Rietkerk, J., Schijndel, A.W.M. van, Hensen, J.L.M. & Ruchti, J.P. (2010).
Evaluation of the Concrete Core Conditioning Performance for Flexible Building Zone Configurations.
Proceedings of the 8th International conference on system simulation in buildings, December, pp. 20, Paper: P102.
Liege: SSB.

Evaluation of the Concrete Core Conditioning Performance for Flexible Building Zone Configurations

Rietkerk[1*], A.W.M. van Schijndel[2], J.L.M. Hensen[2], J.P. Ruchti[1]

(1) Royal Haskoning, Building Services & Structures, P.O. Box 8520, 3009 AM Rotterdam,
The Netherlands

(2) Eindhoven University of Technology, Department of Architecture, Building and Planning,
P.O. Box 513, 5600 MB Eindhoven, The Netherlands

1. ABSTRACT

Today's building design objectives are more and more determined by sustainability, flexibility and the quality of the indoor environment. A potential concept is the application of concrete core conditioning to reduce the energy consumption and increase the thermal comfort. However, the performance of concrete core conditioning in relation to the changing utilization of a building (flexibility) is unknown. This paper gives a developed multi-zone dynamic simulation model of a concrete core conditioning system. This model has been applied for the performance of case studies with large sets of building zone configurations to clarify the consequences of the application of concrete core conditioning for the flexibility of a building with regard to the achievable indoor thermal comfort. It is concluded that the self controllability of concrete core conditioning can accommodate limited flexibility changes without loss of thermal comfort. The combination of concrete core conditioning with an additional local installation component for both heating and cooling makes the concept suitable for flexible building zone configurations. However, the combination of concrete core conditioning and an additional local component should be well-considered, in terms of design and control strategies, in order to achieve the desired energy efficiency.

Keywords: concrete core conditioning, thermally activated building systems, flexibility, modelling, simulation

2. INTRODUCTION

Today's building design objectives are more and more determined by sustainability, flexibility and the quality of the indoor environment. The realization of these design objectives requires the integration of new system concepts within the building design. A potential concept is the application of concrete core conditioning.

Concrete core conditioning (CCC) is a system for the thermal conditioning of buildings and uses water carrying pipes for heating and cooling that are embedded in the centre of the floor/ ceiling construction. It is known as an alternative for conventional installation concepts and emerged as an energy efficient and cost effective system that realizes a good thermal indoor environment (Koschenz et al., 2000). For flexibility the building design should accommodate changes in the work environment in order to fulfil the changing needs of the building user during the complete lifetime of the building. Flexibility, therefore, requires a building design that can be easily modified and serve a variety of purposes for a diverse group of users (WBDG, 2010). Realization of this flexibility requires installation concepts that can be adapted to this changing building use without a decrease of the desired level of indoor thermal comfort. The design of a flexible installation concept requires insight in the parameters that have a direct and indirect relationship between flexibility and indoor thermal comfort. These flexibility parameters are presented in table 1 and formulated by taking into account that flexibility is divided into the categories layout and function. The performance of concrete core conditioning for typical office situations and system parameters has been researched in several studies (Olesen et al. 2004; Lehmann et al. 2006). However, there is no insight between the performance of concrete core conditioning and the changing utilization (flexibility) of a building.

This paper gives a developed multi-zone dynamic simulation model of a concrete core conditioning system and describes the results of the research that has been performed with this model to clarify the consequences of the application of concrete core conditioning for the flexibility of a building with regard to the achievable indoor thermal comfort. According to the methodology of the research the outline of this paper is: section 3 describes the modelling of the concrete core conditioning building simulation model and its verification. Section 4 describes the method used to evaluate the performance of CCC on basis of case studies. In the 5th section the results of the performed simulations are described. Successively, chapter 6 describes the discussion and the paper ends with the conclusions in section 7.

Table 1: Definition of flexibility parameters.

Technical flexibility				
Categories	**Layout**		**Function**	
	geometry of zone orientation of zone		function of zone number of functions within building	
Parameters	**Internal heat gains**	**External heat gains**	**Construction properties**	**Orientation**
	persons lighting equipment	facade insulation glass properties air infiltration	geometry construction mass thermal properties	facade orientation horizontal location in building vertical location in building

3. MODELLING

For performance simulation of CCC a dynamic simulation model has been developed that simulates the heat flow in a building. The considered system that has been modelled into a simulation model is presented in figure 1. This figure shows the complete system that was divided into 4 separate interacting systems: a multi zone building, concrete core conditioning, heat transfer between construction and space and a mechanical ventilation system (HVAC). Therefore, the building simulation model was also divided into 4 separate systems that interact with each other. This is schematically presented in figure 2.

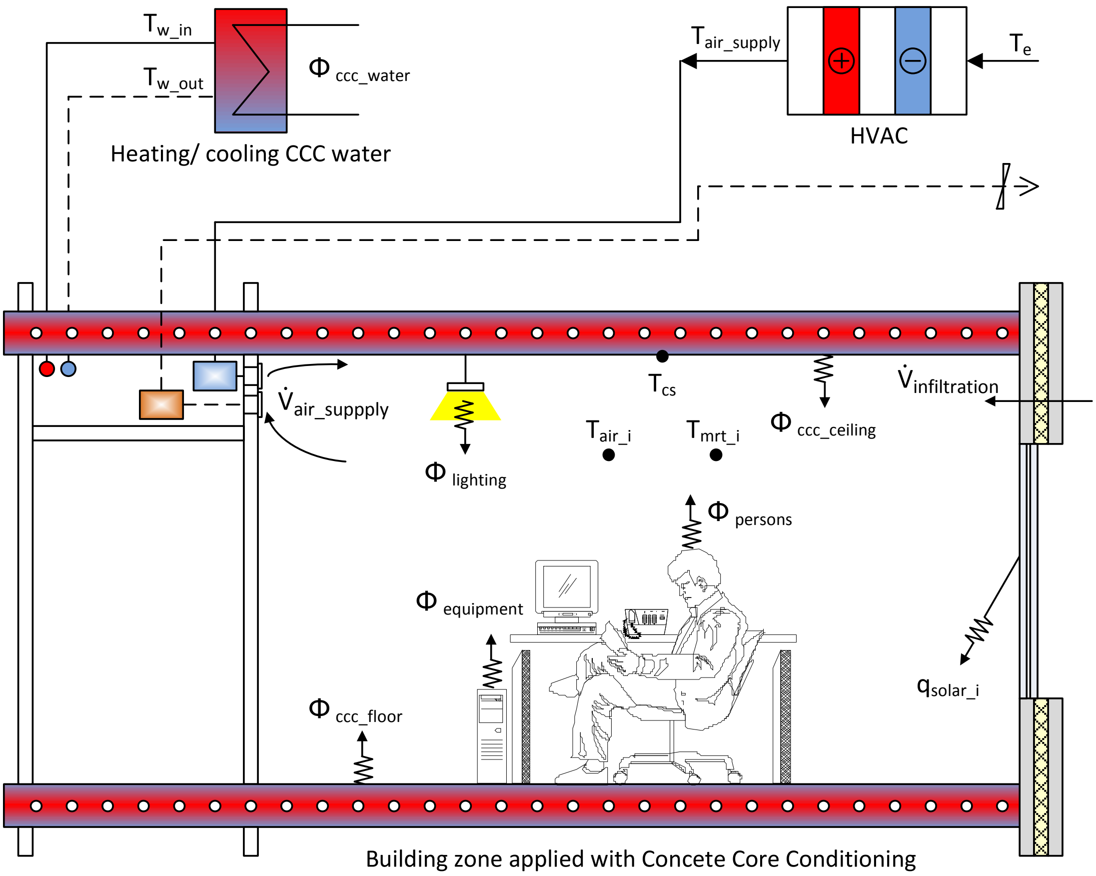


Figure 1: Schematic view of the complete system that has been modelled (see nomenclature for explanation of symbols).

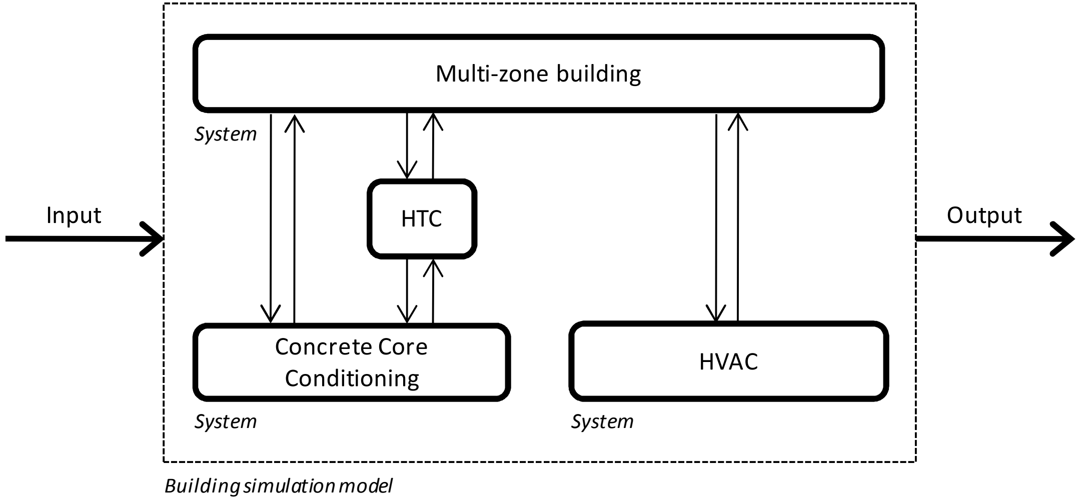


Figure 2: Schematic principle of the CCC building simulation model.

3.1 Modelling the systems

3.1.1 Multi-zone building system

To obtain insight in the performance of CCC for several flexibility scenarios within an entire building the multi-zone building model HAMBase (Schijndel, 2007) was used. This model concerns a validated model for the heat and vapour flows in a building and is used to simulate the indoor temperatures, the relative humidity and the energy use for heating and cooling for one or more zones. For this research only the heat flow within the building was taken into account. Furthermore, the in- and output structure of HAMBase (figure 3) was modified to make the integration of the CCC system model possible.

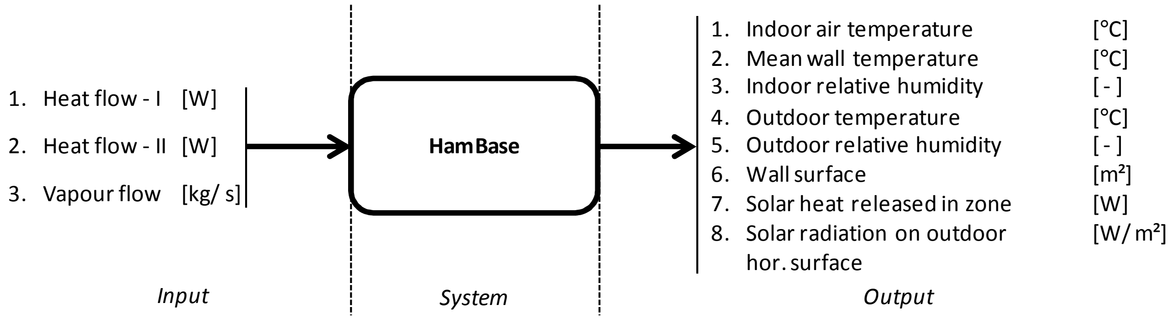


Figure 3: In- and output structure for every zone of the multi-zone building system.

3.1.2 Concrete core conditioning system

Heat transfer processes occur between different temperature levels (figure 4). For constructions applied with CCC these heat transfer processes can be divided into 3 groups:

- Conduction : between the embedded piping system and the construction and between the several construction layers;
- Convection : between the construction and the surrounding air;
- Radiation : between the construction and the surrounding building construction.

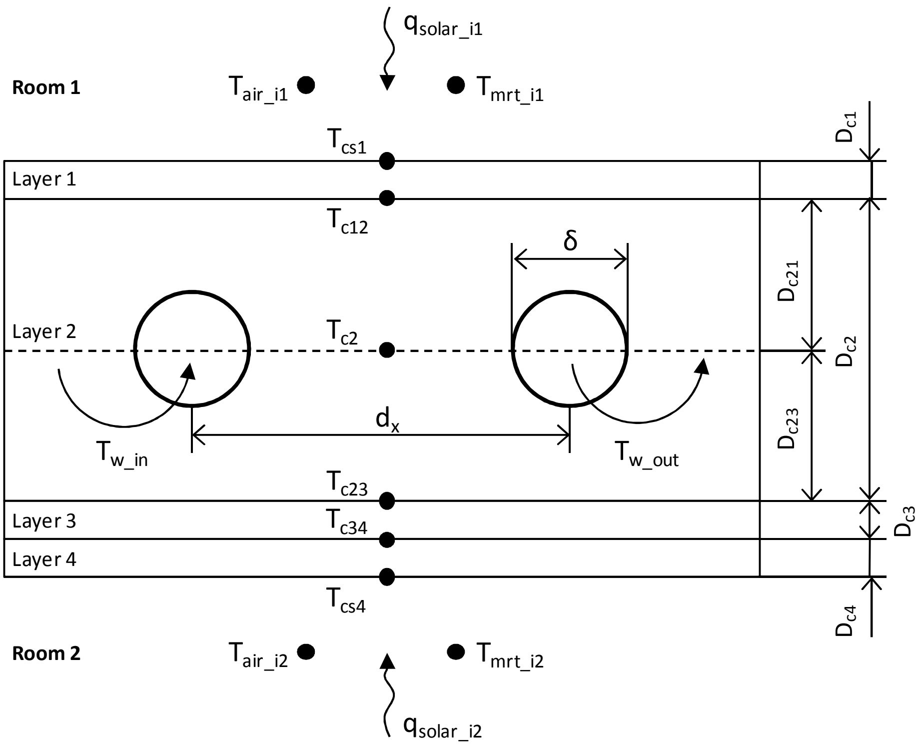


Figure 4: Schematic view of concrete core conditioning in an intermediate floor.

The heat transfer processes can be represented with a thermal RC-network. This network consists of thermal resistances (R) for the representation of conduction, convection and radiation and of capacitors (C) for the representation of the thermal heat storage. Taking into account that CCC can also be applied in ground floors or roofs resulted in the network as presented in figure 5. An important parameter of this network is the thermal resistance R_x. This resistance allows, under certain restrictions, to represent the 3-dimensional heat transfer in the construction by a 1 dimensional heat transfer process with the following relationship (Koschenz et al., 2000):

$$R_x = \frac{d_x \cdot ln\left(\frac{d_x}{\pi \cdot \delta}\right)}{2 \cdot \pi \cdot \lambda_b \cdot A} \quad \text{and counts if} \quad \begin{cases} \frac{D_{c21/23}}{d_x} > 0{,}3 \\ \frac{\delta}{d_x} < 0{,}2 \end{cases} \qquad [1]$$

The mathematical model of the CCC construction is represented by a set of ordinary differential equations (ODE) for each of the possible floor types (roof, intermediate or ground floor). These ODE's are based on the RC-network. An example of these ODE's is presented below for the temperature nodes T_{c1} and T_{c4} in case of an intermediate floor.

$$C_1 \cdot \frac{dT_{c1}}{dt} = \frac{T_{c12} - T_{c1}}{R_1} + q_{solar\_i1} - \frac{T_{c1} - T_{mrt\_i1}}{R_{rad\_fl\_i1}} - \frac{T_{c1} - T_{air\_i1}}{R_{cv\_fl\_i1}} \qquad [2]$$

$$C_4 \cdot \frac{dT_{c4}}{dt} = \frac{T_{c34} - T_{c4}}{R_4} + q_{solar\_i2} - \frac{T_{c4} - T_{mrt\_i2}}{R_{rad\_ce\_i2}} - \frac{T_{c4} - T_{air\_i2}}{R_{cv\_ce\_i2}} \qquad [3]$$

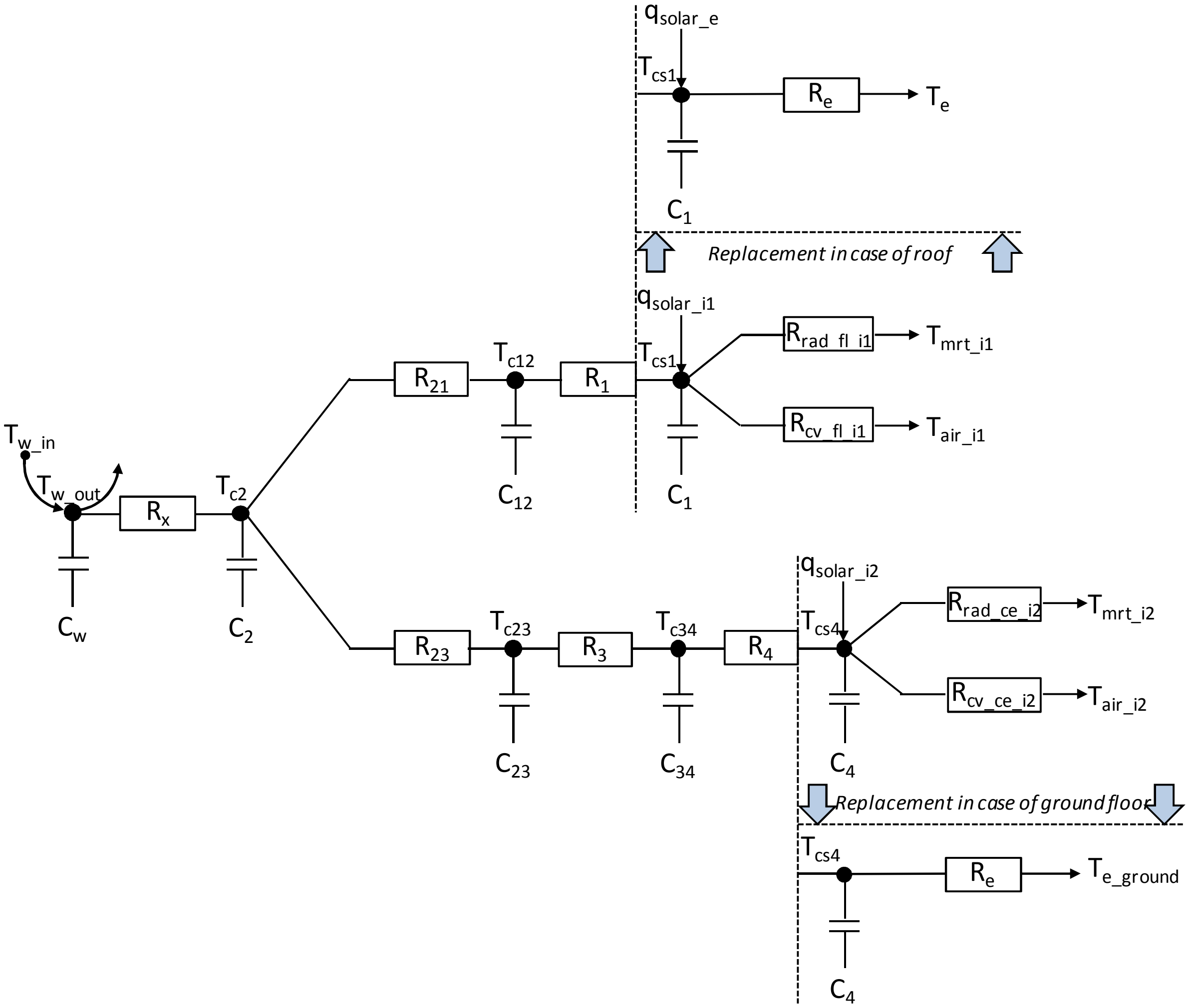


Figure 5: RC-network of concrete core conditioning system: 3 possible structures. In case of a roof the part from temperature node T_1 has to be replaced. In case of a ground floor the part from temperature node T_4 has to be replaced.

The mathematical model of the CCC construction was implemented in Simulink with the use of an S-function that contains the ODE's for a CCC construction of a roof, intermediate and ground floor. Additional equations were implemented in this S-function to realize an in- and output structure that fits with the in- and output structure of the other systems. These equations were implemented to calculate: the zone's mean radiant temperature and the heating/ cooling power of the CCC construction. Furthermore, the Heat Transfer Coefficients (HTC's) were defined as an input, because these coefficients are calculated in another system (see section 3.1.3). This resulted in the in- and output structure of the model as presented in figure 6.

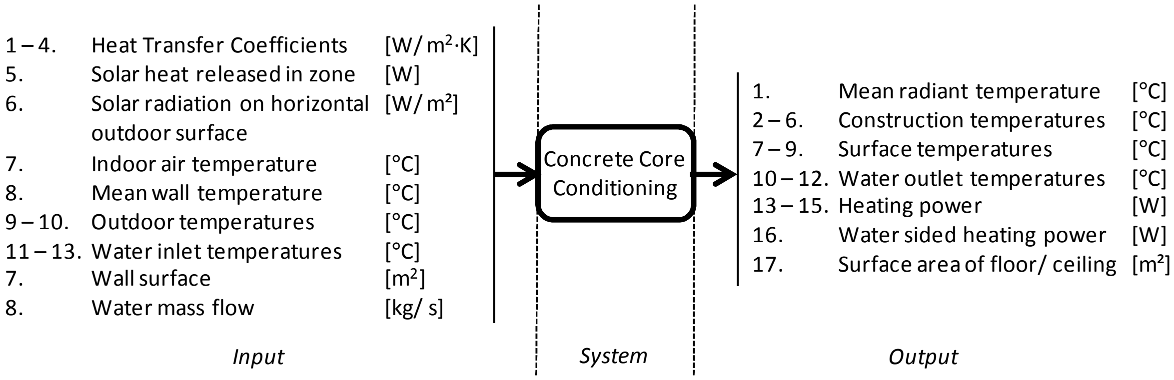


Figure 6: In- and output structure of the concrete core conditioning system.

3.1.3 System for heat transfer coefficients

The heat transfer between a construction surface and a space depends on the size of the temperature difference between the construction and space, but also on the size of the heat transfer coefficient (HTC). The HTC consists of 2 components: (I) a radiant component that represents the heat transfer between the construction surface and the surrounding bodies and (II) a convective component that represents the heat transfer between the construction surface and the air (figure 7). These components are represented by the following equations:

- The radiant HTC is found from (Bruggema, 2007):

$$h_{rad} = 4 \cdot \varepsilon_1 \cdot \varepsilon_2 \cdot \sigma \cdot {T_{mrt}}^3 \qquad [4]$$

- The convective HTC is found from (Recknagel et al., 2005):

Downward convection

$$h_{cv} = 0{,}54 \cdot \Delta T^{0{,}31} \qquad [5]$$

Upward convection

$$h_{cv} = 2 \cdot \Delta T^{0{,}31} \qquad [6]$$

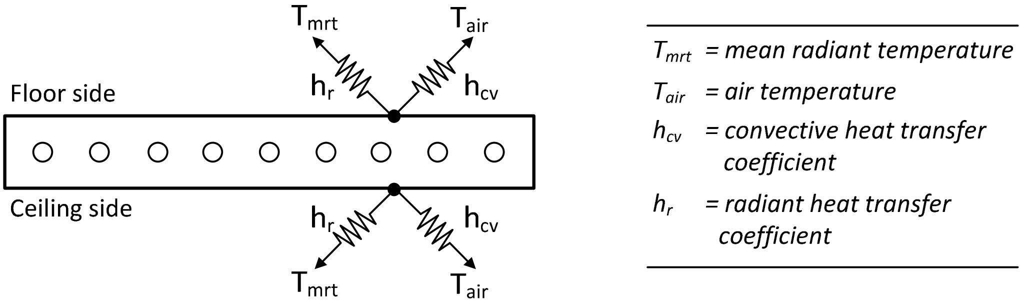


Figure 7: Heat Transfer Coefficients consist of a convective and radiant part.

These equations describe the relationship of the radiant HTC with the mean radiant temperature (T_{mrt}) and the relationship of the convective HTC with the temperature difference between the construction surface and the room air temperature (ΔT). These relationships were implemented in Simulink and led to the in- and output structure of figure 8.

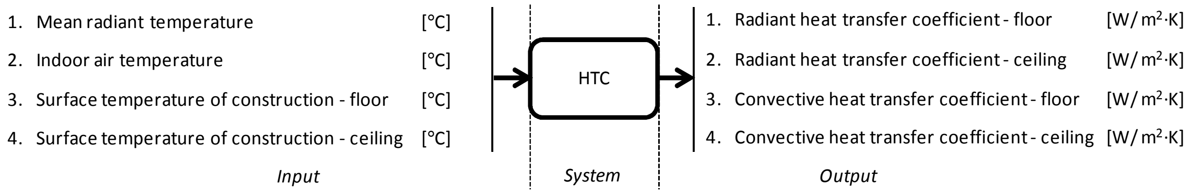


Figure 8: In- and output structure of HTC-system.

3.1.4 Heating, Ventilation and Air Conditioning system

The in- and output structure of the HVAC system which is implemented in Simulink is presented in figure 9. This model contains a heating and cooling coil that represent the heat exchange processes that can take place in the HVAC system:

- The outdoor air heated by the heating coil undergoes a temperature rise. This temperature rise is not accompanied with a change of the absolute humidity;
- If the outdoor air is cooled by the cooling coil the temperature of the air will decrease. This decrease can be accompanied with condensation of the air if the mean surface temperature of the cooling coil is lower than the dew point temperature of the outdoor air.

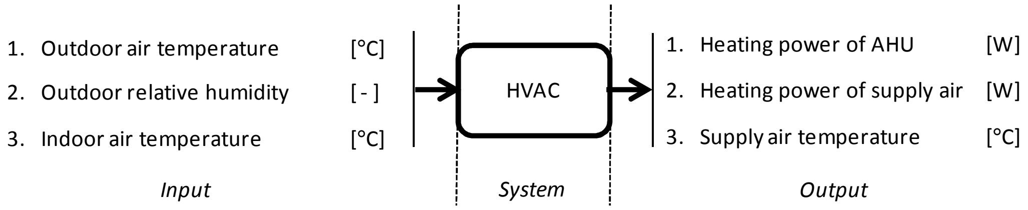


Figure 9: In- and output structure of the HVAC system.

The mathematical model of the heating and cooling coil was based on the representation as presented in figure 10 and the following simplifications:

- The effectiveness of the heat exchange between the water system and the air flowing through the coil is not taken into account;
- The water inlet and outlet temperatures of the coils aren't an input or output respectively of the mathematic model.

The simplifications imply that the mathematic model of the HVAC-system only calculates the energy needed to heat or cool the outdoor air to the desired supply air temperature (T_{air_supply}). For the heating coil this concerns the required sensible heat to increase the temperature of the outdoor air and for the cooling it concerns the sum of the required latent and sensible heat. Hereby, the latent heat is calculated on basis of the difference between the absolute humidity of the outdoor and supply air.

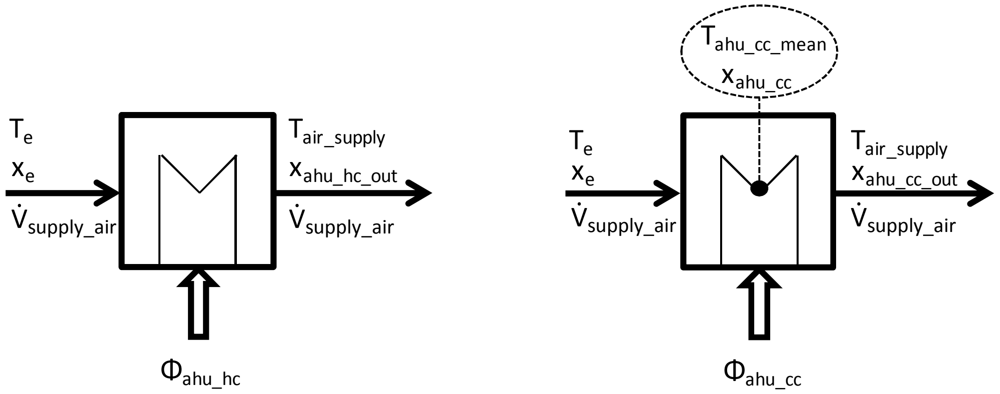


Figure 10: Schematic representation of heating coil (left) and cooling coil (right).

3.1.5 The complete building model with CCC and HVAC

All models were implemented and connected within Simulink and resulted in the CCC building simulation model as presented in figure 11. Within this figure the systems can be distinguished as described in the preceding sections. Furthermore, this model includes:

- Data output
  This part concerns the tools that are available to save and visualize the simulation results.
- Occupancy profile
  This system is used to define the time that the building occupants are inside the zones.

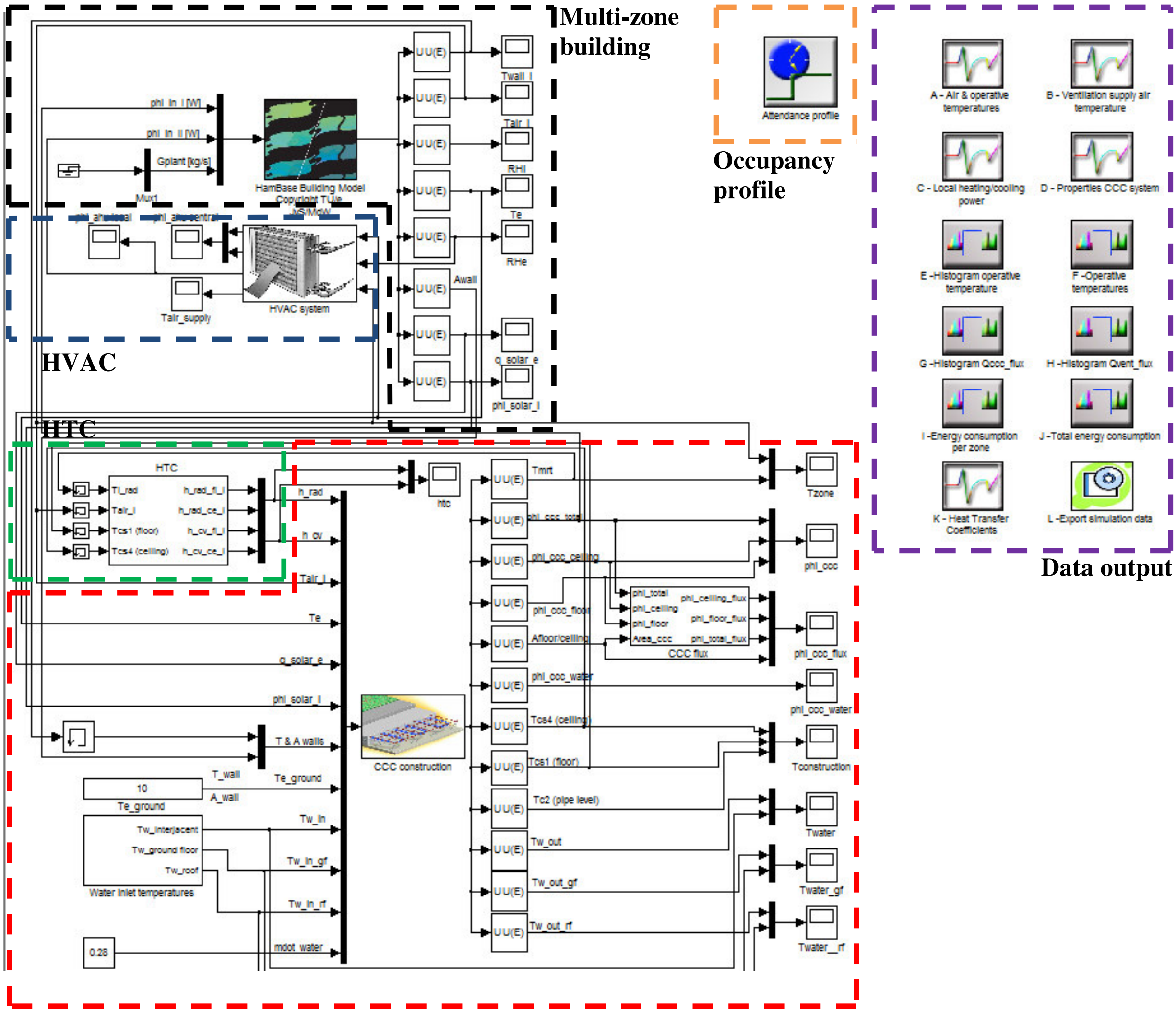


Figure 11: CCC building simulation model in Simulink.

3.2 Verification of the models

The separate systems of the complete building simulation model were verified analytically using energy and mass balances. This concerned a static verification where fixed input values were used to compare the models' results against the results of handmade calculations that were performed with the mathematical models of the specific system.

For the concrete core conditioning system the handmade calculations were performed with the relationships based on the RC-network of the model. The results of these calculations were compared against the output of the simulation model. The verification of the HTC and HVAC system were performed in a similar way, but instead the relationships of the mathematical model were used to perform the handmade calculations. On basis of the results of these verifications it was concluded that for steady-state conditions each of the system simulation models functioned correctly.

The verification of the complete simulation model is practically impossible, due to the large and complex amount of data needed. These data not only includes data from the system (e.g. water, surface and air temperatures), but also data about the exact use of the building during the complete measurement period, because this has a direct influence on the performance of CCC. Therefore, the complete model was verified on basis of a comparison with a reference model, instead of a validation on basis of too time consuming measurements.

The CCC building simulation model was verified on basis of the principle that a free floating simulation with this model should have the same results as a free floating simulation performed with the validated HAMBase model. This free floating simulation was performed for the reference situation of the simulation scenarios (see section 4), but in difference the mass flow of the CCC system was set to 0 kg/s and the supply air volume of the AHU to 0 m^3/ h. This cancelled out the influence of these components to the thermal conditioning of the zone, so the result of the comparison gives insight in the correctness of the implementation of the CCC system within HAMBase. The result of this comparison is presented in table 2. This table shows that for the reference situation the difference between the free floating HAMBase model and free floating CCC building simulation model is small with a maximum of 0.3% for comfort category B (see explanation in section 4.1.3). On basis of this small difference you may conclude that the CCC system was implemented correctly within HAMBase for the realization of the CCC building simulation model.

Table 2: Verification results of CCC building simulation model.

Comfort category	**Results of free floating model**		
	HAMBase	CCC building simulation model	
	satisfaction [%]	satisfaction [%]	difference with HAMBase [%]
A	3.2	3.2	+0.0
B	7.6	7.3	-0.3
C	10.4	10.2	-0.2

4. PERFORMANCE SIMULATIONS: CASE STUDIES

The evaluation of the behaviour of concrete core conditioning in relation to a flexible building concept was focused on gaining insight in the influence of utilization and building parameters on the performance of CCC. This evaluation was done by performing multiple simulation scenarios and analyzing the simulation results on basis of three different performance indicators and a sensitivity analysis. The following steps describe the evaluation process:

1. Definition of simulation scenarios
   For different building zone configurations simulations with the CCC building simulation model were performed. The simulation scenarios describe each of the simulated building zone configurations, including the accompanying input parameter values. These scenarios were formulated on basis of a case study.
2. Performing the simulation scenarios
   On basis of the simulation scenarios a reference situation was selected which describes the reference value of each of the input parameters. On basis of this reference situation the simulations for each of the scenarios were performed.
3. Result analysis
   The behaviour of concrete core conditioning has been evaluated on basis of the performance indicators thermal comfort, thermal power and energy consumption.
   To distinguish the influential from the less influential input parameters a Differential Sensitivity Analysis (Macdonald, 2002) was performed that evaluated the sensitivity of the simulation results for changes in individual input parameters.

4.1 Case study

The case study was, based on the definition of a flexible building concept, formulated as: “A multi-zone building applied with concrete core conditioning that can be adapted to accommodate changes of the working environment so that the function, geometry and orientation of the zones within the building can be changed over time."

More specific, the case study's building concerned a multi-storey building that could be adapted freely to every possible layout (figure 12), function and orientation of zones. To condition the zones the building was applied with concrete core conditioning for heating and cooling and an air handling unit (AHU) for the mechanical supply of fresh air. For both the CCC and the AHU counted that their control strategy was not related with the indoor temperature. Therefore, the climate system could be extended optionally with a local convector to maintain the indoor temperature between specified ranges actively. The flexibility of the case study's building resulted in multiple possible values for each of the building and utilization parameters. These parameters, which are all related to flexibility, were categorized into 3 different input parameter categories. This overview is presented in table 3 and shows all input parameters of the CCC simulation model that are related to flexibility and the values that each of these parameters could have.

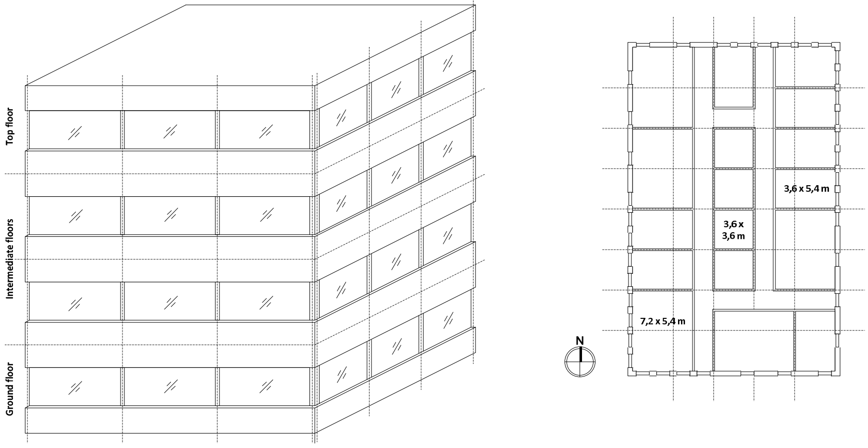


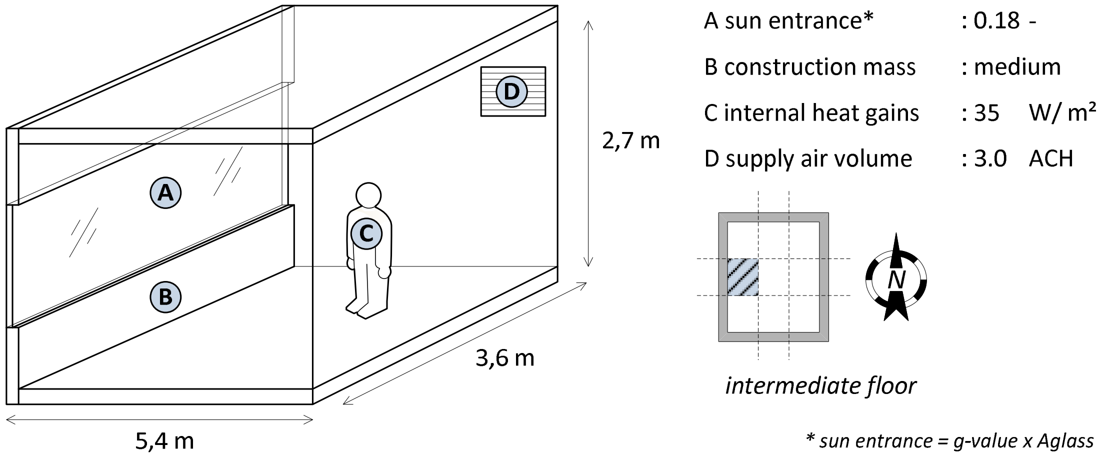
Figure 12: Schematic representation of the case study's building: a multi-storey building with freely adaptable floors.

Table 3: Overview of input parameter values. The table shows for every input parameter several possible values, e.g.: the construction mass of the building can have 3 different values: low, medium and high.

Category	**Input parameter**	**Unit**	**Possible values**						
			I	**II**	**III**	**IV**	**V**	**VI**	**VII**
building	orientation								
	orientation of facade	-	North	East	South	West			
	location within building – horizontal	-	corner	intermediate	internal				
	location within building – vertical	-	ground	intermediate	top				
	geometry of room		*small*	*medium*	*large*				
	depth	m	3.6	5.4	5.4				
	width	m	3.6	3.6	7.2				
	height	m	2.7	2.7	2.7				
	sun entrance	-	6	9	15	18	30	60	
building & system CCC	construction mass		*low*	*medium*	*high*				
	roof	kg/ m^2	150	325	500				
	floor/ ceiling	kg/ m^2	350	475	600				
	ground floor	kg/ m^2	350	475	600				
	external wall	kg/ m^2	150	400	650				
	internal wall	kg/ m^2	35	150	350				
	internal heat gains	W/ m^2	0	20	25	35	45	60	75
system - AHU	supply air volume	ACH	1	2	3	4	5	6	

4.1.1 Simulation scenarios

A simulation scenario concerns a series of simulations that are performed for multiple values of one specific input parameter. The number of simulations to be performed for a specific scenario depends on the number of values that can be used as replacement for the reference value of the input parameter. The defined simulation scenarios are presented in table 4. The reference situation contains all reference values of the input parameters. These reference values were selected from the possible values as presented in table 3 and are visualised in figure 13.



** sun entrance = g-value x Aglass*

Figure 13: Reference value of input parameters.

Table 4: Overview of simulation scenarios including the reference value of each input parameter

Scenario	Variable input parameter	Replacement values	Reference value
scenario 1	orientation of facade	North, East, South	West
scenario 2	location within building - horizontal	corner, internal	intermediate
scenario 3	location within building - vertical	ground, top	intermediate
scenario 4	geometry of room	small, large	medium
scenario 5	sun entrance	6, 9, 15, 30, 60	18
scenario 6	construction mass	low, high	medium
scenario 7	internal heat gains	0, 20, 25, 45, 60, 75	35
scenario 8	supply air volume	1, 2, 4, 5, 6	3

4.1.2 Boundary conditions

The boundary conditions are the parameters that had a fixed value during all performed simulations. The following boundary conditions are specifically mentioned:

- Reference year
  All simulations were performed for a complete year. The selected year concerns the period from 1 May 1974 till 1 May 1975 (The Netherlands). This year is characterized as a year with an average climate, so without extreme hot and cold periods.
- Control strategy for water inlet temperature of concrete core conditioning
  The water inlet temperature is not related to the indoor temperature and has a fixed value. As a result, the temperature in the zone completely depends on the self controllability of the concrete core conditioning system. For the supply temperature a fixed value of 23.5°C has been selected as an average value of the discussed constant control strategies by Olesen (2004).
- Control strategy for the supply air temperature
  The simulations are performed to gain insight in the behaviour of concrete core conditioning. Therefore, it was decided to use a control strategy that minimizes the influence of the supply air on the thermal conditioning of the zone. This resulted in a strategy that is not related to the indoor temperature, but only with the outdoor temperature as presented in figure 14.

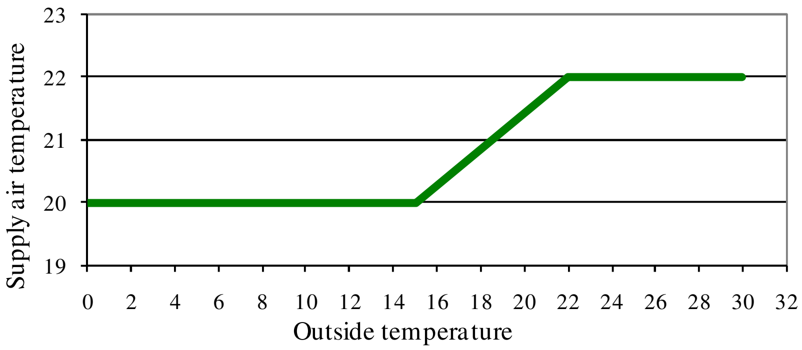


Figure 14: Control strategy of supply air temperature.

4.1.3 Performance indicators

The simulation results were evaluated for the performance indicators thermal comfort, thermal power and energy consumption.

Thermal comfort

The thermal comfort was evaluated by calculating the percentage of occupied hours that the operative temperature satisfied the ranges as presented in figure 15. These ranges define the operative temperature as function of the outdoor temperature for 3 different ranges which are the equivalents of the PMV categories A, B and C of the ISO 7730 (ISO 7730, 2005). The relationship of these ranges with the outdoor temperature was calculated on basis of a) the found relationship for people's clothing behaviour by De Carli et al. (2007) and b) a relative humidity of 40%, 50% and 60% used for winter, mid season and summer, respectively.

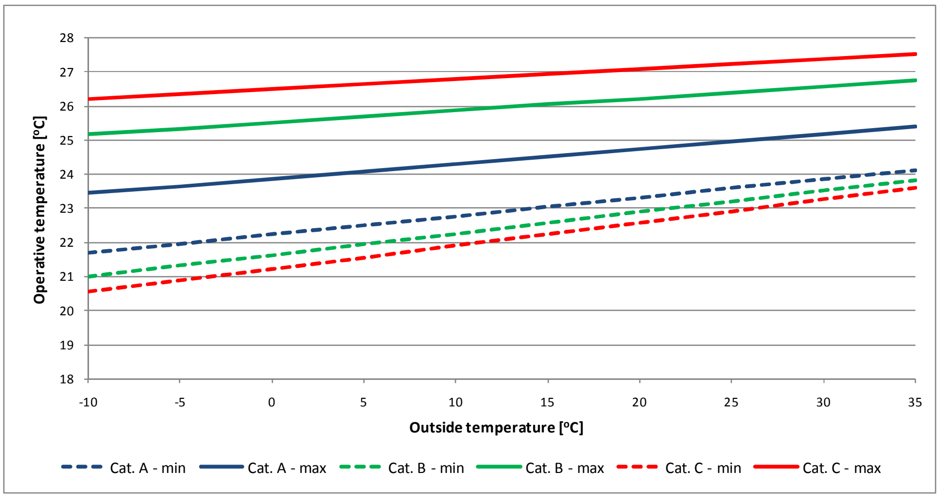


Figure 15: Operative temperature ranges used for the evaluation of the thermal comfort.

Thermal power

Within the building simulation model the zones are conditioned with concrete core conditioning and supply air from the Air Handling Unit. To gain insight in the contribution of each of these systems in the thermal conditioning of the zone, the thermal power of both systems was evaluated. The thermal power concerns the power that both systems contribute to the zone locally. This local thermal power was for both systems evaluated during occupied hours on basis of 3 characteristics:

- Maximum thermal power [W/ m^2]
- Minimum thermal power [W/ m^2]
- Mean thermal power [W/ m^2]

Energy consumption

The total energy consumption was determined by the energy consumption of the concrete core conditioning system and the Air Handling Unit. The energy consumption of both systems was evaluated in order to gain insight in the contribution of each of these systems in the total energy consumption. The energy consumption concerns the total amount of heating and cooling energy removed from the zone by each of the systems during the time that they are in operation:

- Concrete core conditioning:
  Heat or cool the water outlet temperature to the required water inlet temperature;

- Air Handling unit
  Heat or cool the outdoor air to the required supply air temperature.

5. PERFORMANCE SIMULATIONS: RESULTS

The CCC building simulation model has been applied to perform the simulations for each of the scenarios. The simulations have been performed for the case that the indoor temperature is not controlled actively, but completely depends on the self controllability of concrete core conditioning. These results, therefore, give insight in the sole use of concrete core conditioning for the chosen boundary conditions and the variable input parameters of the simulation scenarios.

The simulation results have all been evaluated in a similar way for each of the performance indicators. These results have also been used to perform a sensitivity analysis. The outcome of the sensitive analysis is presented in figure 16 and shows that the thermal comfort is most sensitive for changes of the following 3 parameters: 1) horizontal location, 2) internal heat gains and 3) geometry. Most sensitive is the thermal comfort for changes in the horizontal location of a zone and changes of its parameter value in relation to its reference value can result in a decrease of the thermal comfort with 45% or an increase with 59%. This result can be ascribed to the doubling of the glass façade for the zones along a corner in relation to the reference zone that is not projected along a corner.

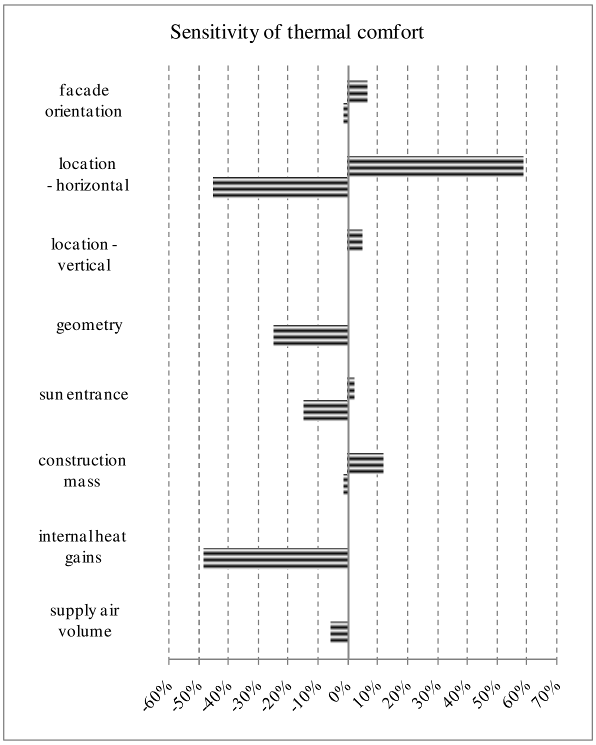


Figure 16: Sensitivity results for thermal comfort.

From the simulation results of each of the scenarios it was found that for neither the simulation scenarios the thermal comfort satisfied one of the comfort categories A, B or C during the complete occupation time. As discussed in section 6 this result requires additional research to gain insight in the effect of the boundary conditions on the performance of concrete core conditioning. For this research, however, it was decided to perform an additional simulation for the same boundary conditions and reference values of each of the variable input parameters, but with the use of an additional installation component. In this situation concrete core conditioning operates in combination with an additional convector unit that controls the indoor temperature actively to maintain a thermal comfort that satisfies category B.

5.1 Overall results

The thermal comfort is sensitive for all flexibility changes and, therefore, parameter values can be distinguished that result in the best achievable thermal comfort. These values are presented in table 5. From this table can also be seen that the influence of the flexibility parameters on the indoor thermal comfort is ranked from most to least influential. For this ranking counts in relation to the reference situation:

- The thermal comfort is most sensitive for changes in the parameters horizontal location, geometry and internal heat gains. Changes of these parameters can result in a decrease of 49% to an increase of 59% of the thermal comfort in relation to the reference situation;
- The sensitivity for the parameters façade orientation, vertical location and supply air volume is less than 10%.

Changes in flexibility parameter values have a direct influence on the thermal heating and cooling power of concrete core conditioning. Figure 17 presents the mean and maximum values that can be achieved:

- The cooling power has a mean value between 12 to 38 W/ m^2 and a maximum value of 213 W/ m^2;
- The heating power has a mean value of 4 – 29 W/ m^2 and a maximum possible value of 66 W/ m^2.

Table 5: Overview of potential best values for each of the flexibility parameters with regard to the best achievable indoor thermal comfort. The flexibility parameters are ranked from most to least influential parameter.

Ranking	**Flexibility parameter**	**Best option (potentially)** with regard to thermal comfort
1	location – horizontal	internal
2	internal heat gains	35 W/ m^2
3	geometry	medium, large
4	sun entrance	15 – 30
5	construction mass	high
6	facade orientation	North
7	supply air volume	2 ACH – 4 ACH
8	location – vertical	top floor

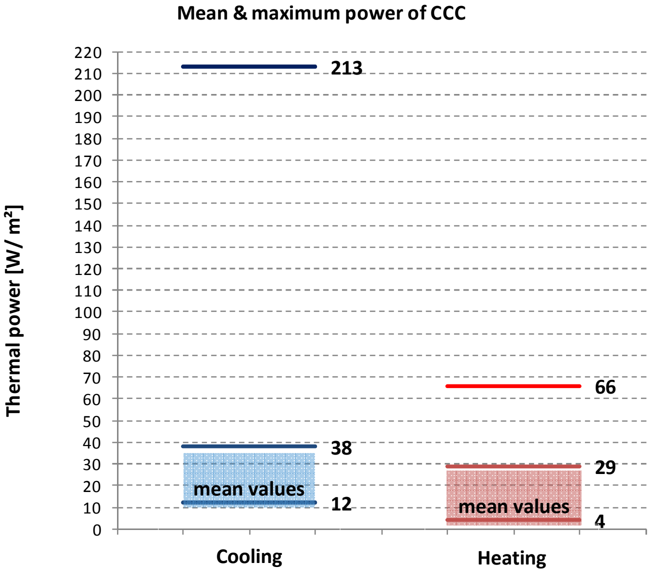


Figure 17: Bandwidth of thermal power of CCC in case of changing flexibility parameters.

The energy consumption is mostly influenced by the location of a zone within a building. In relation to the reference situation it results in an increase of 44% for zones along a corner, while the location on the ground or top floor result in a decrease of 30-35% in relation to the reference situation. On the other hand the influence of changes in façade orientation and internal gains result in relatively small differences with a bandwidth -4% to 8%. The ranking of the influence of flexibility parameter changes on the energy consumption is presented in table 6. An additional convector unit was applied to realize an indoor thermal comfort that satisfied category B and resulted in an increase of the energy consumption with 32%. Furthermore, it was found that the sole use of the convector unit, so without the use of CCC, resulted in increase of the energy consumption with 13% in relation to the reference situation. This means that the current boundary conditions result in a situation in which CCC is not supported very well by the additional convector unit in terms of energy consumption. It can be concluded that the boundary conditions should be redefined to make a better combination of the control strategies between CCC and a local unit possible.

Table 6: Ranking of influence of flexibility parameters on energy consumption. The flexibility parameters are ranked from most to least influential parameter.

Ranking	Thermal power CCC
1	supply air volume
2	location – horizontal
3	location – vertical
4	sun entrance
5	geometry
6	construction mass
7	internal heat gains
8	facade orientation

6. DISCUSSION

The approach of this research resulted in the development of new, literature based, models that were implemented in Matlab/ Simulink and coupled to the validated HAMBase model.

All these models are public domain. However, the integration of these models into 1 CCC building simulation model hasn't been validated, because of the absence of appropriate measurements. The application of this building simulation model is very time consuming and, therefore, it was decided to apply the model only for the specified simulation scenarios and their accompanying boundary conditions. To improve the approach of this research it is recommended to:

- Perform a validation of the complete CCC building simulation model. However, it should be mentioned that measurements of a CCC system could be very complex, because the measured data is only relevant if data about the building use during the complete simulation period is available too;
- Calculate the sensitivity of the performance of CCC for multiple changes in flexibility parameters, so the complete bandwidth of the CCC performance becomes clear;
- Experiment with the influence of the boundary conditions on the performance of CCC in order to evaluate which control strategies and/ or remaining parameters would result in the best performance of CCC.

7. CONCLUSION

The self controllability of CCC is not capable to realize a constant quality of the indoor thermal environment for changing flexibility demands. As a result, there are optimal parameter values which result in the best achievable thermal comfort, but variations of these values will decrease the thermal comfort. To what extent this thermal comfort decreases depends on the type of parameter. This makes CCC an application that can accommodate limited changes of the working environment without loss of thermal comfort.

If CCC is combined with an additional installation component it is possible, obviously, to realize the desired indoor thermal comfort. This result in an increase of the energy consumption, but ensures that under all circumstances, the thermal comfort satisfies the desired conditions. Therefore, the use of an additional installation component makes the CCC suitable for flexible building concepts.

Therefore, concrete core conditioning can be used in flexible building concepts, but it requires the application of additional installation components for the supply of additional cooling and heating power. The combination of concrete core conditioning and an additional installation component result in a climate system that is suitable to accommodate changes in the working environment without loss of thermal comfort. To make this system energy efficient in relation to conventional installation concepts this concept should be well-considered, in terms of design and control strategies, in order to achieve the desired energy efficiency.

NOMENCLATURE

Symbol	*Description*	*Unit*
δ	outside pipe diameter	m
ε_1	emissivity of construction surface	-
ε_2	emissivity of surrounding construction surfaces	-
σ	Stefan-Boltzmann constant (= $5.67 \cdot 10^{-8}$)	$W/ m^2 \cdot K^4$
A	surface area of construction	m^2
d_x	pipe spacing	m
C	thermal capacitance	J/ K
D_c	layer thickness	m
HTC	Heat Transfer Coefficient	$W/ m^2 \cdot K$

q_{solar_i}	solar heat released in zone	W/ m^2
R	thermal resistance	K
R_{cv}	convective heat transfer resistance	K/ W
R_{rad}	radiant heat transfer resistance	K/ W
R_x	thermal resistance between pipe and centre construction layer	K/ W
t	time	s
T_{air}	air temperature	
T_c	construction temperature	°C
T_{cs}	surface temperature of construction of layer	°C
T_e	outdoor temperature	°C
T_{e_ground}	outdoor temperature at ground side	°C
T_{mrt}	mean radiant temperature (unit K in case of calculation of radiant heat transfer coefficient)	°C (or K)
T_{w_in}	water inlet temperature	°C
T_{w_out}	water outlet temperature	°C

Indices	*Description*
i	indoor condition
ce	ceiling side of construction
fl	floor side of construction
1 – 2	number of room or construction layer
3 – 4	number of construction layer

REFERENCES

Bruggema, H.M., 2007. *Betonkernactivering, klimaatplafonds, wand- en vloerverwarming*. TVVL Magazine March 2007, pages 20-28.

De Carli, M., Olesen, Bjarne W., Zarrella, A., Zecchin, R., 2007. *People's clothing behaviour according to external weather and indoor environment*. Building and Environment, pages 3965-3973.

ISO 7730 – Ergonomics of the thermal environment, 2005. International Organization for Standardization.

Koschenz, M., Lehmann, B., 2000. *Thermoaktive Bauteilsysteme tabs*. EMPA, Dübendorf, Switzerland.

Lehmann, B., Dorer, V., Koschenz, M., 2006. *Application range of thermally activated building systems tabs*. Energy and buildings 39, pages 593-598.

Macdonald, I.A., 2002. *Quantifying the effects of uncertainty in building simulation*. University of Strathclyde, Glasgow.

Olesen, Bjarne W., 2004. *Radiant heating and cooling by embedded water based systems*. Technical University of Denmark, International Centre for Indoor Environment and Energy.

Recknagel, H., Sprenger, E., 2005. *Taschenbuch für Heizung und Klimatechnik*. Oldenbourg Industrieverlag München.

Rietkerk, J., 2009. *Flexibility & Concrete Core Conditioning – Synonyms or a contradiction?*. Eindhoven University of Technology, Eindhoven, The Netherlands.

Schijndel, A.W.M., 2007. *Integrated Heat Air and Moisture Modeling and Simulation*. Eindhoven University of Technology.

WBDG, 2010. *Design for the Changing Workplace*. Whole Building Design Guide - the WBDG Productive Committee, www.wbdg.org.