HEURISTIC USE OF ENERGY SIMULATIONS IN BUILDING DESIGN

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ABSTRACT

This paper highlights the difficulty of using energy simulations to answer general questions in typical building design scenarios. By analyzing the question, it is identified that problems of a search-based nature may encounter situations where an exhaustive search is impractical with reasonable resources.

This paper presents the method of using heuristics to solve such questions within just a few simulations. While the solutions may not necessarily be guaranteed to be global or ideal, they are optimal within reasonable limits and sufficient for the types of questions addressed. Two such heuristic methods are proposed and tested via experiment, and the results are presented.

KEYWORDS

Energy simulation, search, heuristic methodologies, overcoming resource limitations

INTRODUCTION

EnergyPlus (Crawley et al. 2001) is a widely validated and used building simulation tool in North America, both in the research arena as well as the building industry. However, the tool is primarily developed as an energy calculator and not a general design decision inquiry tool. The building model has to be explicitly and comprehensively described before EnergyPlus can be used to simulate and predict the various energy related performances of the building. There is thus a disjoint with situations where the question at hand includes portions of the building model as part of the evaluative task. This is a common scenario, especially in design and education tasks where the questions are of a "*what if*" and *"how to"* nature rather than the *"what is"* pretext of post-design model evaluations and verification.

To overcome this problem, a common practice is to conduct parametric simulations: the building model is duplicated to evaluate the performance impact of the variable portions of the model. Similarly, the questions where the evaluative expression is at odds with the processes of EnergyPlus are often structured as optimization problems where stochastic or deterministic variations of EnergyPlus models are evaluated and analyzed. In either case, it is noted that significant resources beyond reasonable means are required to prepare and evaluate the large number of parametric simulations.

In this paper, a heuristic methodology is proposed and tested to significantly reduce the resource requirements and workload of producing reasonable solutions to the category of questions posed. By describing a typical energy-related inquiry where the objective is to understand the effect of solar shades on office buildings in North America, and to obtain the optimal schedule of window shading, this paper shows how the common parametric and optimization approaches would take thousands of hours to simulate, and how a heuristic approach can yield reasonable solutions within just a few simulations.

EXPERIMENT – STAGE 1

The experiment presents an inquiry of how internal window shades affect the building loads within the context of office buildings in North America. The experiment is further structured into 2 stages: first, whether internal window shades have an impact on building loads and if so, the second stage is to find the optimal load impact of the window shades.

For the first stage of assessing the impact of internal window shades on building loads, a complete building model is simulated twice, once without internal window shades and again with internal window shades. The direct comparison of the two sets of results yields data to fufill the question at hand, "*what is the difference in building loads when there are window shades*".

This question in Stage 1 is representative of a typical structured post-design evaluation in the sense that the evaluation is determined: there exists a method of evaluating the unknown, and all the variables required for the evaluation are present. Specifically, the unknown to be evaluated is the building load, the method of evaluation is the energy simulation (or equations as implemented within the energy simulation), and the variables required for the evaluation encapsulated in the complete building model are present.

The fact that certain assumptions are made does not affect the categorization of the evaluation as described thus far, as long as the assumptions are motivated and justified by the question and not the requirements of the evaluator (as described later in Stage 2). For example, the evaluation for Stage 1 requires information on the geometry, location and thermal properties of a building as well as details on the internal window shades not explicitly defined by the original question. However, such assumptions can be reasonably made by limiting the context of the question.

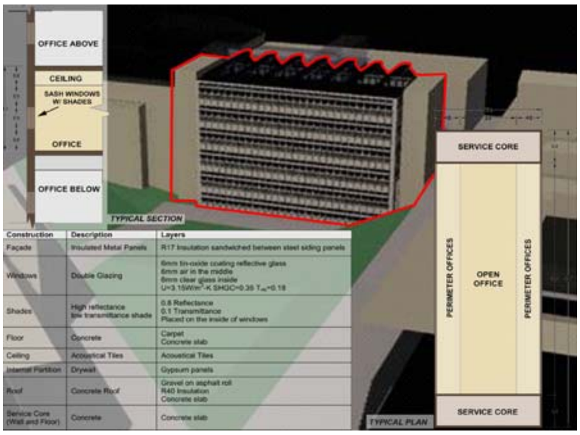

Figure 1 Assumptions for Building Modeled

In this case, the consideration of the Stage 1 question within the context of office buildings in North America allows assumptions to provide a complete building model. The Building as Power Plant (CBPD 2001), a 6-storey office building with 48-thermal zones and 30% glazing area on the facades, shown in Figure 1, is adopted as the base model to evaluate the effect of the window shades. Material properties for a high-reflectance low-transmittance window shade are also adopted.

With the necessary material properties, internal gains, occupancy, schedules and HVAC information present, the building model is simulated using EnergyPlus for 4 locations (Boston, Los Angeles, Miami and Phoenix). 2 simulations are conducted for each loaction, once without any window shading and once with all windows shaded at all times. The results are then tabulated and compared.

The results at this stage show that internal window shades affect the "net heat flow" across windows significantly (approximately 15% depending on orientation and location) and consequently causes a change in the heating and cooling loads. Furthermore, the results also show that internal window shades can result in either an increase or decrease in the building loads at anytime depending on the context: i.e., the indiscriminate use of internal window shades does not necessarily result in an optimized moderation of building loads.

During the heating seasons, raising the window shades when there is sufficient solar radiation would allow the solar heat gain to complement the need for indoor heating, thereby lowering the heating loads. For this to hold true, the amount of heat gain through the windows must be lower than the amount of heat loss through the same windows. During the cooling seasons, the reverse would hold true; reducing the solar heat gains and window gains in general by shading the windows should lower the indoor cooling loads, provided the reduction in heat loss through the same windows is not greater. The potential effect of window shades is thus dependent on 2 properties: its ability to moderate the amount of solar radiation gains as well as the conductive/convective properties of the windows.

EXPERIMENT – STAGE 2

Having established that internal window shades do have an effect on building loads, the question then turns to "*what is the maximum benefit given the use of window shades*". As indicated by the preliminary results of Stage 1, it is necessary to determine the conditions at each time-instance when the decision to raise or lower the internal window shades on each window is to be made. In this experiment, such instances are assumed to be hourly and consistent with the time-step of the simulations.

The previously described logical conditions prescribing when it would be advantageous to use the window shades constitutes the shading control algorithm. A given initial state of conditions such as the outdoor temperature, solar radiation and indoor temperature can be used to determine, through a well-defined procedure, if the windows should be shaded. The resulting tabulation for all the windows indicating the operating decisions (raising/lowering each window shade) to achieve the lowest building loads is then the *optimal* window shades schedule.

The nature of the question is thus changed significantly from that of Stage 1. Whereas there still exists some method for evaluating the unknown (the same energy calculations in EnergyPlus to evaluate building loads), not all the variables required for the evaluation are present in this case. Specifically, the window shades schedule is indeterminate since the required conditions in the shading control algorithm as described earlier can only be obtained from the results of the very same energy simulation that requires this schedule.

This problem is typical of both design and education (as well as research) scenarios as set forth in the introduction section earlier. In this category of problems, the objective is a *search* for some maxima/minima (e.g., the *lowest* building loads) given some set or range of possible states (individual windows *can* be shaded or unshaded). This is contrasted with the category described earlier in Stage 1 where the objective was the *evaluation* of some value in a given function (the building loads of a given building model).

One solution is to conduct an exhaustive search. This requires the enumeration of all possible states, then conducting an energy simulation for each state and comparing the results. This is similar to conducting parametric simulations. The building model is duplicated to evaluate the performance impact of the variable portions of the model, in this case, the window shades schedule. Given 12 windows that can be operated independently in each of the 8760 hourly time-steps, an exhaustive search for the *ideal* state implies simulating 2^{105120} possible states and selecting the one with the smallest building load. This is clearly not feasible with reasonable resources.

The typical approach is then to frame this type of search problem as an optimization problem. In this particular case, the energy calculations as evaluated by EnergyPlus can be described as the cost function, and the various possible permutations of window shades schedules constitute the various candidate solutions. By applying some optimization technique, one can then arrive at the optimal solution where some candidate causes a minima in the cost function. This is equivalent to identifying the particular window shades schedule that results in the minimum building loads, thus answering the initial question.

In principle, this optimization approach works and more importantly, allows the use of a well established energy calculator in arriving at the results. This affords a high level of accuracy as well as confidence in the results. While an exhaustive search is similar in nature to optimization, what differentiates most optimization techniques from an exhaustic search is the possibility of considering less than the total number of enumerated possible states.

Simplistically, an optimization technique can find an optimal state while evaluating less than the enumerations of all possible candidate solutions by capitalizing on some relationship or function between the variable and the cost function, as well as the scalar nature of the variable. The term scalar is used here not to describe degrees of continuity or linearity, but the possibilty of formulating any relevant function. It is then possible to discern some pattern between the cost function and the variable to eliminate certain candidates.

This reduction in resource requirements in finding optimal solutions is of interest and value in the use of energy simulations to address the fairly common open-ended or search-orientated questions. A problem arises however, as in this case, when the variable is not scalar and a pattern between the cost function and the variable metric cannot be discerned. There is no guarantee an exhaustive search can be avoided to determine the optimal solution.

As opposed to variables such as materials that can be measured and sorted by thermal conductivity, it is not clear how the window shading schedule can be metricized to describe various states of the schedule such that some optimization technique can avoid an exhaustive search.

DISCRETE INDEPENDENT TIME-STEPS

This study proposes the use of heuristics to negotiate between the dichotomous concerns of accurary and resources. Given the problem of a large number of possible states of window shades schedule that is difficult to metricize in the problem described in Stage 2, it is accepted that the ideal solution would require huge amount of resources to arrive at. This implies that if some method considers only a subset of all the possible states, the solution might be *optimal* within that subset, but not necessarily *ideal*. This poses the question if such an optimal but not necessarily ideal solution is sufficient to address the initial problem. In situations where providing a solution is time-sensitive, or when the answer containing modifiers such as “might be” or “is at least” is acceptable, the trade off between accuracy and resources may be acceptable or even preferred.

If the solution to the question posed in Stage 2 is of the form “The reduction in building loads is at least/approximately (some quantity)” and the answer can be provided within several man-hours, this is clearly acceptable and arguably preferred to a definitive answer to the question “The definite reduction in building loads is (some quantity)”, which would require the time and resources in conducting 2^{105120} simulations. The examination of the initial question, as well as the fact that many assumptions have been made, further justifies the experiment as an inductive endeavour rather than a case-specific experiment demanding absolute and highly accurate results.

The use of heuristics sacrificies some accuracy for a reduction in the number of simulations required. By considering that the hourly shading control algorithm uses values that the energy simulation can provide, the idea is to see if the hourly algorithm can be solved by “trial-and-error”. The problem then is the dependency between the hourly time-steps. At each 1-hour time-step, the shading control algorithm would determine if the windows are to be shaded, and the building model updated accordingly before the next hour can be simulated. The second set of simulation results describing the new state of conditions is then used by the control algorithm in this iterative process. 8760 simulations would thus have to be conducted incrementally, with a manual adjustment of the window shading schedules at each time-step. This still seems excessive.

As a work-around, the degree of effect between the time-steps given typical changes is analyzed. By partially altering the shades schedule and comparing the changes in the hourly simulation results after the schedule changes, the effect of a schedule change in a particular hour on subsequent hours can be tabulated.

A numerical analysis is conducted by varying the window shading schedules in the building models for all 4 locations in the study. The different schedules were designed not just to analyze the effects of a single-hour condition change on subsequent hours, but also the cumulative effect of multiple-hour condition changes.

As summarized in Table 1 where the conditions of only a single hour are changed, the effect on the next hour (hour 1) is "limited" relative to the magnitude of change at the hour of condition change (hour 0) and the effect on later hours is even smaller. This observation is consistent across all locations. Since the objective is to derive a heuristic technique that would allow us to treat the time-steps as piece-wise independent, the criterion for "limited" is relaxed. As exemplified in Figure 2, this pattern of "limited" next-hour change followed by a rapidly decreasing change in later hours can be discerned.

Given exponentially decreasing pattern, the effect of cumulative changes in multiple time-steps would be similar to that described above. The modified models with the various designed schedules are compared. As indicated by Figure 3 which illustrates the building load impact of half-year shading schedule change, the pattern still holds and the magnitudes of changes do not increase. This allows us to treat the time-steps as piece-wise independent in the following simulations to heuristically derive appropriate window shading schedules.

Having established that the impact of condition changes have only a small impact on subsequent time-steps, the heuristics of treating the time-steps as discrete and independent is applied. While accuracy is sacrificed, we can now use a single annual energy

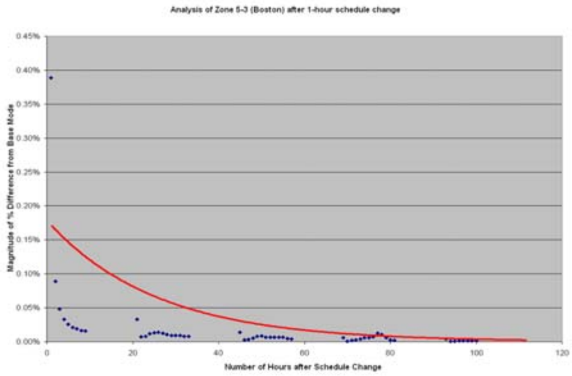

Figure 2 Decreasing influence of condition changes within a time-step on subsequent cooling loads (base model = no shades)

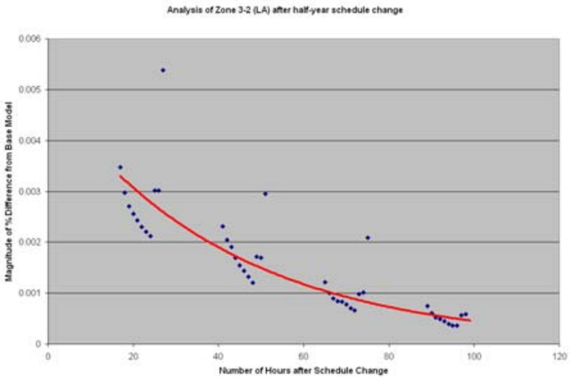

Figure 3 Decreasing influence of cumulative condition changes on subsequent cooling loads (base model = no shades)

Table 1 Percentage Change in Net Heat Flow across Windows after 1-hour of Schedule Change (Boston) (numbers are rounded and values in parenthesis are negative.)

Hours After Schedule Change	Zone 1-1	Zone 1-3	Zone 2-1	Zone 2-3	Zone 3-1	Zone 3-3	Zone 4-1	Zone 4-3	Zone 5-1	Zone 5-3	Zone 6-1	Zone 6-3
0	8.9%	7.0%	10.1%	8.1%	10.4%	7.6%	10.4%	8.4%	10.5%	8.4%	10.4%	8.3%
1	0.0%	(0.0%)	0.0%	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)	0.0%	(0.0%)	(0.0%)
2	(0.0%)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
3	(0.0%)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
4	(0.0%)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
5	(0.0%)	(0.0%)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10	0.0%	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)
20	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)	(0.0%)
30	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
50	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
100	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

simulation to provide values for the window shading control algorithm for all 8760 hours to determine the optimal shading schedule. Another simulation is conducted to calculate the building load as affected by this schedule. Instead of 8760 simulations, this method provides some answer with 2 simulations.

While a concise validation of the solution provided by this method would again require an exhaustive consideration of all possible schedule states, the results from Stage 1 are used to intuitively compare the results. It was found in Stage 1 that the indiscriminate use of window shades at all times causes an overall increase in the annual building load. The analysis of time-step data revealed, as described earlier, that a reduction in building loads can be achieved when the shades are deployed under the right conditions. In this case, the heuristic approach yields a shedule where the windows are shaded for less than 9% of the time.

The comparison of the results from the base case (no shades), shaded case (indiscriminate shading at all times) and the heuristically optimized case in Table 2 shows that the results of the last case are demonstrably correct. It achieved lower annual building loads as expected.

Table 2 Sample analysis of the performance of heuristic approach

		Heating Load [kWh]	Total Load [kWh]	% of Base Heating Load	% of Base Total Load
Boston	Base Case	161043	327433	-	-
	Shaded Case	162627	332527	100.98	101.56
	Heuristic Case	160894	327285	99.91	99.95
LA	Base Case	1914	287624	-	-
	Shaded Case	2299	293684	120.11	102.11
	Heuristic Case	1882	287564	98.33	99.98
Miami	Base Case	157	589189	-	-
	Shaded Case	172	593136	109.83	100.67
	Heuristic Case	155	589183	98.90	100.00
Phoenix	Base Case	6096	602738	-	-
	Shaded Case	6834	605248	112.11	100.42
	Heuristic Case	6088	602730	99.86	100.00

Though small, the magnitude of reductions is sufficent to say that the heuristic approach achieves some reduction in the building loads, whereas the indiscriminate use of window shades 100% of the time actually results in a net increase in the building loads. The magnitude of load reductions has to be considered in the context of various factors such as the surface-area-to-volume ratio of the building, ratio of spaces with windows to all conditioned spaces, internal space gain assumptions, ratio of window loads to total space gains and other considerations which are beyond the scope of this discussion.

ITERATIVE SEARCH

Following the methodology of assuming independent discrete time-steps in the heuristic method discussed, an additional assumption can be made: there exists some optimal shading schedule between the 2 initial schedules, i.e., Base Case and Shaded Case. This allows an iterative search for some better schedule. By holding all conditions except the schedule of window shading constant, a comparison can be made between 2 similar states of a building model to evaluate which schedule of window shading has a lower building load. Since the time-steps are considered discrete, this comparison can be conducted independently at each time-step. By selecting the schedule that yields a lower building load at each time-step, the overall annual window shading schedule can be derived.

The resulting schedule only holds true in the context of the assumptions, and is only a heuristics with no guarantee on correctness. However, the first assumption of discrete time-steps can be relaxed. In this case, there is no presumption that resulting state as defined by the schedule obtained so far will yield the exact time-step results as the state selected during the earlier comparison. The resulting state, as defined by the schedule obtained from discrete comparison, is simulated in EnergyPlus and checked against the 2 initial states to determine if each time-step selection yields the desired results. The benefit of this method is that it allows an iterative search for better states. As a heuristic approach, the amount of work required to find some satisfactory result is independent of the number of time-steps in the simulations, and it avoids an exhaustive search.

Following this method, the Base Case is initially compared with the Shaded Case to analyze both heating and cooling loads at each time-step to determine if each of the 12 windows should be shaded at each hourly time-step. The resulting shading schedule for the entire year is used to form a new model, which is simulated in EnergyPlus. As an iterative step, the hourly loads of this new model is compared with the 2 initial cases (Base Case and Shaded Case for this first iterative step) to determine if the earlier choice yields the desired result (reduction in loads). In the case where this is not true, the decision at the particular time-step is reverted.

For example, a particular window in the Shaded Case might have shown lower resulting loads than the Base Case at a particular time-step initially. The decision at this stage would then to specify the said window to be shaded for the same time-step in the new model. However, after simulating the new model (iterative step), the loads attributed by the same window at the same time may have increased such that it is larger than both the initial Base Case and Shaded Case; the schedule for the said window would then be reverted to no shading.

As summarized in Table 3, this method also yields lower annual building loads, except for Phoenix. Similar to the trend in previous results, the optimization of the window shades show the most heating load reduction in Los Angeles. However, this new method yields the largest cooling load reduction in Boston.

CONCLUSION

While optimization is typically the method used to adapt energy simulations to general inquiries of a search-based rather than evaluative nature, there are situations, such as those presented in the experiment where an exhaustive search is difficult to avoid. In many situations, the sheer magnitude of the number of candidate solutions makes it difficult to solve with reasonable resources.

By analyzing the nature of the initial question, heuristic approaches that introduce additional assumptions or sacrifice some accuracy can be used to achieve optimal solutions. While the solution may not be provable or guaranteed to be global, the reduction in resources may justify the tradeoff.

In this study, the question of "*what is the impact of window shades on building loads*" is identified to be a general inquiry, and two heuristic methods of discrete independent time-steps and iterative search are presented to produce solutions within a few simulations. This is significantly less than the amount of work that has to be done in an exhaustive search.

While the solution is now of the form "*the reduction in building loads is at least/ approximately (some quantity)*" and not absolute, this is deemed sufficient given the inductive nature of the general question.

The application of heuristics has to be done with care, noting the nature of the question and what constitutes satisfactory and sufficient solutions. The independent time-step method presented is clearly not suitable for scenarios where there is strong relationships between time-step conditions; neither is the numerical analysis in the experiment presented. Likewise, the iterative search method is essentially a type of greedy algorithm that might not work when the assumption of some similar but better state does not hold.

As a stark reminder of heuristics as ends justifying means, the results must be checked in some way when attempting to apply such methods; in the experiments described, the extreme cases of no shading and shading at all times were used to check the reasonableness of the results.

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Table 3 Effects of the Iterative Search Method

		Boston	LA	Miami	Phoenix
Base Case	Total Shaded Hours	0	0	0	0
	Total Heating Loads [kWh]	161043	1914	157	6096
	Total Cooling Loads [kWh]	166391	285710	589032	596642
	Total Building Loads [kWh]	327442	287624	589189	602738
Iterative Discrete Comparison	Total Shaded Hours	32985	13022	19136	20358
	Total Heating Loads [kWh]	160575	1861	155	6206
	Total Cooling Loads [kWh]	166121	285482	588843	597430
	Total Building Loads [kWh]	326696	287343	588998	603636
	%-Change Heating Loads	(0.29%)	(2.78%)	(0.72%)	1.80%
	%-Change Cooling Loads	(0.16%)	(0.08%)	(0.03%)	0.13%
	%-Change Building Loads	(0.23%)	(0.10%)	(0.03%)	1.49%