



Multi-objective optimization for diversity and performance in conceptual structural design

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Abstract

For most traditional applications of structural optimization and form finding for conceptual design, it is possible to pursue a single objective to arrive at an efficient, expressive form. However, when developing a modern building, the design team must consider many other aspects of performance, such as energy usage, architectural quality, and constructability in addition to structural efficiency. If used appropriately, multi-objective optimization (MOO) can accurately account for designers' needs and guide them towards high-performing solutions, while highlighting trade-offs between structural considerations and other performance objectives. In response to this potential, this paper presents a new MOO process that can be integrated into the typical workflow for conceptual building designs. This MOO process is original in how it allows for interaction with performance feedback across separate design disciplines while generating diverse, sometimes unexpected results. This paper applies the MOO process to a long-span roof design example while focusing on two quantitative optimization objectives—structural efficiency and operational energy efficiency—in a variety of climate contexts. The results generated in this case study include a diverse range of designs that exhibit clear trade-offs between objectives. Overall, this paper illustrates new potentials of the MOO approach in conceptual design for producing context-responsive, high-performing, geometrically diverse design solutions.

Keywords: structural optimization, conceptual design, multi-objective optimization, design diversity

1. Introduction

When an architect is exploring a conceptual building design, he or she must simultaneously consider and prioritize a multitude of design objectives. A variety of computational methods falling under the category of multi-objective optimization (MOO) have been developed to assist in this effort. However, since MOO is typically used in pure engineering applications where all objectives are quantitative and a single solution is desired, its application to architecture has often led to geometrically uninteresting design spaces with expected solutions. For a conceptual MOO process to gain traction with designers looking for creative, expressive forms, it must yield a diverse range of high-performing results that meet a variety of aesthetic preferences. These results must be generated and evaluated rapidly, while balancing allowances for designer preference with clear guidance towards the best solutions (Mueller and Ochsendorf [12]). Although MOO has demonstrated

significant potential to assist conceptual designers in generating and deciding between high-performing, early-stage designs, it has seen only limited use in practice. There are a variety of reasons for this, including the complicated model translation process that must occur between design and analysis software, the often linear process in which members of the design team are only given small latitude to ‘optimize’ for their own performance goals without reference to other disciplines, and the difficulty of using optimization within a process that includes subjective preferences and design goals that are difficult to formulate numerically (Flager *et al.* [6]).

The goal of recent academic research in this field has been directed at overcoming these limitations, and at exploring the design outcomes generated by an MOO approach to better understand their broad implications for conceptual design. This paper makes a contribution in both areas, first by introducing a new process that can be integrated into existing design tools, and then by employing this process in a conceptual design case study that was selected because it has properties that are generalizable to a wide variety of architectural problems. The case study is tested for a range of climates and orientations to explore how the nature of these architectural problems changes with context. This research is intended as both an initial step in the long-term development of a practical design tool, as well as a means for better understanding trade-offs between the most important design objectives for the subset of architectural typologies in which structural considerations are especially significant.

1.1 Importance of structure and energy as early design objectives

Although there are multiple architectural objectives in a given building design problem, and the general process established in this paper could be used to pursue many of them, this research focuses on two main objectives: structural efficiency and operational energy efficiency. For large buildings or design problems with specific spatial requirements, such as skyscrapers or long-span roofs, consideration of structural form can dominate the conceptual design phase. This is especially true because efficiency depends more on the geometry of a building than on material, sizing, and other building characteristics developed in later stages. Structurally efficient designs reduce material usage and lifecycle costs, and they are generally safer, more durable, and easier to build (Mueller [13]). Structural efficiency also matters for these specific design cases because it can have a larger relative effect on cost, environmental impact, and constructability than in smaller, standard building designs.

The second objective, operational energy efficiency, has perhaps the most sizable impact on whether or not a building can be considered sustainable. Broadly speaking, sustainable design in buildings is concerned with minimizing energy consumption throughout the four main stages of a building’s lifetime: materials manufacturing, construction, use and maintenance, and end of life (Bayer *et al.* [3]). The International Energy Agency [8] estimates that buildings account for 32% of total final energy consumption globally, and a large portion of this is used to keep buildings lit, heated, and cooled. The need for a reduction in energy consumption and carbon emissions due to buildings has been well documented, and although various aspects of building performance (such as daylighting, envelope thermal performance, or ventilation) could be optimized separately, total operational energy as a design goal most effectively addresses the overall needs of contemporary designers.

1.2 MOO for building design

There are a number of researchers who have pursued multi-objective optimization in conceptual building design. Asl *et al.* [2] establish and test an optimization method for whole building energy

performance and daylighting using a parameterized BIM model, illustrating clear trade-offs in window size between usable daylight and thermal performance. However, the building parameterization is limited to the windows rather than controlling the overall form and massing of the building. Flager *et al.* [6] present the most complete example of an MOO building design optimized for structure and energy using *a posteriori* articulation in a process that crosses disciplines and engages a wider range of building performance criteria. Yet this research shares the same limitation of design diversity in that all solutions are restricted to a rectangular geometry, which reduces design freedom in cases where architects may want to be more expressive.

With the introduction of ParaGEN, Von Buelow [14] combines performance feedback from a variety of simulation programs (structural, lighting, acoustical) with aesthetic preferences in design through the use of interactive evolutionary algorithms. By breeding designs that have different fitness functions and storing multiple alternatives in a searchable, graphical database, Von Buelow's proposed workflow gives designers the opportunity to pursue multiple design objectives and visualize trade-offs. Additional researchers have used this powerful framework to explore a number of specific trade-offs in architectural design, including many related to energy performance, but none have tested how these trade-offs change with context or captured the whole-building performance for structurally dominated conceptual designs.

A review of the literature and current state of design practice yields the following research question: how can architectural, conceptual MOO design problems be formulated and solved in a way that generates diverse, high-performing solutions? Additional related research questions arise during the application of MOO to specific structural problems: what design knowledge about the importance of structural efficiency as it relates to other contemporary design goals is generalizable, and is it possible to establish common design rules for specific trade-offs in a given context?

3. Methodology

To address design space formulation and exploration for structure and energy in the conceptual design of long-span roof structures, a case study model was developed and rigorously tested. The procedure for implementing the case study included the development of a parametric design space, sampling that design space, evaluating each design, visualizing each result, and analyzing the overall data (see Figure 1). Each of these steps is explained in the following sections. The design lessons learned from this case study could be applied to a variety of architectural programs that contain large, open, conditioned volumes, such as airports, convention centers, or stadiums.

The initial case study selected for this paper is the conceptual design of an airport terminal structure. The terminal contains a free interior space of 45 m x 100 m, which is spanned by a series of steel arches in one direction and transverse beams between the arches in the other. The sides of the terminal consist of a panelized curtain wall system that mixes transparent glazed panels with spandrel glass panels concealing interior insulation. This structure allows for free occupant movement while providing design opportunities for tuning both natural daylighting and envelope properties for operational energy efficiency. The airport design problem was inspired by an existing bus terminal in Qingdao, Shandong, China that contains a similar 'x-brace' structural system (see Figure 2).

This design example was selected because it explores two major generalizable design problems that trade-off between structural efficiency and operational energy efficiency. The first problem is the

enclosed arch, where greater arch height often leads to higher structural efficiency, but also to more volume that must be heated and cooled. The second problem is the cantilevered overhang, in which increased overhang length could lead to more efficient solar gains and lighting strategies for certain climates and orientations, but also requires more structural material.

In testing the design, three model locations and two model orientations were selected to assess the response of various design options to different contexts. The first location, Boston, has both heating and cooling loads, but is heating dominated. The second location, Sydney, is in a more temperate climate where the required cooling load is slightly higher than Boston's, but the heating load is very small. The third location is Abu-Dhabi, which has no heating load but is dominated by cooling loads that are roughly five times higher than those required by Boston and Sydney. For each of these locations, the model was simulated with both a west-east and south-north orientation to test differences in the impact of the overhang direction.

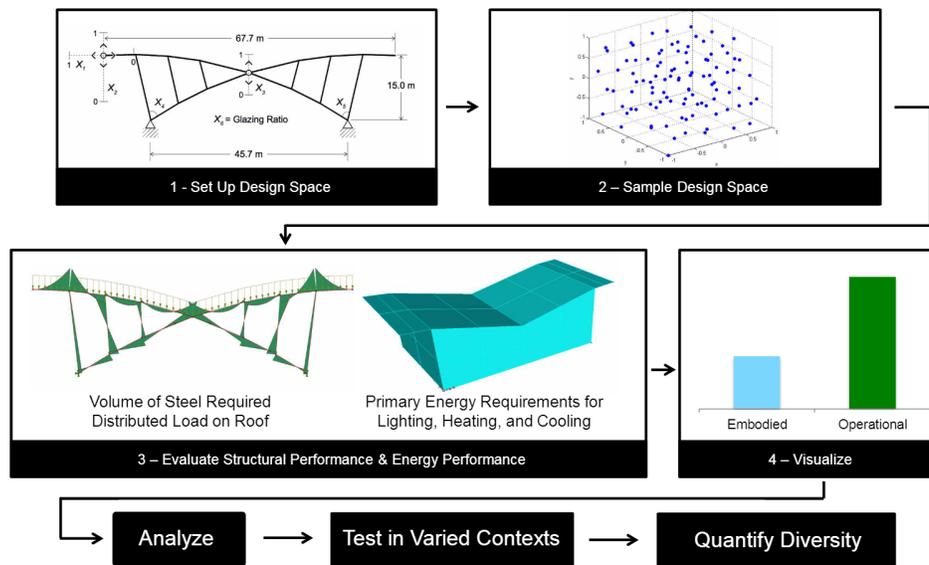


Figure 1: Conceptual MOO process flowchart

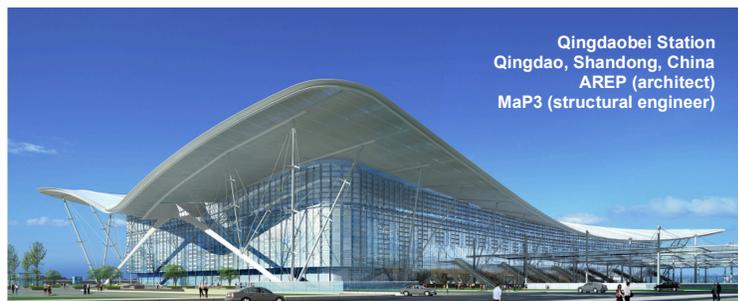


Figure 2: Inspiration for the design case study (Figure from *map3.net*, used with permission)

3.2 Design space formulation

A parametric model of the airport design was generated in Rhinoceros and Grasshopper based on the following geometric parameters: overhang length, starting edge location, starting hinge height, angle of the left half-arch, angle of the right half-arch, and glazing ratio (see Figure 3). To prepare for evaluation of both structural and energy performance, the model included linear elements representing the structural pieces of steel as well as surfaces representing the exterior envelope of the building. The ranges for each parameter were determined based on general design problem constraints, such as a minimum requirement for structure clearance on both the interior and exterior of the building.

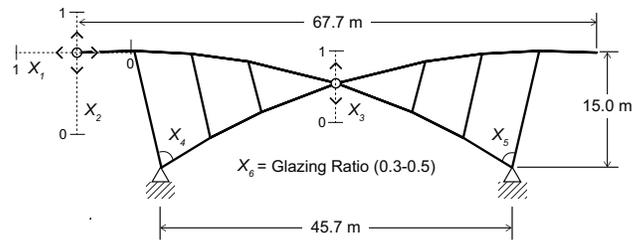


Figure 3: Design parameters for the case study

3.3 Performance evaluation

The performance of each design was measured using plug-ins available for Rhinoceros and Grasshopper. The structural optimization objective was to minimize the weight of steel required, and the energy optimization objective used was to minimize the annual operational energy of the building, which includes requirements for lighting, heating, and cooling. Structural performance for each design was quantified using Karamba [9], a finite element modeler that interacts with Rhinoceros geometry. To calculate the overall weight of structural material, Karamba's sizing feature was used. This feature checks the allowable axial, bending, and buckling loads for each member and then searches through a structural section library to determine the smallest member that can adequately handle each load before outputting the total weight of the structural system. The energy evaluation for each model was performed using ARCHSIM [1], a Grasshopper plug-in that connects Rhinoceros geometry with EnergyPlus, a widely used energy analysis and thermal load simulation program made available by the U.S. Department of Energy. ARCHSIM assigns material properties to each surface of the model, creates thermal zones, and runs a whole year simulation, returning the total amount of energy required to keep the building appropriately lit and temperature-controlled for an entire year. This model accounts for solar and temperature effects, and the envelope assumptions were created based on an energy code compliant building design for the Boston region (see Figure 4).

Structural Details		Envelope Details		Energy Calculation Details		
Steel Beam Elements		Designed to meet MA energy code		Loads → Site Requirements → Primary Energy Requirements		
Wide Flange Beam Sections		(standard efficiency)				
Dead Load	7.18 kPa	Roof R-Value	3.52 K*m ² /W	Load	Site	Generation/Transmission
Arch Spacing	6 m	Wall R-Value	2.64 K*m ² /W	Lighting	100% Eff	33% Conversion Eff
Embodied Energy Coefficient	24.4 MJ / kg	Glazing U-Value		Cooling	3 CoP	33% Conversion Eff
		Airport Usage (equipment, lighting, ventilation all on)		Heating	85% Eff	10% Transmission Losses

Figure 4: Structure, envelope, and energy calculation model assumptions

3.4 Data processing and sampling

Some post-simulation data processing was required to convert the results into directly comparable units. This case study uses the primary energy requirements, in Joules, for each performance metric as the standard unit of comparison. To arrive at this metric, the weight of the steel structure was multiplied by an embodied energy coefficient given by Hammond & Jones [7]. For the energy performance, the model captured each load (lighting, cooling, and heating) separately before multiplying them by on-site and transmission efficiencies and coefficients of performance as detailed in Bourgeois *et al.* [4].

Since the purpose of this case study is to explore relative designs within a specific design space, the primary energy requirements have been normalized to the average for each category. These normalized results are reported as scores, which represent the magnitude of the performance relative to the average, with lower scores considered to be better or more optimal. The Boston case was used as the standard for this normalization when comparing across climates, leading to cooling loads for Abu Dhabi in the range of 7-12 times the average. However, the design scores in every other case range from roughly 0-2.

To ensure a representative sampling of the design space, a Latin hypercube algorithm (McKay *et al.* [11]) was used and then scaled to the appropriate design variables. For each of the six contexts formed by the different locations and orientations, the parametric design was sampled at a rate of $n = 999$. The simulations were completed in a loop within Grasshopper, with the sampling code inputting each design, triggering new evaluations, and recording the performance results.

3.6 Optimization and visualization

In multi-objective optimization for design, there are a number of available methods for selecting the best design based on designer preference. These include using *a priori* articulation of preferences, where a composite weighted objective function is created at the outset, *a posteriori* optimization articulation of preferences, where the designer chooses from a number of near optimal designs after an optimization has been run, and interactive articulation of preferences, where a designer gives input while the algorithm is running (Marler and Arora [10]). For this case study, it was most appropriate to consider post-optimization articulation of preferences, since the purpose of this paper is to show creative and generative potential rather than arrive at a single optimal solution. For each sample, the set of Pareto optimal designs was selected for presentation, since these are considered the ‘optimal’ designs in which the performance in one objective cannot be improved without decreasing the performance in another. The selected designs were found using Pareto Front, a MATLAB function that reads in a list of performances for each iteration and selects the ones that are not dominated by any other design (Cao [5]).

3.7 Diversity

For multi-objective optimization tools to be considered useful by creative architects in exploratory conceptual design, they must produce a wide range of high-performing solutions for potential selection. To quantify the diversity of each optimal set, this paper uses the formula:

$$D = \max\|X_{centroid} - X_i\| \quad (1)$$

where X corresponds to the design vector of size n containing n design variable settings. This diversity metric calculates the Euclidian distance from the centroid of a set of designs to the furthest outlier (Mueller and Ochsendorf [13]). A lower value for D indicates less choice and trade-off in design. The metric effectively measures how different a group of designs are from one another, since a group of similar designs converging towards one solution would have a low score, and a set with a wide range of solutions would have a high score. This metric takes into account each design by its contribution to the centroid calculation, but one particular outlier can heavily affect it. For this reason, the most numerically distinct design in each set is identified in the results section.

4. Results and Discussion

4.1 Results in different contexts

The performance and optimization results of the case study are presented in this section. Figure 5 gives the full results of the case study, including the structural performance for each design plotted against the energy performance in each of the different orientations and climates. In these plots, the entire sample set is shown in gray, while the Pareto optimal points are colored black. The plots are normalized, with 1 being the average in Boston (west-east orientation) and lower scores considered to be better performance. The first column presents the overall results for primary energy requirements on the y-axis, and the second column shows the same plot zoomed in on the best performing designs in the lower left hand corner of the objective space. The last three columns break out the lighting, heating, and cooling loads on the y-axis, showing the effect of climate and orientation on each separate performance factor.

Figure 6 presents both a geometric and graphical representation of each design on the Pareto optimal front for the different contexts. They are ordered from best to worst in terms of structure, or left to right when moving across the graphs in Figure 5. Due to the definition of Pareto optimality, the designs are also ordered from worst to best in terms of energy, a relationship which can be observed by noting the opposite trends of the performance bar graphs given for each design. The figure also gives the calculated diversity for each set and denotes the single design that is most distinct in each optimal set.

The results for each location show a clear Pareto front, although these fronts vary in terms of diversity and number of optimal solutions. A large sample ($n = 999$) was required to arrive at these Pareto fronts of in between 5-10 designs, which was computationally expensive. Each location and orientation shares a few common designs, including the solution (22) that scores the best overall in terms of structure. Most of the solutions are nearly symmetrical, although there is some noticeably patterned asymmetry in the south-north orientation for Sydney, in which the south (left) side windows are allowed to be larger. In every case, the designs trend from highly arched to more flat as the structural score worsens, and in the case of Boston the best energy solutions even have convex arches that allow in as much sunlight as possible. When looking at the loads individually, the Pareto optimal designs do not always form a clear front, but do trend towards the lower left of the graphs.

The designs were most diverse in the Boston S-N orientation, followed by Sydney S-N, Boston W-E, Sydney W-E, and then both Abu Dhabi orientations. In Boston, which requires both heating and cooling loads, the designer appears to have the most choice, with high-performing designs ranging from arch-shaped to flat. Although Sydney fared well numerically in terms of diversity (which can be

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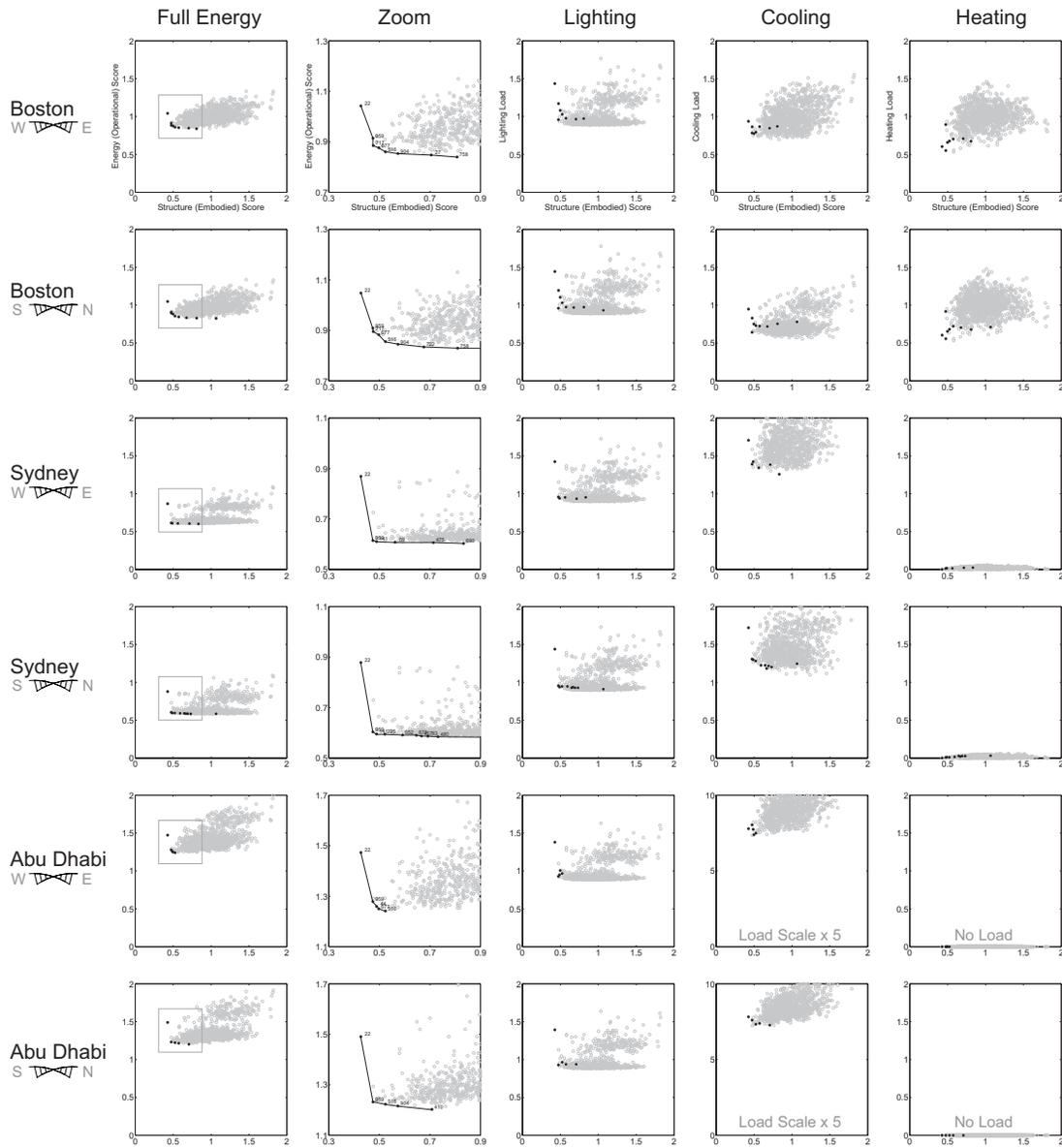


Figure 5: Structural score versus energy metrics compared across contexts

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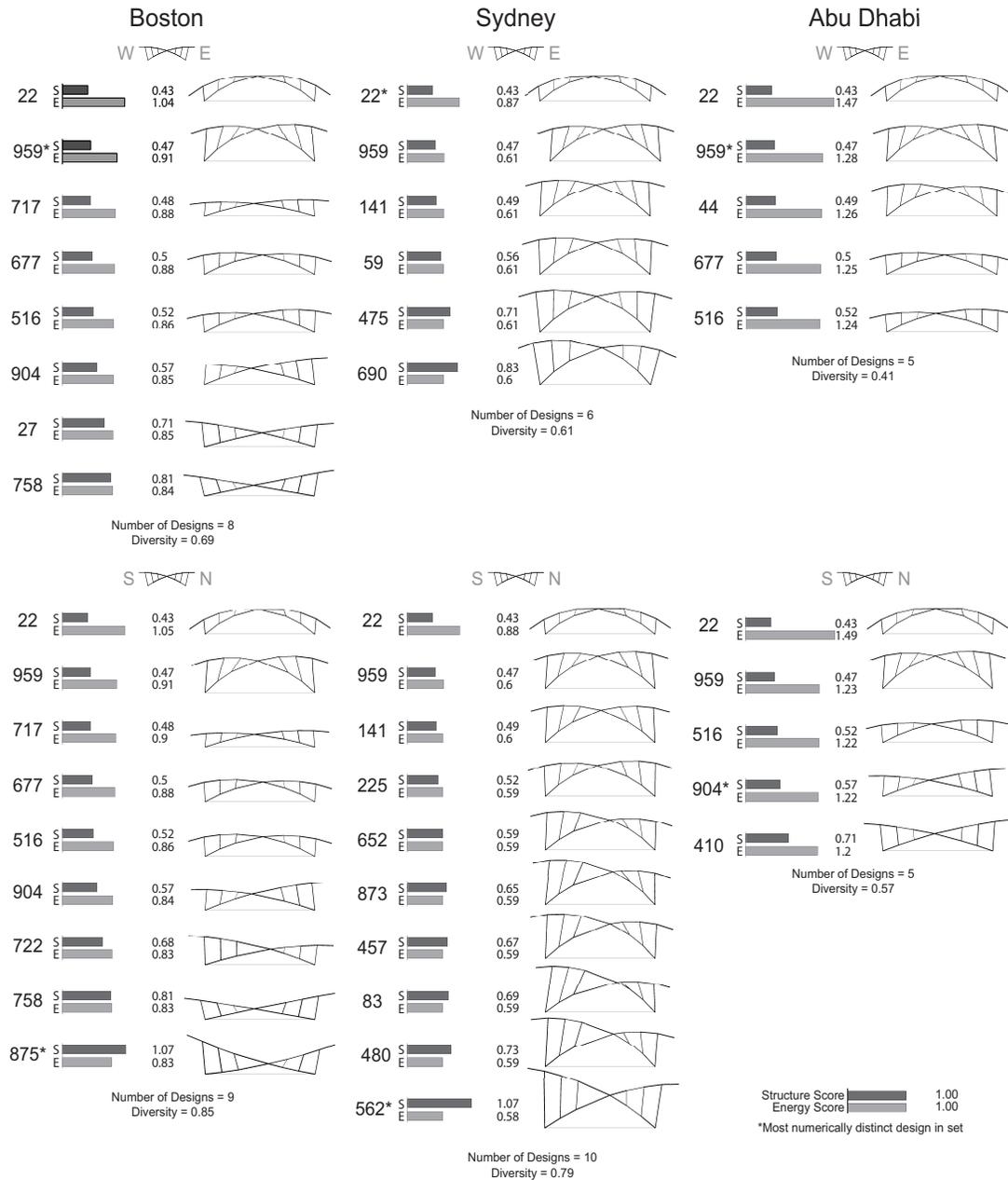


Figure 6: Pareto optimal design sets for each climate and orientation

partially attributed to allowances for asymmetry), it seems as though the temperate climate mostly favors large arches. The solutions for Abu Dhabi were not as diverse, and although they both included highly arched designs towards the left end of their Pareto fronts, the remaining three solutions seemed to be flatter and contain less volume. The S-N orientation yielded more diverse results than the W-E orientation in each set, which demonstrates the impact of the changing shading overhang on the sunniest face of the building.

In general, these results support an argument that mixed heating/cooling climates force designers to pick a performance dimension in which they want to be most successful, whereas temperate climates offer an opportunity to explore pure structural optimization, and climate intense (heating or cooling) regions require designs that more directly respond to that climate. However, this conclusion would have to be further tested for other cases to be generalized.

4.2 Sampling and diversity

The presence of Design 22 on the Pareto front of each sample indicates a weakness of brute force sampling methods. When setting up the problem, a designer can only ensure representative sampling across the design space, since he or she is blind to the objective space until samples are evaluated. Thus, although there are samples relatively close to Design 22 in terms of parameters, it appears isolated on the performance plots. Depending on the size of the sample set and the specific sampling algorithm used, the existence of isolated points could substantially change the shape of the Pareto plot. In Figure 7, the design sample was expanded to include 40 additional designs that were very close to Design 22 in the design space. This manual, directed sampling is an approximation of how an evolutionary algorithm could quickly move towards the Pareto front and establish it at a higher resolution with less computational effort.

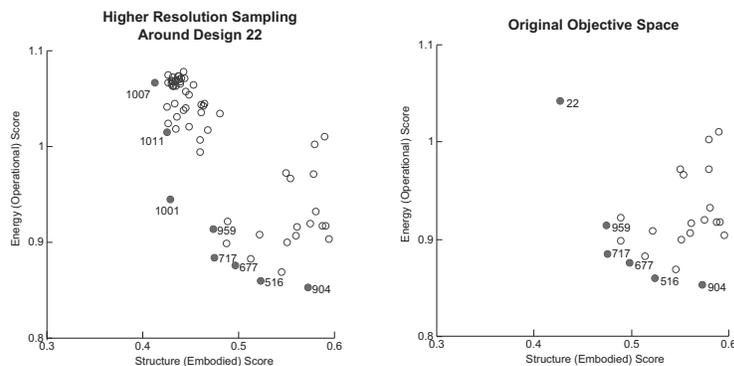


Figure 7: Comparison of the original sample and a directed sample near Design 22 for Boston (W-E)

However, a clear strength of sampling a parametric design space for MOO is that many other potential designs exist slightly off of the Pareto front. In the previous section, only designs on the Pareto fronts were displayed visually. Yet in many cases, a conceptual designer may want even more geometric diversity than the Pareto front offers, and may be willing to pay a slight performance penalty for this

extra diversity. As an example, Figure 8 shows a set including the 35 designs that are closest to the Pareto optimal points for Boston W-E. This new set exhibits an even higher measure of diversity (0.76 compared to 0.69), while performing nearly as well as the points on the Pareto front. The threshold of proximity to the Pareto front could be adjusted until a designer is satisfied with the diversity of results their model is generating, unlocking additional creative capabilities within an MOO process.

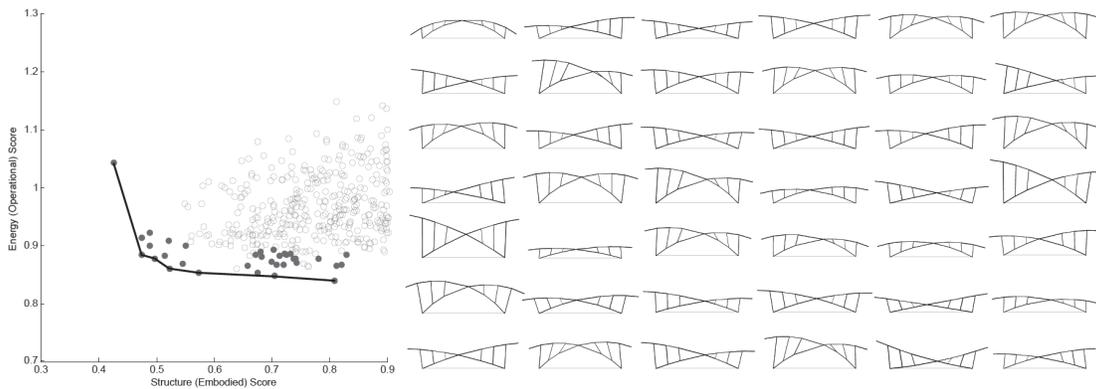


Figure 8: A set of designs located near the Pareto front for Boston (W-E)

5. Summary of contributions

In conclusion, this paper presents a new multi-objective optimization process for structural conceptual design that can be used in cases where the overall form has a considerable effect on the success of the building design. This process was applied to a conceptual proposal for an airport terminal and used to generate a wide variety of high-performing, diverse design solutions based on an initial parametric design. Two significant and broad objectives, structural efficiency and operational energy efficiency, were pursued and trade-offs between the two were compared. A number of generalizable lessons were proposed for the design of enclosed arch structures, as well as open program structures with large exterior overhangs. Overall, the results indicate that trade-offs for these design problems depend significantly on climate. Although rules of thumb exist for designers concerning how these problems change for different contexts, MOO can help designers understand these trade-offs quantitatively and also reveal unexpected relationships between significant architectural objectives.

This research could lead to a number of areas for future work. First, the methodology should be tested on other case studies that explore both arch and overhang trade-offs, as well as entirely different architectural problems. The methodology could also be changed to include other objectives based on what is most useful for designers. In addition, the metrics used in this paper could be expanded, such as calculating a performance penalty for diversity by how far off of the Pareto front a designer must go in the objective space before finding an appropriately diverse set. An evolutionary algorithm could also be employed to more quickly find and explore the Pareto front at a higher resolution.

Ultimately, the goal of this research is the development of an effective, usable MOO process for conceptual designers, and the creation of a tool that implements this process. Further testing of such a tool will allow for more advanced knowledge of the main trade-offs between significant objectives in

conceptual structural building design, as well as a greater understanding of how these trade-offs change with context. Each of these contributions has the ability to make MOO a more viable and valuable tool for conceptual designers, leading to successful, high performing designs.

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