INVESTIGATING THE IMPACT OF MODELLING UNCERTAINTY ON THE SIMULATION OF INSULATING CONCRETE FORMWORK FOR BUILDINGS

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ABSTRACT

Insulating Concrete Formwork (ICF) walls consist of cast in situ concrete poured between two layers of EPS insulation. The system can achieve very low U-values and high levels of air-tightness. This paper investigates the inconsistency in simulation results provided by nine widely used Building Performance Simulation (BPS) tools when calculating the energy consumption and the thermal performance of buildings using ICF. The aim is to identify the impact that the various modelling methods have on the simulation results. There were significant inconsistencies in the simulation results, especially for the annual and peak heating demand. Moreover, among the different calculation methods, the surface emissivity, the infiltration rate and the specification of the internal gains were found to cause significant variations.

INTRODUCTION

In Europe, the built environment accounts for 40% of the total energy use and 36% of the total CO_2 emissions (Foucquier et al.; 2013, McLeod et al., 2013). The UK Government, through the Climate Change Act 2008, has set targets to embrace a long-term climate change mitigation and adaptation strategy and to reduce CO_2 emissions by 80% in 2050 (compared to 1990 levels) (Climate Change Act, 2008).

Alongside carbon reduction targets, the government has to deal with the challenges imposed by the current housing shortage (Pan et al, 2007). Since 1990, population growth increased, whilst the number of completed dwellings per year dropped (Swann et al, 2012). The UK government is committed to increase the number of new houses, since further increase of population to 10.2 million people is expected by 2033 (compared to 2008 levels) (Monahan and Powel, 2011; Swann et al, 2012). One solution to this problem is the increased use of offsite Modern Methods of Construction (MMC). MMC are defined as a number of mostly off-site innovative prefabricated technologies in house building (Pan et al., 2007).

The present study focuses on one of the site-based MMC, called Insulated Concrete Formwork (ICF). ICF consists of modular prefabricated EPS hollow blocks and cast in situ concrete. The blocks are assembled on site and the concrete is poured in the void. Once the concrete has cured, the insulating formwork stays in place permanently. The resulting structure is a typical reinforced concrete wall (Chant, 2012). The ICF wall system has two main advantages in comparison to other lightweight MMC and conventional construction methods; when the concrete is placed, the structural performance of ICF is able to support concrete floors and staircases, increasing the overall thermal mass of the entire structure. Moreover, the system provides complete external and internal wall insulation, eliminating the existence of thermal bridging, providing very low U-values and high levels of air-tightness, when applied properly (Rajagopalan et al, 2009; Chant, 2012). The amount of research associated with ICF is limited in the UK. Nevertheless, previous studies conducted elsewhere (i.e. USA, Canada, New Zealand) describe a number of advantages, such as its thermal resistance and air-tightness, its resilience to fire and other natural disasters, sound reduction, structural strength and durability (NAHB, 1997; Chant, 2012).

ICF is generally perceived as merely an insulated panel. The internal layer of the insulation isolates the thermal mass of the concrete from the internal space and interferes with their thermal interaction. However, there is anecdotal evidence supporting the thermal storage capacity of the element’s concrete core (Chant, 2012). The overall aim of this research is to effectively quantify the “Thermal Mass” of ICF. One important aspect is therefore to understand how dynamic whole Building Performance Simulation (BPS) assesses transient heat transfer in and out of the ICF building fabric.

Spitler defines BPS as the simulation of building thermal performance using digital computers (Clarke and Hensen, 2015). BPS was first introduced in 1960s and it has been an active area of research ever since (Zhu et al., 2012; Clarke and Hensen, 2015). Based on descriptions of the construction, occupancy patterns and HVAC systems, BPS tools perform detailed heat-balance calculations at specified time-steps and are able to predict the energy required to maintain comfortable conditions under the influence of external inputs (i.e. weather, occupancy, infiltration) (Coakley et al., 2014). However, it is generally accepted that there is a high level of uncertainty and sensitivity associated with current BPS methods and tools (Hopfe and Hensen, 2011; Burman et al., 2012). This can lead to a lack of confidence in building simulation.

The main factors contributing to uncertainties and inaccuracies of the simulation predictions reside in the modelling methods and the different algorithms employed by the different BPS tools and are partly a consequence of the user input data (Burman et al., 2012; Zhu et al., 2012; Berkeley et al., 2014; Mantesi et al., 2015a; Strachan et al., 2015).

De Wit (1997) classified the various sources of uncertainty as follows:

- Specification uncertainties, (incomplete or inaccurate specification of building input parameters)
- Modelling uncertainties, (simplifications and assumptions of complex physical processes)
- Numerical uncertainties, (errors introduced in the discretation and the simulation model)
- Scenario uncertainties, (the external conditions imposed on the building)

All models represent a simplification of reality. In order to rely on BPS prediction with a degree of confidence, it is important to represent the actual performance of a building as accurately as possible (Hopfe, 2009). Current state-of-the-art BPS tools have several limitation related to air flow, lighting, HVAC systems, occupants representation and others (Clarke and Hensen, 2015).

This paper is a follow up study (Mantesi et al., 2015a; Mantesi et al., 2015b) aiming to analyse the divergence in the simulation results provided by nine state-of-the-art BPS tools when modelling the energy consumption and thermal performance of an ICF building. The analysis will contrast the simulation results provided by each of the nine BPS tools for the annual energy consumption and the peak thermal loads produced for a single zone test building and for three different construction methods, low mass, high mass and ICF wall assemblies (Figure 1). Furthermore, the paper aims to investigate the implications of the modelling uncertainties associated with the various calculation methods in the simulation results provided by two of the nine BPS tools. The research objectives are:

- To investigate the extent of divergence in the simulation results provided by the BPS tools.
- To investigate the deviation in the energy use when comparing ICF to low and high thermal mass construction methods.
- To identify the key parameters on the calculation algorithms responsible for discrepancies in the simulation results.

METHODOLOGY

The BESTEST method was used in the first step of the analysis to validate the models and to evaluate how each of the BPS tools calculate the effect of thermal mass in the loads calculation. The same single-zone test building was used in the following stages of the study to minimise the variables in the input data related to geometry and zoning, which were specified according to the BESTEST method. Three different construction methods were simulated; ICF, high mass and low mass. The ICF fabric description was based on actual construction details and was used as a reference to specify the U-values of the construction elements, which were kept constant among the three constructions. The main difference among the three building models was the level of thermal mass in the fabric. The input data and the U-values used for the building models are summarised in Table 1.

Table 1: Input data used for the building model

BUILDING MODEL DETAILS	
Floor Area	6m x 8m = 48m^2
Orientation	Long axis on East-West direction
Windows	Two double glazed windows, 2m x 3m each, on south façade, U-Value = 3.00 W/m^{2}K
U-Values (W/m^{2}K)	Walls = 0.106
	Floor = 0.095
	Ceiling = 0.112
HVAC system	Ideal loads
HVAC Set points	20^o Heating/ 27^o Cooling
HVAC Schedule	24hrs (Continuously On)
Internal Gains	200W (other equipment)
Infiltration	0.5ach

The DRYCOLD weather file, downloaded from NREL, representing a climate with cold clear winters and hot dry summers, was used for all simulations (Table 2).

Table 2: Indicative values of the weather file used for the simulations

WEATHER DATA	
Dry Bulb Temperature (C^o)	
Minimum	-24.4
Maximum	35
Mean	9.7
Direct Horizontal Solar Radiation (kWh/m^2.y)	1339.48
Diffuse Horizontal Solar Radiation (kWh/m^2.y)	492.34

The analysis was carried out in two parts. The first part presents an inter-model comparison on the annual energy consumption and the system peak loads, provided by the nine tools for the ICF building. The calculation were performed based on the default algorithms employed by each tool, aiming to reflect on the extent of variations in the simulation results that a user relying on the default settings of the tool would obtain. Error bars were used in the charts to

demonstrate the energy consumption of the low and the high thermal mass building cases. Five of the tools (used for the analysis) were proprietary commercial tools. For reasons of sensitivity and fairness, we have chosen not to name the tools. We do not feel that this distracts from the scientific merit of the paper.
The second stage was a systematic, parametric comparison for two of the BPS tools that provided very similar results in the first instance of the analysis. The aim was to understand the modelling uncertainties associated with the various calculation methods, even when the simulation results are very similar. Prior to proceeding to the parametric analysis it is crucial to determine that any divergence in the results is due to the differences in modelling methods and not caused by other factors. To achieve this, it was important to minimise the differences in the models created. Identical algorithms and constant values were used in both tools, making the models equivalent for comparison, leaving little ground for differences (i.e internal convective coefficients calculation, longwave radiation exchange etc) (Table 3). These two models will be further referred to as "equivalent models".

Finally, a number of special test cases was designed and simulated on the equivalent models aiming to investigate the impact of several key parameters when modelling ICF in whole BPS (Table 4). The results of the analysis are presented for the surface heat gains and losses occurring on the ICF South Wall.

RESULTS

System Loads Comparison

The system loads comparison indicates that the inconsistency in the simulation results provided by the nine BPS tools for the annual energy consumption (Figures 2 and 4) and the peak thermal loads (Figures 3 and 5) is more significant for heating than for cooling. The relative differences in the results, when comparing the maximum and minimum values provided by the tools is 57% for the annual heating demand (Figure 2) and 25% for the peak heating demand (Figure 3). In both cases, tool I estimates the lowest energy consumption, while tools G and H estimate the highest for annual heating and peak heating respectively.
The deviation in the simulation results is lower for the annual cooling energy consumption (Figure 4) and the peak cooling demand (Figure 5). In both cases, tool G estimates the highest values, around 22% increased, compared to tool D, which gives the minimum value for the annual cooling demand and around 14% higher than tool B for the peak cooling loads.
There are also inconsistencies in the simulation results provided by the tools for the other two construction methods. The divergence is again found to be higher for the heating energy consumption (Figure 2) and the heating peak loads (Figure 3). Table 5 summarises the relative differences between the maximum and minimum values in the simulation results for all three building cases. It can be seen that the divergence is always higher for the high mass case.

Table 5: Relative differences between the maximum and minimum estimated energy consumption in [%]

ENERGY USE	ICF	LOW MASS	HIGH MASS
Annual Heating	57%	30%	70%
Peak Heating	25%	18%	34%
Annual Cooling	22%	15%	29%
Peak Cooling	14%	11%	24%

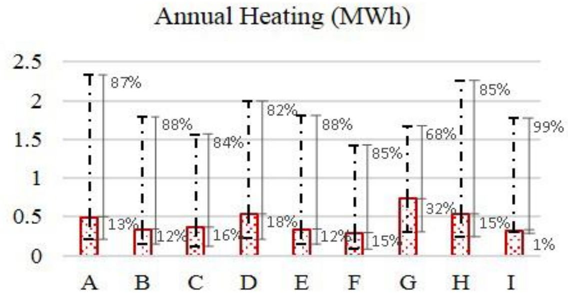

Figure 2: The graph demonstrates the results for annual heating energy consumption (MWh). The bars illustrate the results for ICF, with the upper limit of the dashed line showing the annual heating energy consumption of the low mass construction and the lower limit showing the results of the high mass construction.

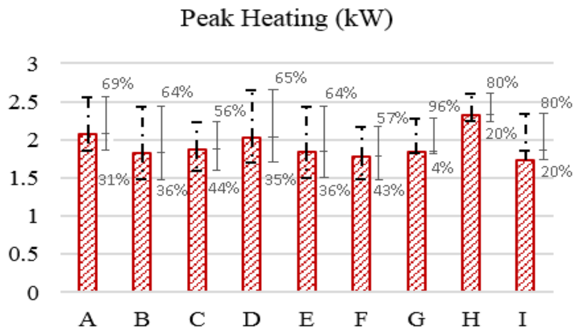

Figure 3: The graph demonstrates the results for peak hourly integrated heating loads (kW). The bars illustrate the results for ICF, with the upper limit of the dashed line showing the peak heating loads of the low mass construction and the lower limit showing the results of the high mass construction.

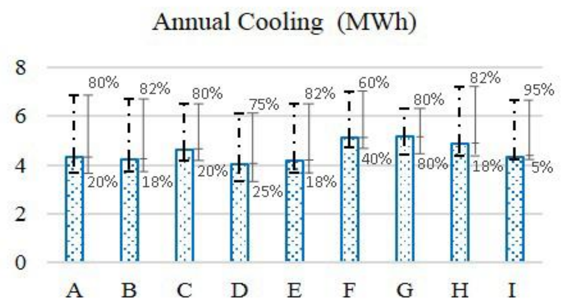

Figure 4: The graph demonstrates the results for annual cooling energy consumption (MWh). The bars

illustrate the results for ICF, with the upper limit of the dashed line showing the annual cooling consumption of the low mass construction and the lower limit showing the results of the high mass construction.

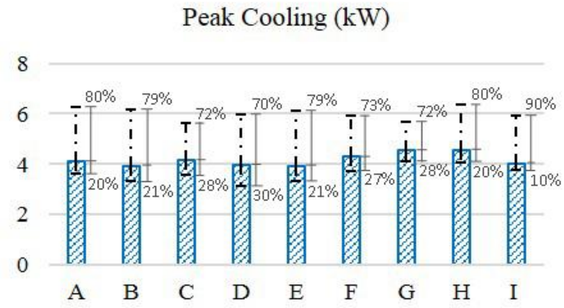

Figure 5: The graph demonstrates the results for peak hourly integrated cooling loads (kW). The bars illustrate the results for ICF, with the upper limit of the dashed line showing the peak cooling loads of the low mass construction and the lower limit showing the results of the high mass construction.

In the comparison of ICF thermal performance to the low and the high thermal mass cases, the general observation is that ICF falls between the aforementioned construction methods and behaves closer to the high thermal mass building. In the annual heating energy consumption ICF requires on average 85% less energy than the low mass case. In the annual cooling demand the difference is around 80% (averaged over all nine BPS tools). In the peak heating and cooling loads, the average reduction is 70% for heating and 77% for cooling. The inter-model comparison shows that in all of the cases (with exception to peak heating demand), Tool I estimates the greatest difference in the energy use between ICF and low mass construction, while tool G estimates the least.

"Equivalencing" the Models

Tools E and I provided very similar results in the inter-model comparison and were selected for further analysis. The same algorithms and user input values were applied (Table 3), to reduce the differences in the models created for comparison. Figures 6 to 9 illustrate the annual energy consumption and the peak system loads for the comparable models plotted monthly.

There is an insignificant divergence in the annual cooling energy consumption and the peak cooling loads, where tool I provides slightly increased demand to tool E during summer months (Figure 7).

Moreover, there is an incompatibility in the peak heating loads for the month of June, where tool E suggests that there is a relatively small demand, while tool I suggests zero demand. Overall, as it can be seen from the charts, there is a general consistency in the results, which confirms that the differences between the two models are minimised and the equivalent models are suitable for the parametric analysis.

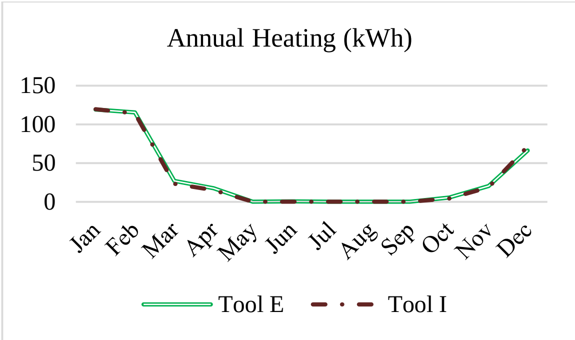

Figure 6: Annual heating energy consumption of equivalent models. Monthly breakdown

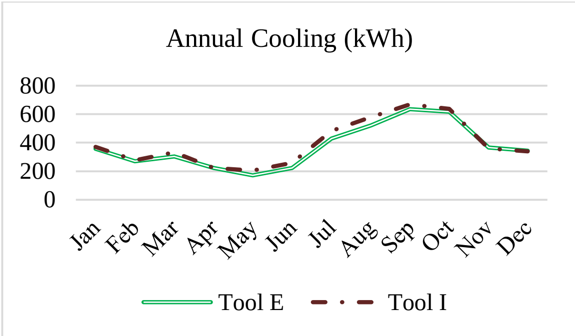

Figure 7: Annual cooling energy consumption of equivalent models. Monthly breakdown

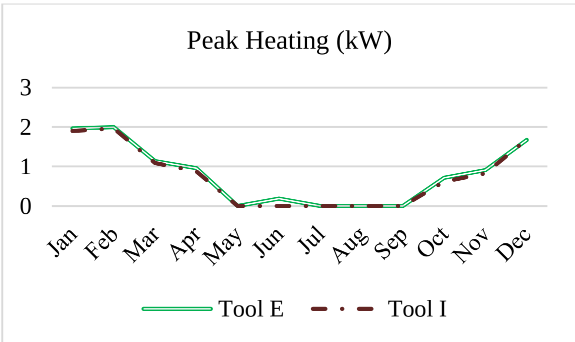

Figure 8: Peak heating demand of equivalent models. Monthly breakdown

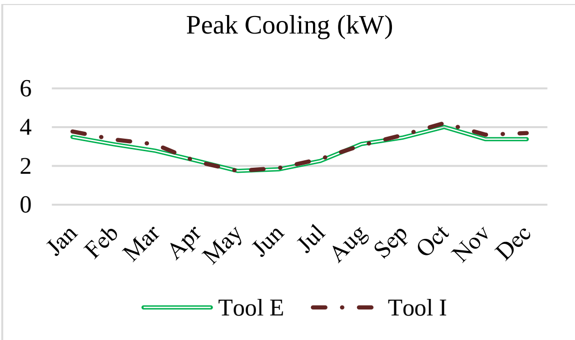

Figure 9: Peak cooling demand of equivalent models. Monthly breakdown

Special Test Cases Results

The test cases included in the parametric analysis are summarised in Table 4. The results are plotted for the

South ICF wall of the test building case. The aim is to analyse how the two BPS tools simulate the performance of ICF with regard to the heat transfer mechanisms that occur in the wall elements. Figure 10 indicates that there is a consistent 9% divergence in the solar gains of the internal surface of the wall in all test cases, which is unaffected of the input variables. Tool E calculates the distribution of beam solar radiation uniformly over the entire wall area, while tool I relies on solar tracking calculations. The results of both tools are slightly decreased in TC4, where the solar absorptance of the wall is increased to 0.6 and the divergence is increased to 11%.

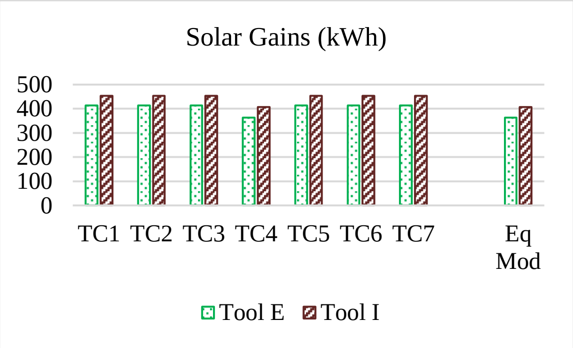

Figure 10: Solar gains in South ICF wall

The divergence in the wall's conduction losses varies in the several test cases (Figure 11). There is an initial 12% difference between the two tools in the basecase, which increases to 18% in TC2, when the default algorithms are used to calculate the internal convection coefficient of the wall surface. The divergence decreases to 6% for TC3, where the surface IR emissivity is 0.9 and then increases again (13%) in TC4 when the solar absorptance is 0.6. In the presence of internal gains, either 100% convective (TC5) or 100% radiative (TC6), the difference between the tools in the conduction losses decreases to 4%. Finally, in TC7, when infiltration is introduced in the analysis, the divergence in the simulation results increases to 20%.

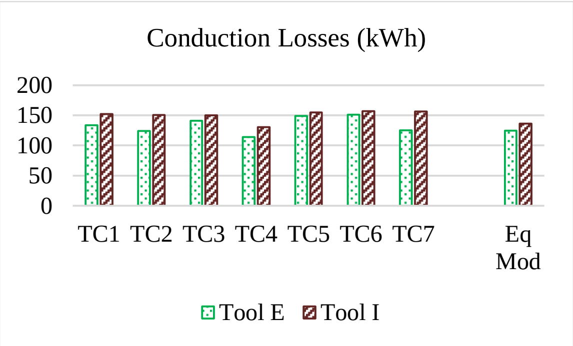

Figure 11: Conduction losses in South ICF wall

Even though the same constant value is used in both models for the internal surface convection coefficient, it can be seen that the convection losses of the internal surface of the South ICF wall varies among the test cases (Figure 12). There is a 41% difference in the basecase, which slightly decreases to 37% in TC2 (default algorithm for convection coefficient). The difference is further decreased when the surface IR emissivity is 0.9 in TC3 to 23%. It is interesting to notice that when the internal gains are 100% convective (TC5) there is a difference of 35% in the convection heat losses of the surface between the two tools. Whereas, when the internal gains are 100% radiative (TC6) the divergence in the results decreases to 13%. Tool E calculates the radiant distribution of the internal gains based on surface absorptance, while tool I calculates their distribution proportional to the wall area.

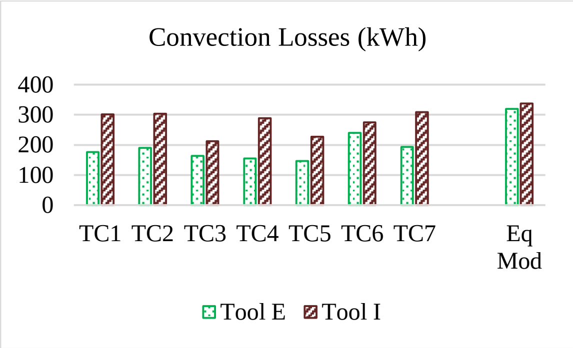

Figure 12: Convection losses in South ICF wall

The maximum inconsistency in the simulation results between the different test cases is found to be in the long-wave radiation losses of the internal surface (Figure 13). In the basecase, tool E shows increased long-wave radiation losses by 61% compared to tool I, which is relatively consistent in TC2, TC4 and TC7. When the surface emissivity increases to 0.9 in TC3, TC5 and TC6 the difference between the two tools is reversed. Tool I gives an increased value for the long-wave radiation losses 16% in TC3 and 13% in TC5 and TC6.

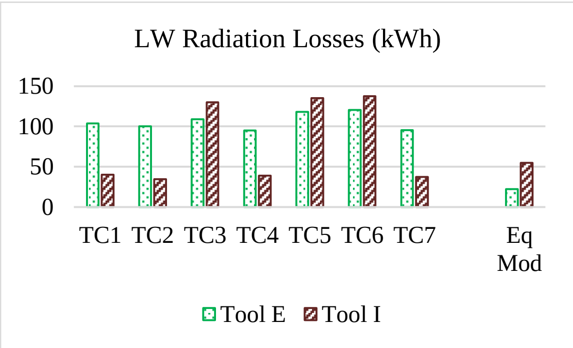

Figure 13: Long-wave radiation losses in South ICF wall

DISCUSSION

The analysis shows that there are inconsistencies in the simulation results provided by the nine BPS tools when modelling an ICF building. The relative differences between the maximum and minimum values were more significant for the annual and peak heating demand. The divergence was obvious in the results provided for the other two construction methods. It was also found that the difference between the maximum and minimum values was more substantial for heating demand and it was increasing according to the thermal mass of the fabric (highest divergence for the high mass building).

The results of the comparative analysis between the ICF, low and high mass construction methods are consistent with the findings from previous studies (Gajda and VanGeem, 2000; Rajagopalan et al., 2009). The general observation is that ICF's energy consumption falls between the other two construction methods and sits closer to the performance of the high mass building.

Two of the tools were used in the parametric analysis of the second stage; the same algorithms and user input variables were used, where possible. The results of the special test cases confirm previous work (Zhu et al., 2012; Mantesi et al., 2015a), indicating that the key factors contributing to inconsistencies in the simulation results provided by different BPS tools reside in the different modelling methods adopted by each tool and fall under the category of modelling uncertainties (Hopfe, 2009).

Among the different sources of heat gains and losses calculated for the internal surface of the ICF South wall, long-wave radiation losses were found to exhibit the greatest inconsistency among the different test cases, although the same view factors were specified for all surfaces in both models. The surface IR emissivity was found to have a substantial impact on the results' divergence.

The inconsistencies in the calculation of surface conduction losses were also found to vary according to the different test cases. The difference between the two tools was decreased when the surface IR emissivity was 0.9 and increased in every other case, reaching the highest value when infiltration was introduced.

Concerning convection heat losses, even though constant values were used for the internal surface convection coefficient, there was divergence in the results provided by the two tools, varying according to the different test cases; the difference decreased when the surface IR emissivity was set to 0.9. Moreover, it was interesting that for 100% convective internal gains the divergence between the two tools was relatively high, while when the internal gains were set to 100% radiative, their difference was significantly reduced, although the two tools use different methods in calculating the radiant distribution of internal gains.

Even though the two tools calculate the distribution of solar gains using different modelling methods, it was observed that it had little impact on the results' divergence. Both BPS tools provided relatively similar results, consistent among the different test cases.

RESEARCH LIMITATIONS

The analysis presented in this paper was based on a simple, unoccupied, single-zone building, using constant values for the dynamic loads (i.e. internal gains, infiltration rates). The impact of variable airflows (ventilation and infiltration), realistic occupancy patterns and internal gains were excluded from the analysis. Moreover, the special test cases were only performed for two of the nine BPS tools included in the inter-model comparative analysis. In order to draw robust conclusions on the impact of the different calculation methods, the parametric analysis should include more BPS tools.

CONCLUSIONS

This paper analysed the divergence in simulation results provided by nine BPS tools, when modelling an ICF single-zone building, aiming to interrogate the extent of variation in the annual energy consumption and the system peak loads estimated by the tools. The results showed that there were significant inconsistencies in the simulation predictions when simulations were performed using the default algorithms employed by the tools. The divergence was found to be more substantial for the annual and peak heating demand and increased accordingly with the level of thermal mass in the fabric. ICF's energy consumption was compared to low and high thermal mass building and it was found to fall between the other two construction methods, performing closer to the high mass building.

Two BPS tools were selected for further analysis. A number of special test cases was designed and simulated, aiming to reflect on the impact of several key input variables on the results divergence. The results of the special test cases indicated that the surface IR emissivity had a significant impact on the simulation of surface long-wave radiation, conduction and convection losses. The infiltration rate affected significantly the inconsistency between the two tools when simulating the surface conduction losses. The divergence in the convection heat losses was affected by the specification of the internal gains to convective or radiative. Finally, the distribution of solar gains was found to have an insignificant impact on the results' divergence.

FUTURE WORK

This work is part of a doctoral research project seeking to investigate the thermal performance of ICF and the accuracy of BPS when modelling an ICF building. The results of the inter-model comparison provided some feedback on the extent of variation among the different tools. However, it is not possible to evaluate the accuracy of BPS predictions. A monitoring study on an ICF building case is planned and it is expected to provide valuable information on the actual energy consumption and the thermal performance of ICF. Moreover, it will serve as a means of empirical validation for the BPS simulation results.

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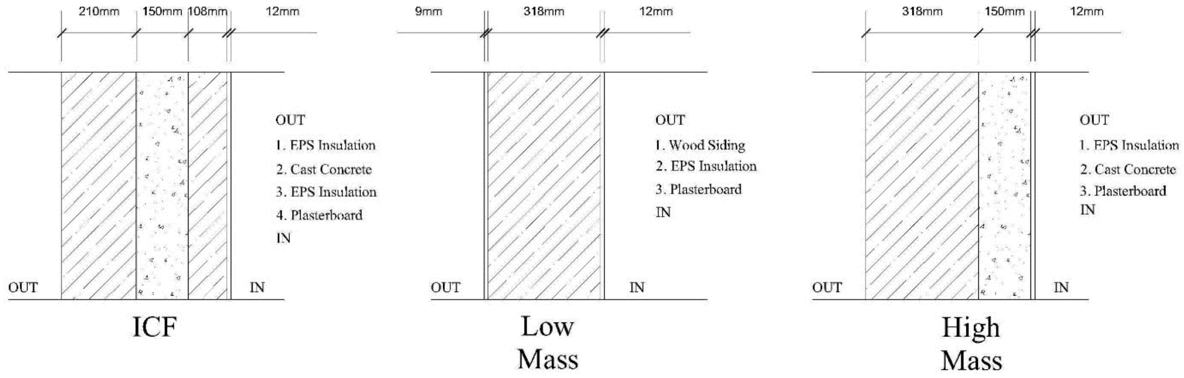

Figure 1: Cross-section of the three wall construction methods used in the analysis

Table 3: Algorithms used in equivalent models

Simulation Solution (Loads, Plant, System Calculations):	Simultaneous Calculations
Time Step:	6/h (10mins)
Warming up:	25 days
Heat Balance Solution Algorithms:	Surface and Air Heat Balance Equations
Conduction Solution Method:	Finite Difference Solution (Space discretisation : 3)
Internal Convection Coefficient:	Fixed, User-defined value (hi=3.16)
External Convection Coefficient:	Fixed, User-defined value (he=24.17)
Radiant Heat Flow Models:	“Script F”
	Mean Radiant Temperature Model
Interior Surface Long-Wave Radiation Exchange:	User-defined view factors
Exterior Surface Long-Wave Radiation Exchange:	Surface, Air, ground and Sky Temperature dependent
Solar Beam and Diffuse Distribution:	Default Algorithms
Sky Diffuse:	Anisotropic Model
Internal Gains - Radiant Distribution:	Default Algorithms

Table 4: Description of Specialised Test Cases Used in the Parametric Analysis

TEST CASES	**INT GAINS (W)**		**INFILT (ACH)**	**IR EMISSIV**		**SOL ABSORP**		**CONV COEF**		**COMMENTS**
	Conv	Rad		Int	Ext	Int	Ext	Int	Ext	
TC1	0	0	0	0.1	0.1	0.1	0.1	3.16	24.17	BaseCase
TC2	0	0	0	0.1	0.1	0.1	0.1	Default	Default	Convection Coefficient
TC3	0	0	0	0.9	0.9	0.1	0.1	3.16	24.17	Long-Wave Radiation Exchange
TC4	0	0	0	0.1	0.1	0.6	0.6	3.16	24.17	Short-Wave Radiation Exchange
TC5	200	0	0	0.9	0.9	0.1	0.1	3.16	24.17	Convective Internal Gains
TC6	0	200	0	0.9	0.9	0.1	0.1	3.16	24.17	Radiative Internal Gains
TC7	0	0	0.5	0.1	0.1	0.1	0.1	3.16	24.17	Infiltration