MANAGING AND COMMUNICATING INFORMATION ON THE STANFORD LIVING LABORATORY FEASIBILITY STUDY

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SUMMARY: *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. We 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, narratives, decisions, integration.*

1. INTRODUCTION

Many envision an Architecture, Engineering, and Construction (AEC) industry where Building Information Modeling (BIM) revolutionizes the way 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 sub optimal 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. Researchers such as Gielingh (1988), Bjork (1989), and Eastman (1999), have proposed systems for modeling and interrelating these multidisciplinary information and processes. 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.

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 and management 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 show how we 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. Fig. 1 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 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.

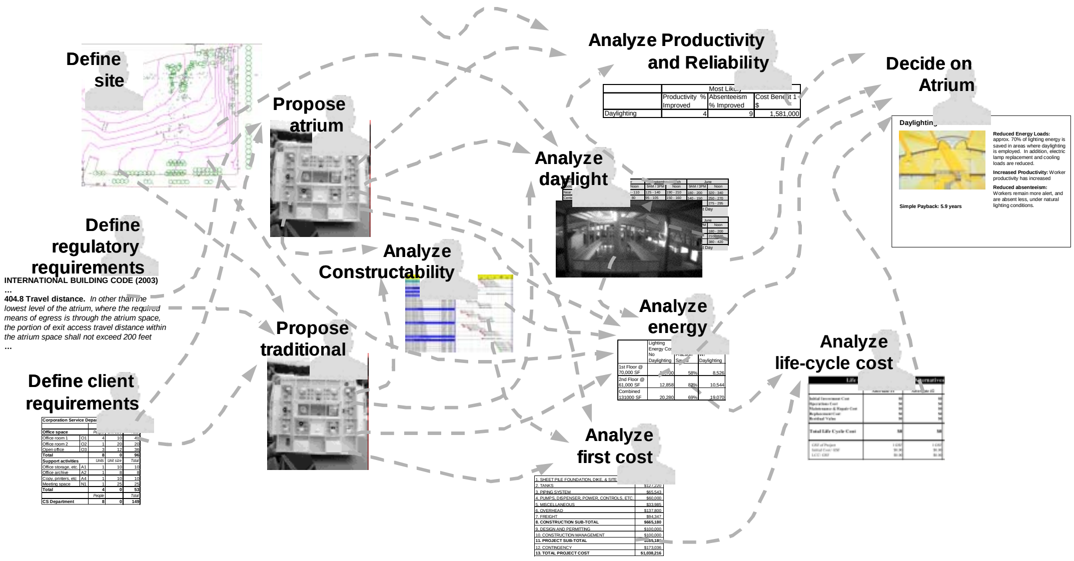

FIG. 1: A portion of the design process an architect and their consultants executed in which they defined functions, proposed forms, analyzed the behavior of these forms, and decided on the appropriate design options based on these analyses.

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 day-lighting 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 needed 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. Many researchers have observed current practice's difficulty integrating information and processes, or developed systems to help them manage this integration, for example: between requirements information and design information (Kamara and Anumba, 2001, Kiviniemi, 2004); between design information and analysis information (Augenbroe, 1995, Kam et al, 2003); between design information and fabrication information (Choo et al, 2004, Haymaker et al, 2004); and between analysis information and decision information (Kunz and Rittel, 1970, 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 Fig. 1 or other formal description that explicitly described and interrelated their design processes, organizations, and products that helped them 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, other consultants, and to the design community as a whole in order to help the team construct more sound sustainable design processes. They also want to communicate these processes in such a way that can be appropriately reused on subsequent projects. Many researchers have observed current practice's difficulty, or have developed systems to help teams communicate their information and processes, for example the Process Protocol (Song et al, 2001), Design Structure Matrix (DSM) (Eppinger et al, 1990), and Building Stories (Martin et al, 2005).

Due to the difficulty managing and communicating their design processes, and to time and budget considerations, 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 Fig. 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).

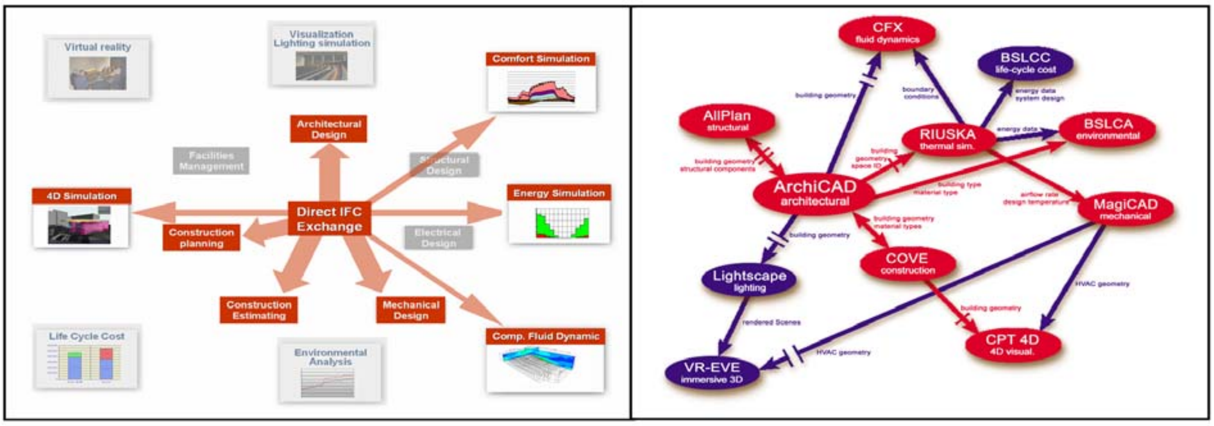

FIG. 2: The envisioned ideal (left) and chaotic reality (right) of information exchange on an auditorium project in Helsinki, Finland.

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 METHODOLOGIES TO ADDRESS MANAGEMENT AND COMMUNICATION

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

The Product – Organization – Process (POP) methodology (Kunz and Fischer, 2005) enables multiple disciplines to collectively 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. Most simply, a POP model can be implemented in a spreadsheet matrix that represents the integrated function, form and behavior of the product, organization and process, as shown in Fig. 4. The object of POP modeling is to assure that the function, form and behavior of each P, O and P model are consistent, and that the integrated set of models are also appropriate and mutually consistent. An example of a measure of appropriateness is that the forms represent the most expensive elements of the design, initially (in a "Level-2" model) the top-ten most expensive product, organization and process forms, measured in terms of money, time or sustainability. An appropriate "Level-3" model represents the hundred most expensive elements. POP modeling thus makes these nine types of interrelated information explicit and encourages the team to design them to be appropriate, and maintain consistency among them as the design evolves.

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. Our goal was to assess whether and how the innovative methods could affect the process of addressing these two significant engineering issues.

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, and to help the team make an informed, quantitative decision the architect prepared a decision matrix (see Fig. 3) in which he listed all the possible room types and evaluated them with regard to six criteria, namely: *net square feet per bed, efficiency, social interaction, future flexibility, popularity* and *fit with the campus plan*.

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. Similar matrices have been used on other design projects (BNIM, 2002). 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.

Room Type Decision Matrix	NSF/Bed (Factor)	Efficiency (Sustainability)	Social Interaction	Future Flexibility	Popularity	Fit w/ Campus Housing Plan
Singles	110 (1.0)	2	3	2	4	?
Doubles	100 (1.1)	4	5	5	3	?
Divided Doubles	110 (1.0)	2	3	2	4	?
Triples	95 (1.16)	4	1	5	1	?
Quads	90 (1.22)	4	3	5	1	?
Suites	135 (0.82)	1	1	1	5	?
Mix	110?	?	?	?	?	?

1 = Worst

5 = Best

FIG 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. Image courtesy EHDD Architects.

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 during the feasibility stage 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, see Fig. 4. In building and using this model, we found 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, Fig. 4 lists all the criteria that the room type must fulfil, 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).

POP Model	Product	Organization	Process
Function	▪ Enable privacy ▪ Popular with students ▪ Encourage social interaction ▪ Suitable for summer use ▪ Efficient with space ▪ Efficient with plumbing ▪ Efficient with structure ▪ Flexible for future reconfiguration ▪ Efficient with energy	▪ Environmental knowledge ▪ Dorm Residence knowledge ▪ Economic knowledge ▪ Include Student Input	▪ Involve student input ▪ Reasonable cost ▪ Reasonable time ▪ Be rigorous
Form	▪ Singles ▪ Doubles ▪ Triples ▪ Quads ▪ Sinks ▪ Showers ▪ T Shape Layout ▪ U Shape Layout ▪ H Shape Layout	▪ Architects ▪ Project Manager ▪ University Architect ▪ Student Representatives ▪ Energy Consultant ▪ Structural Constultant ▪ Housing	▪ Lay out on site ▪ Assess material efficiency ▪ Survey students ▪ Assess privacy ▪ Assess social interaction ▪ Assess energy efficiency ▪ Assess flexibilty ▪ Assess summer usability ▪ Decide on room type ▪ Decide on restroom type
Behavior	▪ Privacy ▪ Popularity with students ▪ Social interaction ▪ Suitability for summer use ▪ Material efficiency ▪ Energy efficiency ▪ Plumbing effiiciency ▪ Space efficiency ▪ Flexibility	▪ Environmental Knowledge ▪ Dorm residence knowledge ▪ Economic knowledge ▪ Student Input	▪ Student Input ▪ Cost ▪ Reasonable time ▪ Rigor

FIG. 4: The POP model for the project information for the room type decision.

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

Fig. 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. Fig. 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 in Fig. 3 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.

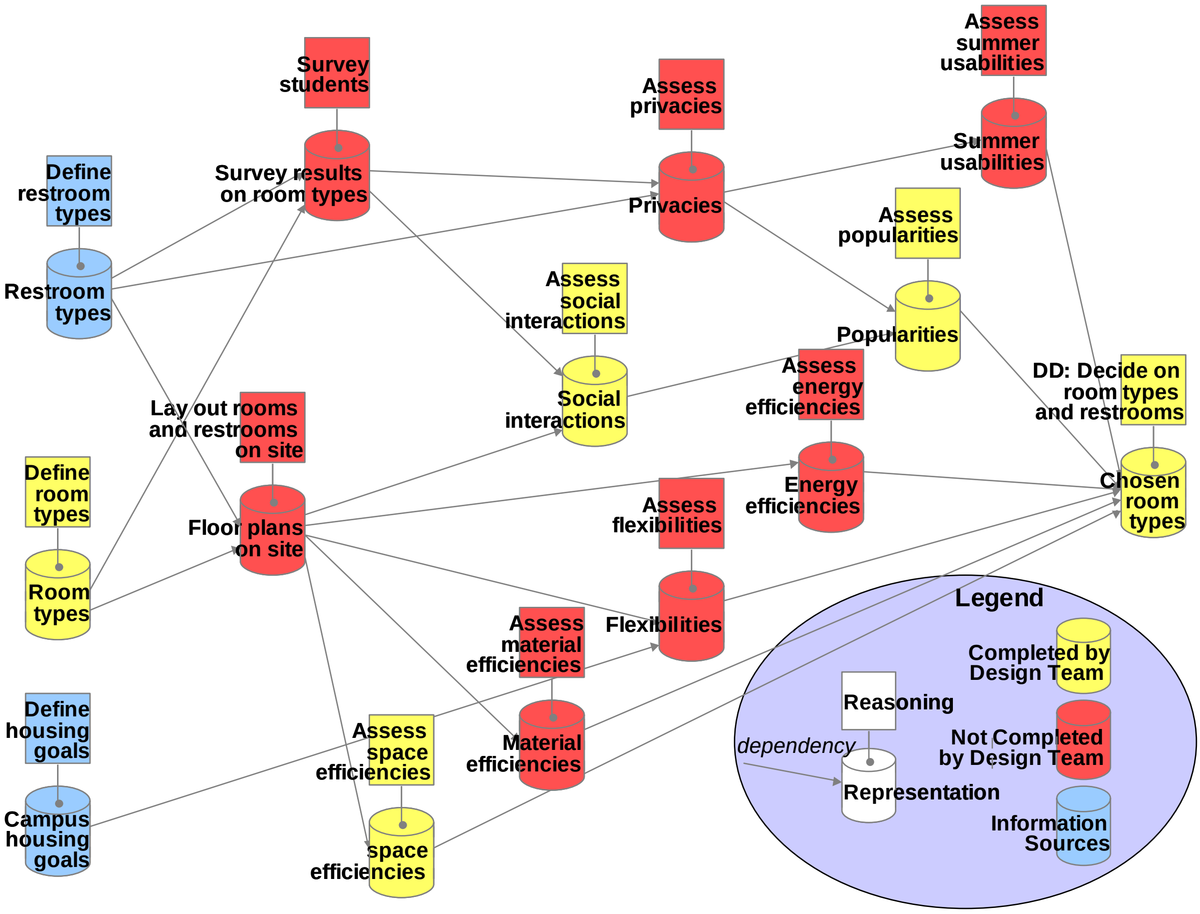

FIG. 5: The Room Type Assessment Narrative: *The diagram shows a composition of reasoning steps and the resulting representations in a process to determine which room type should be chosen for the project.*

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, 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.

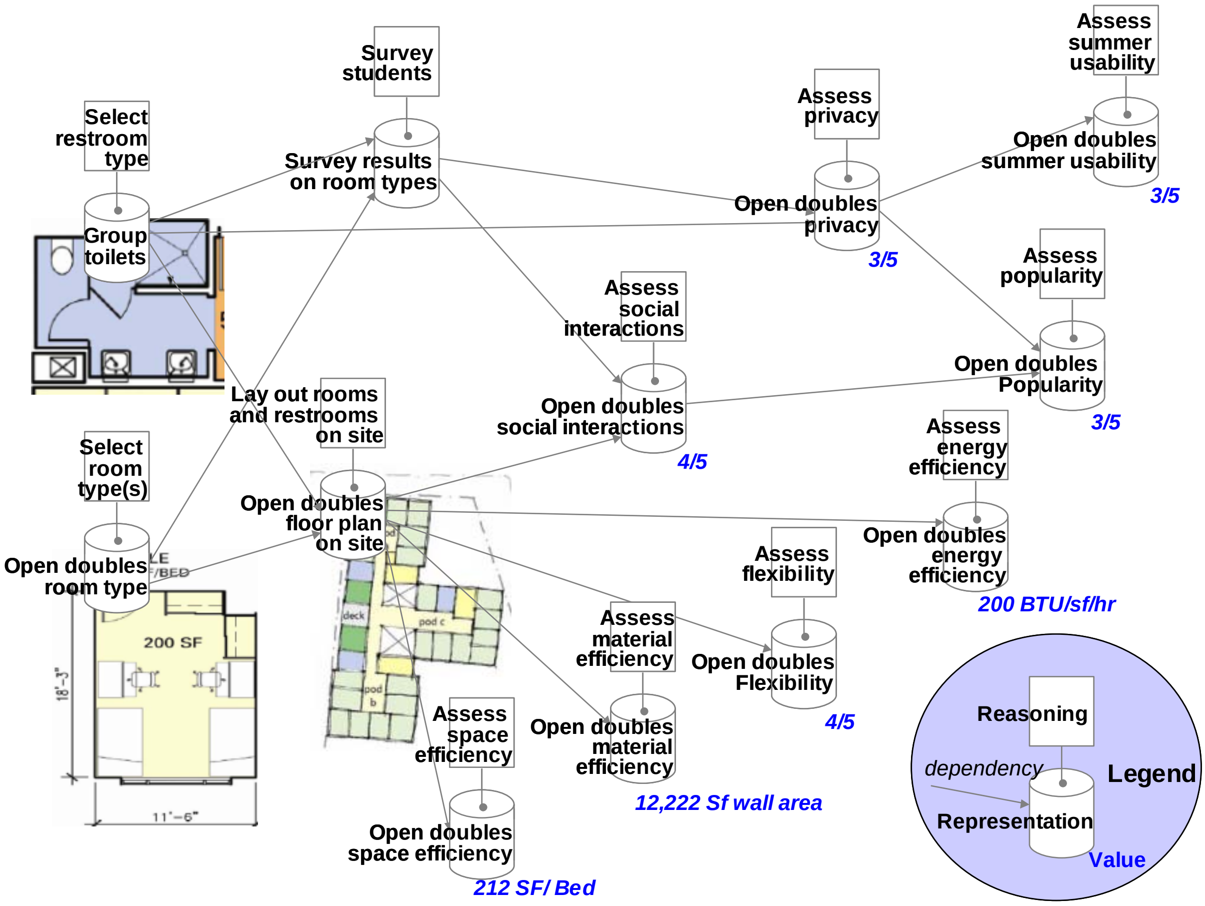

FIG. 6: The Open Doubles Room Type Assessment Narrative. The graphic representation communicates all the analysis results and helps the team understand the information with which the analyses were made. The formal representation allows the computer to control integration between the information.

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 Fig. 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.

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.

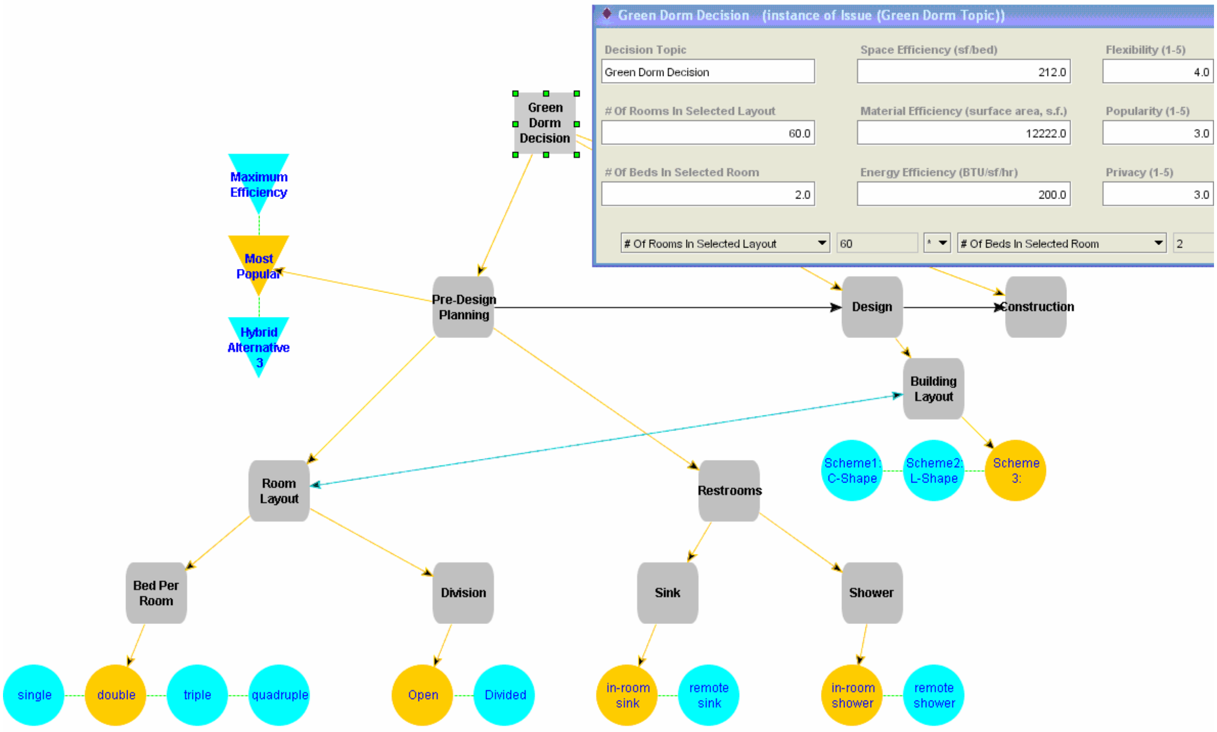

FIG. 7: A Decision Breakdown Structure of the room type decision in the Decision Dashboard. Decision topics are represented by squares, options by circles, alternatives by inverted triangles, and interrelationships by arrows following the semantics of the AEC Decision Ontology.

5.2 Energy Demand and Supply

The energy design process is still evolving, but to date 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 photo-voltaics, 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).

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

Fig. 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 Fig. 9, formalizes the dependencies between information to manage and communicate a design process.

The Energy Narrative has three sub-narratives: the Energy Supply Narrative (blue); the Energy Demand Narrative (red) and the Utility Balance Narrative (purple). The Energy Supply Narrative is subdivided into six narratives: Photovoltaic arrays, passive solar heating, solar water heating, fuel cells, heat recovery from used water, and a bioreactor. Each of these Narratives details the sources of onsite energy generation explored during the feasibility study to match the energy demand. The two grayed-out narratives (fuel cell and bioreactor) denote two alternatives explored, but not included in the energy balance to achieve the zero energy goal. The Energy Demand Narrative describes the model-base demand of the building calculated using eQuest with a set of assumptions about the use, size, shape and material properties of this living lab. This Narrative 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. The Utility Balance Narrative shows the energy exchange with the utilities (electricity and natural gas). Perspectives labeled “NEED” denote information that is missing and correspond to discussions held within the design team, but that didn’t translate into formalized design alternatives.

POP Model	Product	Organization	Process

Function	▼ Establish an image for the GD
	  ■ plug and play bldg
	  ■ park electric car at the lab
	  ■ Perceived goal incongruence within CEE
	  ■ define type of house
	  ■ Programming
	▼ Unparalelled environmental performance
	  ■ Zero Goals
	  ■ Zero Energy
	  ■ Zero Carbon
	  ■ Evaluate standalone facility vs. grid support
	▼ Research testbed for innovative technologies
	  ■ Extensive monitoring
	▼ Constraints/existent conditions
	  ■ Cost <= 294 $/sf
	  ■ Site/Site Selection
	  ■ Technologies
	  ■ Regulatory
		■ Energy professor repsonsible for vision	■ Feasibility Study need approval from BOT
			■ Base bldg budget + research bldg budget
			▼ About $3 million endowment
			  ■ Will pay ~$150,000/yr fro research
			  ■ Research manager
			  ■ Fulfill educational goal
			  ■ Building tweaking
			  ■ Building maintenance
			▼ Design team requirements fro FS
			  ▼ Clear program
			    ■ list of spaces
			    ■ square footage diagram
			    ■ ADA issues
			  ■ Budget aligned with program
			  ▼ Building planning diagram
			    ■ What spaces are in the building
			    ■ Spaces adjacency/connectivity
			    ■ Building massing
			    ■ Windows to wall ratio
			  ■ Design narrative

Form	▼ Site/orientation
	  ■ = Site 2
	  ■ = E-W oriented
	▼ Bldg geometry/shape/floors/facade
	  ■ Envelope: good glass
	  ■ Building shape
	  ■ Buildings Floors
	  ■ Include mechanical blinds/shading
	▼ Materials
	  ■ = Steel frame
	  ■ = Innovative materials for heat storage
	▼ Technologies
	  ■ Put together several scenarios
	  ■ Heating
	  ■ Cooling
	  ■ Lighting
	  ■ Ventilation
	  ■ On site energy generation
	■ Phasing of implementation of Systems
		▼ Energy group
		  ▼ Architect
		    ■ = EHDD
		  ▼ Mechanical/Energy Consultant
		    ■ = Taylor Engineering
		  ▼ Energy Professor
		    ■ = Gil Masters
		  ▼ Cost Estimating
		    ■ = Pankow Builders
		    ■ = Davis Langdon
		  ▼ Campus energy providers
		    ■ = PG&E
		    ■ = Stanford utilities
		  ▼ Water Group
		    ■ = Sheerwood Engineers
		  ▼ Broker for green initiatives incentives
		    ■ Teaches at PG&E
		    ■ www.ongrid.com
		▼ Energy discussion target audience
		  ■ = Housing
		  ■ = Others
		▼ Tension between BOT and CEE
		  ■ Cost estimate (conceptual)
		  ■ Last chance for green bldgs @ SU
		■ Different messages from stakeholders
			▼ Energy performance
			  ■ talk first to energy professor
			  ■ then present ideas to group
			  ▼ Get feedback from Stanford
			    ▼ Energy cooking use
			      ■ = Energy use (btu/meal)
			      ■ = number of meals
			      ■ = Water use (gals/person/day)
			▼ Internal processes (design team)
			  ▼ Drawing GD elements
			    ■ help focusing discussion
			  ▼ Define constraints for zero goals
			    ■ Zero Energy
			    ■ Zero Carbon
			  ■ Create a carbon emissions chart
			  ■ Testing of the goals
			  ■ Base bldg
			  ■ Base and extended systems
			■ External processes (outside design team)
			▼ Research education
			  ■ Too many projects for GD
			  ■ Bring ongrid broker to a class?

Behavior	▼ Cost
	  ■ Need to justify cost efectiveness
	  ■ LCCA: it only considers money
	  ■ dryer heat exchange not economical
	  ■ Basement is not always more expensive
	▼ Energy Performance
	  ▼ Energy model pie demand
	    ■ Efficiency first!!
	    ■ Largest load = DHW
	    ■ Largest uncertainty = plug loads
	  ■ Base building
	■ Users comfort
	■ Architectural considerations
		■ Wrong incentives w/ flat electricity rate	■ Cost estimate is a big issue
			▼ GD not elegible for public rebates
			  ■ Stanford utlilities does not qulify
			■ Stanford utilities do not qualify for incentives
			■ GD qualifies for PG&E rebates
			■ Hard to get to zero energy goal
			■ Energy discussion better structured
			▼ What a succesful program mean?
			  ■ Getting people involved!!

FIG. 8: Energy POP Model.

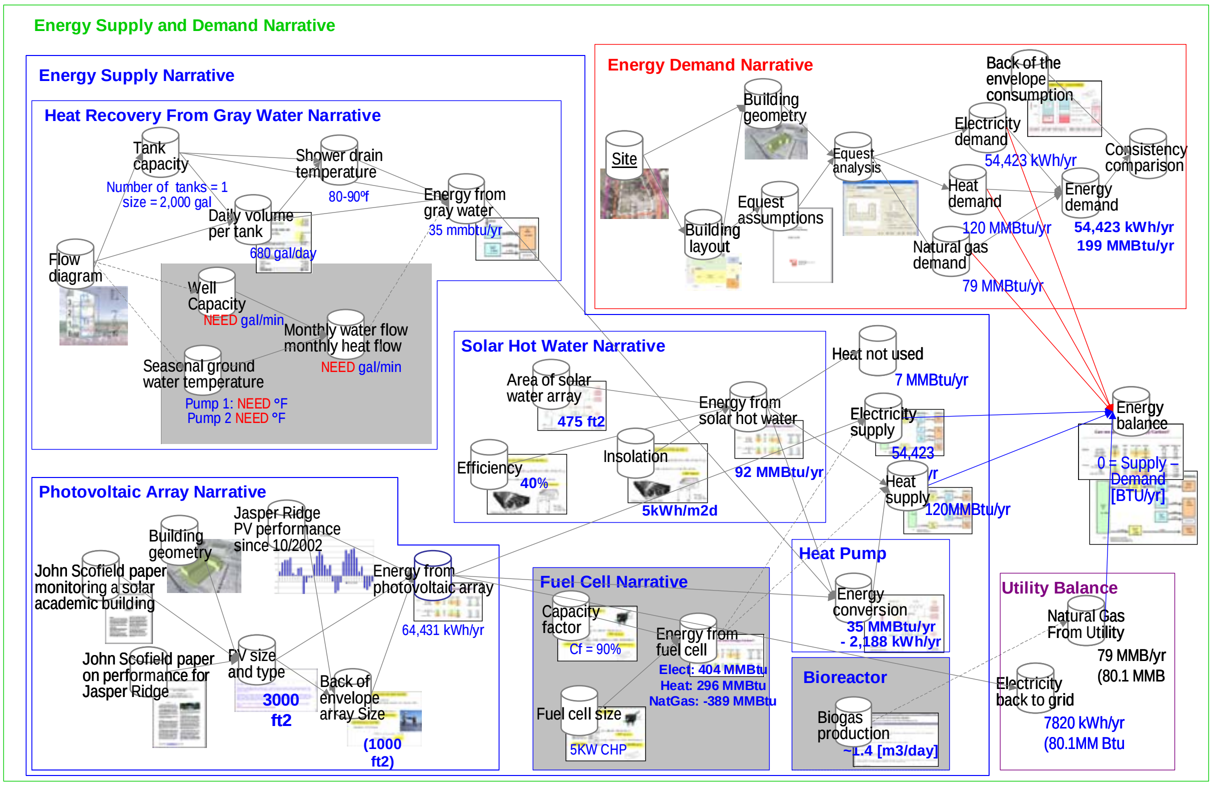

FIG. 9: The Energy Narrative is a snapshot of the status of the design of the energy systems for the Stanford Living Laboratory at the end of November 2005. It reflects the alternatives discussed and analyzed to achieve a Zero Energy Goal, one of the functional requirements requested by the owner. An interactive version of this Narrative, with links to each information representation can be found at: http://www.stanford.edu/people/haymaker/gd/energy-narrative/

Once the reader learns the notation, we find that this Narrative is easy to follow, can help stakeholders understand the complexity and integration of the design, and can be easily modified to incorporate more and better processes and information. Management processes (either manual or automated) can help the team propagate changes through the Narrative to assist in an up to date design. This Narrative can serve as a template for future projects or even for the handoff of the feasibility study to a new team. Avoiding a start from scratch can allow a design team to explore more variations of the design, which can lead toward a better design.

5.2.3 The Energy Decision Dashboard

Fig. 10 illustrates a decision dashboard that extends the room type Decision Dashboard (section 5.1.3) to incorporate the energy decision topics, criterion, and choices. The decision options of passive solar heating, photovoltaic array, solar water heating, fuel cells, and heat recovery from used water are represented as discrete options within the green dorm decision context. The Decision Dashboard distinguishes the currently recommended choices in orange while maintaining other candidate decision choices in cyan. It captures the ripple consequences identified from the narratives with an arrow between building layout and energy demand, signaling that the change of building orientation would influence the energy demand, and hence the evaluation of the energy consumption between energy demand and supply constrained by the zero energy objective. In essence, the decision dashboard presents POP and narrative information in ways that aid in the decision makers' consideration of the decision context (its decision topics, choices, criteria, recommendations, considerations, their relative hierarchy and interrelationships) across different levels of details.

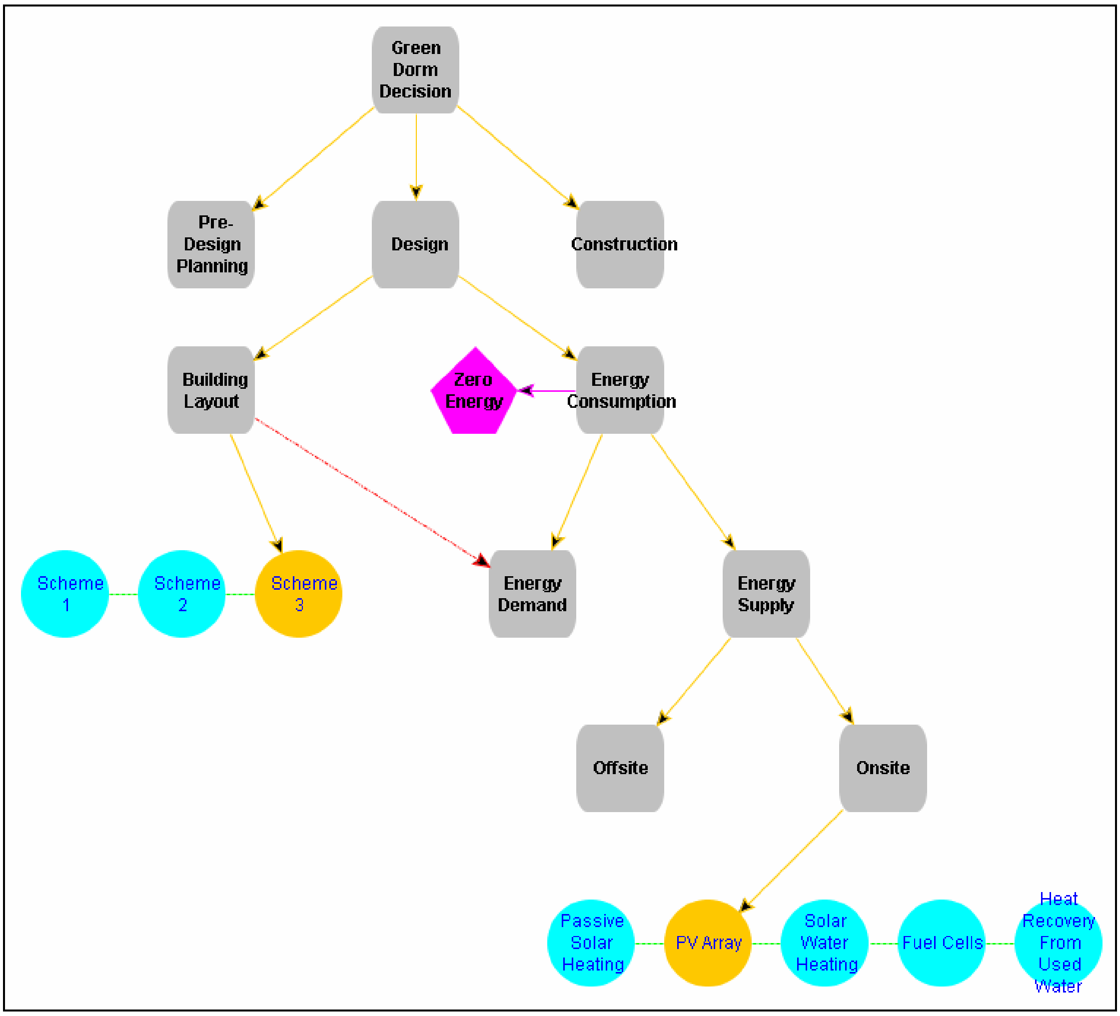

FIG. 10: A Decision Breakdown Structure of the energy decision in the Decision Dashboard as an extension to the room type Decision Dashboard illustrated in Fig. 7.

5.3 Development of a master POP model

5.3.1 POP Models for Individual Design Meetings

During the feasibility 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

A series of POP models are thus generated that document how the design progresses from one stakeholder meeting to the next. Taken together, these POP models cover a large variety of function, form and behavior information – 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 when the information being merged covers the same or similar topics more complex consideration is required; 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 distilled information from Product-Form and from Product-Function, establishing up-to-date representations of common functions and high-level design forms (see Fig. 11) 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 options, which are incorporated into the Master POP model under Product-Behavior. The design team evaluated each option with respect to its impact on the desired functions shown in the leaf nodes of Product Function. We then aggregated the ratings 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/. More information on this process can be found in Haymaker and Chachere (2006).
The Master POP model serves as a declaration of project goals, a summary of product options and an evaluation of the current design options. Fig. 11 shows our Master POP model, focusing on Product. The Behavior evaluation shows two potential design configurations – Baseline Green and Living Laboratory – 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, as demonstrated by their use of this structure to organize the final feasibility report.

PRODUCT		
FUNCTION	FORM	BEHAVIOR
The most desirable housing	Baseline Green	Design Evaluation Survey
Community	Shared "Information Center" (foyer) and entry	Baseline Green (179)
Sense of privacy	Solar orientation for passive solar design	The Most Desirable Housing (48)
Dynamic social life	Radiant slab heating	...
Good neighbor	Optimized 24" O.C. wood framing	A Living Laboratory for Research (83)
Learning	Natural ventilation w/ operable windows	Experimentation (47)
Access to research and education	Efficient light and water fixtures	Demonstration (36)
Enables sustainable lifestyle choices	Fly ash or slag, low-cement concrete	Measurable Environmental Performance (31)
Indoor Environmental Quality	First floor location for building systems lab	...
Thermal comfort	Large roof deck at second level	Economically Sustainable (17)
Lighting quality	Electric car garage	First Cost (2)
Acoustic quality	80% daylit interior	Lifecycle Cost (15)
Healthy materials & air	Living laboratory	Completion Date (0)
A Living Laboratory for Research	100% daylit interior	Living Laboratory (269)
Experimentation	Steel structure per Tipping Mar scheme 2A	The Most Desirable Housing (52)
Design and construction process	FSC-certified wood	...
Sensing	5 kw fuel cell	A Living Laboratory for Research (167)
Building energy	Solar hot water system	Experimentation (86)
Vehicle energy	Greywater heat recovery	Demonstration (81)
Building structure	60 Kw Photovoltaic array	Measurable Environmental Performance (47)
Building materials	Dimmed lighting setback	...
Water	Highest-efficiency lighting and ballast	Economically Sustainable (3)
Demonstration	Building systems monitors	First Cost (-22)
Influence at Stanford	Rainwater collection	Lifecycle Cost (25)
Influence on building industry	Double piping for greywater and blackwater collection	Completion Date (0)
Noteworthy ("WOW" factor)	Greywater collection tanks	
Measurable Environmental Performance	Sustainable materials (lime plaster, salvaged redwood)	
Zero carbon	Extensive green roof, 2 to 4 inches of soil. 1400 sf	
Reduced energy demand	Triple-paned, double low-e windows	
Low/no carbon per kWh	Three foot clerestory pop-up at upper, north-facing rooms	
Low embodied energy	Ventilation well on first floor	
Closed water cycle		
Water efficiency		
Water capture and recycling		
Material resources		
Reduced earthquake losses		
Sustainable material use		
Design for adaptability and deconstruction		
Economically Sustainable		
First Cost		
Lifecycle Cost		
Completion Date		

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.

Fig. 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.
An interactive version of this Narrative, with links to each information representation can be found at:
http://www.stanford.edu/people/haymaker/gd/master-pop-narrative/

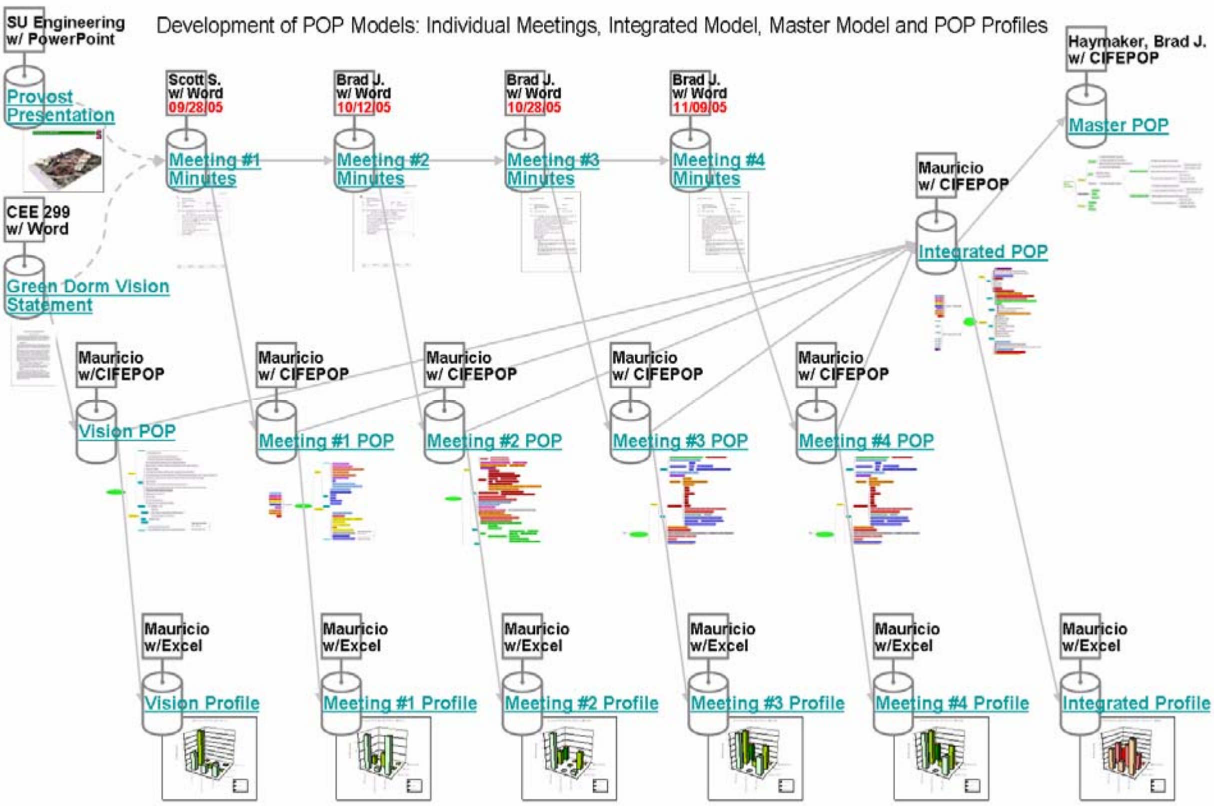

FIG. 12: A Narrative describing the development of Master, Integrated and other POP models for the Living Laboratory design process.

6. NEXT STEPS: INTEGRATING THE 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.

TABLE 1: Types of relationships central to our three approaches.

Methodology	**Relationship Types**
POP Modeling	• Product-Organization-Process classification (POP) • Function-Form-Behavior classification (FFB) See (Kunz and Fischer, 2005) for a discussion of POP and FFB. • Other classification (i.e. Economy-Equality-Environment) • Generic directed relationship
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 with respect to 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.

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) shown in Fig. 13, with a number of interactive screens used simultaneously to display multiple complementary views of inter-related information, provides an experience that supports the discovery and negotiation of multidisciplinary information and relationships.

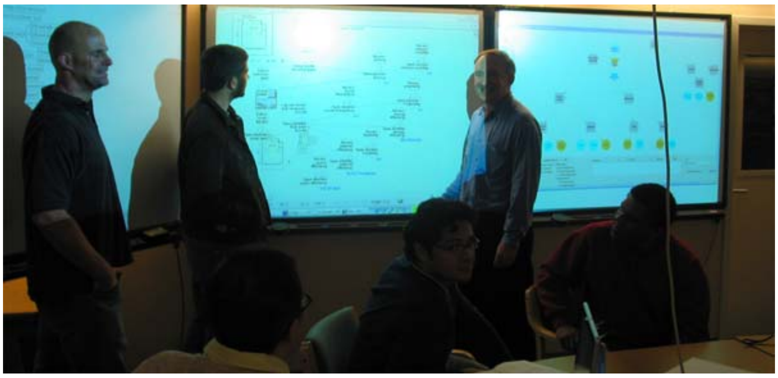

FIG. 13: The CIFE iRoom. The image shows many of the authors. The Room Type POP Model is on the left screen, the Room Type Narrative is on the center screen, and the Room Type Decision Dashboard is on the right screen.

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.

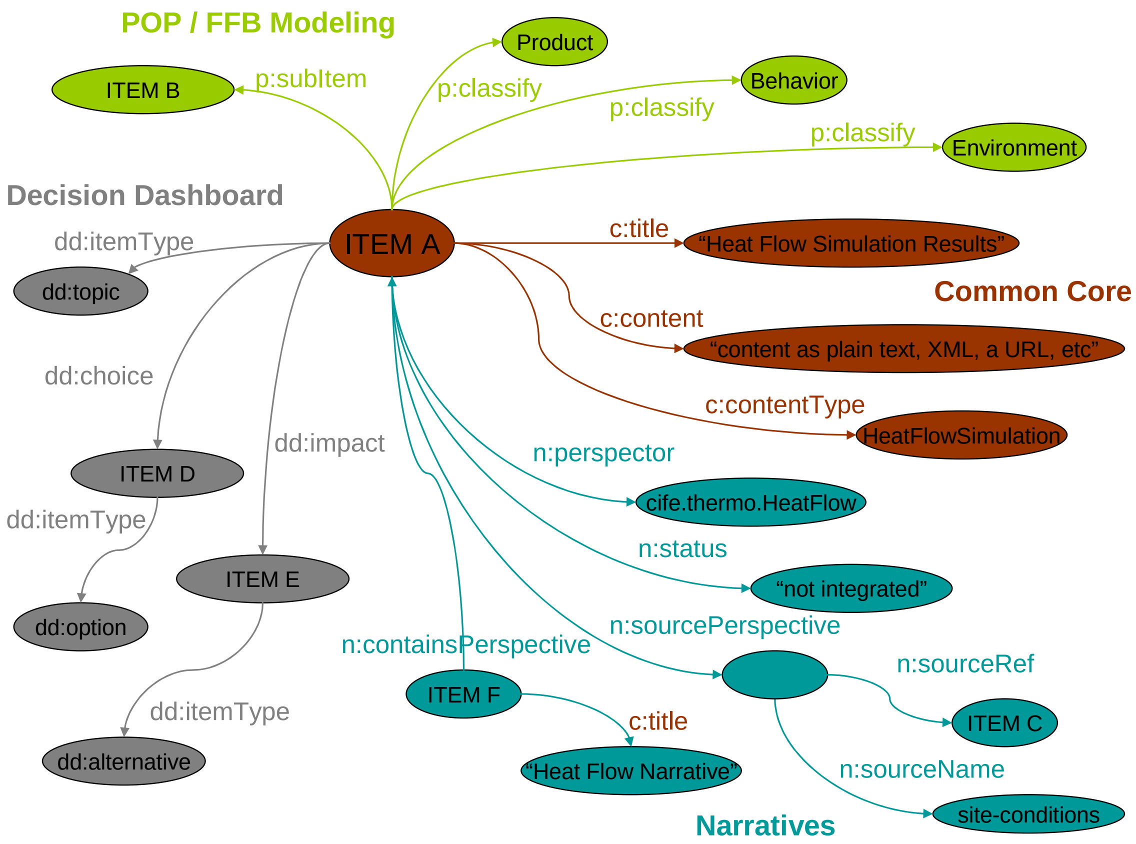

FIG. 14: A fragment of a shared RDF integration model. For clarity, colors associate information items and relationships with their corresponding methodologies. Predicates from the common "core" are shown in red; these core predicates form the common vocabulary for integrating data from multiple tools.

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 to be useful for quickly categorizing and organizing information models in terms of the functions, forms, and behaviors of the design products, organizations and processes. The project overview provided by POP can enable a more completely considered design process, and help communicate much of the information needed to execute the design. However, as the number of items contained in a POP model increases, comprehension becomes more difficult. More research on methods to filter and visualize this information is needed. We found our Narrative methodology to be useful for defining and managing the dependencies between information. Narratives can be a powerful way to communicate, and potentially automate design processes and information to enable the exploration and analyses of more design options. Additional theory is required that can inform the designer as to which information representations to include in a Narrative, which dependencies to model between these information representations, and how to best describe the nature of each dependency. We found our Decision Dashboard methodology helps to clearly define sets of options, consider tradeoffs and fully document decisions. The ability to quickly couple options into alternatives and assess and compare their impacts on project goals can help the project team find better solutions. Further research will explore ways to explicitly structure and weight project goals and to conveniently compare multiple alternatives against each other.

In order to integrate these methodologies in an interactive workspace, we focused on concepts common across all three approaches: information items and typed relationships. In choosing a very generic and simple definition for the core information item concept, we have made it easy for many different approaches to be integrated, perhaps at the expense of expressiveness and accuracy. Beyond agreeing on a common representation model, there are many other challenges on the road to full, fluid use of multiple methodologies within a single context. We must determine a suitable way for applications to be notified of and react to changes in the shared information that originate from other users and other approaches; we must find an intuitive, appropriate paradigm for controlling read and write access to shared information across multiple applications; we must design the framework with future applications, processes and theories in mind; and ideally, we would like to achieve a set of interaction and data-modification patterns that can be consistently implemented across multiple different applications. Our research efforts addressing these challenges are and will continue to be based on an iterative process, whereby individual applications are developed in parallel in order to advance each methodology, while simultaneously developing and working from a shared core that is frequently updated to incorporate and refine common concepts.

Separately, each of our three tools supports 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 methodologies that are fluid and enable AEC projects to quickly and accurately manage and communicate their multidisciplinary information and processes.

8. ACKNOWLEDGEMENTS

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