Optimizing Building Design and Operations

Designers, owners and operators are all faced with a myriad of decisions on how best to achieve their building design and operational goals. Complex and often conflicting objectives can make even the simplest decisions appear challenging. Take, for example, thermal comfort. According to the Department of Energy, adjusting temperature set points by just 1 deg for an eight-hour workday can save commercial building owners 3% in energy costs. This equates to thousands of dollars in savings each year. Clearly, the least costly alternative is to not heat or cool a building. However, we all know this option is not feasible as each adjustment made to save energy and reduce costs can adversely affect occupant comfort and productivity.

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As buildings become smarter, we have gained the ability to dynamically-control our environment to achieve all kinds of goals. Thermal comfort, visual comfort, energy-efficiency and sustainability goals all influence our design and building operations decisions. To try and achieve these goals, we can adjust a dozen different systems to control the indoor environment including ventilation, lighting, heating, cooling, shading and security. As the list of these influential factors grows, mathematical optimization techniques can help us make better building management and operational choices. Within the building design community, these techniques are called design optimization.

Design optimization, in the context of operations research and mathematics, is a relatively new field focused on the use of detailed models coupled with algorithms or heuristics to identify good design choices able to achieve a set of specific goals given a finite set of resources. These techniques are seeing increased use across a number of building sectors as a means to better ensure projects meet performance targets. Models that include dozens of design variables and constraints can be used to seek out and identify optimal, or near-optimal, configurations from among thousands of possibilities.

With design optimization, researchers have mostly focused on multi-objective optimization, which is used to identify a range of good solutions for competing objectives such as the desire to maximize daylight penetration in a building while minimizing solar heat gain. Solutions to a multi-objective optimization problem are called Pareto optimal solutions.

Pareto optimal solutions are those for which an improvement in any objective can only negatively impact the others. In design, we often find solutions that meet our goals, but they are really not optimal. When an improvement can be made to one objective, say illuminance, without negatively impacting one of the other objectives, say uniformity, that change is called a Pareto improvement. A solution (design) that can be improved in at least one design objective without negatively impacting any other design goals is therefore, by default, a *poor* solution.

It cannot be argued that a particular Pareto optimal solution is better in every case than another Pareto optimal solution. If fact, there always exists a weighting of the various objectives such that any single Pareto optimal solution is considered the best. In practice, a decision maker must select a single solution from the Pareto optimal solution set that best meets their overall design goals or business plan.

Pareto optimal solutions can be visualized easily in two-dimensions as a line, or "front," on a standard Cartesian coordinate system. As an example, consider illuminance and uniformity, two common lighting design parameters. Today, lighting designers use their expertise to specify an appropriate suite of luminaires for a particular space. The design is often checked using simulation software to ensure minimum illuminance and uniformity levels are met. Assuming the design meets the project's requirements, it is accepted and installation proceeds. While the design meets project goals, other designs may exist that provide the same or better uniformity, or improved overall illuminance, and with lower lighting power density.

Consider the following 10 designs depicted graphically in **Figure 1.** Each point represents a potential lighting design for a space that requires a minimum of 50 footcandles and an average horizontal uniformity of at least 5-to-1. The point at [60, 5] (60 fc and a uniformity of 5-to-1) is a feasible solution meeting design requirements. However, numerous, additional solutions exist. One could utilize more, low-wattage luminaires to increase uniformity while keeping lighting power densities below code requirements. This design may provide 55 fc with a uniformity of 3-to-1. Another still may provide 50 fc and uniformity of 5-to-1.

With these three designs, [60,5] is not a Pareto optimal solution and should never be selected, because there is an alternate design that achieves [50,5]. In this case, any solution on the straight line connecting [50,5] and [55,3] creates the Pareto front. By moving along the frontier, you can reduce illuminance at the expense of uniformity, or improve uniformity at the expense of unnecessary illuminance, but you cannot improve both at once. Thus, any design not on the front is a poor solution.

Optimization techniques enable designers to confidently identify and select designs that best achieve project goals. These methods are currently being used in a number of interesting ways. Several case studies follow:

- In one recent lighting study, researchers sought to minimize lighting energy use while achieving illuminance and lighting uniformity requirements for an indoor office environment aligning with EN 12464, a widely accepted European standard for indoor workplace lighting (Madias, Kontaxis, & Topalis, 2016). Researchers applied their methods to an existing office area illuminated by 15 identical recessed LED downlights equally spaced within the ceiling plane. The

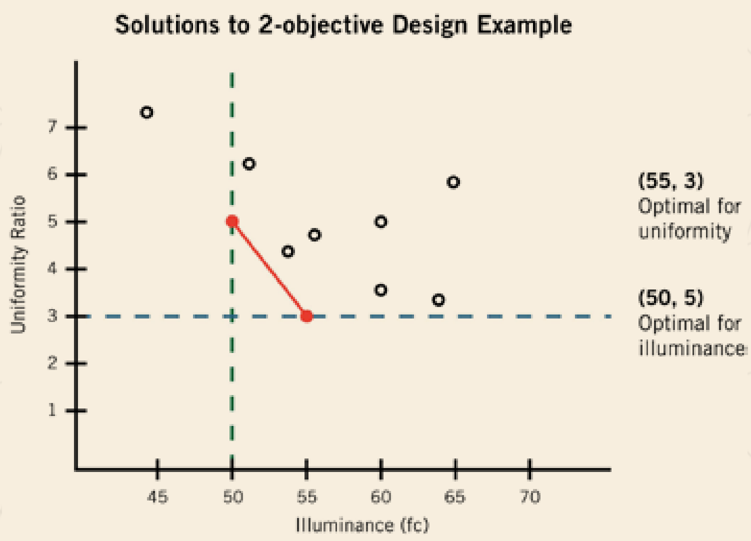

Figure 1. Solutions to a 2-objective Design Example.

Figure 2. CLTC's integrated building control laboratory.

downlights provided dimming from 1-100% of full output, were networked and were controlled using the DALI communication protocol.

Depending on the desired balance of illuminance, uniformity and energy use, the analysis resulted in optimized dimming schedules that provided energy savings between 18-22% as compared to the system operating at 100% full output. Dimmed operating levels of individual downlights varied from 63-99% of full output. All possible designs within that savings range met minimal lighting standards for illuminance and uniformity under EN 12464. In addition, some solutions provided better uniformity at less energy cost than the original design itself.

- In another case, researchers examined the use of high pressure sodium (HPS) lighting for cherry tomato cultivation in a greenhouse environment. By considering available daylight, real-time electricity pricing (RTP) and the photosynthetic needs of the tomato crop, researchers optimized the total income achievable (kilograms of tomatoes per square meter of cultivation) for a four-month, February to June, indoor growing season assuming a fixed tomato sale price (Mahdavian, Poudeh, & Wattanapongsakorn, 2013). By considering the cost of lighting and its impact on plant growth, researchers were able to provide an hourly greenhouse lighting schedule varying between 0-224 watts per sq meter of growing area.
- As a final example, one research group utilized optimization techniques to determine the best metrics for indicating indoor daylight availability and electric lighting energy consumption. Metrics examined included worst-case and average outdoor diffuse illuminance, average daylight factor and spatial useful daylight (sUD). Researchers then developed seven alternative objective functions composed of pairs of design variables having conflicting goals and dependent on different combinations of the preceding metrics, each equally weighted. By optimizing the window-to-wall ratio and indoor reflectance of the ceiling, walls and floor to maximize available daylight and minimize electric energy use, researchers demonstrated that objective functions composed of sUD and worst-case outdoor diffuse illuminance metrics yield the most precise and robust results (Mangkuto, Siregar, Handina, & Faridah, 2018).

At the California Lighting Technology Center, research is in development to apply similar methods to optimize the selection of operational set points and schedules using CLTC's integrated building control laboratory (IBCL) (**Figure 2**). In the May 2017 issue of *LD+A*, CLTC shared an update on its research to develop a building control system capable of integrating HVAC, lighting and fenestration under a unified, automated hardware platform. We discussed system hardware features and the preliminary system control algorithms intended to automatically maximize occupant comfort and energy savings given user-defined system set points and a short list of initial design parameters. Currently, CLTC is working to develop a "control system optimization tool" that will expand the system's automated decision making routines to consider hourly electricity rates, weather data, individual building system response times and other common factors having a direct impact on the building's actual hour-to-hour performance.

Research will consider up to four key objectives: maximize visual comfort, maximize thermal comfort, minimize energy use and minimize carbon emissions. Outcomes will provide a set of options for programming initial system parameters, including occupied light levels, HVAC set points and window shade position. In addition, work will also address automated updates to these parameters to maintain occupant comfort while minimizing the overall cost of operating the building, both financially and environmentally. ◎

References

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