SOLAR HEAT SURPLUS AND SOLAR HEAT SCARCITY: THE INCLUSION OF SOLAR HEAT GAIN IN A DYNAMIC AND HOLISTIC DAYLIGHT ANALYSIS

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ABSTRACT

Solar heat gain is one of the tradeoffs associated with using natural light, and should be considered in any complete daylighting analysis. Because the non-spatial aspect of solar heat gain makes it more difficult to analyze along side illuminance or glare, this paper uses time-variant graphics as a basis of comparison. This paper also introduces a new goal-based solar heat gain metric, Solar Heat Scarcity and Surplus, which was inspired by the balance point analysis method. Although dynamic energy analyses should ultimately be used in determining energy loads, balance point can be as useful indicator in the earliest stages of design. The applicability of this metric to inform design through a validation with the recently released 16 DOE Benchmark Commercial Buildings is discussed, and as a proof of concept, the Solar Heat Scarcity and Surplus metric is applied to a simple options analysis.

INTRODUCTION

Even though solar heat gain is not a photometric quantity but rather a tradeoff associated with daylighting, it is of critical importance in the ultimate energy performance and thermal comfort of a space and should be considered alongside visual concerns in any holistic analysis of daylighting. Unfortunately, it is difficult to understand the impact of solar heat gain on a space's temperature difference or HVAC loads without doing an actual energy analysis. Since energy and daylighting analyses require very different model inputs and types of simulation, most existing daylighting analysis solutions that include solar heat gain are ones which either include or have easy exports to energy analysis tools (Urban & Glicksman 2007, Reinhart et al. 2007, Ecotect web, IES web). The few existing analysis methods that do not require simulation are usually only applicable to certain restricted climate locations and use the existing results from previous energy simulations in their application (de Groot et al. 2003, Hui 1997). Very few of these methods or tools parse the solar heat gain contribution out from the general energy analysis and present it separately as a tradeoff to incoming daylight (Ecotect web, de Groot et al. 2003).

In the earliest stages of design, understanding solar heat gain behavior is a valuable addition to daylight analysis, however the building construction and equipment information might not be available for a detailed energy analysis. For this reason, a simple existing energy balance equation, the balance point method, was chosen for solar energy calculation, and the errors that one might expect when employing this method were analyzed against energy use data from the more complex simulations performed by Energy Plus. The data from the balance point method was then used in a proof of concept for a solar heat gain metric which aims to show how solar heat gain is relatively increasing or decreasing the current energy load. This metric, named Solar Heat Scarcity, respectively Surplus, and abbreviated SHS, provides an indication of the urgency for allowing more solar gain during the heating season (Scarcity), respectively for shading windows more effectively during the cooling season (Surplus).

Finally, because solar heat gain is a non-spatial quantity, it is more difficult to compare it with location-based quantities like illuminance and glare, which are often displayed in spatial grids. On the other hand, daylighting quantities displayed in temporally-based graphics are easily comparable with solar heat gain. The authors have done previous work with temporal graphics and goal-driven metrics based on illuminance and glare measurements (Kleindienst et al. 2008, Kleindienst & Andersen 2009). The SHS results in this paper are given in the same goal-based color scale which was developed for the previous two metrics (Kleindienst 2009).

BALANCE POINT METHOD

The balance point method of building energy analysis can be found in the ASHRAE fundamentals handbook, but a good explanation also exists in Utzinger and Wasley's contribution to the Vital Signs program from

Berkeley (ASHRAE 2009, Utzinger & Wasley 1997). The balance point temperature is defined as "the outdoor air temperature required for the indoor temperature to be comfortable without the use of any mechanical heating or cooling," (Utzinger & Wasley 1997).

The balance point temperature is found through the application of steady-state energy balance equations. The basic equation for the balance point is as follows:

$$T_{BP} = T_{set} - \frac{Q_{SHG} + Q_{IHG}}{(UA)_{building} + (\rho c_p V^{\bullet})_{vent}} \qquad (1)$$

where T_{BP} is the balance point temperature (°C), T_{set} is the thermostat set point temperature (°C), Q_{SHG} and Q_{IHG} are the solar heat gain (from windows) and internal heat gain (W), U is the heat transfer coefficient of the façade (W/m^2°K), A is the area of the façade, ρ is the density of air (kg/m^3), c_p is the heat capacity of air (kJ/kg°K), and $V^{\bullet}$ is the ventilation volume flow rate (m^3/s).

The balance point and outdoor temperature over the course of a day can be graphed in opposition for a visual representation of heating and cooling load potential. Figure 1 shows a schematic graph of the balance point temperature which assumes a static internal heat gain during occupied hours and no internal heat gain during unoccupied hours. In this simple representation, the red line is the thermostat temperature, the green line is the balance point temperature due to internal heat gain only, and the yellow line is the balance point temperature due to both internal heat gain and solar heat gain. The temperature differences between the balance point and the outdoor temperature must be addressed by the heating system (shaded in blue) or the cooling system (shaded in yellow) and are measured in degree hours. The temperature differences themselves are not a load, but

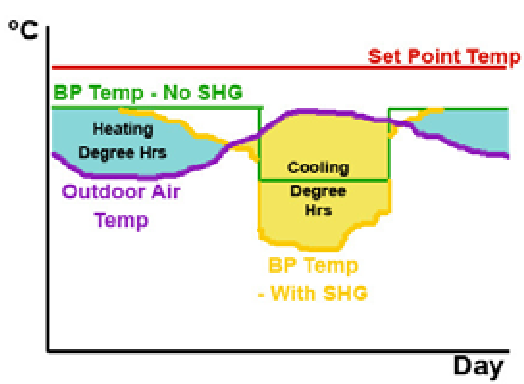

Figure 1. Schematic diagram of how to find heating and cooling degree hours by comparing Balance Point temperatures to the outdoor air temperature.

with the assistance of equation (2), they are instrumental to calculating the predicted load:

$$Load = (T_{out} - T_{BP})[(UA)_{building} + (\rho c_p V^{\bullet})_{vent}] \times t \qquad (2)$$

where the load (J) is positive for cooling, and negative for heating, and *t* represents the appropriate time step in seconds, given the data available.

The greatest weakness of the balance point method is that it cannot handle the transient properties of solar heat absorption and re-radiation by a building's thermal mass. The interaction of solar heat gain with thermal mass vastly complicates an energy analysis, because the rates of absorption and re-radiation are dependent not only on the mass thickness and exposure to direct sunlight, but also on the temperature difference between the mass and its immediate surroundings. The practical result of this interaction is an inevitable delay of the effects of solar heat gain on the building's thermal loads.

There may be other weaknesses inherent in estimations of solar heat gain. One study found that simpler solar heat gain calculations – which did not adequately account for internal absorption, redistribution, and possible re-radiation of heat gain through glass – were likely to overestimate the contribution of solar heat gain (Wall 1997). There also might be errors associated with lumping the heat gains and other variables for the whole building, rather than keeping zones separate. For this paper, the solar heat gain was acquired from Energy Plus while the building was still "zoned". The solar heat gain estimation was the most detailed available in Energy Plus: the 'FullInteriorAndExterior' mode in the field 'Solar Distribution'. To make sure these errors did not lead to unreasonable results, the next section describes two different simulation comparisons between Energy Plus and the balance point calculation.

SIMULATION

The balance point method is based on steady state equations, has limitations in dealing with thermal mass, and cannot be expected to be as accurate as a detailed, dynamic energy simulation program. However, since it also requires a far less detailed input and computation time, it may be more appropriate to early stage design explorations. As a tradeoff associated with natural light, it may be just as valuable to have a ballpark indicator of how much the solar gain is increasing cooling loads or offsetting heating loads. However, even if one accepts this argument, it is good to understand how much balance point results differ from dynamic simulation results.

A comparison between the balance point method and Energy Plus simulations was done using the sixteen benchmark commercial building models made recently available by the U.S. Department (Torcellini et al. 2008, DOE 2008). These buildings were released as Energy Plus models with an accompanying Excel spreadsheet giving building information and energy results, and each of the sixteen buildings was set up to be simulated in sixteen U.S. cities representing different climate zones.

For each building and location, an Energy Plus simulation was compared to two balance point load calculations with similar inputs. Each of the 256 simulation files was modified slightly to extract the necessary inputs for a detailed balance point model from the stepwise variable output of Energy Plus. All energy quantities were output in joules and outputs for heating and cooling energy were normalized by the given COP of the cooling systems or the given heating efficiency where appropriate. Each Energy Plus model was simulated twice: once with normal windows, and once with opaque windows of the same thermal resistance. This was done to parse the solar heat gain contribution from the final simulated energy use.

The balance point method was applied to the Energy Plus models in two ways. The more detailed calculation used the heat gains, ventilation rates, and other variables which are output at each time step from Energy Plus. In essence, this is purely a test of the balance point equation itself, assuming more accurate information than the designer is likely to have during schematic design. The most important feature of these inputs is the detailed schedules for occupancy, heat gains, and the ventilation system required by Energy Plus.

The second balance point calculation was done using the design information for internal heat gain, ventilation, and infiltration which came with the Energy plus models – and a very simple schedule based on occupancy. This is meant to more closely represent the type of information available to the designer during early stage design explorations, as each quantity is a single number for either 'occupied' or 'unoccupied' times of day. Also, all Energy Plus and balance point results were analyzed and compared as daily energy totals (i.e. the summation of hourly results) so as to mitigate some of the balance point's weakness in transient errors.

Finally, heating and cooling loads can be considered part of the same spectrum of heat transfer conditions, and at the zero point between "positive" cooling and "negative" heating conditions, any conventional error is blown wildly out of proportion. In the comparisons shown below, the absolute load difference was more consistent than the conventional error. Because of this, the ratio used for comparison is the difference between balance point load and simulated energy use, divided by the *maximum* simulated heating or cooling energy use (whichever is appropriate):

$$\textit{Maximum Load Ratio (MLR)} = \frac{Q_{BP} - Q_{sim}}{Q_{sim,MAX}} \quad (3)$$

where Q_{BP} is the daily total balance point load, Q_{sim} is the daily total simulated energy use, and $Q_{sim,MAX}$ is either the maximum heating or the maximum cooling daily total energy use for that particular building and climate. The maximum load was chosen as a means of error comparison because it is a representative and a recognizable energy quantity associated with each particular building.

RESULTS

The results can be categorized by annual average MLR as an indicator. To help give an idea of the overall distribution of results, correlation categories have been assigned based on annual average MLR, as shown in Figure 2. The thresholds shown in that table were determined after a visual analysis of many annual energy use and load graphs (such as the ones in Figure 3). The thresholds defining "very good" and "good" specifically are meant to represent a very close correlation between balance point loads and simulated energy use.

From an overall performance standpoint, the simulated energy use of the Retail, Midrise Apartment Building, and Fastfood models were very well represented by both balance point analyses. The Outpatient, Small Hotel, and Small Office models showed "very good" correlation for one of the balance point analyses, and "good" for the other. These are all envelope-dominated

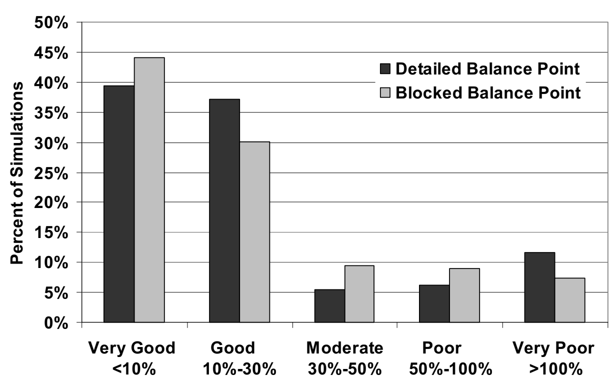

Figure 2. The distribution of average MLR over the 256 building and city simulation combinations. The dark bars show the detailed balance point calculation, while the light bars show the simplified balance point with a blocked schedule.

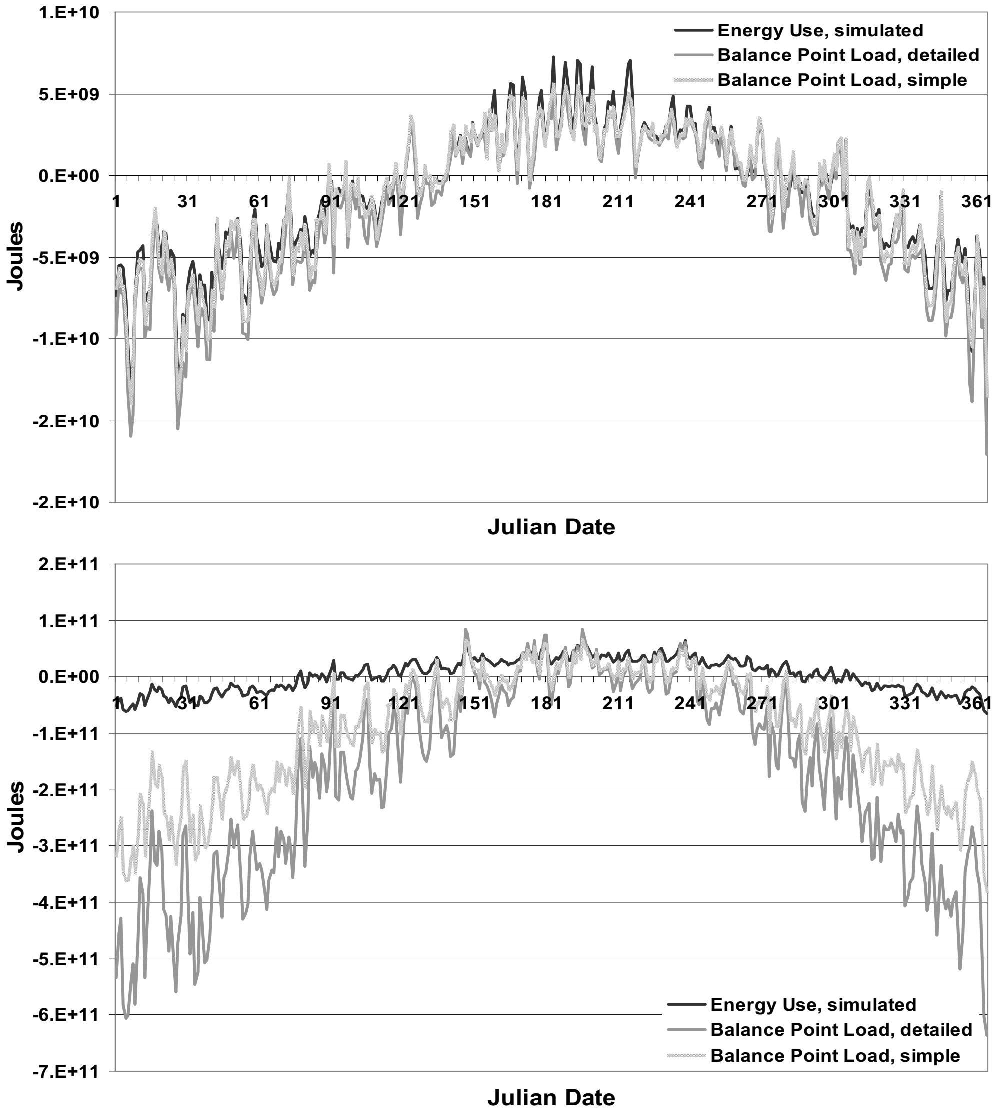

Figure 3. The annual variation in Energy Plus simulated energy use and the two calculations of balance point load for the a very good correlation (Retail, Chicago: above) and a very poor correlation (Large Hotel, Minneapolis: below).

buildings, based on their larger surface to volume ratio and moderate internal heat gain (Lechner 2001). As mentioned above, the three building models which are most internally dominated are the Hospital, the Large Office, and the Large Hotel, which had the worst correlations in general, especially the Large Hotel. In these cases, thermal mass acted as a dampener of the peak energy loads, allowing the heating system to remain off for a far greater amount of time and the cooling system work less hard.

The two other models which exhibit moderate to poor correlation are the simple balance point analyses of the Sit Down Restaurant and both balance point analyses for the Warehouse. In the restaurant's case, the balance point analysis with a simple schedule vastly overestimated the cooling required all year. Another look at the kitchen equipment schedule showed that it never goes above 30% of its capacity (and thus 30% of its heat output) at any time, and the peak uses are tied not to the work day, but to meal times. A re-simulation with an adjusted internal gain weight solved some of the problem, but the uneven schedule between meal times still meant that the simple case overestimated the load in general.) The Warehouse, on the other hand, is a building with several different heating and cooling set point temperatures for the different types of storage zones or office space. The analysis was unfortunately not set up to handle this level of detail, so the correlation between energy use and the calculated balance point loads varies unpredictable from "very good" to "very poor", with the majority of simulations producing "moderate" to "poor" correlations.

A NEW SOLAR HEAT GAIN METRIC

The balance point analysis provides results in terms of energy load. However it is often helpful to give results in terms of user goals. In the case of solar heat gain, the ultimate goal would be to allow just enough solar gain to offset heating load and block any which might add to cooling load. The "right" amount of solar gain would be however much is required for the outdoor temperature to to fall between the two building balance points found using the cooling and heating set point respectively.

Thus, the solar heat gain metric is split into two parts, called Solar Heat Scarcity and Solar Heat Surplus (SHS), based on whether heating or cooling is required:

If $T_{out} - T_{BP,S} \geq 0 \rightarrow$ Solar Heat Surplus (cooling) (4)

If $T_{out} - T_{BP,S} < 0 \rightarrow$ Solar Heat Scarcity (heating)

Solar Heat Surplus (cooling)
(5)

$$= 2 \times \frac{\Delta T_{SHG}}{\Delta T_{SHG} + \Delta T_{IHG}} \times \max\left[\frac{\Delta T_{load,S}}{\Delta T_{SHG}}, 1\right]$$

$$= 2 \times \left(\frac{T_{BP,NS} - T_{BP,S}}{T_{set} - T_{BP,NS}}\right) \times \max\left[\left(\frac{T_{out} - T_{BP,S}}{T_{BP,NS} - T_{BP,S}}\right), 1\right]$$

Solar Heat Scarcity (heating)

$$= \frac{\Delta T_{load,S}}{\Delta T_{load,NS}} = \frac{-\left(T_{BP,S} - T_{out}\right)}{T_{BP,NS} - T_{out}} \qquad (6)$$

where $T_{BP,S}$ is the balance point temperature (°C) based on both internal and solar heat gain, $T_{BP,NS}$ is the balance point temperature (°C) based only on internal heat gain, T_{set} is the heating or cooling thermostat set point (°C), and T_{out} is the outdoor temperature (°C).

The Solar Heat Scarcity is the percent of the heating load not offset by solar gain, and Solar Heat Surplus is loosely based on the percent of cooling load caused by solar gain, as shown in Figure 4. In the top example, the cooling required is less than the Solar Heat Gain alone. In the middle example, that ratio is greater than 1, so the SHS depends on the ratio of SHG to IHG.

Solar Heat Surplus ranges from 0% to 100% and is partially defined by the percent of solar heat gain which needs to be eliminated to bring the cooling load to zero.

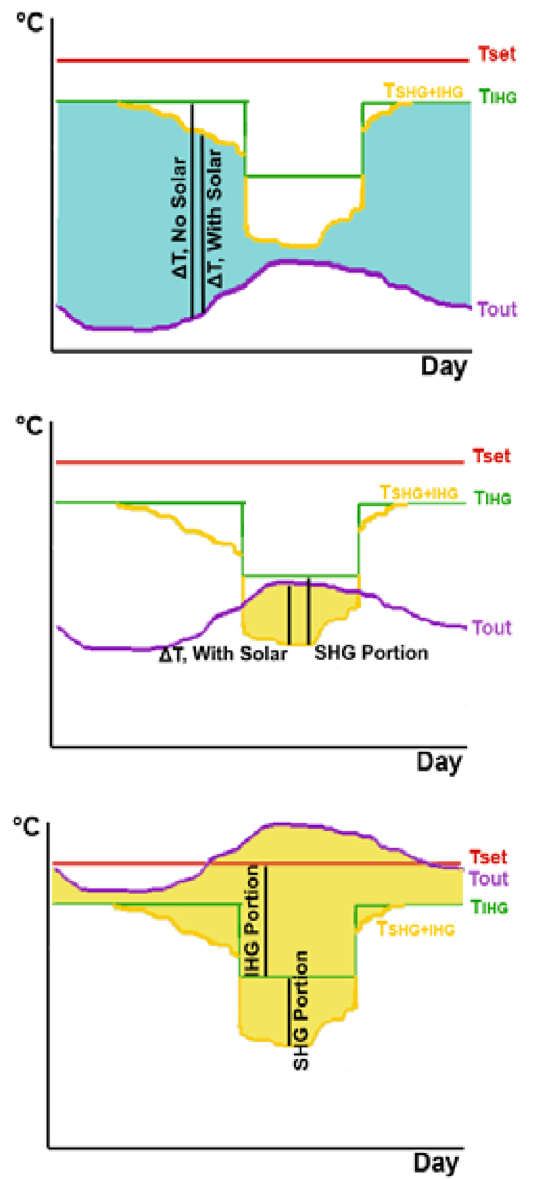

Figure 4. Schematic Example of Solar Heat Surplus (top and middle) and Scarcity (bottom).

However, since the cooling load often exceeds the load caused by solar gain, the definition needs to be modified to keep the metric from saturating at 100% too often. Therefore, this value is also weighted by twice the ratio of the solar heat gain over the total heat gain of the building or space. What this is saying is that the internal heat gain is partially responsible for the cooling load. The factor of two is included to put a greater weight on the solar heat gain when it equals or exceeds the internal heat gain. One effect of this is that buildings with large internal loads may always have a low Solar Heat Surplus, however since most of the cooling load in those cases are due to internal gain, it would be a misrepresentation to attribute too much of the cooling load to solar heat gain.

METRIC VISUALIZATION

As mentioned above, the authors have done previous work on the display of illuminance and glare data using goal-driven metrics on temporally-based graphics (Kleindienst et al. 2008, Kleindienst 2009). Because of the non-spatial quality of solar heat gain, temporal graphics are a very good way in which to compare SHS to other daylighting results. Furthermore, if all metrics are goal-driven, they could even be compared using the same goal-based value scale.

Given any user goal, the simulated result may meet that goal, overstep that goal, or not reach that goal, giving three possible outcomes. Because of this, a triangular, rather than a linear, color scale was adopted for all goal-driven temporal maps (see Figure 5). In this scale, yellow represents results that meet the user's goals, blue represents those which fall short, and red represents those which overstep the goals. Similarly, orange represents results which are partially too high, greenish represents results which are partially too low, and purple represents simultaneously too high and too low. Any color on the triangle is a possible outcome, based on the portions of the results which are in goal range, high, and low.

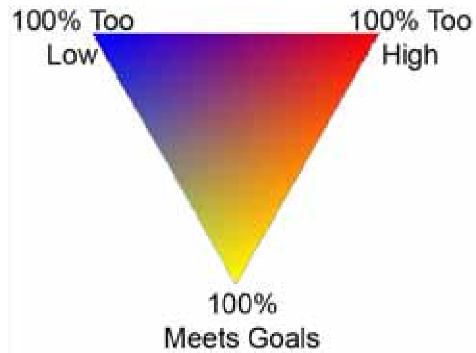

Figure 5. Triangular color key for goal-based metrics.

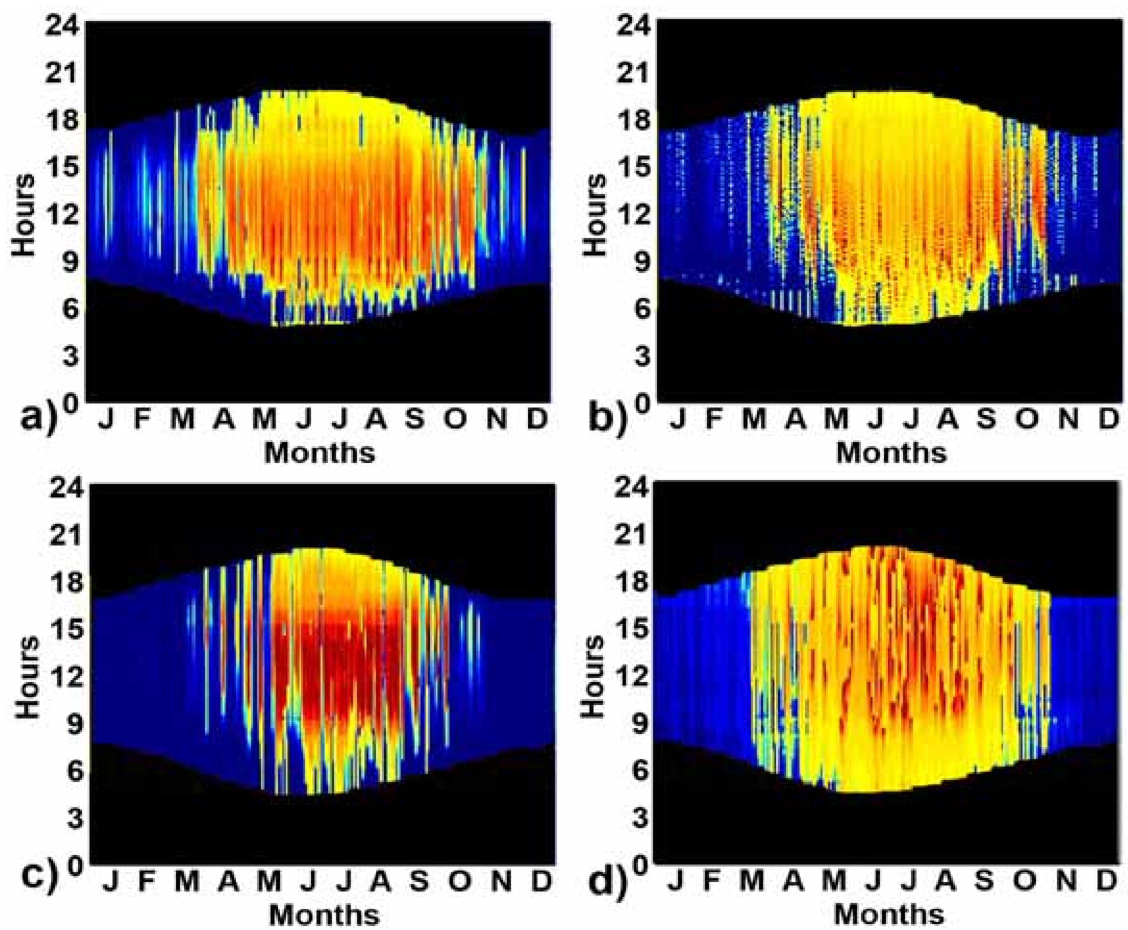

Figure 6. Temporal map representations of Solar Heat Scarcity/Surplus. All temporal maps show the year on the X axis and the day on the Y axis. a) and b) represent the Retail model in Chicago. c) and d) represent the Large Hotel in Minneapolis. The left maps are from detailed balance point calculations and the right are from Energy Plus results.

Using this triangular color scale, there are a couple of different ways to create a temporal graph of Solar Heat Scarcity or Surplus. The graphs in Figure 6 show instantaneous balance point SHS results for the Retail model in Chicago (very good correlation) and the Large Hotel in Minneapolis (very poor correlation). Although both models show some dampening of the solar heat gain peaks in the Energy Plus results, this is much more exaggerated in the Large Hotel model, because it has a much higher thermal mass. Because we are using a simplistic analysis, a more appropriate way of showing Solar Heat Scarcity or Surplus may be by summing daily load totals (such as were shown in Figure 3), rather than instantaneous loads. The SHS percentage derived from these daily totals would be displayed in temporal maps in solid bands of color, since the value would be constant over the day (see Figure 7). The result is a look at seasonal, rather than hourly trends of SHS, but it is more representative of the accuracy of the data involved in balance point calculations.

The daily totals SHS could also be seen as a potential for using thermal mass to balance heating and cooling loads. For instance a daily total SHS near zero (yellow) represents a building with Solar Heat Surplus numbers during the day which balance the Solar Heat Scarcity at night. Proper application of thermal mass should allow the building to store the incoming solar flux during the day and let it off at night when it's colder. That same building would strategically want to block all influx of solar gains during seasons when Solar Heat Surplus was greater overall than Solar Heat Scarcity (orange to red).

Figure 7 indicates a building which has been reasonably well-shaded in the summer (as evidenced by the near-yellow color), and is in a warm enough climate to allow some winter overheating due to solar gains (the orange-red) while also suffering some colder days (the blue stripes). These results came from a simulated south-facing hospital room in Phoenix, Arizona, with external horizontal louvers that provide enough shade during only the warmer half of the year.

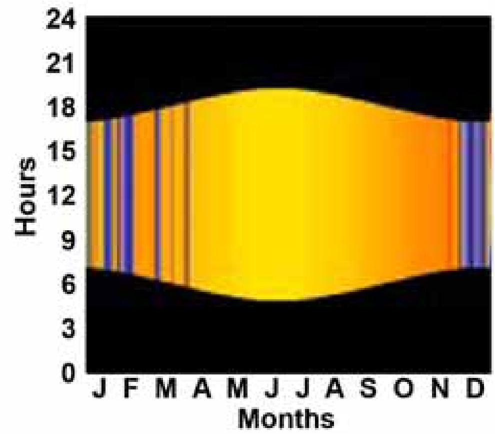

Figure 7. Solar Heat Scarcity or Surplus temporal map displayed in the form of daily totals rather than hourly data.

CONCLUSION

SHS, which is split into Solar Heat Surplus and Solar Heat Scarcity, is a measure of the need for, or the need to get rid of, solar heat gain. It was inspired by and is found using the balance point method as a simple energy calculation and is analyzed against data gathered using the 16 Commercial Benchmark Buildings released recently by Energy Plus. For the most part, the correlations were within 30% when looking at the ratio of the daily load total to the maximum daily load total for the heating or cooling season. The two main causes of bad correlation between the balance point loads and the Energy Plus energy use are large thermal mass, and for the simple balance point calculation, inadequate representation of the model – especially internal loads, variable schedules, and multiple zone set points. It is important to note that while the balance point method was chosen for this study, the SHS metric could even be used in conjunction with a far more complex energy simulation. Most importantly, this paper demonstrated that it is possible to put solar heat gain information into a goal-based temporal format and thus make it more easily comparable with location-based data. Research regarding the use of illuminance, glare, and solar heat gain metrics, which are goal-based and formatted for display in temporal graphics, can be found in (Kleindienst 2009).

This research is part of the Lightsolve project, which was initiated with the object of meeting the needs of architects in the earliest stages of design while promoting a greater understanding of daylighting strategies (Andersen et al. 2008). The numerical results, which are climate-based annual data sets of illuminance, glare and solar heat gain information are presented graphically using temporal maps and goal based metrics along side renderings on a highly visual GUI, designed for architects by architects (Yi 2008). Lightsolve aims to produce fast, unique design analyses, based on local annual climate data with reasonably accurate and intuitive outputs to promote good decision-making.

ACKNOWLEDGEMENTS

This research was supported by the Massachusetts Institute of Technology. The authors would like to thank Les Norford for his analysis advice.

REFERENCES

Andersen, M., Kleindienst, S., Yi, L., Lee, J., Bodart, M., Cutler, B. 2008 An intuitive daylighting performance analysis and optimization approach. Building Research and Information, Vol 36 (6), pp 593-607.

ASHRAE. 2009. ASHRAE Handbook, Fundamentals. Ed Mark Owen. Atlanta, GA.

de Groot, E., Zonneveldt, L., Paule, B. 2003. Dial Europe: A decision support tool for early lighting design. Proceedings of the 8th International IBPSA Conference, Eindhoven, The Netherlands, August 11-14.

DOE. 2009. Net Zero Energy Commercial Buildings Initiative. United States Department of Energy website: http://www1.eere.energy.gov/buildings/commercial_initiative/benchmark_models.html, last accessed, October 2009.

Ecotect website: http://ecotect.com/products/ecotect/features/, last accessed: October 2009.

Hui S.C.M. 1997. Overall Thermal Transfer Value (OTTV): How to Improve Its Control in Hong Kong. Proceedings of the One-day Symposium on Building, Energy, and Environment, Hong Kong, October 16, pp12-1 – 12-11.

IES Virtual Environment website: http://www.iesve.com/, last accessed October 2009.

Kleindienst, S., Bodart, S., Andersen, M. 2008. Graphical Representation of Climate-Based Daylight Performance to Support Architectural Design. LEUKOS, 5 (1), 39-61.

Kleindienst, S., Andersen, M. 2009. The Adaptation of Daylight Glare Probability to Dynamic Metrics in a Computational Setting. Proceedings of the Lux Europa 2009 Conference, Lausanne, September 9-11.

Kleindienst, S. 2009. Time-Varied Daylighting Performance to Enable a Goal-Driven Design Process. PhD Thesis, Massachusetts Institute of Technology.

Lechner, N. 2001. Heating, Cooling, Lighting: Design methods for architects. 2nd Ed. John Wiley & Sons, New York, NY.

Reinhart, C.R., Bourgeois, D., Dubrous, F., Laouadi, A., Lopez, P., Stelescu, O. 2007. Daylight 1-2-3 – A state-of-the-art daylighting/energy analysis software for initial design investigations. Proceedings of the 10th International IBPSA Conference, Beijing, September 3-6, pp 1669-1676.

Torcellini, P., Deru, M., Griffith, B., Benne, K., Halverson, M., Winiarski, D., Crawley, D.B. DOE Commercial Building Benchmark Models. 2008. Proceedings of the 2008 ACEEE Summer Study on Energy Efficiency in Buildings, Pacifc Grove, California, August 17-22. Online source: http://www.nrel.gov/docs/fy08osti/43291.pdf, last accessed October 2009.

Urban, B.J., Glicksman, L.R. 2007. A Simplified Rapid Energy Model and Interface for Nontechnical Users. Proceedings of Oak Ridge National Laboratory, Buildings Conference X.

Utzinger, M., Wasley, J.H. 1997. Building Balance Point. Vital Signs Curriculum Materials Project, University of California – Berkeley, and University of Wisconsin – Milwaukee. August, 1997. Online source: http://arch.ced.berkeley.edu/vitalsigns/res/rps.html, last accessed October, 2009.

Wall, M. 1997. Distribution of solar radiation in glazed spaces and adjacent buildings: A comparison of simulation programs. Energy and Buildings, 26, 129-135.

Yi, L. 2008. A New Approach in Data Visualization to Integrate Time and Space Variability of Daylighting in the Design Process. Masters Thesis, Massachusetts Institute of Technology.