A CASE STUDY IN INTEGRATED PRODUCT, PROCESS, AND ORGANIZATION MODELING IN EARLY STAGES OF SUSTAINABLE DESIGN

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ABSTRACT

Sustainable development requires the design-construction delivery process to incorporate new sets of environmental, social, and economic goals; however, AEC projects today have difficulty clearly and collectively defining these goals, and executing an integrated design process that achieves them. We are designing a framework to enable AEC teams to collaboratively address their sustainable goals using two complementary methodologies: POP Modeling and Narratives. POP Models are a simple, consistent and structured way of capturing and visualizing project information in terms of its product, organization and work process by defining the functions, forms and behaviors. Narratives help to formalize, understand and communicate the dependencies among these pieces of information and thus to define and integrate the design process.

We applied POP Modeling and Narratives to the Feasibility Study of the Stanford Green Dorm. Our initial findings suggest that POP Models help enable and maintain a common understanding of the project goals. Narratives can prove useful to capture and manage integrated multidisciplinary design processes. Together, they can help project teams define their sustainable goals and incorporate them into an integrated design process.

KEY WORDS

sustainability, building information model, early design, integrated design, process model.

INTRODUCTION

We share with many visionaries a picture of the Architecture, Engineering, and Construction (AEC) industry where Building Information Modeling (BIM) revolutionizes the way AEC

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professionals design and manage multidisciplinary projects (Khemlani, 2005). BIM today enables AEC professionals to improve their discipline-specific performance (Kam and Fischer, 2002). However, practitioners struggle to define multidisciplinary project goals (Hill et al, 2001; Kiviniemi, 2005) and deliver an integrated design (Thomsen, 1998; Dong and Vande Moere, 2005).

At the Center for Integrated Facility Engineering (CIFE) of the Stanford University, we believe the future of the AEC industry is on 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 developing, testing and refining VDC methodologies that help AEC projects and stakeholders better define their sustainable goals and integrate them into the design.

We begin this paper by summarizing our observations on a sustainable project and describing the difficulties AEC professionals experience in defining the sustainable goals and implementing them in the multidisciplinary project environment. We then summarize our POP Modeling and Narrative methodologies, and explain the exploratory implementation of these methodologies to the Green Dorm project at Stanford University. We discuss how these methodologies might help teams define the project goals, options and analyses in an integrated product-organization-process approach.

MOTIVATION

Sustainable facilities' design represents a challenge for the design team involved due to the intricate interaction among different aspect of the project, the need to satisfy the broad range of stakeholders' expectations and the sometimes limited experience in sustainability designs of several team members. Even recognizable examples of sustainable buildings face such challenges. (Haymaker and Fischer, 2005). The network of dependencies among pieces of information in a sustainable design is particularly intricate (Vanegas, 2003).

The design and recent construction of a research facility within the Stanford University campus offered us the opportunity to observe some recurrent challenges that today's AEC practitioners face when designing a "sustainable" building. We interviewed the architect of this project and we present some of our findings.

Among the goals of this project, internal consistency with the organization's own environmental research work was the main driver of the design. A small group of aligned decision makers stated early in the design its desire of achieving a facility with minimum carbon impact, both operational and embodied.

The architect identified two barriers the project faced due to its sustainable nature: impossibility of permitting waterless urinals and construction coordination problems with the night sky cooling system. In the first case, the installed waterless urinals were not permitted due to local code regulations – they lacked incoming water supply piping. In the case of the night sky cooling system, the mechanical system was designed to collect water sprayed overnight on the roof to cool off. The cooled water is then stored in a tank to be delivered during the day for radiant cooling as needed. A subcontractor working on the roof disconnected the collection pipes to perform a repair and did not reconnect them due to a lack of understanding of the system and its purpose –in a "normal" project it is unusual to have a closed loop for the roof runoff water. A summer storm over the weekend caused rainwater to leak into the building through the unconnected pipes damaging stored sheetrock and other construction supplies (i.e., the water loop was not closed as designed), causing a construction delay.

The architect believed the "minimize carbon impact" goal definition was pivotal in the final project outcome and helped in the analysis of tradeoffs when different design options were evaluated. It was explicitly identified by the architect as one of the reasons for the project success. However, while this high level goal was clear, the designers struggled defining and communicating other goals (i.e., closed water cycle) and lower level goals (i.e., meet city plumbing codes, and maintain function of systems during construction) related with the waterless urinals and night sky cooling system. A lack of understanding of the local code regulations led to the inability to foresee that situation as an important issue, which ended up causing the failure to approve the waterless urinals installation. A lack of understanding of the functioning of the night sky cooling system led to a failure of the contractor to consider this system in his scope of work.

In addition to the inability to communicate the goals of the project, the designers also struggled with the integration of the design information to achieve these goals. The proposed design alternative of waterless urinals (product-form) didn't fully integrate the local code regulations (product-function: meet code; organization-function: county inspector; and process-function: go through permitting). In the night sky cooling case, a better understanding of the mechanical system functioning by the subcontractor could have avoided the leakage incident. Both cases depict the importance of integration in a sustainable design – at both the system level (night sky cooling) and at the product, organization and process level (urinals).

Although the resulting facility is a remarkable sustainable building (AIArchitect, June 2005), the examples show there is room for improvement. We envision that VDC will enable that sustainable process improvement.

EMERGING CIFE METHODOLOGIES

At CIFE we are developing an integrated framework to help AEC teams better define their project goals and achieve a better integration of the project design. This paper discusses two of the methodologies we are testing and validating: POP Modeling and Narratives.

The POP Modeling methodology (Garcia et al, 2003; Kunz and Fischer, 2005) enables multidisciplinary teams to define the functions, forms, and behaviors (Gero, 1990) of the products, organizations, and processes. 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 required to design the product, should also be considered. POP Modeling makes these nine interrelated models explicit and public and encourages the design team to maintain consistency among them.

The Narrative methodology (Haymaker et al, 2004) enables multidisciplinary teams to define and manage processes consisting of information representations and dependencies between these representations. AEC professionals can use Narratives to graphically and formally define the required functions, propose forms, analyze the behaviors of these forms, and manage and communicate the dependencies among these distributed, interdependent, evolving models. This formal representation of the design process can be used to communicate and control integration.

POP MODELS AND NARRATIVES ON THE STANFORD GREEN DORM

> *"The Stanford Green Dorm is an innovative, sustainable dorm and research building proposed for the Stanford campus. This project is unique in many ways: this is a housing project spearheaded by the School of Engineering; this is an engineering lab within a 47-unit student dorm; but most of all, this is a Living Laboratory for ongoing research and education on sustainable engineering and living."* – ***Stanford University Green Dorm: Feasibility Study Report by EHDD – Winter, 2006.***

In this section we present a brief overview of the Green Dorm project as well as the problems the team has faced during the design and at the end of the feasibility study phase. This paper discusses the overall goal definition process and focuses on one specific process: the analysis and design of the project's energy systems.

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 green dorm on campus. The owner is a large and multidisciplinary 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.

The energy design process has changed during the feasibility study and the energy goals have been refined from a broad "unparalleled building performance" including "minimized energy consumption" definition (stated in the request for proposals), to a more precise call for achieving a zero energy building (feasibility study). 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 design team has coordinated its work through phone calls, e-mail exchanges, and meetings, and they soon added a Wiki (http://vestaldesign.com/greendorm) and online groups discussions to communicate the evolution of the design and manage the voluminous feedback from the large stakeholders group. However, it has been difficult to define and prioritize the project goals and integrate them into the design 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. The current design process is difficult to follow by all the stakeholders, and it is difficult to update when new assumptions are made or when new considerations are incorporated.

In the next sections we describe the POP and Narrative models that we are creating by observing the energy design process, and discuss how these models might help to define the project goals and integrate them into the design process.

THE ENERGY POP MODEL

Figure 1 shows our Energy POP model that contains much of the information and processes the energy design team has been 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 is needed to achieve their energy goals.

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 wall materials for mass (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 about cost ■ Cost estimate (conceptual) ■ Last chance for green bldgs @ Stanford ■ 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 pie for carbon emissions ■ Testing of the goals ■ Base bldg + base systems + 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 ■ Not clear economics for heat exchange for dryers ■ 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 @ SU ■	■ 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 than other research ▼ What a succesful program mean? ■ Getting people involved!!

Figure 1: The Energy POP model shows selective exploded views of aspects of the functions, forms and behaviors of the product, organization and process. This model was created using a "beta" version of a POP model tool developed at CIFE by one of the authors. The model clearly shows that one of the less developed aspects of the design is the organization, where mainly the actors are identified (form), but minimal attention to the functions or behaviors has been given. The POP model helps the design team to identify these issues and check the consistency of the design from function to form and behavior.

Organization-Function reflects the belief that the energy professor is the main responsible for the building energy vision and therefore a key stakeholder. Organization-Form describes the team members and their roles as well as some perceived contradictions among the stakeholders. Organization-Behavior point out that the Stanford Utility's flat electricity rate (as opposed to a time-of-use rate) send the wrong incentive message to the consumers.

Process-Function identifies what are the expected deliverables from the feasibility study and from the Process-Form we can observe the strategies the design team has chosen to achieve them (e.g., internal and external processes). Process-Behavior depicts the team's constant preoccupation about cost and their assumptions about rebate program eligibility (expected process behavior).

THE ENERGY NARRATIVE

Our Energy Narrative, shown in Figure 2, formalizes the dependencies between information of the energy design process. There are three sub-narratives within the Energy Narrative, the supply side, the demand side and the utility balance. The Energy Supply Narrative, which describes the sources of onsite energy generation, has been decomposed into six smaller Narratives that refer to the specific alternatives being analyzed for the building: photovoltaic array, solar water heating, fuel cell, heat pump, bioreactor and heat recovery from gray water. These technologies are part of the "On site energy generation" Product-Form element of the Energy POP Model. The Energy Demand 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 energy simulation software and the back-of-the-envelope approach used by the energy professor to estimate an order of magnitude of the demand and its composition. The Utility Balance depicts the energy exchange of excess electricity sold to the grid and natural gas purchased from the utility.

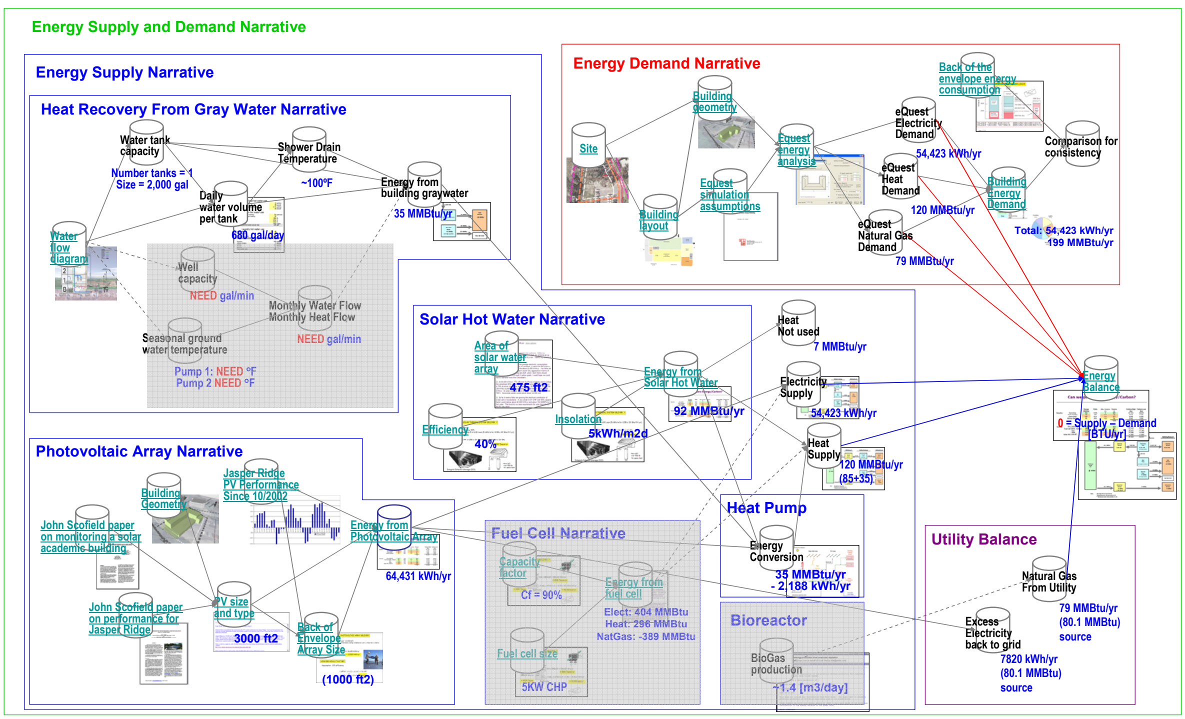

Figure 2: **Energy Narrative.** The Energy Supply and Demand Narrative is a snapshot of the status of the design of the energy systems for the Stanford Green Dorm at the end of the Feasibility Study (mid February, 2006). It reflects the alternatives discussed and analyzed to achieve a zero energy goal. The Energy Narrative has three constituent Narratives: the Energy Supply Narrative (blue); the Energy Demand Narrative (red) and the Utility Balance Narrative (purple). The grayed-out narratives (wells, fuel cell and bioreactor) denote three alternatives that were discussed, but not included in the energy balance to achieve the zero energy goal. The dashed lines denote the dependencies of alternatives explored but not included (grayed-out). Perspectives labeled "NEED" denote information about discussions held within the design team, but that did not translate into formalized design representations. An interactive view of this Narrative, which allows individual representations to be downloaded, can be found at: http://www.stanford.edu/~haymaker/gd/FeasibilityStudy/EnergyNarrative.

THE MASTER POP MODEL

POP Models for Individual Design Meetings

During the feasibility study of the Green Dorm project, we have used the POP modeling methodology to collect, organize and evaluate the information generated during each design meeting. The documentation process relies on two techniques: (1) we create a POP model of the meeting in real-time; when possible we classify new items as related to Product, Organization or Process, and to Form, Function or Behavior, and we record the source of information; (2) once concluded the meeting, we review, corroborate and extend this model with the help of traditional meeting notes and the meeting audio recordings.

Integrated POP Model and Master POP Model

We generated several POP models to document the design information discussed in each stakeholder meeting. Taken together, these POP models document how the design progresses, and cover a broad variety of topics – with some overlap between them, since particular design topics may be discussed in multiple meetings. We also combined the POP models coming from individual design 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 or refinements of them; 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.

As the design progressed 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 more easily evaluated with respect to project goals, and to improve the communicative ability of the POP model. We met this requirement drawing upon the Integrated POP model, and a poll of the stakeholders and generated a Master POP model using the following process: (1) 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 3) and refine these until they serve as an accepted foundation for the entire project team; (2) 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 3 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.

Having generated this explicit representation of the project, we investigated whether it is possible to generate simple metrics to evaluate the state of integration on the project. We analyzed each POP model to calculate 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. At the bottom of Figure 4, the POP profiles evolve from a very product oriented and asymmetric (left), toward a more balanced POP profile (right) of the Integrated POP model.

Figure 4 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.

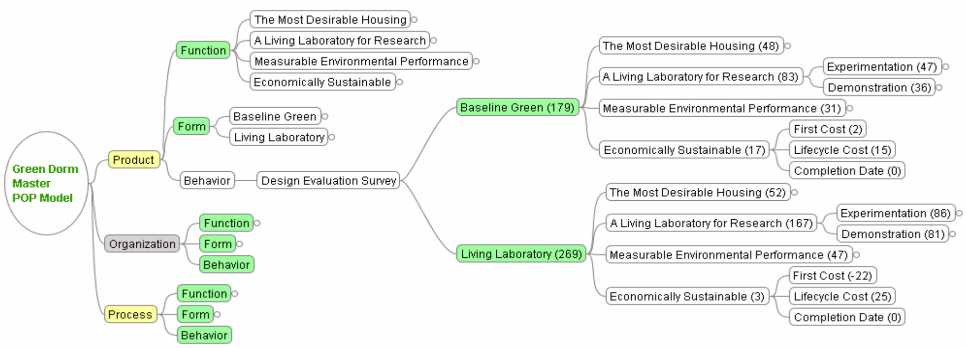

Figure 3: Master POP model, showing the Product-Behavior evaluation of two possible design configurations: Baseline Green and Living Laboratory. The ratings were determined by the design team, who evaluated each option with respect to its impact on the desired functions shown in the leaf nodes of Product Function, then added up to determine the ratings at the higher level node. This version of POP model is presented in a Freemind^{TM} format.

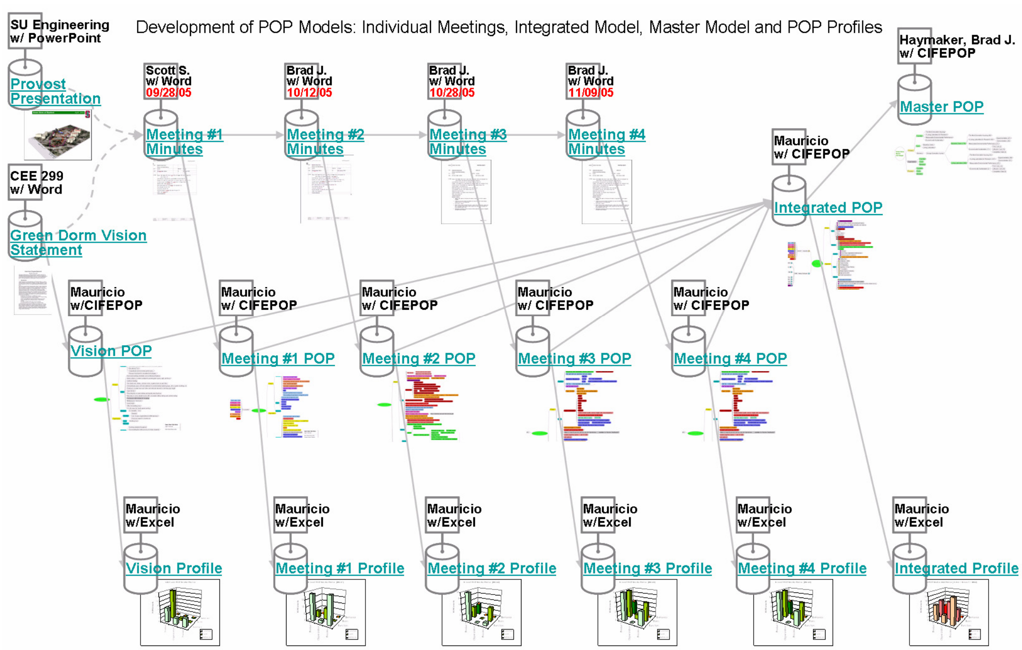

Figure 4: A Narrative describing the development of Master, Integrated and other POP models for the Living Laboratory design process. An interactive view of this Narrative, which allows individual represenations to be downloaded, can be found at: http://www.stanford.edu/~haymaker/gd/FeasibilityStudy/MasterPopNarrative

DISCUSSION AND ANALYSIS OF POP MODELING AND NARRATIVE USE ON THE STANFORD GREEN DORM FEASIBILITY STUDY

In this paper, we presented our use of two CIFE emerging methodologies and how they can assist the design of the Green Dorm at Stanford University. We find that the POP models we defined 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. In this way the POP model can guide designers towards areas where more consideration is needed, and help larger groups of stakeholders quickly understand the goals of the project, and the forms, behaviors, organizations and processes used to achieve these goals. The resulting energy POP model can serve as a departing point for further refinements of the energy systems design (after feasibility). We found the project overview (Master POP model) could be useful in assuring a more integrated design process, and in helping communicate much of the information needed to execute the design, in particular the definition of goals. For example, the POP models helped the design team to define the project goals (Figure 3, Product-Function). From this case study we learned that simplified POP models (e.g., Master POP Model) are particularly useful in conveying a project overview to a large and diverse group of stakeholders, but we might also think of a project in which more detailed POP models could "drive" the design.

We found our Narrative methodology to be useful for defining the dependencies between information. We found this a powerful way to communicate, and potentially integrate and automate design processes and information to enable the exploration and analyses of more design options. We shared our energy Narrative with the energy team and they saw value in the explicit representation of information and its dependencies for the integrated energy design, particularly when changing assumptions and values and understanding the propagation of those changes throughout the proposed design. Once the reader learns the notation, we find that our 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. As reasoning (not shown) can be included at each node, management processes (either manual or automated) can help the team propagate changes through the Narrative to assist in an up to date design (Haymaker et al, 2004), although these management processes have not been implemented in this project. This Narrative can help communicate the design process and its interdependencies to the design team, serve for the handoff of the feasibility study to a new team, or even as a template for future projects to follow and modify.

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 we believe we can design more fluid methodologies that enable AEC projects to quickly and accurately define and communicate the project goals, integrate their multidisciplinary information and processes and provide a replicable process roadmap for projects to come – what seems to us as a natural extension of our research.

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