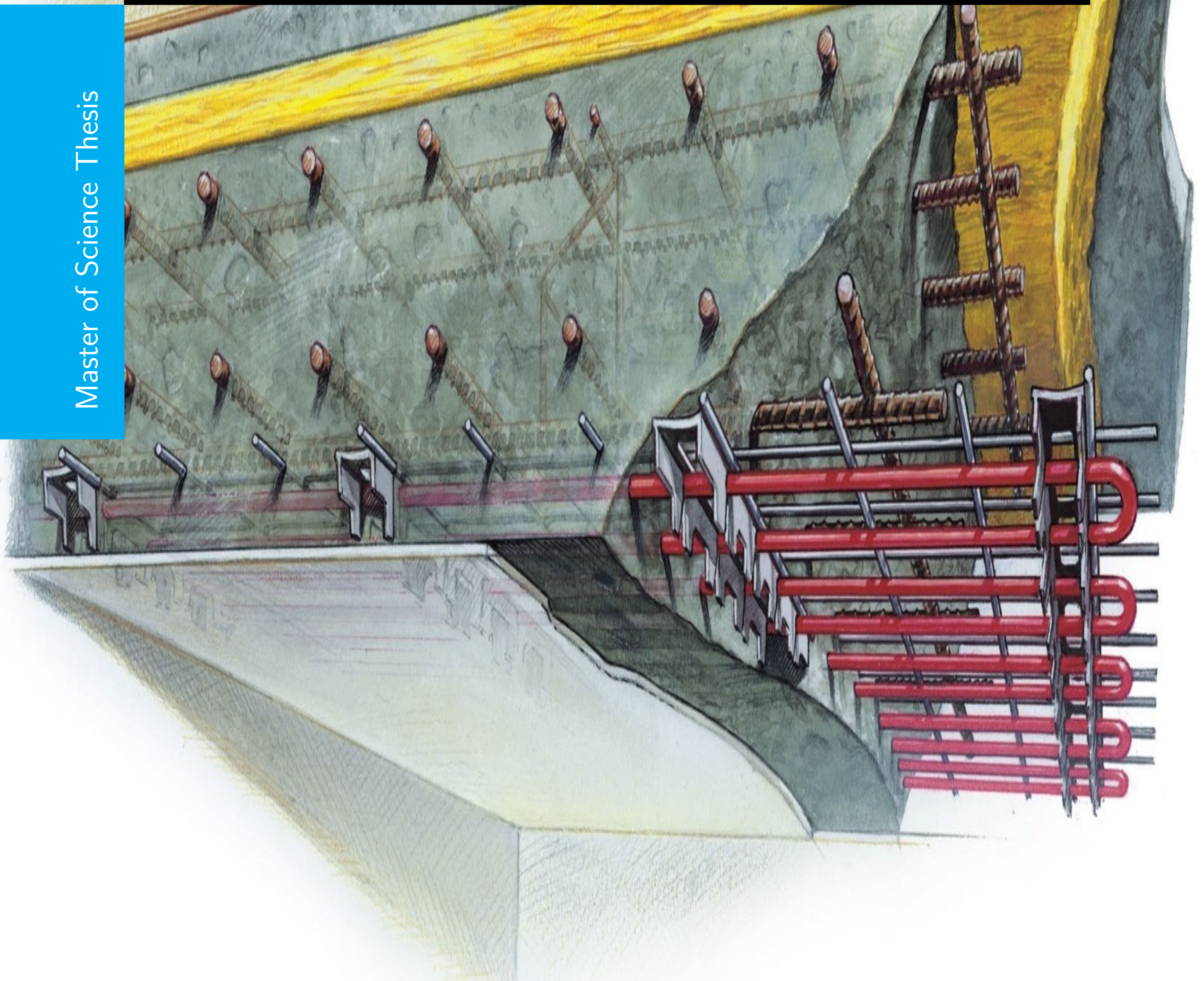
Performance assessment of building energy modelling programs and control optimization of thermally activated building systems

Athinodoros Tzoulis

Master of Science Thesis



Delft University of Technology

Building Engineering

Performance assessment of building energy modelling programs and control optimization of thermally activated building systems

Master of Science Thesis

For the degree of Master of Science in Building Engineering - Building Physics & Technology at Delft University of Technology

Athinodoros Tzoulis

April 15, 2014

Faculty of Civil Engineering & Geosciences (CiTG) · Delft University of Technology

The work in this thesis was supported by Landstra Bureau voor Bouwfysica and DGMR. Their cooperation is hereby gratefully acknowledged.

Summary

In the last decades, there is a lot of discussion about climate change and energy shortage. In building industry great amounts of energy are spent for heating and cooling which in return produce large quantities of CO_2 emissions. Therefore, it is self-understandable that efforts towards more effective and sustainable solutions have to be made.

This thesis deals with Thermally Activated Building Systems (TABS), which refer to temperature - controlled surfaces that heat and cool indoor temperatures by adding or removing sensible heat and where more than half of heat transfer occurs through thermal radiation. Aim of this research is to describe, analyze and evaluate the performance of this system with the help of Building Energy Modelling Programs (BEMPs).

This report consists of two main parts. TABS are modelled with the help of Building Energy Modelling Programs (BEMPs) and specifically EnergyPlus and TRNSYS.

The first part of the report is focused on comparisons of the results between EnergyPlus and TRNSYS. Several models have been tested in the two programs, initially simple growing progressively more complicated to determine the accuracy of the results in several cases. In the final step, models equipped with TABS are designed in EnergyPlus and TRNSYS and their results, regarding inside temperature, are compared.
The study has shown that EnergyPlus and TRNSYS lead to significantly different results for building simulations under the given conditions. Additionally, possible causes of these differences have been found in the modelling processes of the programs.

In the second part of the thesis a combination of two radiant systems for heating and cooling is introduced as shown in the figure below. The first system is concrete core activation (CCA), meaning that heating and cooling is provided by means of circulating water running in tubes embedded in the floor slabs. CCA which is slow response system is coupled with a fast delivery system which is radiative panels. The systems operate in a change-over configuration - CCA operates during night-time and radiative panels during occupation. Additionally, a 2-pipe distribution system is used which is cheaper but may lead to thermal discomfort. This part also provides a guideline or framework on the optimization this system's performance by lowering the energy consumption while maintaining the provisional thermal comfort in acceptable range. The parameters which influence the performance of the system are analyzed

and a way to optimize them is provided. The evaluation of the system has shown that the radiative panels do not contribute significantly in the thermal comfort of a 1-zone model in contrast to CCA.

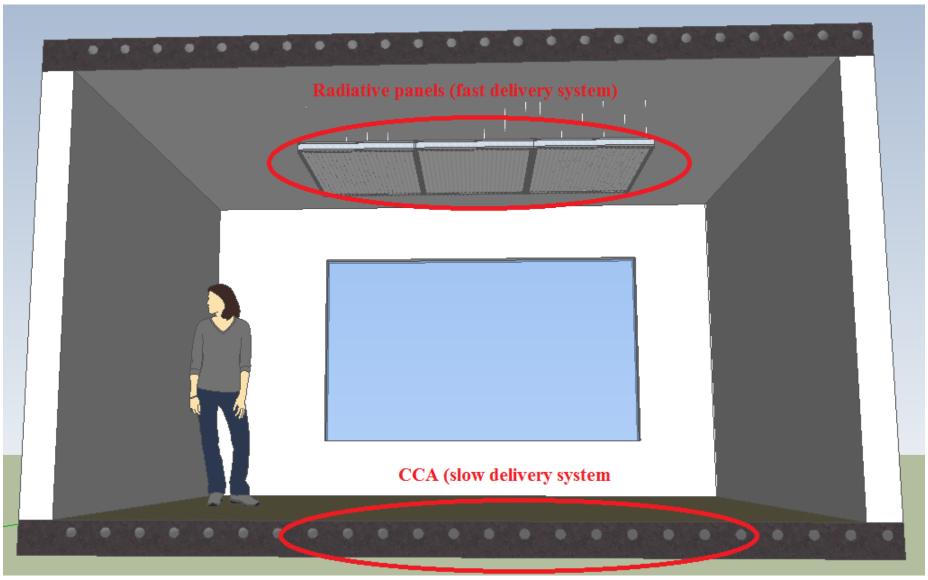


Figure 1: A simple model with combination of CCA and radiative panels

Table of Contents

List of Figures

List of Tables

Preface

This report is the final result of my MSc Thesis, which is the final part of my studies in the faculty of Civil Engineering for the specialization of Building Engineering and specifically Building Technology & Physics. The inspiration of doing my thesis on this subject came after a discussion with my supervisor Willem van der Spoel, who also offered me an internship at Landstra Bureau voor Bouwfysica for conducting this project. During the project I had numerous discussions with several people who gave me feedback and information regarding this topic. I would like to thank them all for their help.

First of all, I would like to thank my graduation committee, namely Andy van den Dobbelsteen and Roel Schipper for their guidance during my research and especially Willem van der Spoel, who was my daily supervisor and advised me throughout the duration of the project. As this project was performed in the form of an internship at Landstra and DGMR, I would like to thank the people working there and especially Bert Swart, with whom I cooperated. Additionally, I cannot omit showing my gratitude to all the people who constitute TUDelft, be it professors, lecturers, fellow students, administrative staff and all others.

I would also like to thank my family, my friends and flatmates for their support during my master studies in Delft.

Thank you a lot!

Athinodoros Tzoulis
Delft, April 2014

Chapter 1

Introduction

According to the Building Performance Institute Europe (BPIE) energy use in European building industry is to a great extent contributive (∼40%) to the European CO_2 emissions that were approaching 4Gt in 2006. Therefore, it is self-understandable that efforts towards more effective and sustainable solutions have to be made to develop methods, products and systems which are cheaper, more comfortable, more efficient and environmentally-friendly.
Inspired by sustainability objectives, a transition to more integrated constructions and installation components is currently taking place. Thermally Activated Building Systems (TABS) are increasingly used. This system is also called Concrete Core Activation (CCA). TABS are basically temperature-controlled surfaces that heat and cool indoor spaces by adding or removing sensible heat and where more than half of heat transfer occurs through thermal radiation. These systems are usually hydronic using water circulation in pipes in thermal contact with the surfaces, in most cases concrete slabs. However, they are slow response systems which may lead to problems if attention is not paid. In this thesis, CCA will be combined with a fast response heating and cooling system and more specifically radiative panels. The combination of these systems ensure high performance in terms of thermal comfort. Although the experience with such systems is growing, it is necessary to research and analyze their potentials further, optimize their performance and maximize the provisional thermal comfort.
Additionally, it is important to state that nowadays all systems can be evaluated with the help of software programs, Building Energy Modelling Programs or BEMPs, which provide as output numerous results in relation to the energy performance, comfort and economy. Engineers, architects and researchers can use BEMPs to assess the performance of a building enabling them to optimize the building design in order to reduce the building's energy consumption.

1-1 Problem definition

As mentioned above, CCA is a slow response heating and cooling system which means that it takes a lot of time for heat and 'coolth' to be delivered to the heated or cooled space. As

a result, in some cases when CCA has been applied, thermal comfort problems have been encountered. The main issue with slow response systems are the controls and their optimization. Therefore, such systems should be designed properly and attention should be paid to their controls. So, the first problem which is faced in this thesis is the optimization of the HVAC system's parameters in order to achieve an optimal performance in terms of energy use and thermal comfort. Additionally, the combination of CCA with radiative panels has been reviewed and a way to optimize their controls has been studied.
The second part of the thesis deals with the comparison of the system's performance, mentioned above, with two BEMPs, EnergyPlus and TRNSYS. Due to the complexity of such software some users handle these programs as 'black boxes', where the user provides the input and obtains output without really comprehending how each software functions and without being sure of their accuracy. This situation may lead to various problems; it makes it difficult for the user to analyze the results, find possible errors made by the user and, most importantly, it is impossible to understand if the program gives misleading results. Since there are a lot of programs conducting similar simulation analyses, it is important for the user to know the program in depth and before starting to use new software it is imperative to study it thoroughly in order to be certain of its capabilities and accuracy. Therefore, this thesis is also focused on the accuracy of BEMPS (in our case EnergyPlus and TRNSYS) and if the modelling procedures of these programs match. According to literature, differences occur between the output of the programs. In this thesis, attempts have been made to find possible causes.

1-2 Research questions

1. What are the calculation methods and the modelling processes which are used by EnergyPlus and TRNSYS to model radiant heating and cooling?
2. Do the results of EnergyPlus and TRNSYS match well? If not, what are the reasons for the discrepancies?
3. What are the parameters which influence the performance of the HVAC system?
4. How can these parameters be optimized to provide heating and cooling by minimizing energy consumption while maintaining thermal comfort at acceptable range?

1-3 Research goal/objectives

1. Assessment of the calculation methods employed by EnergyPlus and TRNSYS with regard to expected and/or required accuracy. Each of the programs works with distinctive methods. EnergyPlus employs different methods (CTFs, FEM) than TRNSYS (semi-numerical, FEM). This part contributes to the clarification of causes of the differences between the softwares.
2. Building of a model in EnergyPlus to demonstrate and calculate the energy and thermal comfort performance of the system. The model is compared with a respective model of TRNSYS in terms of thermal comfort. The differences of the programs' output are analyzed and possible causes are found.

3. Development of a framework on how a model with the combination of CCA and radiative panels can be optimized regarding thermal comfort and energy consumption. The complexity of the model makes it difficult to conduct a systematic optimization research. Therefore, the impact of each parameter is determined separately.

1-4 Companies involved and Guidance

This research project is organized by a collaboration between DGMR and Thermal Comfort Systems (TCS). The simulation that DGMR has prepared has been conducted by TRNSYS and they requested a second opinion and an intercomparison of the results by another program which has been conducted with the help of EnergyPlus and DesignBuilder. TCS designs and engineers CCA systems and provides practical knowledge into the research project.

1-5 Methodology

Objective 1: EnergyPlus and TRNSYS function with different calculation methods. Literature and documentation on how both programs work has been reviewed. The assumptions and limitations of the softwares and their methods have been assessed. Simple but representative test simulations have been conducted and results have been reviewed and compared.

Objective 2: Software documentation on EnergyPlus and TRNSYS has been reviewed in order to model a room in which CCA combined with a fast delivery system (radiative panels) are applied in a change-over configuration. The input data is given according to the requirements of DGMR. The comparison of the results with the two programs has focused on inside temperature and energy consumption as a function of time.

Objective 3: This part is focused on the optimization of the system's parameters. Initially, the geometry of the delivery system (tubing distance, inside tube diameter, etc.) and its effect has been explained. Additionally, the controls of the CCA and the radiative panels have been adjusted in such a way in order to minimize energy consumption while maintaining inside temperatures in acceptable range.

The approach that is used in this research follows the methodology which was mentioned in the previous paragraph. In order to achieve the expected results, various programs have been tested in order to find the most appropriate software. Programs that have been used in this project are:

- **MS Excel** (as a solver with Finite Element Method)
- **EnergyPlus** (as 1st software simulation engine for the energy calculations)
- **DesignBuilder & OpenStudio** (as a Third-Party Graphical User Interface connected with EnergyPlus)
- **TRNSYS** (as 2nd software for energy calculations)

1-6 Thesis outline

This report consists of 9 chapters organized as follows:

- ***Chapter 1*** introduces and motivates the topic and states the graduation project.
- ***Chapter 2*** analyzes the current literature regarding Thermally Activated Building Systems (TABS), Concrete Core Activation (CCA) and radiative panels and introduces important background knowledge that is used throughout this report.
- ***Chapter 3*** introduces the way with which Building Energy Modelling Programs (BEMPs), like EnergyPlus and TRNSYS, function and analyzes possible problems that can be encountered.
- ***Chapter 4*** analyzes the physical and mathematical models behind EnergyPlus and TRNSYS with regard to concrete core activation and heat transfer due to conduction.
- In ***Chapter 5*** simple but representative test simulations are conducted and results are reviewed and compared. Additionally, possible causes of the differences between the programs are explained.
- In ***Chapter 6*** a model with concrete core activation, created in EnergyPlus, is compared with the respective model of TRNSYS.
- In ***Chapter 7*** a framework is developed to optimize the combination of CCA and radiative panels. The optimization refers to energy consumption and thermal comfort.
- ***Chapter 8*** sums up the conclusions of the graduation project and provides recommendations for future work.
- ***Chapter 9*** includes the Appendix.

Chapter 2

Thermally Activated Building Systems (TABS)

By the term thermally activated building systems (TABS), it is meant that HVAC systems are integrated within the structural or non-structural elements of the building, such as slabs or facades. TABS refer to temperature-controlled surfaces that heat or cool indoor spaces by adding or removing sensible heat and where more than half of heat transfer occurs through thermal radiation (American Society of Heating and Engineers, 2008). In case of cooling, heat is transferred from surfaces, occupants, equipment and lights in a space to a cooled surface as long as their temperatures are higher than that of the cooled surface. The radiant exchange affects the air temperature only slightly, while through the process of convection, contact of air with the cooled surface results in decline of inside temperature. The reverse procedure (heating) occurs when the activated surface is at a higher temperature than that of the air and the components within the occupied space. TABS are usually hydronic systems using pipes embedded in building elements to circulate water.
There are two main types of radiant heating and cooling systems. The first type is systems that deliver heating and cooling through the building structure, usually slabs, these systems are also named concrete core activation (CCA). The second type is systems that deliver heating or cooling through specialized panels. Radiative panels are not considered to be thermally activated building systems due to their low thermal mass and limited capability of accumulating heat. However, in this thesis the combination of both systems has been studied.
In most cases this kind of system is implemented in large, multi-storey buildings where conventional HVAC systems may result in high energy consumption. Buildings with TABS use concrete core activation (CCA) as the main heating and cooling distribution system. The term concrete core activation refers to buildings, which are heated and cooled by accumulating heat and 'coolth' in constructions (slabs or walls) and afterwards releasing it to the building. The experience with such systems is growing and with respect to energy performance and thermal comfort, the results are proven to be positive (Hoogmartens and Sourbron, 2011).

2-1 Concrete Core Activation

Thermally activated building systems (TABS) or concrete core activation (CCA) are widely used to provide low temperature heating and high temperature cooling in office buildings. In the Netherlands prefabricated floor slabs with in-built water tubing (wideslab precast concrete floors, BubbleDeck floors, hollow-core slabs, etc.) are gaining popularity.
The concrete floor slabs store heating or cooling energy by means of hot or cold water circulating through the embedded water tubing inside the slab. Thus, the building structure is utilized for storing thermal energy in order to release it when required. The large heat transferring surface of the slab makes it possible to transfer considerable amounts of heat to the occupied spaces. Typically in case of cooling, the circulating water only needs to be 2-4^{o}C below the desired indoor air temperature (Olesen, 2008). When cold water is circulating through the water tubing, heat is absorbed by the actively cooled surface and results in the increase of water temperature at the end of the circuit. For heating, the water supply temperature needs to be around 5^{o}C above the desired indoor air temperature. The heat or cold stored in the concrete core is transferred to the room during several hours - 60% via radiation and 40% via convection. Additionally, since the structural slabs are actually the 'radiators-convectors', heat will be transferred to both the upper and lower storey. A typical room cross-section where CCA is applied is shown in Fig. 2-1.

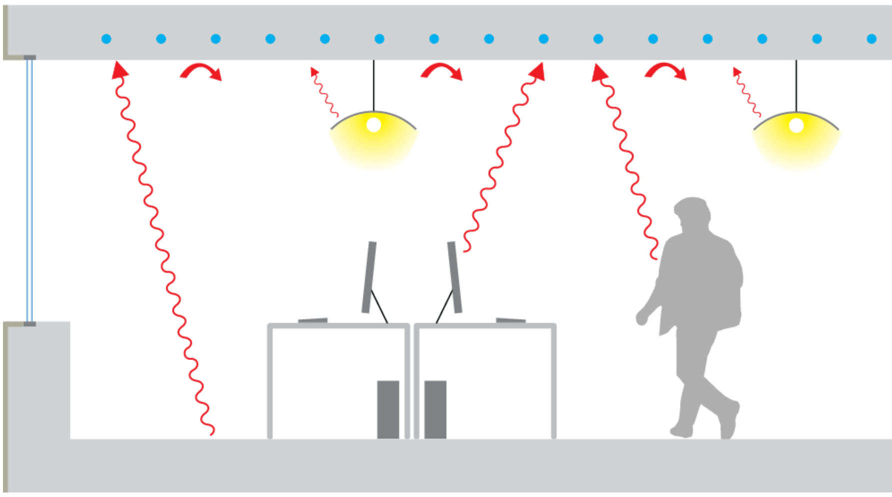


Figure 2-1: CCA applied in a room

Different kinds of slabs in which CCA is applicable are shown in Fig. 2-2, 2-3 and 2-4.

The way the tubing is integrated in hollow-core slabs is shown in Fig. 2-5 and 2-6. The way the water is supplied and discharged to and from each slab is demonstrated. Similar configuration occurs in all kinds of slabs.

The water, which is supplied in each slab in the heating mode, is in the beginning at its maximum temperature and as it travels through the circuit in each slab the temperature is reduced (Fig. 2-7) due to conduction from the water to the concrete slab and eventually to the heated space through convection and radiation. There are several parameters which affect the temperature increase or drop in case of cooling or heating mode respectively.

Figure 2-2: Bubbledeck slabs

Figure 2-3: Wideslab floors

Figure 2-4: Hollow-core slabs

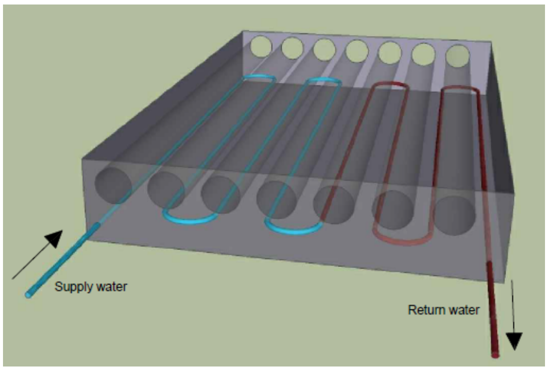


Figure 2-5: Tubing configuration

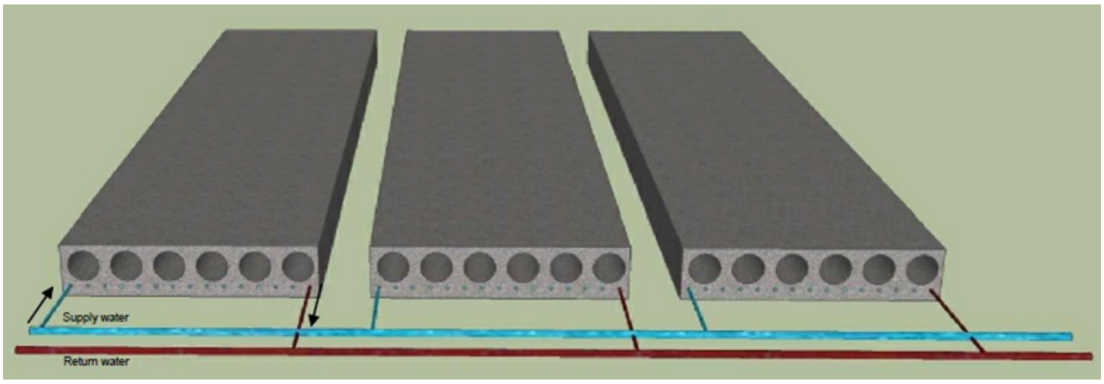


Figure 2-6: Tubing configuration - 3 loops

Some of these parameters are the following:

- Supply water temperature
- Water flow rate
- Span of the slab
- Circuit or tubing length within each slab

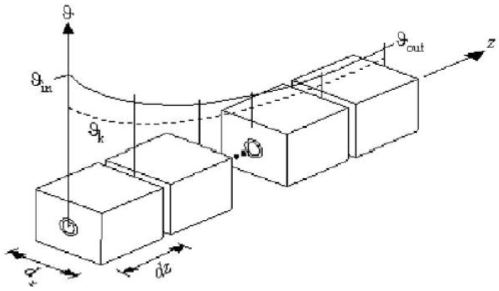


Figure 2-7: Change in temperature along the tubing (Koschenz and Lehmann, 2000)

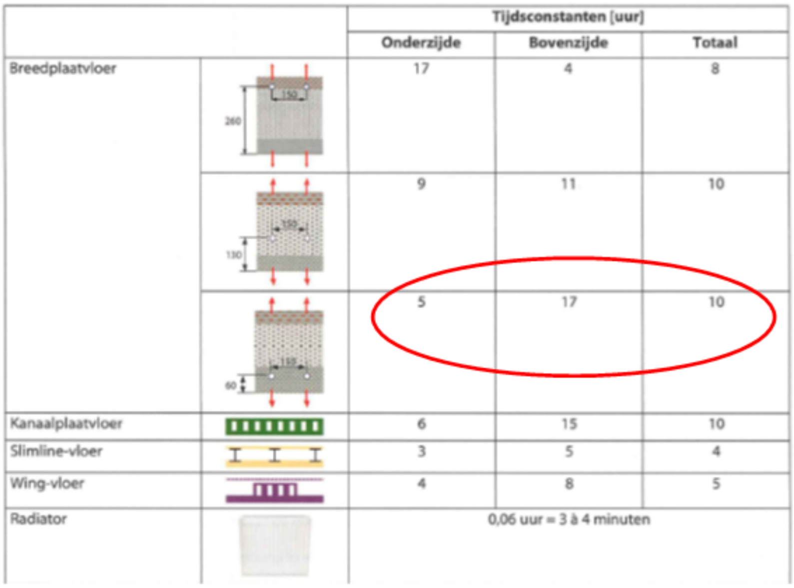
- Tube distance
- Tube diameter
- Tube mantle thickness
- Temperature conditions of the occupied space and the concrete slab
- Depth of the plane where the water tubes are embedded

2-1-1 CCA Controls

Controls are one of the key parameters of concrete core activation. These are the regulators of the system and should be well designed in order to achieve an optimal performance in the building.
As mentioned above, CCA is a slow-reacting system since it needs several hours to release or absorb heat to or from the indoor space. As a result, CCA is required to operate several hours before the occupants of the building arrive. That is the reason why CCA is a very suitable system to be implemented in buildings, which follow a strict occupancy schedule such as office buildings, department stores etc.
Moreover, special attention should be paid on thermal comfort and the control strategy of TABS since there is danger of increase of thermal discomfort with these systems if the controls are not applied properly (Olesen et al., 2002; Glück, 2002). In the following table, response times (time needed to reach 63% of the final heat release) in relation to the type of the slab and the position of the water tubes inside the slab are displayed.

According to Hoogmartens and Sourbron (2011) a lot of conventional TABS control strategies have been investigated:

- Time based control
- Zone temperature control
- Weather dependent supply/average water temperature control
- Intermittent pump operation control
- Constant concrete core temperature control



		Tijdsconstanten [uur]		
		Onderzijde	Bovenzijde	Totaal
Breedplaatvloer		17	4	8
		9	11	10
		5	17	10
Kanaalplaatvloer		6	15	10
Slimline-vloer		3	5	4
Wing-vloer		4	8	5
Radiator		0,06 uur = 3 à 4 minuten		

Figure 2-8: Response time - results of ISSO85

Often a combination of the control strategies, listed above, has been applied. Intermittent pump operation control can reduce the energy use of the circulation pump without violating thermal comfort.

Sourbron et al. (2009) showed, based on measurements and simulations, that unadapted TABS control has a dramatic impact on overall energy performance.

CCA operation only during night hours is beneficial from the energy point of view, but with a slightly higher thermal discomfort according to Olesen et al. (2002). Intermittent pump control could drastically lower energy use, while maintaining a comparable level of thermal comfort. For the supply temperature, a slightly inclined, outdoor temperature dependent cooling curve appeared to be the best in balancing energy use and thermal comfort.

Güntensperger et al. (2005) defined one supply temperature curve, depending on the outdoor temperature, in combination with a pump operation time control. Moreover, they added the concrete core temperature as an extra corrective variable in their building controller simulation. This concrete core temperature together with the room air temperature was used to correct the calculated supply temperature.

Gwerder et al. (2008) proposed four-part zone control as explained below:

1. Outside temperature determines supply water temperature control according to heating and cooling curves (mandatory)
2. Room temperature feedback control (optional)
3. Intermittent operation of zone water circulation pump (optional)
4. Sequence control of zone supply water temperature (mandatory)

To sum up, the most important points of the control strategies are the following:

- Water supply temperature should be based on outside temperature and heating and cooling curves should be applied to it.
- Intermittent pump operation control is strongly advised to lower energy consumption.
- Zone temperature control is suggested to regulate either water supply temperature or pump operation.

2-1-2 Benefits and Drawbacks

TABS as any other system has its advantages and disadvantages and of course a specific field of application.

PROS

- According to Hoogmartens and Sourbron (2011) energy performance of these systems is proven to be more effective than conventional systems. The reduction in energy consumption varies when compared to conventional heating/cooling systems because it is highly influenced by the controls which are applied to CCA.
- With radiant systems, thermal comfort is achieved at warmer interior temperature than all-air systems for cooling scenario, and at lower temperature than all-air systems for heating scenario. Thus, radiant systems achieve energy savings in building operation while maintaining the wished comfort level (ISO 11855-1, 2012).
- Because CCA operates at a water temperature very close to the indoor air temperature, it increases the efficiency of heat pumps, ground heat exchangers and other systems using renewable energy sources (Olesen, 2008).
- Since water tubing is located at the whole surface of an indoor space, CCA provides heating and cooling which is uniformly distributed at the horizontal plane and results in an increased level of thermal comfort inside the occupied area if it is properly installed and controlled. On the contrary, as far as conventional systems such as convectors or radiators are concerned, they are installed mostly under window sills and provide unevenly distributed heat and 'coolth'.
- In case of concrete core activation pipes are installed inside the slab which provides more free space in contrast to radiators or other appliances which take up space.
- CCA prevents dust circulation and dry air during heating up and spreading of bacteria during cooling.

CONS

- CCA is a slow-reacting system since it operates at a low water temperature for heating and at a high temperature for cooling. Its principle is to heat/cool the construction which as a result transfers heat through convection and radiation in a relatively high response time.

- CCA needs a high start-up thermal power due to transient effect as Sourbron (2012) found by measurement data (Fig. 2-9).
- It is not applicable to existing buildings due to the fact that the water tubing is located inside the slab.
- The installation costs of the system are significantly higher than the conventional ones, unlike the operational costs which are prominently lower.
- The system needs to be carefully designed and installed in order not to need maintenance in the future. Although it is said to be a 'maintenance free' system, it is obvious that potential repairs in the circuit (water pipes, mechanical equipment) will result in high costs since the construction (slabs, facade elements) will have to be repaired as well.
- It is more difficult to divide a space, a storey or the building into separate thermal zones with different temperatures due to the fact that the heating/cooling system is integrated inside a structural component of the building which runs at a very large surface.

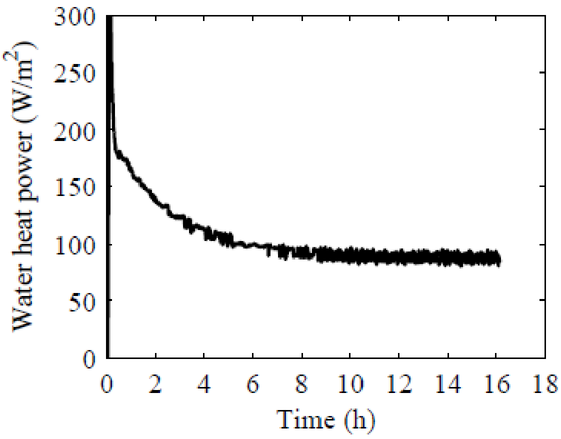


Figure 2-9: Heat power as a response to the step excitation of water supply temperature (Sourbron, 2012)

It is important to note some limitations of CCA in the cooling mode which may reduce the cooling capacity of a floor system.

- Condensation problems may occur at the cooled surface if the dew point temperature is above the surface temperature. The minimum surface temperatures are shown in Table 2-1 according to Olesen (2008).
- Since cooled air has a higher density there may be problems of air stratification where chilled air will be accumulated at the lower part of the occupied space and will lead to unevenly temperature distribution in the vertical axis.

It is important to take into consideration that the convective heat exhange coefficient is much lower for floor cooling than it is for floor heating (Olesen, 2008) as demonstrated in Table

2-1. Therefore, the location of the water tubing inside the slab is of great importance in order to avoid thermal discomfort. In spaces where cooling is dominant (office buildings), the water tubing should be applied as low as possible inside the slab (chilled ceiling), whereas in residential buildings where heating is dominant, the activated layer should be located as high as possible (heated floor).

Table 2-1: Heat exhange coefficient, minimum and maximum recommended surface temperature and cooling and heating capacity (Olesen, 2008)

	Total Heat Exhange Coefficient (W/m^2K)		**Surface Temperature (^oC)**		**Capacity (W/m^2)**	
	Heating	Cooling	Maximum	Minimum	Heating	Cooling
Floor	11	7	29	20	99	42
Ceiling	6	11	27	17	42	99

2-2 Radiative panels

Radiative panels are generally attached to ceilings, but can also be attached to walls. They are usually suspended from the ceiling, but can also be directly attached to it. Their dimensions can vary from 600x100mm to 4800x1500mm and they are just a few centimeters thick. Fig. 2-10 illustrates a typical cross-section of a radiative panel. The water tubing is located between a thin layer of insulation and a metal plate in order to avoid heat transfer to the upper part of the panel. A metal plate is located below the tubes in order to ensure high radiative heat transfer because of the material's high emissivity. Contrary to concrete core activation, radiative panels have lower thermal mass, which means they cannot store the same amount of heating and cooling energy, but they can respond to rapid fluctuations that occur due to changes in the internal and external heat load. Therefore, radiative panels are more suitable for buildings with spaces that have a greater variance in heating and cooling loads (American Society of Heating and Engineers, 2008). Ceiling panels are easily installed and can also be integrated in existing buildings. However, panels tend to cost more per unit of surface area than radiant slabs. Radiative ceiling panels are more effective in cooling mode as illustrated in table 2.1 although condensation problems may occur if the dew point temperature is above the surface temperature. In heating mode radiative ceiling panels are not very effective because of the low convective heat exchange coefficient (Olesen, 2008). Additionally, due to the low density of warm air provided by radiative panels may lead to air stratification issues where warm air is accumulated at the upper part of the occupied space and results in unevenly temperature distribution in the vertical axis.

2-3 Combination of CCA with radiative ceiling panels

This thesis deals with the combination of concrete core activation and radiative ceiling panels. The combination of these systems can result in lower energy consumption keeping thermal comfort in acceptable limits. However, it is important to note that the use of two systems in a building results in higher initial costs.

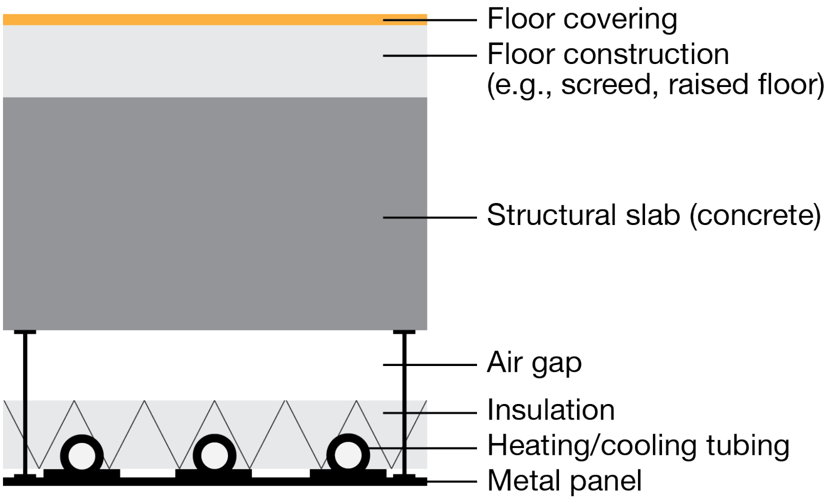


Figure 2-10: Cross-section of radiative panel

Generally, the distribution of such systems consists of four pipes. The four-pipe system includes a distribution system that contains both hot water supply with return lines and a chilled water supply with return lines. This distribution concept allows simultaneous cooling and heating of different zones according to their needs. On the other hand, 2-pipe distribution systems are less flexible because the whole building is either in heating or in cooling mode. Therefore, there is always the possibility that unusual weather patterns or unequally distributed heating/cooling loads among the zones might cause some occupant discomfort.

The innovation in this project is that both systems share the same distribution piping system (2-pipe distribution system), thus obtaining substantial savings on investment costs. In this way, the slow and fast delivery systems are intermittently connected to the same distribution system, i.e. a so-called change-over system, which means that both systems cannot operate at the same time. Additionally, it is impossible to heat one zone and cool another due to the fact that a 2-pipe distribution system is used. Therefore, this might lead in thermal discomfort in some zones of the building. Concrete core activation operates during night hours and radiative ceiling panels during the occupancy hours. In Fig. 2-11, a simple model with combination of CCA and radiative ceiling panel is shown. Radiative ceiling panels are installed at a part of the ceiling plane. The percentage of the ceiling which is covered with panels can influence the efficiency of CCA, since the view factor ϕ is reduced and eventually radiative heat transfer to and from the occupied space is lowered.

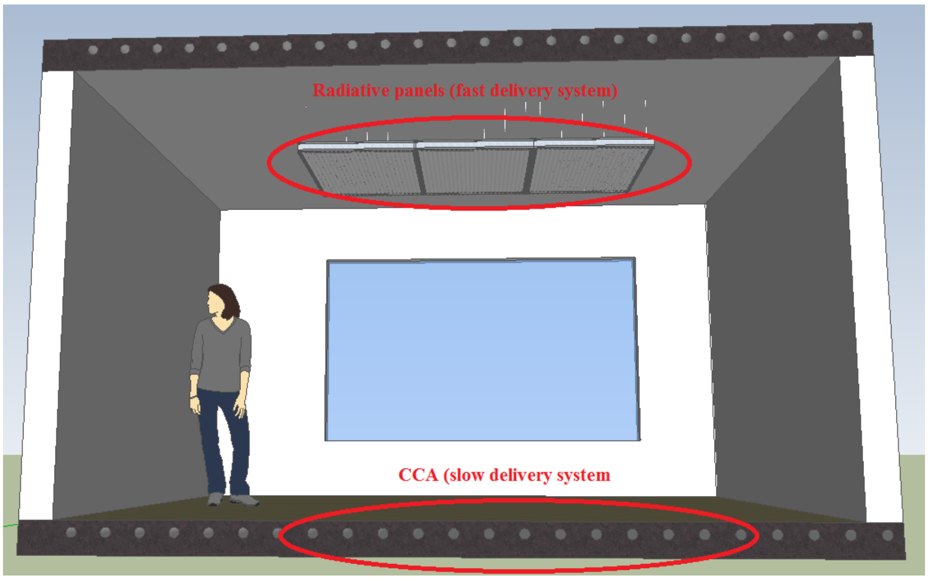


Figure 2-11: A simple model with combination of CCA and radiative panels

Chapter 3

Building Energy Modelling Programs (BEMPs)

As mentioned in chapter 1, one of the objectives of this graduation project is the comparison of TABS with different programs. The first program is TRNSYS and the second one was initially selected to be EnergyPlus. However, more than one program have been tested in order to find the most suitable for the specific system.
In this chapter the physical models behind these programs regarding conduction is shown. Moreover, differences in the output depending on the used software are demonstrated.

Building Energy Modelling Programs (BEMPs) are sophisticated programs mostly dealing with the energy performance buildings. However, according to Zhu et al. (2012); Behrendt et al. (2011) large discrepancies in simulation results can exist between different Building Energy Modeling Programs (BEMPs). As a result, there are claims that some BEMPs are better than others. In order to comprehend these problems, it is essential to identify and understand differences between BEMPs, and the effect of these differences on load simulation results. These differences in the results may be caused due to mathematical issues (interpolation, truncation, discretization errors, etc.), problems in the default values or differences in the calculation methods and modelling processes.

3-1 BESTEST Project

In the BESTEST project (Judkoff and Neymark, 1995), a method was developed for systematic testing of building energy modelling programs and diagnosing the causes of possible differences in the predictions of their results. Field trials of the method were conducted with a number of 'reference' programs selected by the participants to represent the best state-of-the-art detailed simulation capability available in the United States and Europe. The method consists of a series of test case buildings ranging from the extremely simple to the relatively realistic.

The comparison of the output of the participating programs showed a large amount of disagreement, even after all errors found via the diagnostics were fixed. The differences ranged from approximately 20% for prediction of peak loads in test cases with low thermal capacitance to about 66% for prediction of annual cooling loads in the high thermal capacitance test cases (Judkoff and Neymark, 1995).

In the histograms (Fig. 3-1, 3-2), one can see the differences that are provided as output from several BEMPs according to indicative BESTEST cases.

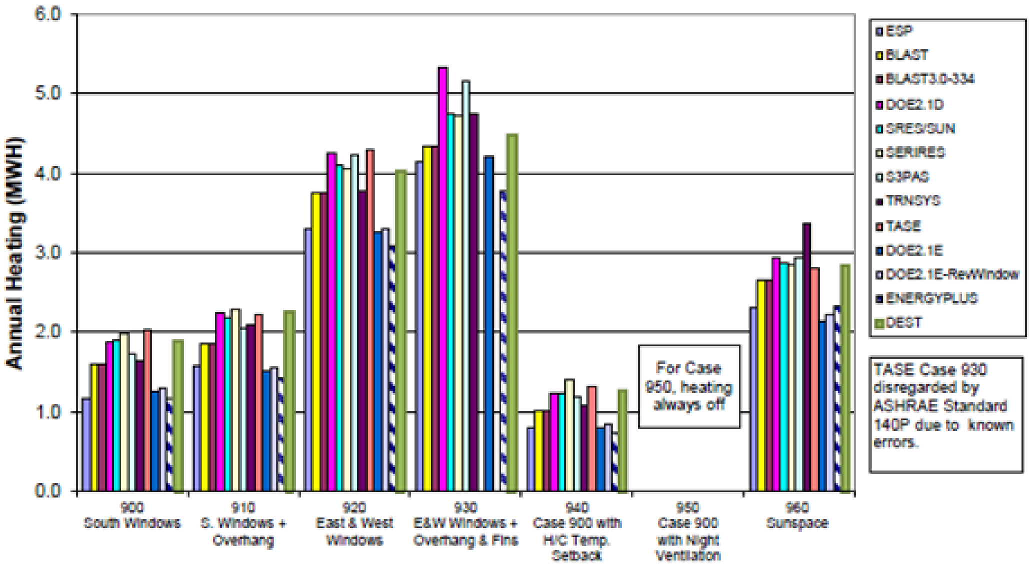


Figure 3-1: BESTEST Case: Standard 140-2007: Comparison high-mass building for annual heating (Zhu et al., 2012)

3-2 EnergyPlus

EnergyPlus originates from the BLAST and DOE-2 programs (Crawley et al., 2001). BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2 were both developed and released in the late 1970s and early 1980s as energy and load simulation tools, addressed to design engineers or architects who size HVAC equipment, optimize energy performance, etc.

Like its parent programs, EnergyPlus is an energy analysis and thermal load simulation program. EnergyPlus calculates the heating and cooling loads necessary to maintain thermal control setpoints, the energy consumption of plant equipment and many other simulation details according to the needs of a designer. Many of the simulation characteristics have been passed from BLAST and DOE-2.

FORTRAN90 was chosen by the developers as the operating programming language for the initial release of EnergyPlus because of its advantages. Since the original version (2001), EnergyPlus code and structure continues to evolve and adopts Fortran Standard. New versions of EnergyPlus are published regularly. EnergyPlus is not a user interface. It is intended to be the simulation engine which can also be complemented by a third-party interface.

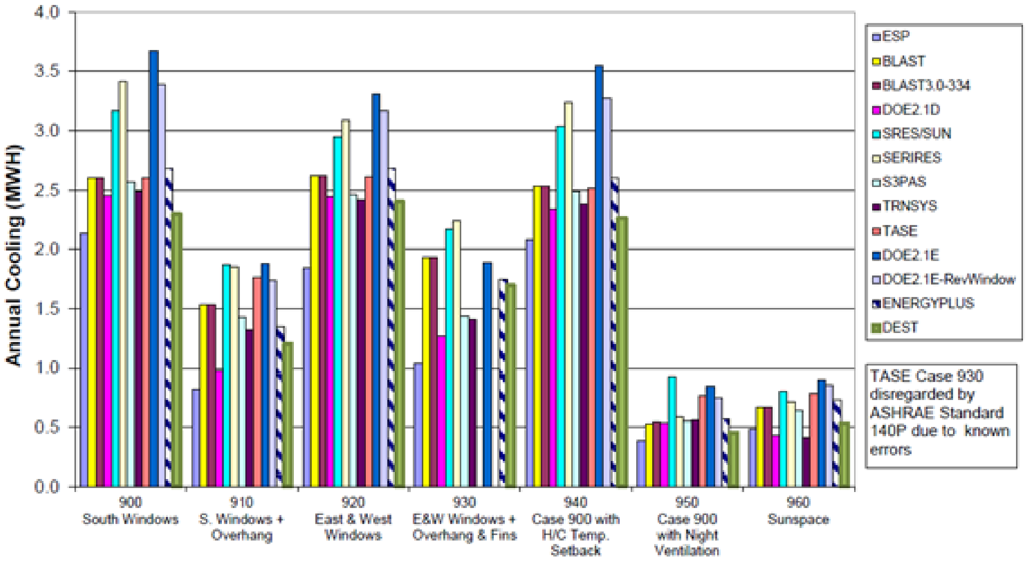


Figure 3-2: BESTEST Case: Standard 140-2007: Comparison high-mass building for annual cooling (Zhu et al., 2012)

The following is a representative list of EnergyPlus capabilities, as given by the U.S. Department of Energy:

- Integrated, simultaneous solution where the building response and the primary and secondary systems are tightly coupled (iteration performed when necessary)
- Sub-hourly, user-definable time steps for the interaction between the thermal zones and the environment; variable time steps for interactions between the thermal zones and the HVAC systems (automatically varied to ensure solution stability)
- Heat balance based solution technique for building thermal loads that allows for simultaneous calculation of radiant and convective effects at both in the interior and exterior surface during each time step
- Transient heat conduction through building elements such as walls, roofs, floors, etc. using conduction transfer functions
- Improved ground heat transfer modelling through links to three-dimensional finite difference ground models and simplified analytical techniques
- Combined heat and mass transfer model that accounts for moisture adsorption/desorption either as a layer-by-layer integration into the conduction transfer functions or as an effective moisture penetration depth model (EMPD)
- Thermal comfort models based on activity, inside dry bulb, humidity, etc.
- Anisotropic sky model for improved calculation of diffuse solar on tilted surfaces

- Advanced fenestration calculations including controllable window blinds, electrochromic glazings, layer-by-layer heat balances that allow proper assignment of solar energy absorbed by window panes, and a performance library for numerous commercially available windows
- Daylighting controls including interior illuminance calculations, glare simulation and control, luminaire controls, and the effect of reduced artificial lighting on heating and cooling
- Atmospheric pollution calculations that predict CO_2, SO_x, NO_x, CO, particulate matter, and hydrocarbon production for both on site and remote energy conversion

Another very important advantage of EnergyPlus is that it allows user-configurable modular HVAC systems which makes it easier for the user to apply a more complicated system according to his/her needs, as in the case of TABS (a change-over system of radiant floors and radiant panels).

3-3 Third-party Graphical User Interfaces

The graphical user interfaces (GUIs) should not be confused with the actual simulation engines which perform the calculations such as EnergyPlus. The whole set-up of the model and the HVAC systems is completed in these GUIs and afterwards EnergyPlus is used to conduct the calculations which lead to the requested results. The major advantage of the GUIs is that one can easily design models and adjust factors of HVAC systems in a user-friendly environment in contrast to EnergyPlus which is much more difficult to use and understand. Another significant advantage of third-party graphical user interfaces is that there is no need to load the EnergyPlus program in order to perform the simulation, but it is automatically opened to conduct the calculation for the results which are requested by the user. There are many graphical user interfaces for EnergyPlus which are available or under development. Some of them allow a wide range of building types to be simulated using EnergyPlus as an engine and there are others which are specialized in particular fields.

The GUIs which have been reviewed during this project were OpenStudio and DesignBuilder in order to decide which is the appropriate one to model thermally activated building systems.

3-3-1 OpenStudio

OpenStudio, as mentioned in the user documentation, is a cross-platform collection of software tools to support whole building energy modelling using EnergyPlus and advanced daylight analysis using Radiance. OpenStudio is an open source, freeware program which anyone can download and edit according to his/her needs.
OpenStudio is a plug-in for SketchUp and allows the use of the standard SketchUp tools to create and edit EnergyPlus zones and surfaces. However, OpenStudio does not yet handle all critical input objects. Changed of the input file may be required outside of SketchUp.

OpenStudio was created by the National Renewable Energy Laboratory (NREL) for the U.S. Department of Energy.

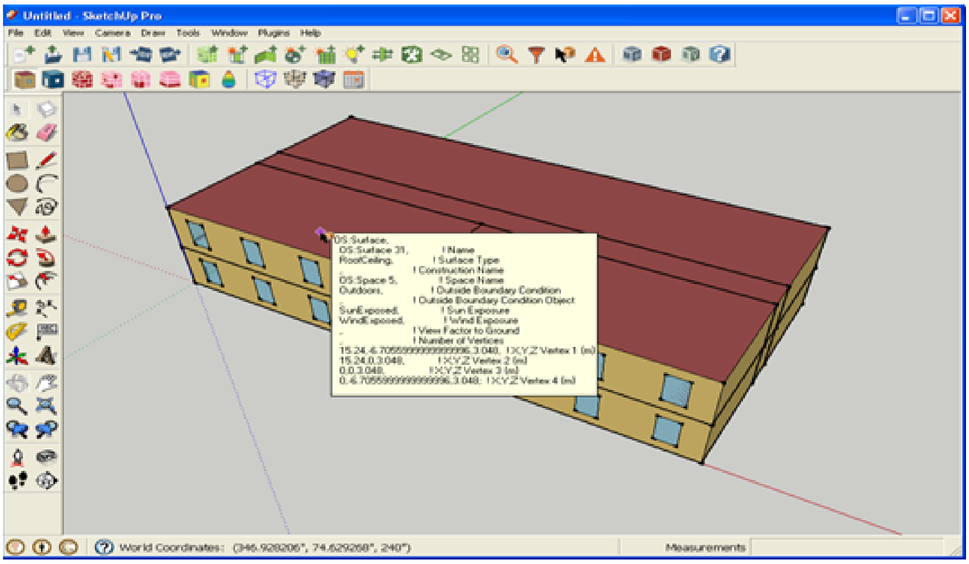


Figure 3-3: Legacy OpenStudio Plug-in for Sketchup interface screenshot (Credit: David Goldwasser/NREL)

In Fig. 3-3 a screenshot of this application is illustrated.

Moreover, OpenStudio is easily accessible and software developers and building researchers are able to view the code, customize it according to their needs and develop new tools using C++, C# and Ruby.

Limitations

Openstudio is not suitable for the study of CCA because it does not support the design of radiant floors, critical to the conduction of this research. Therefore, it was rejected in the early stages of the thesis.

3-3-2 DesignBuilder

DesignBuilder, like OpenStudio, is a third-party user interface for EnergyPlus, a user-friendly modelling environment where one can work with virtual building models. It provides a range of environmental performance data, such as: energy consumption, carbon emissions, comfort conditions, daylight illuminance and HVAC component sizing.
Some typical uses of DesignBuilder, as mentioned on the website of DesignBuilder are:

- Calculating building energy consumption.
- Thermal simulation of naturally ventilated buildings.
- Reporting savings in electric lighting due to use of natural daylight.
- Prediction of natural daylight distribution through Radiance simulations

- Calculating heating and cooling equipment sizes.
- Detailed design of HVAC and natural ventilation systems including the impact of supply air distribution on temperature and velocity distribution within a room using CFD.
- Environmental performance data is displayed without needing to run external modules and import data and any simulations required to generate the data are started automatically.
- EnergyPlus "Compact HVAC" descriptions provide an easy way into detailed analysis of commonly used heating and cooling systems.
- Natural ventilation can be modelled with the option for windows to open based on a ventilation set point temperature.
- Daylighting - models lighting control systems and calculates savings in electric lighting.
- Shading by louvres, overhangs and sidefins as well as internal and mid pane blinds.
- A comprehensive range of simulation data can be shown in annual, monthly, daily, hourly or sub-hourly intervals:
- Parametric analysis screens allow you to investigate the effect of variations in design parameters on a range of performance criteria.
- Generate EnergyPlus IDF files and work with these outside DesignBuilder to access EnergyPlus system functionality not provided by DesignBuilder.

Limitations

- **CCA**: There is no way to design concrete core activation solely in DesignBuilder. Internal sources (water tubing layer) can be created, but can operate either only in heating or cooling mode, whereas CCA should include both heating and cooling.
- **Schedules & Controls**: It is difficult and sometimes impossible to apply complex schedules for the HVAC controls.
- **Bugs**: During the use of DesignBuilder several errors have been encountered, which produced unexpected results, especially when using the 'Autosize' feature. HVAC Autosizing is a DesignBuilder and EnergyPlus feature which automatically sizes HVAC components and plant loops.

The ways to overcome the problems above are analyzed in chapter 6 and in the Appendix.

3-4 Connection between EnergyPlus and Third-Party User Interfaces

- IDF (Input data files) is the standard file format for EnergyPlus models, which contains all the necessary data for the description of a model. It is a text file but with an '.idf' instead of a '.txt' extension.

- All text editors can edit IDF files. Several applications are designed solely to edit IDF files.
- There is a dedicated IDF editing application named 'IDFEditor' or 'EP -Launch' (Fig. 3-4) included with EnergyPlus.

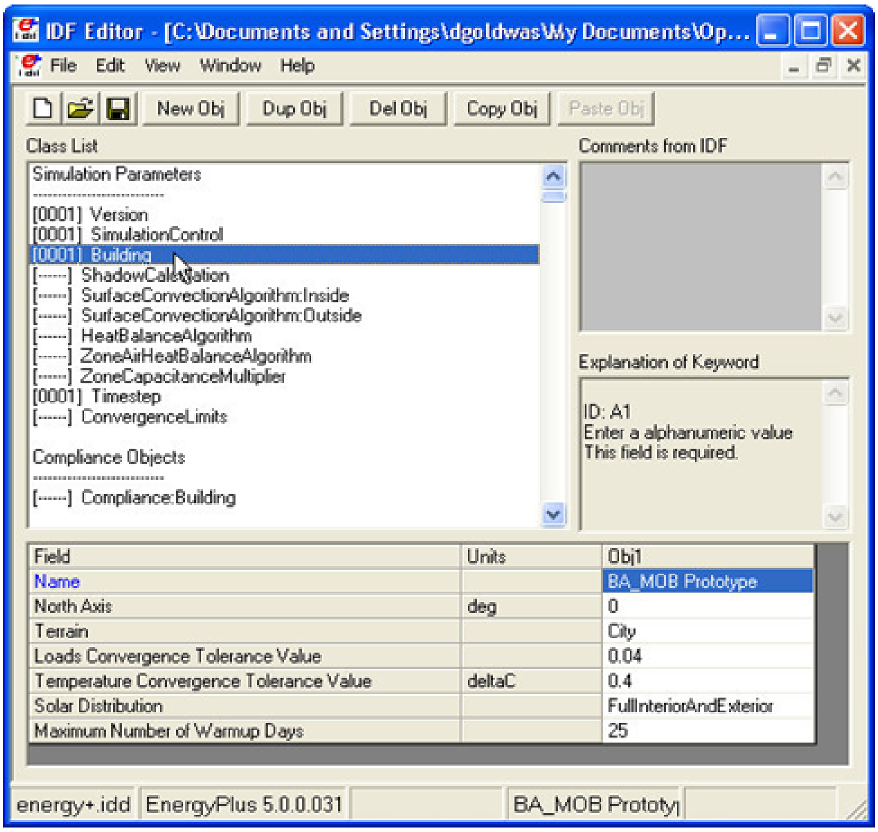
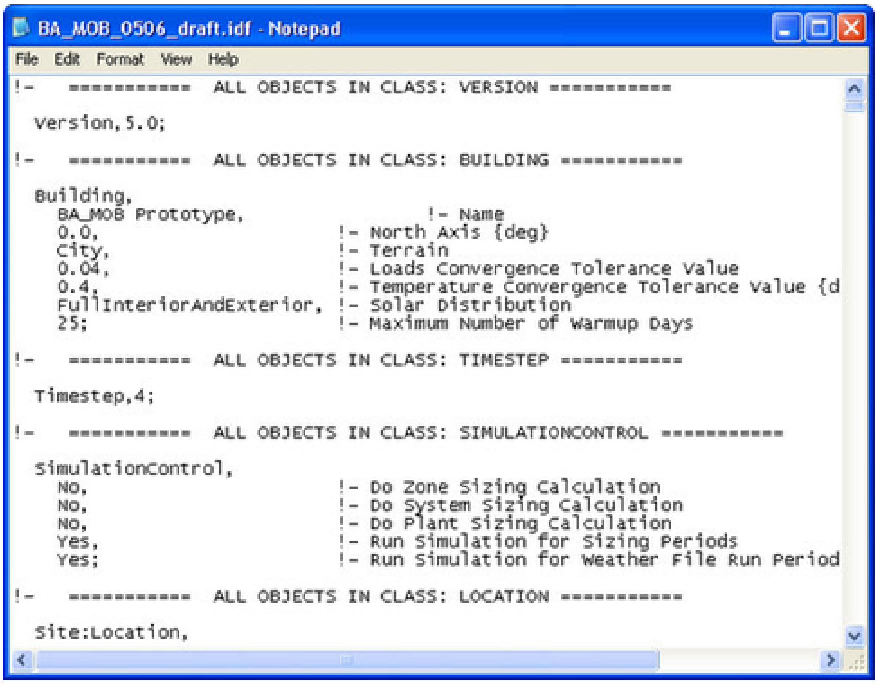


Figure 3-4: EnergyPlus screenshot/IDFEditor (Credit: David Goldwasser/NREL)

In Fig. 3-5 the same information for the building is shown as raw text without a graphical user interface in Notepad.

Procedure followed by Third-Party User Interfaces and EnergyPlus

As mentioned above, EnergyPlus is not a user interface. In Fig. 3-6, one can see how a third-party user interface is used and the connection between the different components of the software.
The user creates the geometry of the model in the graphical user interface and applies specific materials, layers in the constructions and surfaces. It is also possible to introduce HVAC systems and their schedules. The simulation begins with the completion of the model. When the simulation starts, the following procedure automatically takes place. Initially, an IDF file is created, which is the standard file format for EnergyPlus models. The IDF file is processed by EnergyPlus and then the output is finally demonstrated in the GUI used.



BA_MOB_0506_draft.idf - Notepad

File Edit Format View Help

```
!-   ===========  ALL OBJECTS IN CLASS: VERSION ===========

  Version,5.0;

!-   ===========  ALL OBJECTS IN CLASS: BUILDING ===========

  Building,
    BA_MOB Prototype,            !- Name
    0.0,                     !- North Axis {deg}
    City,                    !- Terrain
    0.04,                    !- Loads Convergence Tolerance Value
    0.4,                     !- Temperature Convergence Tolerance Value {d
    FullInteriorAndExterior, !- Solar Distribution
    25;                      !- Maximum Number of Warmup Days

!-   ===========  ALL OBJECTS IN CLASS: TIMESTEP ===========

  Timestep,4;

!-   ===========  ALL OBJECTS IN CLASS: SIMULATIONCONTROL ===========

  SimulationControl,
    No,                      !- Do Zone Sizing Calculation
    No,                      !- Do System Sizing Calculation
    No,                      !- Do Plant Sizing Calculation
    Yes,                     !- Run Simulation for Sizing Periods
    Yes;                     !- Run Simulation for Weather File Run Period

!-   ===========  ALL OBJECTS IN CLASS: LOCATION ===========

  Site:Location,
```

Figure 3-5: Screenshot of an IDF file opened in Wordpad (Credit: David Goldwasser/NREL)

The procedure can be done solely in the GUI without any need for the user to load EnergyPlus or any other simulation engine.
Both DesignBuilder and OpenStudio function with the procedure explained above. The only difference is that OpenStudio uses SketchUp for the design the model's geometry, while DesignBuilder supports this feature itself.
EnergyPlus also offers a dedicated IDF editor, which provides the ability to adjust and correct IDF files created by the GUIs or even create models from scratch. EnergyPlus may be more complicated and less user-friendly, but it is also more flexible and offers more possibilities. Moreover, the simulations are conducted faster in EnergyPlus than in any GUI, which is reasonable since the step of the IDF file creation is omitted.

3-5 Conclusion

To sum up, EnergyPlus is a very useful and easy-to-use tool when combined with a third-party user interface. The 'user-friendly' graphical user interface, like OpenStudio and DesignBuilder, makes it easy for everyone to use and understand. However, there are problems that make complicated HVAC systems, such as CCA, difficult or impossible to be modelled in some applications. The graphical user interfaces do not yet handle complicated controls and HVAC systems. Therefore, some editing of the input file may usually be required in EnergyPlus.

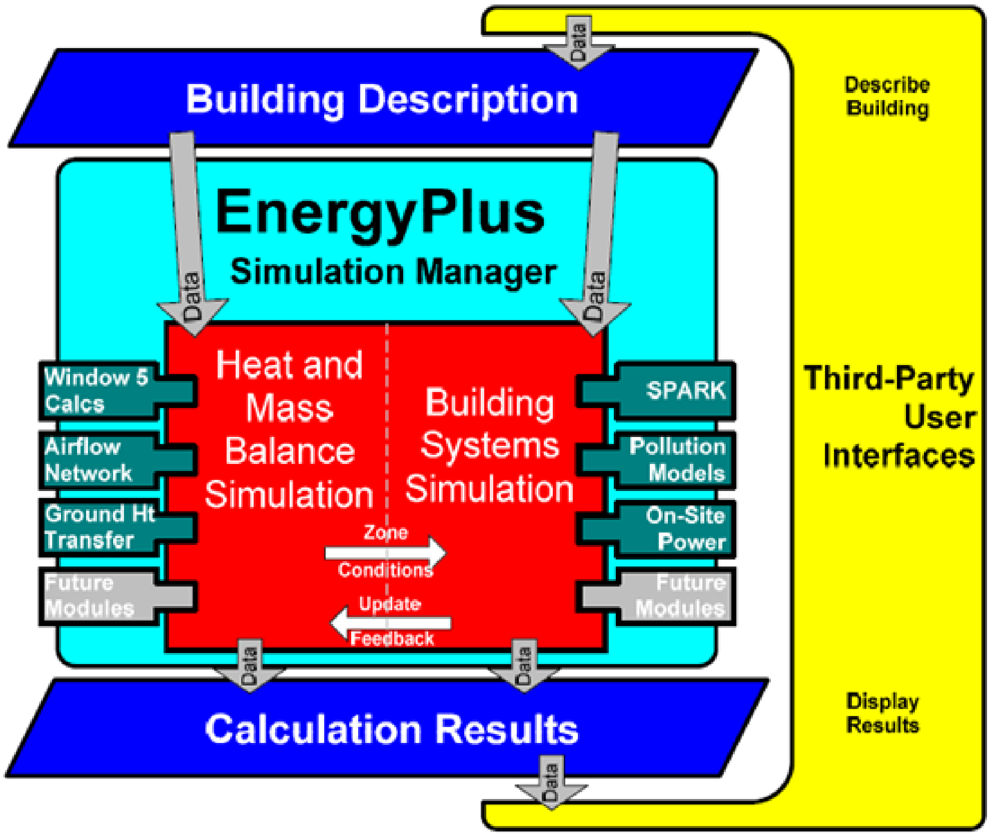


Figure 3-6: EnergyPlus simulation procedure (Crawley et al., 2001)

Chapter 4

CCA thermal models and BEMPs' simulation methods

4-1 The EMPA model

Transient conduction occurs when the temperature within an object changes as a function of time. Analyzing transient systems is more complex than steady-state analysis and must be often solved with approximation theories and the use of computer (Smith et al., 2005). According to Sourbron (2012) transient heat transfer in an object is commonly described with a thermal Resistance-Capacitance or RC-model. In an RC-model, objects are segmented into 'n' layers and each layer is characterized by a thermal capacitance C or 'node'. It is assumed that the temperature inside the material layer is characterized by the temperature of the node. All nodes of adjacent layers are connected via thermal resistances R as depicted in Fig. 4-1.

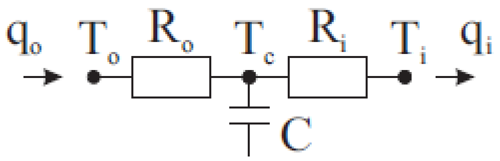


Figure 4-1: RC-model representation (Sourbron, 2012)

In heat transfer theory, lumped capacity solutions are typically used in situations where the conduction heat transfer coefficient λ/d is much larger than the convection coefficient h at the elements surface (Sourbron, 2012). This is presented as the Biot number (Bi) to be very small:

$$Bi = \frac{hd}{\lambda} \ll 1 \tag{4-1}$$

where h the heat transfer coefficient from surface to surroundings (W/m^{2}K), d the thickness (m) and λ the heat conduction coefficient of the material layer (W/mK).

So, for instance, a 20 cm thick concrete slab, with water tubing located in the centre of the slab, used to heat a room, the Bi-number of upper and lower part are:

$$Bi_{lower} = \frac{(h_c + h_r)(d/2)}{\lambda_{concrete}} = \frac{(0.4 + 5.6) \cdot 0.1}{2} = 0.30 \tag{4-2}$$

$$Bi_{upper} = \frac{(h_c + h_r)(d/2)}{\lambda_{concrete}} = \frac{(3.3 + 5.6) \cdot 0.1}{2} = 0.44 \tag{4-3}$$

Since these Bi-number are not very small, this model leads to errors. This example refers to a 1st order RC-model since there is only 1 lumped capacity or 1 internal node in the middle of the slab. In order to have more accurate results, the concrete slab has to segmented into more layers which will reduce the Bi-values.

Attempts to create simplified modelling of CCA have been made by EMPA, the Swiss Federal Laboratories for Materials Testing and Research. The book 'Thermoaktive Bauteilsysteme tabs' (Koschenz and Lehmann, 2000) presents a simplified RC-model for CCA. In this thesis, this model will be addressed as the 'EMPA model'. The heat flow inside the concrete slab which is originally 3-dimensional is transformed into a 1D model. In order to understand the approach that Koschenz and Lehmann (2000) have introduced, the heat flows from the tube plane are taken into consideration and the thermal resistances, included, are reviewed. These resistances will first be discussed in the following paragraphs.
According to Koschenz and Lehmann (2000) there are four resistances when there is heat flow from the center of the water tube to the concrete slab. A typical cross-section of a radiant slab is shown in Fig. 4-2. Fig. 4-3 illustrates the temperatures and thermal resistances inside the pipe. Fig. 4-4 shows the thermal resistances in the RC-network. The parameters of the RC-network are mentioned below:

- R_w: Thermal resistance between the center of the water tube and inside surface of tube mantle.
- R_r: Thermal resistance through the pipe shell.
- R_z: Thermal resistance along the tubing.
- R_x: Resistance originated from the transformation of the triangular arrangement into the star arrangement.
- R_1: Concrete's thermal resistance of the upper part of the slab.
- R_2: Concrete's thermal resistance of the lower part of the slab.
- T_{ws}: Water supply temperature at the center of the water tube.
- T_3: Temperature at the outer side of the tube mantle.
- T_c: Mean temperature at the water tubing plane or equivalent concrete core temperature
- T_{room1}: Room 1 air temperature.
- T_{room2}: Room 2 air temperature.

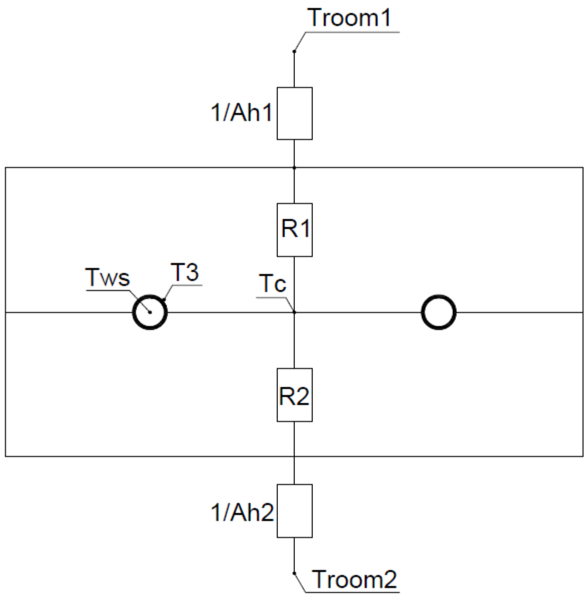


Figure 4-2: Structure of the thermo-active construction element

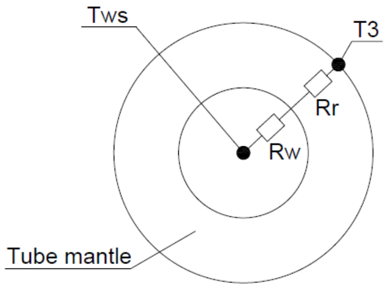


Figure 4-3: Thermal resistances inside a water tube (not in scale)

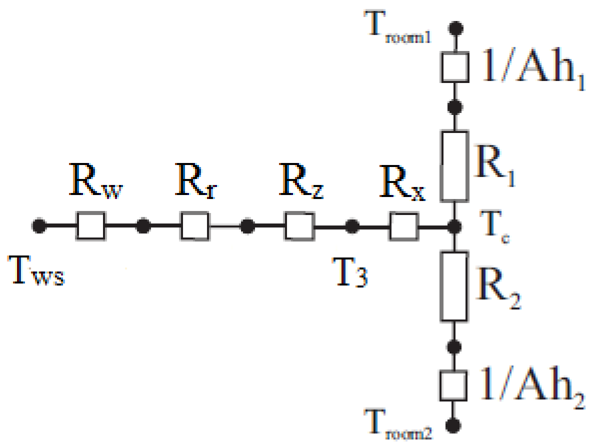


Figure 4-4: EMPA's 1D RC-model of a CCA slab

4-1-1 Thermal transmittance through the tube mantle

Thermal transmittance is defined as the heat transfer from the fluid within the tube with the temperature T_{ws} through the tube mantle to the concrete with the temperature T_3. This is actually two different processes, the process of convection and the process of thermal conductance. In the first step, heat is transferred between water and the tube mantle by forced convection, in effect introducing the thermal resistance R_w. Then energy is exchanged between the pipe material and concrete by thermal conductance, respectively introducing R_r. Both thermal resistances are proportional to the surface area of the construction element $d_x \cdot l$, where d_x is the tubing distance and l is the length of the tubing or circuit length. Thermal resistance by convection for cylindrical areas is expressed in the following formula:

$$R_w = \frac{d_x}{a_w(\delta - 2d_r)\pi} \tag{4-4}$$

where δ is the outside tube diameter,
d_r is the thickness of the tube mantle
and a_w the convective heat transfer coefficient.

The convective heat transfer coefficients a_w for the most common pipe dimensions are shown in Fig. 4-5 for laminar and turbulent flow. With the help of Fig. 4-5, Eq. 4-4 can be transformed into:

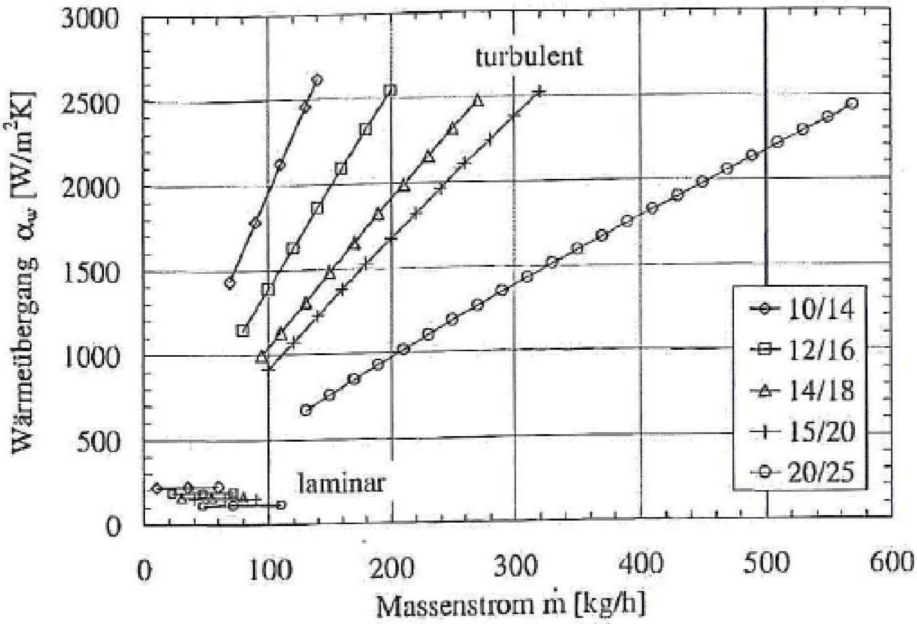


Figure 4-5: Convective heat transfer coefficients for different pipe dimensions for laminar and turbulent flow *($\theta_w = 20°C$; max. flow velocity w=0.5 m/s)* (Koschenz and Lehmann, 2000)

$$R_w = \frac{d_x^{0.13}}{8.0 \cdot \pi} \cdot \left(\frac{\delta - 2 \cdot d_r}{m_{sp} \cdot l}\right)^{0.87} \tag{4-5}$$

The resistance for heat transfer through the tube mantle by thermal conduction can be determined in a similar way. The formula for the reference surface area $d_x{\cdot}l$ (Fig. 4-6) is:

$$R_r = \frac{d_x \cdot \ln\left(\frac{\delta}{\delta - 2 \cdot d_r}\right)}{2 \cdot \lambda_r \cdot \pi} \tag{4-6}$$

where λ_r is the thermal conductivity of the tube mantle.

4-1-2 Mean water temperature in a pipe coil

The temperature inside the tubing is not constant because energy is transferred from the water tubing to the concrete along the pipe coil, as shown in Fig. 4-6. Therefore, the resistance R_z is introduced, which can be calculated by the following formula:

$$R_z = \frac{1}{m_{sp}c\left[1 - exp\left(-\frac{1}{(R_w+R_r+R_x+\frac{1}{U_1+U_2})}\right) m_{sp}c\right]} - \left(R_w + R_r + R_x + \frac{1}{U_1 + U_2}\right) \quad (4\text{-}7)$$

where m_{sp} is water mass flow rate,
c is the specific heat capacity of water,
U_1 is the U-value of the upper part of the concrete slab
and U_2 is the U-value of the lower part of the concrete slab.

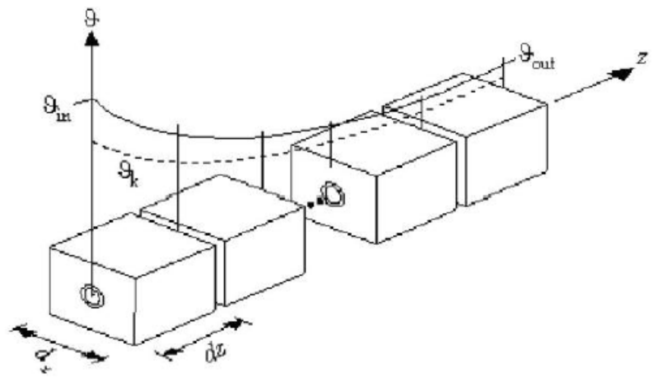


Figure 4-6: Change in temperature along the pipe coil (Koschenz and Lehmann, 2000)

4-1-3 The Resistance R_x

This resistance originates from the transformation of the triangular arrangement into the star arrangement, as it is shown in Fig. 4-7. The resistance R_x depends only on two geometrical parameters, i.e., the distance between pipes d_x and the pipe diameter δ, and on the thermal conductivity of the concrete slab λ_b in the pipe plane. The transformation from triangular to star-shaped network results in the additional temperature T_c for the center point of the star-network. Under the assumption that $d_i/d_x > 0.3$ and $\delta/d_x < 0.2$, the resistance R_x can be approximated as follows:

$$R_x \approx \frac{d_x ln\left(\frac{d_x}{\pi\delta}\right)}{2\pi\lambda_b} \quad (4\text{-}8)$$

where λ_b is the thermal conductivity of the concrete slab.

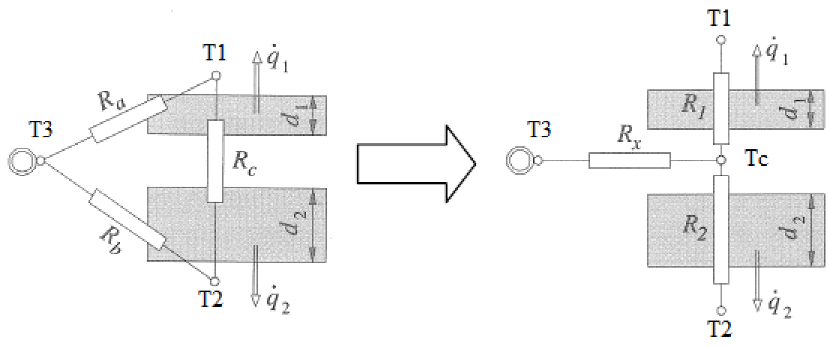


Figure 4-7: Transformation from 2D into 1D heat flow pattern by means of R_x (Koschenz and Lehmann, 2000)

4-1-4 Total resistance R_t

When placed in series, all of the single resistances can be summed up to form a total resistance: $R_t = R_z + R_w + R_r + R_x$

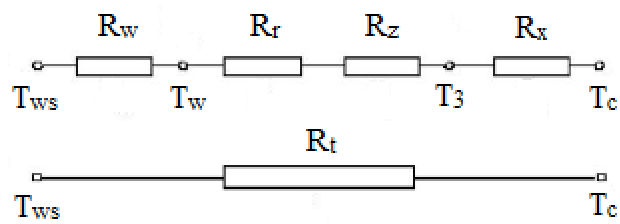


Figure 4-8: Total resistance between water inlet temperature and core temperature (Koschenz and Lehmann, 2000)

It is important to note that the 'EMPA model' only applies for solid concrete slabs and not for slabs with voids (hollow-core, Bubbledeck, Air-box). These parameters have been integrated in other thermal CCA models (Sourbron et al., 2008).

4-2 Modelling in TRNSYS

4-2-1 Integrated model for thermo-active building elements

The EMPA model is followed in TRNSYS to model thermo-active building elements and in our case CCA (Koschenz and Lehmann, 2000). All resistances are calculated according to section 4-1.

4-2-2 Integrated model for chilled ceiling panels

The methodology, that is followed in TRNSYS to model chilled ceiling panels, is based on the EMPA model. R_w is calculated according to section 4-1-1. The remaining resistances are calculated using formulas and approximations according to DIN 4715-1.

4-3 Modelling in EnergyPlus - Simulation models & Radiant system models

This section has been retrieved by the documentation of EnergyPlus. In this section, the methods which EnergyPlus uses to simulate heat conduction and concrete core activation are analyzed and the controls of CCA are explained.

One of the most important forms of heat transfer in energy analysis is heat conduction through building elements such as walls, floors and roofs (ENERGYPLUS, 2013). While some thermally lightweight structures can be approximated by steady state heat conduction, a method that applies to all structures must account for the presence of thermal mass within the building elements. As mentioned in chapter 2, TABS refer to temperature-controlled surfaces that heat or cool indoor spaces by adding or removing sensible heat and where more than half of heat transfer occurs through thermal radiation (American Society of Heating and Engineers, 2008). Moreover, since HVAC systems are integrated in the building's structural components, such as slabs, there is the effect of thermal storage inside them. This fact requires dynamic calculation methods based on transient heat conduction which means that conduction occurs when the temperature within an object changes as a function of time. Therefore, steady state calculations are insufficient. In the following sections the calculation methods of radiant system models is presented.

4-3-1 One Dimensional Heat Transfer Through Multilayered Slabs

Transient one dimensional heat conduction through a homogeneous layer with constant thermal properties is governed by the following equation (Carslaw and Jaeger, 1959):

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{a}\frac{\partial T}{\partial t} \tag{4-9}$$

where: T is the temperature as a function of position and time,

x is the position,

t is the time,

$\alpha = \frac{k}{\rho c_p}$ is the thermal diffusivity of the layer material,

k is its thermal conductivity,

ρ is its density,

c_p is its specific heat capacity.

This equation is typically coupled with Fourier's law of conduction that relates the heat flux at any position and time to temperature as follows:

$$q(x,t) = -k\frac{\partial T(x,t)}{\partial x} \tag{4-10}$$

While analytical solutions exist for single homogeneous layer, the solution generally becomes extremely tedious for multiple layered slab.

EnergyPlus uses a time series solution for transient heat conduction. The most basic time series solution is the response factor equation which relates the flux at one surface of an element to an infinite series of temperature histories at both sides as shown by:

$$q_{i,t} = \sum_{m=1}^{\infty} X_m T_{i,t-m+1} - \sum_{m=1}^{\infty} Y_m T_{o,t-m+1} \tag{4-11}$$

where q is heat flux, T is temperature, i signifies the inside of the building element, o signifies the outside of the building element, and t represents the current time step, and X and Y are the response factors. While in most cases the terms in the series decay fairly rapidly, the infinite number of terms needed for an exact response factor solution makes it less than desirable. Fortunately, the similarity of higher order terms can be used to replace them with flux history terms. The new solution contains elements that are called conduction transfer functions (CTFs). The basic form of a conduction transfer function solution is shown by the following equation:

$$q_{i,t} = \sum_{m=1}^{M} X_m T_{i,t-m+1} - \sum_{m=1}^{M} Y_m T_{o,t-m+1} + \sum_{m=1}^{k} F_m q_{i,t-m} \tag{4-12}$$

where k is the order of the conduction transfer functions, M is a finite number defined by the order of the conduction transfer functions, and X, Y, and F are the conduction transfer function coefficients. This equation states that the heat flux at the interior surface of any generic building element for which the assumption of one dimensional conduction heat transfer is valid is linearly related to the current and some of the previous temperatures at both the interior and exterior surface as well as some of the previous flux values at the interior surface.

A similar equation holds for the heat flux at the exterior surface. The final CTF solution form reveals why it is so elegant and powerful. With a single, relatively simple equation, the conduction heat transfer through an element can be calculated. The coefficients (CTFs) in the equation are constants that only need to be determined once. The only storage of data required is the CTFs themselves and a limited number of temperature and flux terms. The formulation is valid for any surface type and does not require the calculation or storage of element interior temperatures.

There are two main methods for calculating conduction transfer functions: the Laplace Transform method and the State Space method. Both methods are well suited for the main focus of this research, the extension of conduction transfer functions to include heat sources or sinks. The methods will not be analyzed because they are beyond the scope of this thesis.

4-3-2 Extension of CTFs to include heat sources or sinks

The way a radiant system is modelled in EnergyPlus is by adding a source or a sink at the interface between two layers. Degiovanni (1988) proposed a methodology for including sources or sinks in the Laplace Transform Formulation. The combined CTF with the source solution takes the following form:

$$q_{i,t} = \sum_{m=1}^{M} X_m T_{i,t-m+1} - \sum_{m=1}^{M} Y_m T_{o,t-m+1} + \sum_{m=1}^{k} F_m q_{i,t-m} + \sum_{m=1}^{M} W_m q_{source,t-m+1} \quad (4\text{-}13)$$

This relation is identical to Equation (4-13) except for the presence of the last term that takes the heat source or sink into account.

For a heating system that employs electrical resistance heating, the use of a heat source as the input variable is logical. The heat produced by such a system can easily be related to the current passing through the heating wire. However, for a hydronic heating or cooling system, the known quantity is not heat but rather the temperature of the water being sent to the building element.
In a hydronic system, a link between the fluid temperature being sent to the slab and the heat delivered to the slab exist. The most effective way of relating these two variables is to consider the slab to be a heat exchanger. Using heat exchanger relationships, an equation could then be formulated to obtain the heat delivered to the slab based on the inlet fluid temperature.
Most heat exchangers are used to thermally link two fluids. In the case of a hydronic radiant system, there is only one fluid and a stationary solid. Presumably, if the inlet fluid temperature, the system geometry, and the solid temperature are known, then the outlet temperature and thus the heat transfer to the building element can be computed. The solid temperature is the temperature of the building element at the depth where the hydronic loop is located. Typically, this temperature is not known because it is not needed. The goal of both methods of calculating CTFs was the elimination of internal temperatures that are not needed for the simulation. For a hydronic system, it is necessary to extract this information to solve for the heat source term.

A similar equation to 4-14 could be written for the response of the first layer in absence of any source term and is given by:

$$q_{i,t} = \sum_{m=1}^{M} x_{k,m} T_{i,t-m+1} - \sum_{m=1}^{M} y_{k,m} T_{o,t-m+1} + \sum_{m=1}^{k} f_m q_{i,t-m} \quad (4\text{-}14)$$

Rearranging Equation (4.15) provides an equation from which the temperature at the source location may be calculated:

$$T_{2,t} = \sum_{m=1}^{M} \bar{X}_{k,m} T_{1,t-m+1} - \sum_{m=1}^{M-1} \bar{Y}_{k,m} T_{2,t-m} + \sum_{m=1}^{k+1} \bar{F}_m q_{1,t-m+1} \quad (4\text{-}15)$$

where the new coefficients are obtained from the standard conduction transfer functions for the first layer via the following equations:

$$\bar{X}_{k,m} = \frac{x_{k,m}}{y_1} (m = 1, \cdots, M) \quad (4\text{-}16)$$

$$\bar{Y}_{k,m} = \frac{y_{k,m+1}}{y_1} (m = 1, \cdots, M-1) \quad (4\text{-}17)$$

$$\bar{F}_1 = \frac{1}{y_1} \tag{4-18}$$

$$\bar{F}_m = \frac{f_{m-1}}{y_1}(m = 2, \cdots, k+1) \tag{4-19}$$

Seem (1987) used the State Space method for the calculations of the CTFs and concluded that the transfer function equation is the following:

$$T_{s,t} = \sum_{m=1}^{M} x_{k,m} T_{i,t-m+1} - \sum_{m=1}^{M} y_{k,m} T_{o,t-m+1} + \sum_{m=1}^{k} f_m T_{s,t-m} + \sum_{m=1}^{M} w_m q_{source,t-m+1} \tag{4-20}$$

where T_s is the temperature of the node where the heat source or sink is present.

Both methods (Laplace Transform method and State Space method) lead to the same results. However, the State Space method offers a more direct method of obtaining an internal temperature.

As shown above, the actual heat transferred between the building element and the hydronic loop is related to the temperature of the building element at the source location as well as the water system inlet and outlet temperatures. In EnergyPlus, it is assumed that the inlet temperature to the slab (defined by a user schedule and the plant simulation) and the mass flow rate (determined by the control algorithm) are known and that the remaining parameters must be calculated. However, the heat balance equations require the heat transferred to the building element from the water loop in order to calculate the heat transferred from the element to the building environment.

The effectiveness-NTU heat exchanger algorithm is used in EnergyPlus to model hydronic radiant systems, several equations can be defined which establish the relationship between the heat source and the water temperatures. First, a heat balance on the water loop results in:

$$q = (\dot{m}c_p)_{water}(T_{wi} - T_{wo}) \tag{4-21}$$

where q is the energy transferred between the water loop and the building element, m is the mass flow rate of the water, c_p is the specific heat of the water, T_{wi} is the inlet water temperature, and T_wo is the outlet water temperature. The maximum amount of heat transfer that is possible according to the Second Law of Thermodynamics is:

$$q_{max} = (\dot{m}c_p)_{water}(T_{wi} - T_s) \tag{4-22}$$

where q_{max} is the maximum amount of energy transfer that is possible and T_s is the temperature at the source location.

Eq. 4.21, 4.22 and 4.23 have to be combined in order to calculate the surface heat balance.

The effectiveness of the heat exchanger, ε, is defined as the ratio of the actual energy transfer to the maximum possible, or:

$$\varepsilon \equiv \frac{q}{q_{max}} \tag{4-23}$$

For a heat exchanger where one fluid is stationary, the effectiveness can be related to NTU, the number of transfer units, by the following equation (Incropera and DeWitt, 2001):

$$\varepsilon = 1 - e^{-NTU} \tag{4-24}$$

where NTU is defined by:

$$NTU \equiv \frac{UA}{(\dot{m}c_p)_{water}} \tag{4-25}$$

Since the water tubes were assumed to have no effect on the heat transfer process, the only term present in the overall heat transfer coefficient, UA, is a convection term. Thus, the equation for UA is:

$$UA = h(\pi DL) \tag{4-26}$$

where h is the convection coefficient, D is the interior tube diameter, and L is the total length of the tube. The convection coefficient can be obtained from internal flow correlations that relate the Nusselt dimensionless number to other flow properties. For laminar flow in a tube of constant surface temperature, the Nusselt number is defined by:

$$Nu_D = \frac{hD}{k} = 3.66 \tag{4-27}$$

where k is the thermal conductivity of the water. For turbulent internal flow, the Colburn equation can be used to define the Nusselt number:

$$Nu_D = \frac{hD}{k} = 0.023 Re_D^{4/5} Pr^{1/3} \tag{4-28}$$

where Pr is the Prandtl number of water and Re_D is the Reynolds number which is defined by:

$$Re_D = \frac{4m}{\pi \mu D} \tag{4-29}$$

The parameter μ is the absolute viscosity of water. For internal pipe flow, the flow is assumed to be turbulent for $Re_D \geq 2300$.

1D & 2D Modelling

EnergyPlus allows the user to define the detail level of the calculation. One-dimensional calculation refers to simulations which do not take the water temperature difference along the tubing into consideration as an effect that influences the transient heat conduction. One-dimensional modelling is appropriate for electric resistance heating and for hydronic heating (when boiler/hot water heater performance is not affected by return and supply water temperatures).
Two-dimensional modelling refers to simulations which take the difference of water temperature along the tubing into account. However, the way this effect influences the simulation is not clear in the documentation. This is necessary for hydronic radiant cooling situations since chiller performance is affected by the water temperatures provided. Additionally, more accurate results are obtained with this choice.
A few things should be noted about requesting two-dimensional solutions. First, the calculation of the conduction transfer functions (CTF) is fairly intensive and will require a significant amount of computing time (ENERGYPLUS, 2013). Second, the solution regime is two-dimensional internally but it has a one-dimensional boundary condition imposed at the inside and outside surface (i.e., surface temperatures are still isothermal is if the surface was one-dimensional).

4-3-3 Assumptions

In order for the effectiveness-NTU heat exchanger algorithm to be used, several assumptions are taken (ENERGYPLUS, 2013).

- Even though systems defined by this model can vary somewhat, the same characteristic link between the system variables exist. For modelling purposes, the overall water/slab system can be thought of as a heat exchanger. While in principle there are two alternative heat exchanger methodologies, it is more convenient to use the effectiveness-NTU method in this case.
- It is assumed that the building element that contains the hydronic loop is stationary and that its temperature along the length of the tubing is constant. The latter part of this assumption stems from assumptions made in both the one and two dimensional modelling cases. In either case, the source was added at a single node that was characterized by a single temperature. For consistency, this assumption must be made again in the heat exchanger analysis.
- Another assumption for the current EnergyPlus model is that the fluid in the tubing is water.
- Additionally, it is assumed that the thermal properties of the water do not vary significantly over the length of the tubing and that the water flows at a constant flow rate.
- Finally, the temperature at the inside surface of the water tubing is assumed to be equal to the temperature at the source location. In other words, it is assumed that the water tubing itself has no appreciable effect on the heat transfer process being modelled.

However, it is not clear how these assumptions affect the effectiveness-NTU method and generally the way EnergyPlus calculates the heat balance. Therefore, it impossible to make a comparison between the Energyplus and TRNSYS modelling process regarding radiant systems.

4-3-4 Radiant System Controls

EnergyPlus offers two different control schemes for radiant systems: variable flow (ZoneHVAC: LowTemperatureRadiant: VariableFlow) and variable temperature (ZoneHVAC: LowTemperatureRadiant: ConstantFlow). The controls for variable flow low temperature radiant systems within EnergyPlus are fairly simple though there is some flexibility through the use of schedules. The program user is allowed to define a setpoint temperature according to which the system will be operating or not as well as a throttling range through which the system varies the flow rate of water (or current) to the system from zero to the user defined maximum flow rate. The flow rate is varied linearly with the flow reaching 50% of the maximum when the controlling temperature reaches the setpoint temperature. Setpoint temperatures can be varied on a half-hourly basis throughout the year if desired. The controlling temperature can be the mean air temperature, the mean radiant temperature, or the operative temperature of the zone, and this choice is also left to the user's discretion. The user has the possibility to specify on an hourly basis through a schedule the temperature of the water which is supplied to the radiant system. Graphical descriptions of the controls for a hydronic radiant system model in EnergyPlus are shown in Fig. 4-9.

In the constant flow-variable temperature systems, the controls are also considered piecewise linear functions, but in this case the user selects both the control temperatures and the water temperatures via schedules. This offers greater flexibility for defining how the radiant system operates though it may not model every situation. Fig. 4-10 shows how the 'desired' inlet water temperature is controlled based on user schedules. The user has the ability to specify the high and low water and control temperature schedules for heating and cooling. Note that this inlet temperature is a 'desired' inlet temperature and there is no guarantee that the system will provide water to the system at that temperature. The model includes a local loop that attempts to meet this demand temperature through mixing and recirculation.

This schedule specifies the high water temperature in °C for the temperature control of the constant flow heated floor. Water and control temperatures for heating work together to provide a linear function that determines the water temperature sent to the heated floor. The current control temperature is compared to the high and low control temperatures at the current time. If the control temperature is above the high temperature, then the system will be turned off and the water mass flow rate will be zero. If the control temperature is below the low temperature, then the inlet water temperature is set to the high water temperature. If the control temperature is between the high and low value, then the inlet water temperature is linearly interpolated between the low and high water temperature values.

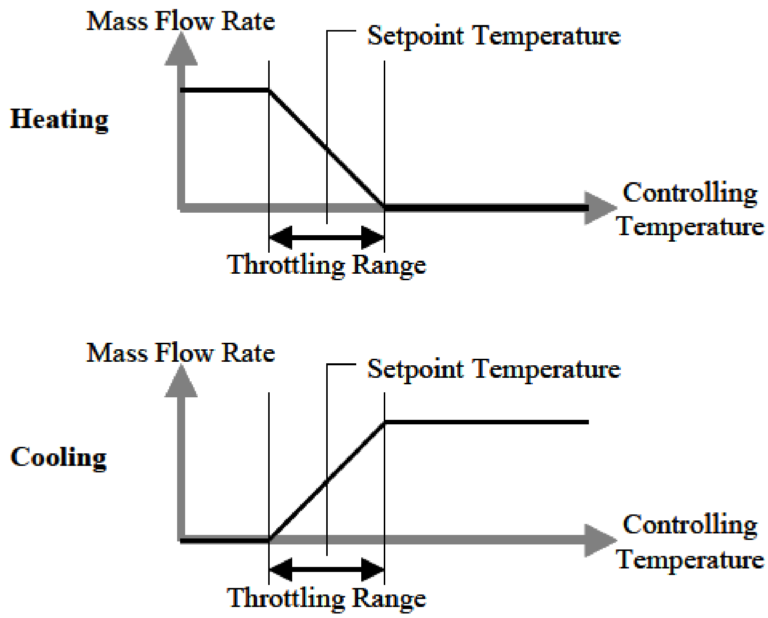


Figure 4-9: Variable Flow Low Temperature Radiant System Controls (ENERGYPLUS, 2013)

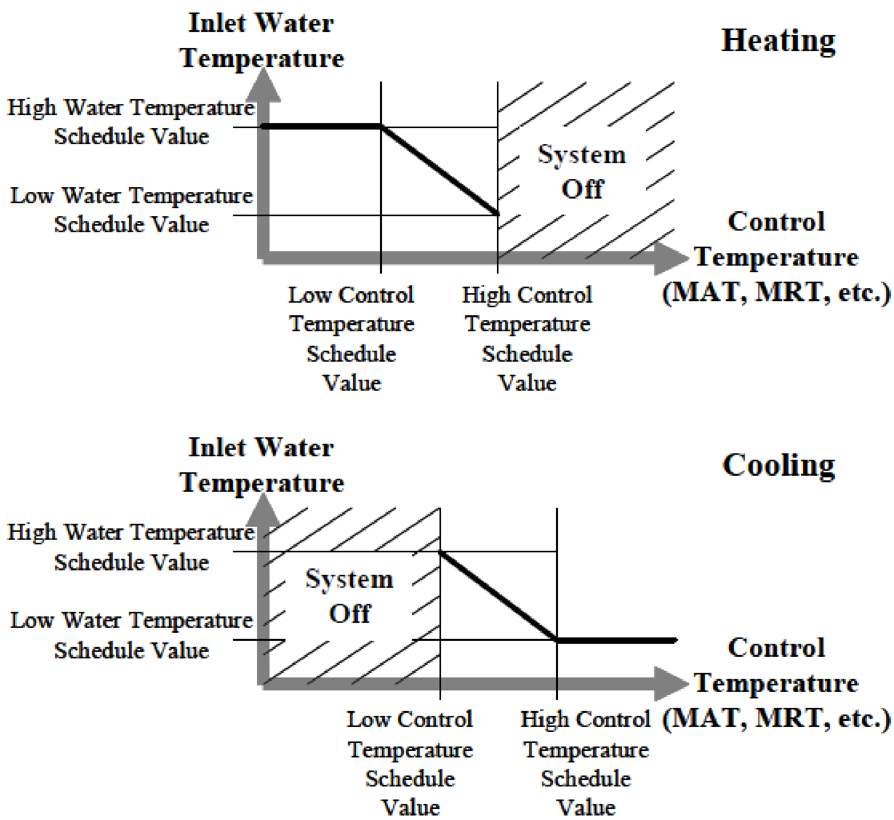


Figure 4-10: Constant Flow - Variable Temperature Low Temperature Radiant System Controls (ENERGYPLUS, 2013)

Chapter 5

Test simulations

Several tests have been performed in order to examine whether the results of EnergyPlus and TRNSYS match. The comparison is made through a number of steps. The first tests are simple but grow progressively more complicated to determine the accuracy of the results.

5-1 Test 1 & Test 2

These two tests have been simulated in order to compare the response time of a basic model.

5-1-1 Test 1 - Basic building

Test 1 is a basic simulation of a room in TRNSYS and EnergyPlus. For this comparison, only the building envelope has been modelled and placed in a constant thermal environment of 0^{o}C. Moreover, no surface of the room is exposed to solar radiation. However, long-wave infrared radiation from the sky still contributes to the heat balance of the room but the sky temperature is set to a constant temperature of 0^{o}C.

- Building dimensions and constructions:
  - The inner dimensions of the room are 5.4m (length)*3.6m (width)*2.7m (height).
  - The room is modelled as a space on the second storey and only one wall (facade) has contact with the outside air. The remaining five surfaces are adjacent to spaces of equal temperature. Therefore, all surfaces apart from the facade are considered to be adiabatic.
  - All surfaces are opaque.
  - All vertical walls have no thermal mass.
  - The facade wall has R-value of 5m^{2}K/W and area of A=3.6*2.7=9.72m^2.
  - The floor/ceiling construction has the following properties:

    * Conductivity: $\lambda = 2.1$ W/mK
    * Specific heat: $c = 920$ J/kgK
    * Density: $\rho = 2400$ kg/m^3
  - The convective heat transfer coefficients (CHTC) are constant for vertical surfaces (inside: 3W/m^{2}K, outside: 18W/m^{2}K). The CHTC for the floor/ceiling construction are calculated by EnergyPlus with the help of TARP algorithm. TARP algorithm calculates CHTC depending on the difference between surface and mean air temperature.

- No HVAC system
- No infiltration
- No internal heat loads
- The initial temperature of the room is at 21^{o}C. Since it is not possible to set an initial temperature in EnergyPlus, the room is initially heated till 21^{o}C and then heating is switched off.

Results

The mean air temperature of the room of Test 1 is shown in Fig. 5-1, as calculated by the two programs. The duration of the simulation is such till the model gets to steady state temperature of 0^{o}C.

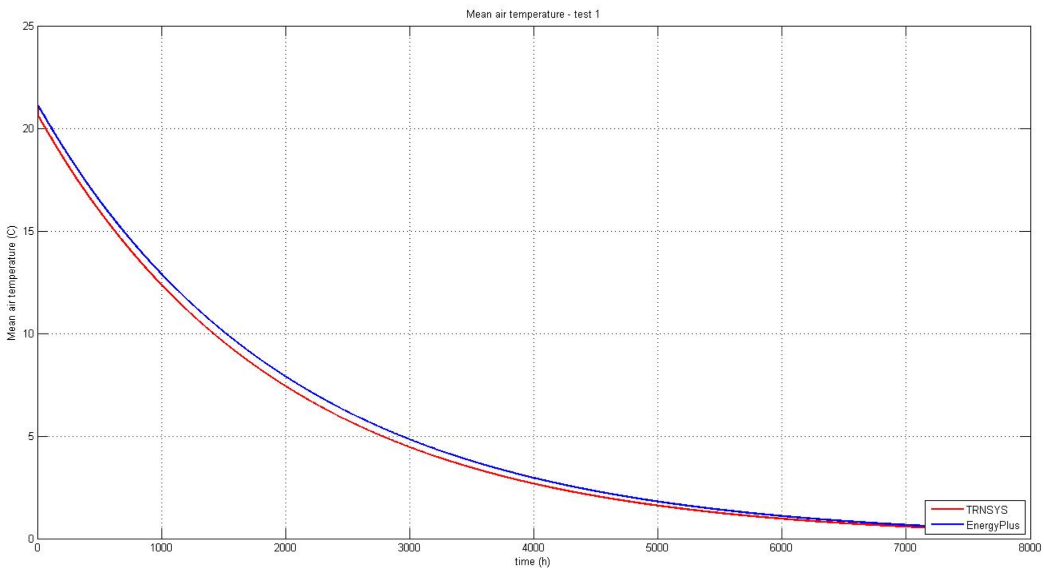


Figure 5-1: Differences in mean air temperature between TRNSYS and EnergyPlus - Test 1

The temperature of TRNSYS is slightly lower than the temperature that has been calculated by EnergyPlus. The reason for this difference probably relates to the fact that the initial temperature of the EnergyPlus model is slighly higher than 21^{o}C.

5-1-2 Test 2

In the second step of the simulations, the basic model (Test 1) was extended with the addition of internal loads. Internal heat gains of 100W (100% convective) were constantly introduced in the room. The duration of the simulation is such till the model gets to steady state temperature.

Results

The mean air temperature of the room of Test 2 is shown in Fig. 5-2, as calculated by the two programs. The steady state temperature is 53.18^{o}C and corresponds to the expected value.

$$Q = \frac{1}{R_{tot}} \cdot A \cdot \Delta T \Rightarrow 100 = \frac{1}{0.04+5+0.13} \cdot 9.72 \cdot (T_{end} - 0) \Rightarrow T_{end} = 53.18^oC \qquad (5\text{-}1)$$

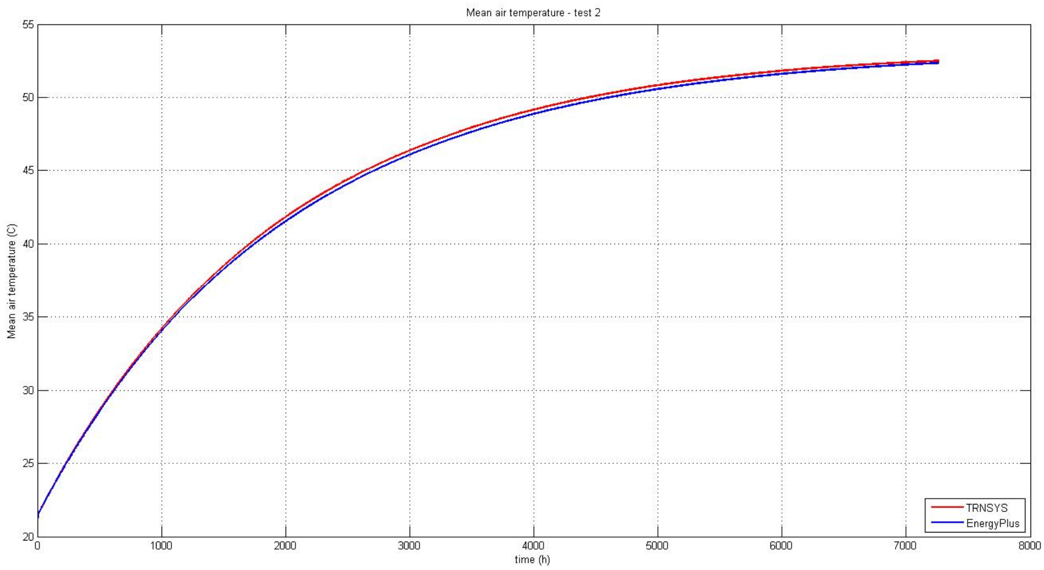


Figure 5-2: Differences in mean air temperature between TRNSYS and EnergyPlus - Test 2

The temperature curves are almost identical.

5-1-3 Conclusions of Test 1 & Test 2

The results in both tests match well in TRNSYS and in EnergyPlus.

5-2 Test 3 & Test 4

5-2-1 Test 3

Test 3 is introduced in order to compare the differences of a model with glazing. Therefore, a window is introduced on the facade wall of the room.

Test 3 is based on Test 1, so no internal loads are present in the room. The differences are the following:

- Window: The area of the window is 7.02m^2 and is divided in two parts:
  - Frame (A=0.7m^2):
    - U-value=2.4W/m^{2}K
    - No thermal mass
  - Glass (A=6.32m^2): It was designed with the simplified window model (see details in the Results section).
    - U-value=0.9W/m^{2}K
    - g-value=0.5
- External heat gains due to ambient temperature according to NEN5060 1%. No surface is exposed to solar radiation. However, long-wave infrared radiation from the sky still contributes to the heat balance of the models and the sky temperature is set to a constant temperature of 0^{o}C.

Hence, the effective U-value of the window is

$$\frac{A_{frame} \cdot U_{frame} + A_{glass} \cdot U_{glass}}{A_{window}} = \frac{0.7 \cdot 2.4 + 6.32 \cdot 0.9}{7.02} = 1.05W/m^2K$$

Results

The mean air temperature of the room of Test 3 is shown in Fig. 5-3, as calculated by the two programs. The duration of the simulation is 1 year.

It is clear that the TRNSYS model provides lower mean air temperature during winter (when the outside temperature is lower than the inside) and higher mean air temperature during summer (when the outside temperature is higher than the inside) than the Energyplus model.

It seems that the differences relate to the addition of the window. There are two mechanisms that influence the mean air temperature of the room. The first mechanism is the heat flux through the facade due to inside and outside temperature difference. Since the U-value of the facade wall is the same in both models, heat flux through this construction should also be the same. However, the absorptance, reflectance and transmittance values of glazing may differ in TRNSYS and in EnergyPlus. The second mechanism is long-wave radiation from the sky and how it is distributed among the surfaces of the room (internal long-wave radiation). In the conclusions of this section, more details are given with respect to these mechanisms and possible causes for the differences are analyzed.

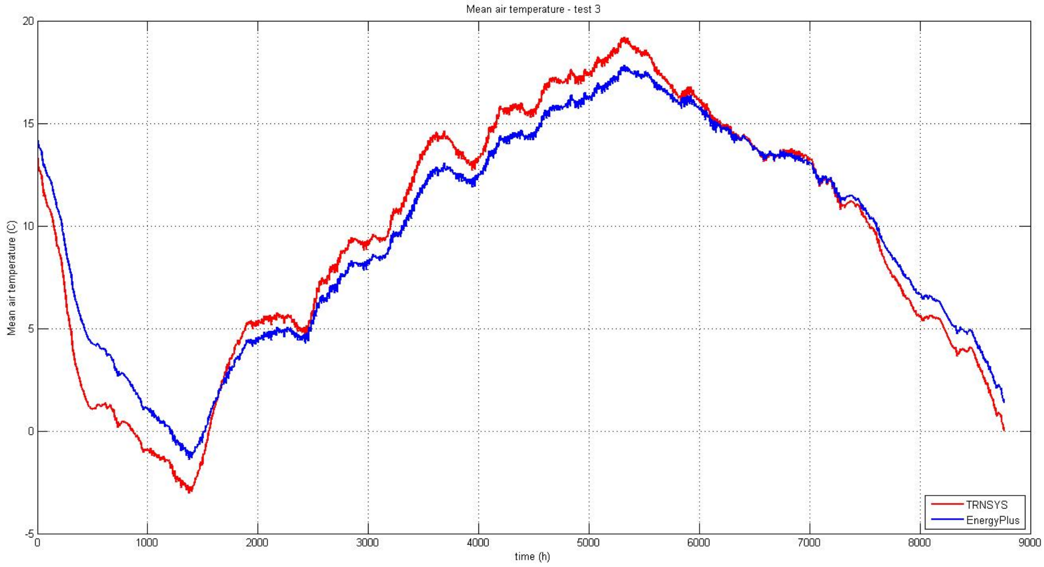


Figure 5-3: Differences in mean air temperature between TRNSYS and EnergyPlus - Test 3

Table 5-1: Maximum temperature difference between TRNSYS and EnergyPlus - Test 3

	Maximum temperature difference (^{o}C)
Cooling mode	-3,26 (EnergyPlus lower)
Heating mode	1,71 (EnergyPlus higher)

5-2-2 Test 4

Test 4 is the simulation of two models performed both by EnergyPlus and TRNSYS. This test is based on Test 3 and is conducted to examine the effect of a glazed facade versus an opaque one. The construction of the facade wall differs in the two models. All the remaining characteristics of the models are identical.

- No internal loads
- External loads due to ambient temperature according to NEN5060 1%
- No solar radiation
- Long-wave infrared radiation from the sky still contributes to the heat balance of the models and the sky temperature is set to a constant temperature of 0^{o}C.

Facade wall of Model 1:

- 100% glazed facade wall
  - U-value=0.9W/m^{2}K

  - g-value=0.5

Facade wall of Model 2:

- opaque facade wall
  - U-value=0.9W/m^{2}K
  - No thermal mass

Results

The mean air temperature of the models of Test 4 is shown in Fig. 5-4, as calculated by EnergyPlus and TRNSYS. The duration of the simulation is 1 year.

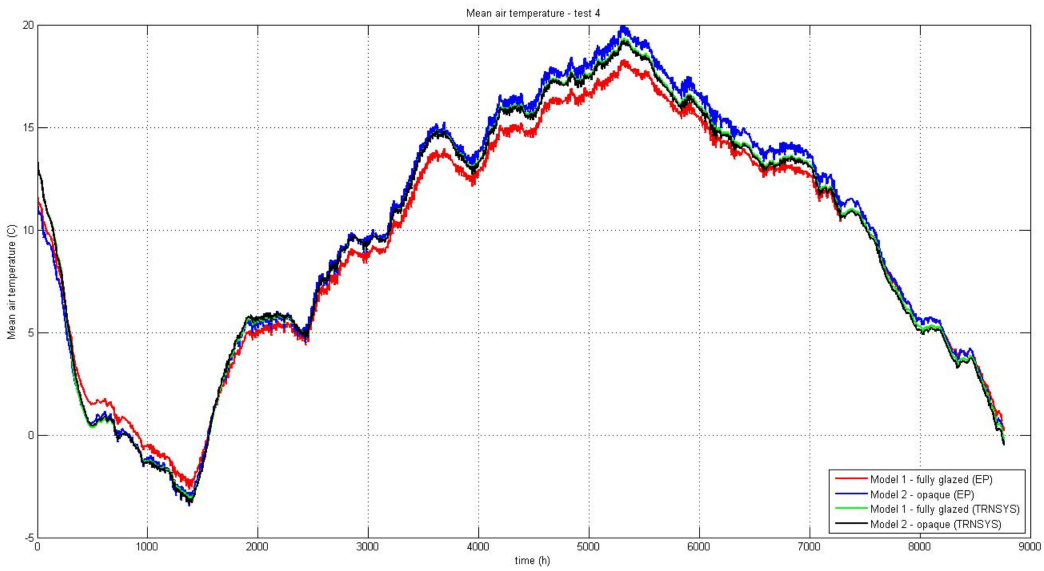


Figure 5-4: Differences in mean air temperature between Model 1 and Model 2 in TRNSYS and EnergyPlus - Test 4

Table 5-2: Maximum temperature difference between Model 1 and Model 2 in EnergyPlus - Test 4

	Maximum temperature difference (^{o}C)
Cooling mode	-1.74 (Model 1 lower)
Heating mode	1.03 (Model 1 higher)

It is observed that the TRNSYS models give similar values of mean air temperature in both cases, which is reasonable since glazing is opaque to long-wave radiation.

On the other hand, EnergyPlus Model 1 (fully glazed facade) provides higher mean air temperature during winter (when the outside temperature is lower than the inside) and lower

mean air temperature during summer (when the outside temperature is higher than the inside) than Model 2 (opaque facade) of EnergyPlus.
Similar results for the inside temperature of the two EnergyPlus models were expected, since, in reality, glazing is opaque to long-wave radiation or in other words the absorptance and emission coefficients of glazing are close to 1 in the infrared spectrum. However, it seems that this is not the case in EnergyPlus. These coefficients for glazing are lower in EnergyPlus, which makes long-wave radiation from the sky affect inside temperature and provide a significant temperature difference between the EnergyPlus models.

TRNSYS and EnergyPlus give similar results for Model 2.

5-2-3 Conclusions of Test 3 & Test 4

It appears difficult to point out the exact causes of the differences of the two programs, since several and complicated modelling processes take place. However, possible causes of these differences may be the following.

- **Glazing modelling**: There are two ways of modelling windows in EnergyPlus. The first way is by creating the glass, assigning all properties of each pane such as solar reflectance, absorptance, thermal conductivity, etc. The second way is a simplified model in which the user only gives the U-value, g-value and visible transmittance of glass. In this simulation the simplified glazing model was selected because only the U-value and g-value of glass were known. However, it is recommended to use the first way because the simplified model may lead to inaccuracies (ENERGYPLUS, 2013). There are several reasons for these inaccuracies:

  - Windows with the same g-value often have different ratios of transmitted to absorbed solar radiation.
  - g-value is determined at normal incidence. However, angular properties of glazings vary with number of layers, coatings. So, products with the same g-value, can have different angular properties.
  - U-value varies with temperature. In the simplified window model, U-value stays constant.

  In TRNSYS, the windows have been selected from a product database and all their properties are automatically assigned to the program. Therefore, there are differences in the U-value and especially in the absorptance and reflectance ratios of the glass between TRNSYS and EnergyPlus, as shown in Fig. 5-4.

- **Internal long-wave radiation**: EnergyPlus uses a grey interchange model for the long-wave radiation among zone surfaces.This model is based on the 'ScriptF' concept. 'ScriptF' makes use of the view factors for each surface and finally the radiant exchange for each surface is calculated with the help of these view factors.

  In TRNSYS all surfaces are assumed to be black for long-wave radiation and uses a star-network model.

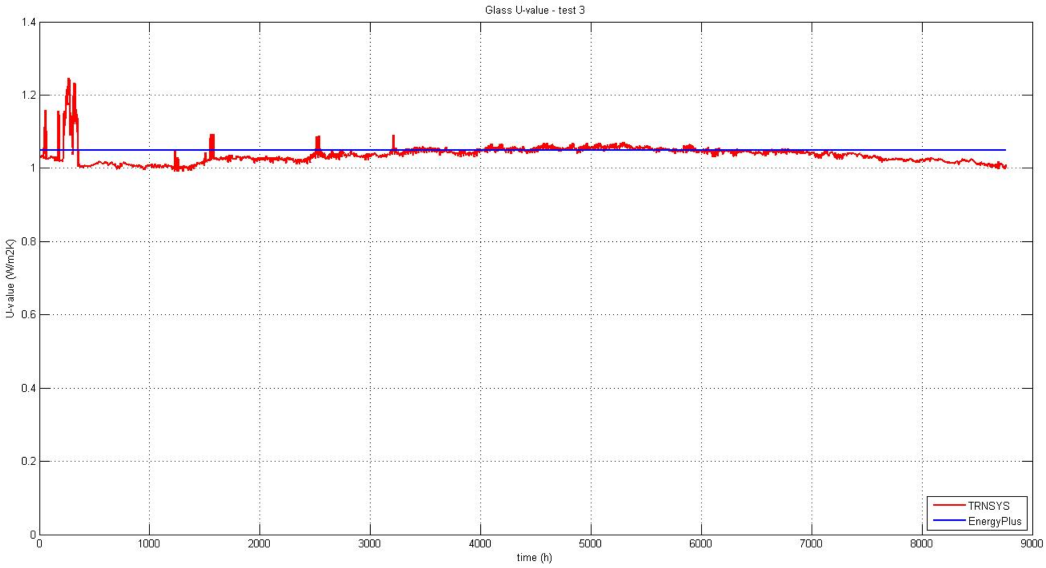


Figure 5-5: Glass U-value in TRNSYS and EnergyPlus - Test 3

- **Convective heat transfer coefficients (CHTC)**: The formulas that are used to calculate inside CHTC for horizontal surfaces are different in both programs. EnergyPlus uses the TARP algorithm, which calculates CHTC depending on the difference between surface and mean air temperature according to the following formulas.

  For warm floor/cold ceiling:

  $$h = 1.51\,|\Delta T|^{\frac{1}{3}} \tag{5-2}$$

  and for cold floor/warm ceiling:

  $$h = 0.76\,|\Delta T|^{\frac{1}{3}} \tag{5-3}$$

  where ΔT = Surface Temperature - Air Temperature

  In TRNSYS the respective expressions are:

  For warm floor/cold ceiling:

  $$h = 2\,|\Delta T|^{\frac{1}{3}} \tag{5-4}$$

  and for cold floor/warm ceiling:

  $$h = 1.08\,|\Delta T|^{\frac{1}{3}} \tag{5-5}$$

  Moreover, the minimum value of CHTC is h=1W/m^{2}K in TRNSYS, whereas in EnergyPlus there is no minimum value.

To conclude, the most important cause for the temperature difference between the two programs is the glazing modelling, more specifically the absorptance coefficients and subsequently how this relates to long-wave radiation from the sky affecting inside temperature.

Internal long-wave radiation and calculation of convective heat transfer coefficients also play a role in these differences. However, these parameters have a smaller impact on the found differences in the tests.

The definition of U-value of glazing and how this relates to absorptance and reflectance ratios of the glazing is the most important cause of the difference. In EnergyPlus these coefficients are lower in the infrared spectrum than in TRNSYS.

5-3 Test CCA

Test CCA is conducted to compare the response time of a concrete slab in a room with concrete core activation between TRNSYS and EnergyPlus. Additionally, the temperature of the slab has been calculated with Finite Difference Method (FDM).

The test model consists of two heated spaces (two floors), between of which lies a thermally activated solid slab (Fig. 5-6). The model has been chosen carefully in order not to have thermal exchange with the outside environment and not to store heat inside the material of the exterior boundaries of the model (walls, ceiling and ground floor). Therefore, there are adiabatic boundary conditions between the heated spaces and the environment. There are no windows and the walls, floor and ceiling are not influenced from sun, wind and temperature.

Dimensions of the model:

- Length: x = 5m
- Width: y = 1m
- Surface area: A = 5m^2 (5m x 1m - dimensions of a prefabricated slab)
- Height of heated space: z = 100mm
- Thermally activated slab thickness: d_b = 200mm
- Thickness of the walls, ceiling and ground floor: d_e = 100mm

Properties of the Concrete Core Activation:

- Outside tube diameter: δ = 16mm
- Thickness of tube mantle: d_r = 1.5mm
- Inside tube diameter: δ - 2d_r = 13mm
- Tubing distance: d_x = 150mm
- Tubing plane (position of the water tubes): 100mm from the bottom of the slab
- Circuit length: $l = A/d_x$ = 34m
- Constant water flow: m= 0.2kg/s

- Specific water flow: $m_{sp} = m/d_x l$= 0.04kg/m^{2}s
- Conductivity of the tube mantle: λ_r = 0.45 W/mK NOT INPUT IN ENERGYPLUS
- Initial inside temperature: 25°C
- Constant water supply temperature: 35°C

Materials and other properties:

- **Slab:** Several materials have been tested from highly conductive like copper to concrete which is the material which will be used in the final test cases.
- **Walls:** The walls are designed to be of no thermal mass in order not have the thermal storage effect leading in more accurate results.

Properties of concrete slab:

- Conductivity: λ_b = 2.1 W/mK
- Specific heat: c_b = 920 J/kgK
- Density: ρ_b = 2400 kg/m^3

Properties of water:

- Specific heat: c_w = 4187 J/kgK

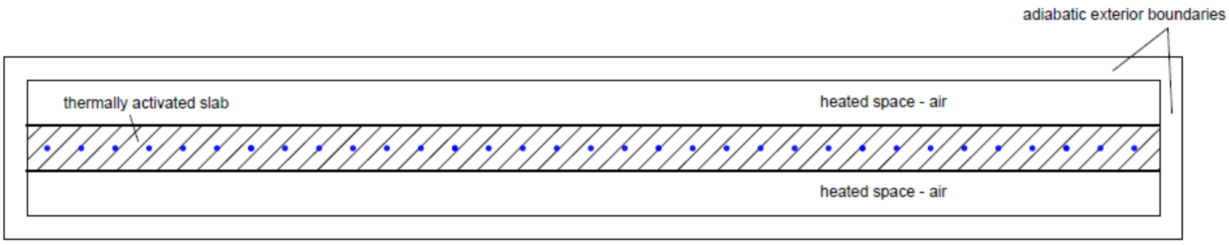


Figure 5-6: First test model

5-3-1 Solution using Finite Difference Method

In the FDM solution, 12 nodes (Fig. 5-7) have been selected from the external to the internal side of the slab. The temperature of the 12 nodes are calculated in a step of approximately 100 seconds each. The values of the resistances R have been calculated according to Koschenz and Lehmann (2000). The internal surface of the slab is an adiabatic boundary. The FDM solution has been created in MS Excel by Mr. van der Spoel.

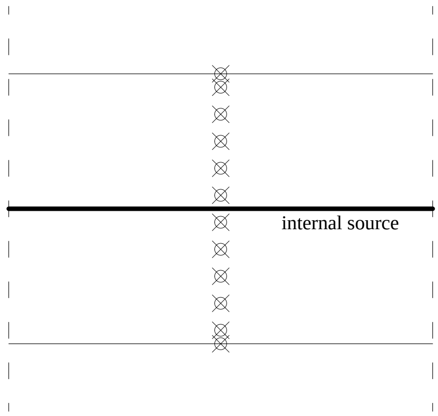


Figure 5-7: Cross-section of the thermally activated slab - internal nodes for FEM

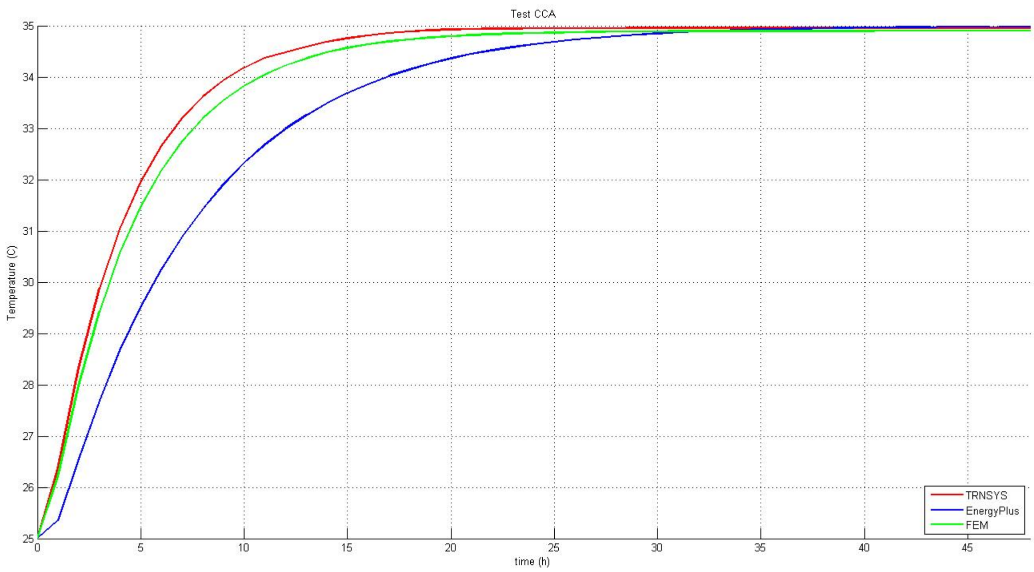


Figure 5-8: Differences in floor surface temperature between TRNSYS, EnergyPlus and FDM - Test CCA

5-3-2 Results

The surface temperature of the floor is compared in this test (Fig. 5-8), as it is calculated by TRNSYS, EnergyPlus and FDM.

TRNSYS and FDM provide similar results, whereas EnergyPlus shows a much slower response. Especially in the beginning of the simulation, EnergyPlus shows a very small temperature increase when compared to the TRNSYS and FDM model. It seems that EnergyPlus is not capable of handling transient responses as good as TRNSYS.

Chapter 6

Test case

In order to compare TRNSYS and EnergyPlus in a more realistic scenario, a test case has been selected to be modelled. Contrary to the test models that have been analyzed in the previous chapter, this test case represents a typical room inside an office building. The data for this test case has been provided by DGMR.

The parameters and properties of the test case are provided in sections 6-1 to 6-5. Results are discussed in section 6-6.

6-1 Architectural data

The room is located at the southwest facade (270^o clockwise from North) of the building on the second storey of the building. It represents a typical office room with dimensions of 5.4m by 3.6m (the small side lies on the facade of the building). The other three sides of the building (partition walls) are facing the inside of the building and therefore assumed as adiabatic (no heat transfer through the partition walls). The floor plan of the room is illustrated in Fig. 6-1. Additionally, there are identical rooms with the same properties above and below the measured room in order to ensure that there is no heat transfer to and from the upper and lower room. Finally, the thermal capacitance inside the room has been increased in order to model the existence of furniture. This fact results in the temperature fluctuations in the room to be a bit dampened because a fraction of heat is absorbed by furniture.

The properties and dimensions of the room components are as follows:

- **Floor/ceiling**:
  - Thickness: d=300mm
  - Thermal conductivity: $\lambda = 2.1$ W/mK
  - Density: $\rho = 2400$ kg/m^3
  - Specific heat: $c = 920$ J/kgK

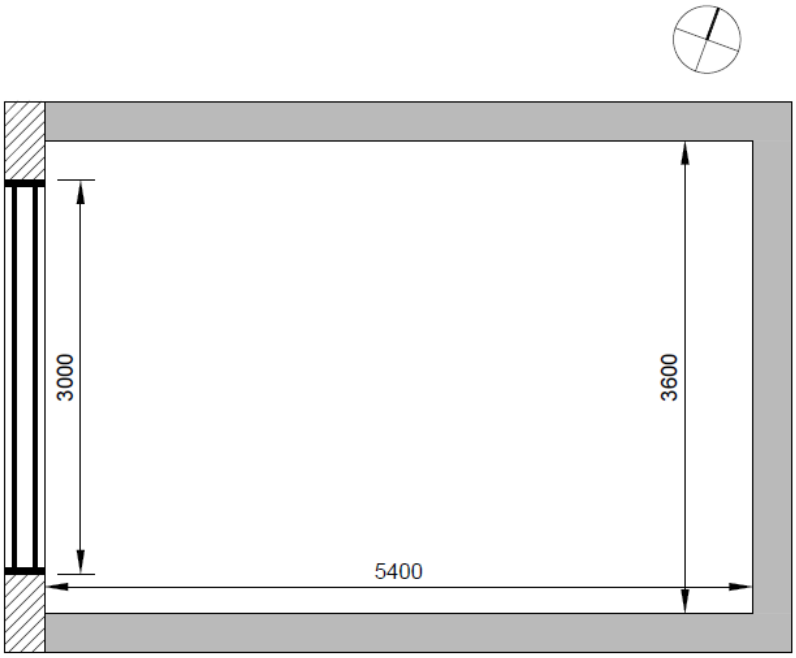


Figure 6-1: Floor plan of the room

- **Partition walls**
  - Thickness: d=100mm
  - $R_c = 1$ m^{2}K/W
  - No thermal mass
- **Facade wall - opaque part**
  - Thickness: d=100mm
  - $R_c = 5$ m^{2}K/W
  - No thermal mass
- **Window** $A = 7.02$m^2 and is divided in 2 parts: the frame and the glazing
  - Frame (A=0.7m^2):
    - U-value=2.4W/m^{2}K
    - No thermal mass
  - Glass (A=6.32m^2): It was designed with the simplified window model.
    - U-value=0.9W/m^{2}K
    - g-value=0.5
- **Shading**

  A customized external shading system is applied on the window with the following properties:

- Thickness $d = 5$mm
- Thermal conductivity: $\lambda = 0.1$ W/mK
- Solar transmittance: 0.2
- Solar reflectance: 0.7
- Shading control: On if solar incident on facade is above 250W/m^2

6-2 Heat gains

Internal heat gains

The internal heat gains are dependent on the occupancy schedule of the building. The occupancy hours are from 08:00 till 18:00 from Monday to Friday. During the occupancy hours the internal heat gains are the following:

- **People**
  - Convective fraction: 4 W/m^2 (50%)
  - Radiative fraction: 4 W/m^2
- **Equipment**
  - Convective fraction: 15 W/m^2 (100%)
  - Radiative fraction: 0
- **Lighting**
  - Convective fraction: 8.64 W/m^2 (72%)
  - Radiative fraction: 3.36 W/m^2

External heat gains

The weather file that is used is NEN5060 with 1% exceeding chance.

6-3 HVAC parameters

Thermal comfort in the room is controlled by ventilation and concrete core activation. The floors of the building are embedded with water tubes, in which chilled or warm water flows according to the needs of the building's users.

6-3-1 Ventilation

The ventilation rate is constant at 10 m^3/hr/m^2 (or 0.054 m^3/s) at a constant temperature of 20^{o}C from 07.00 till 18.00 during weekdays.

The infiltration rate is assumed to be 0.3hr^{-1}.

6-3-2 Concrete core activation

The water tubing is located in the middle of the concrete slab. The rest of the system's parameters are the following:

- 1 circuit (Circuit length: 97.2m)
- Tubing distance: 200mm
- Water velocity: 0.4m/s (or 0.091kg/s)
- Inner tube diameter: 17mm
- Thickness of the tube mantle: 2mm (NOT INPUT IN ENERGYPLUS!)

CCA Controls

The most common and effective control of CCA (Hoogmartens and Sourbron, 2011; Olesen et al., 2002; Gwerder et al., 2008) is one that is based on both the inside and outside temperature.

Since CCA is a slow response system, it operates during night time, so outside the occupancy hours, 18:00 - 08:00, and only during weekdays.
The main idea is to have a setpoint depending on the zone's operative temperature. Intermittent pump operation is proposed which is less power consuming opposed to continuous operation. Cooling starts being provided when inside temperature exceeds 22^{o}C and stops when inside temperature falls below 21^{o}C and heating is on when inside temperature falls below 19^{o}C and stops when it exceeds 20^{o}C. The temperature range (in our case 1^{o}C) in which the pump operates is such in order for the pump not to start and stop frequently (Fig. 6-2).

Regarding water temperature of CCA, it is widely suggested that it depends on outside temperature (Hoogmartens and Sourbron, 2011; Olesen et al., 2002; Gwerder et al., 2008) as shown in Fig. 6-3. The graph of Fig. 6-3 refers to a 4-pipe distribution system, since for the same ambient temperature, it is possible to have cooling in part of the building and heating in another. However, this kind of schedule is not possible to be designed in DesignBuilder or EnergyPlus. Therefore, a simplified schedule has been selected in DesignBuilder (Fig. 6-4). The graph of Fig. 6-4 indicates that a 2-pipe distribution system is used, where no simultaneous heating and cooling of different zones is possible. This simplified schedule, which has been optimized in terms of energy consumption and thermal comfort has been proposed by DGMR.

Water temperature of CCA is 30^{o}C when ambient temperature falls below -13^{o}C, while, when ambient temperature ranges from -13^{o}C to -3^{o}C, water temperature is linearly interpolated between 30^{o}C and 21^{o}C, as illustrated in Fig. 6-4. The water temperatures mentioned above indicate that heating is provided to the occupied space. In case of cooling, respectively, water temperature of CCA is 17^{o}C when ambient temperature exceeds 16^{o}C, while, when ambient temperature ranges from 11^{o}C to 16^{o}C, water temperature is linearly interpolated between 21^{o}C and 17^{o}C. When outside temperature is between -3^{o}C and 11^{o}C, no heating or cooling is provided (dead zone).

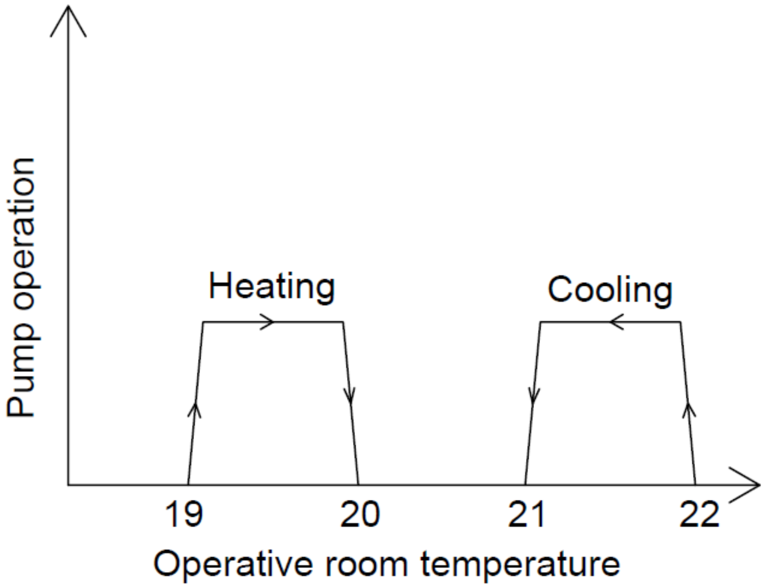


Figure 6-2: Pump control

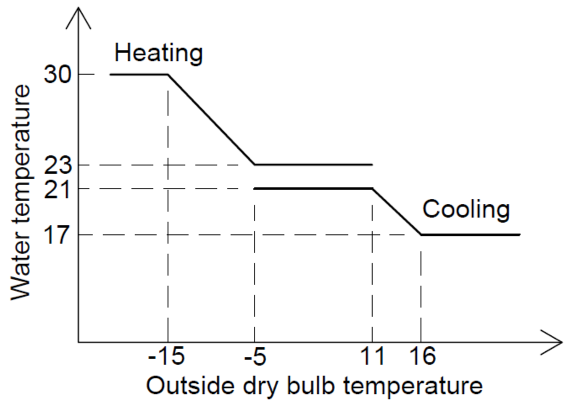


Figure 6-3: Water supply temperature

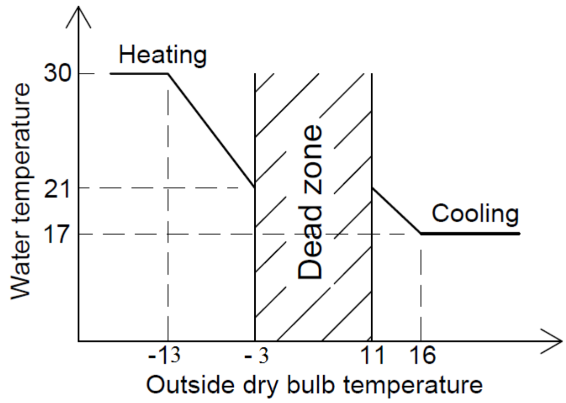


Figure 6-4: Water supply temperature - simplified

To sum up, there are 3 conditions that all have to be met in order for CCA to start operating:

1. From 18:00 till 08:00 (night operation)
2. When outside temperature is below -3^{o}C (heating) or above 11^{o}C (cooling)
3. When operative temperature is below 20^{o}C (heating) or above 21^{o}C (cooling)

6-4 Modelling procedure

The procedure that has been followed to create the model may appear unnecessarily difficult but actually is the easiest way to model concrete core activation currently possible. First, the geometry of the model is created in DesignBuilder with the construction properties as mentioned above. Additionally, internal heat gains and occupation schedule are added in DesignBuilder. The next step is to apply the HVAC system (Fig. 6-5) in the model.

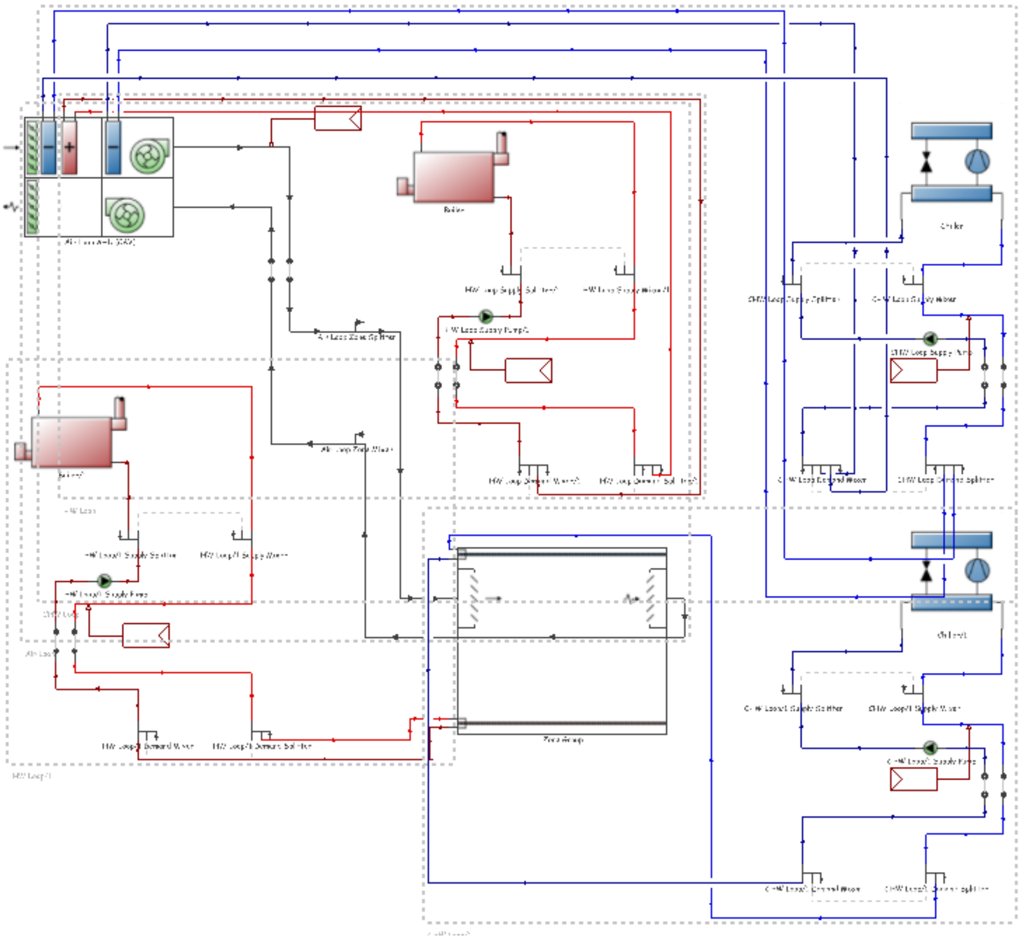


Figure 6-5: HVAC system (DesignBuilder)

The modelling of the HVAC system has been conducted in the Detailed-HVAC mode of DesignBuilder which provides more possibilities than simple or compact mode regarding HVAC components, schedules and controls.

Two chilled water loops (Fig. 6-6) have been designed in order to provide chilled water to the chilled ceiling and the cooling coils in the air handling unit at the desired temperature. The chilled water loop consists of a chiller which cools the water flowing in the chilled ceiling and the cooling coils, a setpoint manager which regulates the water temperature and a water pump circulating the water in the loop.

Respectively, two hot water loops (Fig. 6-7) have been designed to provide hot water to the heated floor and the heating coils. The hot water loop contains a setpoint manager, a water pump and a boiler which heats the water flowing in the heated floor. Moreover, there is a splitter and a mixer in each loop in order to mix the supply with the return water to reach the desired temperature at the time when water is entering the floor.
The reason for having two chilled water loops and two hot water loops is due to the fact that

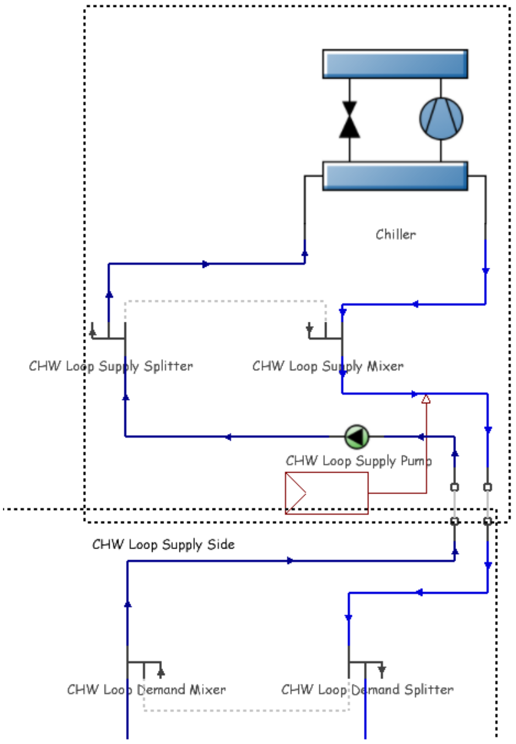


Figure 6-6: Chilled water loop (DesignBuilder)

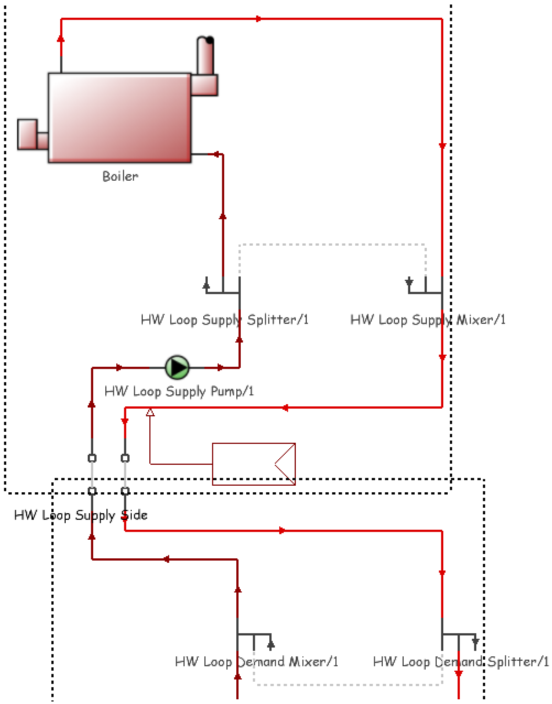


Figure 6-7: Hot water loop (DesignBuilder)

there are different schedules for ventilation and heating/cooling. Therefore, separate water loops should serve each process, thus ventilation and heating/cooling can operate independently. The first chilled water loop provides water to the cooling coils in the AHU and the second one provides chilled water to the floor. The respective procedure happens for heating.

Additionally, an air loop (Fig. 6-8) has been designed for the provision of air to the room. The air loop consists of an air handling unit and a setpoint manager. The air handling unit includes a cooling and a heating coil which adjust the outside air temperature at a desired temperature, a supply and an extract fan which regulate the air flow into and out of the air handling unit.

The components that have been applied inside each room are a heated floor, a chilled ceiling, an air inlet and an air oulet. (Fig. 6-9)

6-5 Program limitations

Although DesignBuilder is an easy tool to design geometry and HVAC systems, it also has some limitations especially regarding HVAC.

First of all, there is no way to design concrete core activation solely in DesignBuilder. Internal sources (water tubing layer) can be created, however they can operate either only in heating or cooling mode.

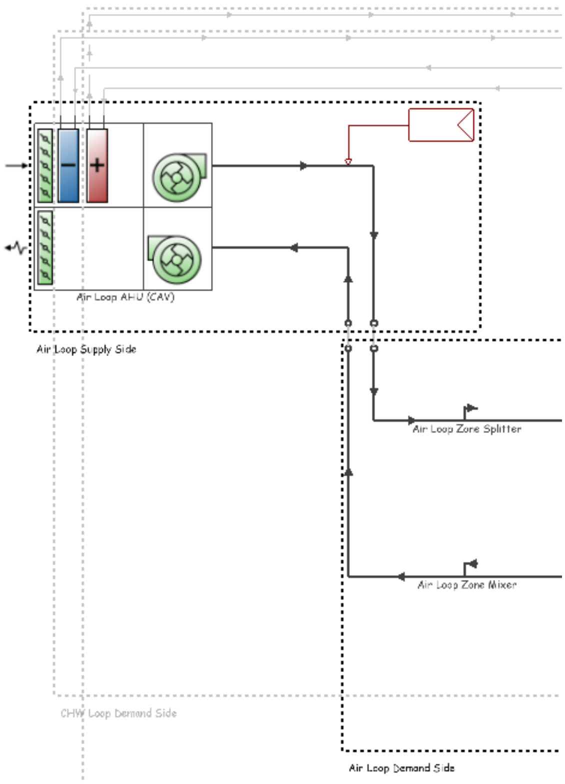


Figure 6-8: Air loop (DesignBuilder)

Secondly, the controls that have been applied on CCA are impossible to be modelled in DesignBuilder. In DesignBuilder CCA can be based either on inside or outside temperature but not on the combination of both as it was initially proposed.
Finally, the first proposed schedule of the water supply temperature (Fig. 6-3) cannot be created either in DesignBuilder or in EnergyPlus.
Additionally, the design of radiative ceiling panels is not supported in EnergyPlus. Therefore, they have been created as concrete core activation with slab consisting of a very thin conductive material.

EnergyPlus has been used to overcome these problems.
In EnergyPlus it is possible to have low temperature panels operating both in heating and cooling mode contrary to DesignBuilder. So, as far as the first problem is concerned, the parameters of the chilled ceiling have been copied to the heated floor in order to have heating and cooling provided from the same internal source. Additionally, some other changes have been made to make the system work properly (For the detailed procedure see Appendix).

Regarding the second problem of CCA control, initially the water supply temperature was calculated according to Fig 6-4. However, the problem was that the system operated according to these setpoints and any thermostats that have been assigned to the room were overriden. So, for example if the outside temperature is below -3^{o}C, heating system is on regardless of the operative temperature. The solution was found in an EnergyPlus feature, the Energy Management System (EMS), which provides a way to develop custom control and modelling

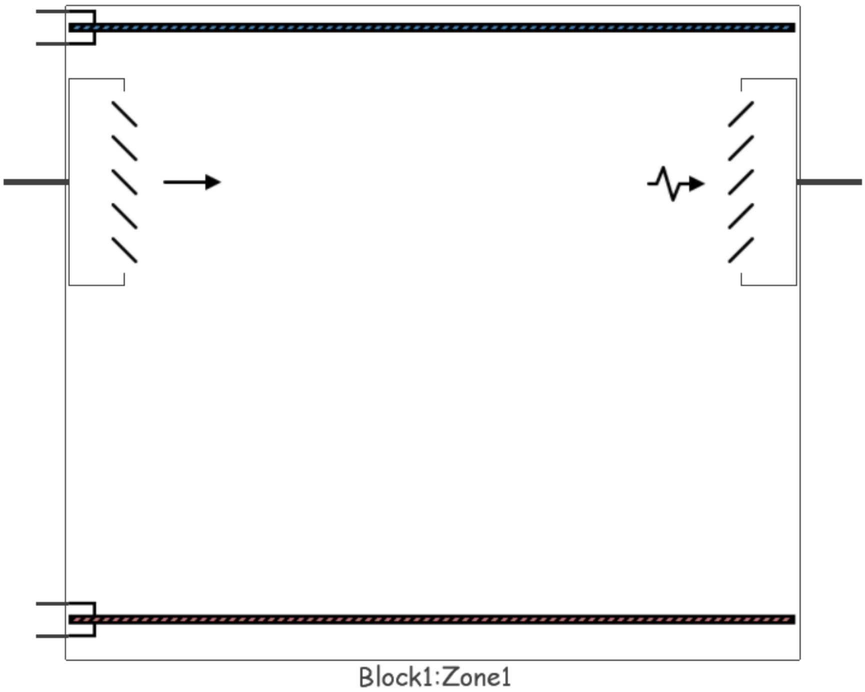


Figure 6-9: Distribution systems (DesignBuilder)

routines for EnergyPlus models. In EMS sensors, actuators and control programs can be added in order to override established features, rather than add a new set of controls. A sensor which measured the inside temperature of the room has been added. Then actuators have been assigned to this sensor and according to the setpoints (Fig. 6.4) which have been defined, a simple control program has been set. So, in case of heating, when the inside temperature is below 19^{o}C the system is operating according to Fig 6-4. When the inside temperature is above 20^{o}C the system is off and in between the system continues doing what it did in the previous timestep. If it is operating at that range, it means that it tries to bring the temperature from 19 to 20^{o}C. If it is off at that range, it means that the inside temperature is dropping from 20 to 19^{o}C.

6-6 Comparison TRNSYS vs EnergyPlus

After all the parameters have been set, the next step was to compare the results. It was decided to compare the model, as explained above, and the respective free floating model meaning the case where there is no CCA operation (ventilation continues operating at the same schedule and temperature). The requested output were the ambient, mean air and operative temperature. Both models have been simulated for the whole year.

Initially, the weather data (ambient temperature and solar radiation values) have been compared. In Fig. 6-10 the ambient temperature is shown as calculated by TRNSYS and EnergyPlus.

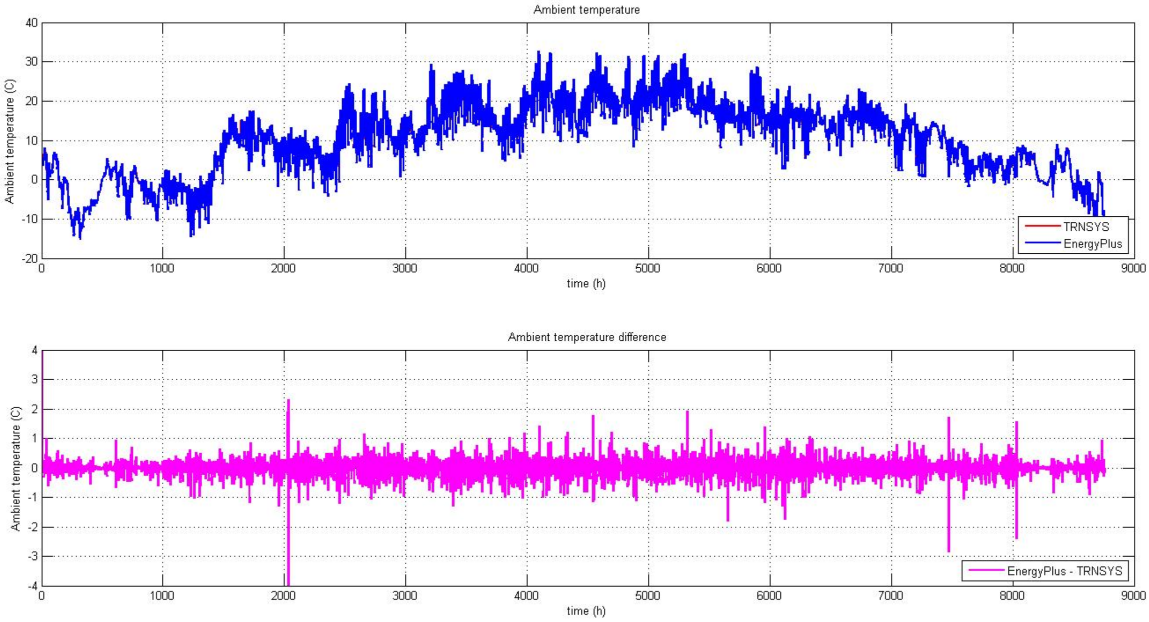


Figure 6-10: Comparison of ambient temperature between the results of TRNSYS and EnergyPlus

The weather data have small differences, which occur due to the different interpolation methods of the two programs. The interpolation is done during the conversion process of the initial weather data into the desired file format that each program uses. In the case of EnergyPlus EPW files are used, whereas TRNSYS supports TMY2 files. Respectively, the solar radiation values have differences between the two programs due to interpolation (Fig. 6-11).

6-6-1 Free floating model

The free floating model, as mentioned above, is the model where CCA does not operate. In our case, the free floating model refers to a model where ventilation operates constantly at 20^oC from 07:00 till 18:00 during weekdays.

Fig. 6-12 illustrates the mean air temperature of the test case throughout the year as simulated by TRNSYS and EnergyPlus. During the whole simulation period, EnergyPlus provides higher mean air temperature than TRNSYS. The temperature difference varies from 1^oC till 5^oC. The highest temperature differences occur during occupation when internal heat loads and solar radiation are at their maximum. Similar results are provided for the operative temperature with slightly lower temperature differences.

As mentioned in chapter 5, glazing modelling is the main cause of temperature differences between EnergyPlus and TRNSYS. Therefore, the same model without the window has also been simulated in EnergyPlus and TRNSYS.

Fig. 6-13 illustrates the mean air temperature of the two models after the removal of the window as a function of time. The mean air temperature is significantly lower in both models as it was expected since there is no transparent surface and the results between the two

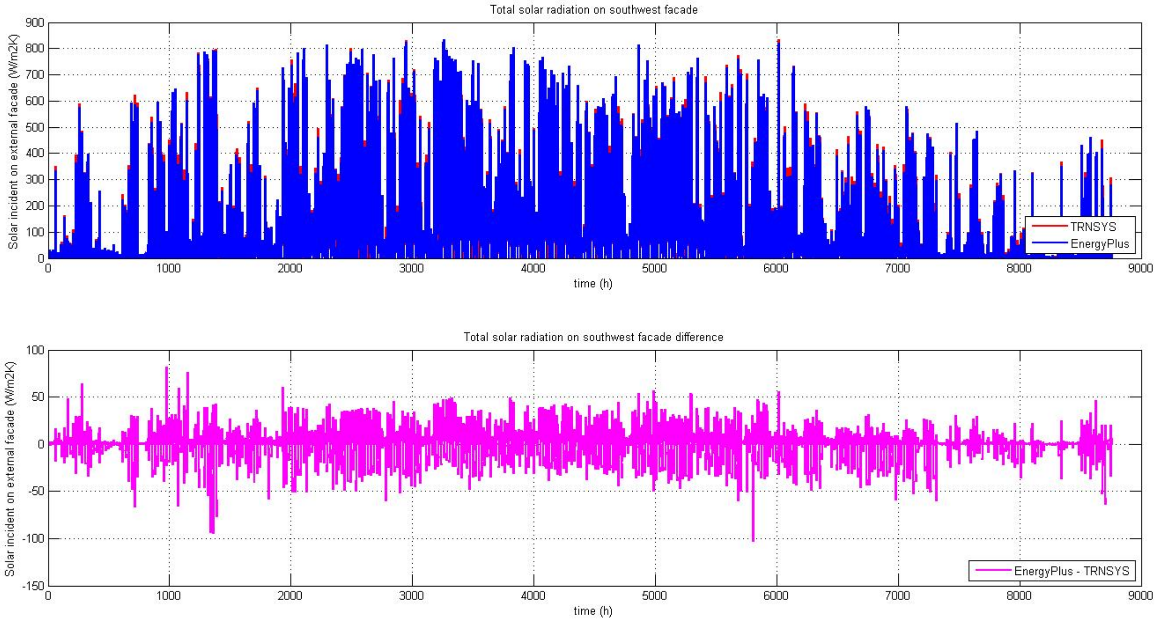


Figure 6-11: Comparison of solar radiation values between the results of TRNSYS and EnergyPlus

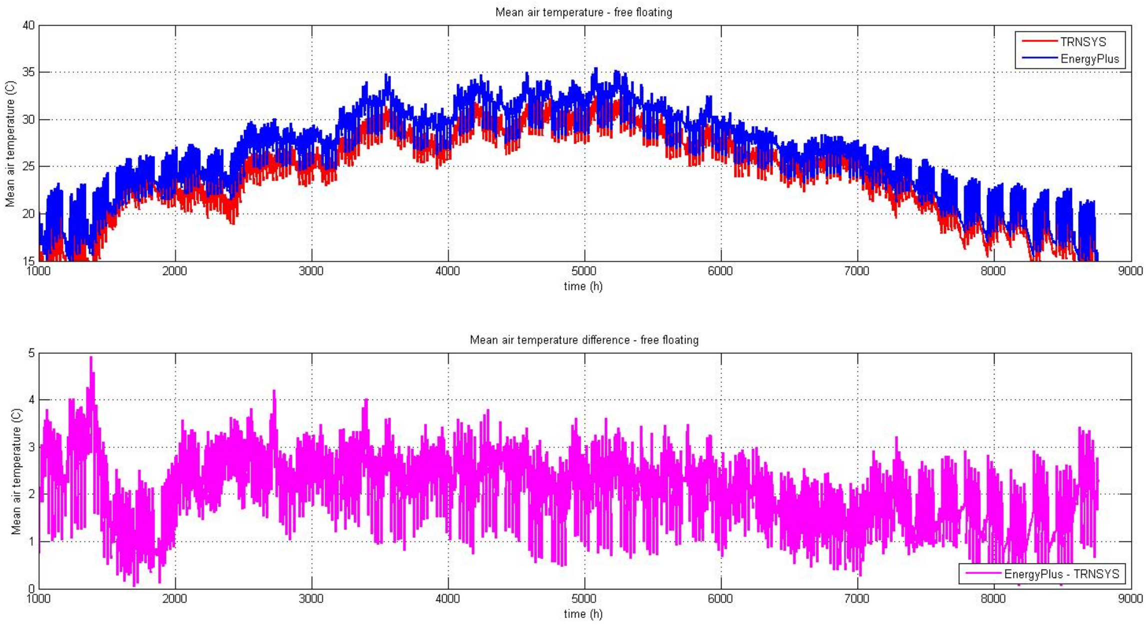


Figure 6-12: Comparison of mean air temperature of the free floating model between the results of TRNSYS and EnergyPlus

programs in this case match well. Inside temperature follows the same pattern both in the mean air and operative temperature.

If we zoom into the mean air temperature graph of a typical week, we can see more clearly the diurnal temperature fluctuations. Fig. 6-14 illustrates the mean air temperature of the models

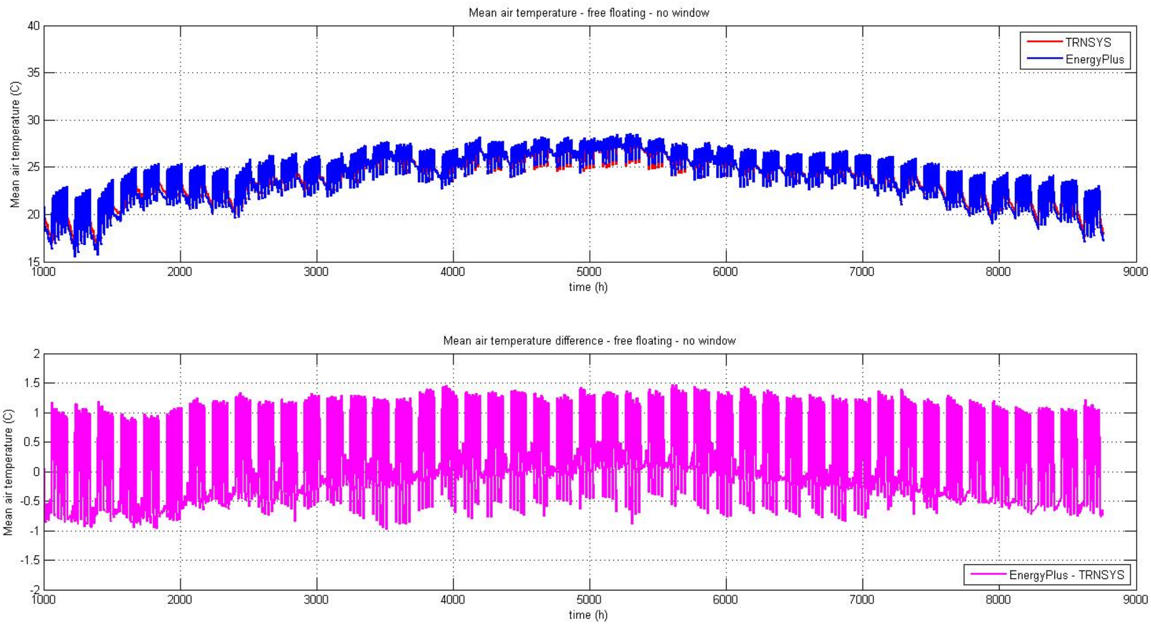


Figure 6-13: Comparison of mean air temperature of the free floating model with no transparent surfaces between the results of TRNSYS and EnergyPlus

during a typical week in February in the heating mode. It is clear that during occupation, the mean air temperature of the EnergyPlus model is approximately 1^{o}C higher than the temperature of the TRNSYS model. On the other hand, outside occupation hours (during night-time and during weekends), EnergyPlus shows lower inside temperatures than TRNSYS (0.5 - 1^{o}C).

Respectively, Fig. 6-15 shows the mean air temperature of the models during a typical week in May in cooling mode. It is again clear that during occupation, the mean air temperature of the EnergyPlus model is higher than the temperature of the TRNSYS model. However, in this case the temperature difference is slighly higher than during heating mode($\sim$1.5^{o}C). On the other hand, outside occupation hours (during night-time and during weekends), EnergyPlus and TRNSYS results match very well. It seems as if the temperature curve of EnergyPlus during cooling mode is shifted a bit upwards.

6-6-2 Model with CCA

In this section the model with CCA is tested and the results of EnergyPlus and TRNSYS are compared. In this case the mean air temperature, as provided by the two programs, is compared. In this case the window is part of the facade. Fig. 6-16 shows the mean air temperature of both models.

The results of the model with CCA follow similar pattern with lower temperature differences than the respective free floating model. This is reasonable since there is an extra heating and cooling system which tries to maintain the inside temperature at the same levels. However, there are relatively high temperature differences between EnergyPlus and TRNSYS models.

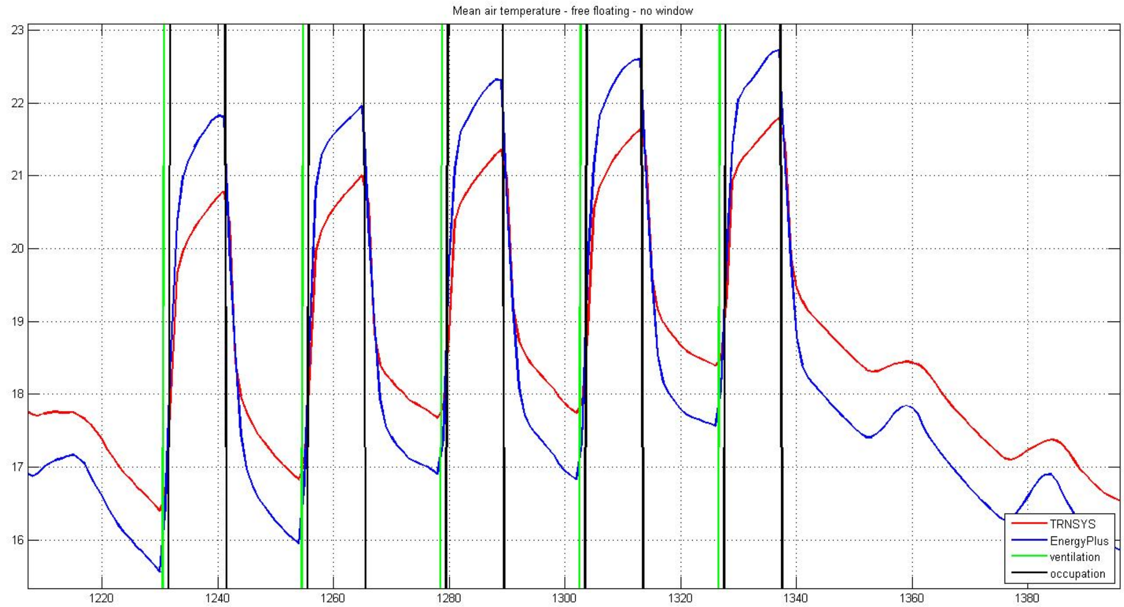


Figure 6-14: Comparison of mean air temperature of the free floating model with no transparent surfaces during a week in heating mode between the results of TRNSYS and EnergyPlus

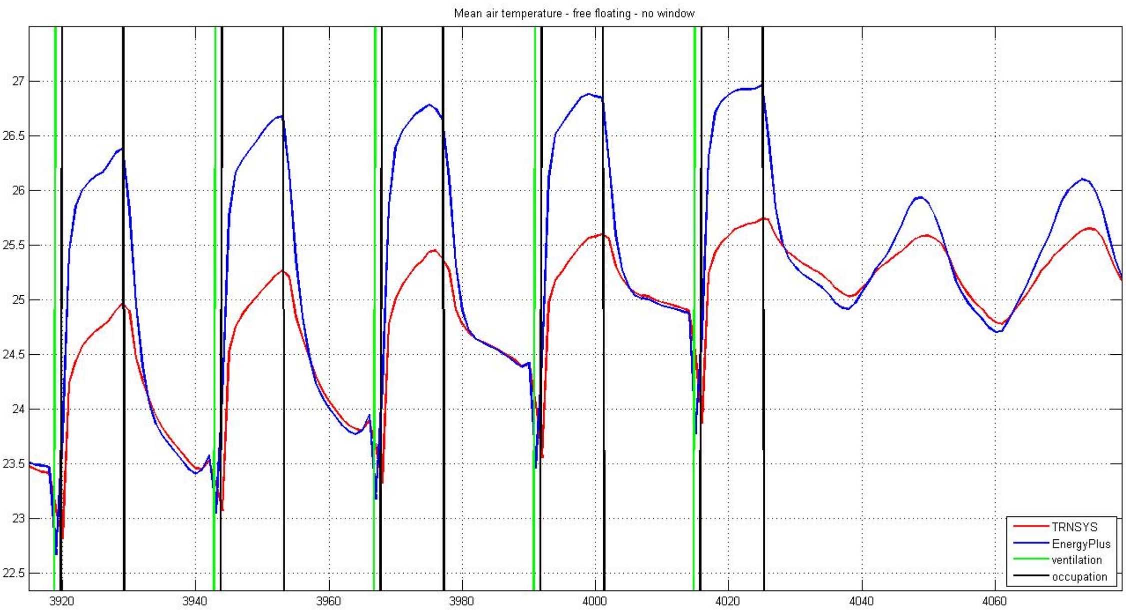


Figure 6-15: Comparison of mean air temperature of the free floating model with no transparent surfaces during a week in cooling mode between the results of TRNSYS and EnergyPlus

EnergyPlus gives higher inside temperatures ($\sim 2^o$C higher) during occupation in the cooling mode than TRNSYS. Outside occupation both programs give similar results in terms of mean air temperature. In heating mode the differences are even higher during occupation.

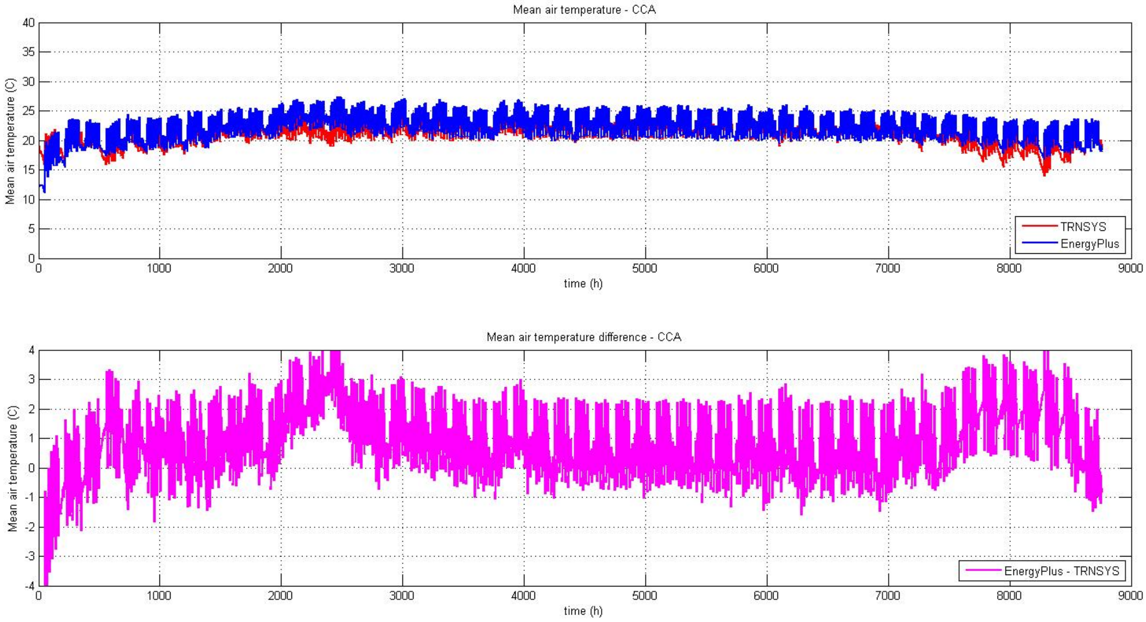


Figure 6-16: Comparison of mean air temperature of the CCA model between the results of TRNSYS and EnergyPlus

EnergyPlus gives 3-4^{o}C higher mean air temperature than TRNSYS.

6-6-3 Conclusions

In both the free floating model and the CCA model, the inside temperatures provided by EnergyPlus were higher than in the TRNSYS models. These high differences occured especially during occupation. The main cause of the temperature differences is the glazing on the facade of the models and more specifically the discrepancy in the absorptance coefficients. In the comparison of the fully opaque models the inside temperatures matched quite well.

Chapter 7

Combination of CCA with radiative panels

This chapter focuses on the combination of concrete core activation with radiative panels for heating and cooling. Additionally, it provides a framework on how the combination of the two systems can be optimized.

7-1 1-zone model

The 1-zone model is based on the test case analyzed in chapter 6, but is extended by adding a radiative panel on a part of the ceiling. Fig. 7-1 shows a typical room in which both systems are installed. Both systems share the same distribution lines, thus obtaining substantial savings on investment costs. In this way, the slow (CCA) and fast (radiative panel) delivery systems are intermittently connected to the same distribution system, i.e. a so-called change-over system, which means that both systems cannot operate at the same time.

Unfortunately, radiative panels cannot be directly modelled in EnergyPlus. Their modelling procedure is explained briefly below.
A separate 'plenum' zone is created for the hanged ceiling space and in the floor of this zone the internal source is imbedded. Then a hole is made at this floor in order to construct the panel with the desired area. As a result a new, very low zone is created above the radiative panel. Finally, a zone air mixer is added to mix the air between the plenum above the radiative panel and the occupied space. Fig. 7-2 illustrates the procedure mentioned above. The constructions and the material properties are the same as in the test case of chapter 6.

The cross-section of the radiative panel is shown in Fig. 7-3 and the material properties are analyzed below.

- Mineral wool
  - Thickness: d=50mm

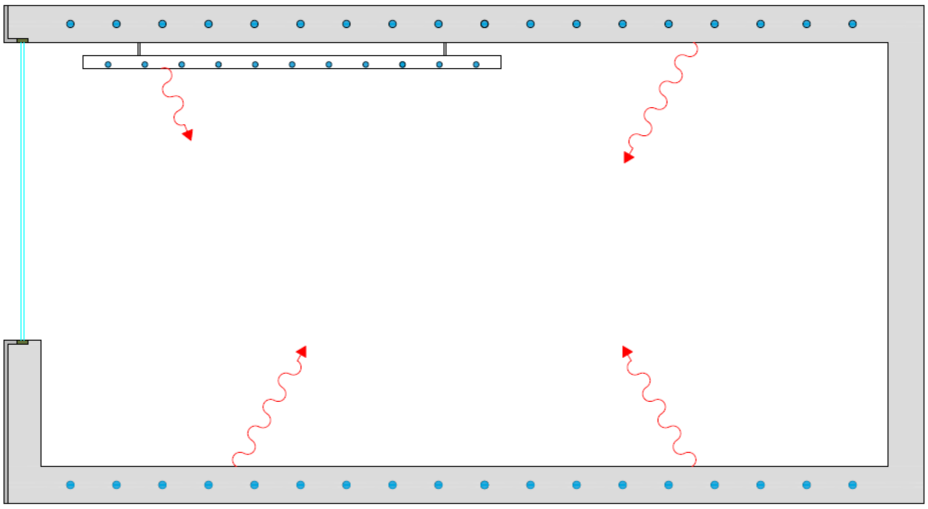


Figure 7-1: Room with combination of CCA and radiative panel

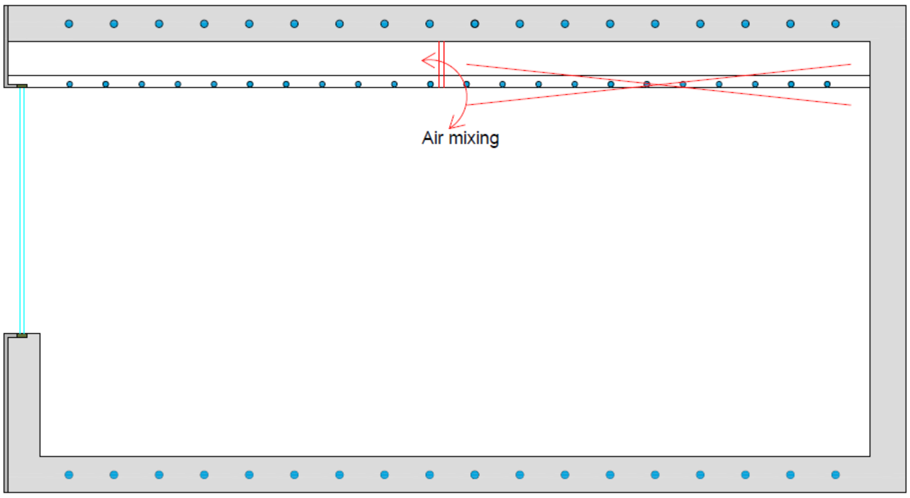


Figure 7-2: Designing a radiative panel in EnergyPlus

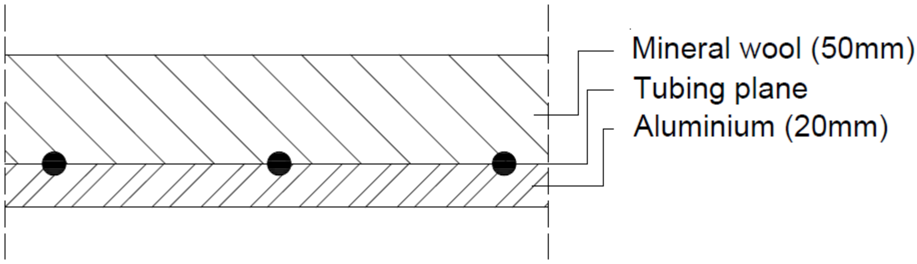


Figure 7-3: Radiative panel cross-section

  - Thermal conductivity: $\lambda = 0.026$ W/mK
  - Density: $\rho = 35$ kg/m^3
  - Specific heat: $c = 840$ J/kgK

- Aluminium
  - Thickness: d=20mm
  - Thermal conductivity: $\lambda = 160$ W/mK
  - Density: $\rho = 2880$ kg/m^3
  - Specific heat: $c = 880$ J/kgK

The radiative panel is located 200mm below the ceiling and its area is A=9.72m^2 (half the area of the ceiling).

The properties of the panel are shown below.

- 1 circuit (Circuit length: 48.6m)
- Tubing distance: 200mm
- Water velocity: 0.4m/s (or 0.091kg/s)
- Inner tube diameter: 17mm

The duration of the simulation is one month (July) because the simulation was extremely slow for the whole year. Moreover, it is more important to compare the system in the cooling mode because internal and external loads are higher.

There are 3 conditions that all have to be met in order for the radiative panel to operate in cooling mode:

1. From 08:00 till 18:00 (during occupation)
2. When outside temperature is above 11^{o}C
3. When operative temperature is above 21^{o}C

Concrete core activation and ventilation operate as mentioned in chapter 6.

7-2 Optimization process

In this section the parameters which influence the performance of the systems are analyzed. This section does not give a final optimized solution, but provides a methodology on how these parameters can be optimized through repetitive simulations. In order to find the optimal solution for every parameter of the model, a number of simulations is needed. In each simulation the value of the parameter will be gradually increased. The output of each simulation will be the inside temperature, the energy consumption and the cost for each change which is applied. In the end, these three parameters will provide the optimal solution. The optimal solution can be defined as the case where a satisfying thermal comfort is achieved with the lower energy consumption and cost.

These parameters are the following:

1. Thermal mass of the zone
2. Properties of CCA
3. Properties of radiative panels
4. Controls of the systems - schedules

The contribution of these factors to the thermal comfort of the room are analyzed in the following paragraphs.

7-2-1 Effect of thermal mass

Thermal mass plays a very important role especially in buildings where TABS are installed because the structural components,such as slabs, store and release heat. Initially, some key terms are mentioned and the way they relate to thermal mass is explained.

Time lag Φ is defined as the time that sinusoidal temperature wave reaches from outdoor surface of wall to indoor. Decrement factor f is defined as the reduction ratio in amplitude of the temperature wave at the indoor surface compared to the outside surface (Ozel, 2013). Time lag and decrement factor are computed using the following relations.

$$\Phi = t_{T_{in}(max)} - t_{T_{out}(max)} \tag{7-1}$$

$$f = \frac{T_{in}(max) - T_{in}(min)}{T_{out}(max) - T_{out}(min)} \tag{7-2}$$

where $t_{T_{in}(max)}$ and $t_{T_{out}(max)}$ represent the time that indoor surface temperatures and outdoor surface temperatures are being maximum, respectively. $T_{in}(max)$, $T_{in}(min)$ and $T_{out}(max)$, $T_{out}(min)$ are maximum and minimum temperatures on the indoor and outdoor surfaces of wall, respectively.

High thermal mass reduces the decrement factor while increasing time lag, as illustrated in Fig. 7-4. This means that the diurnal temperature fluctuations are smaller, but the response of the HVAC system is slower.

The effect of thermal mass has also been tested in the 1-zone model, as illustrated in the next comparison (Fig. 7-5). Two models with different thermal mass have been compared. The first model consists of walls with no thermal mass and the second model is the same but with extra thermal mass in the walls of the room. The walls of the second model have been designed as 200mm thick concrete walls.

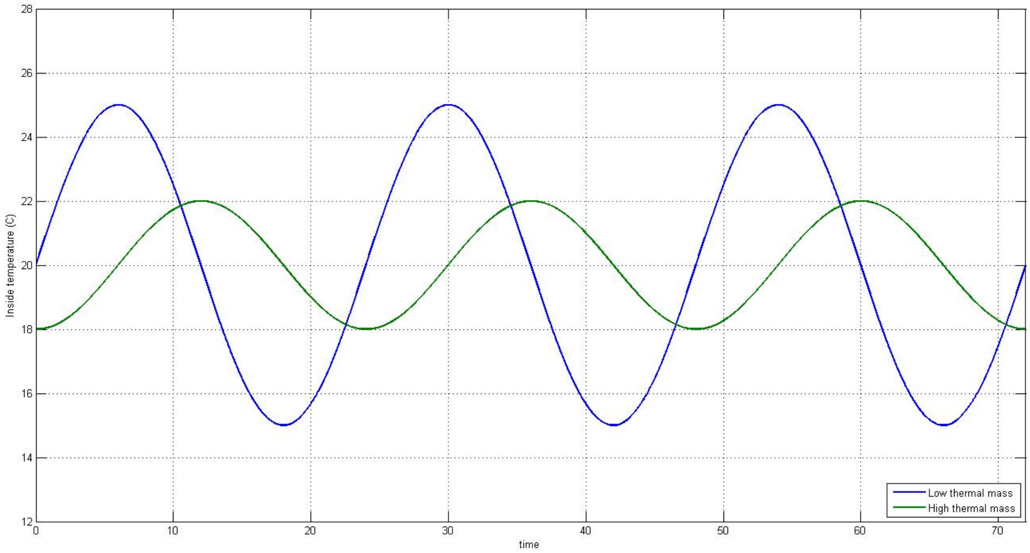


Figure 7-4: Effect of thermal mass

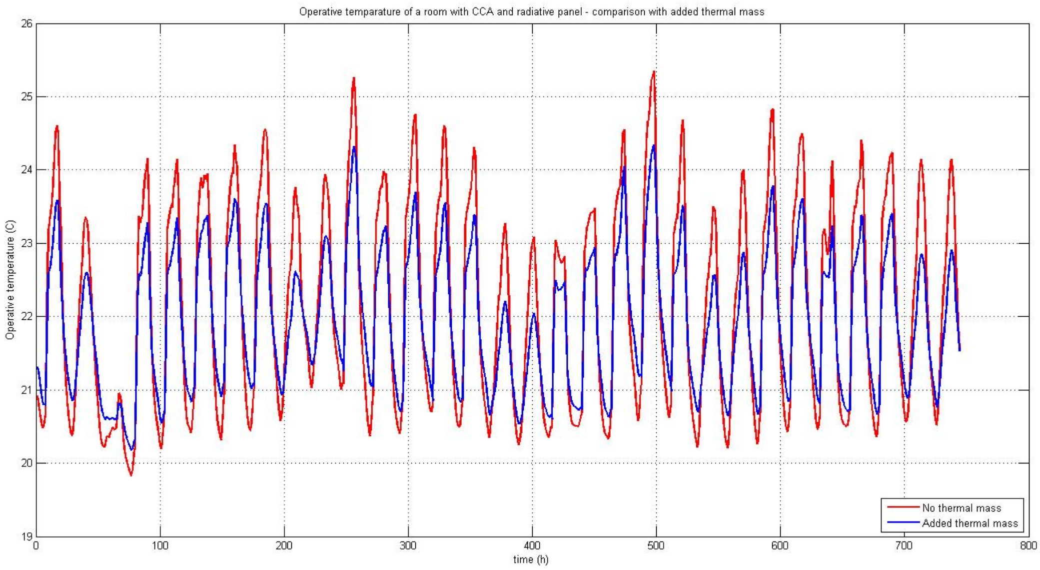


Figure 7-5: Operative temperature comparison with and without added thermal mass during July

The results show the positive effect of thermal mass on thermal comfort. In the model with added thermal mass the operative temperature fluctuations are significantly smaller than in the model without thermal mass. The effect of thermal mass on time lag cannot be seen in the graph.

To sum up, thermal mass is one parameter that plays a significant role in the thermal comfort of thermally activated buildings. Therefore, the thickness and the materials of the constructions should be selected in such a way to achieve a good level of thermal comfort. However, it is necessary to take into consideration the cost of these constructions and their environmental impact.

7-2-2 Properties of CCA

The factors that influence the performance of concrete core activation are:

1. Position of the activated layer inside the slab
2. Inner tube diameter
3. Thickness and material of tube mantle
4. Tubing distance
5. Mass flow rate

Position of the activated layer inside the slab

The position of the activated layer inside the slab should be carefully selected to ensure the optimal thermal comfort inside the model. The installation of the activated layer closer to the lower part of the slab is beneficial in the cooling mode because heat exchange coefficient is higher for ceilings than for floors during cooling. On the other hand, positioning the activated layer closer to the upper part of the slab is beneficial in the heating mode because heat exchange coefficient is higher for floors than for ceilings during heating (see Table 2.1). It should be noted that in office buildings, in which cooling is dominant, the position of the activated layer closer to the lower part of the slab results in better thermal comfort.

Inner tube diameter

Large inner tube diameters lead to high energy emissions and subsequently to better thermal comfort inside the occupied space. On the other hand, large inner tube diameter results in higher energy consumption for pumps and chillers or boilers (depending on the mode the system operates) because the volume of water which is delivered and cooled or heated is larger.

Thickness and material of tube mantle

The thickness and material of the tube mantle are parameters which also influence the performance of CCA. Highly conductive materials and small thickness are best suited because they allow higher heat flux from the tube to the slab and vice versa and subsequently to better thermal comfort. However, pipes made completely out of highly conductive materials lead to high costs and problems during the installation or operation of the system.

Tubing distance

The distance between the tubes is also a parameter which affects the performance of CCA. Smaller tubing distances result in higher heat flux between the activated layer and the occupied space and therefore in a better thermal comfort. However, this also means that larger volume of water has to be delivered to the slabs, which leads to higher energy consumption.

Mass flow rate

Higher mass flow rate, or higher water velocity in the tubing, results in lower thermal resistance between the activated layer and the slab and as a result in better thermal comfort in the room. However, higher velocity leads to larger volume of water and therefore to higher energy consumption.

7-2-3 Properties of radiative panels

The parameters which influence the performance of the radiative panels are similar to these of CCA. The inner tube diameter, tubing distance and mass flow rate are parameters which affect in a similar way the efficiency of radiative panels and they will not be expanded in this section. On the other hand, the area of the radiative panel is a property that affects the panel itself and the CCA performance. So, this parameter is analyzed below.

Area of the panel

Radiative panels, as mentioned in the previous chapters, operate during occupation hours when the inside temperature is outside a specific temperature range. The area of the panel is the factor that actually defines the performance of the system. Large panel area leads to higher heat transfer, whereas small panel area results in lower heat transfer. As illustrated in Fig 7-1, the radiative panels are suspended from the ceiling of the occupied space at a very small distance from it. As a result, part of the thermally activated ceiling is not visible from inside the room. In other words, the view factor of the ceiling is decreased which subsequently lowers the heat transfer due to radiation from and to the slab. View factor in radiative heat transfer is the proportion of the radiation which leaves one surface and strikes another surface. So, it is obvious that larger panel area increases the performance of the radiative panels but at the same time reduces the CCA performance. On the other hand, smaller panel area decreases the performance of the radiative panels but improves the CCA performance (see Fig. 7-6 and 7-7). The optimal panel area can be found by performing a number of simulations, starting with the 1-zone model with a small panel area and gradually increasing the area of the panel. The optimal panel area is defined as the one which results in acceptable room temperatures and the minimum energy consumption and cost.

Effect of the systems

Three different cases have been selected to compare the effect of each system to the inside room temperature of the 1-zone model. In these simulations the area of the radiative panel

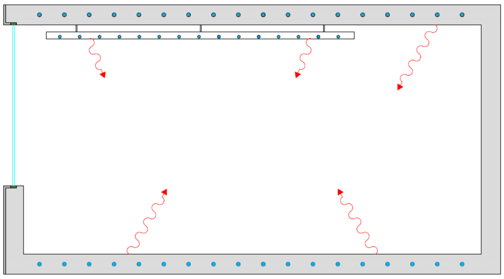


Figure 7-6: Large panel area - Large contribution of radiative panels/small contribution of CCA

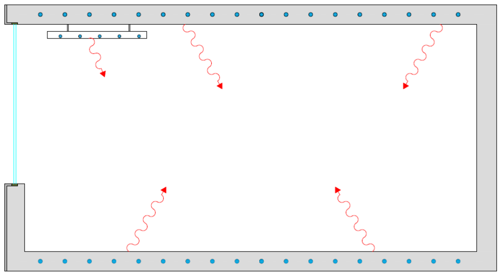


Figure 7-7: Small panel area - Small contribution of radiative panels/large contribution of CCA

covers half the area of the ceiling. The duration of these simulations is one month during summer where the loads inside the room are maximum.

1. Case 1: Both systems are operating
2. Case 2: CCA is constantly off (only the radiative panel is operating)
3. Case 3: The radiative panel is constantly off (only CCA is operating - same as in test case of chapter 6)

In Fig. 7-7 the operative temperature of the model is compared in the three different cases.

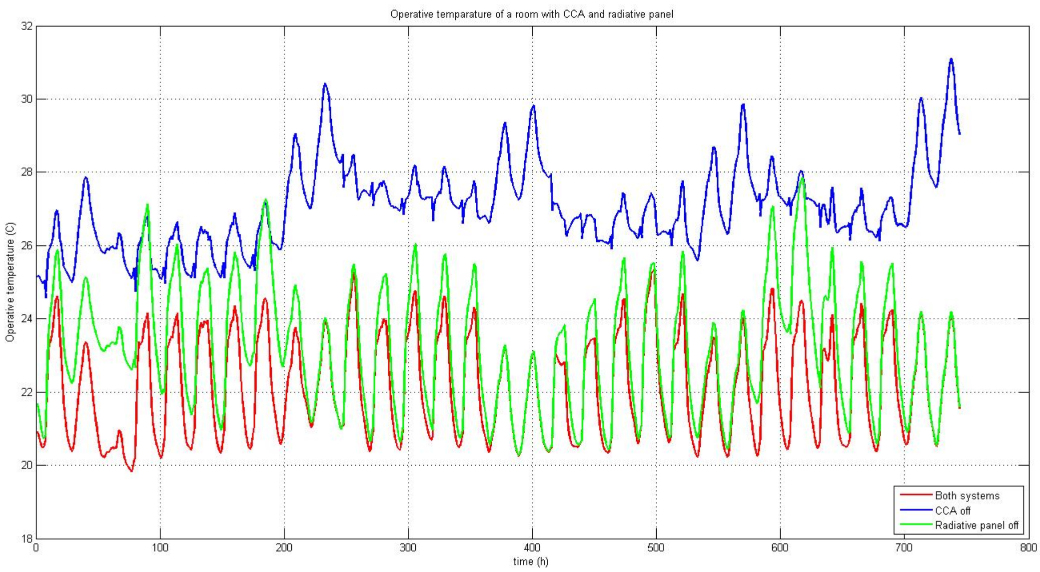


Figure 7-8: Operative temperature comparison in 3 cases during July

The results are reasonable since in Case 1 (both systems operating), the operative temperature is lower than in the other cases. In Case 2 (only the radiative panel operating), the operative temperature gets extremely high. On the other hand, in Case 3 (only CCA operating), the operative temperature higher than in Case 1 but much lower than in Case 3.

This means that CCA is more effective in terms of thermal comfort than the radiative panel. This is also logical since the radiative panel covers half the space that CCA does.

Additionally, we can conclude that the installation of the radiative panels as an extra cooling system results in a small improvement of the room's thermal comfort and probably does not compensate for their high cost.

7-2-4 Controls of the systems

This section is focused on the optimization of the controls of the system that are applied in the model. As in the optimization of the previously mentioned parameters, the controls are optimized based on the thermal comfort inside the occupied space, the energy consumption and subsequently the cost. This procedure takes into consideration the following parameters.

1. Water supply temperature (heating/cooling curves) for each system
2. Temperature setpoints for each system inside the occupied space
3. Schedules for each system

Water supply temperature

As mentioned in the previous chapters, the water supply temperature is based on the outside temperature according to Fig. 7-9. This figure combines the heating and cooling curve into one graph. Between the curves there is a relatively large dead zone (the temperature range in which no heating or cooling is applied). These curves can be optimized by changing the temperature setpoints on both axes.

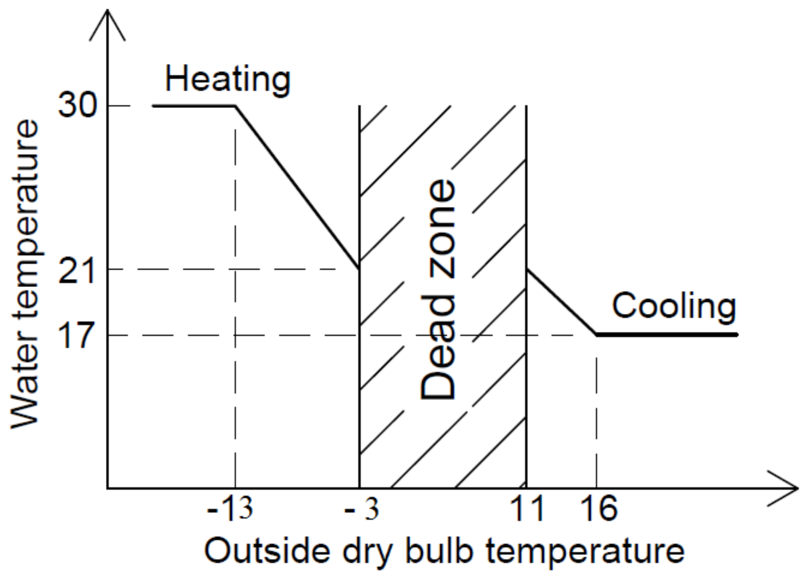


Figure 7-9: Water supply temperature

Shifting the heating curve upwards, results in higher water supply temperature. This leads to higher energy consumption since water is heated to a higher temperature, but a simultaneous increase of the inside temperature. Shifting the heating curve to the right, results in the fact that heating is applied when the outside temperature is higher. This means that the duration when heating is provided, is longer. This, reasonably, leads to higher energy consumption, but higher inside temperatures as well. Additionally, this results into smaller dead zone. This changes are clearly shown in Fig. 7-10. Shifting the heating curve downwards or to the left results in lower energy consumption, but lower inside temperatures.

Regarding the cooling curve, shifting the cooling curve to the left and/or downwards, leads to lower inside temperatures, but higher energy use.

An application of the example mentioned above is shown in Fig. 7-10. The red heating/cooling curves result in higher energy consumption but better thermal comfort inside the occupied space than the black heating/cooling curves.

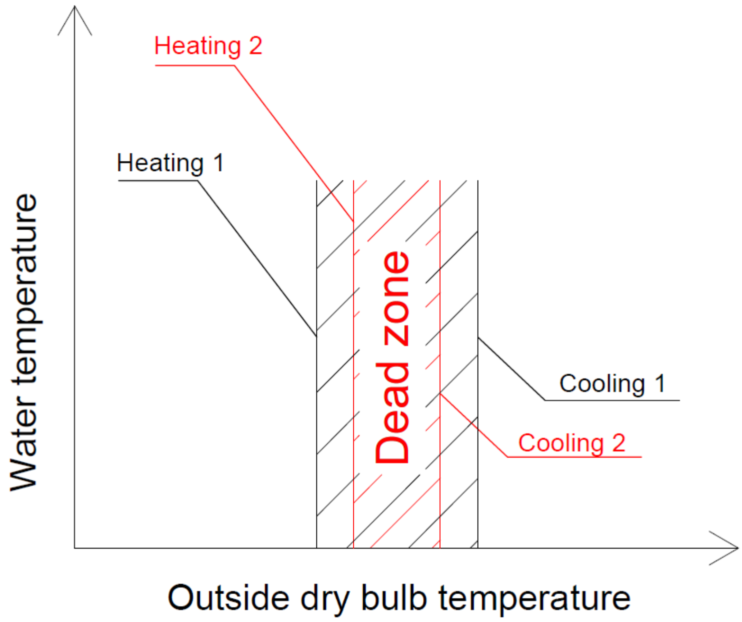


Figure 7-10: Change of water supply temperature

Temperature setpoints inside the occupied space

The temperature setpoints in the model trigger each system according to Fig. 7-11. The water pumps which deliver water to the slab and the radiative panels operate based on these setpoints.

So, it is important to investigate how the change of these setpoints influence the thermal comfort and energy consumption. Regarding heating mode, shifting the left trapezoid to the right results in increase of the heating setpoint. This means that heating is applied when the temperature is higher inside and this leads to more hours of heating and subsequently in better thermal comfort, but higher energy consumption. On the contrary, lowering the temperature setpoints in the room leads to fewer hours of heating and subsequently in worse thermal

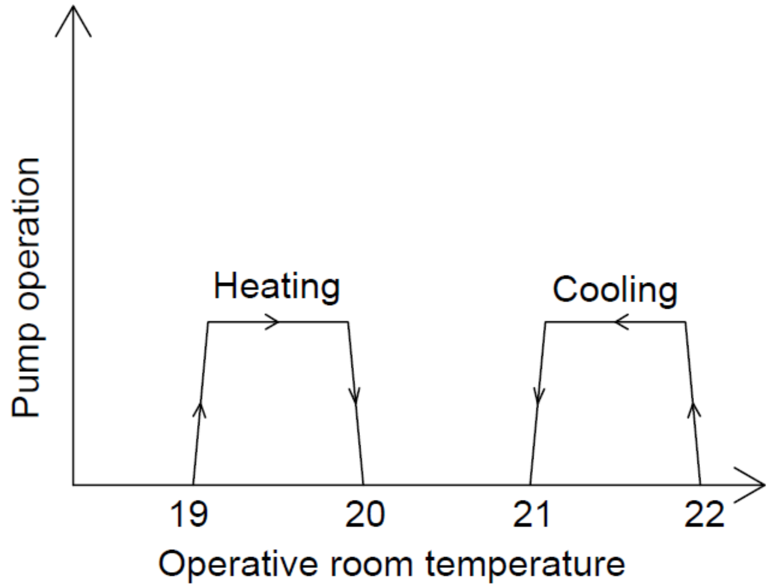


Figure 7-11: Pump control

comfort but lower energy consumption. Regarding cooling mode, lowering the temperature setpoints of the right trapezoid results in more hours of cooling and subsequently in better thermal comfort but higher energy consumption.

These changes are illustrated in Fig. 7-12. The red trapezoids, when compared with the black ones, lead to more hours of heating and cooling and subsequently to better thermal comfort and higher energy consumption.

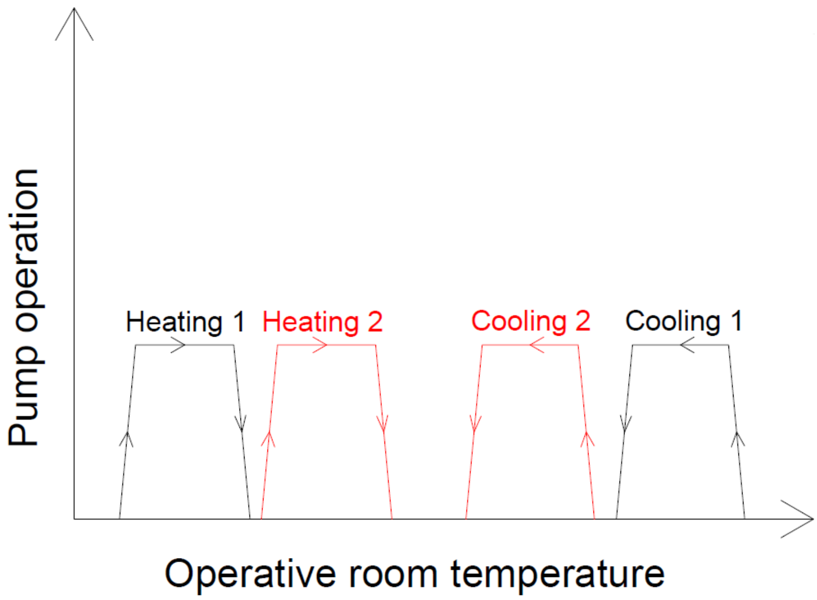


Figure 7-12: Change of pump operation

Schedules

The schedules of the systems refer to their operating hours. The operating hours of concrete core activation are from 18:00 till 08:00 (outside occupation hours). The schedule of radiative panels is from 08:00 till 18:00 (during occupation). This does not force the systems to operate during the whole range of their schedule, but only when outside and inside temperature are at a particular range as well. It is reasonable that the reduction of the operating hours of the systems lead to fewer hours of heating and cooling which results in worse thermal comfort and lower energy consumption.

In the following section, an optimization example is presented by changing the schedules of the systems and the temperature setpoints inside the 1-zone model.

7-3 Optimization example

The optimization of the model is performed in this section by applying different schedules to the cooling systems (CCA and radiative panels). The optimization refers to the minimizing the energy consumption of the system while maintaining inside temperature in acceptable range. The model which has been used for this example is the 1-zone model which has been analyzed in the beginning of this chapter. This example refers only to cooling and the simulation has been performed only for one month in summer. Both systems operate according to their schedule (only cooling):

- **Radiative panel**
  1. From 08:00 till 18:00 (during occupation)
  2. When outside temperature is above 11^{o}C
  3. When operative temperature is above 21^{o}C
- **CCA**
  1. From 18:00 till 08:00 (outside occupation hours)
  2. When outside temperature is above 11^{o}C
  3. When operative temperature is above 21^{o}C

The operating schedules of CCA and radiative panels are shown during a typical day in July (Fig. 7-13). The green trapezoid indicates the operating hours of the radiative panel and the red trapezoid shows the CCA operating hours.

Fig. 7-13 illustrates that radiative panels operate continuously during occupation because of the high internal and external loads. On the other hand, CCA starts operating exactly when the occupation ceases because the operative temperature at this moment is at its maximum. The operation of CCA continues for several hours until operative temperature falls below 21^{o}C. The operating schedule of the radiative panels has limited possibility to be changed since it operates continuously during occupation. So, it was initially decided to optimize the schedule of CCA.

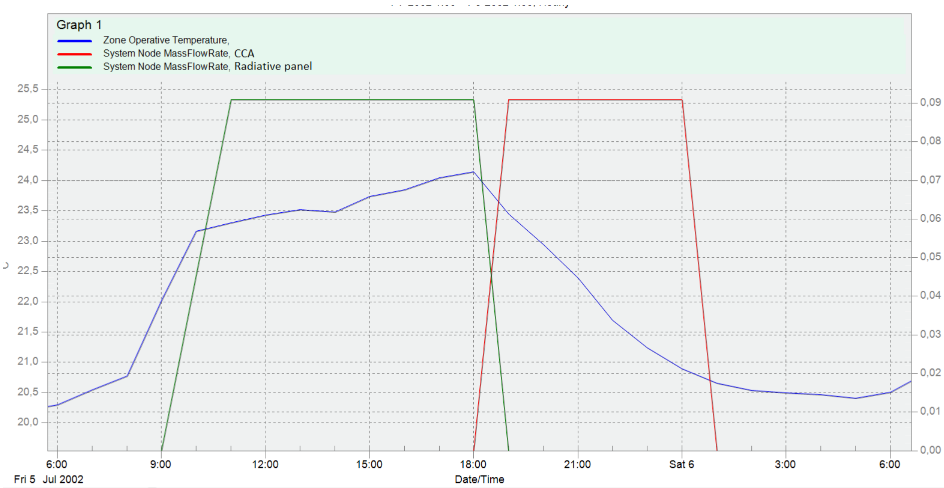


Figure 7-13: Operating schedules of CCA and radiative panels

Since outside temperature is always above 11^{o}C, the only changes that can be made are either in the operating schedule or the temperature setpoints inside the 1-zone model which trigger the systems.

Initially the operating schedule has been changed keeping the inside temperature setpoint constant at 21^{o}C. These are the schedules that have been compared:

- Original schedule: From 18.00 till 08:00
- Schedule 1: From 00.00 till 08:00
- Schedule 2: From 22.00 till 08:00
- Schedule 3: Divided in three parts; from 20.00 till 22:00, from 24.00 till 03:00 and from 06.00 till 08:00.
- Schedule 4: Divided in two parts; from 20.00 till 22:00 and from 24.00 till 03:00.

Shedules 1 and 2 result in the shifting of the CCA operating hours 6 and 4 hours later during night, respectively. However, the number of hours that CCA is operating are still the same without significantly reducing the energy consumption of the system.

Therefore, another parameter has been changed in order to find out its influence in the model. This parameter is the setpoints of the thermostats and have been changed while keeping the operating schedule from 18.00 till 08:00.

- Schedule 5: Thermostat at 21.5^{o}C
- Schedule 6: Thermostat at 22^{o}C

In the end, the combination of Schedule 3 and Schedule 6 has been selected as the optimal result. The following table illustrates the differences in the energy as it is delivered by CCA

Table 7-1: Energy consumption and average operative temperature difference according to the schedules - *Compared with the original schedule.

	CCA energy (*10^8J)	Panel energy (*10^8J)	Total energy (*10^8J)	Average operative temperature difference (^{o}C)*
Original schedule	5,1	2,18	7,28	0
Schedule 1	4,78	2,44	7,22	+0,3
Schedule 2	4,88	2,32	7,2	+0,2
Schedule 3	4,71	2,49	7,2	+0,3
Schedule 4	4,31	2,68	6,99	+0,5
Schedule 5	4,75	2,37	7,12	+0,2
Schedule 6	4,39	2,5	6,89	+0,5
Sch3 and Sch6	3,98	2,61	6,59	+0,65

and the radiative panel along with average operative temperature difference according to each schedule.

The results show that the optimal schedule is the combination of Schedule 3 and Schedule 6:

- **Radiative panel**
  1. From 08:00 till 18:00 (during occupation)
  2. When outside temperature is above 11^{o}C
  3. When operative temperature is above 21^{o}C
- **CCA**
  1. Divided in three parts; from 20.00 till 22:00, from 24.00 till 03:00 and from 06.00 till 08:00.
  2. When outside temperature is above 11^{o}C
  3. When operative temperature is above 22^{o}C

This schedule results in a reduction of 9% while maintaining the operative temperature below 26^{o}C for this specific scenario of room geometry, material characteristics and heat loads.

7-4 Multi-zone model

As mentioned in the beginning of the thesis, the systems (CCA and radiative panels) use the same distribution system and water is delivered to slabs and radiative panels with a 2-pipe distribution system. In contrast to a 4-pipe distribution system, the 2-pipe distribution system allows only hot or cold water to run in the pipes. This means that it is impossible to simultaneously heat and cool zones with different loads. This fact may lead to some occupant discomfort in specific zones. However, the modelling of only one room, which has been performed so far, cannot cover the case above. Therefore, a multi-zone model consisting of several zones with different loads has to be created. This multi-zone model is going to show the effectiveness in terms of inside temperature of a 2-pipe distribution system when CCA and radiative panels are combined. The multi-zone model has not been created in this thesis, but it is proposed as the next step to the modelling of the whole system.

7-5 Evaluation of the system

The combination of concrete core activation and radiative panels is a complex and expensive system. The complexity of the system largely derives from the fact that there are numerous controls and schedules. The research that has been done in this thesis was limited to a 1-zone model. The simulation results have shown that thermal comfort inside the room is maintained even in the hottest months of the year. CCA is the system which mostly contributes to this fact, whereas radiative panels have a significantly smaller effect on inside temperature, as illustrated in Fig. 7-8. This suggests that, in order to achieve better thermal comfort and lower costs, it is more efficient to tweak the CCA system rather than installing the radiative panels.

On the other hand, CCA works based on the temperature of the previous day, in effect making a 'weather prediction' for the next day. In case of inconsistent weather and unexpected loads, CCA system may prove to be insufficient due to its inability to affect the temperature of the same day. In contrast, radiative panels, as a fast delivery system, can solve this issue, because they can start operating when it is necessary, responding directly to the users' needs.

A multi-zone model or a full-scale building has its own set of characteristics, i.e. orientation, hating/cooling loads, geometry, etc. Adopting the results of a 1-zone model on a building injudiciously is erroneous because it leads to inaccurate generalization in any scenario. Additionally, only the modelling of a full-scale building can demonstrate the added value of the combination of the two systems and the possible problems that can arise because of the use of a 2-pipe distribution system.

Chapter 8

Conclusions & Recommendations

8-1 Conclusions

8-1-1 Differences between EnergyPlus and TRNSYS

The first part of the thesis focuses on the accuracy and reliability of EnergyPlus and TRNSYS. This study has shown that EnergyPlus and TRNSYS lead to significantly different results for building simulations under the given conditions. Similar results have been shown in other projects as well (Behrendt et al., 2011). This result is, up to a point, expected since there are settings in each program that they are impossible to be controlled. However, the magnitude of the differences was higher than expected.

It should be noted that it is very difficult to be certain of the exact causes of the differences between the two programs, since several and complicated modelling processes take place. Additionally, the documentation is not sufficient enough to understand how the modelling processes are achieved. Possible causes of these differences are the following.

- It was observed that the introduction of glazing in EnergyPlus models caused unexpected outcome and this was also the main reason for the large differences between Energyplus and TRNSYS.

  This fact is most probably caused by the definition of U-value of glazing and how this corresponds to absorptance, reflectance and transmittance ratios and subsequently to the effect of long-wave radiation from the sky on inside temperature. This was also shown in the results of the test case that was compared in chapter 6 (Fig. 6-12). The differences between the inside temperatures of the two programs were high (up to 5^{o}C), while they dropped sharply when the glazing was removed (Fig. 6-13) . The windows were designed with the simplified model of EnergyPlus in which only U-value and g-value are requested as these were only known for the window. So, it is most likely that the simplified model should not be used because it may lead to approximations and inaccuracies.

- Moreover, apart from the glazing, some other modelling procedures and parameters are calculated differently by each program.

  Convective heat transfer coefficients are calculated by different relations. However, these differences in their calculations are not sufficient to cause so high differences in the final output.

  Internal long-wave radiation is also calculated by a different model.

  Weather data are differently handled in EnergyPlus and TRNSYS, which results in small differencies of the ambient temperature and solar radiation values as calculated by the two programs.

8-1-2 EnergyPlus limitations and problems

EnergyPlus is a powerful tool to perform building simulations. However, it also has some limitations and disadvantages that were encountered during the thesis.

- EnergyPlus is not a user-friendly tool, which makes even the designing of a simple model a very time consuming process.
- It is not possible to apply an initial temperature in the EnergyPlus models. The initial temperature is achieved through a warm-up process and is set automatically. This may result in inaccuracies when comparing the results of the two programs.
- HVAC systems are very difficult to be designed because every component (chillers, coils, etc.) and branch of each HVAC loop should be properly designed and sized, although in most cases the user does not know or care to do so. In some cases, the HVAC system does not comply with the user preferences and in most cases it is the problem of an incorrect component sizing. EnergyPlus has an Autosize feature, which automatically sizes HVAC components, however similar problems were encountered when it was used.
- The HVAC controls are not very flexible and in some cases do not comply with user input.
- Radiative panels cannot be modelled in EnergyPlus.

The combination of EnergyPlus and DesignBuilder is suggested in order to contribute to the designing procedure.

8-1-3 Combination of CCA and radiative panels

The second part of the thesis focuses on a model which is cooled by two cooling systems using a 2-pipe system for water distribution; concrete core activation and a radiative panel. In the final chapter of the thesis, the parameters which influence the efficiency of the two systems were analyzed. These parameters are organized as follows:

- Thermal mass of the zone

- Properties of CCA
- Properties of radiative panels
- Controls of the systems - schedules

These parameters were not optimized, but demonstrated their impact on thermal comfort and energy consumption by gradually changing them.

The current project showed that radiative panels are inefficient in means of cooling in the 1-zone model. Concrete core activation contributed more significantly to achieving thermal comfort. However, it must be noted that the cooperation of the two systems in a 1-zone model may be downgraded. In a full-scale building the operation of radiative panels may prove efficient or even necessary to maintain thermal comfort.

In the end, an optimization example was conducted, where the schedules and temperature setpoints of the HVAC systems were optimized. The optimized schedule resulted in a lower energy consumption by 9%, but also in higher inside temperature (in acceptable range) during cooling mode.

8-2 Recommendations

Regarding the first part of the thesis, which is the comparison of EnergyPlus and TRNSYS, an in-depth study of the documentation of both programs is necessary. All modelling processes, used by both programs, which contribute to the heat balance in a building, i.e. solar radiation, convection, window modelling, etc, have to be separately compared.

As far as the combination of CCA and radiative panels is concerned, the optimization framework, which was proposed, has to be realized. Additionally, a full-scale building equipped with both systems should be modelled in order to evaluate the performance of radiative panels and the use of the 2-pipe distribution system.

Chapter 9

Appendix

Report on applying CCA in Energyplus

Initially, the model is created in Designbuilder v3. The geometry of the building, schedules and HVAC systems have been created in Designbuilder. A heated floor is added at the layer where we want to have the activated layer and a chilled ceiling at the roof of the same zone (see picture below). The water supply temperatures are based on outside temperature. In this case, there are 3 rooms one on top of the other. The room we are studying is the middle one. So, there are 3 zones, 3 chilled ceilings and 3 heated floors.

In the beginning to export the idf file:

File → Export → Export EnergyPlus input file → Simulation

Then open EnergyPlus version 7, browse the IDF file and choose the weather file. In the end open the IDF Editor. DesignBuilder v3 is compatible with EnergyPlus v7.

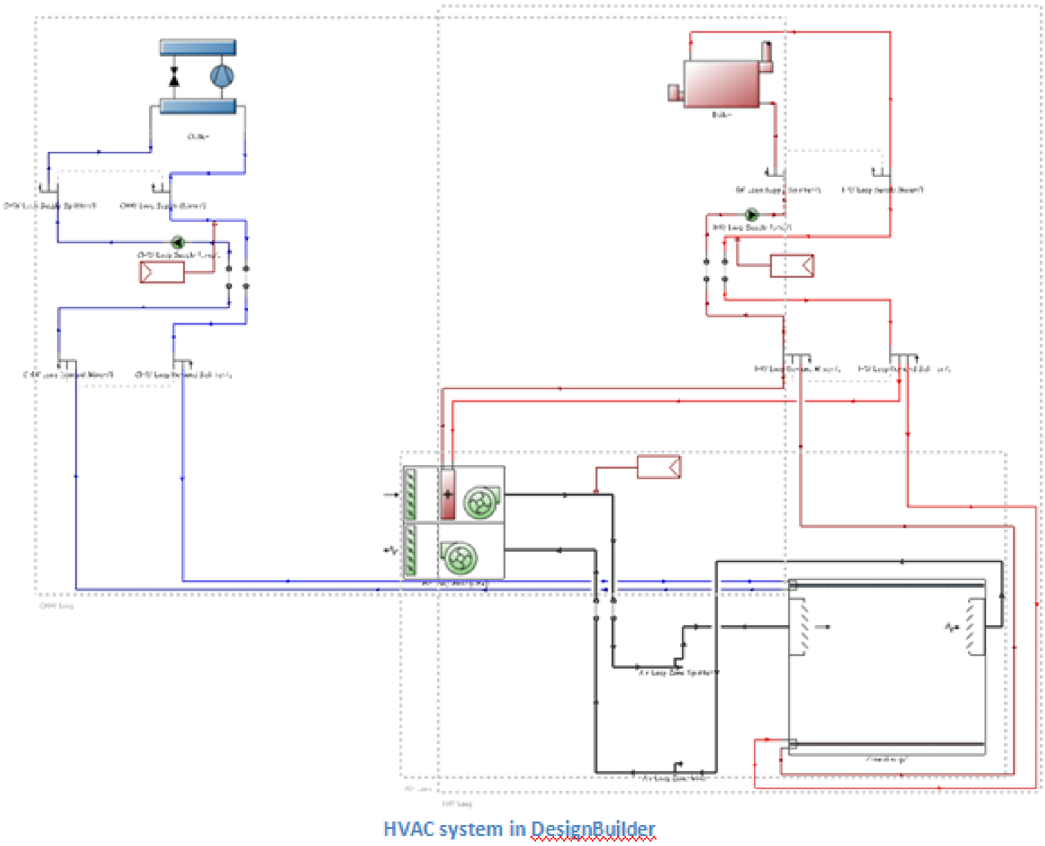


Figure 9-1: HVAC system in DesignBuilder

The changes that have to be made in EnergyPlus (IDF Editor) are the following:

1. In **ZoneHVAC Radiative/convective Units** Group →
   ZoneHVAC: LowTemperatureRadiant:ConstantFlow Object:
   In the heated floor columns fill in the **Cooling water inlet and outlet node name and the cooling water and control temperature schedule names** (6 fields per zone). These fields should be the same as in the chilled ceiling columns.
   Then delete the chilled ceilings.

   In our case, initially we had 6 columns (components - 3 heated floors, 3 chilled ceilings). After the change there should be only 3 columns (heated floors).

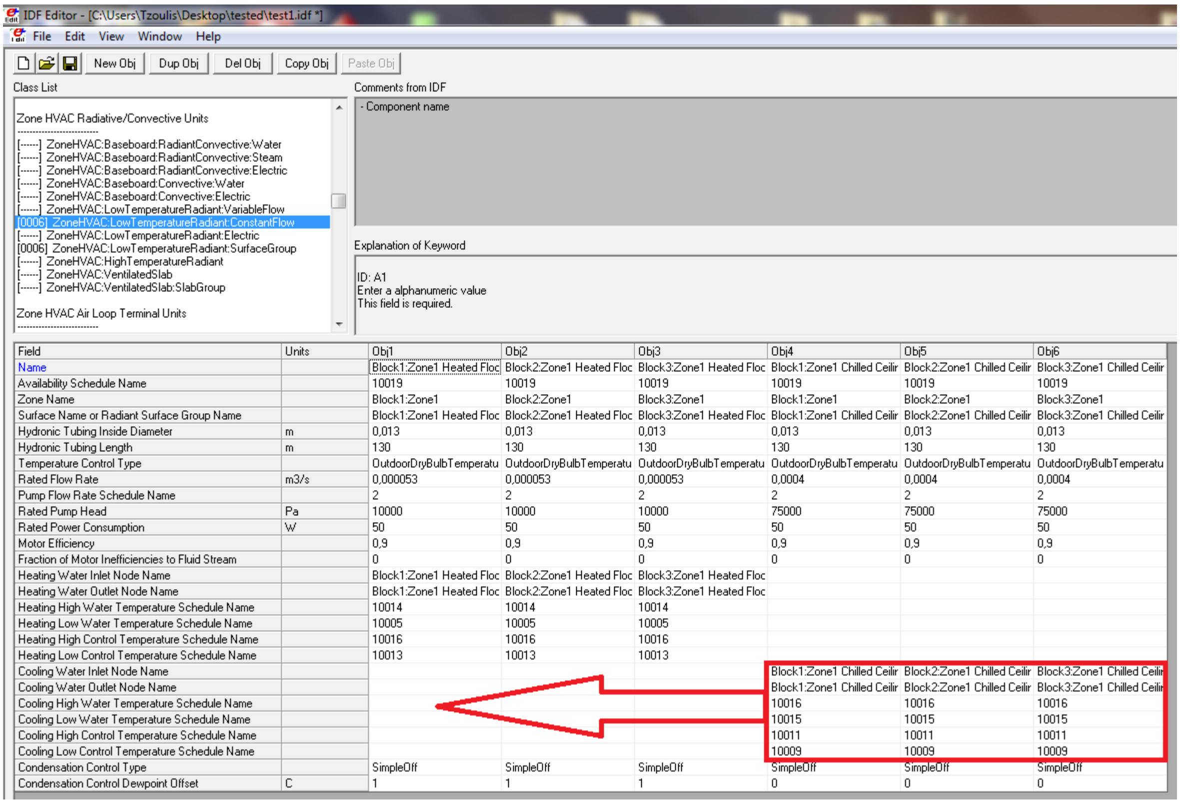


Figure 9-2

2. In **ZoneHVAC Radiative/convective Units** Group → **ZoneHVAC:LowTemperatureRadiant:SurfaceGroup** Object: Delete the 3 last columns (chilled ceilings)

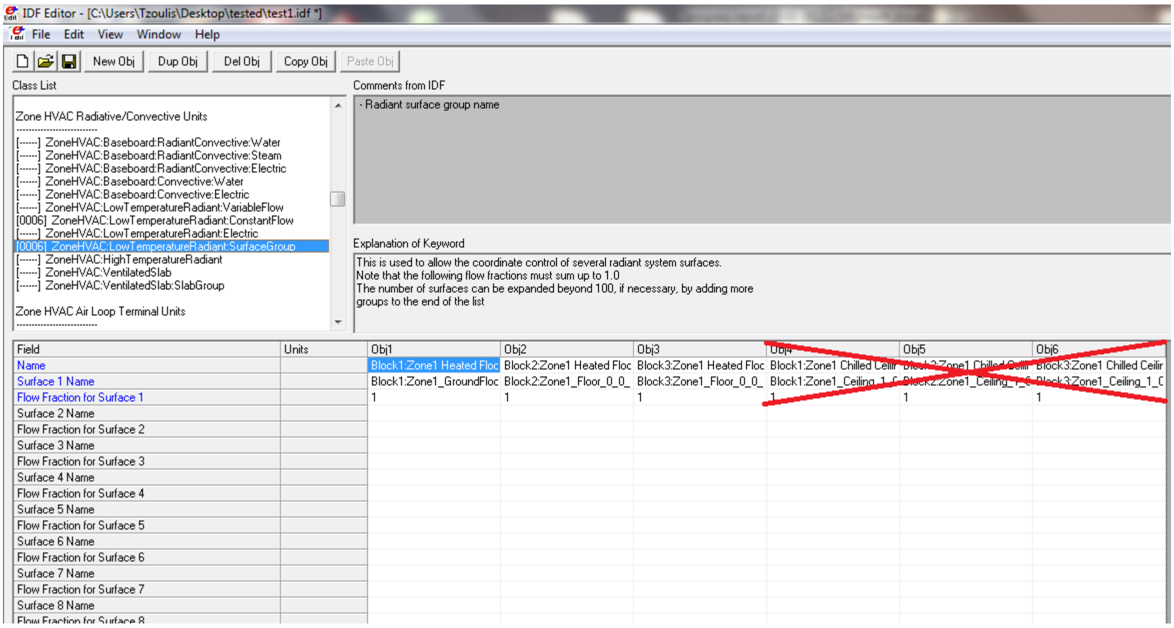


Figure 9-3

3. **Zone HVAC Equipment Connections** Group →
   EquipmentList Object:
   Delete the chilled ceiling and its properties.

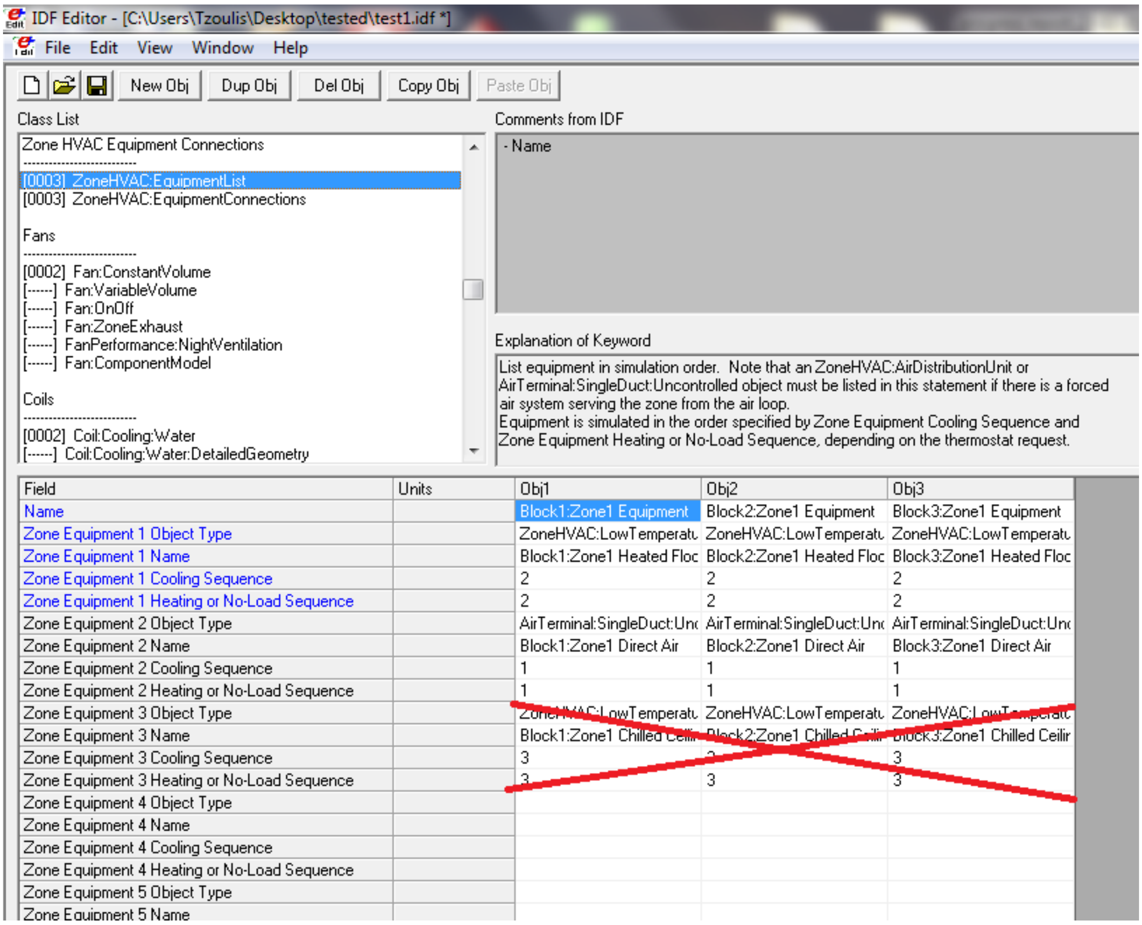


Figure 9-4

4. **Node-Branch Management** Group →
   Branch Object:
   Component 1 name of the **Blockxxx: Chilled ceiling CHW Plant loop branch** should be the same as in the **ZoneHVAC:LowTemperatureRadiant:ConstantFlow** and in **Blockxxx Heated Floor HW Plant loop branch.**

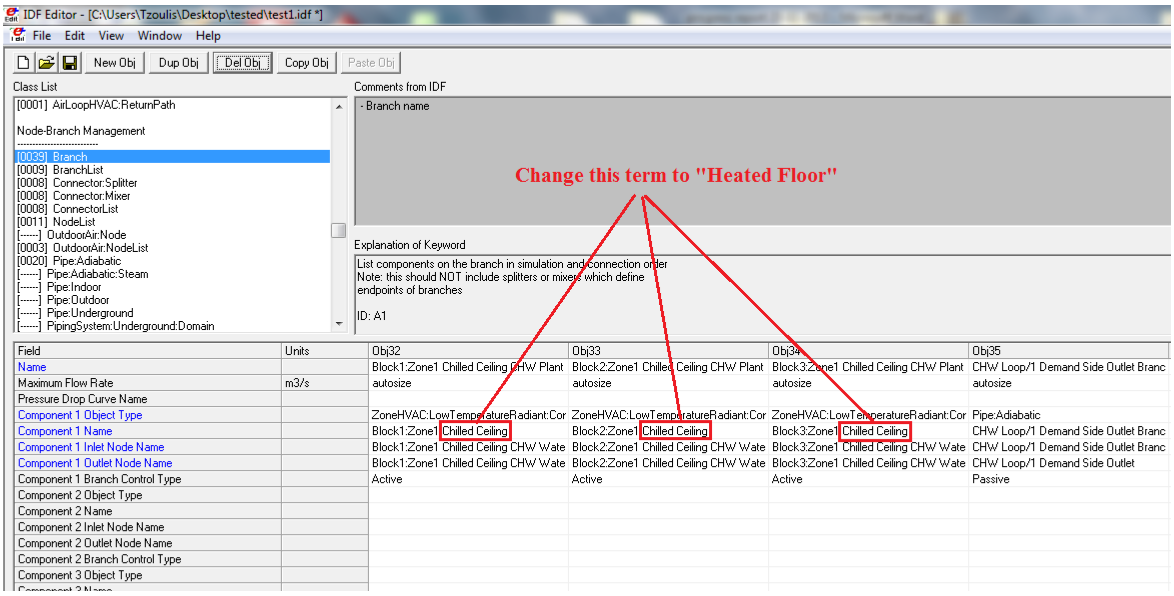


Figure 9-5

These are the main changes that have to be made in order for CCA to work properly.

Bibliography

American Society of Heating, R. and Engineers, A.-C. (2008). *2009 ASHRAE handbook: Fundamentals*. American Society of Heating, Refrigeration and Air-Conditioning Engineers.

Behrendt, B., Raimondo, D., Zhang, Y., Schwarz, S., Christensen, J., and Olesen, B. (2011). *A system for the comparison of tools for the simulation of water-based radiant heating and cooling systems*.

Carslaw, H. and Jaeger, J. (1959). *Conduction of heat in solids*. Oxford science publications. Clarendon Press.

Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., Buhl, W., Huang, Y., Pedersen, C. O., Strand, R. K., Liesen, R. J., Fisher, D. E., Witte, M. J., and Glazer, J. (2001). Energyplus: creating a new-generation building energy simulation program. *Energy and Buildings*, 33(4):319 – 331.

Degiovanni, A. (1988). Conduction dans un mur multicouche avec sources: extension de la notion de quadripole. *International Journal of Heat and Mass Transfer*, 31(3):553 – 557.

ENERGYPLUS (2013). Energyplus engineering reference - the reference to energyplus calculations. Technical report, University of Illinois and the Ernest Orlando Lawrence Berkeley National Laboratory.

Glück, B. (2002). Gesteuerte beladung von thermisch aktivierbaren massivbauteilen. *HLH*, 3:40–45.

Güntensperger, W., Gwerder, M., Haas, A., Lehmann, B., and Renggli, F. (2005). Control of concrete core conditioning systems. *Proceedings of 8th REHVA World Congress for Building Technologies-CLIMA*, 1(October):2 – 9.

Gwerder, M., Lehmann, B., Tödtli, J., Dorer, V., and Renggli, F. (2008). Control of thermally-activated building systems (tabs). *Applied Energy*, 85(7):565 – 581.

Hoogmartens, J. and Sourbron, M. (2011). Wp 6: System operation and controller development - review report of existing control strategies for geo-hp-tabs. Technical report, GEOTABS Project.

Incropera, F. P. and DeWitt, D. P. (2001). *Fundamentals of Heat and Mass Transfer, 5th Edition*. Wiley, 5 edition.

ISO 11855-1 (2012). Building Environment Design - Design, Construction and Operation of Radiant Heating and Cooling Systems - Part 1.

Judkoff, R. and Neymark, J. (1995). Building energy simulation test (bestest) and diagnostic method. Technical report, Internatinal Energy Agency.

Koschenz, M. and Lehmann, B. (2000). *Thermoaktive Bauteilsysteme tabs*. EMPA Dübendorf, Eidgenössische Materialprüfungs- und Forschungsanstalt, Zentrum für Energie und Nachhaltigkeit ZEN.

Olesen, B. (2008). Radiant floor cooling systems. *ASHRAE Journal*, 50(9):16–20.

Olesen, B. W., Sommer, K., and Düchting, B. (2002). Control of Slab Heating and Cooling Systems Studied by Dynamic Computer Simulations. pages 698–707.

Ozel, M. (2013). Determination of optimum insulation thickness based on cooling transmission load for building walls in a hot climate. *Energy Conversion and Management*, 66(0):106 – 114.

Seem, J. (1987). *Modeling of heat transfer in buildings*. PhD thesis.

Smith, J. M., Ness, H. C. V., and Abbott, M. M. (2005). *Introduction To Chemical Engineering Thermodynamics*. McGraw-Hill Chemical Engineering Series. McGraw-Hill, Boston.

Sourbron, M. (2012). *Dynamic thermal behaviour of buildings with concrete core activation*. PhD thesis, KU Leuven.

Sourbron, M., Herdt, R. D., Reet, T. V., Passel, W. V., Baelmans, M., and Helsen, L. (2009). Efficiently produced heat and cold is squandered by inappropriate control strategies: A case study. *Energy and Buildings*, 41(10):1091 – 1098.

Sourbron, M., Khaldi, F., Baelmans, M., and Helsen, L. (2008). Validation of a thermally activated hollow core slab rc-model with measurements and fem simulations.

Zhu, D., Hong, T., Yan, D., and Wang, C. (2012). Comparison of building energy modeling programs: Building loads. Technical report, Tsinghua University, China and Environmental Energy Technologies Division.