Abstract
Sustainable building design is a complex social and technical process in which a broad range of stakeholders must construct and clearly communicate high quality design spaces. This paper summarizes recent assessments of current practice that illustrate how far industry today is from achieving this quality and clarity. Efforts to develop a platform of tools to address these limitations are discussed. PIP helps people communicate, share, and understand collaborative design processes; MACDADI helps project teams identify and manage rationale and consensus on decisions; Design Scenarios helps them generate requirements-driven alternative spaces, BIM, model-based analysis, and PIDO which helps to systematically assess these alternatives for their energy, daylight, structural, and cost impacts; and iRooms and the web, which help to communicate all of this information to engage designers, stakeholders, and decision makers in fast, multidisciplinary design and analysis processes. This new platform considerably improves the quality and clarity of AEC design spaces. However additional work would enable significant additional improvement. The paper concludes with a proposal for how AI might further improve the performance of this platform.

Introduction: AEC & Sustainable Design

In the coming decades, project teams will design unprecedented amounts of new and refurbished buildings and infrastructure. Unfortunately the traditional, precedent-based design processes used today are unsustainable -- financially, environmentally, and culturally. As land, energy, water, and materials become increasingly scarce, building technologies more numerous, and the impacts of the built environment more apparent, AEC professionals will need to make profoundly complex and difficult decisions. Designing sustainable architecture for these new and uncertain conditions requires a fundamental shift from precedent-based to performance-based design. Sustainable design is a complex social and technical process in which broad ranges of stakeholders clearly communicate high quality design spaces.

Methods are evolving to help teams improve the quality and clarity of this information. New contractual arrangements and physical and virtual collaboration spaces make it feasible to assemble large, multidisciplinary teams. New rating systems, guidelines, and codes help frame goals. Building information models and parametric modeling help generate options. Automated analysis tools can rapidly analyze energy, structure, schedule, cost, and many other performance goals. These tools and methods promise to help AEC project teams make the transition from precedent—to performance-based design. However, even as government, industry, and academic leaders are calling for professionals to apply these new methods, successful adoption is proving difficult. Project teams lack socio-technical platforms that allow them to relate and communicate all of this new design information effectively and efficiently.

Many research fields are relevant to developing this new platform, including organizational theory and social networking, design theory and methodology, building information and process modeling, model-based analysis, multidisciplinary design optimization, decision science, human-computer interaction, economics, and artificial intelligence. Several efforts have been mounted with limited success to develop these all-encompassing design environments. Numerous research methods involving ethnography, theory building, tool building, data analysis, and action research are needed to understand where existing methods fail, and how to better fit and improve this platform in practice. This paper discusses one effort to develop such a platform for collaborative sustainable building and infrastructure design, and discusses how the field of Artificial Intelligence, might contribute to its enhancement.

The next section describes methods to describe the quality and clarity of design processes. These definitions are then used to illustrate how design spaces are constructed and communicated today. Subsequently the paper summarizes work to construct an integrated platform of tools. Tests in the laboratory and in practice illustrate the ways in which elements of the platform can individually and collectively improve design space quality and clarity considerably over current methods. However, significant opportunity remains to improve the performance of these processes. The paper concludes with
How to describe and measure AEC processes

To improve design processes, it is necessary to carefully describe and measure them. Our research lab has drawn on a diverse set of research fields including process modeling, lean construction, design theory and methodology, decision science, and artificial intelligence define methods and metrics for describing and measuring design processes. Design involves numerous organizations, processes, and products. To understand this complexity, Narratives are a graphical modeling method to formally describe and relate these components of collaborative processes (Haymaker, 2006).

Design involves the construction of design spaces consisting of objective space, alternative space, impact space, and value space. The need arises to measure the quality of the exploration through these spaces afforded by different design strategies, in order to support their selection and improvement. The Design Exploration Assessment Methodology (DEAM) (Clevenger et al, 2010) provides metrics and procedures for measurement and comparison of design processes in terms of the challenge addressed, the strategy implemented, and the exploration executed.

Design is about making decisions, and the transparency of that process—called the “clarity of rationale”—is crucial. The Rationale Clarity Framework (RCF) (Chachere & Haymaker, 2010) helps teams measure how clearly these design spaces and the relationships between them are communicated.

These methods for capturing and measuring the quality and clarity of AEC design processes to enable the assessment of current practice and provide key insights as to how to improve these processes.

Assessments Of Current AEC Practice

My research group has employed ethnographic-action research (Hartmann et al, 2008), process modeling, and survey to understand the performance of projects. We build detailed process models to understand the design and analysis tasks that teams perform. Our studies illustrate how design teams regularly perform narrow searches of small design spaces (Clevenger & Haymaker, 2010a), and how project teams fail to communicate important components of design rationale, including the identity of stakeholders, their objectives, and the analyses required for these objectives (Haymaker et al, 2010).

We use surveys to test our observations. For example, we found that leading high-rise design firms, consisting mainly of architects, spend a great number of hours generating very few options, and analyze them principally in terms of architectural and economic criteria (Gane & Haymaker, 2010). A survey of a leading multidisciplinary engineering firm confirms these observations, and finds that design teams spend over 50 percent of their time on non-value adding information management tasks (Flager & Haymaker, 2007). In summary, we find that underrepresented teams are developing inadequate statements of objectives and analyses, and are relying on potentially invalid precedent knowledge to perform limited and superficial search of poorly defined and communicated design spaces.

A Platform To Improve AEC Processes

To address these limitation my research group has developed and tested a collaborative platform of tools that assist building designers to generate, evaluate, and develop consensus around far larger and better formulated design spaces than achieved in practice today.

Process Integration Platforms (PIP) provide highly visual and interactive tools to help teams share, plan, execute, and manage multidisciplinary performance-based design and analysis processes (Haymaker et al, 2004; Haymaker, 2006; Senescu & Haymaker, 2009). They help to communicate processes within a project team to improve collaboration, between project teams to improve process sharing, and across a firm or industry to promote understanding and to drive innovation and process improvement.

Design generation methodologies help teams create and manage design spaces. Multi Attribute Interaction Design (MAID) helps teams conceptualize and relate valuable parameters and interactions that maximize multidisciplinary value (Ehrich & Haymaker, 2010). Design Scenarios helps multidisciplinary teams transform these initial parameters into parametric geometric design spaces suitable for multidisciplinary analysis (Gane & Haymaker, 2007; Gane & Haymaker, 2010).

Advance analysis methodologies help teams understand the energy, daylight, human comfort, structure, cost, and lifecycle impacts of their designs. Members of my research group have actively contributed to the General Services Administration’s BIM Guide and the Open Geospatial Consortiums AECOO test bed to help test and industrialize energy analysis methods. We focus on how to integrate each analysis into multidisciplinary design processes. Process Integration Design Optimization (PIDO) methods, adapted from aerospace, help generate, analyze, and optimize the first and lifecycle cost over thousands of candidate building designs (Flager et al, 2009a; Flager et
al, 2009b. Filter Mediated Design (Haymaker et al, 2000) develops a strategy for managing the collaborative generation and analysis of multidisciplinary designs, while the Reference-based Optimization Method (RBOM) helps designers flexibly formulate problems for passive thermal design optimization (Welle & Haymaker, 2011).

The ability to represent so much information requires efficient ways to organize and leverage it, to make complex multi-stakeholder decisions. Importance analysis (Clevenger et al, 2008) reveals key parameters on building performance, helping design teams focus their exploration. Multi-Attribute Collaborative Design Analysis and Decision Integration (MACDADI) helps teams integrate objectives, alternatives, analyses, and values to efficiently develop consensus around decisions (Haymaker & Chachere, 2006; Chachere & Haymaker, 2010; Haymaker et al, 2010). Collaborative spaces, like the iRoom at Stanford, and platforms like PIP help teams easily configure the socio-technical infrastructure needed to meet Project Specific challenges.

To help designers select appropriate strategies, the Design Exploration Assessment Methodology (DEAM) is a method to document and compare design processes and the value they are likely to generate for different challenges (Clevenger & Haymaker, 2010c).

We actively test the methods in the classroom, laboratory, and in practice. A stakeholder using MACDADI remarked, “This is a great exercise -- I really enjoyed it. I hope we can circulate (MACDADI) to a wider group – perhaps a subset of students, staff, alumni, and faculty- that we think would give us good feedback.” A Mechanical Engineer using Design Scenarios on a project commented, “Every project should start like this”. Using PIDO, we helped reduce the steel weight of a stadium structure by 20 percent using PIDO, saving the owner several million dollars (Flager at al 2009).

These tools can become most powerful when integrated and applied by a team of knowledgeable professionals. Through applied research, we are investigating how best to synthesize and use these tools. Figure 1 shows a design charrette in the Stanford iRoom where, in one afternoon, we were able to work with a large group of diverse stakeholders to explicitly capture and communicate the project objectives, investigate several hundred alternatives for their energy, structural, daylight, and other implications, document qualitative analyses on a subset of these options, and clearly communicate which alternatives perform best and why. Our contribution is to synthesize a rich and evolving platform of methods, theories, and tools that help project teams construct, communicate and leverage design space information efficiently and effectively to improve the sustainability of the built environment.

Such methods promise to help project teams to improve conceptual design processes. Figure 2 qualitatively summarize our assessment of current practice compared to our still ongoing observation of the impact our emerging platform of tools can have on this process.

Figure 1: An integrated design charrette in the iRoom. From left to right: a parametric Design Scenario model; A PIDO application analyzing for energy and structural performance; a Process Model (2 screens), describing the design process; and MACDADI value tradeoffs helping to develop consensus about the decision.
However many technical and social challenges remain. Research is needed that works iteratively with industry professionals, researchers, and students to develop and test theory and methods that efficiently and effectively improves the multidisciplinary performance of design teams in their exploration of design spaces. Artificial Intelligence is one field that could contribute to the development of these techniques.

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<tr>
<th>Current Practice</th>
<th>Emerging Platform</th>
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<tr>
<td><strong>Objective Space</strong></td>
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<td><strong>Quality = Low:</strong> Contraints and goals are informally collected, connected, and prioritized. Rating systems such as LEED provide non project specific metrics that are generally not well connected to project specific goals.</td>
<td><strong>Quality = Moderate:</strong> Objectives are systematically defined through stakeholder interview and prioritization. However, stakeholders often have difficulty establishing appropriate metrics and actual priorities for their objectives.</td>
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<td><strong>Clarity = Low:</strong> Objectives are vague, disconnected. No apparent value function exists.</td>
<td><strong>Clarity = High:</strong> All stakeholders goals, constraints and priorities are clearly defined. A value function is formed but leaves significant room for interpretation.</td>
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<td><strong>Alternative Space</strong></td>
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<td><strong>Quality = Low:</strong> Project teams often generate as few as three alternatives. These alternatives are generated based on precedent, and with an architectural focus.</td>
<td><strong>Quality = Medium:</strong> Alternative spaces are systematically generated from stakeholder goals. However, the generation of these alternatives is still informed by informal precedent rather than on expert systems.</td>
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<td><strong>Clarity = Medium:</strong> BIM communicates individual design Alternatives well. Some understanding and documentation of how these models impact downstream analyses exists. However the parameters, ranges, and the rationale behind them, is not clear.</td>
<td><strong>Clarity = High:</strong> Rationale for how designers get from objectives to alternatives is communicated. Alternative space parameters and ranges with investigated alternatives within this space are clear.</td>
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<td><strong>Impact Space</strong></td>
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<td><strong>Quality = Low:</strong> Analyses are often disconnected from alternatives. All objectives are not uniformly analyzed for. Assumptions behind analyses are often missing.</td>
<td><strong>Quality = Medium:</strong> Analyses for several objectives including daylight, energy, and structure are fully integrated and automated. Other analyses are handled qualitatively and only for subsets of objective and alternative spaces. Existing AEC domain tools such as energy analyses are imprecise.</td>
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<td><strong>Clarity = Low:</strong> Multidisciplinary analyses for multiple alternatives are rarely collected and presented, and trends, sensitivities, and tradeoffs between parameters are unclear.</td>
<td><strong>Clarity = Medium:</strong> Impact space for quantitative analyses such as energy and structure are clearly presented. Trend and sensitivity graphs give users intuitive feel for the performance of the design space. Impact space for qualitative analyses is less clear.</td>
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<td><strong>Value Space</strong></td>
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<td><strong>Quality = Low:</strong> No quantification of value. Project reports often argue for the value of one alternative, but systematic calculation of the value tradeoffs of alternatives is often not conducted. Environmental impact reports compare only two alternatives.</td>
<td><strong>Quality = Medium:</strong> Due to less than perfect quality of objective and impact spaces, the quality of the value space is necessarily compromised. However the value space is well connected to objective, alternative, and impact spaces.</td>
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<tr>
<td><strong>Clarity = Low:</strong> As value is rarely calculated, it is not well communicated.</td>
<td><strong>Clarity = High:</strong> Graphs communicating the value of each alternative to each stakeholder and why are provided automatically over the internet as each alternatives is analyzed.</td>
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Figure 2: describes metrics typically observed in current practice compared to those achieved using our emerging platform of tools. Significant improvements can be achieved with careful synthesis of socio-technical methods.
An Opportunity for AI

Artificial intelligence tools, including knowledge-based engineering systems (KBEs), fuzzy logic, inductive learning, neural networks and genetic algorithms, are widely applicable to engineering problems (Pham & Pham, 1999). An issue with such computer-aided design systems is how to deal with meta-issues about where to start from, what to do next, and what simplifications and assumptions should be made. In AEC still today, the design strategy and methodologies for design decision-making reside in the expert human designer’s mind, and are never formalized into computer-implemented procedures or encoded and communicated (Stephanopoulos, 1990). Compounding the issue, existing knowledge management solutions fail to properly interface with KBE applications to iteratively transfer essential knowledge for use in the KBE routines (Curran et al., 2010).

The platform described above goes a long way toward addressing these issues. However, to achieve the highest quality in all four design spaces, designers need the platform to act more fluently with them, “as a consultant and control system”, to identify discrepancies in constraint functions, flaws in the problem formulation, characteristics of the problem, and to select or modify appropriate algorithms or parameters to solve the problem. Two types of knowledge bases can be used in the design-optimization process: existing knowledge bases about a class of design problems which is accumulated over a period of time; and a knowledge base that is accumulated for a particular design problem during the iterative process (Arora & Baeziger, 1986).

Figure 3 diagrams a proposed schematic architecture for an industry wide knowledge system that would be able to provide designers guidance at each step of the process, and continuously learn and improve upon the guidance given. The proposal integrates both Project Specific and Industry Wide knowledge bases. The Project Specific knowledge bases follow distinctions we have developed in our platform. For each design decision, as well as for the entire design selection, a Design Team follows a six-step process (with each step consisting of several interdependent sub steps): Decision Makers define Teams (consisting of Decision Makers, Stakeholders, Designers, and Gatekeepers); Stakeholders define Goals (both qualitative and quantitative including metrics and evaluation procedure); Weights (Stakeholders determine Preferences on Goals, Gatekeepers elevate Goals to Constraints, Decision Makers assess Stakeholder Importance); Alternatives, (individual parameters and ranges considered, and each analyzed Alternative); Impacts (of each Alternative on each Goal based on Metrics established by Stakeholders); Value (calculated from Impacts and Weights). While design and decision-making processes are iterative, it is useful to model only directed dependencies to represent the purposeful flow of information, and to keep track of the status of integration. Each step in this process is itself a detailed process with several sub nodes and dependencies that can be communicated, managed, and automated. Case-based planning can play a role in helping avoid expense for planning, while supporting generative process planning when generative planning is important (Humm et al, 1991).
Figure 3 also proposes several Industry Wide KBEs that learn from Project Specific KBEs, and provide feedback to subsequent Project Specific KBEs. While the dependencies in a project specific KBE are likely to flow primarily downstream (i.e., from Teams to Value) the industry wide KBE systems are likely to have information dependencies that run the other way. That is, learning from physical measurements at real buildings and assessments of value from the design process, the KBE will induce the accuracy of Impacts assessed, the likely Alternatives to achieve high Value given a new set of design Objectives, and Teams that are likely to lead to the development of clear, high quality, high Value generating Design Spaces.

References


