REVIEW OF THE ASSESSMENT OF THERMAL MASS IN WHOLE BUILDING PERFORMANCE SIMULATION TOOLS

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ABSTRACT

There is a plethora of dynamic Building Performance Simulation (BPS) tools on the market, that use different methods in terms of how they calculate the effect of thermal mass in buildings. This paper analyses the ability of six widely known BPS tools to calculate the thermal mass potential in whole BPS. The first stage is focused on the analysis of heating and cooling energy consumption, produced for a single-zone test building. This is done using the IEA Building Energy Simulation test (BESTEST) diagnostic method. The results are compared among the different BPS tools in order to examine the extent of variations. The second stage is a systematic comparison of the tools against some key parameters on the calculation methods and aims to investigate the implications of the inter-model variability on the simulation results. The results indicate that there is a divergence in the BPS predictions, and that the relative differences in the simulation results of the different BPS tools are always higher for high thermal mass.

INTRODUCTION

Climate change has been the focus of much scientific research over the past decades. The most direct impact of climate change is the increase of global temperature maxima, which is also expected to result in significant changes in the weather patterns and increased frequency of extreme weather events (NHBC, 2012a; DEFRA, 2012). With 36% of the UK total Greenhouse Gas (GHG) emissions deriving directly from the built environment (McLeod et al., 2013; NHBC, 2012b), the UK government has set a target to reduce building energy consumption and CO_2 emissions, by focusing on the reduction of fabric heat losses (reduced infiltration, better insulation etc) and the optimal use of solar gains. Being highly insulated, low carbon buildings are particularly sensitive to overheating (NHBC, 2012b).

Previous research has shown that the thermal mass of the building fabric can be used as a means of building's adaptation to climate change and so prevent it from overheating (Hacker et al., 2008). The term thermal mass is used to define all the materials in a building construction that have the ability to store energy at time of surplus and release this energy back in the space at time of scarcity (Ghattas et al., 2013), reducing the internal temperature variations, shifting the time that the peak internal temperature occurs, resulting ultimately in reduced energy use for space conditioning (Al Sanea and Zedan, 2011; Dodoo et al., 2012).

The thermal performance of high thermal mass buildings is characterised by dynamic response to heat transfer, hence when investigating the thermal response of a heavyweight construction it is important to calculate the heat transfer in transient conditions. In respect to heat flow in and out of the thermal mass, the prevailing heat transfer mechanism is conduction. Transient heat conduction is defined by Kossecka and Kosny (1998) as the heat flow that occurs when the temperature within an object is changing as a function of time. Nevertheless, when investigating the effects of thermal mass in whole building energy performance, there are many key influential physical parameters that need to be taken into account (i.e. solar radiation, casual gains, weather data, ventilation flow rates) (Kalema et al., 2008).

When assessing the energy, environmental and thermal performances of high thermal mass buildings, where the dynamic thermal behaviour of the building fabric affects significantly the heat transfer and the thermal response of the building (Davies, 2004), the use of reliable dynamic BPS is essential. BPS was first introduced in 1960s (Zhu et al., 2012) and it has developed significantly ever since. Based on descriptions of the construction, occupancy patterns and HVAC systems, BPS tools can provide predictions on thermal performance and energy consumption of a building. However, there are inconsistencies in the simulation results when modelling an identical building using different BPS tools, referred to as modelling uncertainties (Hopfe and Hensen, 2011). These can lead to a lack of confidence in building simulation. Previous studies on the accuracy of simulation predictions concluded that the key factors contributing to these uncertainties reside in the calculation methods and the different algorithms used in the source code of each tool and are partly a consequence of the input data provided by the user (Kalema et al., 2008; Irving, 1982; Zhu et al., 2012). Irving (1982) compared the simulation results of 23 BPS tools along with their accuracy in modelling the behavior of a real building and concluded that the modelling of thermal mass is highly relevant in determining the calculation of space loads. Muranetto et al. (2013) examined the key factors which are correlated to thermal mass modelling in whole BPS and interogated the impact of several common assumptions on the simulation results (i.e constant combined convective and radiative surface coefficient, fixed distribution of solar gains). They concluded that discrepancies in simulation results are larger for high thermal mass cases.

This work is the first part of a doctoral research project seeking to investigate the thermal behaviour of heavyweight construction methods (Mantesi et al, 2015) and quantify the effects of thermal mass in low carbon building design. The aim of the paper is to provide a comparison of six widely-used dynamic BPS tools, with respect to their ability in calculating the effect of thermal mass, and to investigate the impact of several key influencial parameters in the source code associated with thermal mass calculation. The analysis will compare the tools' modelling capabilities, main features, calculation methods, along with the simulation results provided by each tool for the same building model and for different levels of thermal mass. The research objectives are:

- To identify the existing differences in the solution algorithms
- To question the consistency, or otherwise, among the simulation results provided by the BPS tools
- To identify the key parameters on the calculation algorithms responsible for discrepancies in the simulation results

METHODOLOGY

The research was carried out in three stages. The first was a critical software review to identify the main features and capabilities of six BPS tools. Focus was placed on the different calculation methods and solution algorithms used by each of the tools for calculating the thermal loads of the space and the zone air temperatures. Information was gathered from the tools' engineering manuals, from published reports and previous studies (Crawley et al., 2005; Zhu et al., 2012), and published online databases (DOE, 2015).

The second part focused on model validation and an initial inter-model comparative analysis, using Building Energy Simulation Test (BESTEST) diagnostic method (Judkoff and Neyman, 1995). The BESTEST diagnostic method was developed by International Energy Agency (IEA) in collaboration with National Renewable Energy Laboratory (NREL) in 1993. The method consists of a number of cautiously specified test cases, which progress from very simple to relatively realistic; it is used for evaluating the modelling capabilities of whole BPS tools and for diagnosing errors in their source code (Judkoff and Neyman, 1995). The BESTEST method was used in order to minimise the variables in the input data. Two test suites were selected for the comparison, case 600 (low thermal mass) and case 900 (high thermal mass). The DRYCOLD weather file (downloaded from NREL) was used in the simulations, representing a typical meteorological year (TMY) with cold winter and hot summer dry-bulb temperatures. This stage included a preliminary analysis of the results provided by each BPS tool for annual heating and cooling energy consumption, based on the default solution algorithms,. The simulation results were compared, to evaluate how each of the BPS tools calculates the effect of thermal mass in the loads calculation.

The final stage was a systematic comparison of the BPS tools based on the key influential factors that are associated to thermal mass in whole BPS. A set of specialised test cases were designed and conducted based on the BESTEST method. The aim was to address each factor one by one and evaluate its impact on the simulation results. Table 1 summarises the description for each specialised test case.

RESULTS

BPS Tools' review

The information gathered from the literature review on the main features and the default algorithms used by each of the six BPS tools investigated in the paper are summarised in Table 2.

BESTEST Simulation Results

There is relative consistency in the simulation results given by all six BPS tools for the annual heating energy consumption, for both the low and high mass case (Figure 1 and 2 respectively). Tool A shows an increased annual heating demand when compared to the median of all tools, 8% for the low mass case and 13% for the high mass case.

For annual cooling energy consumption, the inconsistencies were found to be larger in both cases (Figures 1 and 2). Tool C and Tool F show increased cooling demand by 4% and 8% for the low mass case (compared to the median), and by 15% and 18% for high mass case respectively. In contrary, Tool D showed a significantly decreased annual cooling demand compared to the other BPS tools. The difference is 11% for the low mass case and 21% for the high mass case. It was observed that Tool D falls below the BESTEST reference range when the default algorithm is used to calculate the internal surface convection coefficients (as the BESTEST method suggests), yet, it is within the range when constant user-defined coefficients are used.

The general observation from the results for annual heating and cooling energy consumption is that both heating and cooling demand are decreased by approximately 65% in the high mass case. The divergence in the results is greater for the annual cooling demand calculation. The relative differences in the results of all the BPS tools, when compared to the median, are always higher in the high mass case, hence the results confirm that discrepancies are more substantial in a high thermal mass building[1].

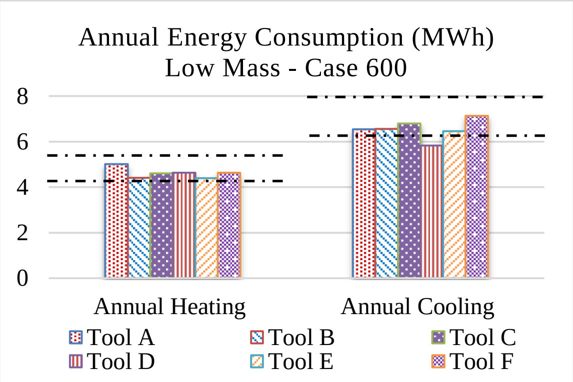

Figure 1: BESTEST Annual Energy Consumption – Low Mass Case 600

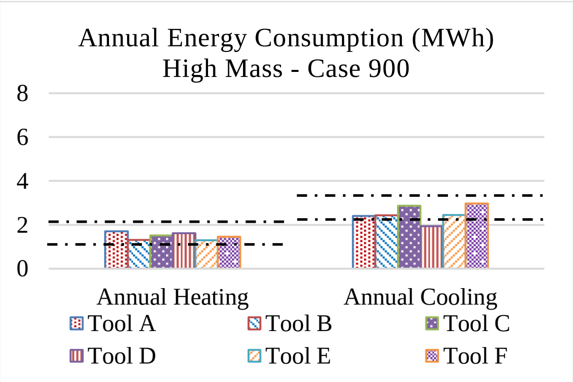

Figure 2: BESTEST Annual Energy Consumption – High Mass Case 900

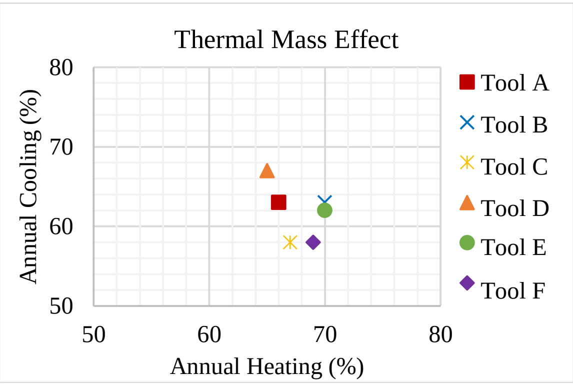

Figure 3: Thermal Mass Effect on Annual Energy Consumption

Figure 3 shows the thermal mass effect in the annual heating and cooling energy consumption. The relative differences between the simulation results for low and high mass cases are summarised and plotted for each of the six BPS tools. The horizontal axis demonstrates the energy savings in annual heating demand due to thermal mass as calculated by each BPS tool. The vertical axis shows the energy saving in annual cooling demand. Regarding the annual heating demand, the maximum deviation in the calculation of thermal mass effect is less than 5% between the different tools. Tool E and B estimate a higher thermal mass benefit, while Tool D estimates the lowest. Regarding the annual cooling demand, the maximum deviation in the thermal mass effect calculation is higher (approximately 10%). Tool D estimates the highest thermal mass benefit and tools C and F the lowest.

Special Test Cases Results

Three BPS tools were selected for further analysis, Tools C, D and F. These showed the maximum differences in the calculation of annual cooling demand in the BESTEST simulation (Figures 1 and 2). Moreover, they were found to have a wider distribution of results when calculating the effect of thermal mass (Figure 3).

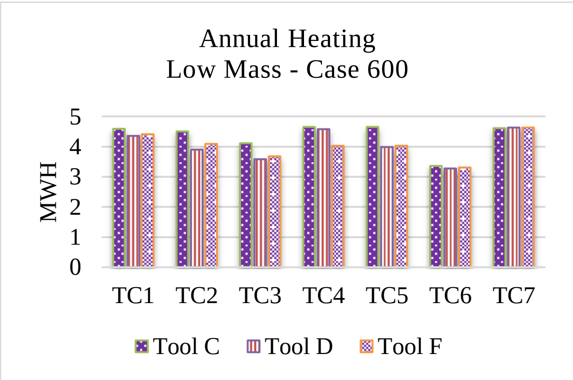

Figure 4: Special Test Cases.. Annual Heating Energy Consumption – Low Mass Case 600

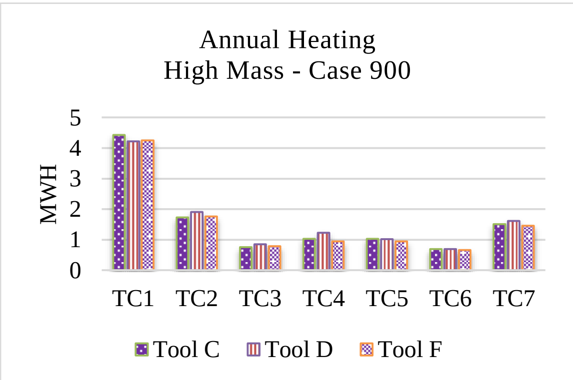

Figure 5: Special Test Cases. Annual Heating Energy Consumption – High Mass Case 900

When investigating the thermal performance of the building in TC1, there is an insignificant reduction in the annual heating demand for the high mass case,

[1] The same finding applies for the peak heating and cooling loads analysis, which has not been included here for sake of brevity.

approximately 3% for all BPS tools. Moreover, there is little divergence in the annual heating demand given by the three BPS tools. Tool C shows a 5% increased annual heating demand when compared to Tool D and 4% when compared to Tool F for both low and high thermal mass cases.

When solar radiation is introduced in the zone air in TC2, the annual heating demand given by Tool C is unaffected for the low mass case, while there is a noticeable reduction in the results provided by the other two tools. Ultimately, the difference in the annual heating demand provided by tool C is further increased to 13% compared to Tool D, and 9% more compared to Tool F. In the high mass case the annual heating demand decreases by approximately 60% in TC2 for all BPS tools. The results' divergence is different from the low mass case. Tool D gives the highest annual heating demand, 10% and 8% more when compared to tools C and F respectively.

In TC3 the annual heating demand is decreased by approximately 10% for the low mass case and by 55% for the high mass case for all BPS tools. Nevertheless, the divergence in the simulation results is unaffected.

When the IR emissivity of the internal surfaces is increased in TC4, the annual heating demand of the space is increased in both low and high thermal mass cases. Nevertheless, comparing the results of tools C and F in TC3 and TC4, shows that the IR emissivity has no impact on the results divergence. Tool D shows increased heating and cooling demand in TC4, because the internal surface convection coefficient is set as constant and user-defined. TC4 and TC5 are analysed in conjunction in order to investigate the impact of the internal surface convection coefficient calculation for Tool D. As explained above, in TC4 the convection coefficient is constant and user-defined and in TC5 it is calculated by the default algorithm employed by the tool. Tool C always uses constant combined convection and radiation surface coefficients. Tool F does not give the option to specify a constant value for the surface coefficients and always uses time-variable calculated coefficients for convection heat transfer. Hence, the simulation results for tools C and F are the same for TC4 and TC5. Tool D shows a significant increase in the annual heating demand in TC4 when compared to the results of TC5 (13% for the low mass case and 17% for the high mass case).

There is a reduction in the annual heating demand when internal gains are introduced, in TC6, for both thermal mass cases and for all BPS tools. Tool C shows the most significant reduction, 28% for the low mass case and 32% for the high mass case (compared to TC5). The inconsistencies in the annual heating results between the three BPS tools are insignificant for TC6 in both low and high mass case.

In TC7, when the infiltration is increased to 0.5ach the annual heating demand is increased in all tools on an average of 28% for the low mass case and 55% for the high mass case. TC7 is essentially BESTEST base cases 600 and 900 and examines the complete zone heat balance calculations when the default algorithms are used for each of the three BPS tools. The inconsistencies in the simulation results for the annual heating demand are insignificant.

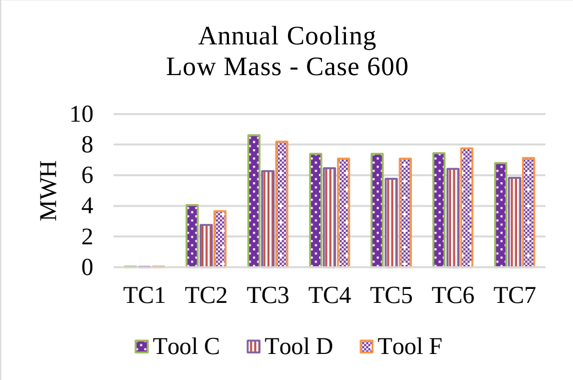

Figure 6: Special Test Cases. Annual Cooling Energy Consumption – Low Mass Case 600

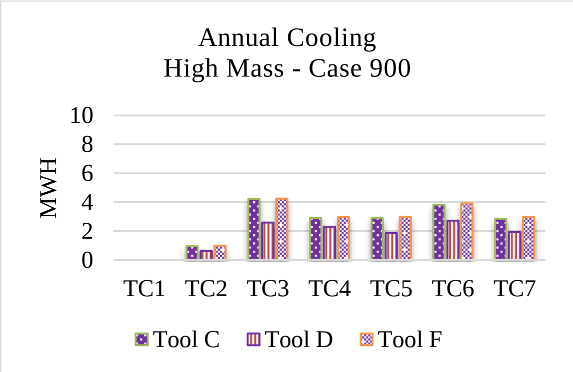

Figure 7: Special Test Cases.. Annual Cooling Energy Consumption – High Mass Case 900

The annual cooling demand in TC1 is almost 0MWh for both low and high mass cases. In TC2 Tool D shows a decreased annual cooling demand 32% less than tool C and 24% less than Tool F for the low mass case. For the high mass case Tool D gives 35% less annual cooling than Tool C and 38% less than tool F.

In TC3 the annual cooling demand is increased for both low and high thermal mass cases (55% and 76% respectively). Tool C shows the highest cooling demand in low mass case, 27% more than Tool D and 5% more than tool E. In the high mass case Tools C and F give the same annual cooling demand. Tool D shows again a decreased cooling demand in both low mass case.

When the surface IR emissivity is increased in TC4, the annual cooling demand is decreased in both thermal mass cases. The aforementioned reduction is more noticeable for Tools C and F, while Tool D produces very little reduction (due to the constant surface coefficients described above). There is a significant difference in the annual cooling demand given by Tool D when comparing the results of TC4 and TC5. When user-defined surface convection coefficients are used in TC4 the annual cooling demand is 10% higher for low mass case and 20% higher for high mass case compared to the cooling demand given for programme-calculated coefficients (TC5).

In TC6, the annual cooling demand is increased for all BPS tools. In this test case Tool F shows the highest cooling demand, 4% more than Tool C and 17% more than Tool D for the low mass case. In the high mass case the divergence in the simulation results is unaffected by the internal gains.

Finally, when the fabric infiltration is raised to 0.5ach in TC7, the cooling demand is decreased in both low and high thermal mass cases for all BPS tools (9% and 25% respectively), but the divergence of the results is again unaffected.

DISCUSSION

Previous studies indicate that the key factors contributing to the inconsistencies in the simulation results of different BPS tools reside in the calculation methods and the different algorithms used by each tool (Kalema et al., 2008; Irving, 1982; Zhu et al., 2012). Following the software review, a number of differences were identified in the algorithms employed by the BPS tools. Based on the BESTEST simulation, the larger discrepancies in the results were identified in the annual cooling energy consumption. Moreover, the maximum deviation in simulation results (regarding the thermal mass effect calculation) was also identified in the annual cooling energy demand. In general, the relative differences in the results of all BPS tools when compared to the median, were always higher in the high mass case. This finding is consistent with those from previous studies reported in the literature review (Munaretto et al, 2013), showing that discrepancies are more substantial in a high thermal mass building

Tool B is a graphical user interface for Tool E. Several insignificant differences were identified in the simulation results provided by these two tools. In order to investigate whether these differences were due to minor inconsistencies in the user-input data or a consequence of the default values used by each tool for the calculations, the same model file was simulated by both BPS tools. The results for annual energy consumption were found to be identical. There were minor differences in the peak loads calculation when different reporting time intervals were selected. These were resolved when the same output time step was used. Hence, any default values used in the graphical user interface of Tool B is not affecting the accuracy of the simulation results.

The results from the special test cases showed that in terms of solid conduction, there was a relatively insignificant inter-model variability on the annual heating results, correlated to the different conduction algorithms, independent of the level of thermal mass. Tool C and D calculate conduction heat transfer based on Conduction Transfer Functions method, while Tool F uses a frequency domain response method. The sequential simulation solution for zone loads, plant and system calculation employed by Tool C, resulted in increased annual heating demand compared to the other two tools that perform simultaneous calculations. The inconsistency in the results of Tool C was similar for both thermal mass cases. In the absence of windows and solar gains there was no annual cooling demand for either thermal mass cases.

Regarding the convective heat transfer calculation, Tools D and F calculate convection dependent on temperature difference. Tool C calculates combined convective and radiative heat transfer. Consequently, Tool C is the only tool that does not perform air heat balance calculation. Instead, it uses weighting factors to calculate the zone loads and internal temperatures. Tool C showed significantly higher heating and cooling demand in the low mass case when investigating the impact of convection on the results discrepancy (TC2). In the high mass case the difference between the simulation results was insignificant Tool D showed an increased heating demand compared to the other two tools in the high mass case and significantly lower annual cooling demand in both low and high thermal mass cases. Moreover, when investigating the effect of internal surface convection coefficient calculation (TC4 and TC5), Tool D showed a very substantial difference in the simulation results for both annual heating and cooling demand and for both low and high thermal mass cases. Hence, Tool D is disadvantageous in calculating convection heat transfer. This is also proven by the BESTEST simulation, where the results from Tool D were found to be within the BESTEST reference range when the internal surface convection coefficients were constant and user-defined and below the range for programme-calculated coefficients.

The analysis showed that the algorithms used to calculate the solar gains distribution within the internal surfaces of the zone have no impact on the inconsistencies (TC3).

Increasing the surface IR emissivity resulted in increased annual heating demand and decreased annual cooling (TC4). Nevertheless, comparing the results of Tools C and F in test cases TC3 and TC4, showed that the calculation of long-wave radiation exchange has no impact on any divergence in the results.

All three BPS tools assume uniform distribution of the radiant internal heat gains, which is proportional to the wall area. Nevertheless, the introduction of internal heat gains had a significant impact on the annual heating demand calculation of Tool C for the low thermal mass case, while it showed no significant impact on the annual heating demand for the high thermal mass case and the annual cooling loads in either thermal mass cases. The calculation of fabric infiltration was found to have relatively insignificant effect on the simulation results discrepancy between the different BPS tools, mostly unaffected by the level of thermal mass.

RESEARCH LIMITATIONS

The analysis presented is based on the BESTEST diagnostic method. The BESTEST building is a simplified single zone enclosure, rigorously defined in terms of input data and relatively poor in respect to energy efficiency. The BESTEST building was selected in order and to minimise the variables in the input data and to eliminate the ground for user input errors. As a result, the impacts of inter-zonal heat transfer, variable airflows (infiltration and ventilation) and variable internal gains were excluded from the analysis. Moreover, as mentioned above, the BESTEST method describes a poorly energy-efficient building, significantly below the UK building energy standards (ZCH, 2009).

CONCLUSIONS

Whole building performance simulation is essential in order to assess the energy and thermal performance of buildings, especially in the case of high thermal mass structures. It has been shown that there are inconsistencies in the simulation results when modelling an identical building using different BPS tools. The analysis focused on the comparison of six dynamic BPS tools, with respect to their ability in calculating the effect of thermal mass. Moreover, the analysis explored the implications of the inter-model variability and the tools' inherent differences on the simulation results.

According to the simulation results provided by the six BPS tools for the BESTEST building and for cases 600 and 900 (low and high thermal mass respectively), the general observation was that the thermal mass of the fabric results in approximately 65% reduction of the annual thermal energy consumption for both heating and cooling demand.

Regarding the divergence in the calculation of annual heating and cooling energy consumption, the analysis showed that the relative differences in the results of all BPS tools, when compared to the median, is always higher for high thermal mass.

The discrepancy on the calculation of thermal mass effect (the difference between low and high mass results) is more obvious for annual cooling energy consumption, around 10%, while for annual heating demand is less than 5%.

A set of specialised test cases was simulated in order to examine the effect of several key influential factors on the results discrepancy and on thermal mass calculation. Among the different algorithms employed by the three BPS tools included in the analysis, the simulation solution for zone loads, plant and system calculation was found to have a noticeable impact on the results discrepancies in both low and high thermal mass cases. The air heat balance calculation showed a significant impact on the simulation results for the low mass case, which was found to be insignificant for the high mass case. The different algorithms used to calculate the internal surface convection coefficient were found to have a substantial impact on the simulation results for both low and high thermal mass cases. Finally, the internal gains calculation showed to affect the discrepancies in the annual heating and cooling demand for the low mass case, but showed no impact on the results divergence for the high mass case. The calculation of long-wave radiation heat exchange and fabric infiltration were found to have an insignificant effect on the simulation results' discrepancy between the three BPS tools, mostly unaffected by the level of thermal mass.

FUTURE WORK

The research was performed for a poorly energy efficient building, based on the BESTEST method. Future work will focus on high performance, low carbon building cases.

It was also based on the default algorithms employed by each BPS tool (i.e. surface conduction, convection coefficients and so on). A comparative analysis between alternative algorithms provided within the same BPS tool will provide a better insight in the impact of calculation methods on the simulation results.

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Table 1
Description of Specialised Test Cases Used for the Systematic Tools Comparison

TEST CASES	INT GAINS (W)	INFILT (ACH)	IR EMISSIV	SOL ABSORP	INT CONV COEF	WINDOWS	COMMENTS
TC1	0	0	0.1	0.1	Default	No	Solid Conduction
TC2	0	0	0.1	0.1	Default	Yes	Convection
TC3	0	0	0.1	0.6	Default	Yes	Solar Gains Distribution
TC4	0	0	0.9	0.6	User-Defined	Yes	User-defined Conv. Coefficient
TC5	0	0	0.9	0.6	Default	Yes	Programme calculated Conv. Coefficient
TC6	200	0	0.9	0.6	Default	Yes	Internal Gains
TC7	200	0.5	0.9	0.6	Default	Yes	Infiltration

Table 2
Calculation Methods and Solution Algorithms

	TOOL A	TOOL B	TOOL C	TOOL D	TOOL E	TOOL F
Simulation Solution (Loads, Plant, System Calculations)						
Sequential Calculations			X			

Simultaneous Calculations	X	X		X	X	X
Time Step Resolution						
Hourly			X	X		
Sub-hourly	X	X			X	X
Heat Balance Solution Algorithms						
Surface Heat Balance	X	X	X	X	X	X
Air Heat Balance	X	X		X	X	X
Zone Weighting Factors			X			
Conduction Solution Method						
Frequency domain response methods						X
Conduction Transfer Functions		X	X	X	X	
Finite Difference Solution	X	X			X	X
Internal Convection Coefficient Calculation						
Fixed Convection Coefficients	X					
Variable Convection Coefficients:						
Dependent on Temperature	X	X		X	X	X
Dependent on air flow	X	X		X	X	
Dependent on CFD-based surface coefficient	X					
User-Defined		X		X	X	
Combined Conv. and Rad. Coef.	X		X			
External Convection Coefficient Calculation						
Wind Speed dependent	X	X			X	
ASHRAE Simple		X		X	X	
Ito, Kimura and Oka correlation						X
TART		X			X	
DOE-2		X	X		X	
User-Defined		X		X	X	X
Combined Conv. and Rad. Coef.	X		X			
Interior Surface Long-Wave Radiation Exchange						
Mean Radiant Temperature Model	X			X		X
“Script F” (exchange coefficients between pairs of surfaces)		X			X	
Stefan-Boltzmann law						X
User-Defined Coefficients		X	X		X	
Combined Conv. and Rad. Coef.	X		X			
Participation of air emissivity in interior radiation exchange						
	X					
Exterior Surface Radiation Exchange						
Stefan-Boltzmann law				X		X
Surface, Air, Ground and Sky Temperature Dependent	X	X	X	X	X	X
Cloud Coverage Dependent	X		X			
Thermal Absorptance Dependent		X			X	
Combined Conv. and Rad. Coef.			X			
Direct Solar Radiation						
Weather File	X	X	X	X	X	X
Sky Diffuse						
Isotropic Model	X		X	X		
Anisotropic Model	X	X			X	X
Solar Beam Distribution						
Solar Tracking	X			X		X
Uniformly distributed over wall area		X	X		X	
Time Point for solar distribution						
Computed at each hour			X	X		
Computed at each time step	X	X			X	X
Internal Gains - Radiant Distribution						
Proportional to wall area	X		X	X		X
Based on surface absorptance		X			X	