

Quantifying the Benefits of Solar Design

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Abstract: It is generally considered by eco-designers that the optimum orientation for a domestic dwelling in a cold temperate climate in the northern hemisphere is with the most heavily glazed façade facing within 30° of south, so that the rooms on that side of the house can make the maximum use of passive solar gain during the heating season. Analysis has been undertaken to quantify the situation for an actual dwelling built in 2004 in Sheffield, England, which features a heavily glazed rear elevation that looks 30° west of north. Eco-designers might expect this to be one of the worst performing orientations for passive solar heating, and so the performance of the design has been evaluated for each of the cardinal and inter-cardinal orientations under three criteria: natural daylighting performance; total solar insolation received and transmitted; and total fabric heat loss for the glazing design. The results are presented in scientific units and also in terms more familiar to UK house-building decision makers; those of BRE EcoPoints and a dwelling's SAP energy rating. Comparison is then made between the predictions of the computational and SAP methodologies, and what the results mean for the eco-designer.

Keywords: daylighting, solar gain, orientation, SAP

1. INTRODUCTION

The dwelling under consideration is the focus of several research studies being undertaken by the School of the Built Environment, University of Nottingham, in partnership with the UK house-builders, David Wilson Homes Ltd (DWH), under the title of Project:LIFE. The overall brief is to establish how a regular family live in a modern home, and to feed the findings back to DWH so that they can improve their designs to better match the actual, rather than perceived, needs of their customers.

The house is a 4-storey structure that features a split floor level between the front and rear of the house on the ground and first floors, a second floor that is built into the roof space that features a Juliet balcony area, a large external decking area on the first floor, and a sunken basement of approximately one third of the floor area of the ground floor. The stairwell is located in the middle of the floor plan, central to all of the living spaces.

The house is built using traditional stone and block masonry that is consistent with the vernacular architecture. The achieved wall, roof and floor U-values meet those expected to be required in the 2005 revision of the UK Building Regulations, Part L.

Pilkington double glazing units that have a 6mm Activ™ self-cleaning outer-pane, 16mm cavity and a 6mm low-e coated K Glass™ inner-pane are used extensively on the house. These units achieve a midpoint U-value of 1.7W/m²K and a light transmittance value of 0.69. [1]

The home's orientation is in line with the neighbouring houses on the site layout, which take advantage of the outstanding hillside view offered by the location with no compromise given to passive solar heating. As a result of this, the home's heavily

glazed rear elevation, which incorporates 68% of the total glazed area, looks 30° west of north.

2. DAYLIGHTING ANALYSIS

The encouragement of the diffusion of natural daylight within a building can lead to significant improvements in occupant comfort and energy efficiency. The additional light can reduce the need for electrically powered artificial lighting, and the absorption of solar thermal gains can reduce the demand for fossil fuelled heating.

The level of daylight in a room is quantified by the calculation of the 'Daylight Factor' (DF), which is the percentage of available diffuse light that will penetrate into the room for at least 85% of the time between 9am to 5pm over the entire year. The DF calculation can be used to estimate how naturally lit each room will appear on an overcast day; allowing changes to be made early in the design process, with minimal design cost implications, to the size and type of glazing used in the windows of each room.

A standard formula derived by Crisp and Littlefair [2] estimates the average DF that can be expected in a room on a typical overcast day for the location, and Table lists the results for the Project:LIFE house.

Building analysis computational packages have been developed more recently that allow the rapid calculation of the DF for every point on a nodal grid within a 3-Dimensional model. The Ecotect package used for this study is developed by Square One [3] and uses the split flux method as developed by the UK's Building Research Establishment (BRE) [4]. The nodal grid approach has the considerable benefit of providing an insightful graphical representation of how the daylight intensity varies across each room, rather than just giving the average value. This can

highlight early on if the window positioning within the property might lead to issues of gloominess, contrast or solar gain overheating. Later on in the design process, the information can assist artificial lighting designers to decide where best to position luminaries.

Figure 1a and 1b illustrate the 3D model that was created for the Project: LIFE house, which includes the surrounding buildings and landscape details to improve the accuracy and visualisation of the solar shading and daylight attributes of the design.

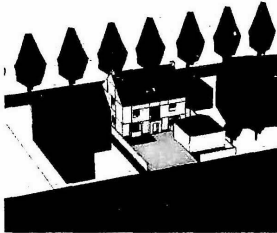


Figure 1a: 3D view of the front elevation

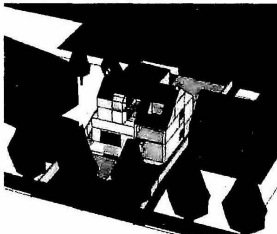


Figure 1b: The heavily glazed rear elevation

A 3-Dimensional nodal analysis grid was created within the building, covering the entire floor area and height of the building. The node spacing was set as 500mm on the horizontal planes, giving 21 nodes in the x-axis (front to rear) and 23 nodes in the y-axis (left to right). The nodal spacing of 960mm gave 10 nodes in the vertical z-axis (basement floor to second floor roof). As an example of the graphical analysis made possible by Ecotect, Figure 2a and 2b show two 2-dimensional plan section views taken of the ground floor level at a working plane positioned 0.85 metres above floor level. The first shows the DFs expected for the house as it is built, the second shows what could be expected if three beneficial features were removed: a 1200 x 1350 mm side window in the sitting room (bottom-middle); the 1515 x 1515 mm glass floor above the entrance hallway (middle-right); and the glazing in the side entrance door to the boot room (top-right). The coloured linear scale represents 0-5% DF; 0-1% is shown as blue, 1-2% as purple, 2-3% as red, 3-4% as orange and 4% and above as yellow.

Table shows the results obtained for each habitable room of the house on a 0.85m high working plane. Visual inspection gave a representative DF

value for each room, taken as that which the majority of the room area exceeds. The range of daylight factors in each room is also noted; information that is unavailable using the Crisp and Littlefair formula.

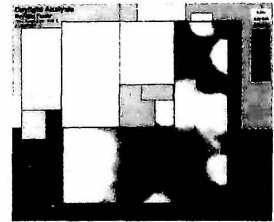


Figure 2a: Ground floor as built

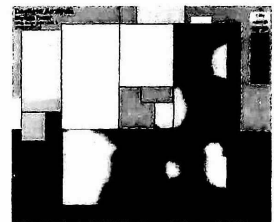


Figure 2b: Ground floor with described alterations

Table 1: Daylight Factors of all habitable rooms, found using [2] and Ecotect 3-D analysis.

Room	DF found using [2]	Majority DF from Ecotect	Range of DFs from Ecotect
Bedroom 5	1.5	1.5	0.8 to 14
Den	1.5	1.25	0.9 to 8.3
Boot Room	2.2	1.5	0.5 to 15
Bedroom 4	2.6	2.0	1.0 to 15
Kitchen-Dining	2.6	4.0	2.0 to 30
Option Room	2.7	2.0	0.5 to 17
Bedroom 2	3.5	2.5	1.7 to 32
Sitting Room	4.6	3.5	2.0 to 28
Bedroom 1	4.9	3.5	2.0 to 29
Bedroom 3	4.9	4.0	1.4 to 62

Although the Ecotect results follow a similar trend as those obtained using [2] in terms of the order of progressively increasing DF, there are differences to note. Apart from the Kitchen-Dining room, the Ecotect values are lower than those found using [2]. This is the result of taking a majority figure rather than an average of the Ecotect nodal values. In Figure 2a it can be seen that for the sitting room (bottom-left) the DF is split half as 3% and half as 5% and above. It was decided that the majority figure was 3.5%; but, as shown in the 'Range' column of Table , the DF is very high (28%) close to the patio doors, which would significantly increase the average value found by [2].

The Ecotect result for the Kitchen-Dining room appears to be inconsistently high. This is a large L-shaped room with an open end joining the sitting room, a partially glazed side entrance door, and an open void to the stairwell landing. These three features are not taken into account in the result found using [2], which only considers the large patio doors and side window. This results in a lower DF than found using Ecotect, which takes account of all the features. It is considered that the Ecotect result is the more accurate of the two.

Overall, it is considered that the two sets of results corroborate each other and that the more detailed findings of the Ecotect model could assist lighting designers in achieving a constant and appropriate daylight level for each room with minimal requirement for artificial lighting. This house is expected to perform very well in terms of daylighting, with just about all habitable rooms exceeding DETR Best Practice Guidelines [5] and meeting the 'Daylight Factor' and 'View of Sky' requirements of Section Hea 1 of the BRE EcoHomes (2005) assessment [6].

3. SOLAR GAINS

The analysis has so far given no consideration to the building's orientation, as the DF calculation is for diffuse sunlight on a uniformly overcast day. This allows a worst-case scenario consideration; so that it can be said with confidence that enough sunlight will enter the rooms to alleviate the daytime use of electric lighting. The ability to maximise the free heating from the sun is closely dependant on a building's orientation however, and so a new analysis approach is required.

A further feature of Ecotect is that it can predict the solar insolation that will fall on any external surface of the model for any hour/day/month of the year, using data from a weather file specific for the location, in this case Sheffield, England.

The building orientation that receives the most solar insolation annually on the glazed areas was found by summing the annual total predicted by Ecotect for each area of glass. Figure 3 shows that the peak is when the rear elevation, which incorporates 68% of the total glazed area, is facing south-east (135°), meaning that the left-right axis of the house lies along a NE-SW axis. The glazed areas are predicted to receive 4650kWh (18%) more solar insolation annually in this orientation than in the actual orientation of 300°.

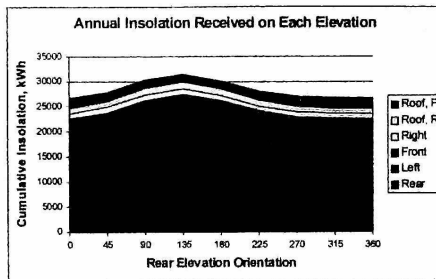


Figure 3: Total insolation for each orientation

The solar insolation received is a combination of a constant diffuse component, and an orientation specific direct component. Figure 4 shows only the direct solar insolation received by the whole house during a more representative October-April heating season, and illustrates how beneficial an orientation of SE to S would be. It is predicted that an optimum orientation of 158° (SSE) would have received an additional 2300kWh (24%) of direct solar insolation during October-April than the actual orientation.

By looking at the monthly solar insolation totals on the largest windows of the house, the sitting room patio doors, it can be seen however that although the southerly orientations receive the most insolation, the majority of the additional insolation comes during the summer period, when the heating system will be turned off and the occupants will likely be opening windows to ventilate the house. Figure 5 shows the monthly figures for four orientations; due north (0°), maximum annual insolation (135°), due south (180°), and the actual orientation (300°). It illustrates why, if the house had been built with a more southerly orientation, there may have been a requirement to block out the additional summer direct gain to prevent overheating, using shading techniques such as overhangs or bris soleil. In the as-built orientation however, the direct solar gain component is small even in the summer months; plus it would require impractically large overhangs to block out the low-lying, afternoon sun.

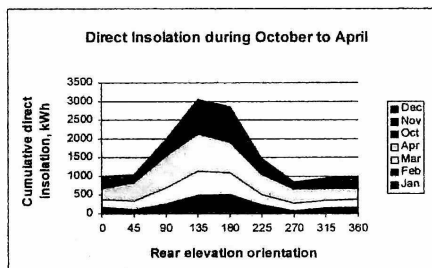


Figure 4: Cumulative direct insolation for whole house over an October - April heating season

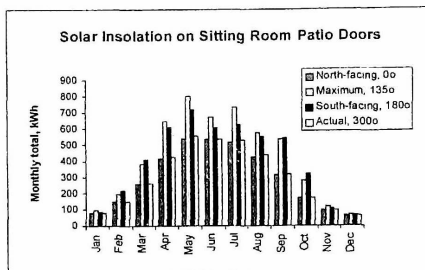


Figure 5: Predicted monthly insolation totals on the Sitting Room patio doors

The analysis was repeated for a house design with more regular window dimensions. The windows of each room on the rear elevation were reduced in size until the calculated DF fell to 2.0, which still meets DETR Best Practice Guidelines. Figure 6 shows the total solar insolation predicted during the heating season, which is 2850–4350kWh (30–38%) less than with the actual window sizes. The benefit of southerly orientations is most reduced, due to the lessened direct gain component. This knowledge would be useful when deciding whether to provide larger windows for improved daylight levels and free heating, when the provision of solar shading and other features to deal with a larger summertime cooling load can have economic costs of their own.

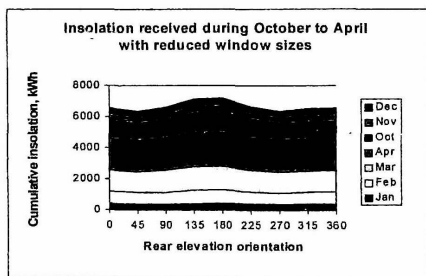


Figure 6: Cumulative insolation with smaller windows

4. SAP ANALYSIS

A main objective of this analysis was to present the data in a format where the benefit of solar gain would become more apparent to the decision makers within a house building company. The government's SAP rating is the preferred method of showing compliance with the Building Regulations Part L, and it is widely expected to play a large role in the energy survey section of the Home Condition Report, which is due to be introduced in the UK in 2007 to meet the requirements of the European Performance of Buildings Directive [7]. The SAP assessment was carried out for each cardinal and inter-cardinal orientation of the rear elevation, with both the actual and reduced window sizes, and Table gives the primary results for three representative orientations. The result for 'Diffuse only light' enables the benefit of direct solar gain to be assessed. The June 2005 draft of the 2005 SAP worksheet was used rather than the Approved 2001 SAP because it takes account of electricity used for lighting and how it can be offset by increased window sizes [8].

It is found that although direct solar gain benefits the house in its actual orientation by reducing the predicted space heating demand by 8.0%, a 19% reduction could have been achieved by a south-facing orientation. The free solar heat gain of a south-facing orientation could therefore have cut 7.4% (£58) from the predicted overall fuel bill, and also led to an extra 2 points under the proposed 2005 SAP scale and a 712kg (8.6%) reduction in the annual CO₂ emissions.

The results for the minimum window sizes lead to some revealing conclusions. It is found that for the more northerly orientations, including the actual as-built orientation, the reduced solar gains are more than compensated for by the reduction in fabric heat loss due to the smaller glazed area. This leads to an overall fall in the annual fuel bills and CO₂ emissions although not by enough to improve the SAP rating.

For the south facing orientation however, there is a slight increase in the annual fuel bill and CO₂ emissions and a 1 point fall in the SAP rating. This apparent contradiction is caused by the smaller windows not taking full advantage of the direct solar gains available from the south. The subsequent increased space heating demand, combined with the increased use of electric lighting, which costs £12 (8%) extra a year, leads to the larger annual fuel bill and fall in the SAP rating.

The conclusion drawn from this is that larger

Table2: SAP Assessments Results

Window Size	Actual Window Sizes				Minimum Window Sizes			
	Diffuse	North	Actual	South	Diffuse	North	Actual	South
Solar gains, W	1128	1522	1620	2389	743	1106	1121	1469
Space heating fuel, kWh/year	33644	31473	30939	27270	31847	29843	29764	27870
Total annual fuel bill, £	828	794	786	728	812	781	779	750
SAP Rating	72	74	74	76	73	74	74	75
Annual kg CO ₂	8801	8380	8277	7565	8526	8137	8122	7755

windows can be used to improve a building's energy performance and SAP rating, but only when the appropriate glazing and building orientation are used.

A further element of analysis included in the Draft 2005 SAP is Appendix P: The Assessment of internal temperature in summer, which predicts the likelihood of overheating problems occurring within the home during the hot summer months. Using this procedure it is found that so long as the windows of the home are opened past 50mm, to give an effective air change rate of 2 ach (air changes per hour) or above, the risk of overheating is deemed "Not Significant"; the lowest of the risk categories. If the windows remain closed however, resulting in an effective air change rate of only 0.2 ach, the risk of overheating is deemed "High", the highest of risk categories. Maintaining an adequate ventilation rate is clearly the key factor in keeping such a heavily glazed home cool in the summer period, which should not be a difficulty for the current occupants in the quiet, secure and pollution-free environment in which the home is built.

5.COMPARISON OF SAP AND ECOTECT GAINS

In order to compare the two sets of results, the assumption of an October-April heating season should be validated. First, the Ecotect October-April insolation was divided by the number of daylight hours for the location over this same period [9], to obtain the average hourly insolation in Watts. This was then multiplied by the same transmission and frame factors as used for the SAP calculations to obtain a 'Transmitted Insolation' value, which was found to be 70–100% of the corresponding SAP solar gains for each orientation. The cause of this large variation was investigated by splitting each result into its direct and diffuse components. This enables a more revealing comparison to be made of the benefit predicted by each method of using a more southerly orientation and increasing the direct solar gains the glazed areas are exposed to.

Table shows the greater importance that the SAP methodology places on the direct component, which varies between 26–53% of the total gains, than is placed on it by the Ecotect calculation, for which it varies between 11–27% of the total insolation.

Figure 7 illustrates the variation within the direct components for each methodology. The results, normalised to that of 315°, show a 233% peak increase in direct insolation at 158° east, whereas the SAP methodologies predict a 180° peak increase in direct solar gains on a due south facing orientation.

Table3: Diffuse and Direct components

	Draft 2005 SAP solar gains		Ecotect 'Transmitted'	
	0°	180°	0°	180°
Total Gains	1522	2389	2186	2614
Diffuse Gains	1128	1128	1956	1956
Direct Gains	394	1261	230	658
Direct Percentage	26	53	11	25

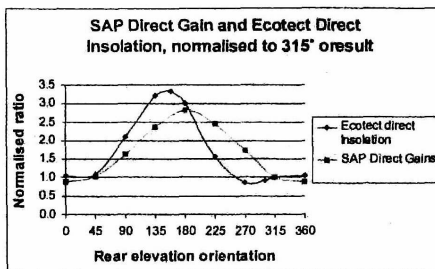


Figure 7: Direct components normalised to 315°

When considered together, these results show that although Ecotect predicts the direct component to be less significant to the overall solar gain total than the SAP worksheet assumes it to be, the predicted variation in direct gains is relatively greater and more orientation dependent under the Ecotect analysis than using the SAP methodology.

It is proposed that the most likely reasons for this disparity come from the modelling data used in each method for the calculation of the solar insolation and gains. Ecotect uses the solar insolation values from its weather data file for Sheffield, which has averaged daily data on temperature, cloud cover and wind speeds for the locality, allowing monthly predictions to be made on the cumulative insolation value as the sun's angle changes throughout each day. The SAP method however uses a single set of 8 solar flux values to calculate the gains coming from each of the 8 cardinal and inter-cardinal orientations during the heating season, whatever the weather and wherever the house is built in the UK. One possibility is therefore that the SAP flux figures may not take into great enough consideration the negative effect that cloud cover can have on the contribution of direct sunshine relative to diffuse sunlight during the winter heating season. Or it could be that the SAP flux figures are averaged from a longer period of the year, whereas the cumulative results found using Ecotect are totalled from daily insolation values.

6. CONCLUSIONS AND FURTHER DISCUSSION

The SAP rating of a dwelling will gain importance as the benefits of domestic energy efficiency become more apparent to house buyers. This is expected to follow the 2007 introduction of the home seller's Home Condition Report (HCR), which will meet the UK's requirements under the European Performance of Buildings Directive [7]. The results from this study could be used by house builders to influence the layout of their sites and the resulting orientations of the homes they build in future, in order to gain an improved rating in the HCR.

The dwelling under investigation was orientated with its rear facade, which incorporates 68% of the overall glazed area, facing 30° west of north. This

orientation makes maximum advantage of the outstanding hillside view that the site offers. The large areas of glazing are found to enhance the diffuse daylight levels within the dwelling, and all habitable rooms are expected to have 'Daylight Factors' and 'View lines of the sky' that exceed the requirements of the DETR Good Practice Guidelines and BRE EcoHomes (2005) assessment. This conclusion was reached using both the standard equation of Crisp and Littlefair [2], and the more detailed analysis made possible using the Ecotect building analysis computational package [3]. Although variations were found to occur between the two methods, these were explained through variations in the modelling and measurement approaches.

Assuming that the heating system is fuelled using natural mains gas, it has also been found however that the choice of orientation will lead to a SAP value for the house that is 2 points less than could have been achieved had the site been arranged to give a southerly orientation to the rear elevation. The annual fuel bill to the house owner is expected to be £58 greater: an increase of 7.4%; and the dwelling is expected to emit close to three-quarters of a ton more CO₂ annually; an increase of 8.6%.

A significant finding off this study is that providing larger areas of glazing can increase a home's SAP rating, but only if it is built with the appropriate orientation and glazing specification. For this particular house it was found that orientations that are roughly 90° or more away from due south lead to increased CO₂ emissions than had it been built with windows that were smaller but still meet DETR Best Practice Guidelines. Of course, if a heavily glazed house is built with a more southerly orientation there is usually an additional requirement to block out the

high direct solar gain in the summer using inexpensive shading techniques such as overhangs or bris soleil. Failure to take account of this can result in the need to provide further HVAC technologies to deal with the large summertime cooling load, which have significant economic and fuel costs of their own. Appendix P from the 2005 Draft SAP was used to show that so long as the house windows can be opened sufficiently to provide an effective air change rate of 2ach, the risk of overheating in this naturally ventilated, heavily glazed home should be "Not Significant". Failure to provide this level of ventilation would result in a "High" risk of summertime overheating.

The final part of the study found that there is a significant discrepancy between the SAP and Ecotect methodologies, in terms of the importance of solar gains from direct sunlight relative to the diffuse gains. The solar flux constants used in the June Draft 2005 SAP worksheet lead to expected direct solar gains that are 35–112% of the diffuse gains, depending on the home's orientation. The direct solar insolation during an October–April heating season is predicted by Ecotect however as only 12–34% of the diffuse insolation. Further investigation found that although the Ecotect program predicts the direct component to be less significant to the overall solar gain total, the additional direct gains predicted for the more southerly orientations are relatively greater and more orientation dependent than they are in the SAP methodology. While two possible reasons for this modelling discrepancy were suggested, the comparison cannot at present be taken any further as not enough is known on where the solar flux and insolation values used by each method are obtained from.

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