Computer Simulation of Energy in Buildings: Predicted Versus Measured Results

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Abstract

The computer simulation of buildings is becoming more common, but the background knowledge required has always been considerable. With building simulation programs becoming more mainstream with built environment professionals, and UK building regulations now requiring simulation for some types of building, the uptake of simulation seems likely to increase. However, there is some controversy over the accuracy of simulation programs, regarding both the model creation and output.

This paper looks at simulation from the point of view of an architect and examines three of the most likely programs an architect would use in adoption of simulation - EDSL TAS V. 9.4.1, IES VE 2018 and ArchiCAD 22 EcoDesigner STAR. These programs have been used to model a Dwelling in Scotland, which has previously had extensive physical building performance evaluation (BPE) conducted. The analysis compares simulations results with each other and with the BPE data.

The comparison found all programs to have strengths and weaknesses. U-value calculators in all of them seemed inconsistent, although all of the overall energy use estimates were more accurate than the standard assessment procedure (SAP). SAP is the method used in the UK for compliance with building regulations. The findings show that all the programs have positive attributes for architects, but despite having the poorest energy use predictions, the comparison found that ArchiCAD 22 EcoDesigner STAR is likely to have the greatest positive impact for an architect due to the familiar environment and minimal additional inputs. It also found IES VE 2018 to be of use due to the flexibility, support and Sketchup plugin, which can afford a familiar environment in which to learn. It found EDSL TAS to be the least suitable for practicing architects.

Introduction

Over 200 countries have signed up to the Accord de Paris, an agreement that action must be taken to lower greenhouse gas emissions (Davenport, 2015). It is widely agreed that buildings create around 40% of these emissions, making reductions in energy used by buildings a vital part of any energy reduction strategy (Scottish Government, 2017, 23). One way of quantifying and understanding the energy requirements of new or altered buildings is through building performance simulation (BPS). Computerised building performance simulation has its origins in the 1960s when the US government required analysis of human habitation of fallout shelters. Although some of this analysis is based around first principles, most of the algorithms for simulation were painstakingly theorised by engineers before being proven in largescale controlled test environments (Crawley *et al*., 1998). The science and theory were continually developed, but it was not until the 1980s that the first BPS tools were applied to help architects. This would have been a highly specialised undertaking involving specialist scientists and a supercomputer. In the 1990s, this software was translated into coding that could be read by desktop computers, encouraging industry into the field. Since then dozens of BPS tools have been created with different algorithms, approaches and priorities (Crawley *et al.*, 2008, 2). These programs are becoming more user friendly and are gradually requiring less background knowledge to use. As these tools become easier to use and yield greater reward, it would seem the uptake of BPS is likely to increase. Currently BPS is rarely used for compliance in the UK, although there are occasions where it is required – complex geometry buildings, for example. SAP (Standard Assessment Procedure) is the most common method of compliance for domestic buildings in the UK, using standard values for building types and sizes. It does this to try to make dwellings more comparable; however, this assessment is based on the building fabric and systems and not on how they would be used. Low energy buildings often underperform in SAP assessments (Murphy *et al.*, 2011).

Simulation models must have precise data in three principal areas to be accurate. Firstly, information inputted by the user about the building geometry and fabric. Secondly, climate and location data, which is loaded into the software from external sources and can be applied to the simulation. Finally, the algorithms of the software - which are beyond the users' control (Coakley, Raftery, and Keane, 2014). Some BPS programs have been validated (including the ones used in this study) to give accurate data in control tests and two within this test can be used for compliance with building regulations. However, these controlled tests require results to be within a range rather than be specific values, which calls into question the certainty of any energy use figures generated (Judkoff and Neymark, 2006).

Additionally, as a fundamental understanding of building physics is still usually required, architects often struggle to use even basic BPS tools. Literature has highlighted a knowledge gap between architects and BPS tool users. This points toward BPS being largely incompatible with

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Architects methods and education, meaning loss of a potentially useful method of environmental design (Mahdavi et al., 2003). However, increasingly architects are creating drawings using a Building Information Model (BIM). This, combined with the increasing usability and accessibility of BPS means that it may now be a realistic possibility for more widespread adoption by architects (Kim et al. 2015). This could allow simulation to become part of the normal iterative process that architects use to design and refine buildings.

This paper shows results of a comparison of three BPS tools and gives comment on the potential use by architects. EDSL TAS V. 9.4.1 (TAS), IES VE 2018 (IES) and ArchiCAD 22 EcoDesigner STAR (ArchiCAD) are used. These programs create an interesting comparison, as both TAS and IES are specialist BPS software platforms with the potential to bring in building geometry from BIM platforms. Both are accredited for compliance for UK building regulations and for gaining LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) credits (‘Validation: EDSL TAS’, 2018) (‘Software Validation | Integrated Environmental Solutions’, 2018). ArchiCAD is primarily a BIM platform for creating 3D models and 2D drawings. The energy simulation capabilities were only added from version 16 (2011). ArchiCAD’s capabilities are not compliant for UK building regulations but do conform to the standard required for LEED certification - ASHRAE standard 140 (‘VIP-Core Dynamic Simulation Engine (Energy Evaluation) | ArchiCAD, GRAPHISOFT’, 2018).

The key comparisons are as follows:

- Floor area created in each program using recommended best practice
- Predicted U-values created within the U-value calculator and measured U-values
- Predicted yearly total space heating
- Predicted yearly space heating per m²
- The predicted effect of ventilation on yearly space heating per m²
- Predicted yearly energy demand from lighting and equipment
- Predicted yearly energy demand for hot water
- Predicted yearly electrical energy usage
- Comparisons of the BPS tools predicted energy use with measured energy use from the dwelling as built

Method

To create a valid comparison the authors chose a small dwelling. The dwelling is simple enough to be comparably modelled in each BPS tool, while being complex enough to draw appropriate comparisons. The dwelling has mostly clear surroundings, with the exception of a raised area to the north-west and a tree line around 20m to the west. The dwelling was built to the PassivHaus (PH) construction standard, and therefore construction had been documented and tested on site. There is also significant building performance evaluation (BPE) with occupant diaries, energy meter monitoring, building fabric testing as well as external and internal humidity and temperature for a full calendar year (Innovate-UK, 2015). The dwelling is located near Dunoon, Scotland, with the development named Tigh-Na-Cladach, (see Figure 1). The one negative about this choice was that it is an end terrace dwelling rather than being a detached property, although the party wall is north facing minimising this negative. The lower right of Figure 2 shows the dwelling evaluated. Figure 3 shows its floor plan.

Figure 1: Tigh-Na-Cladach aerial view.

Figure 2: Dwelling that is simulated is at the lower right.

The process involved the creation of geometry for the simulation model in each BPS tool using best practice (using the tools the way they were designed to be used), learned from official online tutorials, in person training and webinars. Each model was then zoned. This involves separation of each room to different internal conditions within the simulations, allowing different attributes to be applied. The ventilation and infiltration rates were set so as to remove them as a variable (sealed compartments), as initial simulations were run to create a baseline ‘free running’ building that was established to be as similar as possible in all three programs and this value was the easiest number for comparison. To complete the data for a ‘free running’ comparison, weather data was inputted. The weather data used in each BPS tool was the exact same file and format. The closest weather file that could be found was for Oban, a coastal town located 38 miles from Dunoon, which should give very similar conditions given its similar altitude, coastal proximity and geographical location. Sample weeks (or days in the case of ArchiCAD) were run in each BPS tool before occupants or plant were added to ensure parity between the ‘free running’ simulation models. This revealed several input errors, which were corrected.

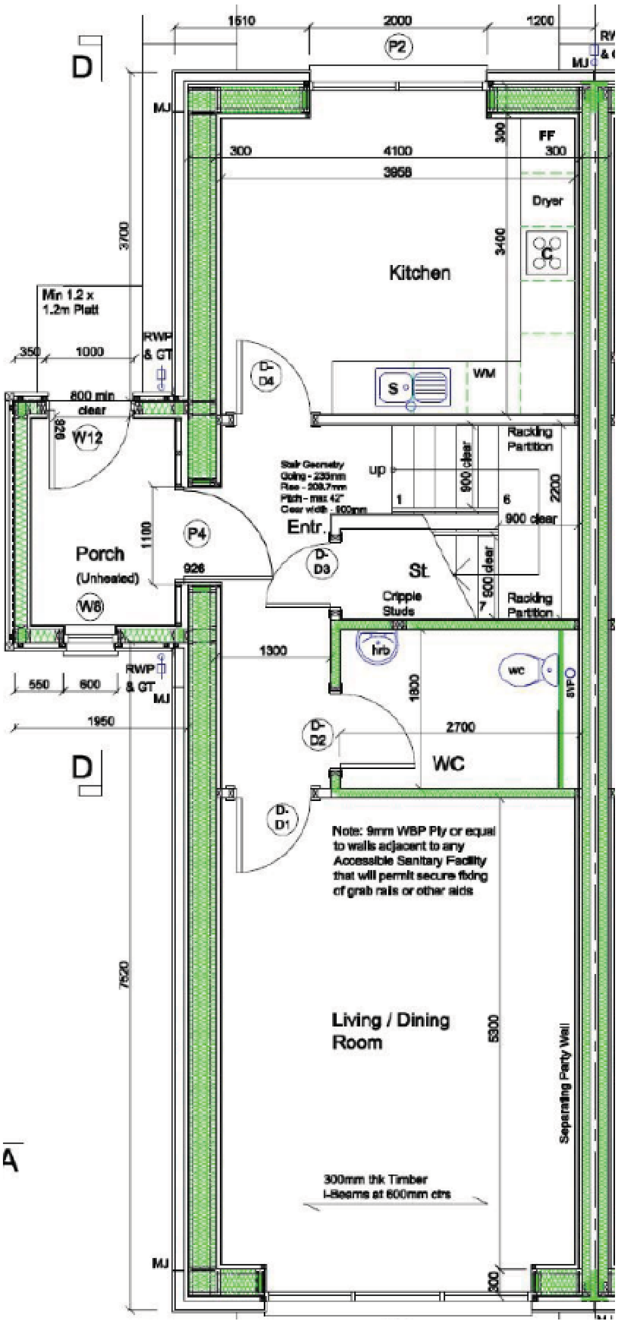


Figure 3: Tigh-Na-Cladach dwelling ground floor plan.

Each simulation model included Plant and occupant profiles along with schedules for internal gains based on occupant diaries completed by householders during the BPE. The diaries detail occupancy, equipment usage and behaviour, making the simulations as accurate as possible.

The weather file was obtained from the EnergyPlus Weather (epw) database online, which is likely to be the source an architect would use if creating a simulation. The .epw file type was chosen as it works with all three programs compared. Table 1A shows a summary of inputs, and Table 2 shows an example input schedule for Lighting.

Table 1: Tigh-Na-Cladach simulation model summary (Innovate UK-Tigh-Na-Cladach BPE report, 2015).

Tigh-Na-Cladach Simulation Inputs			
Occupancy	2		
Air Tightness	0.56ACH		
U-values (W/m²K)	Roof 0.13	Floor 0.16	Exterior walls 0.10
Hot water demand (litre/day/person)	120		
Internal temp’ range	16°C-25°C		
Ventilation rates	85m^3/hour		
Heat pump output + COP	4kW + 3.5		
Orientation	‘North’ wall bearing = 15°		
Solar hot water area, azimuth, angle to south	4.5m², 45°, 15°		
MVHR efficiency	85%		
Weather file	Oban.epw		
Occupancy gain	200W (2 occupants when occupied)		

Table 2: Example Input Schedule for Lighting.

Tigh-Na-Cladach lighting profile			
Lighting (weekday AM)	**Lighting (weekday PM)**	**Lighting (weekend AM)**	**Lighting (weekday PM)**
6am – 8am	7pm–11pm	8am – 9am	7pm–12am

Inter-room air movement inputs in IES and TAS allowed air to move freely between rooms. The MVHR has outlets and inlets in different rooms and air must be allowed to flow between them even with internal doors closed. ArchiCAD does not have an option for inter-room air movement. Therefore, to create a comparable simulation, a MVHR that gave the same attributes was specified in IES and TAS for each room, with the same overall ventilation rates across the dwelling in all programs but is a potential source of error. Different systems were then removed or ‘turned off’ within the simulations to allow a breakdown of loading to compare loading from different aspects of energy consumption. With the comparison of estimated data generated by programs completed, this data was then compared with the data collected during BPE. The estimated yearly energy use generated by the simulation programs was then compared to the SAP figures, which were created for the building for compliance reasons.

Results and Discussion

Measured Floor Area Comparison

For comparison of how each program calculates area, models were created in a way that made the foot print of each simulation model the same. This made the linear measure of exterior walls as close and comparable as possible. This measurement was taken at 12800mm x 3950mm for the internal foot print – 50.56m². Over two floors including the internal porch area, this gives a footprint area of 104.8m². The porch area is not included in the thermal analysis as it is not heated, and therefore generates no loading on the building systems. Table 3 shows the results for each room from each simulation and total area from each simulation model.

Table 3: Tigh-Na-Cladach Simulation Measured Area Comparison.

Area (m²)	IES	TAS	ARCHICAD	SAP
Porch	3.713	3.783	3.615	N/A
Kitchen	13.035	13.035	13.114	N/A
Downstairs hall	5.2	5.541	4.907	N/A
WC	4.77	4.57	4.539	N/A
Living room	20.540	19.908	20.540	N/A
Lower stairs	5.83	6.464	5.813	N/A
Upper stairs	5.83	6.464	5.813	N/A
Bedroom 1	13.035	13.035	13.114	N/A
Bedroom 2	16.605	16.283	16.357	N/A
Bathroom	5.56	5.484	5.451	N/A
Upper hall	8.34	7.886	7.832	N/A
Total area	102.458	102.353	101.095	104
Total heated area (excludes porch)	98.745	98.670	97.48	N/A

The floor areas, room by room across the programs, show no clear pattern of which programs will be similar. One may expect consistency between programs in this area, but due to restrictions on precision within TAS and IES, this is not realistically possible. With the kitchen, ArchiCAD is the largest. With the downstairs hall, TAS is the largest and with Bedroom 2, IES is the largest. However, a look at the totals indicates the software type. TAS and IES are within 0.1% of each other, with ArchiCAD having more than a 1.3% difference from the average of the others. When the input of the 3D model is examined more closely, the reasons for differences in area can be hypothesised.

IES instructors considered the input method used for IES as the best practice. Rooms are represented with single lines, giving no allowance for internal wall thickness. IES essentially draws only the measured climactic zone of a room, rather than the building. Internal walls would obviously have a footprint within the real building (160mm width from architect's drawings). As each model was created with the same footprint, the area taken up by the internal walls would be absorbed into the rooms in IES. Figure 4 shows the ground floor plan with the adjoining dwelling shown in purple, with all walls and openings represented with single lines. TAS uses a method of measuring that seems similar to IES, despite looking substantially different. Although drawing in TAS shows wall thicknesses as shown in Figure 5, the measurements given indicate that the space within the internal walls is included in the measured floor area. This indicates that the measured climactic zones for each room have no space between them in either IES or TAS. The method of input in ArchiCAD is noticeably different as the information added to turn the BIM model into a DSM is added after the BIM model is complete. This means internal wall thickness is not included. This is the same method used for calculation for SAP, despite Table 3 showing the SAP figure is noticeably different. Figure 6 shows the zones as created in ArchiCAD, with only the areas highlighted in grey accounted for. This is due to how the 'tool' that creates these zones in ArchiCAD operates. While it would be possible to alter the zones in ArchiCAD to mimic the method used in IES and TAS, this is not how users are instructed within the user guides or videos made by ArchiCAD.

While the measured floor areas of all three programs are very similar and the overall differences may seem negligible, it is worth noting that great care was taken in the input of the simulation models to make them similar and if another user used a different method of input, the differences could be greater. The difference between measurements for the downstairs hall between ArchiCAD and TAS are around 10%. It is possible this kind of difference could be observed in the simulation of a different building.

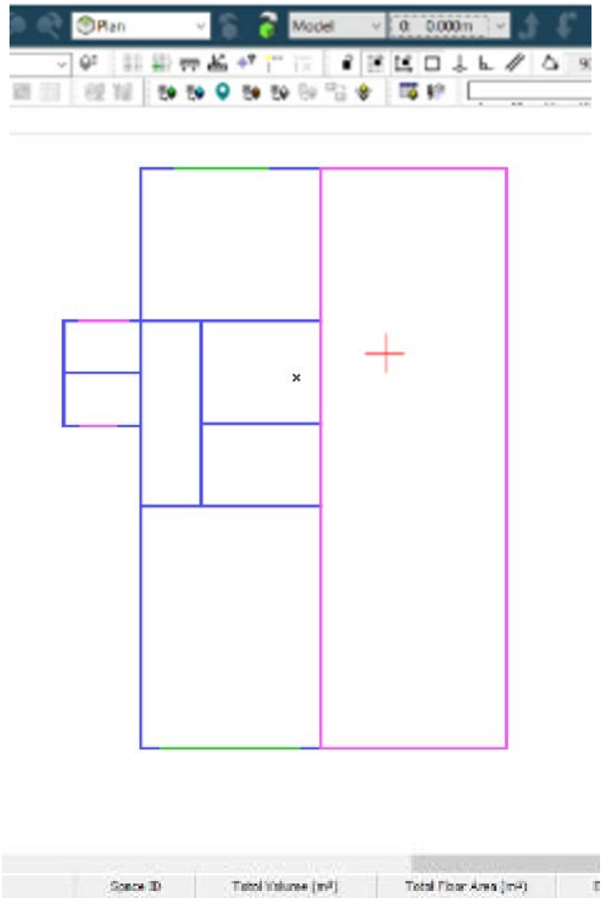


Figure 4: IES ground floor plan.

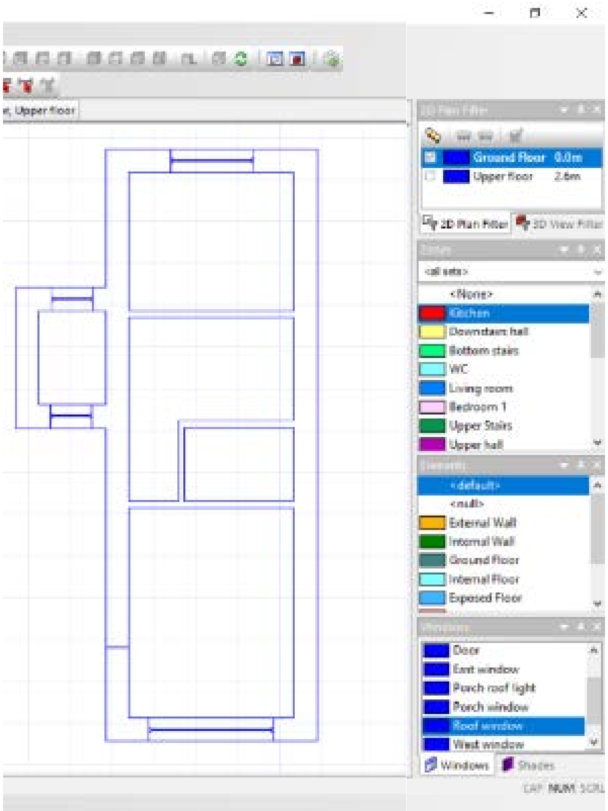


Figure 5: TAS ground floor plan.

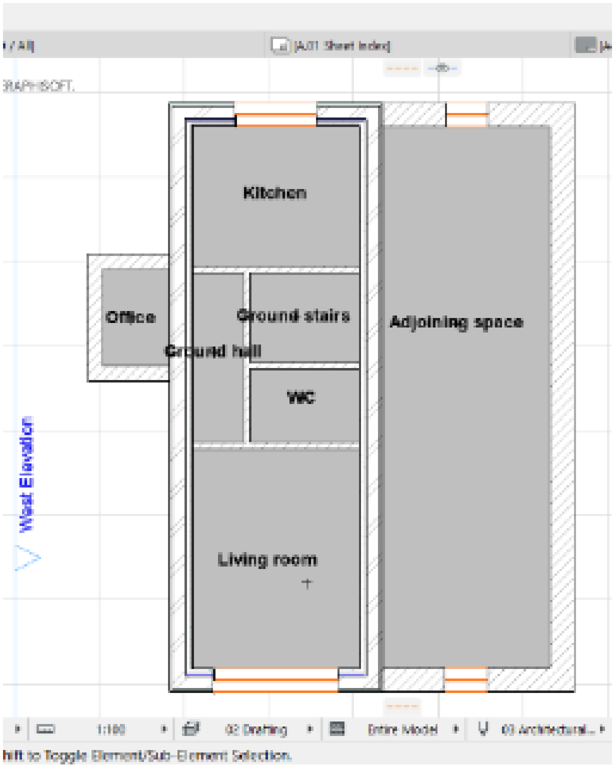


Figure 6: ArchiCAD ground floor plan.

U-Value Comparison

The first attribute given to the drawn models were U-values. This gave an ideal opportunity to compare the built-in U-value calculators in the programs. The build-up for the details used were provided in the architect's drawings that were obtained. These layers were then inputted as closely as possible using each program's material library. Figures 7, 8 and 9 show the build-up for the external wall within each program. As can be seen from the build-ups, the material libraries are substantially different with the built-in library of ArchiCAD being especially limited with a 'best fit' option having to be used for several materials. While custom materials can be made in all programs, it adds another layer of complication and the method for this study was to test the programs 'out of the box'. Table 4 shows the outputs that each program's U-value calculator made.

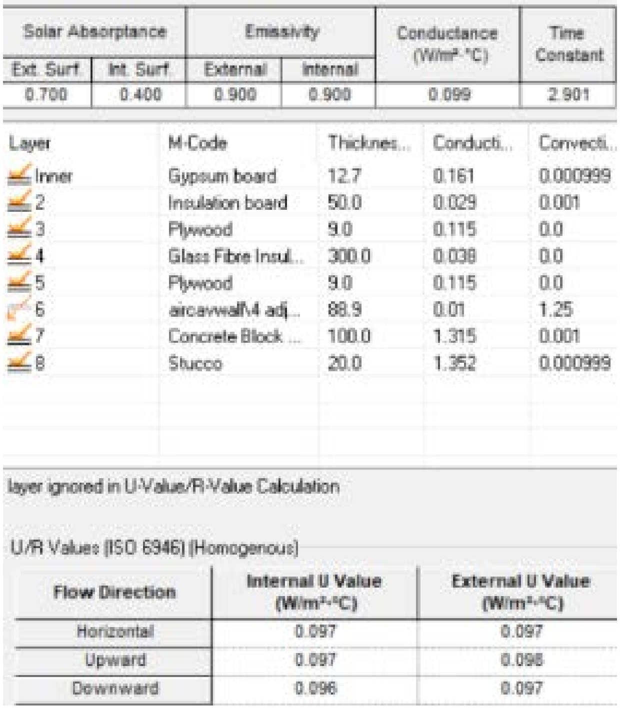
As the U-values calculated before construction are the values used for building regulation compliance, they were used – with the exception of measured values, which will be the most accurate. The results shown in Table 4 point to a case to call into serious question the accuracy of the in-built U-value calculators, but each of the comparisons tells a different story. The comparison for the external walls is largely similar, and they agree with the calculated pre-construction values; which are presumed to have been made with a U-value calculator for compliance (not specified in BPE).

Table 4: Tigh-Na-Cladach U-value Comparison.

	External Walls	**Roof**	**Ground floor**	**Windows**	**Doors**	**Velux**
Calculated pre-construction	0.095	0.094	0.15	0.78	1.16	0.96
ArchiCAD	0.1	0.08	0.16	N/A	N/A	N/A
IES	0.096	0.077	0.117	N/A	N/A	N/A
TAS	0.099	0.078	0.14	N/A	N/A	N/A
Measured in-situ	0.12	0.16	N/A	N/A	N/A	N/A
Simulation values	0.12	0.16	0.15	0.78	1.16	0.96

Material	Thickness mm	Conductivity W/(m·K)
[REX] EXTERNAL RENDERING	20.0	0.5000
[BRO] BRICKWORK (OUTER LEAF)	100.0	0.8400
Cavity	50.0	-
[STD_CHP] Chipboard Flooring	9.0	0.1300
[MFSL] MINERAL FIBRE SLAB	300.0	0.0350
[USPT0001] PARTICLEBOARD - MEDIUM DENSITY	9.0	0.1350
[USIN0000] INSULATION BOARD - HF-B2	50.0	0.0430
[GPB] GYPSUM PLASTERBOARD	12.5	0.1600

Figure 7: IES external wall construction layers.



Solar Absorptance		Emissivity		Conductance (W/m².°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.700	0.400	0.900	0.900	0.099	2.901

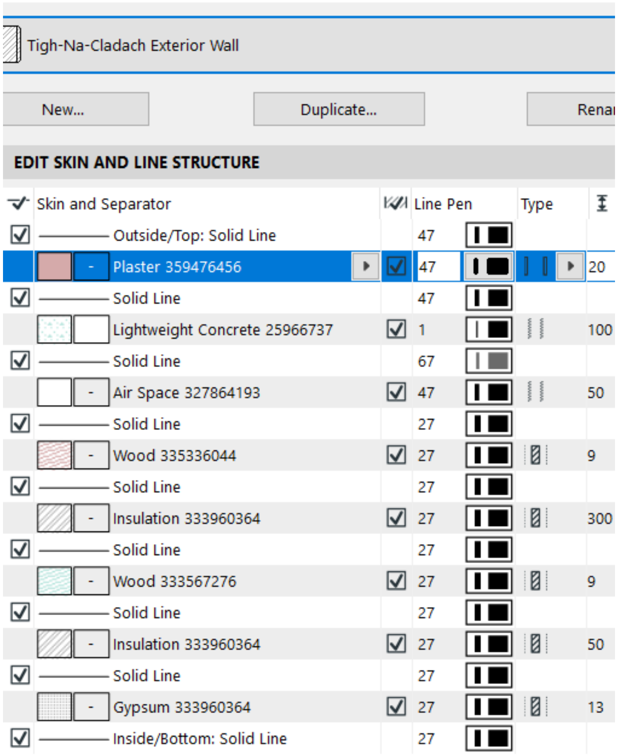
Layer	M-Code	Thicknes...	Conducti...	Convecti...
Inner	Gypsum board	12.7	0.161	0.000999
2	Insulation board	50.0	0.029	0.001
3	Plywood	9.0	0.115	0.0
4	Glass Fibre Insul...	300.0	0.038	0.0
5	Plywood	9.0	0.115	0.0
6	aircavwallV4 adj...	88.9	0.01	1.25
7	Concrete Block ...	100.0	1.315	0.001
8	Stucco	20.0	1.352	0.000999

layer ignored in U-Value/R-Value Calculation

U/R Values (ISO 6946) (Homogenous)

Flow Direction	Internal U Value (W/m².°C)	External U Value (W/m².°C)
Horizontal	0.097	0.097
Upward	0.097	0.098
Downward	0.096	0.097

Figure 8: TAS external wall construction layers.



Tigh-Na-Cladach Exterior Wall

New... Duplicate... Renai

EDIT SKIN AND LINE STRUCTURE

Skin and Separator		Line Pen	Type	
Outside/Top: Solid Line		47		
Plaster 359476456	☑	47		20
Solid Line		47		
Lightweight Concrete 25966737	☑	1		100
Solid Line		67		
Air Space 327864193	☑	47		50
Solid Line		27		
Wood 335336044	☑	27		9
Solid Line		27		
Insulation 333960364	☑	27		300
Solid Line		27		
Wood 333567276	☑	27		9
Solid Line		27		
Insulation 333960364	☑	27		50
Solid Line		27		
Gypsum 333960364	☑	27		13
Inside/Bottom: Solid Line		27		

Figure 9: ArchiCAD external wall construction layers.

With the agreement across the board for the predicted value, the most interesting measurement is the U-value measured from the building as built, which has a noticeable poorer performance than predicted. The roof construction creates broad agreement between the simulation programs, although the U-value calculator that was used for compliance predicts poorer performance. However, the measured value is considerably worse than any of the predictions. This will be in part due to the angle of the roof and possibly weather conditions during measuring. In practice, more heat energy is lost the closer a building element is to horizontal, due to the warmer air from the room rising and heating these elements. They are therefore more able to lose heat to the external environment. The ground floor construction splits the simulation programs by a considerable margin in comparison to the other tests. Unfortunately, measurement of the ground floor U-value was not possible and the as-built value is not available. It is possible that the performance gap in the measured U-values comes from poor workmanship; however, the BPE report for the dwelling mentions that the building was constructed to a particularly high quality. The exposed windy seaside location is also a possible contributor to the performance gap. The spread of the U-values here highlights that even if the algorithms of the simulation engines are reliable, repeatable and reliable data input remains elusive. The U-values for each simulation were adjusted to be the same, in order to create simulations that are more comparable. Measured results were used where possible, with the U-value used for compliance used for floors and the manufacturer values used for doors and windows (obtained from the BPE). A decision was made, that slightly different insulation values between simulations was the best way of creating identical simulation models, meaning each simulation used the same U-values for energy predictions.

Predicted Energy Use Comparison

With the simulations completed to a 'free running' condition, they were then completed and several simulations were undertaken to give a breakdown of how the predicted energy use compared to the measured energy use. Table 5 shows the comparison of the results. Predicted electricity for heat shows that all simulations underestimated the heating demand for the dwelling, with ArchiCAD being the furthest from the measured value and IES and TAS being similar. The BPE monitoring mentions that residents were using electric towel rails constantly for space heating for a significant period during monitoring, which contributed to raising the measured value, and which may explain some of the performance gap. The results for space heating in both the measured and predicted values is extremely low, which is likely a combination of the high thermal performance of PH, the air source heat pump and the occupants being particularly energy conscious, which is mentioned in the BPE. The energy loading of the towel rails (which would be aiding space heating) was also not included in the space heating loads. A more noticeable gap is in the reduction in space heating demand when ventilation requirement is removed. This points towards potentially different methods of calculation.

The energy used for lights and equipment possibly highlight differences between the detailed input possible in dedicated BPS programs and ArchiCAD's 'add on' package. Again, IES and TAS have similar values with the ArchiCAD prediction differing significantly. Predictions for 'energy and equipment' seems to be an area which has made a significant difference in the overall energy predictions. ArchiCAD predicted that almost 53% of energy use would be from lighting and equipment, this output also had the greatest spread of results; possibly, due to the different ways occupant behaviour is inputted.

Table 5: Tigh-Na-Cladach PH dwelling Energy Simulation Results.

	SAP	**IES**	**TAS**	**ArchiCAD**	**Measured**
Total electricity for heat (kWh/m²A)*	1133	540	529	444	579
Total heated floor area (m²)	104	98.7	98.7	97.5	104
Space heating per m² (kWh/m²A)	10.9	5.5	5.4	4.6	5.6
Reduction in space heating when ventilation requirement is removed (kWh/m²A)	N/A	0.8	1.05	1.3	N/A
Lights and equipment (kWhA)	N/A	1914	1709	3005	N/A
Hot water energy demand**	N/A	1942	1809	2178	1685
Total electrical demand***	N/A	4396	4047	5689	4513

*Total electricity for heat considers use of the air source heat pump

**Hot water energy demand considers the solar hot water system

*** Total energy demand considers the air source heat pump and solar hot water system

The overall predicted energy use for the dwelling over the year shows an average value within 5% of the measured energy used. However, not all simulations are equally adept at energy predictions. Both IES and TAS make predictions that are below the measured energy. In this context, both IES and TAS look to have made accurate predictions about the total energy used. The predictions made by ArchiCAD look less accurate in comparison, with energy demand for lights and equipment differing from IES and TAS significantly.

The breakdown of the results shows that ArchiCAD energy use predictions had significant deviation from the other programs and the measured amount. The performance of IES and TAS was similar in broad terms giving similar results. The differences in predicted energy use between different categories seemed to balance out across the simulations as a whole in this scenario. However, other simulations could yield different results.

When compared to IES and TAS, ArchiCAD's predictions seem inaccurate. However, when compared to space heating predictions from SAP they seem excellent. This agrees with previous studies showing that SAP is not a good method for predicting the energy use of low energy buildings. The simulation models support this, with even ArchiCAD being roughly twice as accurate as SAP. This adds to the body of work showing the results of static (SAP) and dynamic simulation are not comparable and indicates that switching to even a simple dynamic analysis would give much greater accuracy for predicted building energy loads towards compliance of UK regulations.

Figure 10 gives an overview of the comparison of the predicted energy use from all three programs and the measured value from the dwelling as built. IES and TAS give consistent predictions across all results with ArchiCAD giving an outlying result for predicted use of lighting and equipment. This seems to skew ArchiCAD's prediction for total energy use. As ArchiCAD's user interface lacks the precision of the other programs, user error cannot be ruled out as part of the discrepancy. However, great care was taken for this input and if there were input errors, improvements to the interface would likely improve them. The difference for U-values between predictions is large and merits further investigation. Possible reasons for gaps in results include poor workmanship, the inbuilt limitations of the U-value calculators or calculation algorithms used. However, as space heating is a relatively small component of the overall energy consumption, it does not seem to have created a large impact on the final figures.

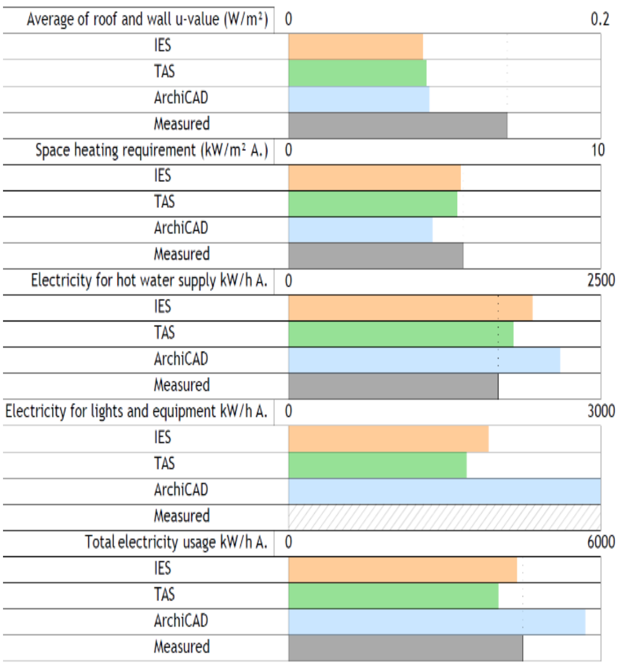


Figure 10: Comparison of predicted and measured energy use.

Conclusion

The comparison of the simulations shows an overall consistency in the predicted energy results. The predicted total energy use for all three programs varies for different reasons and all three have different strengths and weaknesses. No program performed consistently better across all methods of testing. ArchiCAD had the least accurate energy predictions, although the results were still respectable. It is also worth noting ArchiCAD performed better than SAP despite primarily being a drawing program. The accuracy of the U-value calculator used or the accuracy of in-situ U-value measurement are both of concern as the results highlight a performance gap when calculated values are compared to those measured in-situ.

Evaluation of the programs as design tools moves their requirements from just accuracy. Capacity to test the effects of design changes quickly and efficiently within a program could become a valuable tool to architects and designers in guiding designs to lower energy use from an early stage. ArchiCAD has a clear advantage here, as it is a BIM program, so its 3D modelling capabilities are far superior to IES or TAS. Although both IES and TAS can import model data from ArchiCAD, having a simulation tool built in to a program that architects are already using and are familiar with raises questions over the advantage of the purchase of a standalone simulation program for architects. TAS in particular still feels like a research tool, mainly for academics due to its clunky, unintuitive and dated user interface.

The increasing 3D modelling of more buildings in BIM will open the possibility of links with simulation software programs or simulation features being added to BIM programs. These kinds of links will make simulation more accessible to architects. Bringing together accurate dedicated simulation tools with familiar software platforms is likely the best way for architects to create reliable simulation models. As building regulations tighten towards zero carbon targets, the ease of use and accuracy for these programs will likely improve. This should require less knowledge of building physics and allow architects to create simulation models with relative ease. There is also significant potential for BIM components to automatically include the necessary information required for them to be included in an energy simulation. As adoption of BIM becomes widespread, the opportunity for simulation also increases. Current standalone building simulation programs would require a significant investment of time and resources for architects. Integration with existing programs opens the door to use energy simulation as a design tool.

The three simulation programs tested show that the complexity and required background knowledge still put simulation out of reach for some architects. However, given the recent advances made in BIM and the need to design buildings that use less energy, it is likely that building simulation will become a tool for architects in the future if architectural education can be made to be more compatible with simulation and architects are taught the proper background knowledge.

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