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Modelling Buildings For Energy Use: A Study Of The Effects Of Using Multiple Simulation Tools And Varying Levels Of Input Detail.

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Abstract:

Increasingly, legislation (including the imminent requirement for the energy labelling of buildings) is requiring the building industry to produce more accurate estimates of the energy performance of buildings and building services in use. This accuracy is unlikely to be met through means other than dynamic simulation models. However, in practice detailed information about important factors which affect the energy use of both new buildings during the design phase and existing buildings during operation can be very limited.

This paper considers the accuracy with which the existing dynamic simulation models EnergyPlus and ESP-r predict temperature in one existing commercial office building for which the authors have detailed information - including measurements of internal and external conditions at every 15min intervals over 1 year period. It examines the predicted temperatures produced using two different simulation tools with two different modelling strategies: single zoning and multiple zoning. The predictions of internal temperature for the office building are then compared with the physical measurement of temperature in the building to provide an indication of the accuracy with which the complexities of a real situation can be predicted.

The work forms part of the European project AUDITAC: "Field Benchmarking and Market Development for Audit Methods in Air Conditioning", and builds on a previous project undertaken by the Welsh School of Architecture – "AC Energy Use in Offices: Field Monitoring Study".

As part of the process, the paper discusses the strategy used to generate compatible input data for the two energy modelling software packages. The establishment of compatibility is important to enable valid comparisons to be drawn between the different simulation algorithms.

The paper ends by drawing preliminary conclusions as to the most important building modelling variables for the test building, and therefore which variables should have the most time spent on them when establishing values. Similar studies will be undertaken on a number of buildings in various typologies and European climatic conditions to ascertain how the relative importance of these variables changes. This information is particularly important for deciding which data must be provided to enable building modellers to produce the most accurate models possible for energy analysis.

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Background

The recent BESTEST studies[1] have examined how closely various modelling tools agree with each other in modelling simple highly monitored enclosures. These studies show that, even for these simplified situations, the models can vary in their predictions of Temperature and Energy requirements for the buildings.

With these differences at the simple level it is not surprising that there are few independent objective studies which examine how closely modelling tools predict the actual performance of real buildings and building services. This lack of objective studies is worrying as we are rapidly moving towards a reliance on modelling to make major design and investment decisions about our buildings and services, including decisions on whether a design can be built or not.

The Welsh School of Architecture has recently completed a detailed monitoring study of the energy use in A/C systems in a number of UK Office Buildings. The outputs of this work are being used as part of the underpinning data to the AUDITAC project, as well as being used within the UK to help update relevant professional guidance and regulations.

To enable the results of the UK Office study to be applied more generally across Europe the Welsh School of Architecture is using E+ and ESP-r to model a selection of the buildings, usage and services of the monitored UK Office buildings. The aim is to establish how accurately the models predict the monitored conditions in the buildings, with all the uncertainties and inaccuracies that occur in modelling real buildings.

Clearly with only one building modelled then there will still be much uncertainty about how well the models can actually predict the real performance of other buildings and systems. This paper therefore is purely to establish that the range of parameters and their variations input into the models are capable of encompassing the measured temperatures in the real building modelled, and to establish which of the parameters are relatively the most important.

Future work will model a further 14 or so buildings from the study to establish a greater degree of confidence in the findings.

Simulation Tools – Issues and Details

Each of the tools has its own data input requirements, which means that to model exactly the same building in each tool is harder than it appears. Modelling limitations and equivalences referring to geometry, topology, shading and scheduling need to be listed for each tool.

In this comparison, most geometry issues refer to limitations determined by ESP-r such as the maximum number of vertices per zone and per surface, a maximum number of surfaces per zone, a limited number of windows per surface, etc. Most of the topology issues refer to compatibility not restrictions or limitations:

- Each surface cannot be adjacent to more than one surface,
- Surfaces adjacent to zones with similar conditions are assigned as adiabatic
- Voids are modelled in ESP-r as fictitious surfaces and in Energy Plus as internal windows allowing equivalent process of heat transfer between zones.

Shading issues are the most difficult ones to make compatible. In ESP-r they need to be modelled separately and linked to the zone they are going to affect. The geometry is restricted to rectangular shapes and there are no possibilities of rotation around the X or Y axis. There is also no account for interzonal shading or self shading. To allow comparisons to be made shading calculations were set to “off” in both ESP-r and EnergyPlus. This should not affect the calculations for this building greatly as the degree of external shading is minimal. ESP-r also shows limitations in schedule as weekdays are all grouped together.

The thermophysical properties of opaque and transparent materials, ventilation, infiltration and internal gains were also made compatible. Parameters common to both tools are: flow rates, specific heat, density, conductivity, thickness, absorptivity, emissivity, and transmittance.

Modelling Reality – The Case Study

The reality of the modelling of real buildings in use, and the accurate modelling of buildings in the design phase, is that, generally, qualitative but not quantitative data are available for many of the important modelling variables.

Qualitative information for buildings includes descriptions of what the building is made of, its materials, and how the building has been used (the number of people inside it, when they are generally there, and the amount of equipment and lights in its interior). Quantitative information for buildings includes geometry (floor plans, sections, etc.), thermophysical properties of materials, and the magnitude of internal gains, ventilation and infiltration.

Generally, only accurate information about geometry is available for most buildings and, sometimes, general data about occupancy patterns, lighting and small power as in this case study. In this context buildings can only be modelled as best understood and assumptions from zoning to all other missing parameters need to be made.

Case study building description

The case study is a speculative office building in Cardiff (UK) built in 1992. It consists of 2 stories and is steel framed structured, with pre-cast concrete floor decks, masonry cavity walls and a wood frame pitched roof system. The glazing system is clear double and all windows are openable. Only the third floor was considered in this analysis. It is owner occupied with relatively intensive but normal office use, on a hot-desk management style. It is mainly open plan with some small conference rooms and individual offices. Normal occupancy is 8.00am to 6.00pm form Monday to Friday. A survey has been undertaken to establish occupancy numbers and patterns, equipment and lighting details and usage.

Zoning

The first point to be resolved in modelling reality is how to zone the building. There are many issues to be considered in choosing how to zone a building, from the purpose of the modelling itself to limitations of simulation engines and the position of the temperature sensors when the target is to compare to measured data. For this paper the target is to predict internal temperatures and compare them to measured data in a “freerun” period, therefore the zones do not necessarily need to be set based on the installed HVAC system. They need to be in accordance with the enclosure and the sensor location. In this building there is only one sensor and the building is mainly an open plan office. It is believed that a single zone model is more appropriate to simulate average internal temperatures whereas a multiple zone model, trying to reproduce the internal lay-out and occupancy patterns, would be more appropriate to show local temperatures.

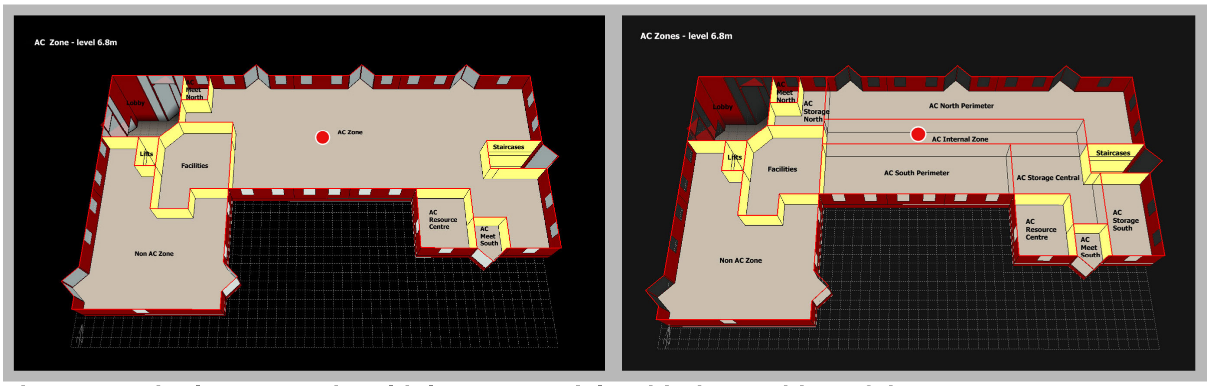

Figure 1 – Single zone and multiple zone models with the position of the temperature sensor

Figure 1 shows the single zone model and the multiple zone model both with the position of the temperature sensor – the red dot. The multiple zone model divides the open plan office into virtual zones according to the occupancy and the lay-out.

However, issues associated with limitations in the simulation engine, as well as the modelling itself, arise when a multiple zone model is to be created. The boundaries between zones are defined based on the internal lay-out and occupancy and are therefore virtual surfaces. Virtual, fictitious or void surfaces have limiting properties in all tools. They basically allow heat exchange through conduction and short wave radiation. No mass exchange and longwave radiation exchange between zones are accounted for. In this context, a simplification of mass exchange between the internal zone, where the sensor is located, and the adjacent ones is made. More complex simulations using CFD or COMIS were not used because of further compatibility issues.

Simulating Reality – The Case Study

The target of the simulation in this Case Study is to see how far predicted temperatures will be from measured temperatures and to check if the predicted temperatures from different sources "agree" with each other. Results will be compared for single and multiple zone models in 'free run' Spring and Summer period conditions. A 'free run' period is one during which no mechanical heating or cooling has been employed in the building and has been identified in this Case Study from measured data as lasting from the 27th of May to 16th of June (Spring season) and from 8th July to 28th July (Summer season) in the year of 2002. 'Free run' conditions are used to reduce the number of modelling variables to be addressed, as modelling a period when heating or cooling are provided would have also needed quantitative and qualitative data about the services, their setpoints and controls.

The simulation will start with a so-called "base" condition, with all the quantitative variables set to "average" values. Average values for thermophysical properties of materials are set according to various sources[2,3,4,5,6,7,8,9]. Air change rates are assigned according to MacDonald[2] and CIBSE[4], Internal Gains are set according to MacDonald[2], CIBSE[4], ASHRAE[10] and Knight[11] and schedules are based on UK data[12].

The values obtained by simulation are to be compared to each other and to the measured data.

Ventilation is assumed to be equally distributed over the floor area, because it is mechanically provided, and infiltration in the multiple zone model is calculated according to the amount of exposed area of each zone. The overall infiltration rate in m3/s is divided by the perimeter exposed area and multiplied by the percentage exposed area of each zone to provide the infiltration rates to each zone. The internal zones are assumed to receive air only from mechanical ventilation.

Mass exchange between the internal zones, using a simplified approach, was not addressed because in ESP-r air can be purchased from only one of the adjacent zones whereas in Energy Plus it can be purchased from as many zones as the user needs. A simplified solution to this problem was adopted by assuming equally distributed internal gains over the open plan office area.

Input values for the sensitivity analysis

Once the building is modelled as best understood with the information available, a probable range of values for each parametric variation is defined to enable a sensitivity analysis to be undertaken. These ranges are obtained from the same sources as the average values above. Parametric runs are divided into 3 groups as shown in Table 1.

Table 1 – Input values for the sensitivity analysis

Group		Minimum	Average	Maximum
Air changes				
	Ventilation Rates	8 l/s person	16 l/s person	36 l/s person
	Infiltration Rates	0.15 ach	0.35 ach	1.25 ach
Internal Gains				
	Activity levels	115 W/person	130 W/person	140 W/person
	Lighting levels	9.79 W/m2	-	11.5 W/m2
	Small power Rates	9.26 W/m2	21.38 W/m^2	37.02 W/m2
Materials				
	Glass transmittance	0.228	0.565	0.901
	Glass conductivity	0.604 W/mK	1.294 W/mK	1.984 W/mK
	Wall insulation conductivity	0.025 W/mK	0.039 W/mK	0.053 W/mK
	Ceiling insulation conductivity	0.025 W/mK	0.039 W/mK	0.053 W/mK

Findings

Comparisons between measured data and predictions from single zone Energy Plus / single zone ESP-r, multiple zone Energy Plus / multiple zone ESP-r and single zone / multiple zone for both tools are primarily done to check which zoning strategy appears to best predict temperatures as close as possible to the measured values, as well as which assumptions would provide best agreement between the tools. The group of comparisons providing the best "match" are then further investigated through a parametric sensitivity analysis using the input values already described.

Single Zone Models

The graphs in Figures 2a and 2b for Spring and Summer periods show that, in general, both software tools "agree" with each other. ESP-r tends to predict slightly higher temperatures than Energy Plus but the shape of both predicted temperatures is very, very similar. Maximum differences between Energy Plus and ESP-r results vary from 0.8ºC, when the minimum Spring temperature occurs, to 0.7ºC, when the maximum Summer temperature occurs. On average temperatures vary 0.1ºC which indicates that even different algorithms provide very similar results once the input data is compatible.

The measured temperature values are shown in red to give an indication of how different the predicted values are from reality, especially in the Summer period. Average differences from predicted temperatures to real ones are shown in Table 2 confirming larger discrepancies in the summer period.

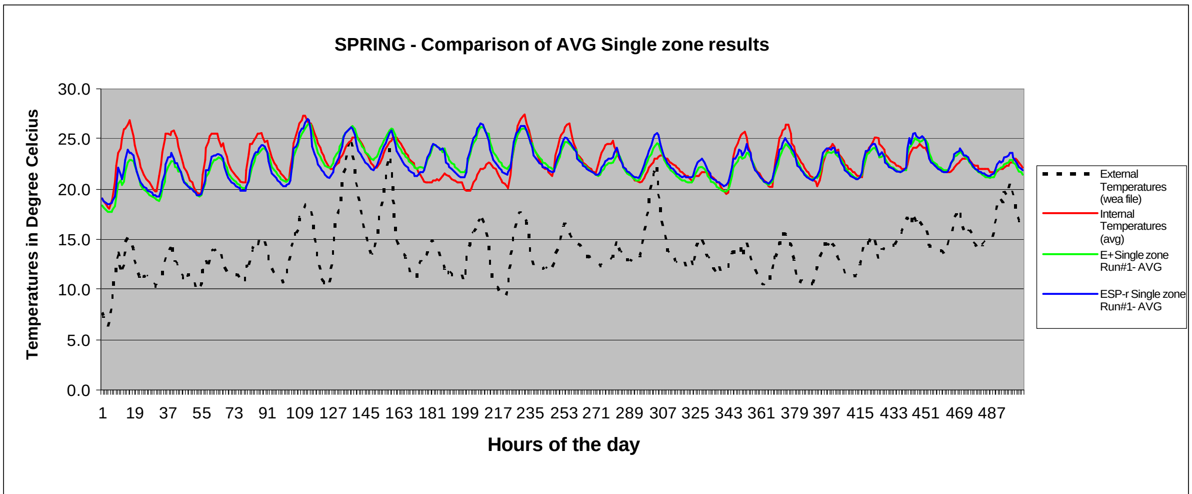

Figure 2a – Comparison of Single zone models in the Spring Season

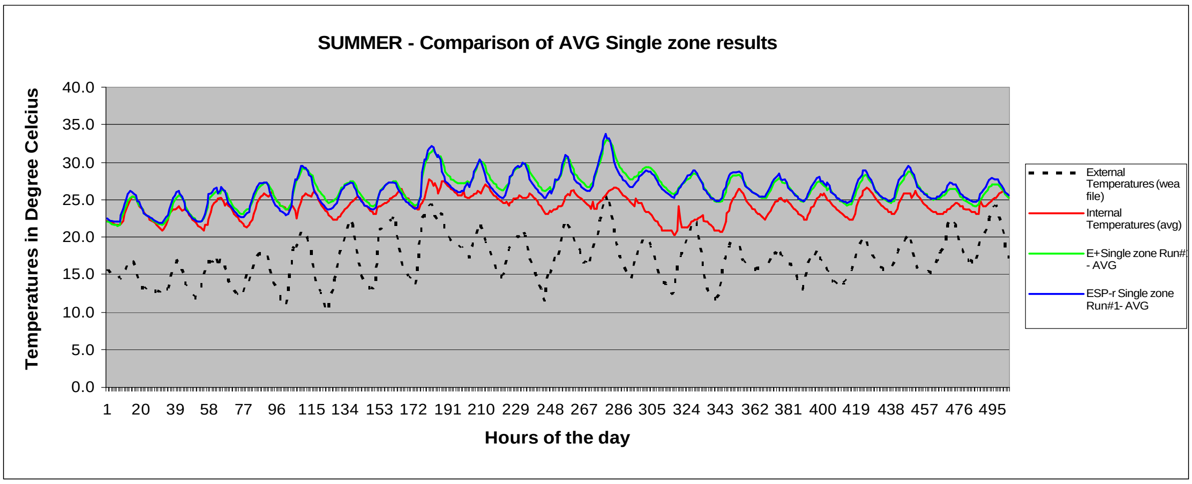

Figure 2b – Comparison of Single zone models in the Summer Season

Table 2 – Statistic analysis of the single zone model - Predicted temperatures

SPRING	**Measured value**	E+ - AVG	ESP-r - AVG	Range of agreement between the 2 software	Difference between the measured and simulated
Average	22.8ºC	22.5ºC	22.6ºC	0.1ºC	From 0.2ºC to 0.3ºC
Stand Dev	1.8ºC	1.7ºC	1.6ºC	0.1ºC	From 0.1ºC to 0.2ºC
Max	27.4ºC	26.5ºC	27ºC	0.5ºC	From 0.4ºC to 0.9ºC
Min	18.1ºC	17.7ºC	18.5ºC	0.8ºC	0.4ºC

SUMMER	**Measured value**	E+ - AVG	ESP-r - AVG	Range of agreement between the 2 software	Difference between the measured and simulated
Average	24.1ºC	26.4ºC	26.3ºC	0.1ºC	From 2.2ºC to 2.3ºC
Stand Dev	1.5ºC	2.1ºC	2.1ºC	0ºC	0.6ºC
Max	27.7ºC	33ºC	33.7ºC	0.7ºC	From 5.3ºC to 6ºC
Min	20.3ºC	21.5ºC	21.8ºC	0.3ºC	From 1.2ºC to 1.5ºC

Multiple Zone Models

In this case, the graphs in Figures 3a and 3b show that the software do not "agree" with each other as closely as they do in the single zone model. Differences between Energy Plus and ESP-r vary from 2.3ºC when the maximum Spring temperature occurs to 6.6ºC when the minimum Spring temperature occurs. In general, Energy Plus underestimates temperatures in Spring but is near the measured temperatures in Summer. ESP-r is near the measured temperatures in Spring but overestimates the temperatures in Summer.

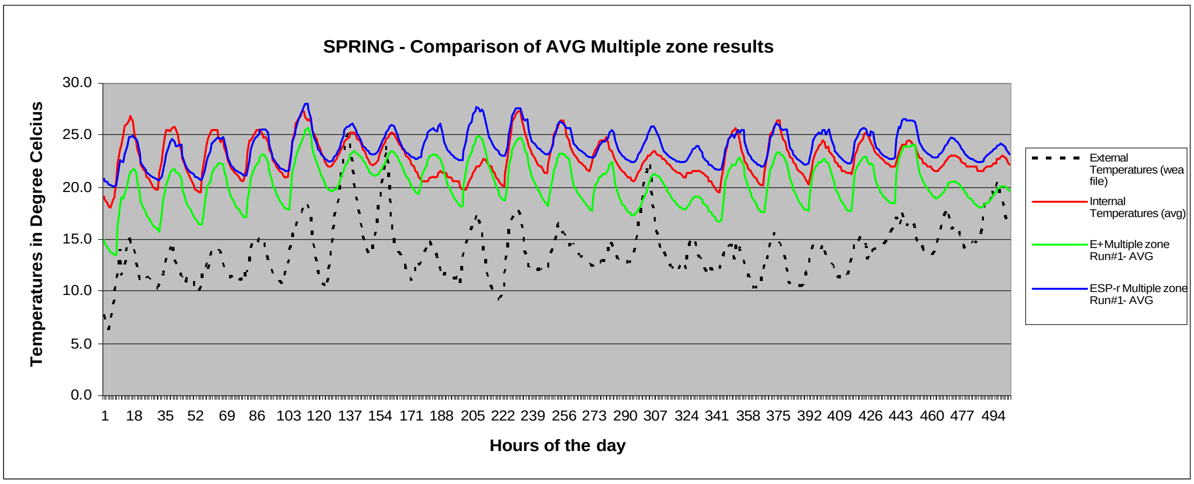

Figure 3a – Comparison of Multiple zone models in the Spring Season

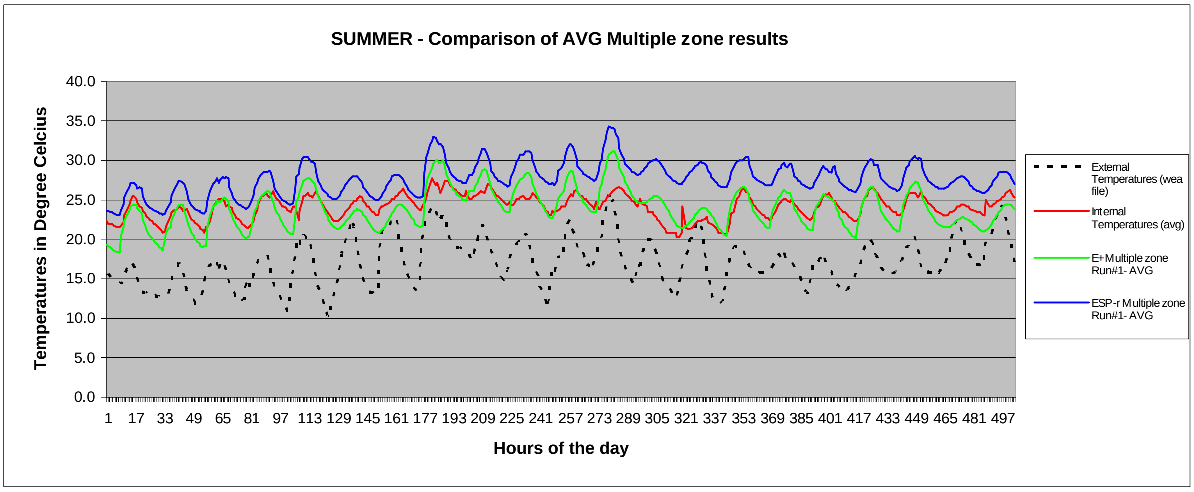

Figure 3b – Comparison of Multiple zone models in the Summer Season

Table 3 provides a simple statistic analysis on the measured and predicted temperatures and simplifies the understanding of the graph.

Table 3 – Statistic analysis of the multiple zone model - Predicted temperatures

SPRING	**Measured value**	E+ - AVG	ESP-r - AVG	Range of agreement between the 2 software	Difference between the measured and simulated
Average	22.8ºC	20.3ºC	23.8ºC	3.5ºC	From 1ºC to 2.5ºC
Stand Dev	1.8ºC	2.2ºC	1.6ºC	0.6ºC	From 0.2ºC to 0.4ºC
Max	27.4ºC	25.7ºC	28ºC	2.3ºC	From 1.7ºC to 0.6ºC
Min	18.1ºC	13.5ºC	20.1ºC	6.6 ºC	From 2ºC to 4.6ºC

SUMMER	**Measured value**	E+ - AVG	ESP-r - AVG	Range of agreement between the 2 software	Difference between the measured and simulated
Average	24.1ºC	23.9ºC	27.7ºC	3.8ºC	From 0.2ºC to 3.6ºC
Stand Dev	1.5ºC	2.5C	2.1ºC	0.4ºC	From 0.6ºC to 1ºC
Max	27.7ºC	31.2ºC	34.4ºC	3.2ºC	From 3.5ºC to 6.7ºC
Min	20.3ºC	18.3ºC	23.1ºC	4.8ºC	From 2ºC to 2.8ºC

Single zone models compared to multiple zone models

According to the graphs in Figures 4a and 4b, the most noticeable trend is that generally the single zone models appear more consistent with each other and the measured temperatures. Therefore whilst it is difficult to draw any firm conclusions about the use of single zone versus multiple zone models from this data, there do not appear to be any compelling reasons to undertake the greater complexity of multiple zone modelling.

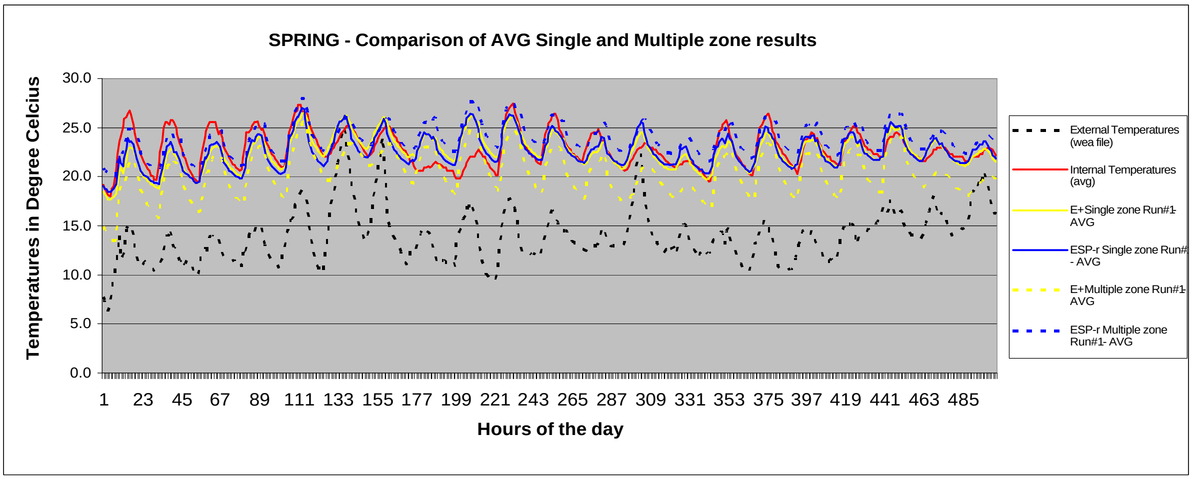

Figure 4a – Comparison of Single and Multiple zone models in the Spring Season

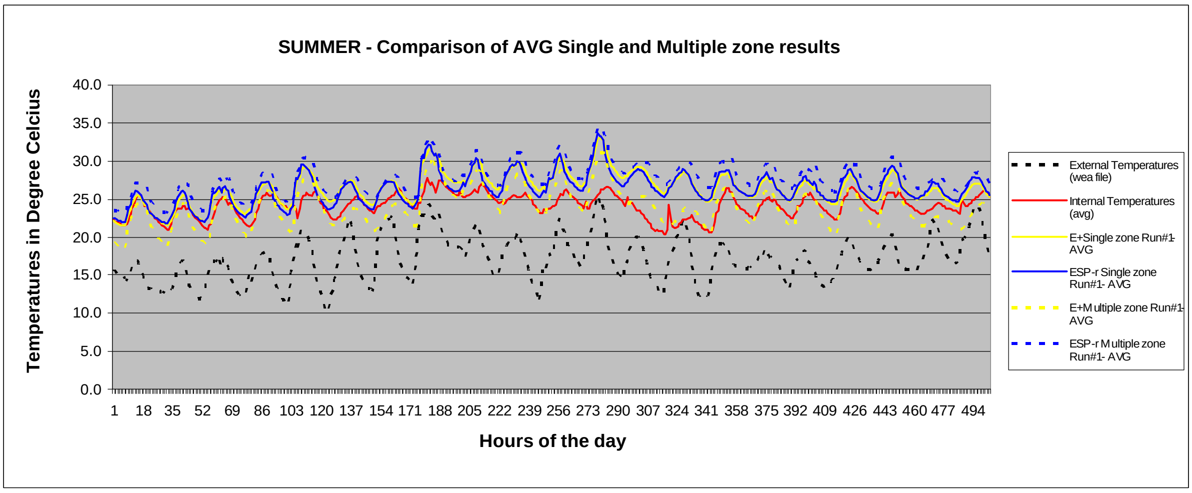

Figure 4b – Comparison of Single and Multiple zone models in the Summer Season

Sensitivity analysis of single zone models

As the single zone models are the ones that best “agree” with each other and show results very similar to the measured temperatures in this building, we chose to undertake the sensitivity analysis on these models.

Table 4 shows the range of agreement between the 2 software for all the runs that are part of the sensitivity analysis. Differences in predicted temperatures vary from 0.1ºC to 0.9ºC between Energy Plus and ESP-r data confirming the good degree of agreement in all the parametric runs. And in most of the cases measured temperature tends to fall within the predicted temperature ranges.

Table 4 – Statistic of the sensitivity analysis - Predicted temperatures

SPRING	Measured value	Air Exchange: Range of agreement between the 2 software	Air Exchange: Temperature variations	Air Exchange: Range of variation	Internal Gains: Range of agreement between the 2 software	Internal Gains: Temperature variations	Internal Gains: Range of variation	Materials: Range of agreement between the 2 software	Materials: Temperature variations	Materials: Range of variation
Average	22.8ºC	Between 0.1ºC and 0.2ºC	From 19.3ºC to 24.8ºC	5.5ºC	Between 0ºC and 0.2ºC	From 21ºC to 24.4ºC	3.4ºC	Between 0ºC and 0.2ºC	From 21.4ºC to 23.9ºC	2.5ºC
Stand Dev	1.8ºC	Between 0.1ºC and 0.3ºC	From 1.4ºC to 2.7ºC	2.3ºC	Between 0ºC and 0.1ºC	From 1.4ºC to 2.2ºC	0.8ºC	Between 0ºC and 0.1ºC	From 1.6ºC to 1.8ºC	0.2ºC
Max	27.4ºC	Between 0.1ºC and 0.6ºC	From 24.6ºC to 31.2ºC	6.6ºC	Between 0.1ºC and 0.5ºC	From 25.3ºC to 30.3ºC	5ºC	Between 0.4ºC and 0.6ºC	From 26ºC to 28.1ºC	2.1ºC
Min	18.1ºC	Between 0.3ºC and 0.8ºC	From 12.9ºC to 20.5ºC	7.6ºC	Between 0.7ºC and 0.9ºC	From 17ºC to 19.4ºC	2.4ºC	Between 0.6ºC and 0.8ºC	From 16.6ºC to 20ºC	3.4ºC

SUMMER	Measured value	Range of agreement between the 2 software	Temperature variations	Range of variation	Range of agreement between the 2 software	Temperature variations	Range of variation	Range of agreement between the 2 software	Temperature variations	Range of variation
Average	24.1ºC	Between 0.1ºC and 0.2ºC	From 22.9ºC to 28.7ºC	5.8ºC	Between 0ºC and 0.2ºC	From 26.2ºC to 28.3ºC	2.1ºC	Between 0ºC and 0.3ºC	From 25.1ºC to 27.8ºC	2.7ºC
Stand Dev	1.5ºC	Between 0.1ºC and 0.2ºC	From 1.9ºC to 2.7ºC	0.8ºC	Between 0ºC and 0.2ºC	From 1.9ºC to 2.7ºC	0.8ºC	Between 0ºC and 0.1ºC	From 2ºC to 2.3ºC	0.3ºC
Max	27.7ºC	Between 0.5ºC and 0.8ºC	From 29.4ºC to 37.5ºC	8.1ºC	Between 0.6ºC and 0.7ºC	From 30.5ºC to 36.9ºC	6.4ºC	Between 0.2ºC and 0.8ºC	From 32.4ºC to 34.2ºC	1.8ºC
Min	20.3ºC	Between 0.1ºC and 0.6ºC	From 17.8ºC to 23.2ºC	5.4ºC	Between 0.3ºC and 0.6ºC	From 20ºC to 22.9ºC	2.9ºC	Between 0.1ºC and 0.4ºC	From 20.4ºC to 23.1ºC	2.7ºC

A quick analysis of each individual statistic data for the parametric runs shows that in the air change runs the use of minimum ventilation rates will predict the highest internal temperatures in Summer and Spring; Maximum infiltration rates will predict the lowest internal temperatures in Summer and Spring and both ventilation and infiltration rates exert a strong influence on the predicted temperatures and therefore need to be as accurate as possible. In the internal gain runs, assuming that the number of people, lights and equipment are as accurate as possible, as well as information about the luminaires, small power loads are shown to be the most significant parameter influencing the temperatures. In the material runs minimum and maximum predicted temperatures are most affected by the transmittance of glass.

Figures 5a to 7b shows these results graphically, and also show how the predicted temperature varies with time for the most significant parameters of the sensitivity analysis.

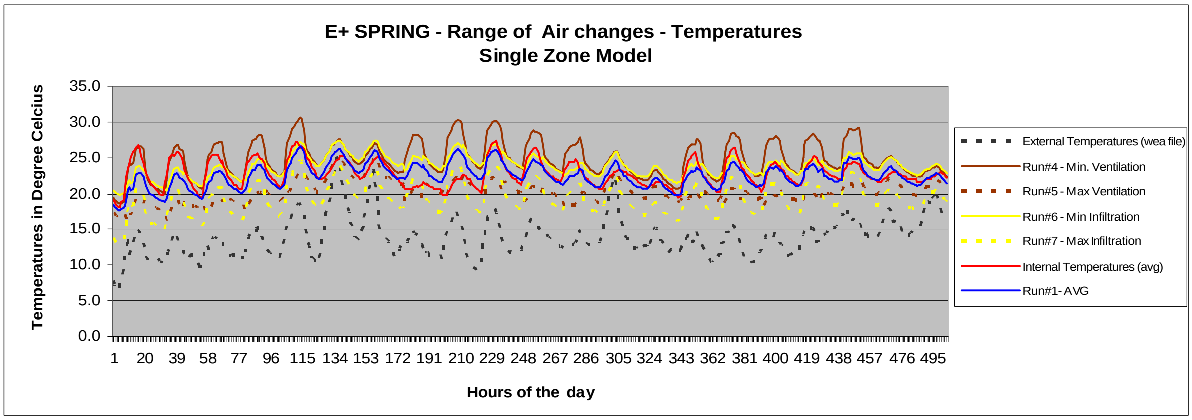

Figure 5a – Sensitivity analysis varying air change rates – Spring season

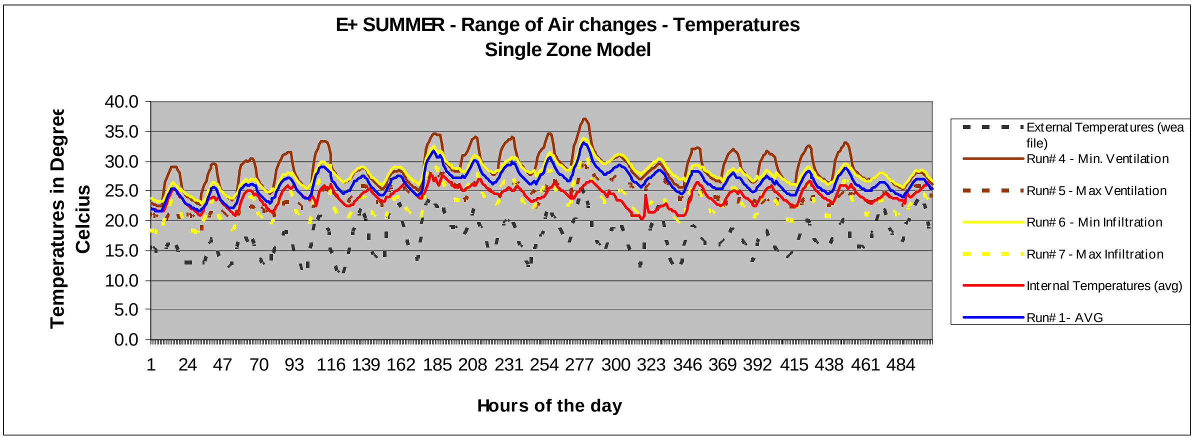

Figure 5b – Sensitivity analysis varying air change rates – Summer season

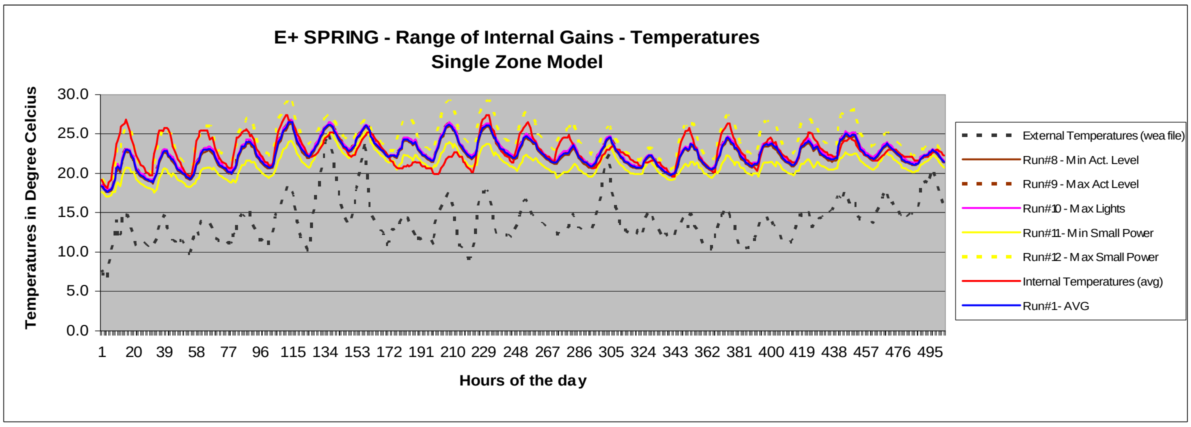

Figure 6a – Sensitivity analysis varying small power gains – Spring season

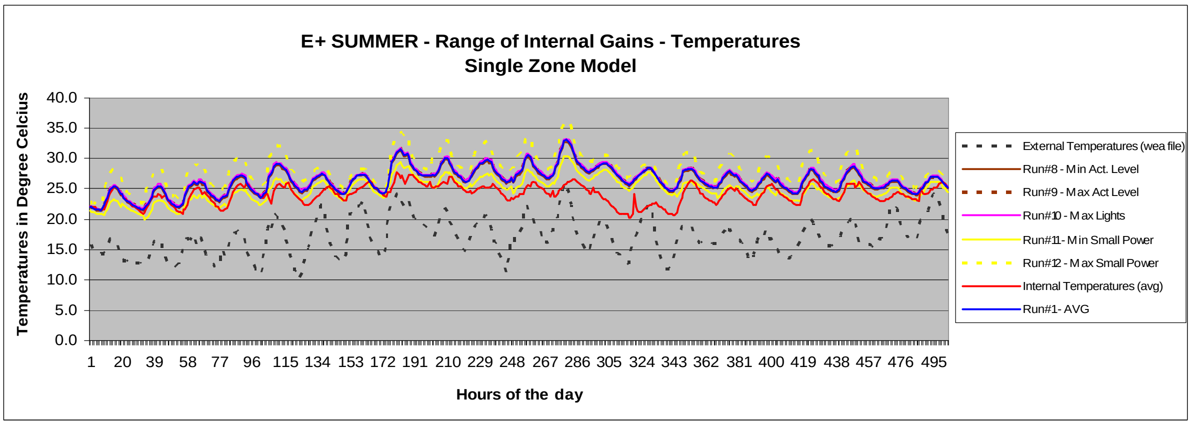

Figure 6a – Sensitivity analysis varying small power gains – Summer season

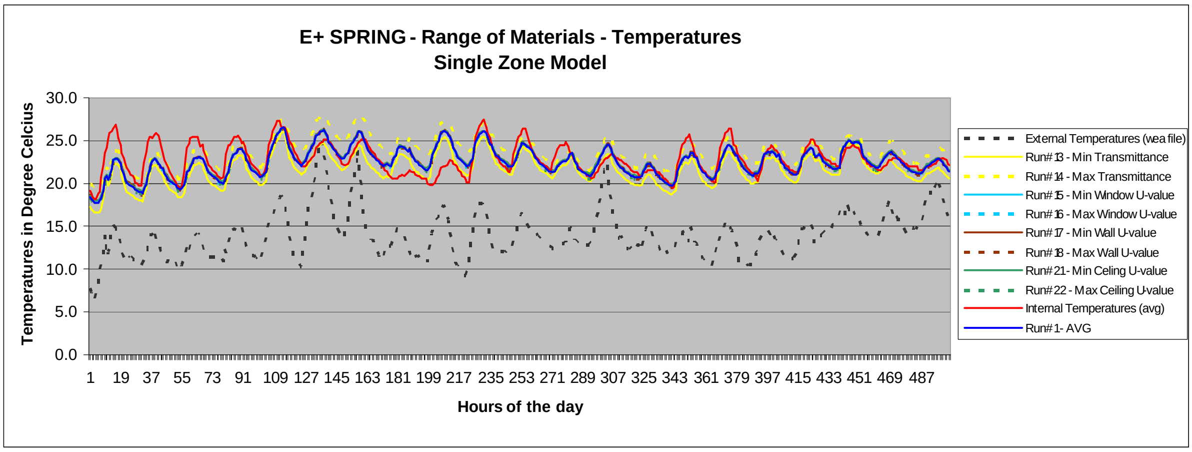

Figure 7a – Sensitivity analysis varying glass transmittance – Spring season

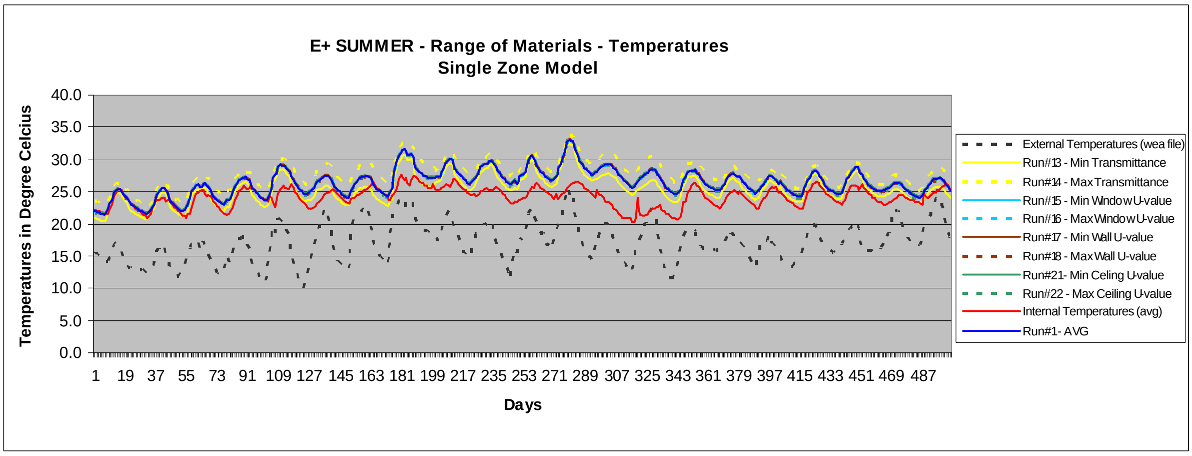

Figure 7b – Sensitivity analysis varying glass transmittance – Summer season

Conclusions

The results show that it is possible to model one building in 2 different tools with different input criteria and still obtain very similar predictions of performance running a single zone model analysis. But it is important to know what these input criteria must be to obtain this equivalence. A future paper will provide these parameters in detail.

It is also possible to conclude that for this building, in these weather conditions, assuming the sets of parameters based on the survey, the best option is to run a single zone model analysis. Zoning with virtual surfaces does not provide results that "agree" with each other using different simulation tools. Also the variations in these results when compared to the measured temperatures introduce even more uncertainty in the reliability of the predictions.

The parameters that appear to most affect the predicted internal temperatures when no mechanical heating or cooling is being provided, assuming that data about the people, lights and equipment are correct, are, in order of influence:

- Ventilation rates and infiltration rates
- Small power gains
- Transmittance of glass

Further investigations of the "match" between predicted and measured temperatures are still necessary as results in this paper were addressed using simple summary statistics and visual comparisons of graphs. A frequency distribution of the temperature differences would be recommended to see variations between predicted and simulated temperatures on a time varying basis.

The overall conclusion from this work is that it is possible to use different building simulation tools to predict the temperatures obtained in buildings with reasonable agreement between the tools and reality provided the input details and values are carefully researched.

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