A SYSTEM FOR THE COMPARISON OF TOOLS FOR THE SIMULATION OF WATER-BASED RADIANT HEATING AND COOLING SYSTEMS

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ABSTRACT

Low temperature heating and high temperature cooling systems such as thermally activated building systems (TABS) offer the chance to use low exergy sources, which can be very beneficial financially as well as ecologically when using renewable energy sources.

The above has led to a considerable increase of water based radiant systems in modern buildings and a need for reliable simulation tools to predict the indoor environment and energy performance.

This paper describes the comparison of the building simulation tools IDA ICE, IES <VE>, EnergyPlus and TRNSYS. The simulation tools are compared to each other using the same room and boundary conditions.

The results show significant differences in predicted room temperatures, heating and cooling degree hours as well as thermal comfort in winter and summer.

INTRODUCTION

Over the past years, building simulation has become more and more important for the design of new buildings. Building simulation can be used to (i) increase comfort, (ii) decrease energy consumption and at the same time (iii) lower the overall costs for heating and cooling.

Providing better comfort can increase productivity and reduce sickness or other problems of the occupants. Reducing the energy consumption in buildings can contribute greatly towards the goal of a sustainable society. From 2006 to today, the delivered energy for residential and commercial buildings has risen and its share has increased from 15 to 20 per cent (U.S. Energy Information Administration, 2009, 2010). The use of low temperature heating and high temperature cooling systems, such as thermally activated building systems (TABS) can help to reduce this share. TABS can be operated using temperature levels close to the desired room temperature due to the use of large heat transfer areas. The consequential decrease of the temperature difference leads to the opportunity to use renewable energy sources, many of which can also be considered as low exergy sources. In this way not only energy consumption can be reduced but also exergy destruction can be minimized.

A transition from current heating and cooling systems to low temperature heating and high temperature cooling is also needed to be able to decrease losses in the distribution systems of centralized energy supply like district heating and cooling plants and increase energy performance of decentralized energy systems like heat pumps, chillers, boilers, co-generation etc..

Compared to full air conditioning systems the use of water based cooling may reduce investment costs in equipment, lower operation costs and reduce building height (building materials). Reducing the overall first costs of a building increases its attractiveness to investors. Whereas reducing the running costs is attractive for the user. It is however, important in future cost analysis to look both at investment and running costs, when evaluating the cost benefits of different concepts.

Whereas the simulation of air based heating and cooling systems is supported by most simulation tools, not all of them support the use of thermally activated building systems (TABS)(Crawley et al., 2005b). In most cases the simulation of TABS requires the installation of an additional module to the regular simulation tool or can only be performed by some questionable modification like simulating the TABS as an additional space.

In the end, the question remains how reliable the simulation of TABS is and how the results compare to an actually existing building. This paper is trying to answer this question for a selection of simulation tools.

PROGRAM OVERVIEW

Different commercial available simulation tools have been used to model a modern office building using TABS for heating and cooling purposes. These simulation tools are IDA ICE (4.101), IES <VE> (6.3 April 2011), Energy Plus (6.0.0) and TRNSYS (16.01.0003).

IDA ICE 4

URL: www.equa.se/ice

The modular dynamic multi-zone simulation tool, IDA Indoor Climate and Energy (IDA ICE), is a commercial program which was first released in May 1998. It can be used for the study of the thermal indoor climate of individual zones as well as the energy consumption of the entire building. IDA has been programmed in the simulation languages Neutral Model Format and Modelica using symbolic equations. Depending on the experience of the user and the complexity of the problem at hand, three different, but integrated user levels are available: Wizard, Standard and Advanced.

The Wizard level can be used to make fast and easy simulations of a single room. It can be used to calculate heating and cooling loads. Both, the Standard as well as the Advanced level are capable of simulating multiple zones within a building. The Standard level is used to build the general simulation model using the available domain specific concepts and objects, such as zones, heating devices or windows. The Advanced level can then be used to edit the mathematical model of the system.

The modular nature of IDA ICE makes it possible to write individual models extending its capabilities as needed by the individual user. (Crawley et al., 2008)

IES <VE>

URL: www.iesve.com

IES <VE> is a commercial simulation platform with the first major version 3.0 released in the late 1990's. The program combines several software components for different simulation tasks.

The main modelling tool in IES <VE> is ModelIT, where it is possible to construct a 3D model of rooms or a whole building. Additionally, CAD data can be imported using plug-ins (e.g. in Revit or SketchUp) or by importing CAD files (e.g. DFX).

For the dynamic thermal simulation, the component ApacheSim is used, whose calculations are based on first-principle mathematical models of heat transfer processes.

ApacheSim can be linked to other components of IES <VE> to include detailed results of shading devices and solar penetration (SunCast), airflow analysis (MacroFlow), component based HVAC systems (ApacheHVAC) and lighting (LightPro, RadianceIES). The results can also be exported for a more detailed CFD simulation by Microflow. (Crawley et al., 2005a; IES, 2011)

EnergyPlus

URL: http://apps1.eere.energy.gov/buildings/energyplus/

EnergyPlus is a new-generation building energy simulation program based on DOE-2 and BLAST, with numerous added capabilities. It was released in April 2001, and developed by several U.S. Universities with support from the U.S. Department of Energy, Office of Building Technology, State and Community Programs. EnergyPlus is actually a trademark of the U.S. Department of Energy and a new version of the tool is periodically available online.

EnergyPlus is a stand-alone simulation program without an (user friendly) graphical interface. EnergyPlus is capable of making whole building energy simulations. It enables to model heating and cooling loads, levels of light, ventilation, other energy flows and water use. It allows to simultaneously model different kinds of embedded systems, obtaining simulation output as the real building would. It includes many innovative simulation capabilities, like, but not limited to, time-steps less than an hour, modular systems and plants with integrated heat balance-based zone simulation, multi-zone air flow, thermal comfort, water use, natural ventilation, and photovoltaic systems.

The building model and the input files can be made through the program itself or imported from different building design programs (EERE, 2011).

TRNSYS

URL: http://sel.me.wisc.edu/trnsys/index.html

TRNSYS, standing for transient system simulation program, is a complete and extensible simulation environment. It is commercially available since 1975 (Klein, 2006). It is a flexible tool designed to simulate the transient performance of thermal energy systems. TRNSYS was first developed in a joint project between the University of Wisconsin-Madison, Solar Energy Lab and Colorado State University, Solar Energy Applications Lab in the 1970's.

TRNSYS is an algebraic and differential equation solver in which components are connected graphically in the simulation studio. In building simulations, all HVAC components are solved simultaneously with the building envelope thermal balance and the air network at each time step. The simulation results are based on the individual component simulation performances which can be selected from the simulation studio. It is suitable for the simulation of complicated systems. Users can easily accomplish the desired system control strategies by writing the logical programming or use simple equations thanks to TRNSYS open source code.

TRNSYS also includes the program TRNEdit, which is an all-in-one editor for reading and writing TRNSYS input and output files. TRNEdit can also perform parametric TRNSYS simulations and plot data from the TRNSYS simulation output (Crawley et al., 2008; Klein, 2006; Price and Blair, 2003).

METHODS

In order to analyse the quality of the simulations, it was decided that they should start on a basic level. The complexity of the simulations has been increased from one stage to the next. At the final stage, which is not part of this paper, the simulations will represent a real building, for which extensive measurement data for multiple years is available. Through comparison of the simulation results with the genuine measurement data, it is then possible to evaluate the simulation quality. In the present paper only the results of the different tools are compared with one another.

Comparison of operative temperature

Through the analysis of the operative temperature it is possible to quickly assess the general correlation of the simulation results. If the trend of the lines is synchronized, it is possible to conclude that the programs react similar to the changing input data.

Deviation of operative temperature

By comparison of the average calculated operative temperature of all included tools with the individual operative temperature, it is possible to observe how the differences between the tools change over the course of the year.

Degree hours

Degree hours of overheating for summer as well as for insufficient heating in winter were calculated. In this case however they can naturally not be used to assess the quality of the installed system. Instead, they can be used to easily compare the programs.

Thermal comfort

The thermal environment can be assessed through the thermal comfort categories introduced by the standard EN 15251 (CEN, 2007). This method of representing the results describes the percentage of occupied hours when the operative temperature exceeds the specified ranges.

Other metrics

For the comparison of any heating or cooling system, a number of other metrics such as energy consumption or other comfort factors are of cause relevant. However, due to the nature of the simulation tools , parameters such as draught, vertical air temperature gradients, and radiant temperature asymmetry cannot be calculated.

In the present study the energy use for auxiliary equipment like fans and pumps are not included. Some of the tools can calculate this directly and in other tools the information for calculating this part of the total energy consumption will be available

Using default settings

As far as possible the different default settings of the tools have been used. This will likely result in a lower correlation between the results of the different tools. On the other hand, it is not likely that a user is adjusting any of the default values without any incentive. It was therefore decided that - rather then trimming all possible variables to unison in order to get the highest possible correlation - to leave them as they were to get a more realistic deviation.

TABS

For the final stage in this paper, TABS were modelled in all tools. In the following, the used approach for each of the tools is described.

- IDA allows for the simulation of TABS on both, the Standard and the Advanced level. The TABS is hereby inserted as an additional layer in the slab construction.
  On the Standard level, the input values are limited to design cooling and heating power, temperature difference for design power, controller (Pi, Proportional, Thermostat or always on), coil mass flow, depth in the slab and a heat transfer coefficient that should be selected in accordance to standard EN 15377-1 (CEN, 2008).
  On the Advanced level, additional changes to the system can be made, including, but not limited to, changing the pipe length and inner diameter, the heat capacity of the liquid in the pipes or fine tune the control of the system.
  In both cases the slab temperature is assumed to be constant over the entire area.
- In IES <VE>, TABS are simulated by splitting the internal ceilings into a ceiling - room - ceiling construction.
  The ceiling construction should be divided at the pipe level. The room representing the slabs should be small and the surface resistances should be adjusted to give the construction a more realistic heat transfer behaviour.
  The easiest way to obtain results for the thermal behavior of the office room is to use ApacheSim. Here, the temperature of the fictive room between the ceilings is set to the supply temperature of the real system. It can be controlled by either giving it absolute values or using a profile based on, for instance, the air or operative temperature of an office room, the outside air temperature or an equation including both.
  A more complicated, but also more promising approach for evaluating TABS is ApacheHVAC. In which ”radiators” or ”cooled ceilings” should be introduced into the fictive room between the ceilings. In this case, care should be taken also of heat transfer coefficients, water flow rates and heating or cooling areas of the systems.
- EnergyPlus allows to simulate TABS including an internal source layer in the floor/ceiling construction. Water flow and internal diameter, length of the pipes and distance between the tubes are required. Supply water temperature in the system/tubes can be set, but the final system control has to be based on a set point temperature (here the indoor air temperature).
- TRNSYS simulates TABS by defining an active layer in the floor or ceiling. The definition process begins similarly to that of a normal wall. The parameters like pipe spacing, pipe outer diameter, pipe wall thickness and pipe wall conductivity are required when defining the active layer.
  To ensure a correct calculation, a minimum mass flow rate (generally greater than $13\, kg/m^2h$) has to be set. The ordinary piping system has been modelled in two segments in this simulation.

The reasoning behind this approach

The comparison of computer tools is a laborious and time consuming business. Virtually all parameters have to be controlled and sometimes this might not even be completely possible. In any case, one can argue that this approach is valid and offers a high insight into the program at an academic level. On the other hand many of these adjustments might be omitted while "just" simulating a real building, simply because they are unknown. Consequently this means that many of the default values remain unchanged and influence the outcome of the simulation. For this reason it is important to see how the results are changing with increasing complexity of the simulations.

SIMULATION

As mentioned before, the comparison is made through a number of stages. In the following, the stages presented in this paper are explained in more detail. In the end, some fundamental differences between the tools are mentioned, that should also be controlled for further analysis.

Stage 1 - Basic building

As a first step of the comparison, a basic simulation has been made in the selected simulation tools. For this comparison, only the building envelope has been modelled and placed in the outdoor thermal environment. Internal loads as well as any installations (e.g. heating and cooling systems, lighting and others) have been neglected.

- Building dimensions and construction as reference building (see figure 1).
- Infiltration is at 0.2 ACH.
- Simulation of zones A, B, C and D as indicated in figure 1 (only zone A used).
- No HVCR&H systems.
- No internal loads.
- Weather data for Brussels (TRY from ASHRAE 2001).

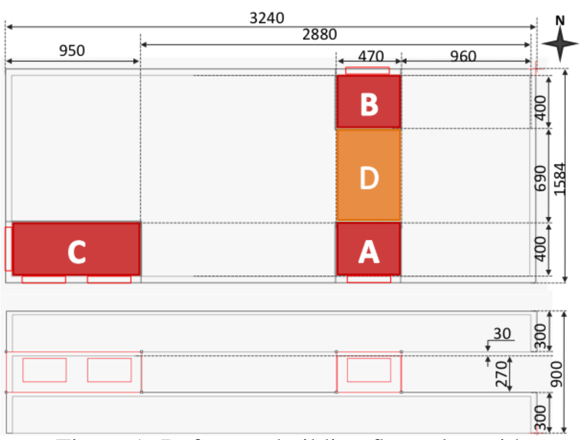


Figure 1: Reference building floor plan with indication of simulated zones - 2nd floor

Stage 2a and 2b - Shading

In the second stage of the simulations, the simple model was extended with shading. For Stage 2a internal shading and for Stage 2b external shading was used. In both cases the shading was modelled to represent Venetian blinds with an angle of 45°.

Stage 3a and 3b - Ventilation

Both stage 3a and 3b have been based on stage 2a. For both stages the air was supplied untreated from the outside and exhausted without heat recovery. In stage 3a 5.6 $l/s \cdot person$ and in stage 3b 10 $l/s \cdot person$ of outside air have been provided.

Stage 4 - Internal Loads

Starting from the model of stage 3b, internal loads were introduced for stage 4. The loads for stage 4 where:

- Occupants: 2 with 1 MET and summer: 0.5 CLO, winter: 1 CLO; Schedule: Workdays from 7:00 to 16:00 with break from 12:00 to 13:00, else not present.
- Lighting: 10 W/m^2; Schedule: Workdays from 7:00 to 8:30 at 100 %, then linear decline to 0 % at 11:00, else off.
- Equipment: 75 W/Occ (Computer and Screen); Schedule: Workdays from 7:00 to 16:00, else off.

Stage 5 - TABS

For the modelling of TABS the data given in table 1 has been used as indicated for each program. For the comparison the default values from TRNSYS have been used except for the h-value (H-water-pipe-fin coefficient as defined in EN 15377-1) wich is only used by IDA and suggested within the program.

Differences between tools

The following points are differences between the four programs that can have a considerable impact on simulation results. The different approaches for the calculation of a TABS system were introduced in the TABS section of the METHODS.

- All tools but IES <VE> have the possibility to model occupants based on MET and CLO values. In IES <VE> it is necessary to specify the heat generation in absolute values (e.g. W/m^2). This means that in IES <VE> the heat delivered to the zones is constant for the entire year, whereas it depends on the room temperature when a real occupant model is used. Between IES <VE> and IDA, this difference can exceed 200W.
- In all simulation tools it is possible to adjust a number of parameters. These parameters can influence the run time of the simulation as well as its accuracy. Bad selection of these parameters can even lead to a premature termination of the simulation. This is especially true for IDA as it becomes more and more challenging to solve the

Table 1: Input data used for the simulation of TABS depending on the simulation tool

parameters	Values	IDA	IES	E+	TRNSYS
pipe conductivity	$1.26\frac{kJ}{h \cdot m \cdot K}$	–	+	–	+
pipe spacing	150 mm	*	+	+	+
inner pipe diameter	12 mm	*	+	+	+
pipe wall thickness	2 mm	*	+	–	+
depth in slab	200 mm	+	+	–	+
constant water flow	350 kg/h	+	–	+	+
supply temp. summer	22 °C	+	+	+	+
supply temp. winter	24.5 °C	+	+	+	+
h-value	$30\frac{W}{m^2K}$	+	–	–	–

+ required; – not used by tool;

* optional on advanced level

system of differential equations the more complex it gets. For instance the by default existing heat recovery unit should be deleted if it is not used. It can otherwise prolong the simulation time considerably and in extreme cases even lead to the premature termination of the simulation.

- The warm-up phase is handled differently for all of the programs. The used settings are:
  IDA: 14 days of periodic simulations with the first day of the simulation period.
  IES: 30 days of dynamic simulations with the last days of the previous year.
  EnergyPlus: Up to 100 days (default 25) of warm up. Iterations are aborted once the start-up temperature ($23°C$) converges with the ambient temperature.
  TRNSYS: Two year simulation, first year as start-up phase.
  If any of these times are set too short it will have a negative impact on, at least, the beginning of the simulation. Also the different approaches, periodic or dynamic, can have an influence since they will lead to different starting conditions for the simulations.

Apart from these points many other settings could have an influence on the outcome of the simulations.

RESULTS AND DISCUSSION

Stage 1

For the simulations at stage 1 the results for the operative temperature (T_{op}) are shown in figure 2. The development of T_{op} for all tools shows the same characteristic. The differences in the beginning of the simulations are a result of different start-up procedures between the programs. The lower peak temperatures for IDA and IES found in the summer time could be explained by a higher sensitivity to small infiltration rates, for EnergyPlus and TRNSYS it seems to be vice versa. For simulations without any infiltrations (not presented in this paper) the highest temperatures were found to be in a much closer range of one another.

For reference the outdoor air temperature is included here.

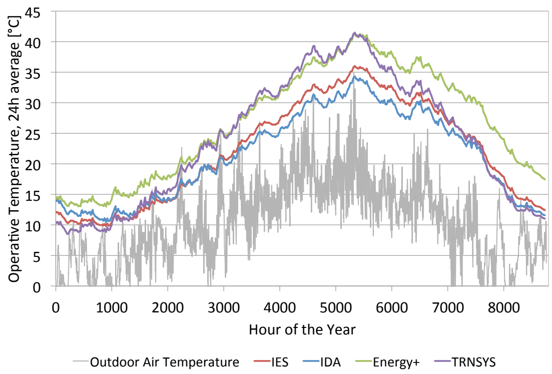


Figure 2: Operative temperature (24h moving average) for Stage 1

Figure 3 shows the deviation of the operative temperatures (T_{op}) for each simulation tool from their common average simulation result. For the basic building the deviation is very high. This deviation however decreases from here on as can be seen in figure 6b.

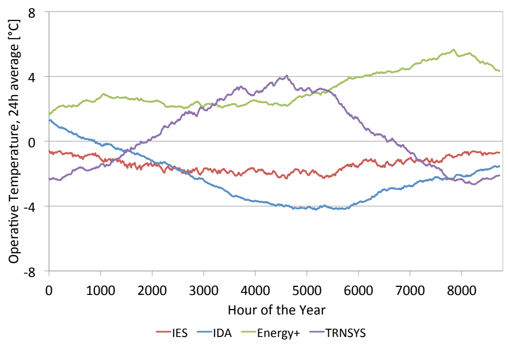
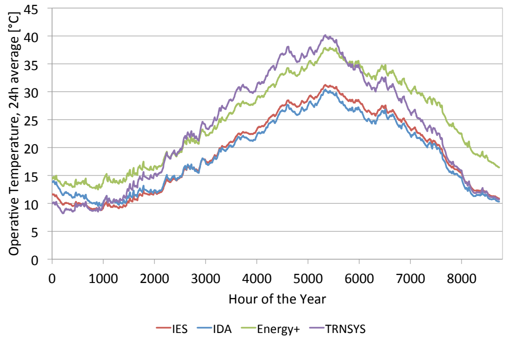


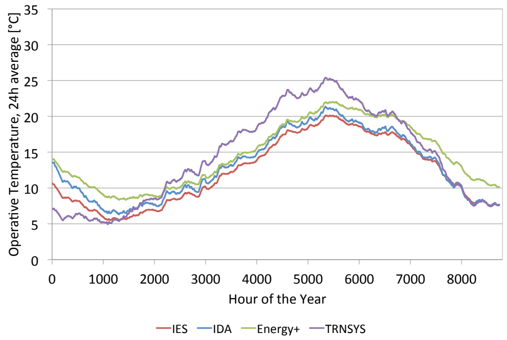
Figure 3: Operative temperature difference between average simulation results and indicated tool for stage 1. (24h moving average)

Stage 2

Introducing blinds (internal for stage 2a and external for stage 2b) lowers the temperature and results in a smoothed short term temperature fluctuation as can be found by comparing figures 2, 4a and 4b. Between the simulation of internal and external shading, the agreement between the tools is higher for external shading. The overall shape of the curve however remains unchanged.

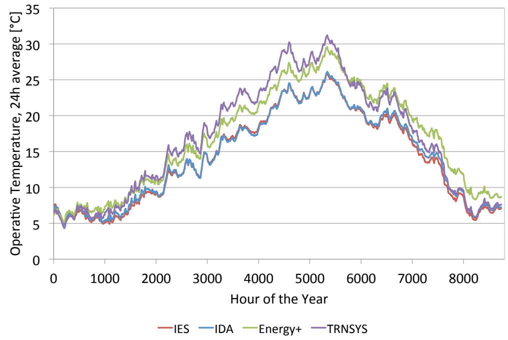


(a) Stage 2a - Internal Blinds

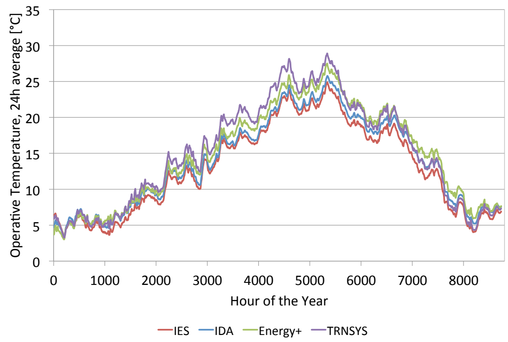


(b) Stage 2b - External Blinds

Figure 4: Operative temperature for internal and external shading.



(a) Stage 3a (2a + Ventilation: $5.6\ l/s * person$)



(b) Stage 3b (2a + Ventilation: $10\ l/s * person$)

Figure 5: Operative temperature for two different ventilation rates.

Stage 3

Through the introduction of ventilation the, results of the simulation tools are coming closer together. IES and IDA show significant lower temperatures during the summer for Stage 3a ($5.6\ l/s \cdot person$), compared to EnergyPlus and TRNSYS as seen in figure 5a. Looking at figure 5b for Stage 3b ($10\ l/s \cdot person$) all simulation tools are much closer to each other.

Stage 4

Starting from Stage 3b, the addition of internal loads increases T_{op} for all tools. Figure 6a shows that the agreement between the tools however remains high. The deviation of the operative temperature, from the average has its maximum at about $2\ K$ as ilustrated in figure 6b.

Stage 5

Finally TABS are added to the building simulation. As can be seen in figure 7, the calculated temperatures are fluctuating by around $5°C$ (based on a $24\ h$ average) for all tools. However, the fluctuations are not, as on all previous stages, synchronous between the tools.

Figures 8a and 8b show the comfort categories achieved with the used rudimentary controll for TABS. Both, for winter and summer the results are not the best. This is not due to the TABS itself but rather to the poor control of them. However, the results for each tool are quite different and would not necessarily trigger the same reactions by the engineer using the tool.

Degree hours

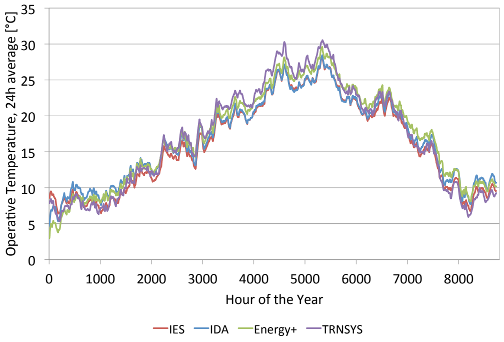
Tables 2 and 3 show the calculated degree hours of cooling and heating for each tool and stage for setpoint temperatures of $24.5°C$ and $22°C$ respectively. As has been expected, the degree hours for each tool show the same consistent pattern.

For cooling (Table 2) they drop from stage 1 to stage 3a gradually with each building improvement. The increase from 3a to 3b is due to the higher ventilation rate. Especially for TRNSYS the higher air supply has an overall cooling effect, which is also reflected in the heating period. Naturally, the values for stage 4 are increasing again as additional loads are present in the zone. The addition of a cooling system (TABS) again reduces the remaining degree hours.

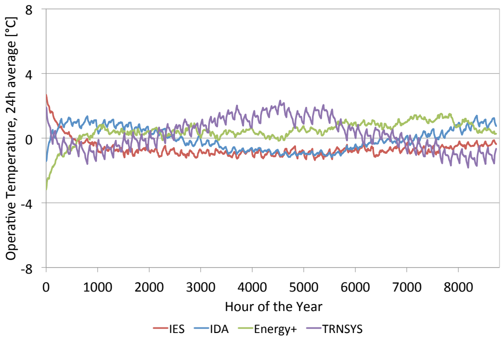
Comparing the different tools to one another, it is apparent that the results are significantly different for most stages. IDA shows for all stages the by far lowest cooling degree hours. EnergyPlus and TRNSYS calculate the highest cooling degree hours.

For heating (Table 3) the pattern is exactly reversed. This is of cause only consequent. Shading reduces solar gains, the ventilation replaces warm indoor air with colder outside air and the internal loads provide heat. Regarding the heating degree hours, the results are closer together the more complex (higher stage number) the simulation becomes.

The degree hours presented in tables 2 and 3 show that results of each tool are too different to always draw



(a) Stage 4 (3b + Internal Loads)



(b) Stage 4 (3b + Internal Loads)

Figure 6: Operative temperature and temperature difference with internal loads.

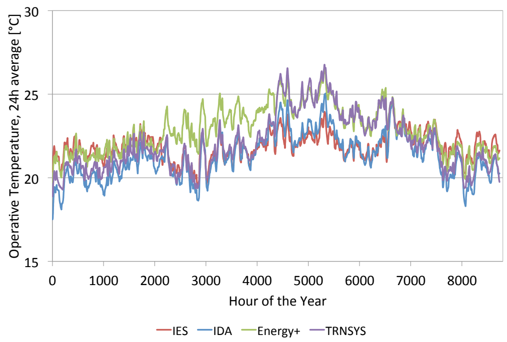


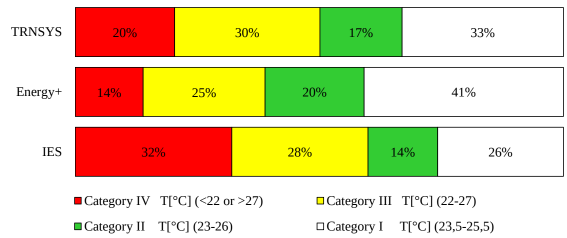
Figure 7: Operative temperature for Stage 5 (24h moving average)

the same conclusion from them. This shows the dangerous potential of building simulation. Depending on the used tool (and detail of the simulation), one might come to different conclusions depending rather on the choice of the tool than the building itself.

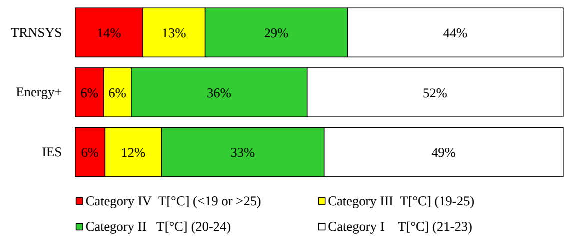
CONCLUSIONS

The present study has shown that different building simulation tools lead to essentially different results for building simulations under the given conditions. This result is not unexpected considering that not all possible settings were controlled. However the magnitude of the differences was higher than expected.

Part of these differences can be explained through the different detail between the models. The way occupants, shading, TABS and other things are modelled



(a) Stage 5 - Comfort Categories Summer



(b) Stage 5 - Comfort Categories Winter

Figure 8: Comfort categories with operating TABS.

differs greatly. For instance in IES occupants are more similar to equipment, having a constant heat production, in IDA this heat production is greatly depending on the air temperature.

A second reason for the differences between the tools are the default parameters that have not been adjusted. Using different parameters will consequently effect the outcome of the simulation.

Even though the tools did not predict the same results at each stage, the relative changes in the results new

Table 2: Calculated degree hours of cooling to 24.5°C from April through September

Stage	IDA	IES	Energy+	TRNSYS
	[degree hours in thousand] (cooling)			
1	14.2	20.3	36.1	34.9
2a	5.7	8.5	26.0	31.0
2b	0.0	0.0	0.0	0.2
3a	0.0	0.0	0.0	0.2
3b	0.2	0.2	3.3	5.6
4	1.4	1.4	3.1	4.7
5	0.1	0.1	1.7	1.2

Table 3: Calculated degree hours of heating to 22°C from October through March

Stage	IDA	IES	Energy+	TRNSYS
	[degree hours in thousand] (heating)			
1	28.3	29.0	16.3	31.0
2a	33.9	34.9	18.7	32.6
2b	50.7	54.0	41.4	53.2
3a	50.7	54.0	41.4	53.2
3b	54.0	55.8	46.0	50.6
4	42.9	46.9	43.5	47.6
5	6.2	1.9	2.6	4.4

input parameters (from stage to stage) are similar for all tools.

Inserting a TABS system in the model showed a reduction in operative temperature differences between the simulating tools.

Essentially the results show that the choice of the simulation tool can greatly influence the building evaluation through the simulation, since in a real world case not all variables are known.

The simulation of TABS has lead to a much smaller deviation of simulation results than on any previous stage.

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