Balancing Act: Managing Multi-Objective Problems in Comprehensive Studio

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This research explores the application of dynamic multi-objective optimization (DMOO) concepts and tools within a comprehensive studio context to help students deal with dynamic multi-objective design problems in a comprehensive studio context. DMOO offers a rigorous conceptual framework and provides methods for the comparative analysis of design solutions and their trade-offs. To test this claim, a pedagogical methodology to integrate these concepts and tools is described and then validated through the comparative analysis of two different comprehensive studio sections. The results show that use of DMOO concepts and tools in the early and late stages of design does improve exploration of trade-offs between possible design solutions.

INTRODUCTION

The architectural design process involves balancing multiple quantitative and qualitative objectives, understanding the trade-offs between these objectives, and dynamically reprioritizing them when the goals of the project inevitably change. Architectural design problems can therefore be understood as dynamic multi-objective problems (DMOPs). Failing at this balancing act in real-world projects can lead to cost overruns, under-performing buildings, and injury. Educating students to manage dynamic multi-objective problems is therefore crucial in preparing them for some of the challenges of practice.

In North American universities, the comprehensive, or integrative studio, represents an important moment in the curriculum where students are likely to encounter especially challenging DMOPs due to the integrative thinking required at a number of scales. Providing students with concepts and tools to handle these problems at this stage is therefore crucial to their success in the studio and their development as architects. But how can educators effectively teach students to manage these problems within a comprehensive studio context? What concepts and tools can students use to efficiently explore the trade-offs possible between multiple objectives within a space of possibility?

Traditional pedagogical approaches to teaching comprehensive studio has emphasized the application of factual and procedural knowledge, while focusing less on knowledge involving models and theories of the design process itself (e.g., conceptual and metacognitive knowledge).[1] This type of strategic thinking, however, can be crucial in allowing students to understand and breakdown the complexity of a comprehensive design problem. It can promote critical reflection on the definition of the problem as well as on the models of design process that might be used to solve the defined problem. Further, it can provide students with conceptual frameworks to more rigorously compare design solutions. Exposing students to heuristic models that deal specifically with DMOPs might therefore help students to better understand and address comprehensive studio problems.

Dynamic multi-objective optimization (DMOO) is an emerging area of research in the fields of computer science and optimization that offers a rigorous conceptual framework by which to better understand DMOPs.[2] It also provides methods to find optimal design solutions as well as methods for the comparative analysis of those solutions and their trade-offs. This research proposes an approach to integrate DMOO concepts and tools into a comprehensive studio curriculum. Further, it assesses the following two claims through a comparison between two different comprehensive studios: 1. In the analysis and schematic design phases, DMOO provides a conceptual framework that improves comparative understanding and exploration of precedents when tested against action centric approaches; 2. In the latter design stages, DMOO provides a conceptual framework and search methodology that improves exploration of trade-offs possible between objectives. The results of this assessment demonstrate that DMOO concepts and tools increase instances of comparative thinking and the exploration of trade-offs in the early and latter stages of design.

PRECEDENT COMPREHENSIVE STUDIO PEDAGOGY

In order to address the challenge of developing integrative thinking in a comprehensive studio context, previous work has tended to take one of two approaches. The first approach emphasizes the use of factual (i.e., facts and details) and procedural knowledge (i.e., methods for doing), with little to no focus on conceptual knowledge (i.e., generalizations, principles, theories, models) and metacognitive knowledge (i.e., knowledge about how knowledge is created, strategic thinking).[1,3] In this approach, students are encouraged to think conceptually in the initial phase of the term in order to develop a design position and then factual and procedural knowledge is emphasized to produce a design specification related to that position.[4] Another approach encourages students to develop conceptual, factual, and procedural knowledge related to their project simultaneously.[5] Both approaches only emphasize conceptual knowledge in relation to developing a design position, and metacognitive knowledge is not emphasized at all. This limitation means that thinking involving models and theories of the design process itself as well as strategic thinking to modify such models to create necessary knowledge is largely absent. One result of this deficit is that students lack a conceptual framework that allows for rigorous comparative analysis between different design solutions and this limits design exploration.

An alternative approach has been to add additional emphasis in these underrepresented areas in order to help students deal with the multi-objective nature of design problems. Specifically, some research has explored the application of multi-objective optimization methods in design studios.[6] This approach gives students a way of conceptualizing multi-objective problems and provides a rigorous framework to compare design solutions but emphasizes a model of design problems and design processes to find solutions that are static. This research builds on this approach but goes further by emphasizing a dynamic model of the multi-objective design problem. Further, it introduces new pedagogical methods, assessment methods, and tools for helping students deal with dynamic multi-objective problems in a comprehensive studio context.

A METHOD FOR INTEGRATING DMOO INTO COMPREHENSIVE STUDIO

The fourth-year comprehensive studio in the College of Architecture at the University of Nebraska-Lincoln takes place in the final term of the undergraduate architectural program. The studio's curriculum includes addressing nine learning objectives found in the National Architectural Accrediting Board (NAAB) Student Performance Criteria (SPC) list over a 16-week period. This list of requirements is challenging to cover with sufficient depth, rigor, and creativity in a term, and integrating new technology into the mix can further add to the demands on students and instructors.

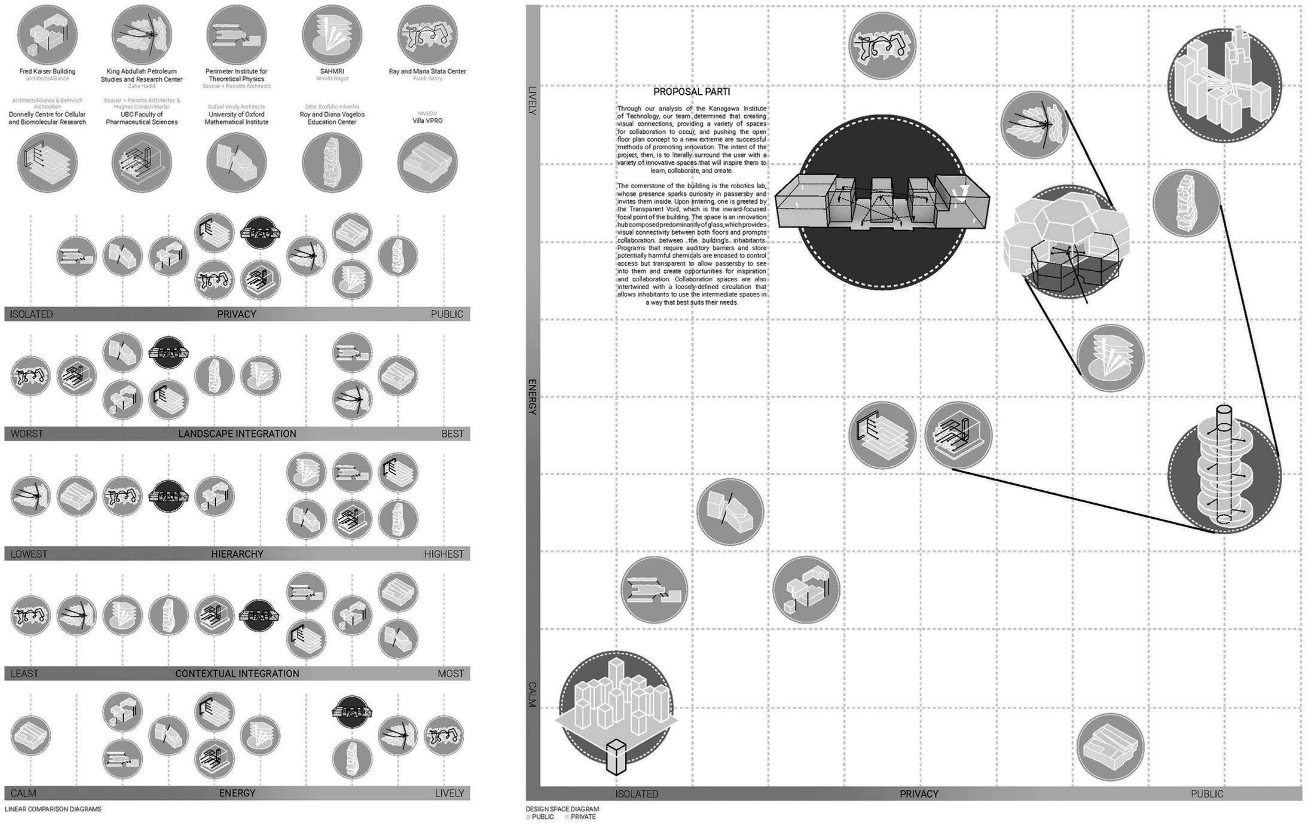
The schedule for the term was separated into five phases: analysis; schematic design; intermediate design; and synthesis. DMOO concepts and tools were then chosen to support these phases. Specifically, in the initial stages of design (i.e., analysis and schematic design phases), students are given a lecture and introduced to key DMOO concepts. The concept of decision variables (i.e., design parameters) and decision space (i.e., space of possible parameter configurations) is first discussed to get students thinking about the relationship between the specification of geometric design parameters and how that choice produces a certain space of possibility for designs. The dynamic nature of decision spaces during a design process is also a key point of emphasis – as architects may start out working with one set of design parameters and add or delete them as the design is developed and new information comes to light.

The concept of quantitative (i.e., mathematically measurable goals) and qualitative (i.e., aesthetic goals) objectives is then discussed along with how these two different types of goals might be evaluated. The discussion provides the opportunity for students to reflect on the ways they have measured the performance of their designs in both quantitative and qualitative ways in past studios and stimulates them to think of new methods for evaluation. The role of such metrics is also discussed from a rhetorical point of view - in terms of how the visualization of these metrics can be used to make an architectural design position more convincing.

Students then learn that the objectives of a project define a space of performance possibility for a design (i.e., objective space). Further, they learn that in multi-objective problems there is usually not just one solution to a problem but several different possible solutions representing different trade-offs between objectives.[7] The last point of emphasis is that objectives can and do change during a design process due to changing priorities, constraints, and new information on what goals are actually attainable.

In the analysis phase, students are then asked to apply these concepts to the analysis of a set of precedent architectural projects. In the exercise, students first identify the most important objectives related to the design project for the term. They then use these selected objectives to construct a space of possible design solutions (i.e., an objective space) for the analysis. This objective space is then graphically represented, and each precedent is mapped to this space of possibility. This mapping operation visually reveals how each project relates to one another and also reveals areas in the objective space that seem to be over-explored and under-explored by the precedents. Figure 1 shows a representative example of this analysis.

In the schematic design phase, students are then asked to use this map in a generative fashion to create new organizational ideas for their term project. Based on an exercise developed by Tom Hartman at the Design School at Arizona State University, students are then asked to generate new parti ideas through two generative operations: extrapolation (i.e., generating ideas at the extremes of the objective space) and interpolation (i.e., generating ideas by interpolating between existing projects in the objective space). Both of these generative operations are shown in the right side of Figure 1 and are used by each team to develop an organizational approach to the term project. This generative map helps to bridge the gap between analysis and design ideation. Further, the introduction of these concepts helps to stimulate meta-cognitive thinking – as students realize that the definition of an objective space for a project can be generative of new knowledge, and as that definition changes, so does the knowledge created.



PROPOSAL PARTI

Through our analysis of the Kanagawa Institute of Technology, our team determined that creating visual connections, providing a variety of spaces for collaboration to occur, and pushing the open floor plan concept to a new extreme are successful methods of promoting innovation. The intent of the project, then, is to literally surround the user with a variety of innovative spaces that will inspire them to learn, collaborate, and create.

The cornerstone of the building is the robotics lab, whose presence sparks curiosity in passersby and invites them inside. Upon entering, one is greeted by the Transparent Void, which is the inward-focused focal point of the building. The space is an innovation hub composed predominantly of glass, which provides visual connectivity between both floors and prompts collaboration between the building's inhabitants. Programs that require auditory barriers and store potentially harmful chemicals are encased to control access but transparent to allow passersby to see into them and create opportunities for inspiration and collaboration. Collaboration spaces are also intertwined with a loosely-defined circulation that allows inhabitants to use the intermediate spaces in a way that best suits their needs.

Figure 1: An example of student work from Drew Doyle and Craig Findlay in which DMOO concepts are used to comparatively analyze a set of precedent projects and identify design opportunities, David Newton Univeristy of Nebraska-Lincoln College of Architetcure.

INTEGRATING DMOO INTO THE LATTER STAGES OF DESIGN

In the latter stages of the term (i.e., intermediate, design development, and synthesis stages), student teams are introduced to methods and digital tools for decision space definition and exploration (e.g., parametric modeling); evaluation of objectives (e.g., daylighting, structural, and aesthetic performance analysis); and exploration of objective spaces (e.g., computational optimization). The concepts defined during the analysis and schematic phases are also used by the students in these latter phases to think meta-cognitively about the given design problem and the methods they might use to search a space of possibility and comparatively evaluate design solutions.

In the intermediate design phase, the focus is mainly on decision space definition and exploration, as well as, the evaluation of objectives. Specifically, teams are asked to use parametric thinking and modeling to develop and explore a structural-spatial system to accommodate their program parti ideas developed in the schematic phase. In parallel, teams are asked to list and prioritize specific objectives (i.e., quantitative and qualitative goals) for their project and to identify ways of measuring those objectives. Teams are given tutorials on computational performance analysis to aid in evaluating quantitative objectives such as structural and daylight performance. Qualitative objectives relating to aesthetics and embodied experience are given equal weight during desk critiques, and teams are asked to develop methods to assess these objectives. These developed methods can be computational, but more often involve the creation of a rationale for associating design features with an aesthetic or experiential quality.

In the design development and synthesis stages of the term, the focus shifts towards the exploration of objective spaces (i.e., space of possible designs) and exposing students to methods for the discovery of optimum design solutions. Specifically, students are given a lecture on the topic of multi-objective optimization and given high-level summaries of a number of established methods used in computer science to find optimal solutions (e.g., enumerative; deterministic; and stochastic methods).[7] Stochastic methods use the random sampling of a space of possible designs to iteratively converge on a set of optimal solutions. These methods are also the most flexible optimization approach and can balance exploration (i.e., divergence) of a design space with strong convergence characteristics (i.e., ability to narrow-down to a set of highly optimal solutions). These processes are therefore emphasized in the studio, and concepts associated with these methods, such as the concepts of divergence and convergence, are used to help teams better understand

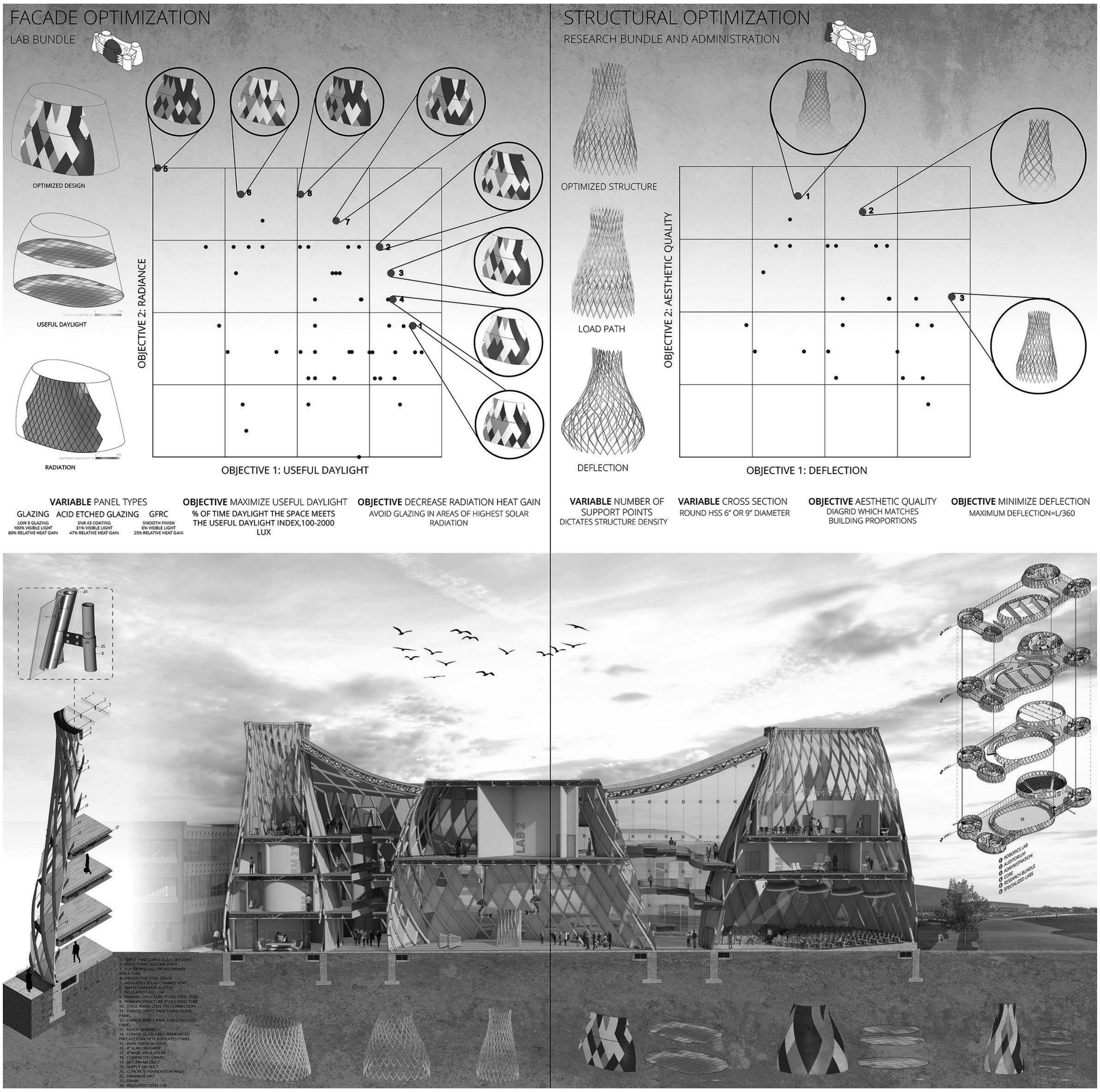
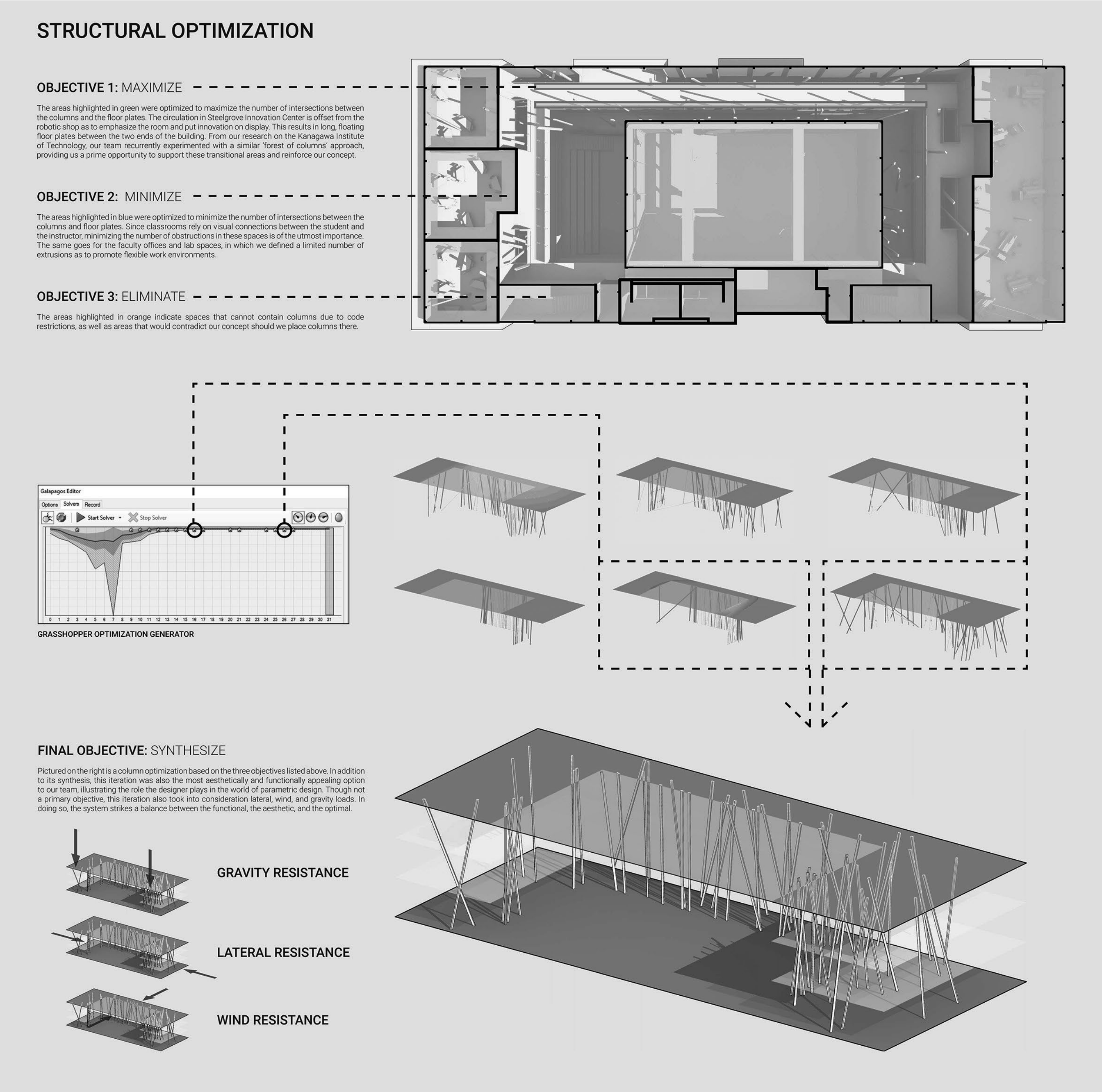


Figure 2: Pictured above is work from the latter stages of design by Shayla Dick and Kristina Schneider, David Newton University of Nebraska-Lincoln College of Architecture.

the process of design as a structured process of searching a space of possibility that involves both expansive and contractive search operations. Further, the dynamic nature of such a search is emphasized, because design parameters and objectives often change in the process of design.

A custom digital toolkit for dynamic multi-objective optimization (DMOO) developed by the author called "Design Breeder" is made available to teams to aid in the exploration and optimization of their designs. Design Breeder was designed and developed as a plug-in for the Grasshopper 3D parametric design environment, allowing users the ability to interact with the optimization process in unique ways and to optimize for both quantitative and qualitative objectives at the same time. Specifically, the toolkit allows users to dynamically change the number of objective functions and decision variables as the optimization process runs – providing a greater explorative capacity than previous approaches. Design Breeder also allows for the optimization of multiple qualitative objectives (i.e., aesthetic or experiential goals) simultaneously. It accomplishes this by asking users to



STRUCTURAL OPTIMIZATION

OBJECTIVE 1: MAXIMIZE

The areas highlighted in green were optimized to maximize the number of intersections between the columns and the floor plates. The circulation in Steelgrove Innovation Center is offset from the robotic shop as to emphasize the room and put innovation on display. This results in long, floating floor plates between the two ends of the building. From our research on the Kanagawa Institute of Technology, our team recurrently experimented with a similar 'forest of columns' approach, providing us a prime opportunity to support these transitional areas and reinforce our concept.

OBJECTIVE 2: MINIMIZE

The areas highlighted in blue were optimized to minimize the number of intersections between the columns and floor plates. Since classrooms rely on visual connections between the student and the instructor, minimizing the number of obstructions in these spaces is of the utmost importance. The same goes for the faculty offices and lab spaces, in which we defined a limited number of extrusions as to promote flexible work environments.

OBJECTIVE 3: ELIMINATE

The areas highlighted in orange indicate spaces that cannot contain columns due to code restrictions, as well as areas that would contradict our concept should we place columns there.

FINAL OBJECTIVE: SYNTHESIZE

Pictured on the right is a column optimization based on the three objectives listed above. In addition to its synthesis, this iteration was also the most aesthetically and functionally appealing option to our team, illustrating the role the designer plays in the world of parametric design. Though not a primary objective, this iteration also took into consideration lateral, wind, and gravity loads. In doing so, the system strikes a balance between the functional, the aesthetic, and the optimal.

Figure 3: An example of student work from Drew Doyle and Craig Findlay in the latter stages of design. David Newton, University of Nebraska-Lincoln College of Architecture.

periodically direct the search based on selecting solutions that are closer to the user's qualitative goals. This solution ranking then guides the search towards a user-defined reference direction in the objective space that is able to find more solutions that exhibit the desired quality.

Teams used the Design Breeder toolkit in combination with performance analysis tools to develop and explore the design space of their projects throughout the development and synthesis stages of the term. In Figure 2, the design development of one team is shown. In the top left of the figure, the primary structural system is optimized for deflection as well as an aesthetic objective related to the smoothness of the structural pattern. In the top right of the figure, the glazing pattern of the facade is explored in relation to useful daylight and solar irradiance objectives. For both tasks, a graph of the objective space with the Pareto optimal solutions is shown. This graph serves as a map to help the students understand the "landscape" of their design space. It helps teams understand the available trade-offs between objectives and also to identify areas that are under-explored. Under-explored areas can mean that the decision space for the project needs to be changed so that designs can be produced to reach these areas. Visualizations like these, therefore, inevitably help to guide the redefinition of the design and also the objectives being pursued.

In Figure 3, the work of another team focusses on the exploration of designs for a "forest" of columns in relation to minimizing deflection, producing uninterrupted spaces in designated areas, and maximizing aesthetic objectives related to the density and dynamism of the column arrangement. The specific optimization task shown is one snapshot of a longer process in which the specific objectives being pursued, and their priority changed several times in relation to feedback from reviewers. At the initial stages of the design, maximizing structural performance was the highest priority, and in later stages, aesthetic and program goals took the lead in guiding the search. DMOO concepts therefore provided a useful vocabulary to help teams rigorously discuss and to think critically about their stated objectives.

ASSESSING THE EFFECTIVENESS OF DMOO INTEGRATION

This research began with the following two hypotheses: 1. In the analysis and schematic design phases, DMOO provides a conceptual framework that improves comparative understanding and exploration of precedents when tested against action centric approaches; 2. In the latter design stages, DMOO provides a conceptual framework and search methodology that improves exploration of trade-offs possible between objectives. In order to assess the validity of these claims, the student work of a comprehensive studio using the methodology described above is compared with the work produced by a comprehensive studio not using the stated methodology. Specifically, the test involves comparing a studio taught by the author in the spring of 2018 that utilizes DMOO and one taught by the same party in 2015 that does not use DMOO. Both studios had identical phases of design and schedules, and in both, students worked on projects in teams of two.

As described previously, in the DMOO-based studio DMOO concepts and tools are integrated into all phases of the design process. This methodology is tested against an action-centric model of the design process.[8] In this model, each team works under the guidance of their instructor and from a set of minimum requirements to structure their own approach to defining, balancing, and exploring the trade-offs between objectives at beginning and advanced stages of design.

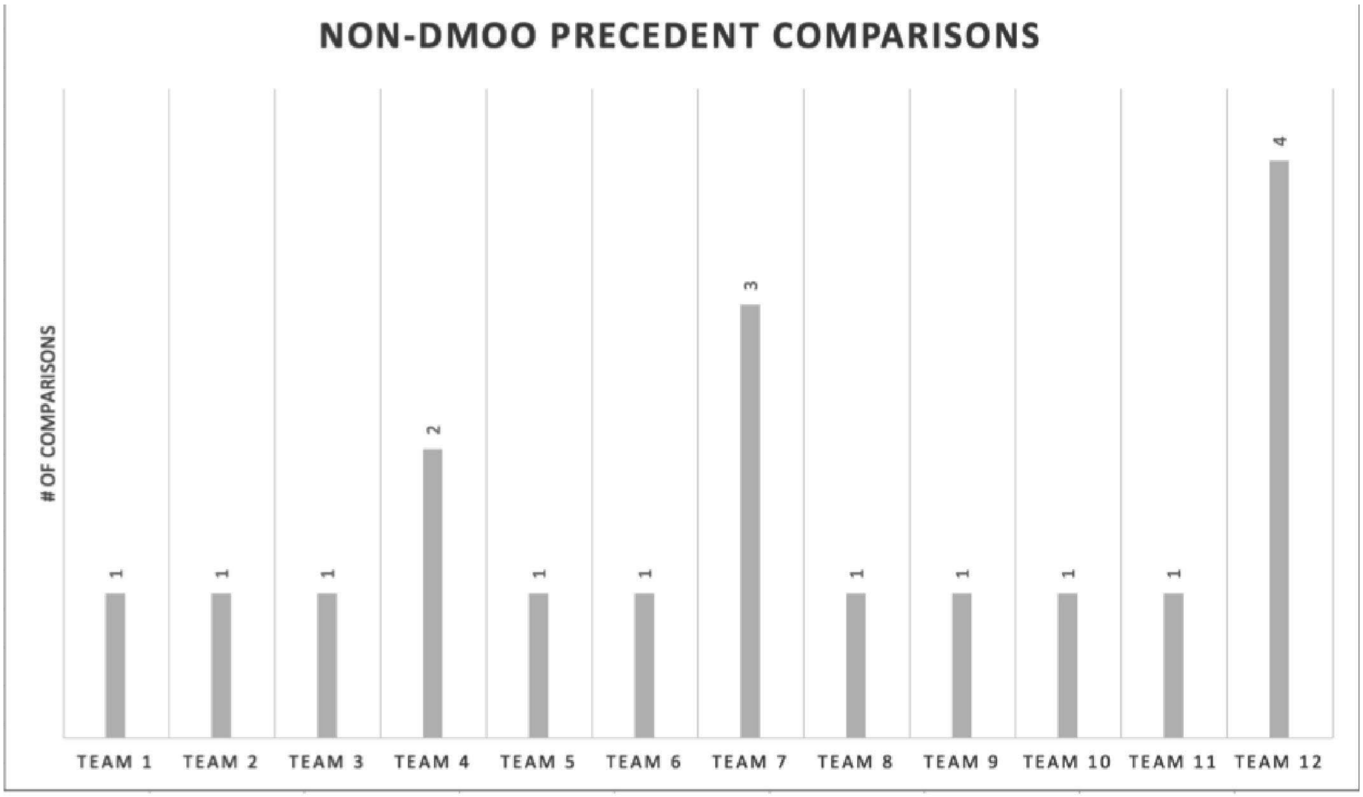
In order to assess the validity of the first hypothesis, the work from each studio was analyzed for evidence of comparative thinking and design exploration. A student work example from the DMOO-based studio can be seen in Figure 1. This was done by looking through the final work of both studios for the analysis and schematic phases of the term and tallying instances where comparisons between two or more precedent projects was evidenced through diagrams, text, or drawings. The results of this analysis can be seen in Figure 4. These results show that on average there was evidence of around 43 instances of comparative thinking per team for the DMOO-based studio. In contrast, the other studio averaged only 1.5 comparisons per team. Students in this group were encouraged to think comparatively but were left to develop their own methods of comparison. This resulted most often in a comparison with only one other project.

To assess the validity of the second hypothesis, the midterm and final work of both studios was examined for evidence of the exploration of trade-offs between project objectives. Specifically, instances where drawings, renderings, or diagrams were used to show a comparison between two or more design solutions was tallied. Samples of student work for the final phase of the term can be seen in Figure 2 and 3. Further, the results for this analysis can be seen in Figure 5. The data shows that the DMOO-based studio outperformed its competitor by more than double during the midterm and by seven times in the final review.

These preliminary results, although encouraging, need further verification through the development of improved metrics to compare studio work and additional studies with other studio sections. The development of metrics to measure evidence of comparative or explorative design thinking poses the most challenges. The approach used in this research could have benefited from a more developed schema for what constituted evidence of comparative thinking and exploration of trade-offs. The data collection was also too narrow, because it focused on the final products from each phase and ignored the daily development of each project.

One significant challenge in integrating DMOO concepts and tools into a comprehensive studio context is training students with the necessary technical know-how to use advanced computer modelling, performance analysis, and optimization processes within the quick pace of the studio. A further challenge is the computer resources needed to run multi-objective optimization processes in a timely manner. For example, running daylighting analysis and structural analysis simultaneously on a hundred different designs can take several hours on a standard laptop. This lag time can create a significant roadblock to exploring design alternatives.

An important takeaway from the research, from the point of view of the instructor, was that the DMOO concepts alone provided a significant impact on comparative thinking and gave the students a shared vocabulary to discuss objectives and the design process itself (i.e., meta-cognitive thinking) during desk critiques and with each another. This suggests that it might be possible to sidestep the use of advanced computational tools altogether and improve learning outcomes from the concepts alone. Another important realization was



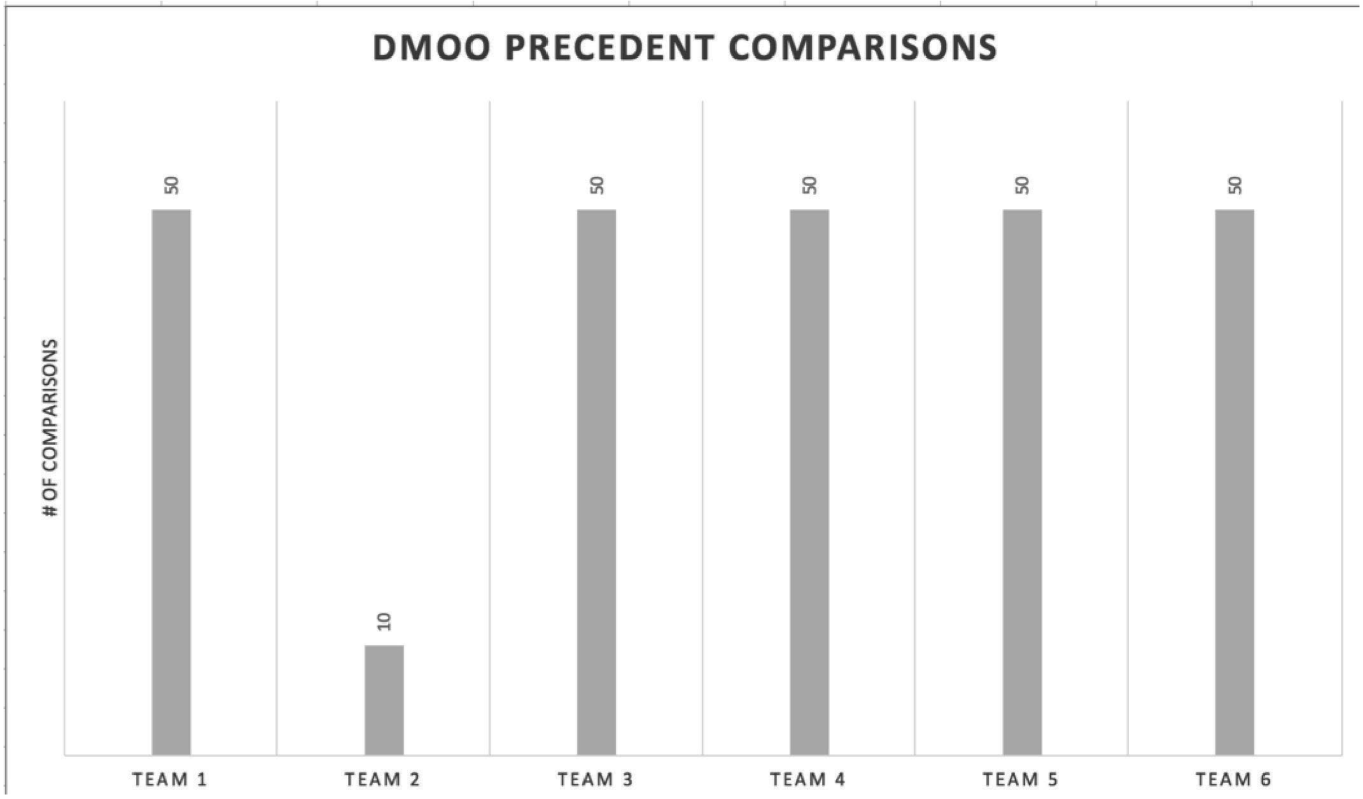


Figure 4: (Top) Shows the assessment results from the analytic and schematic phases of the term for the comprehensive studio not using DMOO concepts or tools. (Bottom) Shows the results for the DMOO-based studio, David Newton Univeristy of Nebraska-Lincoln College of Architetcure.

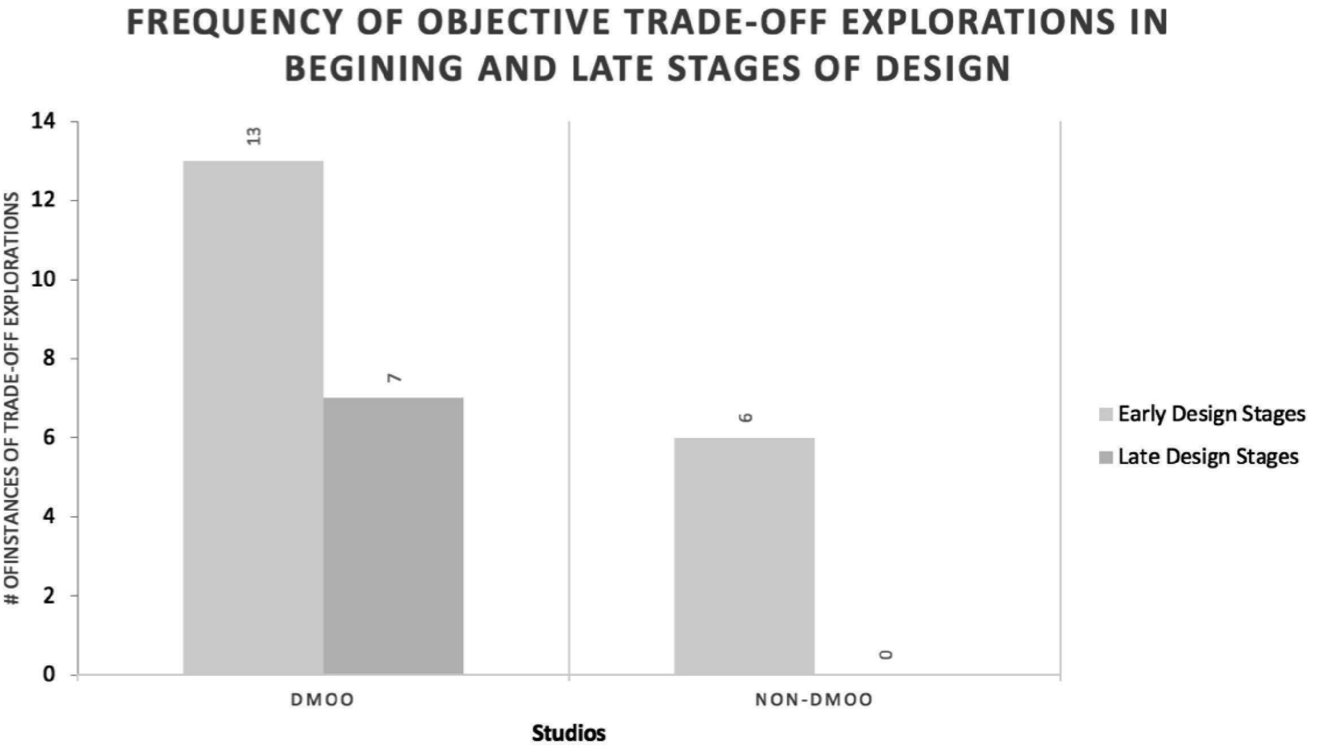


Figure 5: Shows the analysis results for the intermediate and synthesis stages of design, David Newton Univeristy of Nebraska-Lincoln College of Architetcure.

that emphasizing the importance of qualitative objectives throughout the term helped to keep projects from falling into the realm of purely rational, linear, and quantitative thinking. Providing students with custom digital tools that allowed qualitative evaluations to be integrated with quantitative ones was key to insuring that quantitative thinking did not dominate the design process.

CONCLUSION AND FUTURE WORK

The aim of this research was to explore the effectiveness of integrating concepts and tools from the field of dynamic multi-objective optimization to help educators effectively teach students to manage dynamic multi-objective problems within a comprehensive studio context. These techniques were assessed for their ability to promote comparative thinking and the exploration of trade-offs between design solutions. A comparative study between two comprehensive studios - one using DMOO concepts and tools and the other not using them – revealed that the DMOO-based approach aided in comparative thinking and exploration of tradeoffs throughout the beginning and latter phases of the term.

Future work will need to verify these results by conducting further studies on more studio sections and also develop improved metrics to measure the effectiveness of DMOO integration. This work will also need to evaluate whether DMOO concepts, DMOO tools, or both simultaneously applied in a studio context, has the most impact on positive learning outcomes. Developing faster and more user friendly DMOO tools is also a pressing problem for future investigation.

The development of concepts and methods that can help students effectively balance multiple objectives in the architectural design process is a pressing need as the profession is asked to engage problems of greater and greater complexity in response to environmental, social, and economic crisis. This research represents a step in this direction, but as noted, there are many challenges ahead, and much work still to be done to prepare students with the tools they will need to tackle these wicked problems.

ENDNOTES

1. Krathwohl, David R. 2002. “A revision of Bloom’s taxonomy: An overview.” *Theory into Practice* 41 (4):212-218.
2. Azzouz, Radhia, Slim Bechikh, and Lamjed Ben Said. 2017. “Dynamic multi-objective optimization using evolutionary algorithms: a survey.” In *Recent Advances in Evolutionary Multi-objective Optimization*, 31-70. Springer.
3. Bloom, Benjamin Samuel, Committee of College, and University Examiners. 1964. *Taxonomy of Educational Objectives*. Vol. 2: Longmans, Green New York.
4. Fisher, Matthew W, Thomas W Leslie, and Gregory S. Palermo. 2009. “Post-Mortem: Eight Years of Comprehensive Design Experiments and What Comes Next.”
5. Bovill, Carl, Amy E. Gardner, and Gregory Wiedemann. 1997. “Intention, Form, and Execution: A Comprehensive Studio Curriculum.” *Journal of Architectural Education* 51 (2):84-91.
6. Benjamin, David. 2012. “Beyond Efficiency.” *Digital Workflows in Architecture*:14-25.
7. Coello, Carlos A Coello, David A Van Veldhuizen, and Gary B Lamont. 2002. *Evolutionary Algorithms for Solving Multi-objective Problems*. Vol. 242: Springer.
8. Ralph, Paul. 2010. “Comparing two software design process theories.” *International Conference on Design Science Research in Information Systems*.