MANAGING AND COMMUNICATING PROJECT INFORMATION, DESIGN PROCESSES, AND DECISIONS ON THE STANFORD LIVING LABORATORY PROJECT

Stanford University Living Laboratory Feasibility Study: Fall 2005

SUMMARY: Architecture, Engineering, and Construction (AEC) projects require multidisciplinary solutions. Today AEC professionals have formal methods to help them manage and communicate much of a single discipline’s information; however, they lack formal methodologies to manage and communicate information and processes among multiple disciplines. As a result, AEC projects have difficulty quickly and accurately achieving their many objectives. We are designing and implementing three methodologies to help AEC professionals overcome these difficulties. Using our POP methodology AEC professionals can organize information models in terms of the functions, forms, and behaviors of the design products, organizations and processes. Using our Narrative methodology they can communicate and manage the integration of design processes by defining and controlling the dependencies between information models. Using our Decision Dashboard methodology, they can consider tradeoffs amongst options and document decisions. In this paper we present our application of these methods to case studies from the feasibility study of a “Living Laboratory” currently being designed at Stanford University, discuss how these methodologies might enable AEC professionals to better manage and communicate their multidisciplinary design processes and information, and describe ongoing efforts to develop integrated software prototypes for these methodologies in an interactive workspace.

KEYWORDS: process modeling, organization modeling, product modeling, design theory, relationships, categorization, dependencies, narratives, decisions, integration, sustainable design.

1. INTRODUCTION

Many envision an Architecture, Engineering, and Construction (AEC) industry where Building Information Modeling (BIM) revolutionizes the way AEC professionals design and execute multidisciplinary projects (Khemlani, 2005). BIM today is enabling many AEC professionals to improve their single discipline’s performance. However, the methods for managing and communicating multidisciplinary information and processes remain ad-hoc. AEC professionals tend to optimize for their discipline-specific performance sometimes to the detriment of other disciplines, and late, over-budget, and functionally unsatisfactory projects are common.
Kunz and Rittel (1970) describe design as a social process in which AEC professionals simultaneously formulate statements about problems as well as statements about possible solutions to those problems. Gero (1990) and Schön (1991) describe design as goal-oriented, decision-making, exploration and learning processes in which AEC professionals develop functional requirements, propose potential design forms, analyze the behavior of these forms with respect to their functions, and decide which options most effectively satisfy their requirements. However, even with this theory and BIM, AEC professionals continue to have difficulty organizing the large amounts of information and processes on their projects, controlling the integration of the information as they execute these processes, and evaluating the information to make and document decisions.

At Stanford University’s Center for Integrated Facility Engineering (CIFE), we envision an AEC industry where professionals use Virtual Design and Construction (VDC): the integrated use of multi-disciplinary models to improve performance with respect to explicit functional objectives (Kunz and Fischer 2005). We are designing, implementing, and testing VDC methodologies that help AEC projects better manage and communicate their design processes and information. AEC professionals can use the POP methodology to define and organize the functions, forms, and behaviors (FFB) of their product, organization and process (POP) information (Kunz and Fischer, 2005). They can use the Narrative methodology to define the dependencies between information models to generate competing forms and analyze their behaviors, and control the integration of these processes (Haymaker et al 2004,). They can use the Decision Dashboard (DD) methodology (Kam 2005) to understand multidisciplinary tradeoffs and document decisions. These methods expand the focus of BIM beyond the representation of information towards the representation of the relationships and processes between information.

To motivate our research, we begin this paper by summarizing our observations on AEC projects and describing the difficulties AEC professionals experience in managing and communicating multidisciplinary design information and processes. We then summarize our POP, Narrative, and Decision Dashboard methodologies, and apply these methodologies to the Living Laboratory project at Stanford University. We discuss how these methodologies might help teams more quickly and accurately manage and communicate their processes and information. We conclude by describing our progress towards implementing this methodology in our CIFE iRoom (CIFE Interactive Workspaces Group, 2002). The scientific purpose of this research is to define and test formal methodologies that help teams manage and communicate relationships and processes between multidisciplinary design information. The practical purpose is to help AEC professionals improve their multidisciplinary designs.

2. DESIGN OF A SUSTAINABLE OFFICE BUILDING
This case describes and diagrams part of a design process followed by an architecture firm to determine the costs and benefits of employing an atrium in an office building (Haymaker and Fischer, 2005). The design team knew that employing atria could be an effective way to take advantage of natural light, reduce building energy consumption, improve the quality of the work environment, and thus enhance the productivity of the
occupants. However, atria can also cause uncomfortable glare conditions, have constructability and maintenance issues, and result in a larger building footprint that costs more money and takes longer to build. Therefore the design team evaluated whether or not to employ an atrium on this project. Figure 1 describes and diagrams some of the requirements they defined, some of the design options they proposed, some of the analyses they performed and a summary of the decision they ultimately reached. The lines in the diagram are dashed to indicate that the relationships and processes between this multidisciplinary information was not explicitly managed or communicated using a computer.

![Diagram](image)

**Figure 1:** A portion of the design process an architect and their consultants executed in which they defined functions, proposed forms, analyzed the behavior of these forms, and decided on the appropriate design options based on these analyses. The AEC professionals are represented as grey figures. The text at each professional describes the reasoning he performed to construct his information. The lines indicate observed flow of information, we show them as dashed because these relationships were not formally communicated or managed in the computer. They first defined the site description, regulatory requirements, and client requirements. Based on this functional information, they proposed two design options, a design with an atrium, and a more traditional design with no such daylighting feature. Next, they set about to analyze these designs. They measured the amount of daylight in key work areas and at key times of the day, and analyzed the sufficiency and comfort of the lighting conditions. They used this information to estimate how much artificial lighting would be needed, factoring this amount into an analysis of the amount of energy each design would consume in a year. They then analyzed the time and cost of construction for each design. Using the first cost, and the energy consumption, they estimated the lifecycle cost of each design. They relied on all these analyses to inform their client, and themselves, as to the cost and the benefits of the atrium, enabling the client to make an informed decision.

While the resulting building is recognized as a highly innovative and successful example of sustainable architecture (Leventhal 2001), the design team could have managed and communicated their design processes and information more effectively:

**Manage:** Many organizations of professionals, including owners, architects, specialty engineers, and contractors came together and executed processes to define functions, propose forms, analyze behaviors and make decisions. These processes were interrelated,
for example the regulatory requirements contained information that was need for the atrium design, which contained information that was needed for the energy analysis, which contained information that was needed for the lifecycle cost analysis, which, along with the energy analysis, contained information that was needed for the decision. In this case the design team manually managed these processes and information, leaving only enough time to iterate through these processes and propose and analyze a few options, and they had difficulty doing so accurately. We’ve documented many of the difficulties teams experience when managing information amongst disciplines today. Some examples: between requirements information and design information (Kiviniemi 2004), between design information and analysis information (Kam et al 2003), between design information and fabrication information (Haymaker et al 2004), and between analysis information and decision information (Kam, 2005).

Communicate: The design team described the processes they executed to determine the costs and benefits of the atrium in several documents and e-mails. Many of the required design functions, proposed forms, analyzed behaviors, and resulting decisions were described in these documents. However, there was no diagram such as Figure 1 or other formal description of their design processes, organizations, and products that helped the design team and stakeholders organize and understand all the information and processes used to arrive at this decision. The architect reports a desire for more effective and explicit ways of communicating their design processes and information to the owner, to consultants, and to the design community as a whole in order to help the team construct a more sound sustainable design process on the current project, and enable it to be understood and reused on subsequent projects.

Due to the difficulty in managing and communicating their design processes, the team was not able to fully explore the design space. For example, they did not explore many configurations of atria layout to determine the optimal layout for the energy, daylight, cost, and other criteria identified as important. Better management should lead to more design and analysis iterations and better communication should lead to better team understanding, broader stakeholder input, and repeatability of the processes. Better communication and management should lead to improved designs.

3. BIM SUPPORTED DESIGN OF UNIVERSITY BUILDING
In recent years AEC professionals have had success managing and communicating information by modeling building project information in the computer. Despite promising progress to date in improving single discipline performance, we only see ad-hoc management and communication of multidisciplinary collaboration. We review a recent successful application of BIM, and identify some limitations from that state-of-the-art example.

The HUT-600 auditorium project in Helsinki, Finland is one of the first industry projects to use an array of multidisciplinary BIM tools in the design process (Kam et al 2003). The architects, structural engineers, energy consultants, HVAC designers, and construction managers developed specific BIMs that addressed their discipline’s needs. As a result, these individual BIMs enabled the end-users to better visualize the design;
the architects to improve their efficiency in producing design documents; and the energy and cost consultants to improve performance of their specialty services. However, the design process among the BIMs was ad-hoc and cumbersome in spite of the availability of an interoperable data exchange standard (See Figure 2). The team made decisions by focusing on single proposals, such as HVAC choices (e.g., under floor versus conventional HVAC systems) or architectural features (e.g., skylight versus windows), without a method to methodically look through all the choices and understand their impacts on multiple disciplines (e.g., impacts of architectural features on HVAC choices).

Figure 2: The diagram captures both the design team’s vision for management and communication of information and processes (left) and the difficult reality (right) on an auditorium project in Helsinki, Finland (Kam and Fischer 2002). We find that BIM today does not manage or communicate the processes between multidisciplinary information. As a result, the design team was unable to look systematically through many options, analyze their impacts on multiple disciplines, assess the analyses and clearly document their decisions.

This example illustrates that AEC professionals in many disciplines are benefiting from state-of-the-art BIM-oriented computer applications, such as architectural visualization, daylight analysis, energy simulation, cost estimating, etc. However, we are finding that BIM standards alone do not adequately serve to manage and communicate multidisciplinary processes and information in AEC projects. The team lacked formal methodologies with which to organize the large amount of their function, form, and behavior information, to control the integration of this information as they executed their processes, to convey these information and processes to a large number of design team members and stakeholders, and to clearly document their decisions.

4. EMERGING CIFE METHODOLOGIES TO ADDRESS THESE LIMITATIONS

In our effort to help AEC teams better manage and communicate multidisciplinary design processes, we are investigating three methodologies: POP, Narratives, and the Decision Dashboard.

The POP methodology (Kunz and Fischer 2005) enables multiple disciplines to define the functions, forms, and behaviors of the products, organizations, and processes. As the cases illustrate, AEC professionals today commonly represent the form and often the behavior of the product (e.g., the architectural and structural systems and components of
buildings, and their analyses). However, other aspects, such as the functional requirements of the products, and the functions, forms and behaviors of the organizations and processes needed to design the product, should also be managed and communicated. POP makes these nine interrelated models explicit and encourages the team to design and maintain consistency among them.

The Narrative methodology (Haymaker et al 2004) enables multiple disciplines to manage and communicate dependencies between information models. The cases show that AEC projects formally represent information models, but do not formally represent or manage the design processes used to construct and integrate these models. AEC professionals can use Narratives to graphically and formally define required functions, propose forms, analyze the behaviors of these forms, and manage and communicate the dependencies among these distributed, interdependent, evolving models.

The Decision Dashboard (DD) methodology (Kam 2005) enables multiple disciplines to decide amongst project options and to manage and communicate these decisions. The cases show that AEC projects lack a formal methodology with which to consider multidisciplinary tradeoffs, and make and document decisions. Represented as Decision Breakdown Structures (DBS), decision information in the DD includes decision topics, criteria (functions), competing sets of options and alternatives (aggregations of options), and their relationships. The DD allows design teams to interactively change and evaluate choices as the decision process evolves, making the relevant information explicit and available for stakeholders to manage and communicate their decisions.

5. POP MODELS, NARRATIVES, AND DECISION DASHBOARDS ON THE LIVING LABORATORY

During the fall of 2005, Stanford University hired a design team consisting of architects, structural engineers, mechanical engineers, electrical engineers, civil engineers, construction consultants and cost estimators to perform a feasibility study for a Living Laboratory on Stanford University’s campus. This building is to house approximately 50 students and serve as a test bed for research and education on sustainable building and living. At the time of writing, the design team has held 7 meetings with the owner: itself a large team consisting of project managers, housing representatives, a cost engineer, the University architect, an energy manager, student representatives, and several professors and researchers with interests ranging from innovative water treatment, to renewable energy strategies, to innovative structural solutions, to design process modeling. This paper focuses on two specific design processes in the feasibility study: the choice of room types and the analysis and design of the project’s energy systems.

5.1 Room Type Decision

An important early decision for the design team was to select a room type. This decision had significant impact on the project on many levels as room type influences overall footprint, the amount of material required in the dorm, the location of bathrooms, and has other important social, economical, ecological, research, and education impacts.
To understand the issue, the architect prepared a decision matrix (see Figure 3) in which he listed all the possible room types and evaluated them with regards to six criteria, namely: net square feet per bed, efficiency, social interaction, future flexibility, popularity and fit with the campus plan. The intention of the matrix is to help the team make an informed, quantitative decision with respect to all the main factors that relate to the issue of room type selection. Similar matrices have been used on other design projects (BNIM 2002), and provide a compact yet highly communicative view of complex multidisciplinary information. In this case, the architect first assigned numbers ratings based on his own experience with the idea that they would be changed at the meeting by the group. The diagram facilitated a great deal of discussion about this decision.

However, we observed that, as used, the matrix did not communicate and manage some important information and processes about this decision. First, the sources of information were not clear. The matrix does not cite student surveys that were used for the assessment of social interaction and popularity, nor does it refer to any information to support the analyses carried out for sustainability or efficiency. It would be easier to appreciate the accuracy of this compilation with explicit access to supporting documents.

![Figure 3: This figure shows the room type decision matrix prepared by the lead architect in order to assess various room type alternatives for the project. This matrix explicitly demonstrated the range of alternatives and the criteria that were considered, putting them in a standard tabular format for a clear graphic representation. However, the matrix fails to manage and communicate the implicit information sources, analysis processes, and decisions. Image courtesy EHDD Architects.](image)

As used, the matrix also did not communicate implicit information and processes within the dorm room type decision matrix. For example, whether these rooms should have sinks and baths was a significant discussion topic, yet the matrix does not address this issue. In fact, the existence of a sink/bath in a room would certainly affect the popularity, flexibility and efficiency ratings of the given room type. Similarly, privacy was an important part of the discussion, particularly as the summer usage of the rooms would require privacy for the individual conference visitors. However, the matrix only partially addresses this issue by referring to the popularity and social interaction, but it does not explicitly measure privacy.
As used, the matrix also did not adequately manage and communicate the decision. For example, this matrix was not updated to convey the justification for the ultimate selection of singles and divided doubles. Looking at this matrix one would tend to pick doubles for the Living Laboratory, as it seems to be the highest ranked alternative. However, during the discussion, the university’s housing office said that singles and divided doubles work best with today’s students, and given that a major goal in the project is to be attractive to students, this drove the decision. The expected reduction in environmental performance would presumably be balanced into other design decisions downstream, but the need to do this is not explicitly managed or communicated either. As the room type decision impacts subsequent work, such as building layouts and other design and analysis processes, it seems important that we find ways to better manage and communicate this process.

We have applied three of our methodologies to the room type decision. We show how an AEC team might organize the project information using the POP methodology, propose and analyze room alternatives using the Narrative methodology, and choose the best options using the Decision Dashboard methodology. In this case, we use the actual Living Laboratory project’s room type decision process observed in practice to provide the foundation for our modeling efforts, but suggest ways to improve upon these processes and information in some cases. Following is a description of these individual models.

5.1.1 The Room Type POP Model
We formulated a POP model in which we classify the information needed to make the room type decision. Figures 4A and 4B are views on the model. In Figure 4A we show a hierarchical view that we constructed using a freely available software program called FreeMind (http://freemind.sourceforge.net). In addition to POP-FFB classification, we use generic directed relationships between information items to show other types of relationships. For example, we further classified information in Product-Function in terms of Environment, Economy, and Equity (EEE) (McDonough and Braungardt, 2002). We also constructed decomposition relationships in Product-Function-Economy-Low First Cost, choice relationships in Product-Form-Room Types, and type relationships in Product-Behavior. We show collection relationships in Organization-Form and attributes on the items in the collection. Figure 4A attempts to show many types of relationships between project information. Figure 4B shows a simpler view in a 3x3 matrix.

In building and using these models, we find that POP allows a quick grasp of the many information items that the team can manage and communicate related to the room type decision. In the product category we find a wide range of functional requirements, alternative forms, and measured behaviors of the forms. For example, Figure 4A lists all the Environmental, Ecological and Economical criteria that the room type must fulfill, such as privacy, popularity, social interaction, efficiency. It also contains several strategies to address these goals (different room and restroom types), and ways to measure the relative success of these forms with respect to the functions (such as privacy and efficiency).
Figure 4: The POP model categorizes the project information for the room type decision. The figure represents the POP model in two formats. The matrix (B) shows the Functions, Forms and predicted Behaviors (rows) of the Product, Organization and Process (columns). The tree (A) structure represents the same POP – FFB decomposition at a higher level of detail, and it also represents some intermediate structure, such as Equity-Economy-Environment and relationships such as contains and type. In the matrix view, a small circle indicates that the node has hidden additional detail. Although at first appearing complex, the POP model helps manage and communicate much of the important information related to the room type decision. We find the matrix helpful to summarize the structure of a set of related project issues that is understandable by most stakeholders and the tree helpful to show some additional detail concerning those issues, which is helpful for the stakeholders who have detailed interests in those project issues.
In the organization category, we find the actors who need to be involved in making an informed decision. The function category calls for a multidisciplinary organization; the form category describes a team that includes an energy consultant, a structural consultant, a campus-housing advisor, a project manager, student representatives and architects. The Behavior category contains some measurements as to how well this organization is contributing to a knowledgeable and multidisciplinary design process.

In the process category we find the functions, forms, and behaviors of the processes needed to execute the project. Explicitly stating the need to be on time, low on cost and still rigorous sets the tone for an involved decision making process. The process explicitly defines the need to lay out rooms on the site plan, assess privacy and efficiencies, etc. and can be replicated for a similar project in the future by following the form of the process. The items in the behavior category measure the risks, costs, and other behaviors of the processes.

By guiding us to classify the information as to whether it describes the functions, forms or behaviors of the products, organizations and processes, the POP methodology enabled us to construct a descriptive, balanced overview of the project information.

The next two methodologies, Narratives and Decision Dashboard are designed to help teams manage and communicate specific kinds of relationships between these information models.

5.1.2 The Room Type Assessment Narrative

Figure 5 shows our generic Room Type Assessment Narrative. The diagram illustrates where we modified certain processes and information (in blue and red) where we thought we could enhance the process followed for the Living Laboratory design. The Narrative attempts to describe a process that a design team can execute to make an informed room type choice. Figure 6 shows a Narrative that illustrates the design and analysis of a single room type instance, the Open Doubles type, and represents a portion of the information in the Room Type Assessment Narrative.

As used, the decision matrix did not contain an explicit consideration of the impact of room choice on building layout on the site. In our Room Type Assessment Narrative, the design sequence starts by proposing a product form (choosing a room type) and then laying out the rooms and restrooms on the site. Only then, according to this Narrative, can you evaluate efficiencies and popularities. The Narrative then analyzes the form in regards to material efficiency, privacy and social interaction, among other considerations. Notice that Process-Form items in the POP model appear in the Narratives as the “reasoning.” Further, notice that the design options this Narrative generates can be found in Product-Form and Product-Behavior. Product-Function should be included in this Narrative as source information to both Product-Forms, and Product-Behaviors, but is omitted to improve overall readability of the figure.

As used, the decision matrix also did not help to manage the analyses needed to populate the matrix and keep it integrated as new information was entered and modified. Narratives go beyond a tool to communicate information and dependencies; they can also
help to manage these dependencies. When source information is changed, the integration status of dependent information is flagged, stating that the reasoning must be reconsidered. The Narrative can automatically construct dependent information if automated reasoning is available.

We do not consider the Room Type Assessment Narrative to be optimal - more development and testing are needed. However, considering the ever-increasing economical, ecological and equitable functional requirements, design options, and analyses that designers have to keep in mind, we find Narratives can offer a concise, accurate, flexible, reusable, modifiable means to communicate and manage the dependency information and processes needed for the room type decision. Having completed the Narratives for all the design alternatives, the design team needs to work through this information, then reach and document a decision. In the next section we apply the Decision Dashboard to the room type decision, and discuss how it helps to see the big picture and decide on the most reasonable room type for the Living Laboratory.

Figure 5: The Room Type Assessment Narrative: The diagram shows a composition of reasoning steps and the resulting representations in a process. We use the Narrative to manage and communicate some of the goals proposals and analyses of the room type decision. This Narrative captures an idealized case where a more comprehensive analysis on this room type has been executed than was done with the room type matrix. Beyond articulating all the dependencies between these items, it also cites the information sources (blue elements) and additional design and analyses (red items) that were not explicit in the matrix representation of this process. Arcs represent information passed from one node to another. When implemented in the computer, the arcs in a narrative are implemented as computer datastructures, whose semantics and data types we do not show in this figure to preserve simplicity. Much of the data can also be found in the POP model, shown in Figure 4.
5.1.3 The Room Type Decision Dashboard

As used, the matrix did not effectively manage the decision choices and their interrelationships and communicate the recommendation to the decision makers of the Living Laboratory. For example, it did not distinguish the choices and interrelationships between room types and restroom types. It also only presented one particular state (or snapshot) of information that was not kept up to date with the decision process.

Using the Decision Dashboard ontology and methodology, we built a Decision Breakdown Structure (DBS) to support the management and communication of the room type decision for the Living Laboratory (See Figure 7). The DD categorizes 11 interrelated decision topics (e.g., pre-design planning, design, room layout, restroom). Associated with each decision topic are their corresponding criterion (e.g., minimum efficiency), options (e.g., number of beds per room, open or divided, in-room or remote amenities), and alternatives (e.g., maximum efficiency alternative, most popular alternative). The DD-based model enables an explicit representation of the multidisciplinary decision information and supports a two-way communication between the decision makers and computer about what different competing alternatives entail, and the significance of a decision topic relative to the overall decision context.
Figure 7: A Decision Breakdown Structure of the room type decision in the Decision Dashboard. Decision topics are represented by squares, options by circles, alternatives by inverted triangles, and interrelationships by arrows following the semantics of the AEC Decision Ontology.

Complementing the DBS is a set of DD methods (defined in the AEC Decision Method Model, Kam 2005) that supports information management throughout the decision-making process. These methods integrate, reference, retrieve, and present information in ways that are dynamic and flexible. For instance, the DD methods facilitate the coupling, de-coupling, swapping, and re-coupling of different options to formulate an alternative;
the methods enable DD-based decision topics to reference electronic design documents (e.g., rendering of design options, student survey, etc.) for quick retrieval. The methods can embed attributes (i.e., behaviors such as net square feet, popularity score) in different ontology components for quick, flexible, and pertinent evaluation between choices (i.e., forms) and criteria (i.e., functions). We find the DD contributes to effective communication and management of the decision making process, helping a design team evaluate the multidisciplinary tradeoffs, and to make and document decisions.

5.2 Energy Demand and Supply
The energy design process is still evolving, but so far the energy design team - principally the architect, the mechanical and energy consultant, electrical consultant, and a professor of energy systems - has examined and refined goals, proposed different options to achieve these goals, and analyzed these proposals for the satisfaction of these goals.

The energy goal was first broadly described in the CEE department’s vision statement prepared in the request for proposals as “unparalleled building performance”, including “minimized energy consumption.” When the architect was hired, that goal was further refined toward pursuing a “zero energy” building. However, the mechanical and energy consultant asked for an even more precise definition of that goal, pointing out that a “zero energy” goal could mean, for example, a zero net user of electricity (i.e., the kWh produced in a year equals the amount consumed in that same period); or a zero net buyer of electricity (i.e., the building generates clean energy at peak hours, e.g. from photovoltaics, or a fuel cell, so it can sell power at a higher rate to the grid; then during off-peak hours it can buy energy at a reduced rate from the grid). These goals continue to evolve at the time of writing. The team also performed a detailed model-based energy load analysis to determine the likely schedule and amount of required energy in the building, and checked this for consistency against a back-of-the-envelope estimate performed by the energy professor.

Meanwhile, the design team proposed techniques for generating cleaner and lower-cost energy to meet the demand and still achieve their zero energy goals. Their preliminary energy balance (i.e., demand and supply) considers five sources of onsite energy generation (building orientation for passive solar heating, solar panels, heat pumps, fuel cells and methane gas from a bioreactor). They analyzed these different techniques and presented a set of PowerPoint slides to the owners, which can be found at: http://www.stanford.edu/people/haymaker/gd/Meeting-5_11-30-05_Energy.pdf

The energy design team started this work through phone calls, e-mail exchanges, and coordination meetings, and they soon added a Wiki (http://vestaldesign.com/greendorm) and e-mail lists to communicate the evolution of the design and manage feedback. However, even with the Wiki and matrices it has been difficult to manage and communicate their information and processes amid the cost and time pressures, involvement of multiple stakeholders, evolving performance targets, and innovative and unproven design and technologies. It remains difficult to know which information is most relevant, and how it all fits together. In one case, members of the design team based their work on the wrong property lines for several weeks, which impacted building orientations, and therefore energy demand and passive heating calculations. Generally, stakeholders who are not
intimately involved in the design find it difficult to sift through the project information and reconstruct the process.

In the next sections we describe POP models and Narrative models that we are constructing by observing the energy design process, and discuss how these models might help to better manage and communicate this design process.

5.2.1 The Energy POP Model
Figure 8 shows our Energy POP model that contains much of the information and processes the energy design team is discussing in the energy design process. The model remains a work in progress as the design team continues to define and refine the information that are needed to achieve their energy goals. However, we find the categories make explicit and public the issues of the design being considered, and can help the team visually perceive the consistency and integration of the design. For example, Product-Function contains five high-level goals of the project. Within each of these we identified specific sub-requirements that, if satisfied, would contribute to the higher goal. For example, the chances of attaining unparalleled Environmental Performance would be improved if the building achieved zero-energy or zero-carbon, and potentially operate off the grid. Product-Function also shows that, at least up until this point of the conversation and according to our encoding, the energy design will not have an impact on the Educational Tool goal. In this way the POP model can guide designers towards areas where more consideration is needed.

5.2.2 The Energy Narrative
The current design process is difficult to follow by stakeholders, and it is difficult to update when new assumptions are made or when new considerations are incorporated at either side of the supply-demand balance. For example, in one meeting, a stakeholder wanted to know what the impact of changing the solar array size and orientation would be. The design team was not able to answer that immediately, needing to go back to the office and return with the answer two weeks later. Our Energy Narrative, shown in Figure 9, formalizes the dependencies between information to manage and communicate a design process. There are two constituent Narratives to the Energy Narrative, the supply side and the demand side. The Energy Supply Narrative has been decomposed into five smaller Narratives that refer to the specific alternatives being analyzed to provide energy for the building: Photovoltaic arrays, passive solar heating, solar water heating, fuel cells, and heat recovery from used water. The demand side depicts the two concurrent approaches in use to calculate the estimated demand for energy for the Living Laboratory: a model based approach developed by the mechanical and energy consultant using an energy simulation software and the back-of-the-envelope approach used by the energy professor to calculate an order of magnitude estimate of the demand and its composition.
Figure 8: Energy POP Model. The evolving Energy POP Model shows exploded views of the product and process and a collapsed view of the organization.
5.3.1 POP Models for Individual Design Meetings

During the ongoing design stage of the Living Laboratory project, our research team has used the POP Modeling methodology to collect, organize and evaluate the information generated during each design meeting. The documentation process relies on two techniques: In a first pass a POP model of the meeting is created in real-time; when
possible new items are classified as related to Product, Organization or Process, and to
Form, Function or Behavior, and the source of information is recorded. In a second pass
after the meeting has concluded, this model is revised, corroborated and extended with
the help of traditional meeting notes.

5.3.2 Integrated POP Model of Ongoing Design
In this way a series of POP models are generated that document how the design
progresses from one stakeholder meeting to the next. Taken together, these POP models
cover a large variety of topics – there is of course some overlap between them, since
particular design topics may be discussed in multiple meetings. Therefore, we also
combined the POP models stemming from individual meetings into a single Integrated
POP model. The integration process is at times straightforward aggregation, but requires
more complex considerations when the information being merged covers the same or
similar topics; in these cases the author of the Integrated POP model applies another layer
of refinement and re-organization to ensure a consistent, consolidated overview of the
entire design to-date.

5.3.3 Master POP Model
As the design history and thus the complexity of the Integrated POP model grew, we
found the need for a high-level summary of the design, allowing overall progress to be
evaluated with respect to project goals, and to improve the communicative ability of the
POP model. To meet this requirement, we drew upon the Integrated POP model, as well
as other sources of information, and generated a Master POP model using the following
process: First we distill information from Product-Form and from Product-Function,
establishing up-to-date representations of common functions and high-level design forms
(see Figure 10) and refine these until they serve as an accepted foundation for the entire
project team. We then asked the design team to evaluate these forms with respect to
functions and thus obtained ratings for the current design, which are incorporated into the
Master POP model under Product-Behavior.

The Master POP model serves as a declaration of project goals, a summary of product
options and an evaluation of the current design state. Figure 10.c demonstrates a Master
POP model in which the Behavior evaluation allows two potential design configurations -
Baseline Green and Living Laboratory – to be compared and understood in terms of their
overall ratings and their performance towards individual goals. This POP model has been
circulated to the design team and they concur that this model is a comprehensive
description of the current state of the design. We have not yet performed the same
processes for Organization and Process.

5.3.4 POP Profiles
It is possible to analyze each POP model to calculate, for example, a simple metric
indicating how well the design has been balanced in addressing the Product, Organization
and Process components of the project, and how fully its Function, Form and Behavior
have been considered. In each such “POP Profile” a matrix of columns provides a
visualization of the number of information items present in the corresponding section of
the POP model. These profiles provide a convenient and concise overview of the
project’s focus through various stages of the design process.
Figure 10: Master POP model, showing the Product-Function and Product-Form sections.

Figure 11: Master POP model, showing the Product-Behavior evaluation of two possible design configurations: Baseline Green and Living Laboratory. The ratings were determined by the design team, who evaluated each option with respect to its impact on the desired functions shown in the leaf nodes of Product Function, then added up to determine the ratings at the higher level node. For example, the Baseline Green Design is considered to be more economically sustainable than the Living Laboratory, mainly because the Living Laboratory has a significant negative impact on First Cost. The ratings of the leaf nodes for other Behaviors are not shown for space. The complete POP model can be downloaded from: http://www.stanford.edu/people/haymaker/gd/master-pop
Figure 12 presents a Narrative that describes our process for developing POP models from individual meetings and meeting minutes, as well as for developing our Integrated POP, Master POP, and POP profiles.

6. NEXT STEPS: INTEGRATE OUR METHODOLOGIES IN OUR INTERACTIVE WORKSPACE

The majority of current methods and tools used in AEC practice focus on pieces of information (such as elements of a CAD design, requirements, material orders) and aggregated information (such as CAD drawings, design documents, presentations, material catalogs). POP Modeling, Narratives and the Decision Dashboard individually provide three new ways to work with AEC project information by formalizing important relationships and processes amongst this information. The following table summarizes the types of relationships central to our three approaches and used in test cases discussed above.
### Methodology | Relationship Types
--- | ---
Decision Dashboard | • Aggregation  
• Choice  
• Requirement  
• Impact  
• Process  
See Kam 2005 for the full definition of these relationship types.

Narrative Approach | • Source Perspective - existence of dependency on source information  
• Perspector - nature of the dependency. Relates representation to the reasoning that constructs it.  
• Status – the integration status of a Perspective wrt its source Perspectives  
• Contains; relates a Narrative to the Perspectives it contains  
See Haymaker et al 2004 for a detailed discussion of these relationship types.

POP Modeling | • Product-Organization-Process classification (POP)  
• Function-Form-Behavior classification (FFB)  
See Kunz and Fischer 2005.  
• Other classification (i.e., Economy-Equality-Environment)  
• Generic directed relationship

In many cases, the same information was used in all three methodologies. We believe that even greater potential can be met by creating an interactive environment that integrates all three methodologies into a single system and provides a framework for including additional tools and methods in the future. We are investigating an integrated, shared representation for information items and relationships as a means to assure smooth flow of information throughout these methodologies. In our integrated framework, we envision that information will be created and modified using all three emerging methods, combining their output into one integrated data-store. Any given item may have relationships and attributes corresponding to any or all of our existing, hybrid or future methods and tools. A collaborative environment such as the iRoom (CIFE Interactive Workspaces Group 2002) see Figure 13, with a number of interactive screens used simultaneously to display multiple complimentary views of inter-related information, provides an experience that supports the discovery and negotiation of multidisciplinary information and relationships.
Successful integration of these methodologies depends on a common underlying information model. A directed labeled pseudo-graph structure provides a flexible means of representing relationships between information. These graphs will consist of a large set of nodes with arcs between them; directed means that each arc has a defined direction, labeled means that each arc has a name, pseudo-graph means that there can be more than one arc between two nodes. Storing these structures in a distributed data repository will allow information to be shared and reused between models. This repository can also be used to store metadata and references to external information which are relevant to the modeled projects, such as requirements and building codes, CAD drawings, design analyses, and decision information.

Figure 14: For clarity, colors associate information items and relationships with their corresponding methodologies. Predicates from the common "core" are shown in red; these core predicates form the common vocabulary for integrating data from multiple tools.
Our integrated model will consist of a collection of statements where each expresses a typed relationship between information items. An existing Internet standard, the Resource Description Framework (RDF) provides for the encoding, exchange, and reuse of a similar form of structured metadata. RDF is targeted at describing information resources in the form of web pages, but at a more abstract level, there is no need to distinguish between a web page and, say, a CAD drawing. Conforming to the RDF specification, at least in part, provides immediate access to existing open source and commercial tools for storing, manipulating, querying, and performing logical inference operations on these models. An RDF model consists of resources (in the computer science, not project management, sense), which represent people, places, documents, tasks, etc. Each resource has a URI (uniform resource identifier), which uniquely identifies it within the model. The contents of a model are described by an unordered set of statements. Each statement defines a relationship consisting of three items, a subject, predicate, and object. The subject is a URI referencing a particular resource (which may be internal or external to the model), the predicate is a URI representing a labeled arc from the subject to the object, and the object is either a literal value or a URI referencing another resource.

The model repository is based on an RDF triple store, which is a database specialized to store and retrieve statements as described in the previous section. An integrated HTTP (web) server allows concurrent access by multiple clients on a network. The POP Modeling, Narrative Approach, and Decision Dashboard tools will be adapted to store and retrieve models using a simple query language layered on top of the HTTP protocol.

7. DISCUSSION
In this paper, we presented our application of three emerging methods to case studies from the design of the Living Laboratory at Stanford University. We found our POP methodology is useful for quickly categorizing and organizing information models in terms of the functions, forms, and behaviors of the design products, organizations and processes. We found the project overview to be useful in assuring a more completely considered design process, and in helping communicate much of the information needed to execute the design. We found our Narrative methodology to be useful for defining and controlling the dependencies between information. We found this a powerful way to communicate, and potentially manage and automate design processes and information to enable the exploration and analyses of more design options. We found our Decision Dashboard methodology helps to clearly define sets of options, consider tradeoffs and document decisions. Separately, each of these tools support a subset of the processes AEC professionals struggle to perform while defining functions, proposing forms, analyzing forms, and making decisions on their projects today. By developing an integrated methodology on what we find common – a focus on the relationships between information - we believe we can design more fluid methodologies that enable AEC projects to quickly and accurately manage and communicate their multidisciplinary information and processes.
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