Commercial Building Design Pathways Using Optimization Analysis

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ABSTRACT

Whole-building simulation and analysis has demonstrated a significant energy savings potential in a wide variety of design projects. Commercial building design, however, traditionally integrates simulation and modeling analyses too late in the design process to make a substantial impact on energy use. The National Renewable Energy Laboratory (NREL) commercial building group created an optimization platform called Opt-E-Plus that uses multivariate and multi-objective optimization theory to navigate a large parameter space and find economically valid, energy-saving solutions.

The analysis results provide designers and engineers valuable information that influences the design. The pathways are not full "construction ready" design alternatives; rather, they offer guidance about performance and cost criteria to reach a range of energy and economic goals. Having this knowledge early in the design phase helps designers establish project goals and direct the design pathway before they make important decisions. Opt-E-Plus has been deployed on several projects, including a retrofit mixed-use building, a new NREL office building, and several nationwide design guides. Each of these projects had different design criteria, goals, and audiences. In each case the analysis results provided pathways that helped inform the design process.

This paper will discuss the high-level optimization framework, describe how the analysis was deployed on three real projects to help inform various design pathways, briefly discuss the limitations of the current implementation, and quickly address the future development needed on the optimization framework to further integrate the analyses into the design process.

Introduction

Commercial building design traditionally does not use simulations and modeling to influence design until too late in the process. The National Renewable Energy Laboratory (NREL) has developed an analysis package designed for buildings specific applications, called Opt-E-Plus (NREL 2010), to help analyze commercial building energy use and consumption, and to influence building design early in the design process. Opt-E-Plus was applied to three separate design projects: a mixed-use retrofit project in Sacramento, a new net-zero energy Research Support Facility (RSF) at NREL, and a series of nationwide design guides. Each project had unique building types, owners, objectives, and audiences, but all three were committed to saving energy and reduce costs, and needed early design stage information to influence the overall building design. The analysis platform will be discussed at a high level to provide a basic understanding of its functionality, and then the use and outcome of the platform results will be presented for each project.

Problem Statement

Building simulation is not commonly integrated into the building design process in order to make meaningful changes to the building design. Common uses of building simulation are to determine code compliance and to achieve accreditation. Unfortunately, these activities typically occur too late in the process to influence the building design and so may not actually save energy (Turner & Frankel 2008). Furthermore, the standard code-compliant building is not the most energy efficient, but is the least energy-efficient building allowable.

In order to allow modeling and simulation to impact the built environment, it is critical to create simulation models quickly, allow for high-level large-scale perturbations, verify the models and results, evaluate economic impacts, and present results that enable users to set goals and understand the relative energy and economic tradeoffs for their projects. NREL continues to overcome these difficulties by developing analysis tools that can be used to influence the design process during different stages.

Opt-E-Plus in the Design Process

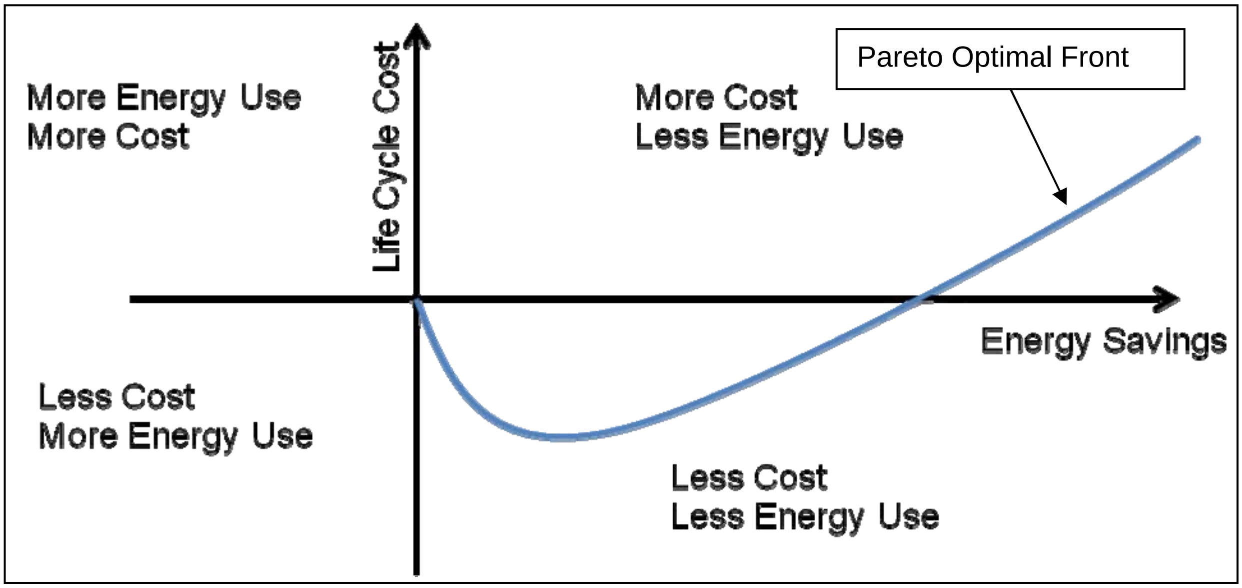
Opt-E-Plus was developed to support development of low- and net-zero energy buildings by integrating simulation and optimization in the design process. Energy and economic goals are still vague at the early design phase, so Opt-E-Plus presents a range of design options, each of which minimizes energy use at a particular economic cost. This range of design options is also known as a Pareto optimal front in formal multivariate optimization terminology (Ellis et al., 2006). These options enable designers and engineers to set project goals based on a reasonable understanding of the tradeoffs between energy use and economics for a particular project. Such goals are more likely to influence the design process as they cannot be brushed aside as easily as goals with no quantitative backing. Opt-E-Plus utilizes the U.S. Department of Energy's whole-building energy simulation engine EnergyPlus (Crawley et al. 2008) to ensure that interactions between energy design measures (EDMs) (e.g., lower lighting power density results in lower cooling energy but increased heating energy) are accurately captured. An EDM is a perturbation to the building model that influences the objective functions (it does not have to save energy). Although EnergyPlus is a very detailed calculation engine, the focus at this stage is on whole-building integration strategies rather than on details of a single subcomponent.

How It Works

The starting point for an Opt-E-Plus design optimization is a baseline model that encapsulates the basic requirements for the project, including location, floor area, program, loads, and other typical code-compliant options (HVAC, schedules, etc). After manually verifying the baseline's input values, energy use, and economic results, the design team generates a list of potential EDMs to be applied to the baseline model. The Opt-E-Plus internal building model maintains the logic needed for valid EnergyPlus files (e.g., applying an evaporative precooler will automatically place the component as the first component in the outside air stream). GenOpt (LBNL 2010) is a similar program that operates more generically allowing for multiple optimization algorithms on any simulation input file. Opt-E-Plus has similar functionality as GenOpt, except that it operates specifically on EnergyPlus' input and output.

Through automated processes, each EDM is applied to the baseline building to create candidate models. The costs of the EDMs are typically dimensioned to account for changes during the optimization such as costing the HVAC per cooling capacity or walls per area. Each candidate model falls into four possible quadrants and the optimal candidates bounded by the Pareto optimal front (curved line) as seen in Figure 1. The X-axis in the Figure 1 is Energy Savings; however, depending on the design objective, it may be beneficial to display the units in absolute energy (e.g., design goal for net-zero energy building), in which case the curve will be in the opposite direction.

Figure 1: Four Quadrants of Simulation Results



Each EDM must represent a design option that the developer believes can be practically applied. Each EDM comes with associated costs that represent a best estimate of the incremental cost to apply it over the baseline case. More constraints (such as number of stories) can be added to the baseline definition at this stage, but these will limit the EDM search space explored and may reduce opportunities for energy and cost savings.

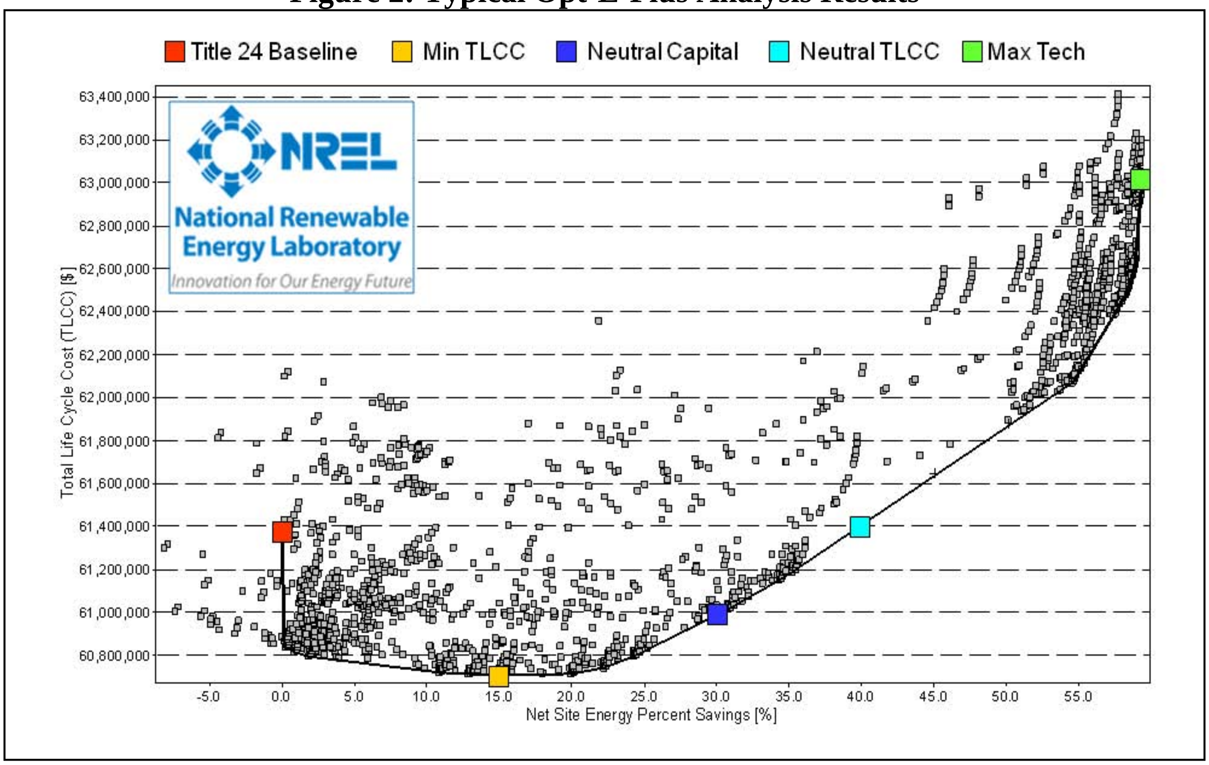
Once the baseline model and EDMs are defined, Opt-E-Plus employs an iterative search technique to find EDM combinations that best balance percent energy savings with life cycle cost when applied to the baseline building (Ellis et al. 2006). At each iteration, Opt-E-Plus applies the possible EDMs to the current Pareto optimal building design and performs an EnergyPlus simulation for each combination. If any newly generated building design is chosen as a new Pareto optimal design, the iterative algorithm continues. This algorithm greatly reduces the number of potential building designs evaluated relative to a full enumeration of all possible options. Opt-E-Plus can take advantage of supercomputer resources at NREL to run these simulations in parallel. In this way, a fully parameterized space of more than a million combinations can be optimized and run in one day with about 5,000 EnergyPlus simulations.

Running the optimization analysis using Opt-E-Plus is fairly automated and does not take an inordinately long time. However, the challenge in performing a building optimization analysis using Opt-E-Plus is to define the baseline building and generate the set of EDMs with associated costs. Some details may be known at the early design stage, especially where baseline data or EDMs from similar past projects can be reused, but rough estimates must be developed in areas in which the builder does not have design experience with energy performance or cost estimation. The design team needs to agree on these so the EDMs can result in equally weighted decisions about the output of the optimization analysis. Fortunately, if baseline assumptions or EDM definitions change dramatically, the optimization analysis can be rerun at a minimal cost.

Expected Results

The output of Opt-E-Plus is unique in that it does not just present a single optimal design; rather, it shows a range of designs, each of which minimizes energy use for a particular economic cost. Typically, life cycle costing is used so that the additional capital costs required to implement many EDMs may be recouped through lower utility bills over some analysis period. Figure 2 shows the typical output of an Opt-E-Plus analysis. In this figure, each point represents a unique combination of EDMs that defines a single potential building design and corresponds to an EnergyPlus simulation run.

Figure 2: Typical Opt-E-Plus Analysis Results



The analysis in Figure 2 selected five designs that are of most interest to the designer. The five selected designs progress from the baseline building to the maximum energy savings possible (left to right). As the energy savings increase, total life cycle cost first decreases as cost-effective EDMs—such as increased insulation and reduced window area—are applied. At higher levels of energy savings, less cost-effective EDMs such as photovoltaics (PV) require higher incremental costs to achieve similar incremental energy savings. From left to right these designs are:

- The Baseline building (Title 24 defined the baseline in Figure 2). This is included for reference in cost and energy savings.
- The Minimum Life Cycle Cost building. This should be chosen for minimizing life cycle cost only.
- The Neutral Capital Cost building. This should be chosen to maximize energy savings with constrained initial capital costs. This point is not determined in Figure 2, rather another plot that is Capital Cost versus Energy Savings.
- The Neutral Life Cycle Cost building. In this design initial investments in energy efficiency pay for themselves over a user-defined life cycle analysis period. This is also equivalent to the baseline building in life cycle cost.
- The Maximum Savings point, This represents the maximum energy savings possible without regard to cost.

Expected Impact on the Design Process

Opt-E-Plus generates a set of potential building designs, but none of these points represent construction-ready building designs. Rather, the design combinations generated by Opt-E-Plus represent high-level combinations of EDMs that capture the interactions between different options in energy performance and cost. The primary utility of the Opt-E-Plus analysis is to set project level goals and basic strategies to meet those goals based on quantitative, whole-building analysis. This includes high-level goals such as payback period and total energy savings as well as individual energy and economic goals for each engineering team (fabric, lighting, HVAC, etc). These goals are essentially the input assumptions made (e.g., install and commission daylighting controls for $0.40/ft^2). If a team cannot meet its goals, the project coordinator understands that energy savings must be compensated by another building component to meet the goal. Currently, the analysis results must be reviewed by experienced building engineers and modelers to reduce the impact on the uncertainty in baseline model generation and economic impacts.

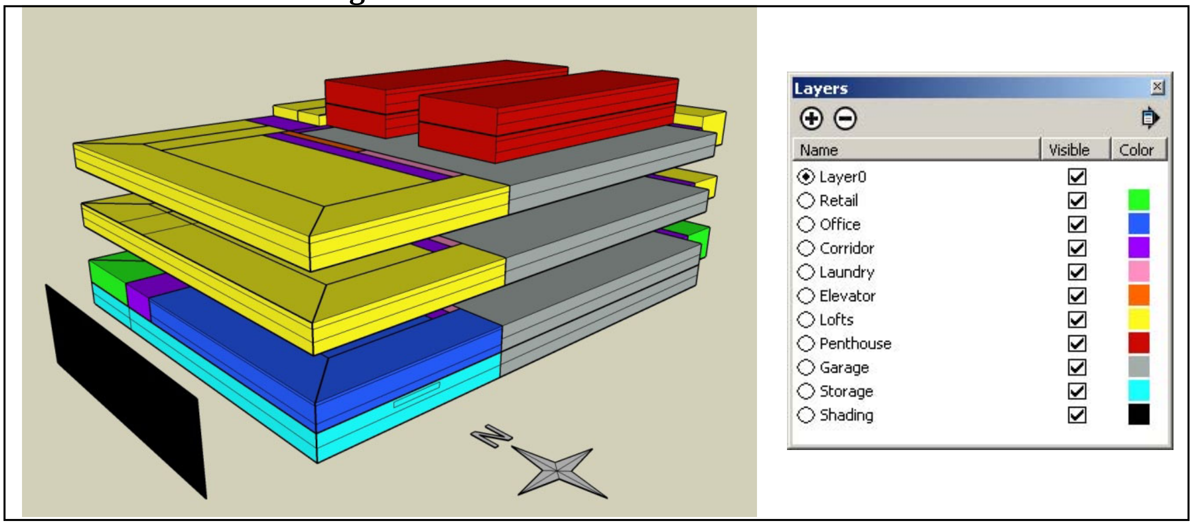
Opt-E-Plus

Mixed-Use, Retrofit/New Construction Design Project

The Sacramento Municipal Utility District requested that NREL's commercial buildings group perform an energy optimization analysis for a proposed mixed-use development in Sacramento (Macumber 2009). At the beginning of the project, the stated goal was for a zero-energy building; however, this was more of a "zero-energy vision" than a hard zero-energy goal, according to one zero energy buildings definition (Torcellini et al. 2006). In reality, the developer was willing to explore a range of energy performance and corresponding economic costs, and chose to use net site energy and economic life cycle costs over a 10-year life cycle with a 2.3% discount rate to evaluate energy performance.

The first step was to develop a prototypical baseline building that was verified manually for accuracy. Geometry for the baseline model was derived from preliminary architectural drawings. Separate conditioning, internal gain, and program information was developed for each of the office, retail, residential, garage, laundry, storage, and corridor space types. Building constructions were based on actual constructions from past projects for parking garage, interior surfaces, and existing structures. Constructions were based on nominally Title 24-compliant constructions for exterior walls, roofs, and slab. Fenestration constructions were based on a similar past project. The baseline HVAC system was assumed to be packaged single-zone air-source heat pumps for conditioned spaces and demand-controlled ventilation for the parking garage.

Figure 3: Floor Plan from the Southwest



The next step was to develop the set of EDMs that might be applied to the baseline model to create candidate low-energy models. Examples of EDMs considered in this work include increased roof and wall insulation, reduction of lighting and interior equipment loads, and installation of solar hot water and PV systems. The cost and performance of certain EDMs, such as more insulation or improved windows, were well known from previous projects. However, the cost and performance of other EDMs, such as more efficient elevators, were not as well known, so the design team developed rough estimates.

Results

Zero energy is a difficult goal to meet, especially for buildings with a low roof area to floor area ratio; thus, we found no solution to achieve that with the EDMs and costs developed during this work. We did find that significant energy savings could be achieved for this project under favorable economic criteria. The Minimum Life Cycle Cost building achieved 14.9% energy savings at lower capital and life cycle costs than the Baseline building. The Neutral Capital Cost building achieved 30.8% energy savings at equal capital costs and lower life cycle costs than the Baseline building. The Neutral Life Cycle Cost building achieved 40.0% energy savings at higher capital costs but equal life cycle costs to the Baseline building. Finally, the Maximum Savings building achieved 63.7% energy savings at higher capital and life cycle costs than the Baseline building. A summary of the differential costs and energy savings related to each building variation is given in Table 1.

Table 1: Economic Differential and Energy Savings Summary

Building Variation	Incremental Capital Cost($)	Incremental Life Cycle Cost ($)	Net Energy Intensity kBtu/ft^2 (MJ/m^2)	Percent Savings
Baseline	NA	NA	50.1 (569)	NA
Minimum Life Cycle Cost	–$432,473	–$661,192	42.6 (484)	14.9%
Neutral Capital Cost	$150,722	–$356,961	34.6 (393)	30.8%
Neutral Life Cycle Cost	$754,812	$40,250	30.0 (341)	40.0%
Maximum Savings	$2,798,237	$1,655,481	20.4 (232)	63.7%

New Construction Office Building

Problem Statement

NREL's 219,000-ft^2 RSF is scheduled to open in the summer of 2010 and will house 822 employees on NREL's Golden, Colorado, campus. It will be one of the most energy-efficient office buildings in the country and is to be one of the first large net-zero energy buildings (NZEBs) and is projected to achieve the U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) highest rating, LEED Platinum.

As with most NZEBs, energy was the first priority of the design team. It was determined early that for the RSF to reach NZEB status, it first had to be as energy efficient as possible. Originally, the contractual requirement was to have annual "pre-PV" energy use intensity (EUI) of 25 kBtu/ft^2 (284 MJ/m^2). The targeted EUI was based on 650 employees and 220,000 ft^2. The RSF will also house a data center that will service the entire NREL campus. Included in the EUI goal is a prorated portion of the data center's annual energy consumption based on the number of employees, which has been increased from 650 to 822. With the increase in employee density and space efficiency, the RFP allowed for a EUI goal adjustment on a per person basis. With 822 employees and 219,000 square feet, the target EUI has been adjusted to 32 kBtu/ft^2 with the prorated datacenter, or 35 kBtu/ft^2 including the full data center. These EUI requirements were included as part of the core requirements for the RSF during the bid process. NREL researchers performed Opt-E-Plus analyses and collected data from other high-performing buildings nationwide to verify that this energy specification could be met within the project's budget.

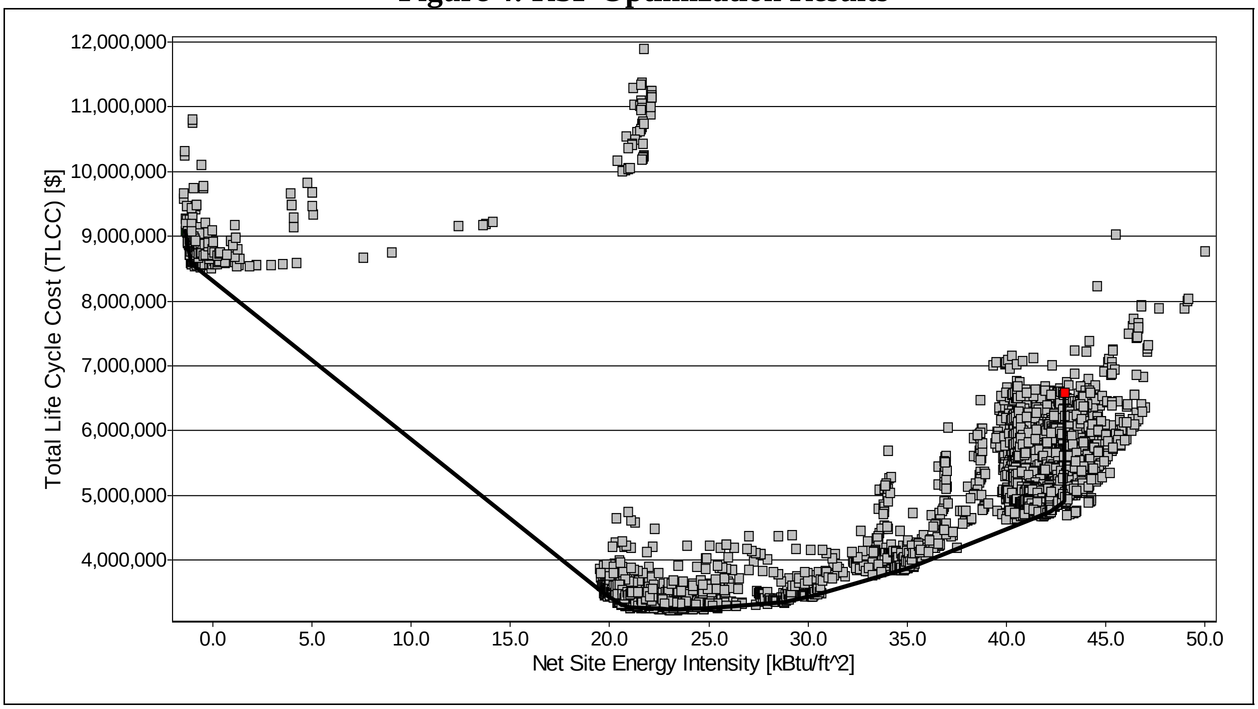
Results

With hard energy goals established at the beginning of the project, the design team worked to integrate building form, lighting, HVAC, computers, server equipment, and other subsystems. One design aspect of particular interest is the building's lazy-H configuration on a long east-west axis. Because of the layout of the building, the occupied zones are 60 feet wide. This narrow floor plate offers daylighting and natural ventilation to a large area.

If the two wings were set side by side, the building would have an aspect ratio of 13.5. As the aspect ratio increases from 1 (a square footprint building), to 13.5 and beyond, the building envelope area increases significantly. This higher aspect ratio allows daylighting and natural ventilation in a larger portion of the occupied building. The drawback is in increased heat transfer through the envelope. NREL researchers used Opt-E-Plus to vary the aspect ratio of a prototypical building to assess the design team's narrow floor plate design decision.

Researchers also considered reduced plug load and lighting intensities, daylighting controls, decreased window-to-wall ratios, window shading, increased exterior wall and roof insulation levels, more efficient window constructions, natural ventilation, and PV. Opt-E-Plus enabled the benefits of each strategy to be weighed against its costs and included interactions between technologies. Figure 3 shows the swoosh graph produced by Opt-E-Plus. The Y-axis is no longer percent savings, but is absolute Net Site Energy, as the goal was to reach 0.0 kBtu/ft^2 (0.0 MJ/m^2) (with PV). The buildings in Figure 4 become more efficient as they move from right to left. The upper left corner collection of simulations represents the results that include PV fully covering the roof (and the panel efficiency was adjusted to achieve net-zero energy). These points achieve the net-zero energy goals, but also incur a higher life cycle cost than the baseline.

Figure 4: RSF Optimization Results



The conclusion of this study was that the higher aspect ratios did generally reduce energy use relative to their lower aspect ratio counterparts; however, the increased envelope area also increased first capital costs. The aspect ratio of 13.5 chosen for the RSF was beyond the point where energy savings paid back for the additional envelope costs. For a building with true net-zero energy goals, however, this was still appropriate relative to other more expensive measures such as PV. This analysis does not include nonenergy benefits to a narrow floor plan such as increased views to the outdoors.

The Minimum Life Cycle Cost building achieved 46.4% energy savings at lower capital and life cycle costs than the Baseline building. The Neutral Capital Cost and Neutral Life Cycle Cost building achieved 51.4% energy savings at lower capital and life cycle costs than the Baseline building. (In both Capital Cost and Life Cycle Cost, there was not a true Neutral Cost building; the neutral cost point fell where the simulations begin to include PV.) Finally, the

Maximum Savings building achieved 103.2% energy savings at higher capital and life cycle costs than the Baseline building. A summary of the differential costs and energy savings related to each building variation is given in Table 2.

Table 2: Economic Differential and Energy Savings Summary

Building Variation	Incremental Capital Cost($)	Incremental Life Cycle Cost ($)	Net Energy Intensity (kBtu/ft2)	Percent Savings
Baseline	NA	NA	42.9	NA
Minimum Life Cycle Cost	–$1,515,508	–$3,343,683	23.0	46.4%
Neutral Capital Cost	–$1,183,514	–$3,105,941	19.7	51.4%
Neutral Life Cycle Cost	–$1,183,514	–$3,105,941	19.7	51.4%
Maximum Savings	$5,321,453	$2,502,860	–1.4	103.2%

Nationwide Design Guides

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is developing tools to help achieve its vision of market-viable NZEBs by 2030 (Jarnagin et al. 2008). To this end, ASHRAE, in conjunction with the American Institute of Architects, the U.S. Department of Energy, the USGBC, and Illuminating Engineering Society, has been developing Advanced Energy Design Guides (AEDGs) to chart technically feasible, cost-effective design paths leading to net-zero energy status for commercial buildings.

Thus far, six AEDGs have been completed, providing prescriptive design recommendations to reach 30% energy savings compared to buildings that meet the minimum requirements of the ASHRAE 90.1-1999 code. Recommendations are provided for eight ASHRAE climate zones across the United States. Each AEDG is accompanied by a Technical Support Document (TSD) that describes the process and methodology used to develop the AEDGs recommendations, including detailed descriptions of modeling assumptions and results. A set of 50% energy saving AEDGs is currently under development, and several TSDs are already finished. Two of these, analyzing energy use in medium-box (40,000–50,000 ft^2) general merchandise (Hale et al. 2009) and grocery stores (Leach et al. 2009), and employed optimization, through Opt-E-Plus, as the primary tool to select 50% energy savings design packages.

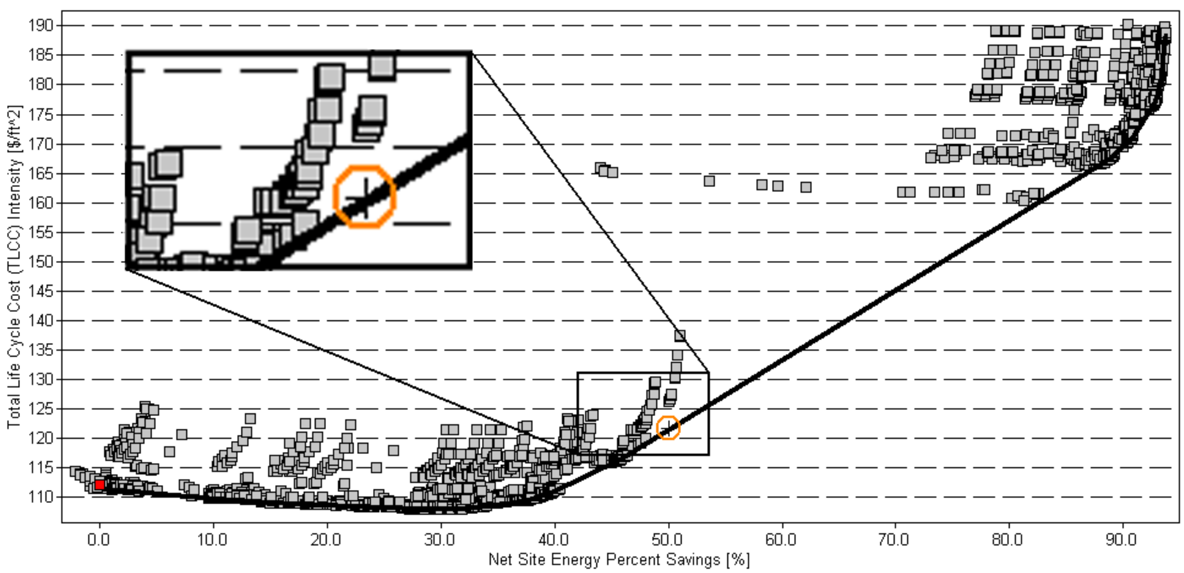
The steps to complete the nationwide design guides were similar to the other cases. First, we defined a prototypical building model containing the space types, programs, and end uses required for each building type. Hourly TMY2 files from large cities in the climate zones under consideration were used to represent spatio-temporal variability in meteorological conditions. The representative cities include 1A-Miami, 2A-Houston, 2B-Phoenix, 3A-Atlanta, 3B-Las Vegas, 3C-San Francisco, 4A-Baltimore, 4B-Albuquerque, 4C-Seattle, 5A-Chicago, 5B-Denver, 6A-Minneapolis, 6B-Helena, 7-Duluth, 8-Fairbanks. The prototype buildings were then tailored to meet the climate-specific requirements of ASHRAE 90.1. Prescriptive requirements were taken from ASHRAE 90.1-2004 (ASHRAE 2004) and ASHRAE 62.1-1999 (ASHRAE 1999).

The design team assembled a list of EDMs intended to reduce building energy consumption, specifying performance and costs based on the available literature (Hale et al. 2009; Leach et al. 2009). This list was peer reviewed by industry partners to verify the assumptions for each EDM. The EDMs were common in the two buildings except for refrigeration in the grocery store and high plug loads for the general merchandise store. Finally, the use of Opt-E-Plus determined EDM combinations that best balanced net site energy savings and Five-Year Total Life Cycle Cost.

Results

The results of the optimizations typically resulted in a swoosh graph that had more than 50% energy savings. In cases where PV was not required to reach 50% energy savings, the first point on the Pareto front to meet or exceed the energy savings target was selected as the low energy design. When PV was included in the design, energy savings were quite significant, because the EDM specified covering 60% of the net roof area (roof area minus skylight area). To select a 50% energy savings design, the PV was scaled back using a postprocessing algorithm until the energy target was exactly met. Figure 5 shows an example where this postprocessing was applied, the high plug load general merchandise store in climate region 3B (Las Vegas, Nevada). The selected 50% energy saving building is marked by the "+" surrounded by an orange circle.

Figure 5: Example Opt-E-Plus Output With PV Post-Processing: Climate Zone 3B (Las Vegas, Nevada), High Plug Load Scenario



The results suggest that 50% net site energy savings compared to a minimally compliant ASHRAE 90.1-2004 case could be achieved in general merchandise (low and high plug load cases) and grocery stores in almost all cases without relying on renewable energy generation such as PV panels. The main exceptions occurred in the high plug load general merchandise stores in climate zones 2B and 3B where plug/process loads represent a large fraction of the energy demand in the baseline building, since we only investigated one minor measure to manage those loads. The following list contains some EDMs the optimization can deliver as recommendations for all climate zones:

- Reduce lighting power density by 47%, and install occupancy sensors in the active storage, mechanical room, restroom, and office zones.

- Equip rooftop HVAC units with high-efficiency fans.
- Install daylighting sensors tuned to a 46.5 fc (500 lux) set point.
- Reduce south façade window-to-wall ratio by 50%.
- Replace baseline exterior walls with better insulated constructions.
- In grocery stores, replace baseline frozen food and ice cream refrigerated cases with efficient, vertical models with doors and hot gas defrost.
- In grocery stores, replace baseline meat display cases with models that have efficient fans, anti-sweat heater controls, electric defrost, and sliding doors.

EDMs for which selection varied by climate zone included:

- Skylights were selected in warm and hot climates where there is ample sunlight for daylighting.
- High coefficient of performance (a 20% increase over baseline) HVAC rooftop units were selected in all but the cold and marine climates, which have low cooling loads.
- Infiltration reduction measures (front entrance vestibule and envelope air barrier) were selected often, especially in humid and cold climates.

The suggestions are very "high-level" criteria needed for each major subsystem. Design teams can take these suggestions and decide which specific technologies can cost-effectively provide the required energy savings performance for their specific projects.

Conclusions

The optimization platform was used in three scenarios to provide feedback to design teams on varying design pathways. In the case of the retrofit analysis, the original building energy goals were shown to be unachievable, but provided the design team with valuable information to set new goals. In the new construction, the aspect ratio was verified and shown to be a viable solution. Finally, in the nationwide design guides, the energy savings and economic goals were shown to be achievable.

Opt-E-Plus has helped researchers study the relative impacts of various design decisions at a high level early in the design process. The results generated give design pathway guidance through high-level advice for a developer, architect, and design team. As seen in the examples above, the results can be used to persuade investors to agree to higher capital costs due to life cycle savings from reduced utility bills. The architect can also balance desires for more windows with the project's goals to reduce first costs and energy use. A design team leader can determine which subsystems need to perform better in order to meet the overall energy goals. The integration of economics in the energy simulation results provides justification for the EDMs and helps produce an equally weighted evaluation. The analysis is sensitive to errors in assumptions about performance and cost of the various EDMs. Future versions of the optimization platform plan to incorporate uncertainties of performance and cost throughout the whole design process and optimizations, along with integration of other simulation analysis tools to augment the analysis.

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