A SEQUENTIAL SEARCH TECHNIQUE FOR IDENTIFYING OPTIMAL BUILDING DESIGNS ON THE PATH TO ZERO NET ENERGY

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ABSTRACT

A zero *net* energy (ZNE) building produces as much energy on-site as it uses annually -- with a grid-tied, net-metered photovoltaic (PV) system and active solar water heating. On a plot of annual costs (the sum of utility bills and mortgage payments for energy options) versus percent energy savings, the path to ZNE extends from a base case building through a series of energy-saving designs to the ZNE building. The optimal path is defined by connecting the points for building designs that achieve various levels of energy savings at minimal cost (establishing the lower bound of results from all possible building designs). *BEopt*, a computer program for building energy optimization, calls the DOE2 and TRNSYS simulation programs and automates the optimization process. The optimization method involves sequentially searching for the most cost-effective option across a range of categories (e.g., wall type, ceiling type, window glass type, HVAC type, etc.) to identify optimal building designs along the path to ZNE. The method is particularly well suited to ZNE path optimization, because it deals with discrete options, finds intermediate points along the path and, in the process, identifies a number of near-optimal alternative designs.

1. BACKGROUND

1.1 Types of Zero Energy Buildings

Historically, fully autonomous zero energy buildings have been built, independent of any connection to the utility grid. In a new approach, the zero *net* energy building, promises more widespread applicability. The ZNE building uses grid-tied, net-metered PV and active solar to produce as much energy on-site as it uses annually.

1.2 Source versus Site Energy Accounting

ZNE can be defined in terms of site energy (used at the building site) or source energy (sometimes called primary energy). For electricity purchased from a utility, site energy can be converted to source energy to account for power plant generation efficiency and electrical transmission and distribution losses. The source-to-site energy ratio for electricity typically has a value of about 3, depending on the mix of electrical generation types (coal-fired, natural gas combined cycle, nuclear, hydropower, etc.). From a societal point of view, source energy better reflects the overall consequences of energy use and is appropriate for ZNE buildings analysis.

2. THE PATH TO ZERO NET ENERGY

Energy and cost results can be plotted in terms of annual costs (the sum of utility bills and mortgage payments for energy options) versus percent energy savings as shown in Figure 1. The path to zero net energy extends from a base case (e.g., a current-practice building, a code-compliant building, or some other reference building) to a ZNE building with 100% energy savings. The optimal path is defined by connecting the points for building designs that achieve various levels of energy savings at minimal cost, i.e., that the lower bound of results from all possible building designs. Alternatively, net present value or other economic figures of merit could be shown on the y-axis.

Points of particular significance on the path are shown in Figure 1 and can be described as follows. From the base case at point 1, energy use is reduced by employing building efficiency options (e.g., improvements in wall R-value, furnace AFUE, air conditioner SEER, etc.). A minimum annual cost optimum occurs at point 2 (assuming the

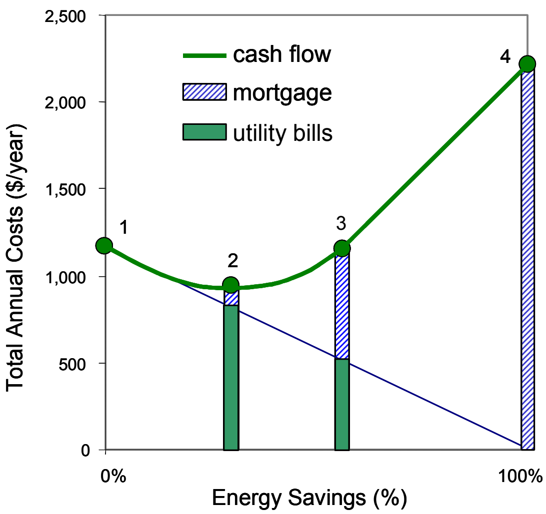

Fig. 1: Conceptual plot of the path to ZNE.

minimum does not occur at the base case). Additional building efficiency options are employed until the marginal cost of saving energy for these options equals the cost of producing PV energy at point 3. From that point on, the building design is constant and energy savings are solely due to adding PV capacity, until ZNE is achieved at point 4.

3. BUILDING ENERGY OPTIMIZATION

Building energy simulations are often used for trial-and-error evaluation of "what-if" options in building design, i.e., a limited search for an optimal solution. In some cases, a more extensive set of options is evaluated and a more methodical approach is used. For example, in the Pacific Gas and Electric ACT^2 project, energy efficiency measures were evaluated using DOE2 simulations in a sequential analysis method that explicitly accounted for interactions [1].

With today's computer power, the bottleneck is no longer simulation run time, but rather; the human time to handle input/output. Computerized option analysis has the potential to automate the input/output, evaluate many options and perform enough simulations to explicitly account for the effects of interactions among combinations of options. However, the number of simulations still needs to be kept reasonable, by using a search technique rather than attempting exhaustive enumeration of all combinations of options. Even with simulations that run in a few seconds, exhaustive enumeration run time is prohibitive for the millions of combinations that can result from options in, say, ten or more categories.

Several computer programs to automate building energy optimization have been recently developed. For example, EnergyGauge-Pro uses successive, incremental optimization (similar to the ACT^2 approach) with calculations based on the "energy code multiplier method" for Florida [2]. GenOpt is a generic optimization program for use with various building energy simulation programs and user-selectable optimization methods [3].

3.1 Constrained versus Global Optimization

From a purely economic point of view, building energy optimization involves finding the *global* optimum (the minimum annual cost) that balances investments in efficiency versus utility bill savings. However, there are sometimes non-economic reasons for targeting particular level of energy savings. Given a particular energy savings target, economic optimization can be used to determine the optimal design (lowest cost) to achieve the goal. This sort of *constrained* optimization can also apply for other target levels of energy savings between the base case and ZNE, and is the basis for establishing the optimal path to zero net energy.

3.2 Discrete versus Continuous Variables

In theory, optimal values can be found for *continuous* building parameters. In the practice of designing real buildings, however, the process often involves choosing among *discrete* options in various categories. For example, options in the wall construction category may include 2x4 R11, 2x4 R13, 2x6 R19, 2x6 R19 with 1 in. foam, 2x6 R19 with 2 in. foam, etc.

If discrete option characteristics for a particular category fall along a smooth curve, a continuous function can be used for to represent in an optimization methodology (along with other discrete and continuous categories). 'After optimization, the discrete options closest to the optimal values can be selected. However, the resulting combination of options may not necessarily be truly optimal, because when the option nearest (but not equal) to the optimal value in one category is selected, the optimal values for other categories may change.

Even if energy use as a function of a particular building parameter is well behaved, the introduction of costs (e.g., for particular wall construction options) may introduce significant irregularities. In fact, given the discrete products available in many categories (wall construction, glass type, air conditioners, furnaces, etc.), a smooth, continuous energy/cost function occurs in relatively few cases (e.g., loose-fill ceiling insulation). In general, if discrete options are to be considered, they should be dealt with as such.

3.3 Near-Optimal Solutions

It is advantageous for the optimization methodology to present multiple solutions (optimal and near-optimal). Near-optimal solutions achieve ZNE or a particular level of energy savings with total costs close to the optimal solution total cost. Given uncertainty in cost assumptions and energy use predictions, near-optimal points may be as good as optimal points. For various non-energy/cost reasons, the alternative construction options in near-optimal solutions may be of interest to building designers. Some such solutions can be identified by the optimization search technique, while others can be added with perturbation techniques.

4. IMPLEMENTATION

4.1 *BEopt* Software

The DOE-2 simulation program [4, 5] is used to calculate energy use as a function of building envelope options and heating, ventilation, and air conditioning (HVAC) equipment options. Appliance and lighting option energy savings are calculated based on energy-use-intensity factors and schedules input into in DOE-2. TRNSYS [6] is used to calculate water heating loads and energy savings for solar water heating. TMY2 weather data [7] are used for all simulations.

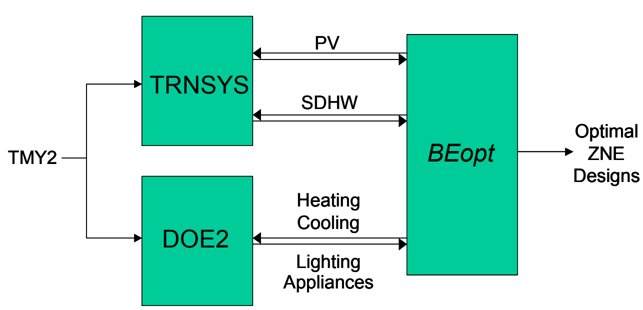

Fig. 2: Optimization with multiple simulation programs.

The TRNSYS simulation program is also used to calculate annual electrical energy production from a grid-tied PV system. The PV array is modeled using the approach developed by Sandia National Laboratories [8] and the database of performance characteristics published on its Web site (http://www.sandia.gov/pv/pvc.htm). Perfect maximum power point tracking is assumed. The inverter efficiency is assumed to follow the shape of a Trace SW series inverter, with a capacity of 1.2 times the rated PV array output at standard rating conditions.

BEopt, a program for building energy optimization, calls DOE2 and TRNSYS and automates the optimization process (see Figure 2). *BEopt* scans the specified DOE2 and TRNSYS input files to identify categories and options that are then displayed so the user can select options to be evaluated. Then, an optimization is run and results are shown graphically. *BEopt* can also be used to run parametric simulations based on combinations of the options selected.

4.2 Search Technique

BEopt can use different optimization methodologies, depending on objectives. Previously, we implemented a method to optimize ZNE buildings based on iteratively finding options with minimum marginal cost in each category [9]. We proposed extending the use of this method to determine the path to ZNE by curve fitting a few key points (i.e., that base case point, the minimum cash flow point, the PV take-off point, and the ZNE point) [10].

In this paper, we describe a search technique method for sequentially finding points along the optimal path to ZNE. The choice of this search methodology was influenced by several factors. First, we are interested to find intermediate optimal points all along the path, i.e., minimum-cost building designs at different target energy savings levels, not just the global optimum or the ZNE optimum. Second, *discrete* rather than *continuous* building options are to be evaluated to reflect realistic construction options. Third, an additional benefit of the search strategy is the identification of near-optimal alternative designs along the path.

The chosen method involves searching all categories (wall type, ceiling type, window glass type, HVAC type, etc.) for the most cost-effective option at each sequential point along the path to ZNE (see Figure 3). Starting with the base case building, simulations are performed to evaluate all available options for improvement (one at a time) in the building envelope and equipment. Based on the results, the most cost-effective option is selected as an optimal point on the path and put into a new building description. The process is repeated. At each step the marginal cost of saved energy is calculated and compared with the cost of PV energy. From the point where further improvement in the building envelope or equipment has a higher marginal cost, the building design is held constant and PV capacity is increased to reach ZNE.

4.3 Special Cases

Figure 3 shows one fewer option being evaluated in each successive iteration. This would be the case if once an option is included, that option remains in the building design as the building undergoes further improvements. Also, all options are selected in the "forward" direction, i.e., with positive energy savings.

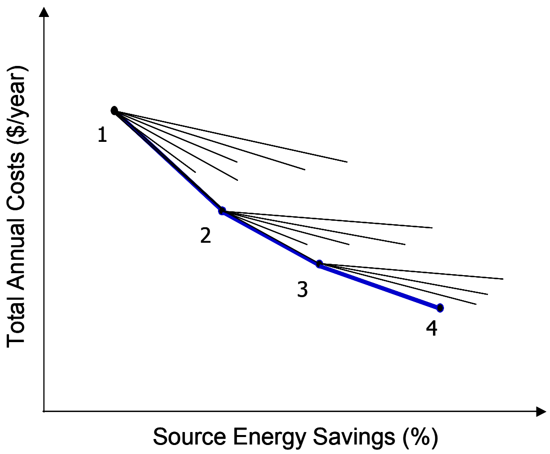

Fig. 3: Illustration of sequential search technique.

4.3.1 Invest/Divest

The actual *BEopt* search technique does not assume that once an option is in the building design, it stays in. In addition to evaluating new options, each iteration evaluates the removal of options in the current building design. This can result in negative energy savings and points to the left of the current point. These backward-looking evaluations allow for the possibility that one aspect of the building (say, HVAC efficiency) may initially be improved, and then when other aspects (say, envelope insulation levels) are sufficiently improved and loads reduced, it may no longer be cost optimal to have highly efficient HVAC.

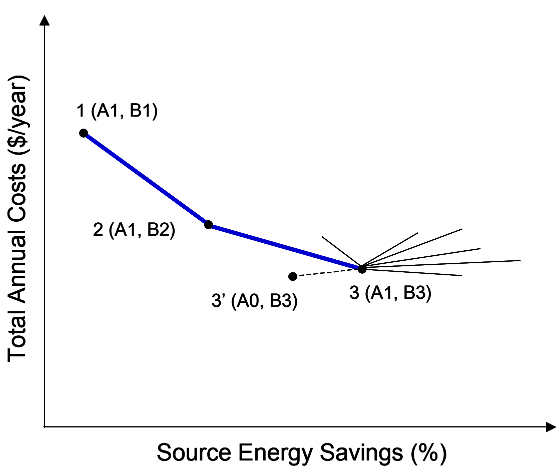

Fig. 4: Illustration of an invest/divest special case.

This phenomenon is illustrated in Figure 4: starting at point 1 (A1, B1), category B is improved to point 2 (A1,B2) and again to point 3 (A1, B3). On the next iteration, an optimal point is found by looking backward to point 3' (A0, B3) where reduced investment in category A is more cost-effective than continuing with high levels of investment in categories A and B. In this case, *BEopt* replaces point 3 with point 3' and proceeds.

4.3.2 Large Steps

BEopt also keeps track of points from previous iterations and checks to see whether they may be better than results of the current iteration. This phenomenon is illustrated in Figure 5: starting at point 1 (A1, B1), a large energy savings option (in category A) at point 3' (A2, B1) is less cost-effective than a small energy savings option (in category B) at point 2 (A1, B2), but when another option (say, option A2 again) is added to achieve the additional energy savings at point 3 (A2, B2), it turns out to be less cost-effective than the original large-savings option at point 3' because of negative interaction between options A2 and B2. In this case, *BEopt* replaces point 3 with point 3' and proceeds.

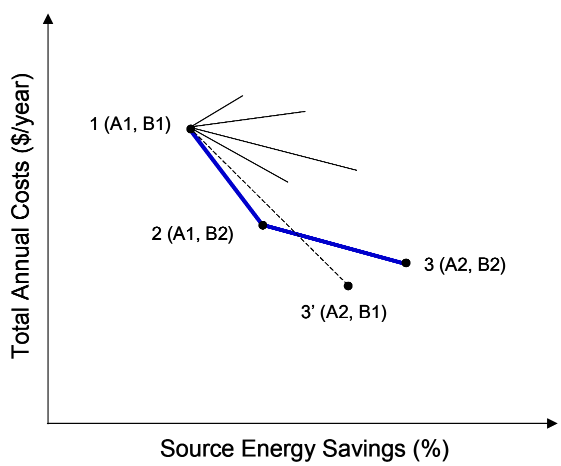

Fig. 5: Illustration of a large step special case.

4.3.3 Positive Interactions

The previous two special cases involved negative interactions between options; a third type of special case involves synergistic interactions. For example, thermal mass may facilitate passive solar heating with extra south-facing window area. This phenomenon is illustrated in Figure 6: starting at point 1 (A1, B1), point (A1, B2) is rejected while point 2 (A2, B1) is selected. But then, with option A2 in place, the performance of option B2 is so improved that the superior performance of point 3 (A2, B2) eliminates point 2.

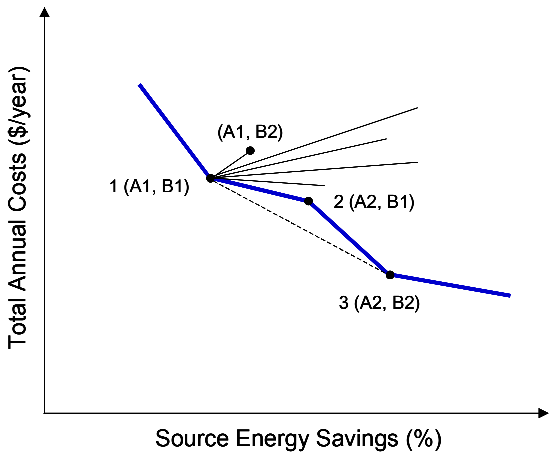

Fig. 6: Illustration of a positive interaction special case

The sequential search technique will select positively interacting options if one of the options is first individually selected (as shown in Figure 6); then the process may continue in a bootstrapping fashion. However, it is also possible that neither option will be selected by itself, which makes it impossible for the bootstrapping process to begin or continue. This is a potential shortcoming of the sequential search technique. One possibility is for the user to identify potential synergies and develop combined options so the synergistic options are evaluated together.

5. SAMPLE RESULTS

Optimization results for multiple climates are given elsewhere [11], along with detailed descriptions of simulation assumptions, inputs, and building envelope and equipment efficiency options available for optimization.

Figure 7 shows sample optimization results. The curve represents the optimal path to ZNE. The symbols indicate optimal building designs along the path (at various levels of energy savings) found by the search technique.

Starting from the base case, total annual costs decrease while energy savings increase. The initial rate of decrease in annual costs (i.e., the slope of the curve) is remarkably linear. No-cost options (such as window redistributions) lead to pure utility cost savings, which proceed along downward-sloping lines from the base case annual costs (y-axis intercepts) to the lower right corner of the graph (zero utility bill cost at 100% energy savings).

The final straight-line part of the curve corresponds to the cost of PV to achieve ZNE. The slope is proportional to the per Watt cost of PV and inversely proportional to the solar radiation.

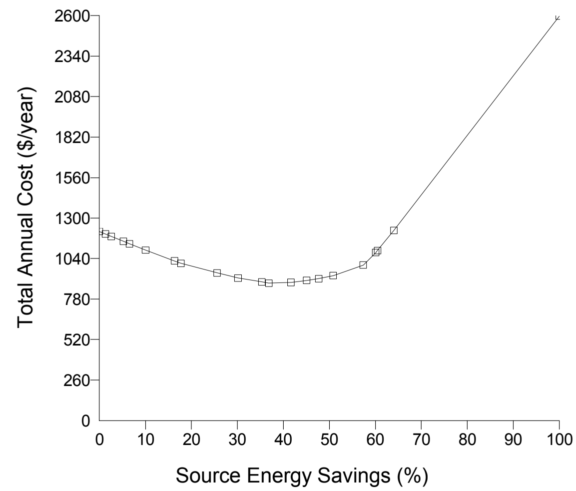

Fig. 7: Sample optimization results.

A close-up view of the sample optimization results are shown in Figure 8. Each symbol represents a particular simulation in the optimization search (with different search iterations indicated by different colors or shade of grey). *BEopt* allows the user to step through the results one iteration at a time to see how the optimization progresses. The user can also zoom in, select individual points, display associated building characteristics, and evaluate optimal building designs.

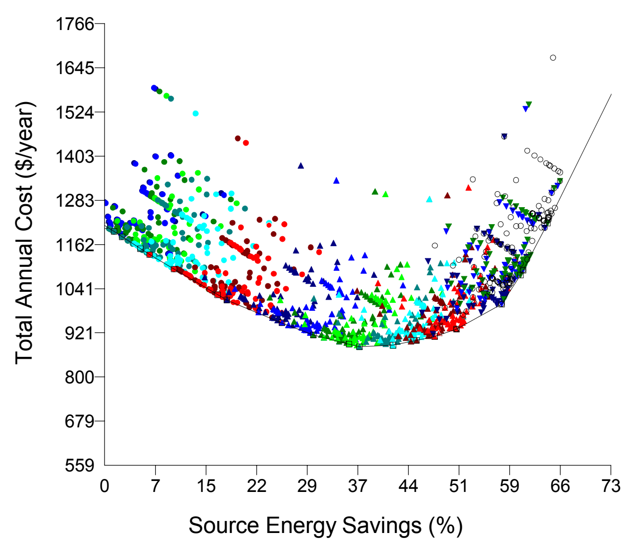

Fig. 8: Close-up of sample optimization results.

6. CONCLUSIONS

A sequential search technique for identifying optimal building designs on the path to zero net energy has been developed and implemented in *BEopt*, a computer program for building energy optimization. *BEopt* calls the DOE2 and TRNSYS simulation programs and automates the optimization process. The optimization method involves sequentially searching for the most cost-effective option across a range of categories (wall type, ceiling type, window glass type, HVAC type, etc.) to identify optimal building designs along the path to ZNE.

The sequential search technique has several advantages. First, it finds intermediate optimal points all along the path, i.e., minimum-cost building designs at different target energy savings levels, not just the global optimum or the ZNE optimum. Second, *discrete* rather than *continuous* building options are to be evaluated to reflect realistic construction options. Third, some near-optimal alternative designs are identified (that can serve as a starting point for generating a more complete set by permutations).

In addition to simply searching for the sequence of optimal improvements in building design along the path, *BEopt* also handles special cases with negative interactions: 1) removing previously selected options and 2) re-evaluating previously rejected combinations of options. Special cases with positive interactions can be handled by the sequential search technique, but may require the user to define combined options to facilitate optimization.

7. FUTURE WORK

Additional testing and validation are needed for a wide range of locations and building descriptions. Many issues remain to be addressed including: developing additional categories and options, refinement of cost assumptions, HVAC equipment resizing, effects of time-of-day and demand rates, discrete PV-related costs for modules/arrays and inverters, constraints such as limited available roof area, embodied energy, optimization studies for different regions and climates, and methods to identify and characterize near-optimal solutions.

8. ACKNOWLEDGMENTS

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