A methodology to plan, communicate and control multidisciplinary design processes

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ABSTRACT: Architecture, Engineering, and Construction (AEC) projects require multidisciplinary solutions. To develop these solutions, AEC professionals need to construct their discipline specific information, but they also need to interrelate and make trade-offs with the information of other disciplines. Today AEC professionals have formal methods to construct much of their single discipline information; however, they lack formal methodologies to plan, communicate and control their multidisciplinary processes. As a result, AEC professionals struggle to design and execute good multidisciplinary solutions. By leveraging existing industry and our own methods and technology, we are designing and implementing such a formal methodology. Using this methodology, AEC professionals will collaboratively and iteratively define their objectives using our POP (Product, Organization, Process) method. They will develop options and analyze them using our Narrative method. They will decide upon options using our Decision Dashboard method. To develop this methodology, we are gathering test cases from ongoing AEC projects, implementing our methodology in the CIFE iRoom, re-enacting these test cases and conducting live charettes with our implemented methodology, and validating the extent to which this methodology enables AEC professionals to better communicate and control their multidisciplinary design processes. The scientific purpose of this research is to better formalize and manage design processes among many AEC professionals and their information. The practical purpose of this methodology is to enable AEC professionals to improve their multidisciplinary designs.

1 INTRODUCTION

Building Information Modeling (BIM) promises to revolutionize the way AEC professionals design and execute projects. Many anticipate a future where they will collaboratively use computer-based methods to improve the multi-disciplinary performance of their designs rapidly and execute these designs effectively (Khemlani, 2004). Today, AEC professionals are currently benefiting from discipline-specific BIMs and methods that improve single discipline performance. However, iterative multidisciplinary processes are difficult due to ad hoc methods for information communication and control. It is therefore difficult to optimally execute these projects. AEC professionals tend to sub optimize for single disciplinary performance, making late, over-budget, and functionally unsatisfactory projects all too 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) similarly characterize design as a goal-oriented, decision-making, exploration and learning process. Through literature review and observation of AEC projects, we have identified four interrelated and iterative design processes that we believe AEC professionals could formalize, and therefore better communicate, and control. AEC professionals need to be able to *define* the important functions their designs need to perform. They need to *propose* design forms, and they need to *analyze* the behavior of these forms with respect to their many required functions. Finally they need to *decide* which options most effectively satisfy their many functions. We observe that today AEC professionals struggle to *communicate* their goals, proposals, analyses, and decisions among project participants. They also struggle to *control* the integration of this information with the information of other participants and throughout this iterative define, propose, analyze and decide (DPAD) design process. As a result, AEC professionals struggle to *optimize* the multidisciplinary performance of their designs.

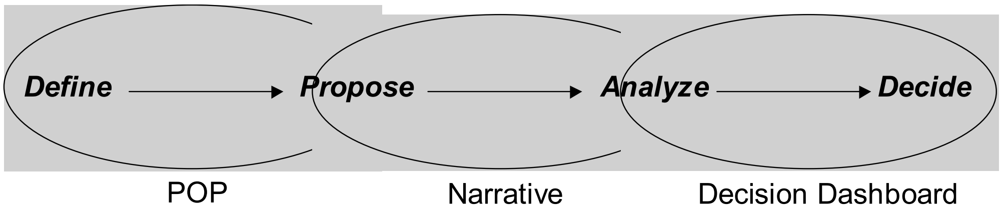

Figure 1: We are formalizing four interrelated design processes to help AEC professionals better communicate and control them: *define* design functions, *propose* design forms (these can be product, organization or process forms), *analyze* these forms, and *decide* on forms. To formalize these processes, we propose to integrate three CIFE methods: *POP* enables AEC professionals to *define* the functions, forms and behaviors of the products, organizations, and processes. *Narratives* enable AEC professionals to *propose* and develop many design forms and *analyze* these. *Decision Dashboard* enables AEC stakeholders to compare analyses, make tradeoffs, *decide*, and document their decisions.

We are therefore working to design and implement a methodology that enables AEC project teams to better communicate and control their DPAD processes. This methodology builds on three recent projects at the Center for Integrated Facility Engineering. AEC professionals will define the important functions, forms, and behaviors (FFB) of their products, organizations and processes (POP) using the POPFFB (or POP for short) method. They will rapidly propose and analyze many competing forms using the Narrative method. They will decide amongst these competing forms, making multidisciplinary tradeoffs and driving the project towards improved performance using the Decision Dashboard (DD) method. See Figure 1.

In this paper we describe a test case to motivate our methodology. We then describe our ongoing effort to formalize and implement this methodology. We are gathering test cases from current AEC projects. We are implementing this methodology in the CIFE iRoom. We will re-enact our test cases, and conduct live charettes using our implemented methodology. We will validate our methodology with respect to AEC professionals' ability to communicate and control their multidisciplinary design processes and information.

2 MOTIVATING TEST CASE

This test case describes and diagrams the design process an architecture firm went through to determine the costs and benefits of employing an atrium in an office building in Northern California. Figure 2 describes and diagrams some of the requirements they defined, some of the design options they proposed, some of the analyses they performed and a summary of the decision they made. The lines in the diagram are dashed because this process was not formalized in the computer.

The architect knows that atria can be effective ways to take advantage of natural light, reduce building energy consumption, and improve the quality of the work environment, and thus the productivity of the occupants. However, atria can cause uncomfortable glare conditions, have constructability and maintenance issues, and result in a bigger building footprint that costs money and takes longer to build. Therefore the architect wanted to know if they should employ an atrium on this project. They first defined the site description, researched the regulatory requirements, and worked with the client to define the client's requirements. Based on this functional information, they then proposed two design options, a design with an atrium, and a more traditional design with no such daylighting feature. Next, they set about to analyze these designs. They analyzed the amount of daylight in key work areas and at key times of the day, measuring 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 how long each design might take to construct, and how much each design might cost to construct. Using the first cost, and the energy consumption, they estimated the lifecycle cost of each design. They used all these analyses to inform their client, and themselves, as to the cost and the benefits of the atrium, from which the client could make a decision.

While the building is recognized as a highly innovative and successful example of sustainable architecture (Leventhal 2001), the architect struggled to effectively communicate and control this design process, and they did not optimize this design:

Communication: The architect provided a series of Microsoft Word™, Excel™ and other documents, containing over one hundred pages, in which they described the process they executed to determine the costs and benefits of the atrium. While the required design functions, proposed forms, analyzed behaviors, and decisions appeared in these documents, no diagram such as Figure 2 or other formal description of their DPAD design process that formally defined and interrelated these concepts existed for this project. The architect has expressed a desire to more effectively communicate their design process to the owner, to consultants on this and on subsequent projects, and to the design community as a whole in order to share a sound sustainable design process.

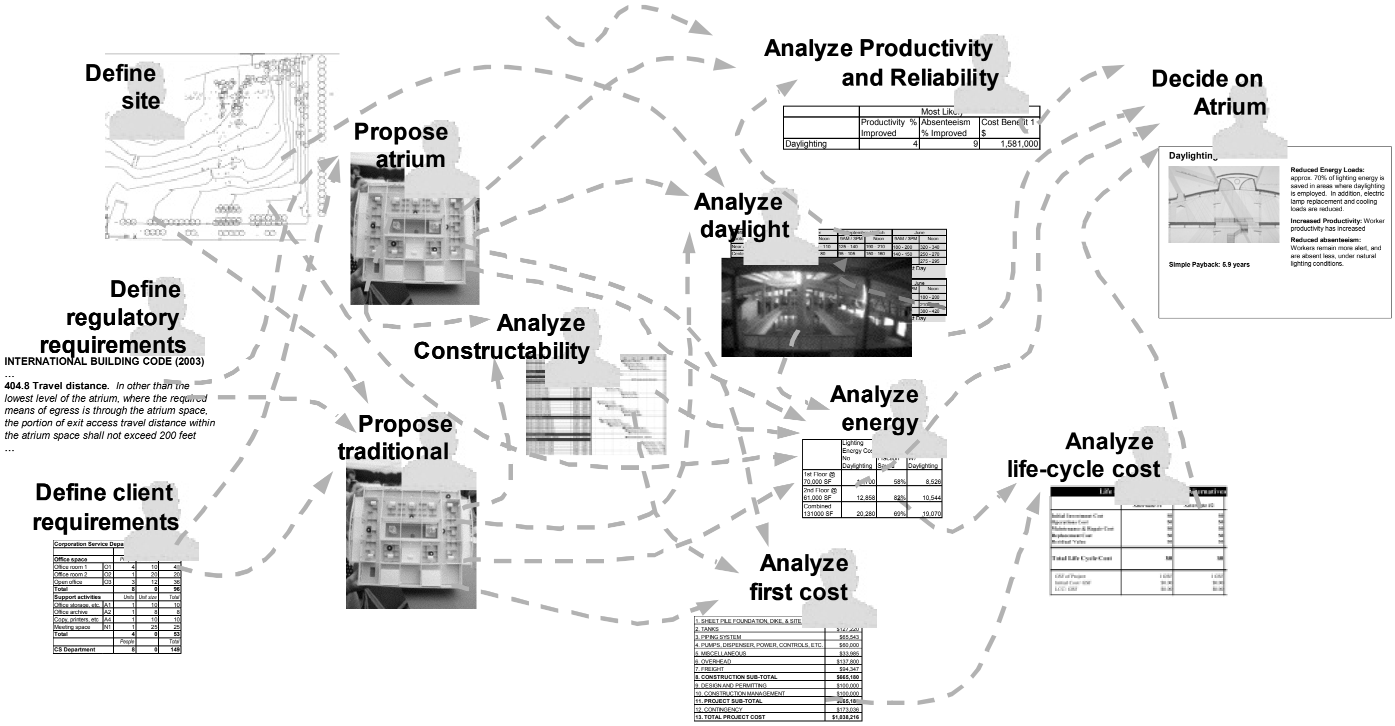

Figure 2: A portion of the design process an architect and their consultants executed to define project requirements (functions), propose design options (forms), analyze these options based on many requirements (behavior), and decide on the appropriate design options based on these analyses.

Control: The architect also struggled to control this design process. On examining their documents we found a failure to accurately integrate information from the energy analysis into the life cycle cost analysis. Integration difficulties between discipline-specific information have been well documented, for example: between requirements information and design information (Kiviniemi, 2004), between design information and analysis information (Kam and Fischer 2002), between design information and fabrication information (Haymaker et al 2004), and between analysis information and decision information (Kam, 2004).

Quality of Design Solution: Because of the difficulty communicating and controlling this design process, the design team was not able to fully explore this design. For example, they were unable to sufficiently explore many configurations of atria layout to determine the optimal layout for the energy, daylight, cost, and other criteria they determined were important. The ability to formally define and manage their information, the interdependencies between this information, and the decisions based on this information would have enabled the design team to more effectively communicate their design process to the owner and other project participants, more effectively control and automate this process for the exploration of more options, and thus improve their multidisciplinary design solutions.

3 POINT OF DEPARTURE

3.1 *Limitations of current BIM to support multidisciplinary design processes*

The concept of modeling a building project in a computer has had successes and received a lot of publicity in recent years. Despite promising progress to date, we only see ad hoc management of BIMs in support of the multidisciplinary collaboration. We review a successful multidisciplinary application of BIMs and identify some limitations from that state-of-the-art example.

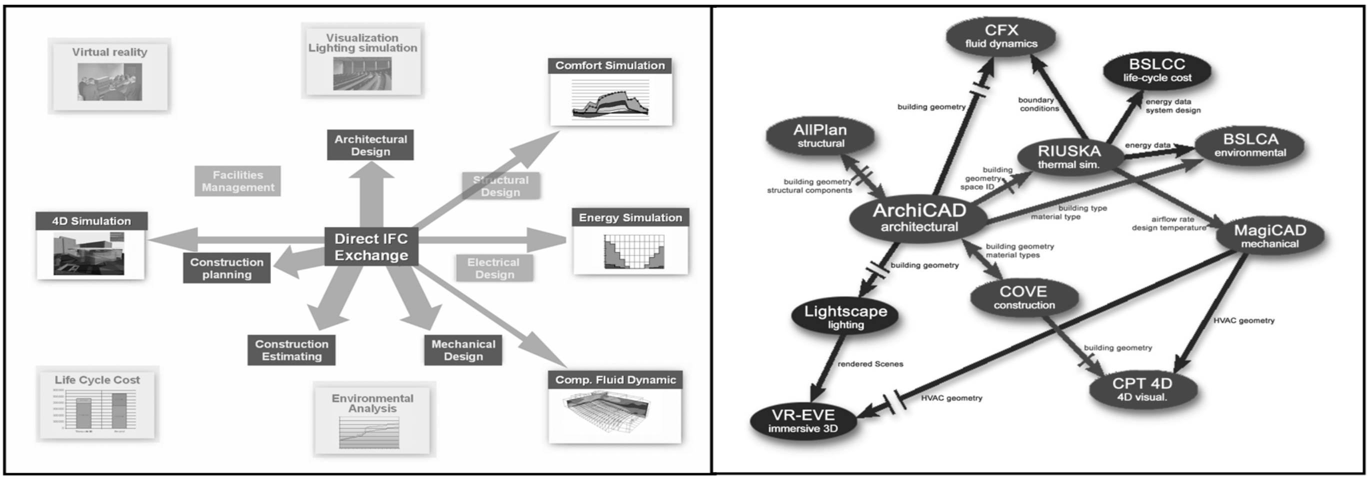

Figure 3: We captured both the theoretical concept (left) and the "chaotic" reality (right) of information exchange among the many BIMs from the HUT-600 Auditorium project in Helsinki, Finland. Although the project benefited from various domain-specific BIMs, iterative multidisciplinary proposals, analyses, and decision tradeoffs were difficult due ad hoc methods for information communication and control.

The HUT-600 auditorium project in Helsinki, Finland is one of the first industry projects to use an array of multidisciplinary BIMs in the design process (Kam and Fischer 2002). The architects, structural engineers, energy consultants, HVAC designers, and construction managers developed specific BIMs that addressed their disciplinary needs. As a result, these individual BIMs enabled the end-users to better visualize the design; the architect to improve his efficiency in producing design documents; and the energy and cost consultants to improve performance of their specialty services. However, the exchange process among the BIMs was ad-hoc and cumbersome in spite of the availability of an interoperable data exchange standard (See Figure 3). Decision-making focused on single-disciplinary proposals, such as HVAC choices (e.g., underfloor versus conventional systems) or architectural features (e.g., skylight versus windows), but not on integrated choices across multiple AEC disciplines (e.g., structural system relationships with different architectural or HVAC choices). There were no means or methods to define multidisciplinary objectives, propose and analyze multidisciplinary options, and make tradeoff decisions.

As this state-of-the-art example illustrates, AEC professionals in many disciplines are benefiting from BIM oriented computer applications, such as architectural visualization, daylight analyses, energy simulation, cost estimating, etc. Emerging data structures such as the Industry Foundation Classes (IAI 2005), CIMsteel Integration Standards (Steel Construction Institute 2003), and the Green Building XML Schema (GBXML 2005) are supporting limited data exchanges, and a number of software applications are implementing these data standards. We do not envision that a single BIM will adequately serve to communicate and control multi-disciplinary interests present in a building project. The case study illustrates that current AEC methodologies do not enable AEC professionals to easily communicate and control design processes consisting of many BIMs, such as multidisciplinary objectives, proposals, analyses, and decisions.

3.2 *Three Emerging CIFE Methods to Address These Limitations*

In our effort to address current limitations of BIM's to support multidisciplinary communication and control of design processes, we investigate three promising CIFE methods—POP, Narratives, and the Decision Dashboard as the starting points for our research.

The POP method (Kunz and Fischer 2005, Garcia et al 2003) enables AEC stakeholders to collaboratively *define* the important functions, forms, and behaviors of the products, organizations, and processes of an AEC project. For example, most BIMs are most commonly used to represent the form of the product (e.g., the architectural and structural systems and components of buildings). However, other aspects of the project design – as shown in the other cells of the POPFFB matrix – need to be made explicit and designed as well (see Figure 5). The POP method enables a broader and balanced communication and integration of these nine types of interrelated information models shown in the matrix. We suggest AEC project teams use the POP method to collaboratively define and communicate their many types of information.

The Narrative method (Haymaker et al 2004) enables AEC stakeholders from multiple disciplines to formally and iteratively construct information models from other information models and control the integration of these evolving, distributed, multidisciplinary models. AEC professionals will use Narratives to *propose* many options, and *analyze* these options by formally defining the dependencies between the defined functions, proposed forms, and analyzed behaviors, and to control the integration of these models. The Narrative method provides a graphical view of these dependencies.

The Decision Dashboard method (Kam 2005) enables AEC professionals to decide amongst project options. Represented in Decision Breakdown Structures (DBS), decision information includes competing sets of criteria (functions), decision topics, options, and alternatives (aggregations of options), and their relationships. The Decision Dashboard allows stakeholders to interactively change and evaluate choices as the decision process evolves. The DD makes all relevant decision information explicit and available for stakeholders to make and document informed decisions. It facilitates, but does not replace, the analysis or negotiation processes that are vital in AEC decision-making.

4 RESEARCH METHODS

To design our methodology, we are currently gathering test cases, refining the POP, Narratives, and Dashboard theory and prototypes, integrating the prototypes in the CIFE iRoom, implementing the test case into the prototypes, holding charrettes with AEC professionals, and validating our research. The following subsections explain these research tasks in further detail.

4.1 *Gather Test Cases*

We are observing real AEC projects and formulating case studies like those described in Sections 2 and 3. We are collecting the many representations the AEC professionals construct, and we document the issues they discuss. We are developing these observations into manageable test case scenarios, and use them to motivate, and develop criteria against which to validate, our work.

4.2 *Refine and Implement Our Methodology*

We are refining existing POP, Narrative and DD modeling application prototypes, deploying them in the CIFE iRoom, and defining interfaces among these prototypes. The interface development relies on a generic Representation object, which all three methods specialize for their purpose. POP adds the POPFFB classification, Narrative adds dependency information, and DD adds Decision classification and relationships.

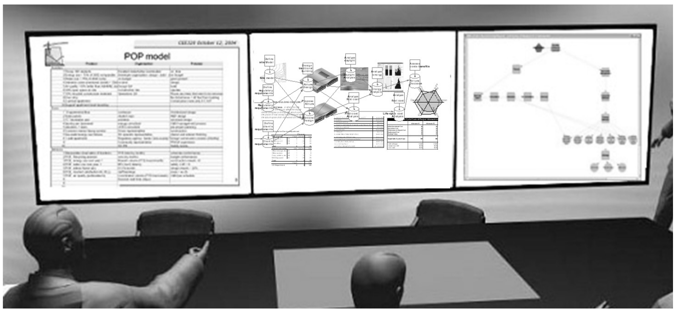

Figure 4: A mock up the integrated POP (left screen), Narratives (center screen), and Decision Dashboard (rights screen) in the CIFE iRoom.

4.2.1 *Define and Analyze with POP Modeling*

AEC professionals will use POP modeling (see figure 5) to define the key project requirements (i.e. functions), options (i.e., forms), and analyses (i.e., behaviors) of the project's Products, Organizations, and Processes (see Figure 5). Current POP models are built in Microsoft Excel; we plan to develop a simple prototype with a similar interface that will enable AEC professionals to define each of the Product-Organization-Process-Form-Function-Behavior *Representation* elements. POP modeling will promote synchronous, communication of multidisciplinary information models among the project's stakeholders.

	Product	Organization	Process
Function	Respond to Site Regulatory Requirements Clients Requirements Good Daylighting Low Lifecycle Cost …	Energy Expertise Product. Expertise Daylight Expertise Fast Inventive …	Sustainable On time On budget Meet LEED Reqmts
Form	**Atrium** **No Atrium** Green Roof Metal Roof Raised Floor HVAC Overhead HVAC	Energy Consultant Construction Mgr Lighting Consult- Architect Daylight Software …	Design Sched Const. Schedule LEED Certification
Behavior	**Daylight Analys.** **First Cost Analys.** **Energy Analys.** **Lifecycle CostsAnalys.** **Productivity Analys.** **Structural Analys.**	Many Options Good Light *Analys* Good Prod Analys Minimal Rework …	Meet Finish Date Meet Budget No Change Orders Minimal Latency Many Light Analys.

Figure 5: POP models define the important Forms, Functions, and Behaviors of the project's Products Organizations and Processes. For example, this POP model defines an atrium and no atrium as two proposed form options, and defines the need for several analyses of the behavior of these forms, including Daylight, Cost, Energy and Productivity (shown bold).

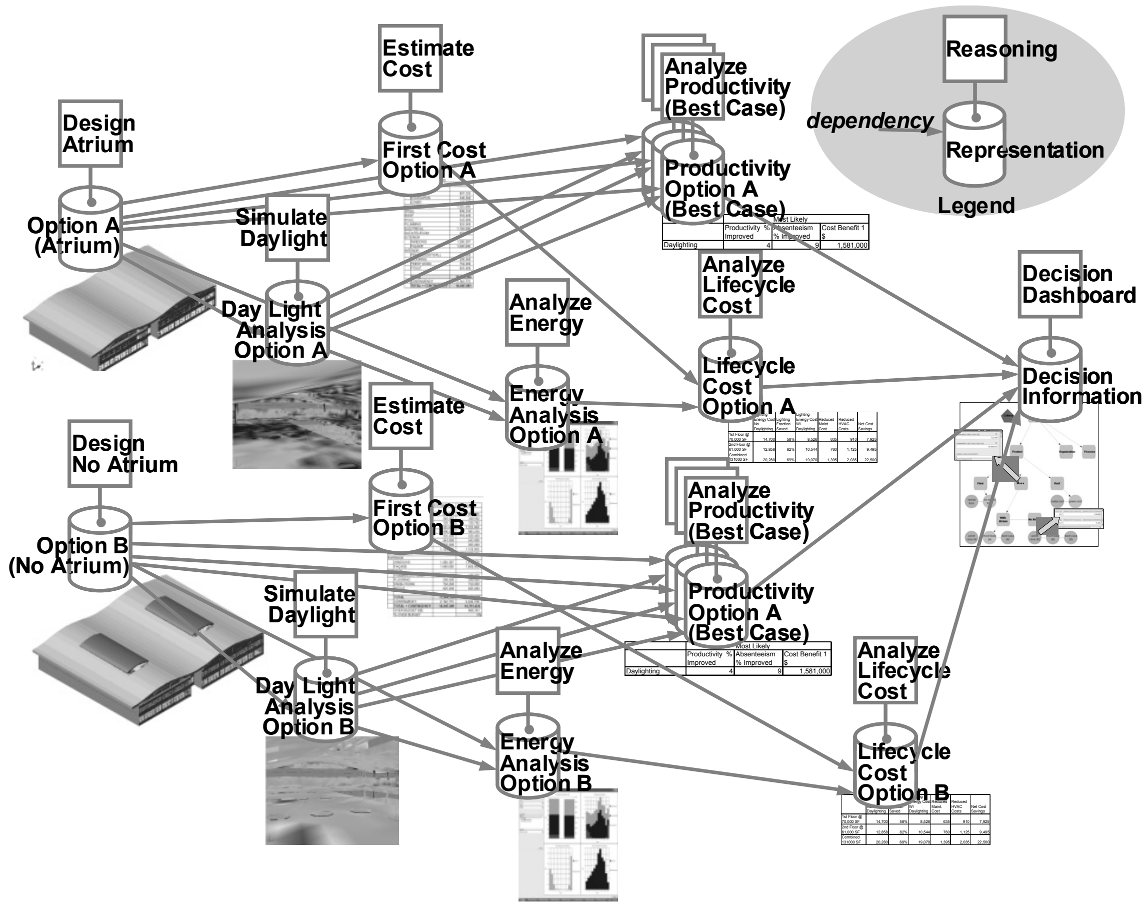

Figure 6: Narratives formalize and control the dependencies between information models. This Narrative formalizes the dependencies between the Atrium and No Atrium design options, and the many analyses of these options. The information in these Narratives serves as input to the Decision Dashboard.

While the POP model makes the main elements of a project's Function, Form, and Behavior with respect to its Product, Organization, and Process explicit, it does not make the dependencies between these elements explicit and therefore does not inform the process the project organization should carry out to design the project forms to accomplish the functions. Narratives inform this process by representing these dependencies.

4.2.2 *Propose and Analyze with the Narratives:*

Narratives (see figure 6) formalize and control the sources, nature, and status of the dependencies amongst information models. A node in a Narrative consists of Representation and Reasoning. The representation (e.g., a BIM describing the architectural design of the office building with an atrium) serves as the information repository for professionals and their software tools for a particular task (e.g., Estimate Cost). The reasoning specifies how the task (a combination of human and software activity) transforms the information from the information sources (repositories) into the information generated by the task. By relating tasks (including their representation elements and tools) to each other a network of dependencies between, for example, forms and behaviors emerges, allowing AEC professionals to design, communicate, and control the design process explicitly. AEC professionals will use Narratives to help them propose and analyze different competing options (e.g., propose atrium and other designs, and perform energy and cost analyses). Our current implementation of Narratives constructs and controls dependencies between geometric models (Haymaker et al 2004b); this research will extend the Narrative implementation to construct and control dependencies between generic representations.

4.2.3 *Analyze and Decide with the Decision Dashboard:*

Through the application of POP models and Narratives, professionals should be able to generate the right options with the best multi-disciplinary process possible. Now, AEC stakeholders need to make the appropriate trade-offs between and decisions about the generated options. To do so, they then can use the Decision Dashboard (DD, see figure 7) to make design decisions from information constructed in both the POP and Narratives applications. The form and behavior elements of the POP and Narratives inform the options from which the stakeholders need to select the best. The functions become the criteria against which the options will be evaluated. The Narratives give the decision makers the confidence that the options were analyzed in a consistent and integrated way. They also offer the potential to adjust or redo the analyses quickly and consistently should

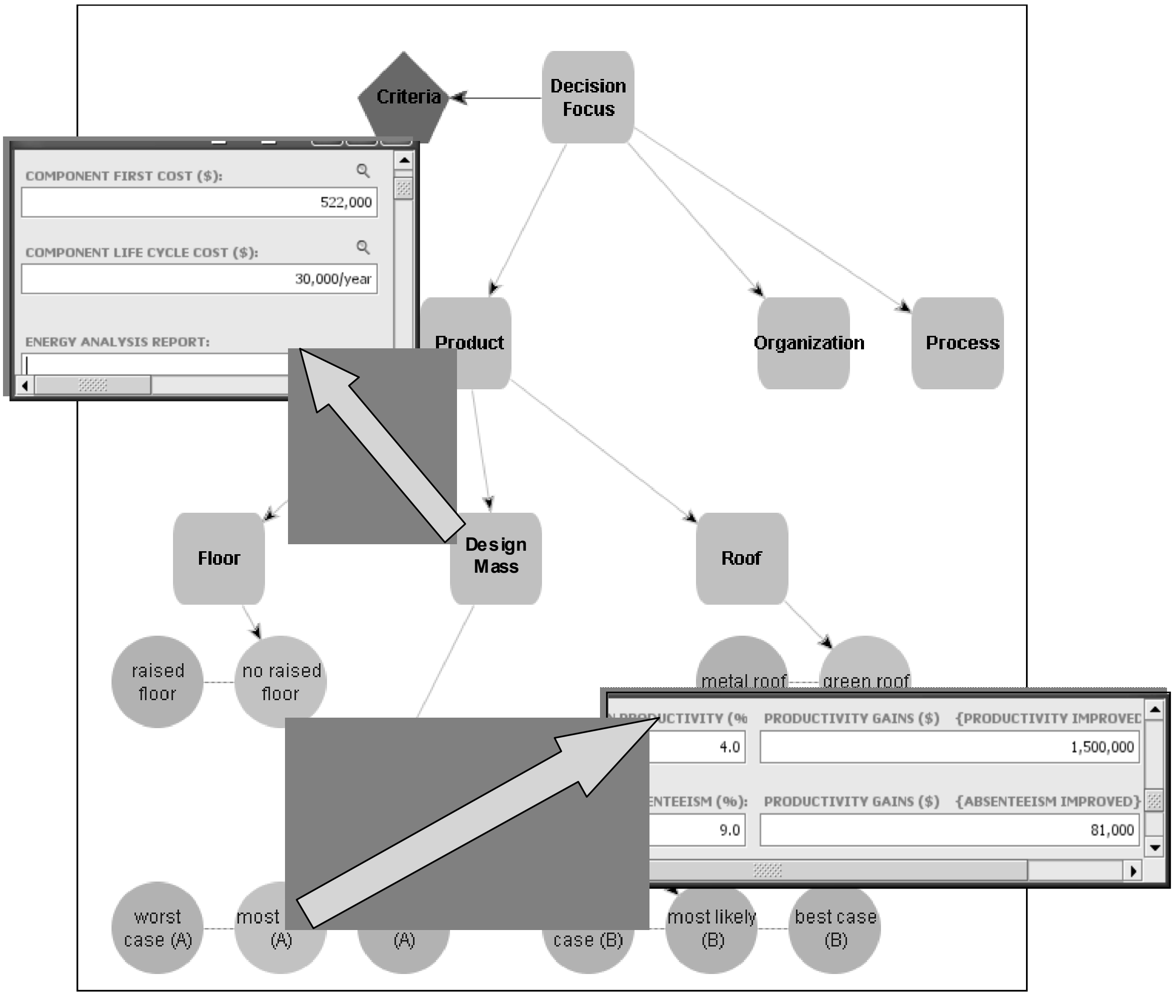

Figure 7: The Decision Dashboard enables AEC professionals to manage project options and facilitate the decision-making process. This DD organizes the atrium and no atrium design options under a decision topic called "Design Mass". Each Design Mass option has associated worst, most likely, and best-case options for the productivity analyzed in the Narrative. When a DD user switches the arrow from one option to another, the DD automatically propagates the effects of this change up this hierarchy, such that the currently selected decision topic, such as Design Mass, has productivity, lifecycle cost, and any other attributes that are defined lower in the hierarchy.

the criteria or options change during the decision making process. Thus, the DD serves as a decision-support tool for AEC professionals to analyze integrated decision information and to document the decision-making process for other AEC stakeholders.

4.2.4 *Apply the methodology*

We will re-implement the test cases we gather using our *DPAD* methodology. We will also re-enact these test cases in charettes with students and AEC professionals. These charette participants will first use the POP approach to define the important models for the project. They will then use the Narrative framework to establish and control the interdependencies (either manually or automatically) between these models. Finally, the participants will use the Decision Dashboard to organize, enhance, and document the decision trade-off process. As the prototype matures, we will work with these participants to apply our methodology on their current multidisciplinary design and analysis problems.

4.2.5 *Validate the methodology*

The test cases will allow us to validate for the extent to which POP, Narratives, and DD help AEC professionals communicate and control their multidisciplinary projects. While gathering case studies, we are documenting the performance of the AEC teams in terms of the following communication and control metrics. We will then compare the performance of AEC teams using our methodology with this baseline data:

Communication: We will measure the number of stakeholders involved, the number of contributions made by these stakeholders. We will also measure the quality of communication by these stakeholders through a DEEP analysis (Garcia et al, 2003). DEEP measures the amounts of time AEC professionals spend in meetings Describing, Explaining, Evaluating, and Predicting. The purpose of this metric is to measure if AEC teams are communicating effectively. The idea being that if they can spend less time Describing and Explaining, and spend more time Evaluating and Predicting, they are communicating more effectively, and adding more value.

Control: We will measure the latency and rework involved in the data integration among different information models. We can measure the amount of time each information model remains not integrated with respect to the information models on which it depends. We can also measure the amount of time AEC professionals spend working on information that is not integrated. The purpose of this metric is to measure how quickly and accurately AEC teams are able to control their design processes.

5 CONCLUSION

AEC projects lag behind other industries in formalizing and controlling their processes. This is in large part due to the multidisciplinary and unique nature of AEC projects. We are working to design a collaborative design environment in which AEC teams can formalize their DPAD design processes . We are doing so through specializing three interrelated methods: POP, Narratives, and Decision Dashboard.

We expect that more formal and transparent definition, proposal, analyses, and decision processes will improve the communication between the many information models and the many stakeholders. We also expect that our refined prototype and interfaces will minimize data re-entry and shorten integration delay across multidisciplinary needs, enabling better process control. Finally, we expect that improving the communication and control of the multidisciplinary design processes will improve the quality of multidisciplinary solutions.

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