A Case Study in Teaching Construction of Building Design Spaces

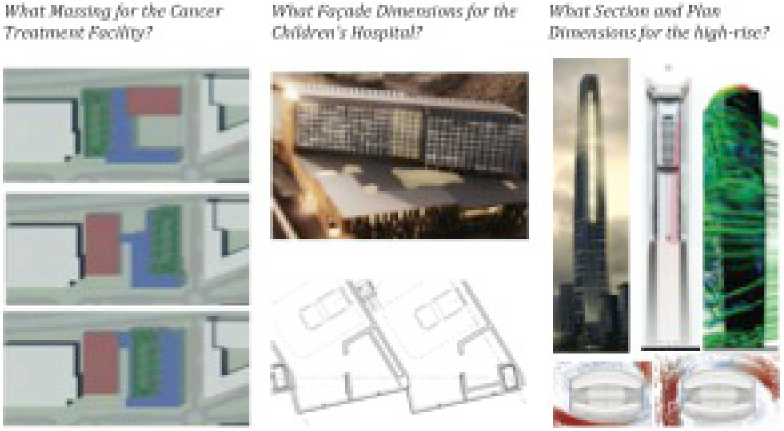
Mahsa Nicknam[1], Marcelo Bernal[2], John Haymaker[3]
[1]Georgia Institute of Technology
[1]mnicknam@gatech.edu, [2]marcelo.bernal@gatech.edu, [3]john.haymaker@coa.gatech.edu

Abstract. *Until recently, design teams were constrained by tools and schedule to only be able to generate a few alternatives, and analyze these from just a few perspectives. The rapid emergence of performance-based design, analysis, and optimization tools gives design teams the ability to construct and analyze far larger design spaces more quickly. This creates new opportunities and challenges in the ways we teach and design. Students and professionals now need to learn to formulate and execute design spaces in efficient and effective ways. This paper describes curriculum that was taught in a course "8803 Multidisciplinary Analysis and Optimization" taught by the authors at Schools of Architecture and Building Construction at Georgia Tech in spring 2013. We approach design as a multidisciplinary design space formulation and search process that seeks maximum value. To explore design spaces, student designers need to execute several iterative processes of problem formulation, generate alternative, analyze them, visualize trade space, and address decision-making. The paper first describes students design space exploration experiences, and concludes with our observations of the current challenges and opportunities.*
Keywords. *Design space exploration; teaching; multidisciplinary; optimization; analysis.*

INTRODUCTION

In the current practice, the process of designing buildings is rapidly becoming more collaborative and integrated through the use of Computer-Aided Design and Engineering (CAD/CAE) technologies. However the use of these technologies in the early stage of design is limited due to the time required to formulate and complete design cycles. A new class of technology, involving automated multidisciplinary analysis and design space exploration is increasing by the order of magnitude of the number of alternatives that a design team can generate and analyze (Haymaker, 2011). This creates new challenges in the ways we educate tomorrow's designers and managers in schools of architectural, engineering, and construction. Students and industry professionals must learn to work together to formulate and construct design spaces in order and understand performance trends and trade-offs to solve issues central to practice.

Geordia Tech's curriculum demonstrates an important issue in digital design education. Georgia Tech's Schools of Architecture, Civil Engineering, and Construction, offer a variety of courses in design studio, design theory and process, computer-aided design (CAD), building information modeling, parametric design, energy analysis, structural analysis, cost analysis, decision analysis. However our Institute lacks integrated courses that help students un-



What Massing for the Cancer Treatment Facility?

What Façade Dimensions for the Children's Hospital?

What Section and Plan Dimensions for the high-rise?

Figure 1
Design professionals gave design challenges that students formalized into multidisciplinary building design space exploration processes.

derstand how to work together to systematically formulate, execute, and understand multidisciplinary building design spaces.

Several organizations and associations such as the American Institute of Architecture (AIA) Technology in Architectural Practice [1], the National Council of Architectural Registration Boards (NCARB) award for the integration of practice and education [2], the American Society of Civil Engineers (ASCE) excellence in civil engineering education teaching workshop series [3] and the Associated General Contractors of America (AGC) BIM Education program [4] support the efforts of academic programs to create and implement effective new curriculum that bring together students from multiple disciplines, industry professionals, and advanced design technologies to learn to address practical design challenges. To address this need, some curriculums are emerging in architectural schools such as Columbia University, Harvard University (Kara and Georgoulias, 2013) and University of Southern California and Stanford University (Gerber and Flager, 2011).

This paper describes new curriculum under development in Georgia Tech's Schools of Architecture and Building Construction that engages architecture, engineering, construction, and computer science students and industry professionals in collaborative multidisciplinary design space construction and exploration processes. The curriculum engages students in a team-based approach to problem formulation alternative generation, alternative analysis, design space exploration and optimization, and trade-space visualization and decision-making.

METHODOLOGY

The methodology in this course consists of five phases that are described in more detail below: Problem formulation, alternative generation, alternative analysis, design space exploration and optimization, and trade space visualization and decision making. The students utilize these phases to construct design spaces for the professional challenges in the semester long group project.

Problem formulation

In this first phase, we engaged professional designers to present challenges from their own practice that they felt could have benefitted from more exploration if they were given more time and better tools. Figure 1 and the following text describe the challenges presented by the design teams. The benefits of engaging design teams in this way were twofold. It helped students confront real world design challenges without needing to spend too much time gathering information about them. It also gave professional designers access to new design space

		Massing 1		Massing 2		Massing 3	
Goals							
First Cost Minimize $	Assignment	2		3		1	
		-5.00	44.00	-2.00	41.00	0.00	0.00
Parking proximity Walking distance from garage to check-in Linear ft	Assignment	20		15		40	
		-15.00	52.00	-25.00	74.00	0.00	Importance
Daylighting Maximize	Assignment	300		100		200	
		200.00	100.00	0.00	Importance	100.00	57.00
Constraints							
Site Boundaries		no		no		yes	
Connectivity There must be at least one path that connects all 4 program elements.		no		yes		yes	

Figure 2
A preliminary Wecision model developed by a group of students to define the project goals and objectives, including the units and criteria for measurement.

exploration tools and ways of thinking about their challenges.

- Case 1: Cancer treatment center
  A new cancer treatment process provides an opportunity to develop a new design methodology. The professional design team found the massing phase challenging because of the very large equipment involved with the new treatment process. Several programming and crane access issues constrained the potential solutions somewhat, but the design team was interested in more systematically exploring the tradeoffs of different building massing in terms of their visibility from highway, energy consumption, daylight factor, sensitivity to adjacent neighbors, and connection to adjacent green space.
- Case 2: Children's hospital
  The hospital, located in the Middle East, was conceived to emphasize western healthcare ideas such as patient comfort, equality, and external views. The students were asked to evaluate the current proposal and provide insight into how the geometry and solar shading could be modified to improve solar and day lighting performance, thermal gain, and patient views. The design team focused on the trade-off between designing for solar radiation and day lighting factor; however, other factors contributed to the final evaluation including total square footage and aesthetic attributes.
- Case 3: Mixed-use tower
  The tower in china was conceived with the vision of a "the Breathing Tower" that uses green energy techniques, including passive lighting and ventilation. The student's goal in analyzing the design for the tower involves optimizing the quality and comfort levels of the occupants. They look at performance criteria such as daylighting, passive ventilation, structural stability and attempt to preserve the grace and symmetries of the original design aesthetic, while keeping costs at a minimum.

Students first used Wecision's Choosing by Advantages model (Abrams et al., 2013) to model the organizations involved, the goals and constraints they needed to consider, the range of alternatives they wanted to explore, and the preferences on outcomes (Figure 2). They also enter initial estimates of what they believe the outcomes are likely to be based on intuition.

Students then developed Meta Model (MM) in System Modeling Language (SysML) to describe the structural and behavioral aspects (Reichwein and Paredis, 2011) of their design challenges. The MM is an abstract model of the data of the actual geometric model. It captures the structural aspects of the model such as domain specific semantics, attributes and relationships among parts through block or class definitions. From these definitions multiple

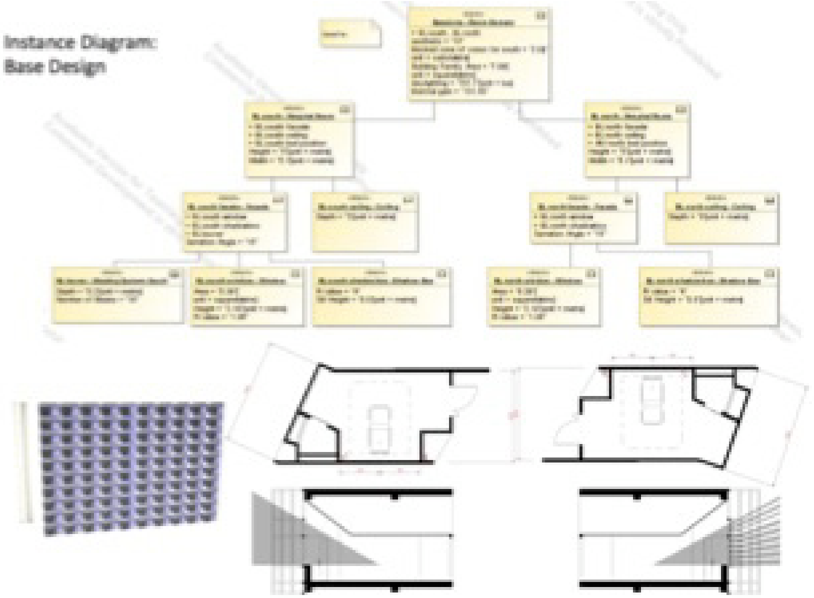


Figure 3
A SysML block instance diagram describes the data blocks and relationship used to generate alternatives for the room dimensions in a children's hospital.

Instance Models (IM) of design alternatives can be generated by changing the parameters. The behavioral aspects of the challenges are captured though activity diagrams that represent the sequence of actions to be performed in order to generate, analyze and select a design alternative that describe the generative and analytical systems in their design spaces.

They used SysML Block and Instance diagrams (Figure 3) to describe the alternative's components and relationships that will be important in the analysis, and SysML Activity diagrams (Figure 4) to describe the analysis processes they wish to perform on these models. In these diagrams they explore and communicate the detailed input parameters for analysis tools, as well as the output parameters of the analysis, and whether they are to be minimized or maximized.

Alternative generation

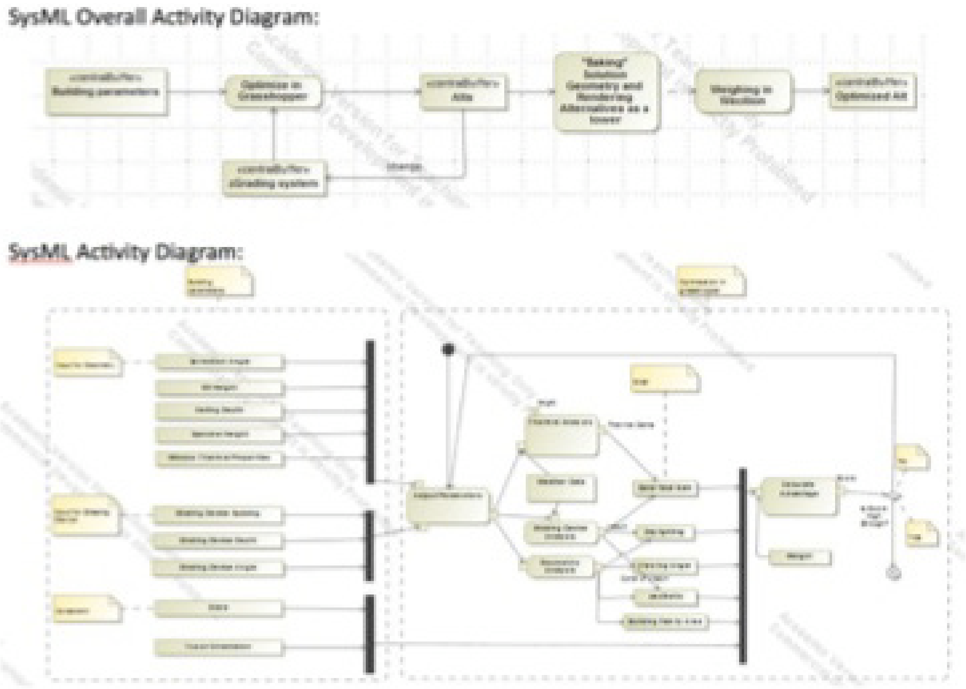
In the second phase, to represent the design alternatives geometrically, students then made associative parametric design models that are driven by the design variables specified in the MM. In some cases custom scripting is also included to enable topological transformations that are difficult to achieve using parametric logic alone. The students tested the parametric model and generated different alternatives by modifying the variable values (Figure 5).

Students used commercial parametric design tools such as Rhino/Grasshopper, Revit, and Digital Project to generate the parametric model. Output of these tools would be a set of architectural forms in which their geometry and properties are easily modified by changing the parameters.

Alternative analysis

In this third phase, the integration of their parametric model with analysis tools allows students to analyze and evaluate the performances of different alternatives in a design space and compare them based on their performance metrics. To this end, students need to integrate CAD and CAE tools in a way that the data flows between the tools in an au-

Figure 4
A SysML activity diagram describes the high-level integration and optimization process, as well as detailed processes for each goal analysis.



tomated fashion to reduce design cycle latency. The simulation and analysis tools were selected based on the performance objectives, inputs, and familiarity from among available commercial software such as EnergyPlus, Green Building Studio, eQuest, DIVA, and IES VE for energy analysis, SAP2000, GSA Oasys, STAAD, Karamba, and ETABS for structural analysis, Radiance, Ecotect, DIVA, and Daysim for Daylighting simulation. Figure 6 shows student daylight analyses comparing the original design team's design with one of the alternative's generated from their parametric model.

Students were introduced to experimental workflows such as ThermalOpt (Welle et al., 2011) and BiOpt (Flager et al., 2013) that build in data transformations and strategies that help prepare models for fully automated simulations and contain domain specific knowledge necessary for more efficient optimization. Students were also encouraged to develop their own workflows, for example students in the high-rise group developed a customized workflow to minimize the total structural weight. The developed workflow is able to calculate the wind pressure on the façade based on ASCE 7-10, calculate tip deflection on the top of the building, and modify the columns' cross section until achieving the most efficient column sections (Figure 7). Students in the Cancer Treatment Facility developed several geometric scripts to analyze designs automatically for visibility from the highway, sensitivities to adjacent buildings, and access to open space (Figure 8).

Design space exploration and optimization

Due to the potential size and complexity of potential building design spaces, analyzing and testing for every parametric variation can be impossible. Additionally, many of the design objectives are hard to formalize, and so it is often more fruitful to en-

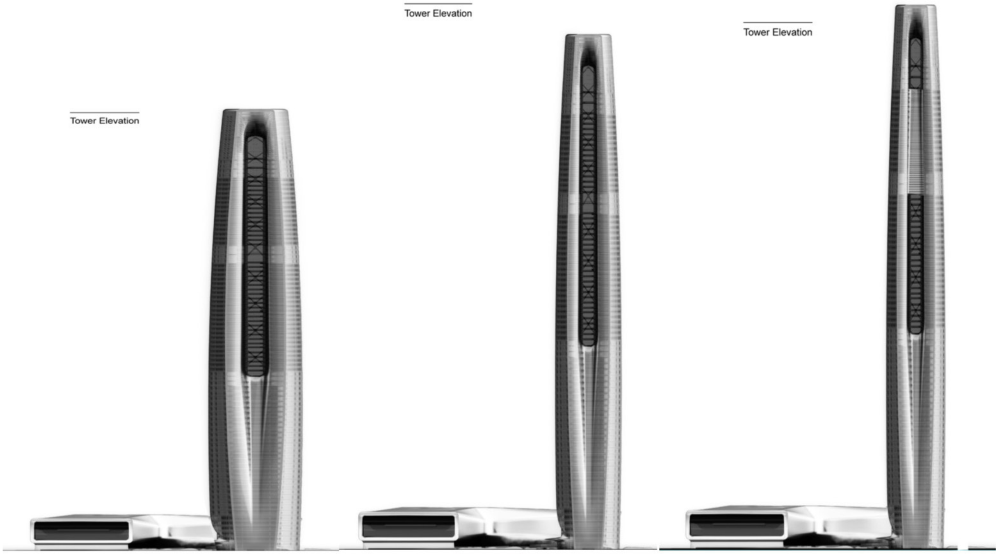


Figure 5
A range of tower designs generated from the student's parametric model.

able the designer and tool to work iteratively visualizing and generating aspects of the design space. Hence, in this fourth phase, the students learn to apply computational techniques such as design of experiments and use optimization and sensitivity algorithms to systematically guide the generation of alternatives. Students used commercial design exploration and optimization tools such as Octopus and Galapagos by Grasshopper, and ModelCenter.

Trade space visualization and decision making

The visualization of performance enables students to engage in computer-based exploration and visualize tradeoffs. In this final phase, the students learn how to use Pareto frontiers, performance trends, and sensitivity analyses in order to make informed decisions in guiding the optimization process. They used the built in tools provided by ModelCenter and Wecision. Figure 10 shows two examples of student approaches to exploring the multidisciplinary design spaces.

At the end of the class, students return to Wecision to identify several prominent alternatives in the design spaces they explored, and to report on the multidisciplinary performance and weigh the importance of the advantages of each alternative. At the end each alternative is evaluated based on its total advantages.

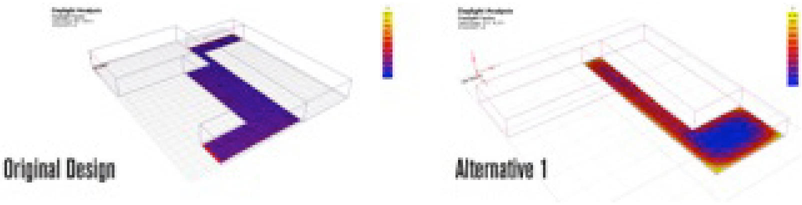


Figure 6
Students analyse alternative designs for structural performance, daylight, energy, cost and more.

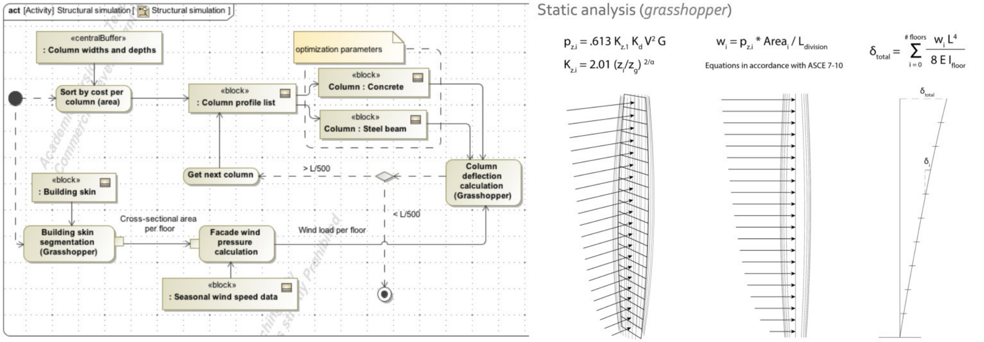


Figure 7
Students developed a custom process for analysing high-rise structural performance.

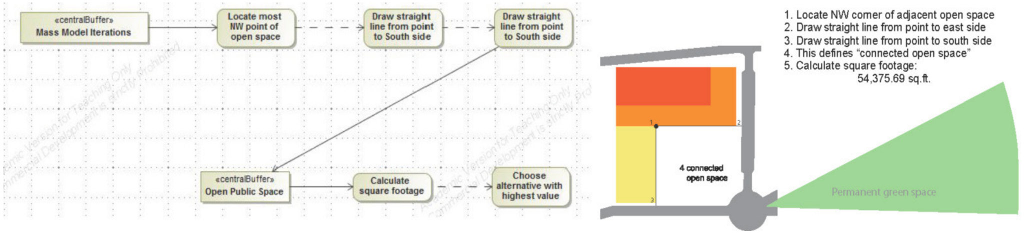


Figure 8
Students developed a custom process for analysing the projects relationship to adjacent green spaces.

CONCLUSION

This paper described an exploratory class in which students from multiple disciplines worked with industry mentors, and learned how to formulate design space exploration problems, parametrically define alternatives, integrate CAD and CAE tools to rapidly analyze alternatives, explore design spaces and trade-offs, and make and communicate decisions. Students learned to build and integrate models to iteratively search through a space of designs and negotiate to find the best and most sustainable designs. We discuss several challenges in teaching the class, and discuss ongoing work to overcome them.

Improve team formation

Students appreciated the multidisciplinary teams in which students have individual domain knowledge

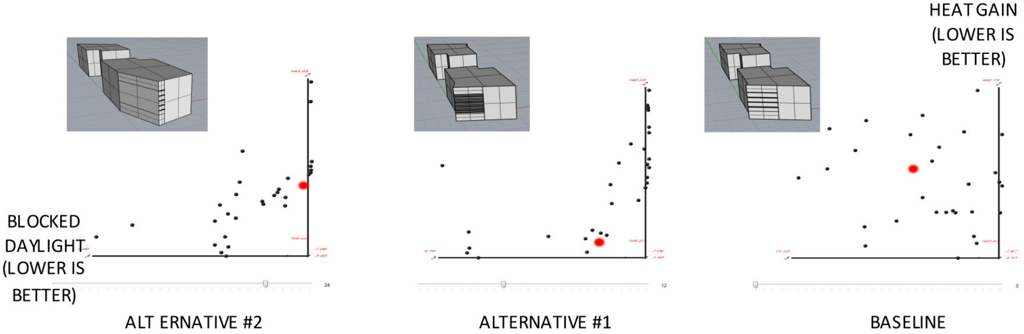


Figure 9
Students developed an optimization process, each team found designs that outperformed the industry chosen design, for the objectives analysed.

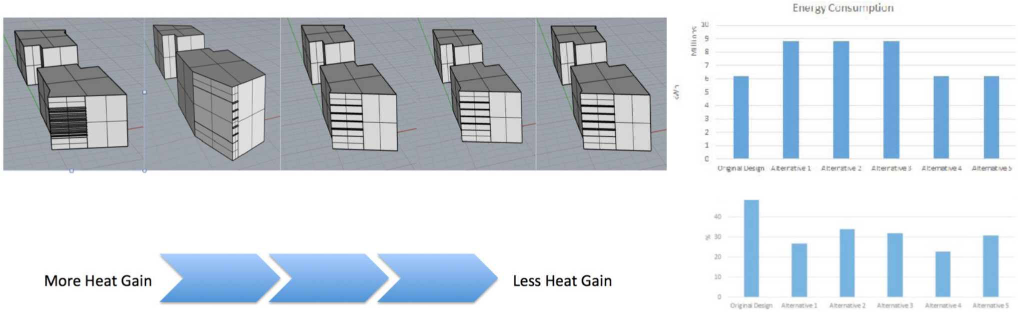


Figure 10
Students experienced with different methods of exploring and communicating design space exploration information.

and skills to contribute. Each teams requires an appropriate mixture and level of domain knowledge in the programs as well as general computer scripting. In future versions of the class we plan simple tutorial exercises early in the class, and delay choosing teams a few weeks until we have developed a better understanding of student skills and interest.

Separate learning of concepts from applying concepts

We taught students the concepts and tools directly in the context of the industry problems. This was

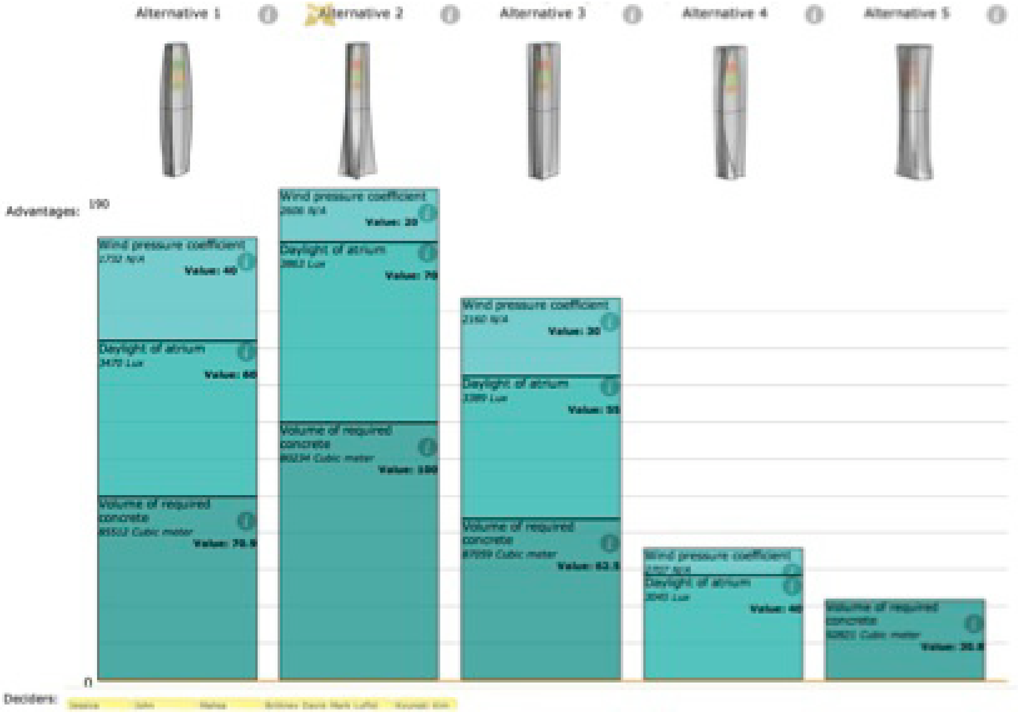


Figure 11
A final Wecision model that communicates the multidisciplinary advantages of a selection of alternatives in the design space.

difficult because of the large number of concepts students needed to absorb at one time, and the fact that there was no ground truth to determine if students were applying the concepts "correctly." We are creating a series of short tutorials for a simple example that teach students the fundamental concepts of design space exploration. Students will begin to learn about the industry problems early in the class, but will not begin to apply these concepts until they have completed the introductory tutorials.

Improve integration of tools

While several workflows are emerging, some workflows are very complex, and require better documentation for students to be able to apply them. Others are overly simple, and students quickly run into objectives they cannot analyze, alternatives they cannot generate, and spaces they cannot explore because of limitations of one workflow or another. Another important area to improve integration is between meta modeling tools like Wecision and MagicDraw with CAD and analysis tools. Despite the limitations in terms of integration, the meta, parametric, analysis and decision models co-evolve during the design exploration process. Not all the knowledge integration occurs at the tool level. For example, while the students implement the parametric model based on the meta model they also evolve the meta model by adding, deleting or editing attributes required by the actual parametric geometric model. Therefore, the issue of integration it is not only related to implementation of the interoperability among tools, it is also related to the development of co-evolution (Dorst and Cross, 2001) mechanisms and methods, since the different models are abstractions that represent only aspects of the design challenge interacting with other aspects.

Improve ability to systematically frame, define and formulate the challenge

This process is beneficial to the designer when there is a schematic idea, with strong initial intuitions for effective performance. For time efficiency a well thought out schematic will cut down on the parametric ranges, allowing quicker model building and computational processing time. There are very few prior cases to look to understand best practices for how designers best frame design exploration problems, how to choose the right objectives, and parameterization of the problem. Through better metrics for describing challenges, and more case studies that illustrate good and bad problem formulations, we would be able to improve the efficiency and effectiveness with which students formulate design problems.

Improve the ability adopt and adapt the right strategy to the right challenge.

Given a clearly understood set of objectives, students have difficulty identifying and applying the right strategy. We teach students to explore the sensitivity of each input parameter and the influence of weighting the different goals in each challenge guides to the next set of decisions. However, we need better documentation of the strategies that are available, and better assistance in finding the right strategy for the right challenge.

Improve the ability to assess and compare explorations.

Ultimately as designers we want to choose the strategies that enable the best exploration, and as instructors we want to be able to evaluate and guide students towards ever better exploration, Research is ongoing to define the metrics for assessing the efficiency and effectiveness of design exploration (Clevenger et al., 2011; Senescu and Haymaker, 2013). Development and integration of these metrics into design systems will enable students assess and compare their own explorations to those of other students and professionals on similar challenges.

ACKNOWLEDGEMENTS

We would like to thank the students of the class: Eliah Cappi, Jonathan Cook, Kyungki Kim, Mark Luffel, Jessica Marquardt, David Moore, Jaesuk Park, Natalia Quintanilla, Keyan Rahimzadeh, Philip Richardson, Daniel Snider, Di Sui, Jun Wang and Tianyao Zhang.

We also want to thank the industry mentors including Keith Besserud at Skidmore Owings & Merill (SOM) and Diana Davis, Bruce McEvoy, Mark Tagawa, Dawn Mixon Bennet, and David Green and their colleagues at Perkins+Will who helped formulate and critique the design spaces. We thank the Digital Building Laboratory and the Georgia Tech Schools of Architecture and Building Construction for their support.

REFERENCES

Abraham, K, Lepech, M, and Haymaker, J 2013, 'Selection and Application of Decision Methods On a Sustainable Corporate Campus Project', *Proceedings of the 21st Annual Conference of the International Group for Lean Construction, IGLC*, Fortaleza, Brazil.

Chok, K, and Donofrio, M 2010, 'Abstractions for information based design, *International Journal of Architectural Computing,* 08(03), pp. 233-256.

Clevenger, C and Haymaker, J 2011, 'Metrics to Assess Design Guidance', *Design Studies*, 32(5), 431-456.

Dorst, K and Cross, N 2001, 'Creativity in the design process: co-evolution of problem–solution', *Design Studies* 22(5), 425-437.

Flager, F, Welle, B, Bansal, P, Soremekun, G and Haymaker, J 2009, 'Process Integration and Design Optimization of a Classroom Building', *Journal of Information Technology in Construction (ITcon),* Vol.14, pp. 595-612.

Flager, F, Adya, A, Fischer, M and Haymaker, J 2011, 'BIOPT: a Method for Shape and Member Sizing Optimization of Steel Frame Structures', *CIFE Technical Report,* No. 202.

Gerber, D and Flager, F 2011 'Teaching Design Optioneering: A Method for Multidisciplinary Design Optimization', *Proceedings of the ASCE Conference: Computing in Civil Engineering*, Miami, FL, USA, pp. 883-890.

Geyer, P 2012, 'Systems modelling for sustainable building design', *Advanced Engineering Informatics,* 26(04), pp. 656-668.

Haymaker, J 2011, 'Expanding Design Spaces', *Academy of Engineering's 2011 US Frontiers of Engineering Symposium - Engineering Sustainable Buildings*, Google Headquarters, Mountain View, CA, September 19 – 21.

Kara, H and Georgoulias, A (ed) 2013, *Interdisciplinary Design: New Lessons from Architecture and Engineering*, Actar, New York, USA.

Oxman, R 2008, 'Digital Design as a challenge for design pedagogy: theory, knowledge, models and medium', *Design Studies, 9(2), pp. 99-120.*

Oxman, R 2008, 'Performance-based Design: Current Practices and Research Issues', *International Journal of Architectural Computing,* 06(01), pp. 1-17.

Oxman, R 2009, 'Performative Design: A Performance-model of digital architectural design', *Environment and Planning B: Planning and Design*, 36(6) pp. 1026-1037.

Reffat, R 2007, 'Revitalizing architectural design studio teaching using ICT: Reflections on practical implementations', *International Journal of Education and Development using Information and Communication Technology (IJEDICT),* 03(01), pp. 39-53.

Reichwein, A and Paredis, C 2011, 'Overview of Architecture Frameworks and Modeling Languages for Model-Based Systems Engineering', *Proceeding of ASME 2011 International Design Engineering Technical Conference & Computers and Information in Engineering Conference,* Washington, DC, USA.

Roudavski, S 2011, 'Selective Jamming: Digital Architectural Design in Foundation Courses', *International Journal of Architectural Computing*, 09(04), pp. 437-462.

Senescu, R, and Haymaker, J 2013, 'Evaluating and Improving the Effectiveness and Efficiency of Design Process Communication', *Advanced Engineering Informatics*, pp. 293-313.

Shea, K, Aish R and Gourtovaia, M 2003, 'Towards Integrated Performance-based Generative Design Tools', *Proceeding of eCAADe 21,* Graz, Austria, pp. 553-560.

Welle, B, Haymaker, J and Rogers, Z 2011, 'ThermalOpt: A Methodology for BIM-Based Passive Thermal Multidisciplinary Design Optimization', *Building Simulation,* 4(4), pp. 293-313.

[1] www.network.aia.org
[2] www.ncarb.org
[3] www.asce.org/exceed
[4] www.agc.org