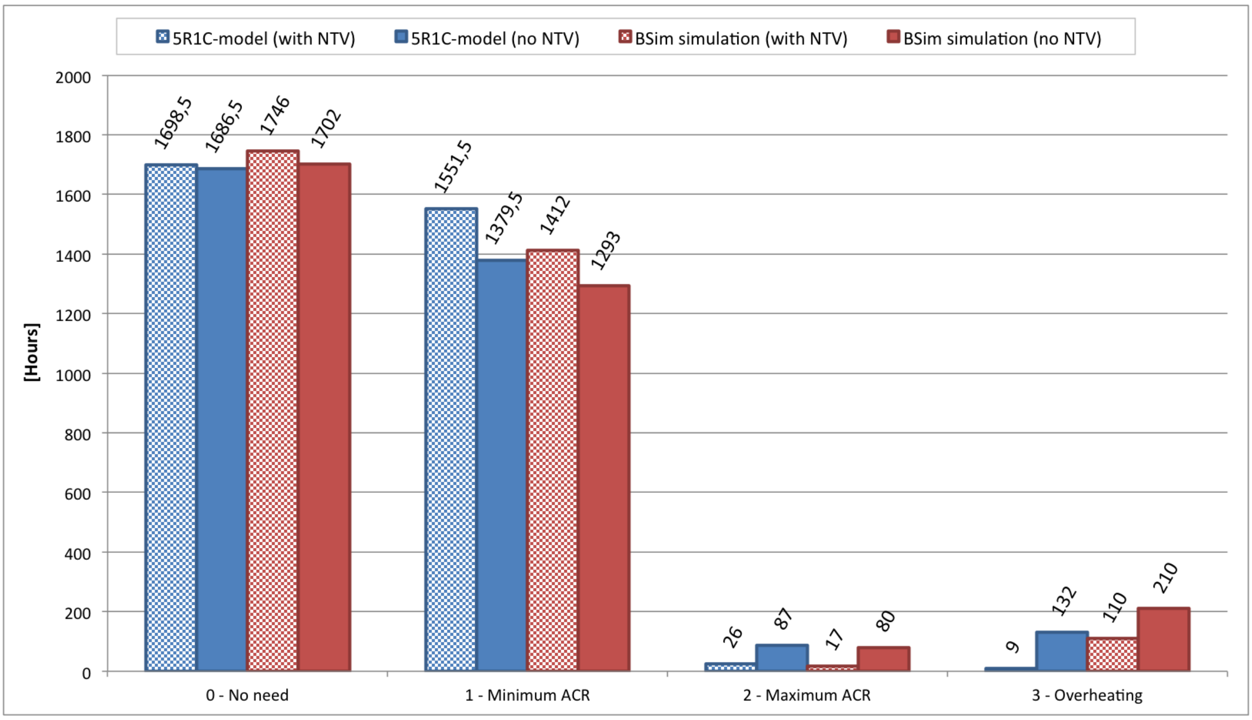

Figure 12.20. VC hour distribution with and without NTV with control strategy 1. (Working hours)

The figure shows that a huge drop in VC mode [3] appears after the implementation of NTV. Even though only the minimum ACR is used, it is very efficient in minimising the overheating issue. Furthermore, the results repeatedly verify that 5R1C-model underestimates the risk of overheating in comparing with BSim. Even tough the results have changed compared to the initial case, the deviation in the results from the two methods is still the same.

It was previously determined that the control strategy has an impact on the results, see section 12.1 on page 101, *Control Strategy 2*. Therefore, calculations with control strategy 2 are made in the 5R1C-model and BSim to observe the effect on overheating after NTV is implemented. The results are compared to control strategy 1 with NTV in figure 12.21. The room is still ventilated with the minimum ACR ($1.9\,\mathrm{h}^{-1}$) during periods when NTV is activated.

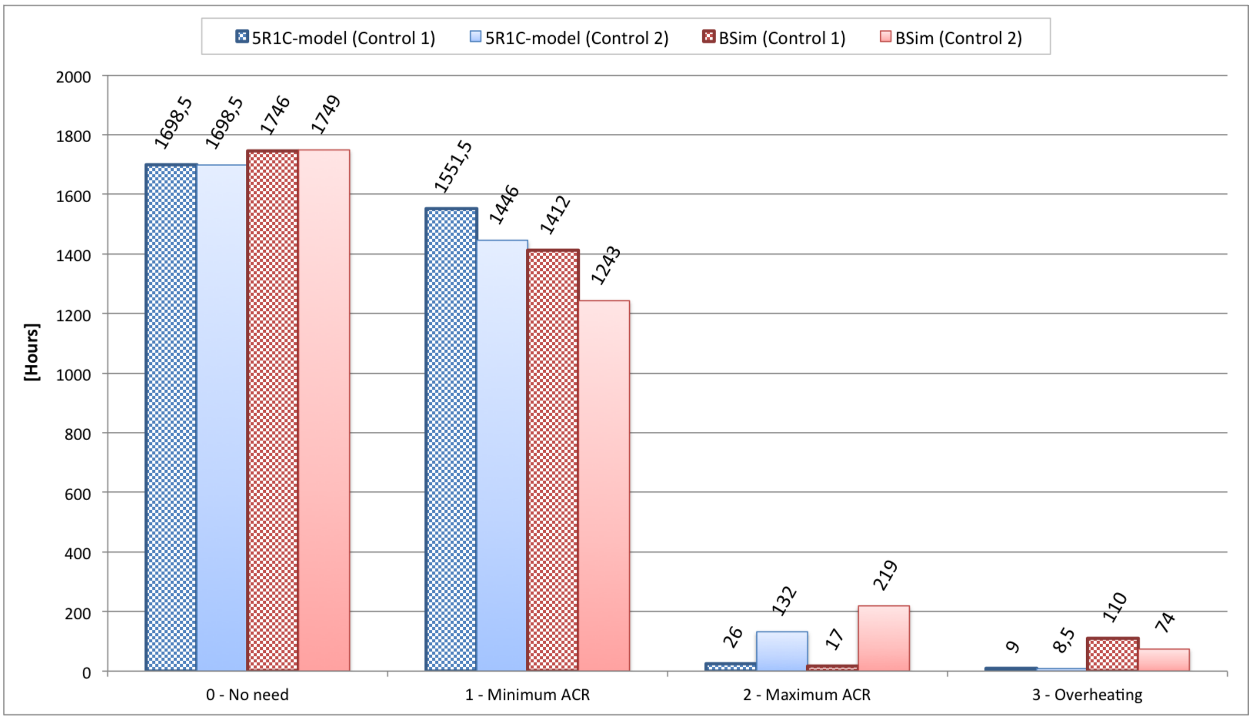

Figure 12.21. VC hour distribution with and without NTV. (Working hours)

Control strategy 2 gives larger number of hours when VC mode [2] is activated. It is because this control strategy has a lower cooling set point than control strategy 1. 5R1C-model still underestimates the number of hours with overheating compared to BSim. The 5R1C-model resulted in almost the same low number of hours when overheating occur for both control strategies. This is valid even though the need for VC mode [3] was not the same without NTV (see section 12.1 on page 101, *Control Strategy 2*). The temperature during working hours is above the comfort range for 9 hours with control strategy 1 and for 8.5 hours with control strategy 2. However, these results become clear if we look closer at the periods when the room is experiencing the overheating. After analysing calculated internal air temperatures (see Appendix CD under *Robustness*) it was observed that the most critical overheating occurs on the 11^{th} of June. The VC modes for 11^{th} of June with both control strategies for 5R1C-model as well as the outdoor air temperature are illustrated in figure 12.22 on the next page.

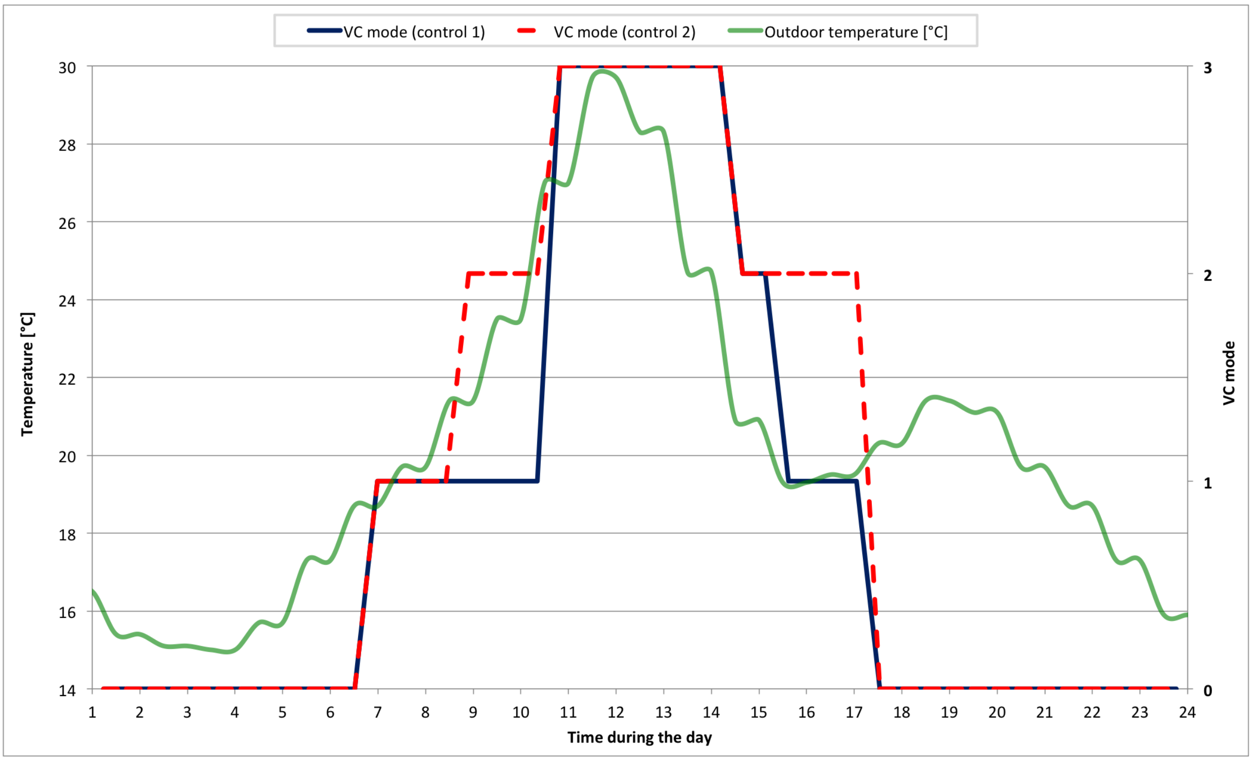

Figure 12.22. Outdoor temperature and VC modes with control strategy 1 and 2 on the 11^{th} of June. (5R1C-model)

The outdoor temperature has exceeded the internal comfort range (20 - 26 °C) already at 10.30, and thereby the outdoor air is not useful for direct ventilative cooling. It can be seen that both control strategies switch to VC mode [3]. Therefore, in periods when outdoor temperature is rapidly raising it is better to keep ventilating the room with minimum ACR. VC mode [1] is used for 6 hours in case with control strategy 1, whereas it is active only for 2 hours with control strategy 2. This is because control strategy 1 has higher cooling set point (26 °C) than in control strategy 2 (24.5 °C). This means that control strategy 2 is starting to ventilate the room with high ventilation rates sooner than it would be if control strategy 1 was used.

To observe the maximum effect from the NTV, a constant ventilation rate equal to the maximum ACR ($3.5\,\mathrm{h}^{-1}$) was enabled outside the working hours during the three summer months. The comparison of NTV for 5R1C-model based on control strategy 1 using minimum or maximum ACR is shown in figure 12.23 on the facing page.

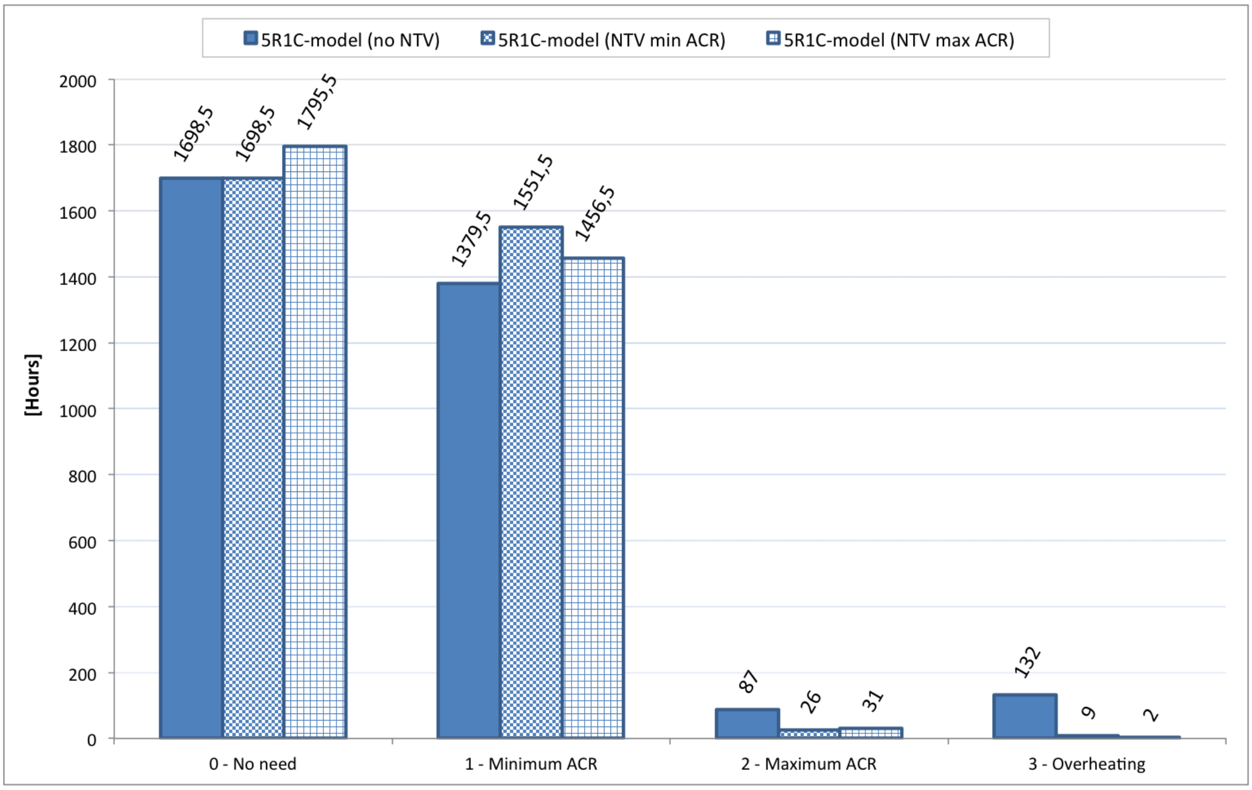

Figure 12.23. Comparison of VC hours for control strategy 1 with NTV. (Working hours)

The number of hours when heating is required has now increased in comparing with previously used ventilation strategies (initial without NTV and NTV with min ACR). This is because increased ventilation rate during the night decreases the room temperature, and entails that heating is needed during some periods (at the start of occupation hours). It can also be seen that the number of hours when increased ventilation rates (VC mode [2]) are activated has decreased by 56 hours in comparing with the initial case. However, the biggest change was observed in decrease of overheating hours (VC mode [3]).

A mayor reduction of the overheating hours may be achieved if the NTV is implemented in the ventilation control strategy. It might also be said that the most optimal ventilation control is the one where NTV with constant ACR of $1.9\,\mathrm{h}^{-1}$is applied outside the working hours during the three summer months. However, this might be valid for this particular case. In other buildings with different loads, construction materials etc. some higher ACRs might be required for efficient utilisation of NTV. Furthermore, the results from 5R1C-model after implementation of NTV follow the same tendencies as BSim.

12.5 Office Type

In this section the robustness of the 5R1C-model will be tested by changing the room type. Therefore, a 1 person office, which is another common office type in Aarhus municipality building, was selected to see if the tool still estimates a realistic VC potential. In comparing with the 3 person office used before, the main differences are:

- Room size (geometry)
- Heat loads

One person offices are located on all floors and have only minor variations in their dimensions. It was decided to look at the office with internal dimensions of 2.80 m x 3.99 m x 3.41 m (height x width x depth) which is located on south side on the top floor of the case study building. It is assumed that the room is occupied by one person with the occupation intensity of 85 %. The occupation period is all year from 08.00-17.00 during the weekdays, which means that, in this case, there is no summer vacation. [Grontmij, 2011]

In comparing with 3 person office, the total value of internal heat load from persons, equipment and lighting is lower as there are less people and equipment inside the room. The heat loads per floor area are presented in table 12.2.

	All year (excl. summer) $[W/m^2]$	Summer vacation $[W/m^2]$
1 person office	24.2	24.2
3 person office	27.4	20.2

Table 12.2. Heat loads during the year.

The heat load per floor area is slightly lower for 1 person office than for 3 person office. However, during the summer holidays the value of internal heat loads for 1 person office is larger than in 3 person office, as there are only 2 persons during this period in the 3 person office.

The room is ventilated by means of single sided natural ventilation. Minimum ACR for atmospheric comfort is calculated to be 1.56 h^{-1} [Dansk Standard, 2007]. Maximum ACR remained the same as it was in case with 3 person office (3.5 h^{-1}), based on information from [Grontmij, 2011].

Heating and cooling set points are the same as they were in the initial case. Thermal comfort is ensured using the control strategy 1.

Construction elements and windows are also the same as they were in the initial case.

The monthly VC hour distribution is presented in figure 12.24 and 12.25 for 5R1C-model and BSim.

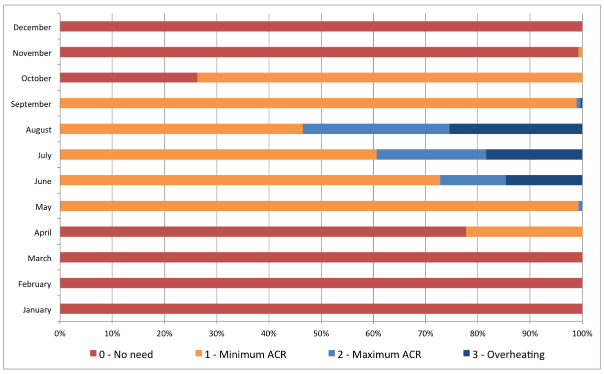

Figure 12.24. 5R1C-model. (1 person office)

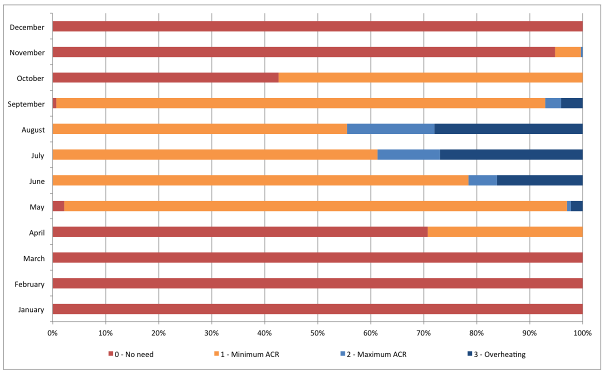

Figure 12.25. BSim. (1 person office)

Almost the same VC hour distribution is found in the two tools. It is difficult to see the exact differences in distribution of VC mode [1] [2] and [3]. Therefore, the results for 1 person office are summarised and presented in figure 12.26.

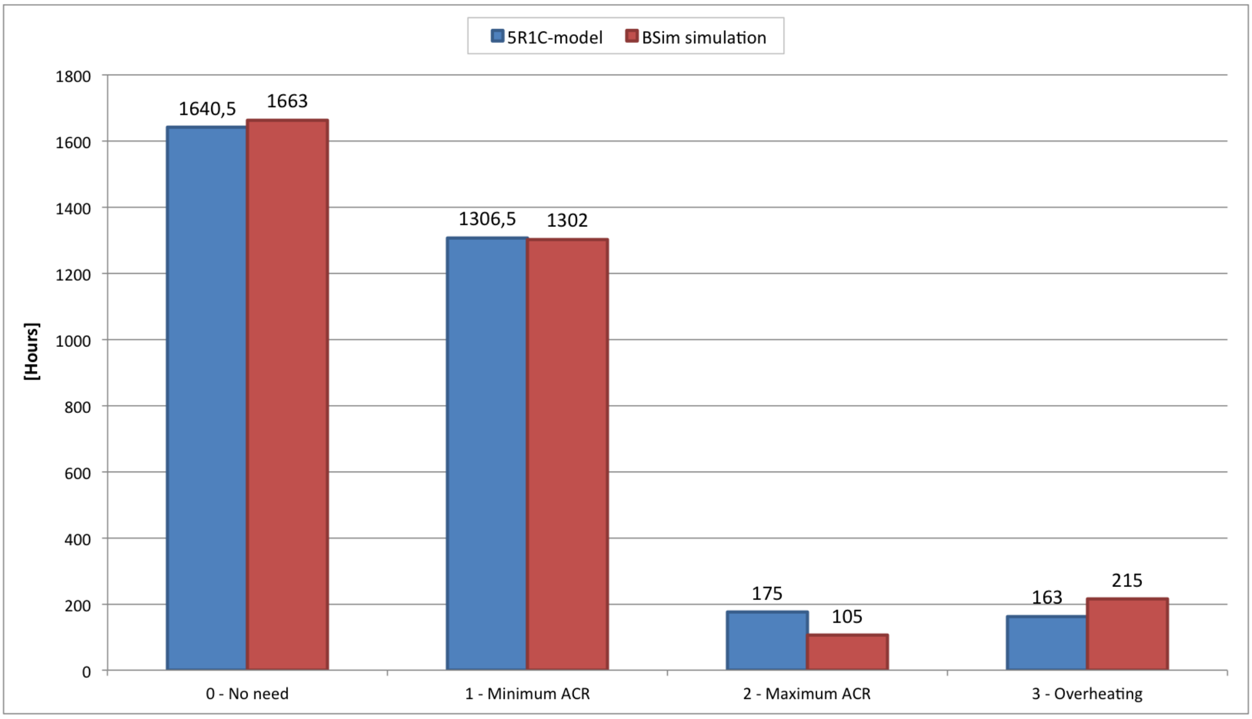

Figure 12.26. VC hour distribution for 1 person office. (Working hours).

Once again the results from the 5R1C-model are in a good correlation with results from the BSim simulation. However, there is a difference for VC mode [3] (52 hours) between the two methods. This difference is decreased compared to the initial case study for the 3 person office.

12.6 Extreme Cases

In the previous sections it was observed that the largest deviation between the 5R1C-model and BSim occur in calculated number of hours when VC mode [3] is activated. The difference in results between 5R1C-model and BSim is illustrated in figure 12.27.

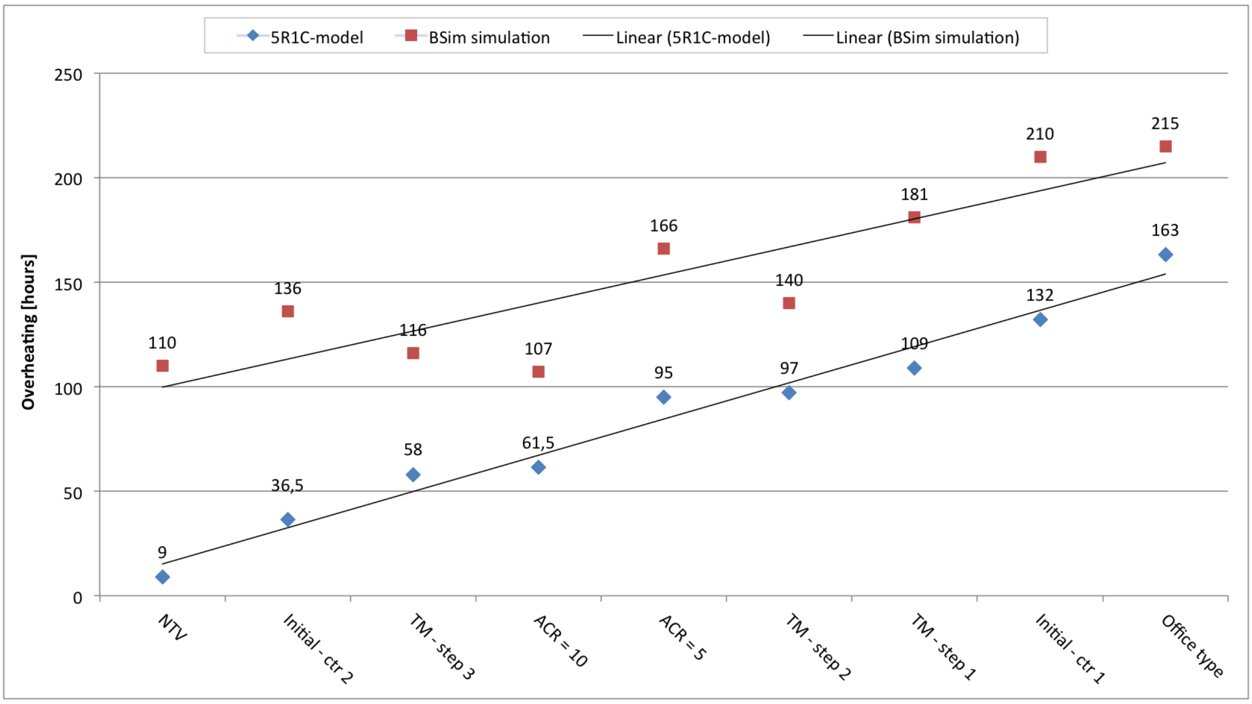

Figure 12.27. Number of overheating hours from previous cases. (Working hours)

The graph shows that 5R1C-model in all cases estimates less overheating hours than BSim does. However, these results only cover the range from 9 to 210 hours, which is not that critical. It would be interesting to see how the results look in extreme cases with more overheating hours. The aim of this section is to subject the 5R1C-model to different combinations of increased internal and solar heat loads to observe the deviation in estimated overheating hours between the 5R1C-model and BSim.

Therefore, 3 person office with control strategy 1 without NTV will be subjected to increase in heat loads. Input parameters that are going to be changed are: climate and heat loads.

Different Climate
To observe the difference in overheating hours if the building is located in different climate, climate data for Barcelona are implemented into 5R1C-model and BSim simulation. Barcelona is selected due to appearance of more extreme weather conditions during the summer period (higher outdoor air temperatures and solar loads). It is expected that the number of overheating hours will be significantly higher if compared to the initial climate zone (Denmark).

People Load
In reality, there might be situations when there are more people in the room than it was originally designed. For example, such situation may occur if there is a meeting. Therefore, it is interesting to see how the increase in internal heat loads from people affects the difference of calculated number of hours when VC mode [3] is activated. The increase in people loads is performed in two steps:

- **Step 1** - It was assumed that there is no summer vacation and there are 3 persons in the office all year round.
- **Step 2** - The number of people that are occupying the room is increased from 3 to 6 persons (no vacation).

Solar Loads
In order to see if changes in solar heat load will still have the same pattern in resulting number of overheating hours as shown in figure 12.27 on the preceding page, it was decided to make changes in the solar heat gains. At first, the amount of heat entering the room due to solar radiation is gradually increased by changing the amount of shading of the facade window bands in BSim. Afterwards, data regarding energy from sun through window (qSunRad) for every hour are extracted from BSim and implemented into the 5R1C-model. Solar heat loads are increased in following steps:

- **Step 1** - Solar shading is deactivated only in the upper band windows.
- **Step 2** - Solar shading is deactivated only in the middle band windows.
- **Step 3** - Solar shading is deactivated in upper and middle window bands.

It must be noted that the lower window band does not have any solar shading devices.

The results illustrating number of hours with overheating (VC mode [3] in 3 person office with changed climate, people load and solar shading are compiled in figure 12.28 on the following page together with cases presented in figure 12.27 on the preceding page.

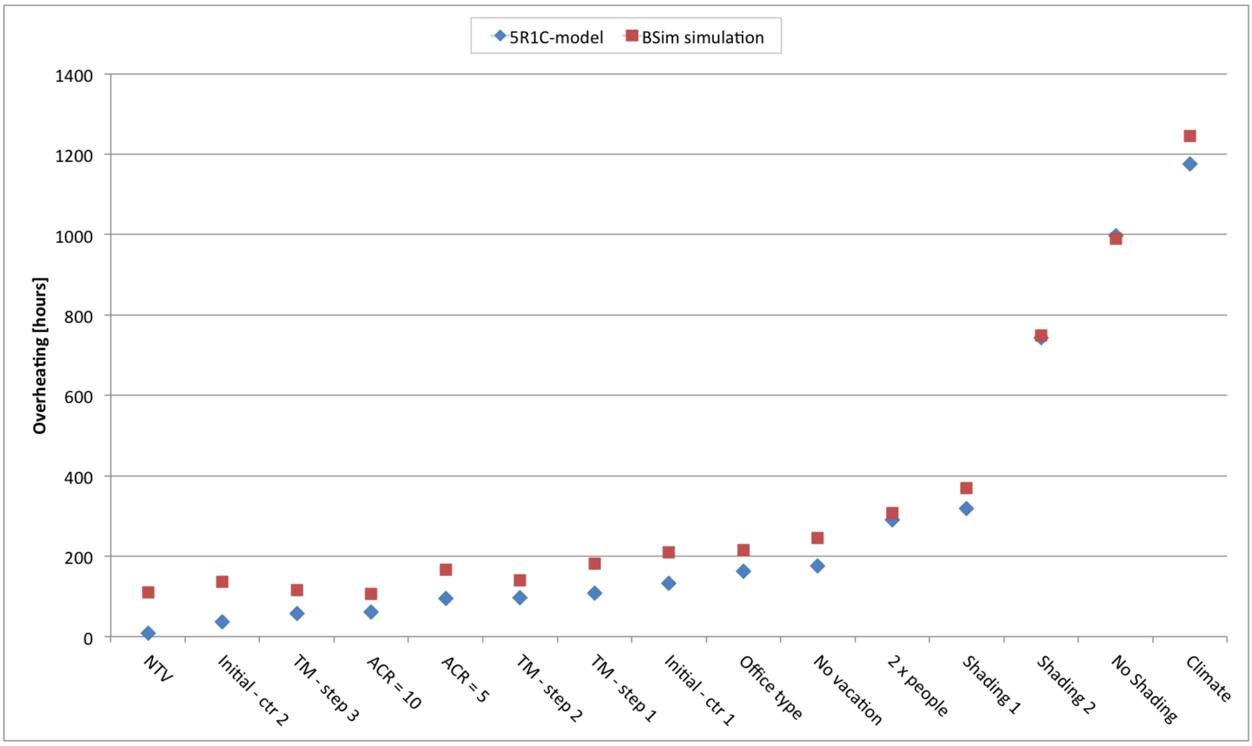

Figure 12.28. Comparison of overheating hours form 5R1C-model and BSim. (Working hours)

After running the above mentioned simulations, the resulting number of overheating hours varied from 9 to 1245 hours. By analysing all calculation cases, it was found out that the difference between the results of 5R1C-model and BSim simulation has a tendency to decrease with the increase in calculated overheating hours. It was observed that the smallest difference of resulting overheating hours occurred when the amount of solar shading was reduced. Moreover, in case with no solar shading BSim calculated lower amount of overheating than 5R1C-model. This is the only calculation case when BSim estimated lower amount of overheating hours than 5R1C-model. It was also noticed that the difference between the results decreased when the people load was doubled. These observations lead to conclusion that 5R1C-model generates more realistic results in cases with high solar and internal heat loads. Complete Excel Calculations and BSim simulations can be found in Appendix CD.

13 Discussion

VC Buildings in Denmark

During the state-of-the-art investigation of ventilatively cooled buildings it became evident that mainly one company (WindowMaster) have designed the solutions. At this point, the Danish market of automated control of natural ventilation (including direct VC) is dominated by this particular company. The obtained knowledge about VC design is compiled from extensive literature studies. This entails that it is possible to objectively evaluate the ventilatively cooled building stock in Denmark, thus allowing to find characteristic design patterns. It became evident that VC solution is designed specifically for each particular building, and no standard VC solutions are applicable. The solutions are affected by different limitations for example is it new or renovated building, and which type of building it is. Even though most of the material regarding VC cases was provided by one company, individual VC design approach is still noticeable. Therefore it can be argued that the obtained general design patterns for VC buildings in Denmark are presented objectively.

As the determined design patterns are based on information mainly regarding office and educational buildings, question my arrive if these are applicable for residential and other type of buildings. In terms of influence from site, layout, form and morphology, the VC design principles remain the same for residential buildings. However, attention need to be paid to the control strategy due to different occupation periods and indoor climate requirements.

VC Potential Tools

The main goal of a simple decision making tool is that it leads to the same conclusion as if a more advanced tool was used. When a simple predesign tool is used to estimate the potential for ventilative cooling, the final results should indicate if it is possible to cool the building by ventilative cooling. For example, it might lead to a conclusion that natural cooling is not capable to deal with the cooling need and mechanical cooling is needed.

At first glance, the results from original EURAC VC potential tool looked promising. However, the validation of the tool by comparing it to BSim revealed some issues. The tool tends to underestimate the number of overheating hours. For example, the estimated number of overheating hours for the initial 3 person office was nearly five times (169 hours) lower than in BSim. This might entail misleading conclusion that ventilative cooling can cover the need for cooling, and NTV or mechanical ventilation is not needed. Furthermore, the effect from ventilating with the minimum ACR is significantly underestimated. The steady-state methodology entails these discrepancies in the results as the cooling effect from the previously calculated ACR is not taken into account. In addition, the approach of estimating the cooling need is doubtful. The idea of using a heating balance point temperature based on constant internal temperature set point and constant heat loads entails misleading results. In reality, the highest internal heat load occur often during the day, which coincides with the highest solar loads. This could entail more critical overheating problems. Furthermore, the EURAC VC potential tool does not take the thermal mass of the building into account. In reality, most of the buildings in Denmark can be classified as medium or heavy thermal mass buildings. It is expected that the discrepancy in results will decrease in case with medium or heavy thermal mass buildings. The higher amount of thermal mass would often decrease the number of overheating hours in the reality. This is different in the original EURAC VC potential tool, as the thermal mass of the building does not have an impact on the results. As only a light building was investigated with EURAC VC potential tool, the actual effect from increased thermal mass is not tested.

Unfortunately, after implementation of varying heat loads and bounding the ACR, the modified EURAC VC potential tool did not result in more trustworthy results. Therefore, one may argue that steady-state approach does not yield accurate results in predicting the VC potential. The tool is not useful to estimate the VC potential in Denmark, however the results might improve in other climate conditions.

As the results for the case study showed, the estimation of VC potential by 5R1C-model are in good correlation with BSim. Furthermore, the same similarity was seen during the robustness analysis of the 5R1C-model. The investigation of heating impact on VC hour distribution revealed that no significant changes during the cooling season appear, after heating was enabled in BSim. The investigation of impact from different control strategies entails that the 5R1C-model is capable of generating acceptable VC hour distribution. Changing the thermal mass revealed that the simple approach of dealing with the thermal mass could be the reason for underestimation of overheating hours in 5R1C-model. This means that the way the thermal mass is calculated is not the reason for overestimation of hours with overheating.

There is a small need for VC during the transient months. Heating is not implemented in 5R1C-model, which might slightly underestimate the cooling need during this period. Heating was implemented in BSim and the results for the cooling season remained unchanged. However, an increase for VC mode [1] outside cooling season appeared. It turned out that VC mode [1] accounts for ventilation needs for both indoor air quality (health) and thermal comfort. If a better distinguish between these to aspects was integrated in selection of VC modes, it would be easier to evaluate the exact impact from heating. If a cooling need in the transient season or winter would appear, this need should be handled with care. Cooling during winter and transient season with cool external air would typically lead to thermal discomfort. Therefore, technical solutions with either preheating of the ventilation air or heat recovery must be considered. Since the cooling need during the transient months is insignificantly small if compared to the one in summer months, it was decided to disregard heating in the 5R1C-model.

In the 5R1C-model the estimation of thermal mass is simplified. The value of thermal mass is slightly overestimated compared to a more advanced method. For the case study, these differences did not lead to any noticeable changes in the estimated VC potential. Therefore, the simple approach of estimating the thermal mass is maintained in the 5R1C-model.

As the name (5R1C) of the model indicates, only one capacitance is used to deal with thermal mass. This is different from BSim, were several capacitances are used. This simplification could be the reason for the differences in the calculated VC potential in the case study. During the investigation of the robustness several calculations with increased thermal mass where made.

The same underestimation of overheating hours appeared. This simple approach entails that the calculated internal air temperatures are more stable than in BSim. More stable temperatures and less overheating indicates that the effect from the thermal mass is overestimated by 5R1C-model. The extreme cases with high number of overheating hours showed some notable results. The deviation in overheating hours considerably minimised after the heat loads were increased. This could indicate that the simple approach with one capacitance for the thermal mass was the main reason for the discrepancy in the earlier results. The increased heat loads become the dominant factor in the extreme cases. In cases with high heat loads the impact from dealing with the thermal mass is not distinctive. Furthermore, BSim accounts for the increase in temperature in the outer thermal mass due to solar radiation. This entails a reduction in transmission loss through the construction.

When designing a simple tool it is important to stick to simple and reliable solutions, which is also applicable to the control strategy. The control strategy and the VC mode selection algorithm are connected. After increased maximum ACR and simplified NTV were implemented in the tool, it still provided realistic results. The VC hour distributions changed as expected, and fit rather well with the VC hour distribution from BSim.

Transparency, robustness and reproducibility are very important qualities of calculation tools. Developed VC potential tool (based on 5R1C-model) can be considered being transparent, as it is easy to keep track of each calculation step. This is because the VC potential is estimated based on dynamic energy balance calculation that consists of a set of equations containing trustworthy values with known background. Furthermore, the tool is created on the Excel platform, which is well known and familiar to most of the users. During the robustness analysis it is proven that the VC potential tool, based on 5R1C-model, can be considered as robust since it is able to produce results with rather good accuracy under different inputs. Thus, one may argue that 5R1C-model is able to generate rather accurate prediction of VC potential in office buildings of different size and complexity. Another important requirement for calculation method is reproducibility, which means that the calculation method will generate the same result regardless of the user. So far the reproducibility of the method has not been tested as the tool has only been used by the authors. To argue that the method is reproducible, the VC potential tool, based on 5R1C-model, still needs to be tested by others. In terms of affordability and efficiency the 5R1C-model can be described as easy to learn and use. The input data regarding building geometry, materials and climate data are easy to acquire and enter into the calculation tool. Moreover, monthly VC hour distribution is clear and easy to read from the bar graph and summary table. Further improvements must be made in estimation of solar heat loads, before the reproducibility of the model can be tested.

The developed VC potential tool based on 5R1C-model is named *VC-Advisor*, and can be found in Appendix CD.

14 Conclusion

By looking at the climatic conditions in Denmark, it was found out that there is a considerable climatic cooling potential. During the work on the database of Danish buildings with natural ventilative cooling, it was observed most of the cases are office and educational buildings. The analysis emerged that cooling efficiency is largely dependent on building design elements such as location, form, envelope as well as the internal layout of the building. This means that naturally cooled buildings are subjected to several limitations in their design. Naturally cooled building must be designed in such a way that natural driving forces of ventilation system are enhanced if ventilative cooling should be the main cooling system. Therefore, in order to end up with efficient cooling solution, natural cooling should be considered already during the early design phase.

During state-of-the-art investigation of naturally cooled buildings in Denmark, it was observed that VC enhancing solutions, like land and sea breeze together with man-made wind guiding solutions, are utilised to facilitate the performance of natural ventilation. By looking at the form of the observed buildings, it became evident that long stretched box type multi-storey buildings placed perpendicular to the prevailing wind direction are preferred for efficient utilisation of VC. In large, quadratic-formed buildings, an atrium located in the middle of the building, or a staircase with operable ventilation openings in the roof are typical solutions for enhancing the performance natural ventilation. Open plan morphology is desirable in naturally cooled buildings as there is less resistance to the airflow paths inside the building.

Depending on which ventilation principle is used, it became evident that the position of ventilation openings is selected in a way to facilitate the performance of natural driving forces as well as to minimise the risk of draft. The most widely used natural ventilation principle in observed newly built buildings is stack ventilation, whereas single-side ventilation is used as main ventilation principle in renovated buildings. When looking at the ventilation principles from the ventilative cooling perspective, it became clear that some problems with the efficiency of stack ventilation might occur during the summer due to low temperature difference. To overcome this issue many buildings are using multiple ventilation principles. For example, wind driven cross or single-side ventilation are used in periods when stack ventilation cannot be utilised. Hybrid ventilation with fans is implemented in many buildings to assist the natural ventilation to secure the needed ACR regardless of weather conditions. It was also observed that during the periods when outdoor temperature is low, mechanical ventilation with heat recovery is used in most of the buildings that are compiled in the database.

In order to facilitate the utilisation of ventilative cooling in newly designed as well as renovated buildings, a simple VC potential tool, based on dynamic heat balance calculation, is developed by the project group. 5R1C-model is intended to be used in decision making process during predesign phase of cooling system.

Comparison of results between 5R1C-model and BSim reviewed only slightly difference in VC mode [3], while the results for VC mode [0], [1] and [2] were almost similar. The 5R1C-model shows the right tendencies but tends to slightly underestimate the number of hours with overheating.

Since the 5R1C-model originally does not include the heating option, the analysis of heating impact on the VC hour distribution was performed in BSim. It was found out that heating has an insignificant impact on the VC mode [2] and [3] during the transitional months. Thereby, it was concluded that the implementation of heating does not have a significant impact on VC potential during the cooling season. This is because overheating most likely occurs during the summer and not during the transient or winter months.

Simulations with different thermal mass showed that the increase in thermal mass considerably decreases the number of overheating hours. When investigating the effect of thermal mass on VC hour distribution, interesting observations regarding VC mode [1] were noticed during spring and autumn. The number of hours of VC mode [1] decreased in 5R1C-model, whereas it increased in BSim. This is related to different approach in evaluation of the effect from thermal mass, which also was observed in the diurnal temperature swing. The calculated internal air temperatures for the 5R1C-model are more stable than the results from BSim. Deeper analysis of the overheating hours revealed that the number of hours change with the same gradient in both 5R1C-model and BSim when the thermal mass is gradually increased. This indicates that the 5R1C-model overestimates the effect from thermal mass and thereby estimates more stable and lower indoor air temperatures.

During the validation and robustness analysis of 5R1C-model it was found that the tool works well under different initial conditions. Improving the control strategy, increasing the ACR, implementation of NTV or increasing the building thermal mass in the 5R1C-model entailed the expected changes in results.

So far the 5R1C-model has proven to yield a reliable estimation of VC potential. The results in all variations (control strategy, thermal mass, ACR, NTV) of the case study office space were always in a good correlation with the results from the BSim simulations. The investigation of robustness by submitting the 5R1C-model to different combinations of increased internal and solar heat loads showed that the deviation in overheating hours between the 5R1C-model and BSim has a tendency to decrease with the increase of heat loads. However, it is not yet proven that this tool will work for other buildings as it has only been tested on theoretical models. This project leads to the final conclusion that the 5R1C-model based on dynamic heat balance looks promising and generates reliable estimation of VC potential. This means that is possible to get a reliable estimation of VC potential by simple predesign tool already in the early design phase.

Because the 5R1C-model is intended to be used during the decision making process of VC design during the predesign phase, it is decided to rename the tool to VC-Advisor.

15 Recommendations for Further Work

Currently, one of the most obvious shortcomings of the VC potential tool based on the 5R1C-model is its inability to determine the internal solar loads. So far data regarding the amount of heat entering the room due to solar radiation were extracted from the results of BSim simulation. Therefore, accurate calculation method for determination of solar heat loads must be implemented in 5R1C-model to use it as a stand-alone tool.

Furthermore, several improvements could be added to the control strategy. First of all, several external air temperature set points could be implemented into the existing control strategy. The minimum allowable outdoor air temperature could be specified. This would ensure that the room is not ventilated with too cold outdoor air, thus eliminating the risk of cold drought and moisture condensation related problems. Another set point could be related to maximum allowable ventilation air temperature used for cooling with increased ACRs. In periods when there is a rapid increase in outdoor air temperature it would be beneficial to start ventilating the room with minimum ACR already before the cooling set point is reached. Thus, the increase of indoor air temperature would be slowed down and offset to later.

In order to further investigate the impact from the simplified application of thermal mass, more simulations with different thermal mass and heat loads could be performed. Special attention should be put on simulations with low thermal mass. This is because it is expected that the divergence between the results of 5R1C-model and BSim should decrease in low thermal mass buildings. Hopefully, these calculations would verify previously made conclusion regarding the effect from thermal mass and lead to a solution for minimising the discrepancy between the results.

5R1C-model needs to be tested under laboratory conditions to test its reproducibility. The tool must be further validated by testing it on other buildings by performing a set of field measurements and then comparing the obtained results to the predicted VC potential from the 5R1C-model. The method has been verified by comparing the results with only one building indoor climate simulation program. It might be good in comparing with BSim, but the results could also be compared to other simulation programs (EnergyPlus, IDA ICE), real cases or experiments.

To observe the complete impact from the heating system during the transient months, the selection algorithm for VC mode [1] could be changed by splitting it into two parts: ventilation need for indoor air and quality and ventilation need for thermal comfort. One way of doing this would be by looking at calculated ACR. For example, if the calculated ACR for cooling is equal or higher than 70 % of the minimum ACR, it would be considered that VC is needed. The rest part of VC mode [1] would be considered as room ventilation due to indoor air quality.

Finally, it must be noted that some work must be done to make the tool more organised and user friendly and still maintain its simplicity and transparency. So far it is difficult to estimate the uncertainty of the calculation tool. More detailed sensitivity analysis of the input parameters should be performed, to determine the uncertainty of the tool. For example, sensitivity analysis of thermal mass, heat loads and ACRs is needed before concluding on the uncertainty of the tool.

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Part IV

Appendix

EURAC VC Potential Tool A

In the following a calculation example with the original EURAC VC potential tool is presented. All calculations can be found in the Appendix CD.

A.1 Calculation Example

In this part the calculation example is made using the original EURAC VC potential tool. Calculation example is made for standard 3 person office located on the south side of the building. Data regarding example room geometry are shown in table A.1:

Parameter		**Value**
Floor height [m^2]	H	2.8
Envelope area [m^2]	$A_{envelope}$	14.23
Heated floor area [m^2]	A_{floor}	27.93

Table A.1. Room geometry.

Calculation starts with specifying the building assumptions:

- **Total internal plus solar heat gains [q_{in+s}]** are obtained as follows:

$$q_{in+s} = \frac{q_{people} + q_{equipment} + q_{sun}}{A_{floor}} = \frac{255\,\mathrm{W} + 255\,\mathrm{W} + 205\,\mathrm{W}}{27.93\,\mathrm{m}^2}$$
$$= 25.5\,\mathrm{W/m}^2$$

  Where:

q_{sun}	Daily average heat load from the sun during cooling season [W]

- **Minimum required mass flow rate [$\dot{m}_{min}$]** of the ventilation system is determined using the methodology described in [Dansk Standard, 2007]:

$$\dot{m}_{min} = 3\,\mathrm{pr} \cdot 7\,\mathrm{l/s/pr} + 27.93\,\mathrm{m}^2 \cdot 0.7\,\mathrm{l/s/m}^2$$
$$= 40.55\,\mathrm{l/s} = 1.84\,\mathrm{h}^{-1}$$

- **Average heat transfer coefficient of the external constructions [U_{avg}]**. In this case it is the average U-value of the external wall, windows and roof constructions.

$U_{avg} = 0.45\,\mathrm{W/m^2 \cdot K}$

The next step is to specify the temperature control. The temperature control set points are listed in table A.2

Set point		**Value**
Maximum dew point temperature [°C]	T_{dp}	17
Internal cooling set point during the day [°C]	$T_{i,csp,day}$	26
Internal cooling set point during the night [°C]	$T_{i,csp,night}$	28
Internal heating set point during the day [°C]	$T_{i,hsp,day}$	20
Internal heating set point during the night [°C]	$T_{i,hsp,night}$	14

Table A.2. Temperature control set points.

Now the outdoor heating balance temperature ($T_{o,hbp}$) can be calculated according to equation A.1.

$$\begin{aligned} T_{o,hbp} &= T_{i,hsp} - \frac{q_{in+s}}{m_{min} \cdot c_p + \sum U_{avg} \cdot \frac{A_{envelope}}{A_{floor}}} \\ &= 20\,^{\circ}\mathrm{C} - \frac{25.5\,\frac{\mathrm{W}}{\mathrm{m^2}}}{1.432\,\frac{\mathrm{l}}{\mathrm{s}} \cdot \mathrm{m^2} \cdot 1006\,\frac{\mathrm{W}}{\mathrm{m^2 \cdot K}} + 0.45\,\frac{\mathrm{W}}{\mathrm{m^2 \cdot K}} \cdot \frac{14.23\,\mathrm{m^2}}{27.93\,\mathrm{m^2}}} \\ &= 6.98\,^{\circ}\mathrm{C} \end{aligned} \tag{A.1}$$

In order to illustrate the selection of VC modes at exact date and time needs to be specified. For example, 13:00 on the 12^{th} of May can be selected. Data regarding time and climate are shown in table A.3.

Date	Time	$T_{o,db}$ [°C]	RH [%]	$T_{o,dp}$ [°C]
12.05	13:00	14.0	65.2	7.0

Table A.3. Time and weather data.

The VC mode can be selected based on the evaluation criteria described in section 7.2 on page 58, *Tool Description*. In this case the outdoor temperature is within the range of VC mode [2], which states that direct ventilative cooling is useful when:

$$\begin{aligned} T_{o,hbp} + (T_{i,csp} - T_{i,hsp}) &\leq T_{o,db} \leq T_{i,csp} \\ 6.98\,^{\circ}\mathrm{C} + (26\,^{\circ}\mathrm{C} - 20\,^{\circ}\mathrm{C}) &\leq 14\,^{\circ}\mathrm{C} \leq 26\,^{\circ}\mathrm{C} \end{aligned}$$

and the outdoor dew point temperature ($T_{o,dp}$) is lower than 17 °C (or 65 % RH):
7.0 °C <17 °C

Required ventilation rate for cooling can be calculated from equation 8.1 on page 62:

$$
\begin{aligned}
\dot{m}_{calc} &= \frac{q_{in+s}}{c_p \cdot (T_{i,csp} - T_{o,db})} \\
&= \frac{25.5\,\frac{\mathrm{W}}{\mathrm{m}^2}}{1006\,\frac{\mathrm{J}}{\mathrm{kg \cdot K}} \cdot (26\,^{\circ}\mathrm{C} - 14\,^{\circ}\mathrm{C})} \\
&= 0.002\,\frac{\mathrm{kg}}{\mathrm{s \cdot m^2}} = 2.26\,\mathrm{h}^{-1}
\end{aligned}
$$

In this case the calculated ventilation rate ($\dot{m}_{calc}$) is lower than maximum possible ventilation rate by single side ventilation ($\dot{m}_{max} = 3.5\,\mathrm{h}^{-1}$), which means that it is realistic to cool down the room by means of direct VC.

5R1C-model B

In the following a calculation example with the 5R1C-model is presented. All calculations can be found in the Appendix CD..

B.1 Calculation Example

The following section describes the calculation and assumptions made for the calculation of the heat balances for a *3 person office*.

Before starting the calculation for each time step, different constants for the room have to be calculated. They are calculated based on the formula revealed in chapter 8 on page 61, *5R1C-model*. The calculation can be seen in the Excel document, *5R1C-model - Case study*, in the Appendix CD. The different constants for the room are:

Parameter	**Value**
S	6302.38 kJ/C
$H_{tr,ms}$	1583.81 W/°C
H_{ve}	*Varying*
H_{sa}	284.95 W/°C
H_{tr}	12.24 W/°C
$Timestep, \tau$	0.5 h

Table B.1. Constant for the 3 person office. Calculation can be seen in the Appendix CD.

The new weather file from DRY, is used to obtain the external temperatures and the load from the sun. Rest of the loads are taken according to the assumptions described in section 6.2 on page 52.

Φ_{conv} is one half of the internal heat loads (lighting, people and equipment) and Φ_{rad} is the rest of the internal heat loads plus the heat load from the sun.

In the following a calculation example is illustrated. The calculation is made for 6^{th} of July at 09.30. The calculated temperatures from the previous hour are:

$$T_m = 25.37\,°\mathrm{C}$$
$$T_{si} = 25.84\,°\mathrm{C}$$
$$T_{air} = 25.87\,°\mathrm{C}$$

Before calculation of all coefficients (a,b and c) the needed ACR must be calculated. Only T_m and T_{si} from the previous calculation are used from the temperatures. T_{air} is set to the cooling set point (26 °C).

Parameter	**Value**
S	6302.38 kJ/C
$H_{tr,ms}$	1583.81 W/°C
H_{ve}	53.03 W/°C
H_{sa}	284.95 W/°C
H_{tr}	12.24 W/°C
Φ_{conv}	279.5 W
Φ_{rad}	744.5 W
T_e	21.6 °C
T_{air}	26.0 °C
T_m^{-1}	25.37 °C
T_{si}^{-1}	25.84 °C
c_p	1006 J/kg°C
τ	0.5 h

Table B.2. Values for calculation of the needed airflow.

$$\begin{aligned}
&m_{calc} = \\
&-(S \cdot (H_{tr,ms} \cdot \Phi_{conv} + H_{sa} \cdot \Phi_{rad} + H_{sa} \cdot \Phi_{conv} + H_{tr} \cdot \Phi_{conv} - H_{tr,ms} \cdot H_{sa} \cdot T_{air} \\
&- H_{sa} \cdot H_{tr} \cdot T_{air} + H_{sa} \cdot H_{tr} \cdot T_e + H_{tr,ms} \cdot H_{sa} \cdot T_m^{n-1}) \\
&- (H_{tr,ms})^2 \cdot H_{sa} \cdot \tau \cdot T_m^{n-1} + (H_{tr,ms})^2 \cdot H_{sa} \cdot \tau \cdot T_{si}^{n-1})/ \\
&(S \cdot (H_{tr,ms} \cdot c_p \cdot T_e + H_{sa} \cdot c_p \cdot T_e + H_{tr} \cdot c_p \cdot T_e - H_{tr,ms} \cdot c_p \cdot T_{air} \\
&- H_{sa} \cdot c_p \cdot T_{air} - H_{tr} \cdot c_p \cdot T_{air}))
\end{aligned}$$

$$m_{calc} = 0.0527\,\mathrm{m^3/s}$$

Now all coefficients can be calculated:

Coefficients	**Value**
a_1	0.8743
a_2	0.1257
b_1	0.9653
b_2	0
b_3	0.0075
b_4	0.0272
b_5	0,0005
b_6	0.0006
c_1	0.8431
c_2	0.1569
c_3	0.0030

Table B.3. Coefficients for the 3 person office. Detailed calculation can be seen in the Appendix CD.

Only a_1 and a_2 are constant during the entire calculation for all hours. Other coefficients are varying depending on time (inside or outside working hours) and the needed ACR. It can be seen that $a_2 > 0.1$, even though a time step of 0.5 h is used. Because the value of a_2 is close to 0.1, and that the calculation is used as a simple design tool, it was decided not to decrease the time step any further.

In this example the calculation time is inside the working hours, which lasts from 08:00 to 17:00. The time step is set equal to 0.5 h.

All information to calculate the temperatures is now known and equation 8.4, 8.5 and 8.6 on page 65 can be applied:

$$
\begin{aligned}
T_m^n &= 0.8743 \cdot 25.32\,^\circ\mathrm{C} + 0.1257 \cdot 25.72\,^\circ\mathrm{C} \\
&= 25.37\,^\circ\mathrm{C} \\
T_{si}^n &= 0,9653 \cdot 25.37 + 0.0075 \cdot 21.6\,^\circ\mathrm{C} + 0.0272 \cdot 21.6\,^\circ\mathrm{C} + 0.0005 \cdot 279.5\,\mathrm{W} + 0.0006 \cdot 744.5\,\mathrm{W} \\
&= 25.83\,^\circ\mathrm{C} \\
T_{air}^n &= 0.8431 \cdot 25.83\,^\circ\mathrm{C} + 0.1569 \cdot 21.6\,^\circ\mathrm{C} + 0.0030 \cdot 279.5\,\mathrm{W} \\
&= 26.00\,^\circ\mathrm{C}
\end{aligned}
$$

As the result shows, the internal air temperature becomes 26 °C. In this case the needed ACR is less than the maximum, which means that it can be used to reach the cooling set point.

BSim Model Descriptions C

In the following sections different input parameters for the BSim models are presented. Two different models are presented. The first one is the original model, which is used for validation by measured BMS data. The second one is for the 3 person office, which looks much alike the original just with some changes in the different systems. The second BSim model is used for all the simulations in chapter 11 on page 79 *Comparison of VC Potential Tools for Case Study* and 12 on page 101 *Robustness of 5R1C-model*, with different modifications depending on the different cases.

All the BSim models can be found in the Appendix CD.

C.1 Original Model

In the following different input parameters for the original BSim model that is used for validation by the BMS data is described. The BSim model can be seen on the Appendix CD under *BSim Models*.

The geometry of the 3 person office, is presented in figure C.1.

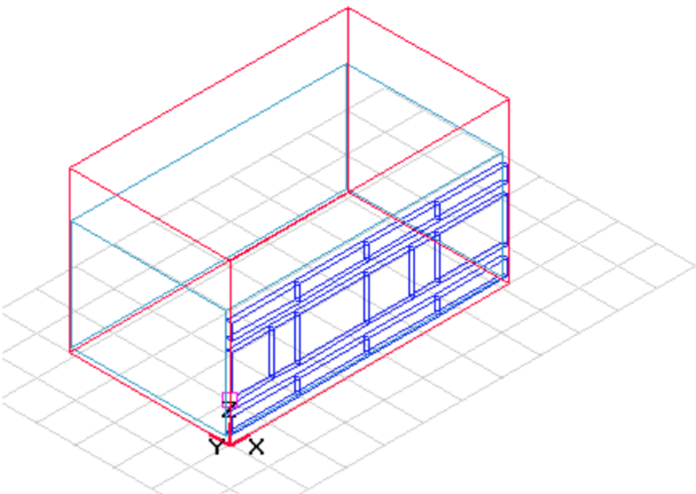

Figure C.1. Geometry of the 3 person office used in BSim.

The construction elements are the same as mentioned in chapter 6.2 on page 52, *Initial Case - 3 Person Office*.

The different inputs for the model are presented in following tables.

Equipment	
Heating load	0.3 kW
Profile	85 % (8-17)
Schedule	Working hours (Weekday 8-17)

Table C.1. Input parameters for equipment.

People	
Number of people	3 pers
Heating load per. pers.	0.1 kW
Profile	85 % (8-17)
Schedule	Working hours (Weekday 8-17)

Table C.2. Input parameters for people.

Lighting	
Task light	0.018 kW
General lighting	0.14 kW
Lighting control	200 lux
Control strategy	Continuous
Schedule	Working hours (Weekday 8-17)

Table C.3. Input parameters for lighting.

Heating	
Power	0.6 kW
Set point	21 °C
Design temp.	−12 °C
Minimum power	0.022 kW
Ext. temp. - min. power	20 °C
Schedule	Always

Table C.4. Input parameters for heating.

Mechanical ventilation	
Max. ACR	$2.4\,h^{-1}$
Heat exchange	0.85
Set point °C	20 °C
Set point CO_2	790 ppm
System	VAV
Min. inlet temp.	16 °C
Max. inlet temp.	21 °C
Schedule	Oct-Apr (weekdays 8-17) and May-Sep (weekdays 8-17)

Table C.5. Input parameters for mechanical ventilation.

Natural ventilation	
Max. ACR	$3.5\,h^{-1}$
Type	Single sided
Set point °C	22 °C
Set point CO_2	790 ppm
Schedule	April - September (Weekdays 8-17)

Table C.6. Input parameters for natural ventilation.

NTV with natural ventilation	
Max. ACR	$3.5\,h^{-1}$
Type	Single sided
Set point °C	21 °C
Schedule	April - September (17-8)

Table C.7. Input parameters for NTV with natural ventilation.

NTV with mechanical ventilation	
Max. ACR	$2.4\,h^{-1}$
Set point °C	21 °C
T_{op} - T_e	2 °C
T_{op} - set point	2 °C
Min. inlet temp	14 °C
Schedule	June - August (17-8)

Table C.8. Input parameters for NTV with mechanical ventilation.

Infiltration	
Basic ACR	$0.046\,h^{-1}$
Profile (infiltration)	100 % (1-24)
Schedule	Always

Table C.9. Input parameters for infiltration.

Solar Shading	
Shading factor	0.2
Activation by solar load	120 W/m^2
Adjustment limit	75 W/m^2
Activation by temperature	23 °C
Maximum wind speed	15 m/s
Control strategy	Continuous
Placing	External
Schedule	Always

Table C.10. Input parameters for solar shading.

C.2 Initial Case

In the following input parameters used for the BSim model for *Initial Case* are described. The BSim model can be seen on the Appendix CD under *BSim Models*.

The geometry of the room is shown in figure C.2.

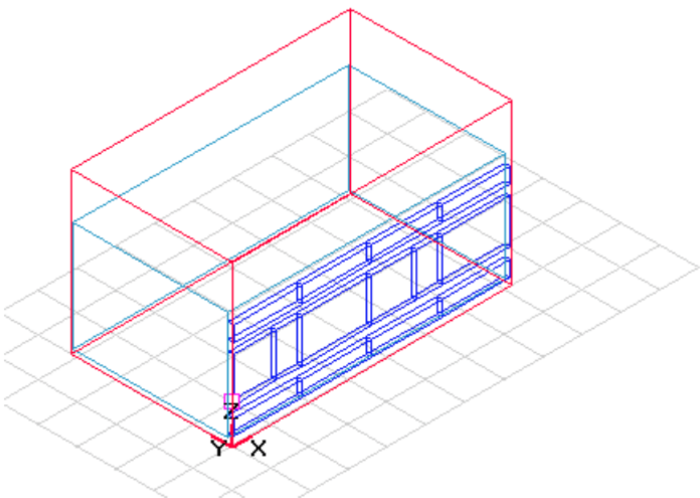

Figure C.2. Geometry for the 3 person office used in BSim.

The construction elements is the same as mentioned in chapter 6.2 on page 52, *Case 1 - 3 Person Office*.

The different inputs for the BSim model are presented in the following tables.

Equipment	
Heating load	0.3 kW
Profile	85 % (8-17)
Schedule	Working hours (Weekday 8-17)

Table C.11. Input parameters for equipment.

People	
Number of people	3 pers
Heating load per. pers.	0.1 kW
Profile	85 % (8-17)
Schedule	Working hours (Weekday 8-17)

Table C.12. Input parameters for people.

Lighting	
Task light	0.018 kW
General lighting	0.14 kW
Lighting control	200 lux
Control strategy	Continuous
Schedule	Working hours (Weekday 8-17)

Table C.13. Input parameters for lighting.

Infiltration	
Basic ACR	1.9 h^{-1}
Profile (infiltration)	2 % (1-24)
Schedule (infiltration)	May - September (17-6)
Profile (heating season)	100 % (1-24)
Schedule (heating season)	October - April (6-17)

Table C.14. Input parameters for infiltration.

Ventilation	
Min ACR	1.9 h^{-1}
Max ACR	3.5 h^{-1}
Control strategy	VAV control
Schedule	May - September (6-17)

Table C.15. Input parameters for ventilation.

Solar Shading	
Shading factor	0.2
Activation by solar load	120 W/m^2
Adjustment limit	75 W/m^2
Activation by temperature	23 °C
Maximum wind speed	15 m/s
Control strategy	Continuous
Placing	External
Schedule	Always

Table C.16. Input parameters for solar shading.

Case Study - All Hours D

In the report only the results inside working hours (08.00-17.00) are presented. In the following sections results for all hours are shown.

D.1 Original EURAC VC Potential Tool

Graphical interpretation of VC hour distribution for every month is illustrated in figure D.1.

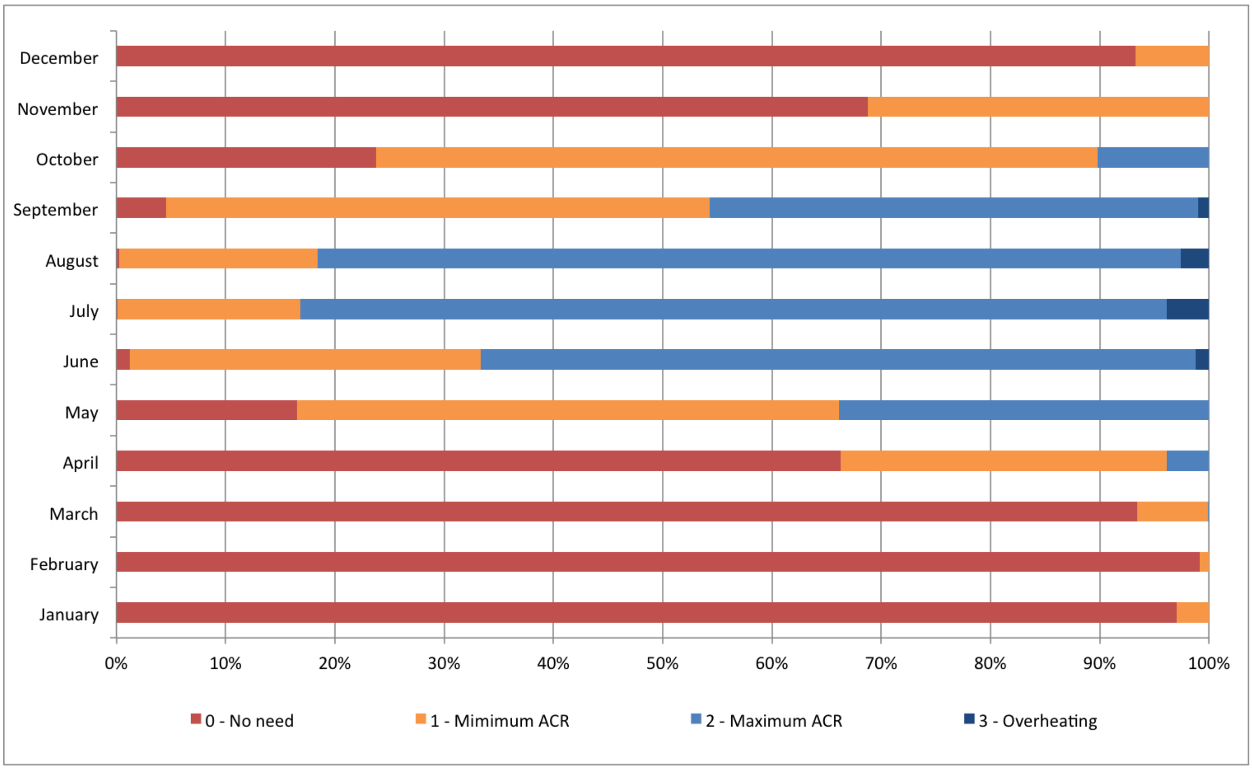

Figure D.1. VC hours from original EURAC VC potential tool. (All hours)

Furthermore, the results for all hours during the year are presented in table D.1.

Month	**0** No need	**1** $m_{min} = 1.9\,\mathrm{h}^{-1}$	**2** $m_{max} = 3.5\,\mathrm{h}^{-1}$	**3** Overheating
January	722	22	0	0
February	666	6	0	0
March	695	48	1	0
April	477	215	28	0
May	123	369	252	0
June	9	231	471	9
July	1	124	590	29
August	2	135	588	19
September	33	358	322	7
October	177	491	76	0
November	495	225	0	0
December	694	50	0	0
Total	4094	2274	2328	64

Table D.1. VC hour distribution from the original EURAC VC potential calculation. (All hours)

D.2 Modified EURAC VC Potential Tool

Graphical interpretation of VC hour distribution for every month is illustrated in figure D.2.

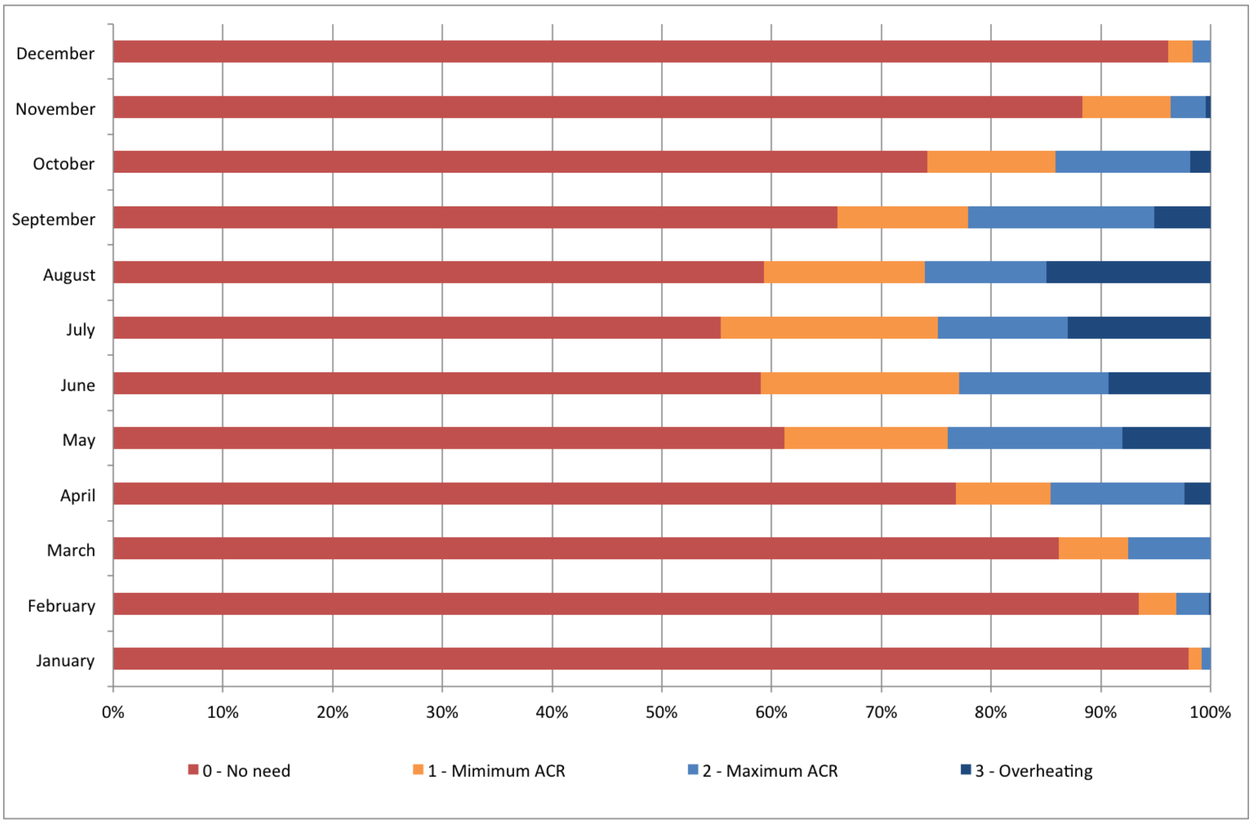

Figure D.2. VC hours from modified EURAC VC potential tool. (All hours)

Furthermore, the results for all hours during the year are presented in table D.2.

Month	**0** No need	**1** $m_{min} = 1.9\,h^{-1}$	**2** $m_{max} = 3.5\,h^{-1}$	**3** Overheating
January	729	9	6	0
February	628	23	20	1
March	641	47	56	0
April	553	62	88	17
May	455	111	118	60
June	425	130	98	67
July	412	147	88	97
August	441	109	83	111
September	475	86	122	37
October	552	87	91	14
November	636	58	23	3
December	715	17	12	0
Total	6662	886	805	407

Table D.2. VC hour distribution from the modified EURAC VC potential tool. (All hours).

D.3 5R1C-model

Graphical interpretation of VC hour distribution for every month is illustrated in figure D.3.

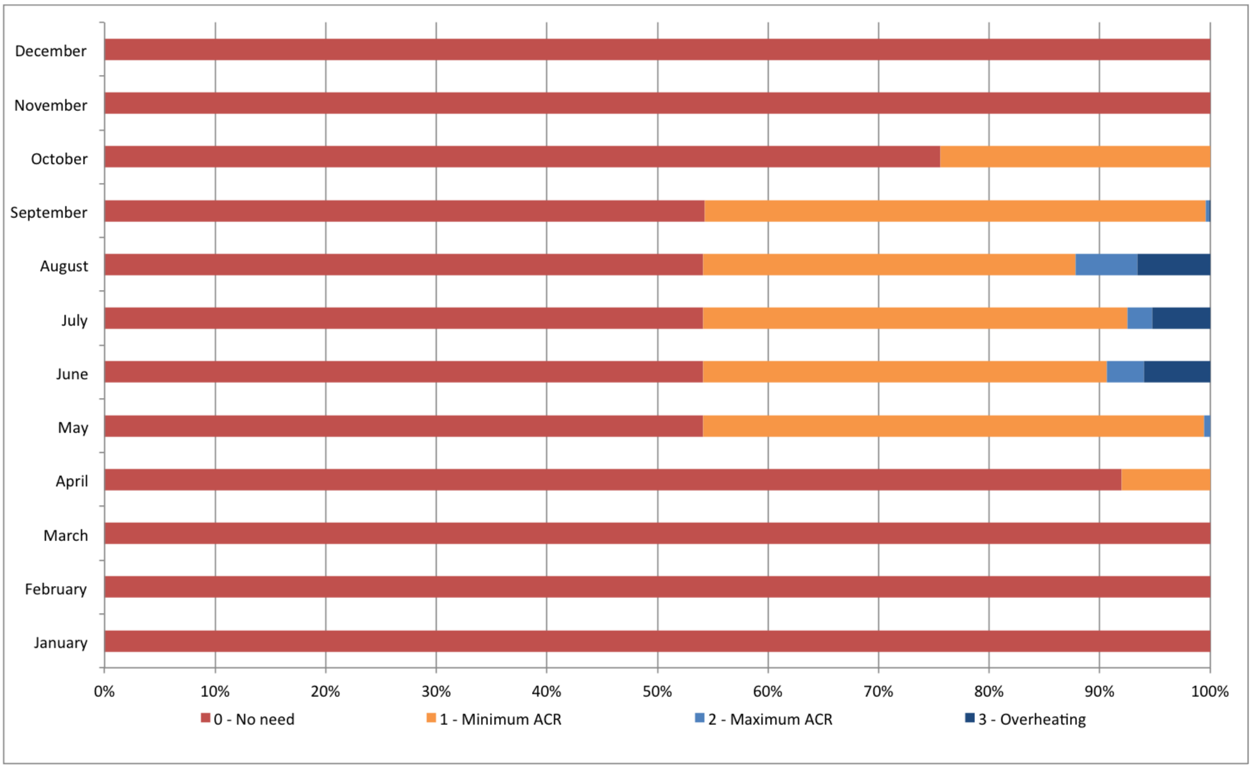

Figure D.3. VC hours from 5R1C-model. (All hours)

Furthermore, the results for all hours during the year are presented in table D.3.

Month	**0** No need	**1** $m_{min} = 1.9\,h^{-1}$	**2** $m_{max} = 3.5\,h^{-1}$	**3** Overheating
January	744	0	0	0
February	672	0	0	0
March	744	0	0	0
April	662.5	57.5	0	0
May	403	337	4	0
June	390	262.5	24.5	43
July	403	285	17	39
August	403	250.5	41.5	49
September	391	326	2	1
October	562.5	181.5	0	0
November	720	0	0	0
December	744	0	0	0
Total	6839	1700	89	132

Table D.3. VC hour distribution from the 5R1C-model. (All hours)

D.4 BSim Simulation

Graphical interpretation of VC hour distribution for every month is illustrated in figure D.4.

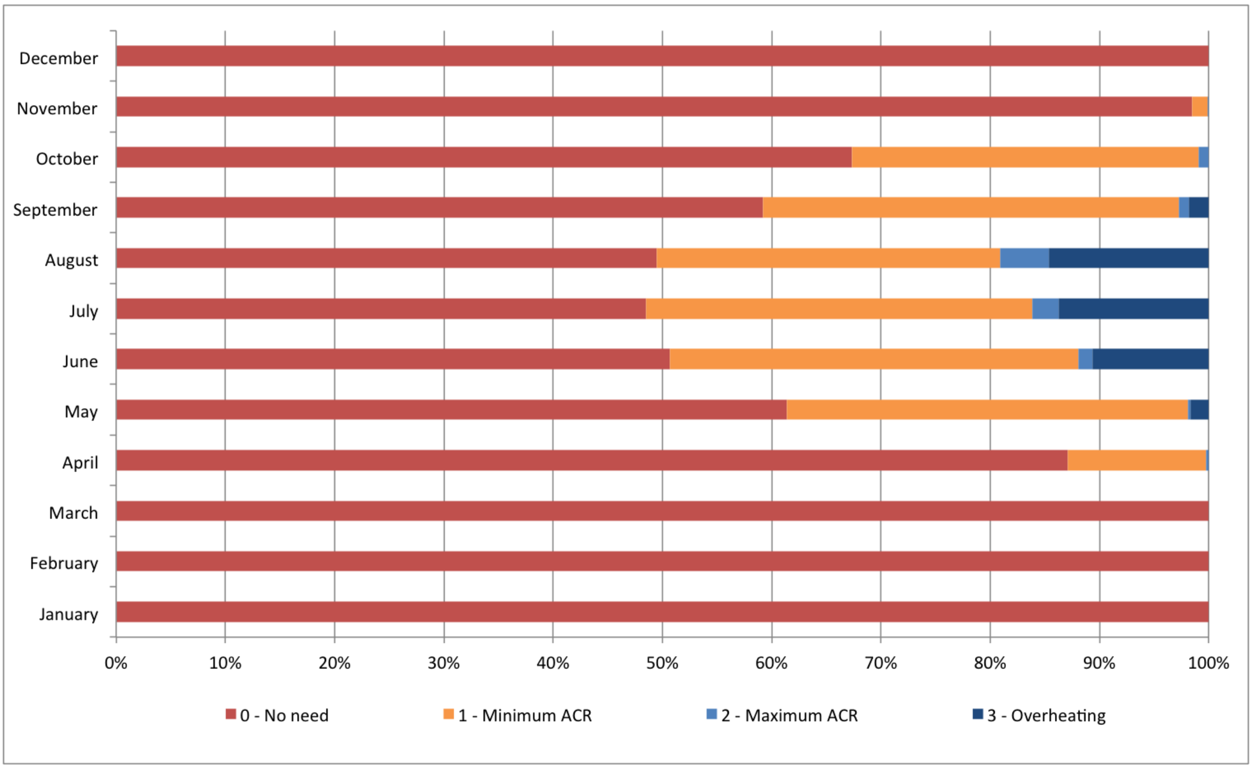

Figure D.4. VC hours from BSim simulation. (All hours)

Furthermore, the results for all hours during the year are presented in table D.4.

Month	**0** No need	**1** $m_{min} = 1.9\,h^{-1}$	**2** $m_{max} = 3.5\,h^{-1}$	**3** Overheating
January	744	0	0	0
February	672	0	0	0
March	744	0	0	0
April	627	91	2	0
May	442	264	2	12
June	377	278	10	79
July	361	263	18	102
August	368	234	33	109
September	426	274	7	13
October	501	236	7	0
November	709	10	1	0
December	744	0	0	0
Total	6715	1650	80	315

Table D.4. VC hour distribution from the BSim simulation. (All hours)

Robustness of 5R1C-model E

The results presented in chapter 12 on page 101 *Robustness of 5R1C-model* are based on the values presented in the following sections. The sections consist of table showing exact monthly VC hour distribution for each robustness analysis. The tables are based on the calculations made in the excel spreadsheet and BSim simulations placed on the Appendix CD.

E.1 Office Type

5R1C-model				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	210	60	0	0
May	0	277	2	0
June	0	196.5	34	39.5
July	0	169	58.5	51.5
August	0	129.5	78.5	71
September	0	267	2	1
October	73.5	205.5	0	0
November	268	2	0	0
December	279	0	0	0
Total	1640.5	1306.5	175	163

Table E.1. VC hour distribution from the 5R1C-model. (Working hours)

BSim Simulation				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	191	79	0	0
May	6	256	2	6
June	0	219	15	45
July	0	171	33	75
August	0	155	46	78
September	2	249	8	11
October	119	160	0	0
November	256	13	1	0
December	279	0	0	0
Total	1663	1302	105	215

Table E.2. VC hour distribution from the BSim simulation. (Working hours)

E.2 Control Strategy

5R1C-model				
Month	**0** No need	**1** $m_{min} = 1.9\,h^{-1}$	**2** $m_{max} = 3.5\,h^{-1}$	**3** Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	215.5	54.5	0	0
May	0	246.5	31.5	1
June	0	124	110	36
July	0	107	140	32
August	0	83.5	169	26.5
September	0	226.5	42.5	1
October	111.5	167.5	0	0
November	270	9	0	0
December	279	0	0	0
Total	1686	1009.5	493	96.5

Table E.3. VC hour distribution from the 5R1C-model. (Working hours)

BSim simulation				
Month	**0** No need	**1** $m_{min} = 1.9\,h^{-1}$	**2** $m_{max} = 3.5\,h^{-1}$	**3** Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	197	71	2	0
May	17	210	43	0
June	0	161	77	41
July	0	132	107	40
August	0	112	115	52
September	8	213	46	3
October	133	139	7	0
November	259	10	1	0
December	279	0	0	0
Total	1703	1048	398	136

Table E.4. VC hour distribution from the BSim simulation. (Working hours)

E.3 Maximum ACR

5R1C-model - $5\,h^{-1}$				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	215.5	54.5	0	0
May	0	275	4	0
June	0	207	31	32
July	0	225.5	21.5	32
August	0	225.5	21.5	32
September	0	267	2	1
October	111.5	167.5	0	0
November	270	9	0	0
December	279	0	0	0
Total	1686	1387	117	95

Table E.5. VC hour distribution from the 5R1C-model with $m_{max} = 5\,h^{-1}$. (Working hours)

5R1C-model - $10\,h^{-1}$				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 10\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	215.5	54.5	0	0
May	0	275	4	0
June	0	208	40	22
July	0	227	32.5	19.5
August	0	193.5	67	19
September	0	267	2	1
October	111.5	167.5	0	0
November	270	9	0	0
December	279	0	0	0
Total	1686	1392	145.5	61.5

Table E.6. VC hour distribution for the 5R1C-model with $m_{max} = 10\,h^{-1}$. (Working hours)

BSim Simulation - $5\,h^{-1}$				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	197	71	2	0
May	17	239	4	10
June	0	223	12	44
July	0	204	25	50
August	0	180	47	52
September	8	242	10	10
October	131	141	7	0
November	259	10	1	0
December	279	0	0	0
Total	1701	1310	108	166

Table E.7. VC hour distribution from the BSim simulation with $m_{max} = 5\,h^{-1}$. (Working hours)

BSim Simulation - $10\,h^{-1}$				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 10\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	197	71	2	0
May	17	239	4	10
June	0	225	22	32
July	0	211	38	30
August	0	184	68	27
September	8	243	11	8
October	131	141	7	0
November	259	10	1	0
December	279	0	0	0
Total	1701	1324	153	107

Table E.8. VC hour distribution from the BSim simulation with $m_{max} = 10\,h^{-1}$. (Working hours)

E.4 Thermal Mass

E.4.1 Materials

The different materials for each changed construction element are presented in table E.9.

Construction element	Area	Material
Step 1 - Partition wall	19.6 m^2	Concrete (100 mm)
Step 2 - Adjacent partition walls	22.3 m^2	Concrete (100 mm)
Step 3 - Roof	27.9 m^2	Concrete (100 mm) Stone wool (50 mm) Ventilated airspace (378 mm) Reinforced concrete (270 mm) Stone wool (450 mm) Bitumen felt

Table E.9. Changes of the construction elements for each step.

E.4.2 Results

5R1C-model - Step 1				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	234	36	0	0
May	0	279	0	0
June	0	212.5	20	37.5
July	0	234.5	12	32.5
August	0	204	37	38
September	0	269	0	1
October	84.5	194.5	0	0
November	270	9	0	0
December	279	0	0	0
Total	1677.5	1429.5	69	109

Table E.10. VC hour distribution from the 5R1C-model for step 1 . (Working hours)

5R1C-model - Step 2				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	252	18	0	0
May	0	279	0	0
June	0	214	19	37
July	0	238	11	30
August	0	211.5	38.5	29
September	0	269	0	1
October	65	214	0	0
November	267	3	0	0
December	279	0	0	0
Total	1673	1446.5	68.5	97

Table E.11. VC hour distribution from the 5R1C-model for step 2 . (Working hours)

5R1C-model - Step 3				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	257.5	12.5	0	0
May	0	279	0	0
June	0	230	19.5	20.5
July	0	250	8	21
August	0	228.5	27	23.5
September	0	269	0	1
October	28.5	250.5	0	0
November	263	7	0	0
December	279	0	0	0
Total	1638	1526.5	54.5	66

Table E.12. VC hour distribution from the 5R1C-model for step 3 . (Working hours)

BSim Simulation - Step 1				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	209	61	0	0
May	5	262	0	3
June	0	221	11	47
July	0	221	7	51
August	0	192	17	70
September	1	257	2	10
October	142	137	0	0
November	265	5	0	0
December	279	0	0	0
Total	1711	1356	37	181

Table E.13. VC hour distribution from the BSim simulation for step 1 . (Working hours)

BSim Simulation - Step 2				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	228	42	0	0
May	1	269	0	0
June	0	225	12	42
July	0	230	5	44
August	0	210	15	54
September	0	270	0	10
October	142	137	0	0
November	270	0	0	0
December	279	0	0	0
Total	1730	1383	32	140

Table E.14. VC hour distribution from the BSim simulation for step 2 . (Working hours)

BSim Simulation - Step 3				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	247	23	0	0
May	0	270	0	0
June	0	232	12	35
July	0	237	5	37
August	0	222	13	44
September	0	270	0	10
October	130	149	0	0
November	270	0	0	0
December	279	0	0	0
Total	1736	1403	30	116

Table E.15. VC hour distribution from the BSim simulation for step 3 . (Working hours)

E.5 Simplified NTV

E.5.1 Control Strategy 1

5R1C-model - NTV with Min. ACR				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	215.5	54.5	0	0
May	0	275	4	0
June	13	247	1	9
July	0	270	9	0
August	0.5	267.5	11	70
September	0	269	1	0
October	110.5	168.5	0	0
November	270	0	0	0
December	279	0	0	0
Total	1698.5	1551.5	26	9

Table E.16. VC hour distribution from the 5R1C-model for NTV with min. ACR - Control strategy 1. (Working hours)

5R1C-model - NTV with Max. ACR				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	215.5	54.5	0	0
May	0	275	4	0
June	49	213	6	2
July	32.5	237.5	9	0
August	20	248	11	70
September	9	260	1	0
October	110.5	168.5	0	0
November	270	0	0	0
December	279	0	0	0
Total	1795.5	1456.5	31	2

Table E.17. VC hour distribution from the 5R1C-model for NTV with max. ACR - Control strategy 1. (Working hours)

BSim Simulation - NTV with Min. ACR				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	197	71	2	0
May	17	239	2	12
June	23	221	1	34
July	5	247	1	26
August	11	237	3	28
September	12	248	0	10
October	133	139	7	0
November	259	10	1	0
December	279	0	0	0
Total	1746	1412	17	110

Table E.18. VC hour distribution from the BSim simulation for NTV with min. ACR - Control strategy 1. (Working hours)

BSim Simulation - NTV with Max. ACR				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	196	72	2	0
May	17	238	2	13
June	43	208	1	27
July	28	227	1	23
August	18	241	1	19
September	14	251	1	4
October	133	139	7	0
November	259	10	1	0
December	279	0	0	0
Total	1797	1386	16	86

Table E.19. VC hour distribution from the BSim simulation for NTV with max. ACR - Control strategy 1. (Working hours)

E.5.2 Control Strategy 2

5R1C-model - NTV with Min. ACR				
Month	**0** No need	**1** $m_{min} = 1.9\,h^{-1}$	**2** $m_{max} = 3.5\,h^{-1}$	**3** Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	215.5	54.5	0	0
May	0	246.6	32.5	0
June	13	207.5	41	8.5
July	0	249	30	0
August	0.5	255.5	23	0
September	0	264.5	5.5	0
October	110.5	168.5	0	0
November	270	0	0	0
December	279	0	0	0
Total	1698.5	1446.5	132	8.5

Table E.20. VC hour distribution from the 5R1C-model for NTV with min. ACR - Control strategy 2 . (Working hours)

BSim Simulation - NTV with Min. ACR				
Month	**0** No need	**1** $m_{min} = 1.9\,h^{-1}$	**2** $m_{max} = 3.5\,h^{-1}$	**3** Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	197	71	2	0
May	17	210	43	0
June	24	201	27	27
July	5	213	36	25
August	11	183	64	21
September	14	216	39	1
October	133	139	7	0
November	259	10	1	0
December	279	0	0	0
Total	1746	1243	219	74

Table E.21. VC hour distribution from the BSim simulation for NTV with min. ACR - Control strategy 2 . (Working hours)

E.6 Extreme Cases

E.6.1 Climate

5R1C-model				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	174	105	0	0
February	49	203	0	0
March	3	276	0	0
April	0	270	0	0
May	0	205.5	34.5	39
June	0	37.5	43.5	189
July	0	0	1	278
August	0	0	0	279
September	0	0	2	268
October	0	93	63	123
November	9	257.5	3.5	0
December	62	217	0	0
Total	297	1664.5	147.5	1176

Table E.22. VC hour distribution from the 5R1C-model. (Working hours)

BSim Simulation				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	144	131	4	0
February	110	137	5	0
March	69	195	12	3
April	13	242	14	1
May	0	176	34	60
June	0	69	34	176
July	0	2	7	270
August	0	0	1	278
September	0	3	26	241
October	0	78	1	200
November	36	210	8	16
December	115	159	5	0
Total	487	1402	151	1245

Table E.23. VC hour distribution from the BSim simulation. (Working hours)

E.6.2 Solar shading

Step 1 - Deactivation of Shading in Upper Band

5R1C-model - Step 1				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	197	73	0	0
May	0	245.5	12.5	21
June	0	147.5	40	82.5
July	0	114.5	83	81.5
August	0	62	98.5	118.5
September	0	223.5	30.5	16
October	80	199	0	0
November	265	5	0	0
December	279	0	0	0
Total	1631	1070	264.5	319.5

Table E.24. VC hour distribution from the 5R1C-model. (Working hours)

BSim simulation - Step 1				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	275	4	0	0
April	178	88	4	0
May	7	204	19	40
June	0	166	41	72
July	0	129	51	99
August	0	114	39	126
September	1	210	33	26
October	114	151	7	7
November	249	19	2	0
December	279	0	0	0
Total	1634	1085	196	370

Table E.25. VC hour distribution from the BSim simulation. (Working hours)

Step 2 - Deactivation of Shading in Middle Band

5R1C-model - Step 2				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	203	0	0
March	279	0	0	0
April	167.5	88	12.5	2
May	0	91.5	96	91.5
June	0	35	87	148
July	0	13	70.5	195.5
August	0	0	34	245
September	0	116	93	61
October	22	233	24	0
November	220	50	0	0
December	279	0	0	0
Total	1498	626.5	417	743

Table E.26. VC hour distribution from the 5R1C-model. (Working hours)

BSim Simulation - Step 2				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	248	4	0	0
March	246	28	5	0
April	153	74	14	29
May	1	133	37	99
June	0	86	66	127
July	0	52	50	177
August	0	37	49	193
September	0	145	44	81
October	84	133	19	43
November	236	29	5	0
December	279	0	0	0
Total	1526	721	289	749

Table E.27. VC hour distribution from the BSim simulation. (Working hours)

Step 3 - No Solar shading

5R1C-model - Step 3				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	261	18	0	0
April	144.5	103	7	15.5
May	0	37.5	88	153.5
June	0	9	63	198
July	0	0	31.5	247.5
August	0	0	7.5	271.5
September	0	45.5	119.5	105
October	0	213	60.5	5.5
November	190	79.5	0	0
December	279	0	0	0
Total	1406	505.5	377	996.5

Table E.28. VC hour distribution from the 5R1C-model. (Working hours)

BSim Simulation - Step 3				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	238	12	2	0
March	223	34	13	9
April	143	47	21	59
May	0	102	42	126
June	0	48	59	172
July	0	23	47	209
August	0	19	36	224
September	0	111	46	113
October	66	124	17	72
November	220	35	9	6
December	279	0	0	0
Total	1448	555	292	990

Table E.29. VC hour distribution from the BSim simulation. (Working hours)

E.6.3 No Vacation

5R1C-model				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	215.5	54.5	0	0
May	0	275	4	0
June	0	204.5	22.5	43
July	0	172	52	55
August	0	137	65	77
September	0	267	2	1
October	112	167	0	0
November	270	0	0	0
December	279	0	0	0
Total	1686.5	1277	145.5	176

Table E.30. VC hour distribution from the 5R1C-model. (Working hours)

BSim Simulation				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	197	71	2	0
May	17	239	2	12
June	0	218	10	51
July	0	169	29	81
August	0	153	37	89
September	9	240	8	13
October	131	141	7	0
November	259	10	1	0
December	279	0	0	0
Total	1702	1241	96	246

Table E.31. VC hour distribution from the BSim simulation. (Working hours)

E.6.4 2 x People Load

5R1C-model				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	237	33	0	0
May	0	272	3	4
June	0	192.5	11.5	66
July	0	161	31	87
August	0	124.5	27.5	127
September	1	259	4	6
October	142.5	136.5	0	0
November	270	0	0	0
December	279	0	0	0
Total	1739.5	1178.5	77	290

Table E.32. VC hour distribution from the 5R1C-model. (Working hours)

BSim Simulation				
	0	**1**	**2**	**3**
Month	No need	$m_{min} = 1.9\,h^{-1}$	$m_{max} = 3.5\,h^{-1}$	Overheating
January	279	0	0	0
February	252	0	0	0
March	279	0	0	0
April	209	56	5	0
May	36	56	163	15
June	8	99	116	56
July	0	84	96	99
August	0	89	71	119
September	22	78	152	18
October	154	114	11	0
November	260	9	1	0
December	279	0	0	0
Total	1778	585	615	307

Table E.33. VC hour distribution from the BSim simulation. (Working hours)