Narratives: Composing and controlling persistent assistants to communicate, integrate, and automate multidisciplinary design and analysis

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Abstract

We discuss an approach in which engineers formally and iteratively construct information representations, called Perspectives, from information in other Perspectives using personal computational assistants, called Perspectors. Engineers can select from predefined, reusable, Perspectors, or program new Perspectors, and compose them into directed acyclic graph structures, called Narratives, to quickly and accurately construct useful dependent Perspectives. The approach also formalizes simple management processes with which professionals can control the integration of their Perspectives with respect to the Perspectives on which they depend. The result is an evolving, distributed, multi-disciplinary and integrated project model. We describe one conceptual Narrative that formalizes a multidisciplinary cost-benefit analysis to help designers choose amongst sustainable strategies. We describe one implemented Narrative that automatically generates a metal decking contractor's connection details that are needed to connect concrete slabs that are described in an architect's model and steel beams that are described in a steel detailers model. We discuss how these Narratives could have enabled engineers to better design, communicate, integrate, and automate their design processes than is possible on a recent state-of-the-art AEC projects. Narratives are intended to enable engineers from multiple disciplines to engage in novel, automated, and integrated design and analysis by easily yet formally constructing and integrating Perspectives from other Perspectives.

Introduction

Architecture, Engineering and Construction (AEC) projects are multidisciplinary, constructive, iterative, and unique processes. On these projects, AEC professionals, such as architects, consultants, contractors, detailers, and fabricators use task-specific representations to design, plan, and execute a project. These representations contain information that is ideally structured for their specific task, describing everything from existing conditions, to project requirements, to design options, to design analyses, to construction documentation, to fabrication, to installation and as-built information AEC Professionals often construct the information in these representations based on information in other engineers' representations, Dependent representations often become source representations of other dependent representations: A network of dependencies between distributed, task-specific representations emerges as the design progresses. When source representations are modified, dependent representations often must be integrated.

That is, AEC professionals develop what we call narratives for their own work and interweave them with narratives of other engineers. The Oxford English Dictionary defines a narrative as "An account of a series of events, facts, etc., …with the establishing of connections between them." In AEC practice, narratives help professionals expose cross-disciplinary impacts and integrate their work with the work of other project stakeholders; however, currently these narratives are not formally represented or managed. Surprisingly, the connections between different disciplines information, in this case the dependencies, are not generically represented but rather stored locally, or in the heads of the professionals.

This way of constructing, organizing, and communicating project information is proving to be time-consuming, error-prone, and expensive. AEC professionals would benefit from computational assistance in constructing and integrating their project specific engineering narratives. However, AEC projects are unique, formalizing the dependencies between their representations a priori has proven very difficult. This paper describes the need for, and a proposed way toward, enabling AEC professionals to define their own formal MDA Narratives. These Narratives consist of a collection of design and analysis representations, "connected" by dependencies.

We first describe industry test cases that illustrate the multidisciplinary, constructive, iterative, and unique character of AEC projects. The test cases show that these projects can be structured as MDA Narratives, that it is difficult today to predetermine the specific content of these narratives, and that therefore engineers could benefit from methods that enable them to more easily and formally construct and control their own project specific MDA Narratives. We then review the knowledge base of the AEC profession with respect to representing and

interrelating multidisciplinary project information and propose professionals need a simple, formal, generic, expressive collection of generic representation, reasoning, and management methods that enable AEC professionals to collaboratively construct and control MDA Narratives. These methods should be persistent, in order to control the integration of Narratives. We describe our ongoing efforts to implement such methods, examples of one implemented and one conceptual Narrative, and ongoing efforts to validate the benefits of Narratives with respect to how they enable AEC professionals to better communicate, integrate, and automate their MDA design processes.

Test Cases: the narrative structure of AEC projects

This section briefly describes two test cases that illustrate the implicit narrative structure of AEC projects, the difficulties professionals have executing these projects, and the benefits that could be derived by formalizing the narrative structure of these projects.

Cost benefit analysis for skylights and atria

On each project, Cradle-to-Cradle (C2C) designers like William McDonough Partners (WMP) study local and global conditions and work to define and exceed project specific economy, ecology, equity, and elegance goals. William McDonough says that C2C designers work toward these goals by asking and answering many questions (McDonough 2004). Yet in order to answer their questions, C2C designers often need to ask other related questions: an implicit narrative of interconnected questions (reasoning) and answers (representations) emerges as the project progresses. This test case describes a narrative of questions and answers that WMP raised regarding the costs and benefits of employing various design strategies such as an atrium and skylights.

Figure 1 describes and diagrams the narrative of questions WMP and their consultants asked, the answers they constructed for these questions, and the information dependencies between these questions and answers. The lines are dashed because the dependencies, or connections, between representations were not formalized in the computer.

WMP knows that atria and skylights can be effective ways to take advantage of natural light, reduce building energy consumption, and improve the quality of the work environment. However, both skylights and atria cost money, can cause uncomfortable glare conditions, and have constructability and maintenance issues; and atria generally result in a bigger building footprint. Therefore WMP wanted an answer to the question: What are the costs and benefits of skylights and an atrium on this project?

This building was to house some of the client's most valued and talented employees. Were the added daylight from the skylights and atrium to appreciably improve the productivity and reliability of their workforce, this would be a strong argument for including these features. WMP studied industry data that has measured the improved productivity and reliability of the workforce in similar environments, and constructed a reasonable estimate for the expected productivity gain and absenteeism improvement in a strategically day lit space compared to a more traditional, artificially illuminated space. As a business, they needed to weigh this expected productivity gain against the expected lifecycle cost of constructing and operating the building. To calculate this cost, they asked what the added construction cost and potential energy savings (due to the reduction in artificial light) would be. In order to answer these questions, they needed to ask how much natural light would enter the building should different combinations of skylights and atria be employed. In order to answer these questions, they needed to ask what a building with and without atria and skylight might look like. In order to answer these questions, they asked about the client's requirements, the prevailing regulatory requirements, and the characteristics of the site.

No diagram or other formal description of such a narrative existed for this project. WMP provided a series of Microsoft Word™ documents, containing over one hundred pages, in which they described the process they executed to determine the costs and benefits of the skylights and atrium. Because of the time and resource constraints, WMP was not able to fully explore this narrative. For example, they were unable to sufficiently explore many configurations of skylight and atria layout to determine the optimal layout for the energy, daylight, cost, and productivity criteria they determined were important. We believe the ability to formally represent this narrative in the computer would have enabled WMP to more effectively communicate their design logic to the owner and other project participants, more effectively integrate and automate their design representations for the exploration of more options, and achieve more optimal design solutions.

Design and fabrication of deck attachments

Figure 2 describes a portion of the design and construction of the Walt Disney Concert Hall's steel and concrete frame. The lines are dashed because on this project the connections between representations were not formalized in the computer; the project engineers maintained them in an ad-hoc and manual manner. The architect (see Figure 2A) constructed and integrated a Concrete Slabs representation describing the boundary of each concrete slab on the project. From this and other representations, the structural engineer (see Figure 2B) constructed a Framing Center Lines representation describing the centerline of each steel member required for the frame of the building. The steel detailer (see Figure 2C) constructed a Steel

Framing representation describing the boundary of each steel member and its fasteners. The metal decking detailer (see Figure 2D) constructed a Deck Attachments representation describing where to install attachments to connect the metal decking for concrete floor slabs to the structural beams (see Figure 2F). The metal decking detailer constructed this representation by drawing a line along the edge of each beam where an attachment was required (see Figure 2G). The steel fabricator (see Figure 2E) fabricated the beams, welding the required deck attachments to the respective beams in the shop. The design process was iterative. Changes in the design of the concrete slabs needed to propagate through the narrative, requiring modifications to the steel design and therefore to the deck attachment design.
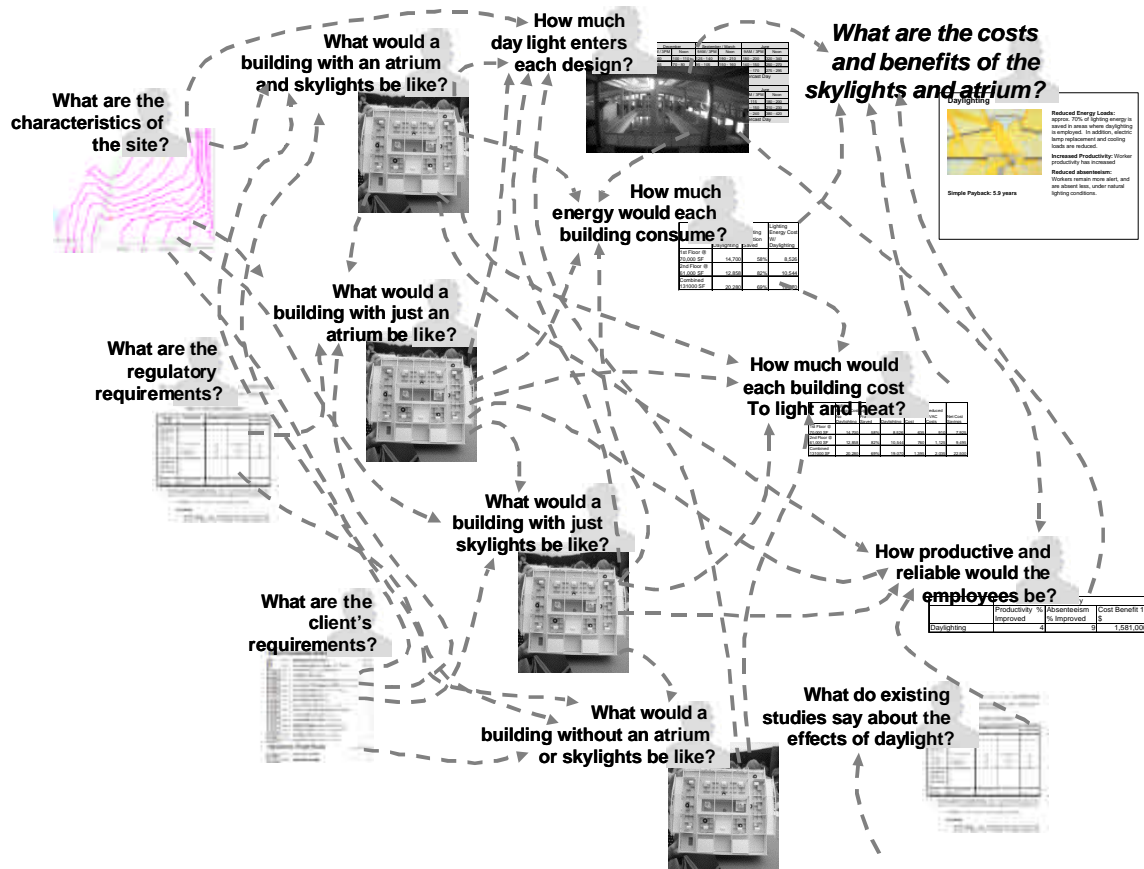

Figure 1: A narrative of questions (reasoning) and answers (representations) that WMP used to understand the cost benefit of using an atrium and configuration. The arrows between answers and subsequent questions are shown as dashed because the dependencies are not formally represented in a computer.
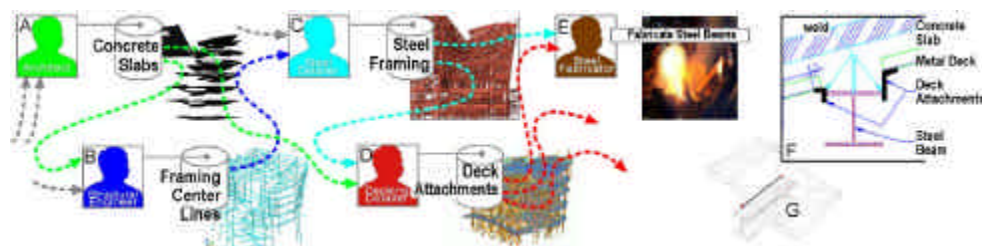

Fig. 2: A portion of the narrative the AEC professionals used to design and construct the Walt Disney Concert Hall. AEC professionals (humans shown in boxes) construct task-specific representations (shown as database barrels) from other representations. The arrows are shown as dotted, because the connections between these representations remained implicit; the engineers did not formalize them either in their documentation or in a computer model.

Observations from test cases

The test cases illustrate (Haymaker et al 2004a) that AEC projects are *multidisciplinary*: AEC professionals on these projects construct discipline-specific representations of the project to do their work. AEC projects are *constructive*: these professionals construct representations from information in other representations. AEC projects are *iterative*: When source representations are modified, dependent representations must be integrated. AEC projects are *unique*: Atria and deck attachments are an issue on some, but not all projects. Finally, as practiced today, AEC projects are *error prone, time-consuming and difficult*.

In Haymaker et al 2004 a, we proposed that AEC professionals could have addressed many of these difficulties by formalizing their MDA Narratives. More specifically, we propose that MDA processes could be augmented by, if not founded on, simple formal, generic, expressive methods to construct information by formalizing its dependency on other disciplines' information and by controlling the integration of this information as the project progresses. A formal MDA Narrative could emerge as AEC professionals iteratively apply and manage such methods.

Formalization:

In Haymaker et al 2004 b we proposed formalization for Narratives. Called the Perspective Approach this formalization enables AEC professionals to specify the sources, status and nature of the dependency of their representation, called a Perspective, on other Perspectives.

· *Sources:* The source information on which dependent information depends.

· *Status:* Integration status of the information with respect to its source information.

· *Nature:* The reasoning method (automated or manual) that constructs the dependent information from source information. We call this reasoning method a Perspector.
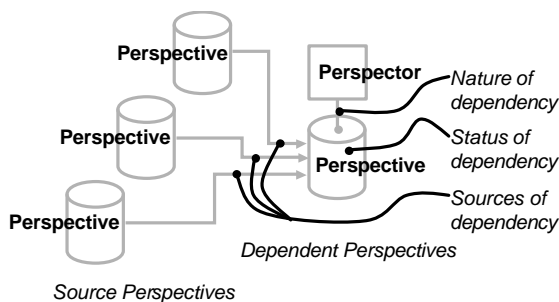

Figure 3: Formalizing the sources, nature, and status of the dependency of a dependent view on source views.

Fig. 3 diagrams this formalization of the dependency of dependent information on source information(s). Fig. 4 shows that a formal Narrative can emerge form the iterative

application of this representation method. It also shows that the Perspectors are generic, and can therefore specify either human or automated, off-the-shelf or user defined reasoning.

The Perspective Approach also formalizes Management Processes to help AEC professionals control the integration of these Narratives in which Perspectives are persistently notified when source Perspectives are modified. Perspectors can be persistently run, to reintegrate these Perspectives automatically, or, can wait for user requests to integrate.
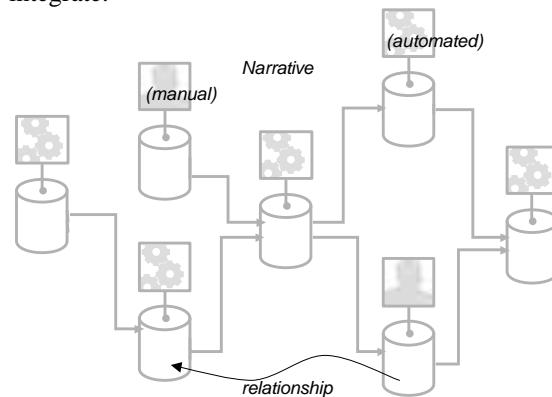

Figure 4: A Narrative emerges from the repeated application of the formalism described in A.

POD: Approaches to building information modeling

In this section we discuss related efforts in research and practice in the area of representing, reasoning about, and managing building information models. We first discuss efforts to formally represent building information. We then discuss efforts to develop reasoning algorithms to automate the construction and analysis of this information. Finally, we discuss efforts to integrate representation and reasoning into project model frameworks for AEC. We conclude that while the representation and reasoning work serves as excellent building blocks for Narratives, efforts to integrate AEC project information, which primarily relies on predefined, centralized project models, do not adequately address the multidisciplinary, constructive, iterative, and unique nature of AEC processes.

Representation: Most AEC projects today rely on proprietary information formats, resulting in serious interoperability difficulties when multiple project stakeholders adopt different proprietary solutions. To address these difficulties, industry and government have initiated major efforts in the area of generic engineering data standards, including STEP (Standard for the Exchange of Product data (ISO, 1994)) and IFC (Industry Foundation Classes (IAI, 2004)). For example, the schema defined in IFC 2.X enables an engineer to represent Ifcbeam features and Ifcslab features. As currently formalized, these

standard representation languages do not contain an explicit mechanism for representing the existence, status, and nature of the dependencies between information from different disciplines.

Reasoning: Computer programs that automatically construct useful task-specific dependent information from source information are increasingly used in practice today. AEC professionals are using programs for daylight analysis (Radiance 2004), energy analysis (DOE2 2004), structural analysis (SAP2000 2004), cost estimating (Timberline 2004), and automated steel detailing (Tekla, 2004), among other uses. Considerable research is devoted to improve on and extend these suites of task-specific, automated design and analysis programs. We discuss many of these efforts in Haymaker et al 2004c.

Other approaches to constructing task-specific representations of project information are more generic. Query languages (Date and Darwen 1993) enable the automatic selection or limited transformation of information in a model into a view. Feature Recognition (Dixon and Poli 1995) identifies instances of feature classes in a geometric model. Recent approaches in mechanical engineering (Lou et al 2003) investigate generic CAD query languages that enable engineers to query a model for geometric features. Generally, today there is a wealth of task-specific and generic reasoning tools, but what is needed is a general, simple framework to integrate these methods.

Project Model Frameworks: To address this need, some (i.e., Eastman and Jeng 1999, Haymaker et al 2000, Autodesk 2003, Sacks et al 2004) develop reasoning and management that constructs and controls dependencies of information in a predefined central model. For example, Eastman and Jeng 1999 formalize a system, called EDM-2, in which applications construct task-specific views of a central model and write information back into the model. Other applications then reconstruct their task-specific view of this modified central model. Others (Khedro and Genesereth 1994, Sriram 2002, Bentley 2003) develop similar reasoning and management approaches that construct and control dependencies between information in a federation of predefined task-specific views. In both these central and federated model approaches, system programmers are generally required to define the nature of the dependencies.

Parametric techniques (Shah and Mäntyla [35]) enable professionals to define sets of related numeric or symbolic equations that can be solved to realize feasible designs. Commercially available parametric modelers, such as CATIA, provide tools to assist engineers both in generating 2D sketches from which 3D form features are parametrically generated and also in specifying the assembly of these form features parametrically with respect to the positions of other form features. Some systems employing parametric techniques are being commercially introduced specifically for the AEC industry, such as XSteel (Tekla 2003), Revit (Autodesk 2003), Object Genome System (Onuma 2004), and Generative Components (Bentley 2004). While some successes are being reported within the context of single domains (Sacks 2004), parametric techniques are not being widely used in the AEC industry to integrate the work of multiple disciplines. This is because, as currently formalized, these techniques have not adequately supported the multidisciplinary, constructive, iterative, and unique nature of AEC projects: They do not enable professionals to easily and formally construct new representations from information in other professionals' representations, and control the integration of these representations as the project progresses.

Project management systems, such as Primavera (2004), are task-focused representations of a project. They represent precedence dependencies among tasks and are used to calculate issues such as project duration. They do not contain an explicit representation of task-specific information, nor do they represent or manage the nature and status of the dependencies between this information.

Current project modeling frameworks do not provide adequately simple, formal, generic, expressive methods that AEC professionals need to construct and control their MDA Narratives. Instead professionals are utilizing a hodgepodge of AEC systems that in many ways complicate the streamlining and integration of information and communication.

ONGOING WORK: FORMALIZING AND IMPLEMENTING MDA NARRATIVES

This section describes ongoing work in which we are gathering and formalizing test cases; building frameworks in which to implement the test cases, and validating Narratives in terms of their ability to improve communication, integration, and automation, and by extension, design.

Gather and formalize test cases

Figure 5 diagrams and describes a formal MDA Narrative for the cost-benefit analysis test case. The figure shows that any Perspector can itself be decomposed into a sub-Narrative. Such decomposition aids the thought process when constructing a Narrative, and enhances the readability of a composite Narrative.

Decomposition of Perspectors into sub-Narratives can conceptually extend to a very low level. In Haymaker et al 2004b & c, we compose a sub-Narrative of geometric selection, reformulation and generation Perspectors that together automatically construct the Deck Attachments Perspective from the Concrete Slabs and Steel Framing Perspectives. See Figure 6. In these papers, we also show that these Perspectors can be reused in different Narratives, suggesting that a generic language of low-level Perspectors can be defined and reused, significantly reducing or eliminating the need to write computer code.
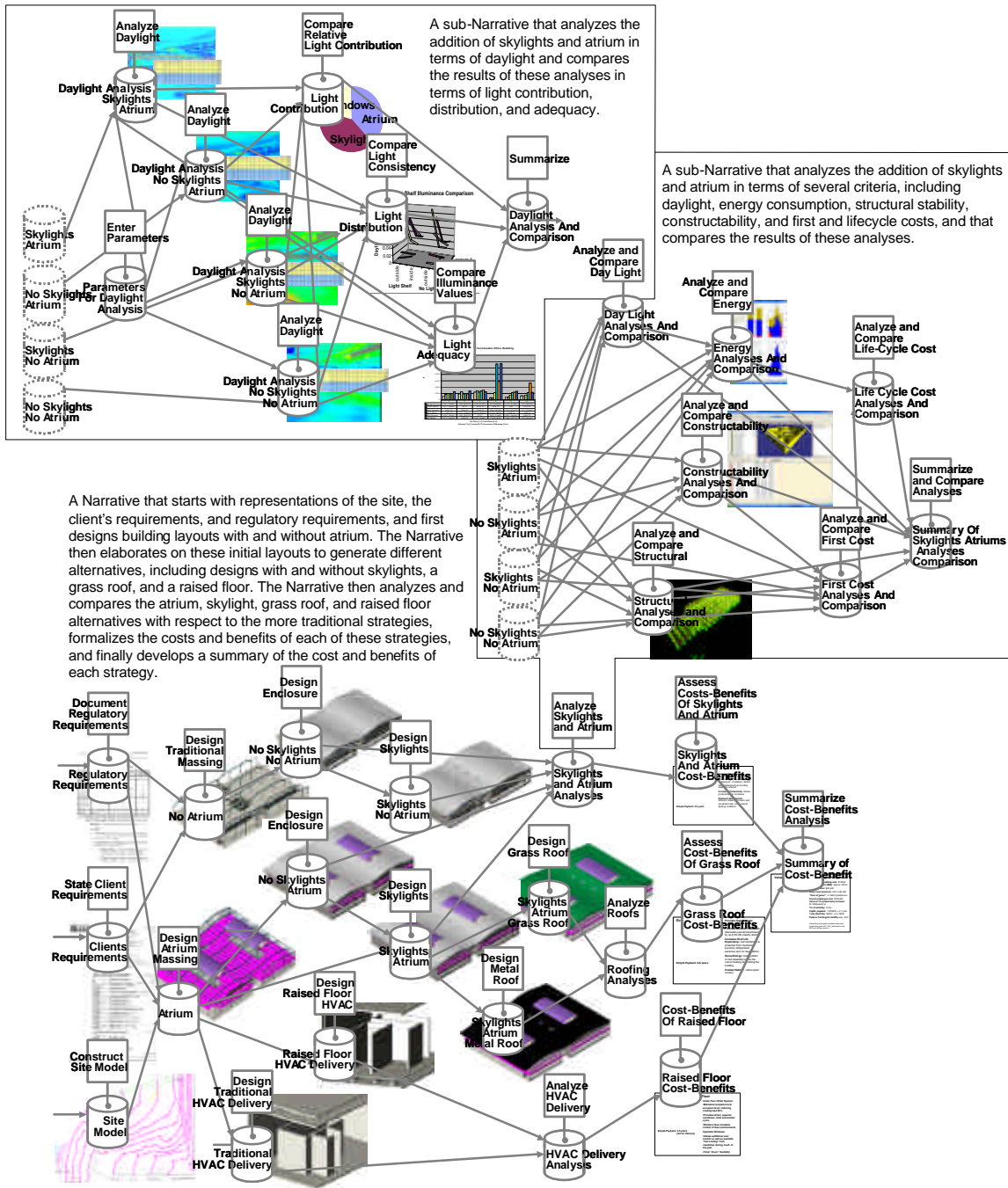
A sub-Narrative that analyzes the addition of skylights and atrium in terms of daylight and compares the results of these analyses in terms of light contribution, distribution, and adequacy.

A sub-Narrative that analyzes the addition of skylights and atrium in terms of several criteria, including daylight, energy consumption, structural stability, constructability, and first and lifecycle costs, and that compares the results of these analyses.

A Narrative that starts with representations of the site, the client's requirements, and regulatory requirements, and first designs building layouts with and without atrium. The Narrative then elaborates on these initial layouts to generate different alternatives, including designs with and without skylights, a grass roof, and a raised floor. The Narrative then analyzes and compares the atrium, skylight, grass roof, and raised floor alternatives with respect to the more traditional strategies, formalizes the costs and benefits of each of these strategies, and finally develops a summary of the cost and benefits of each strategy.

Figure 5: A conceptual Narrative to formalize a cost-benefit analysis

Find Deck Attachments Perspector

The Find Deck Attachments Perspector analyzes the Slabs Perspective (produced by the Architect) and the Steel Framing Perspective (produced by the Steel Detailer) to automatically construct the Deck Attachments Perspective. The Find Deck Attachments Perspector also relates each deck attachment with their associated slab and beams. This Perspector can be decomposed into a sub Narrative that reformulates slabs and beams then performs geometrical analyses and generates deck attachments where they are required. A rendering of a typical feature is shown under each representation.
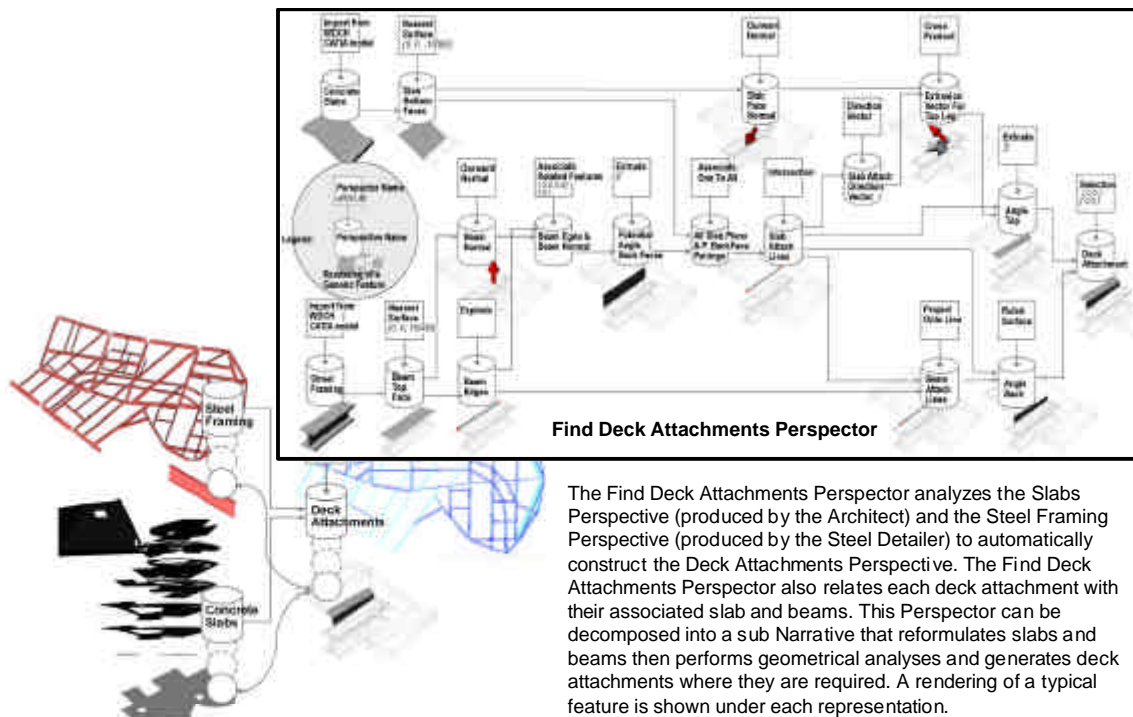
Figure 6: Applying Narratives to the Deck Attachment test case.
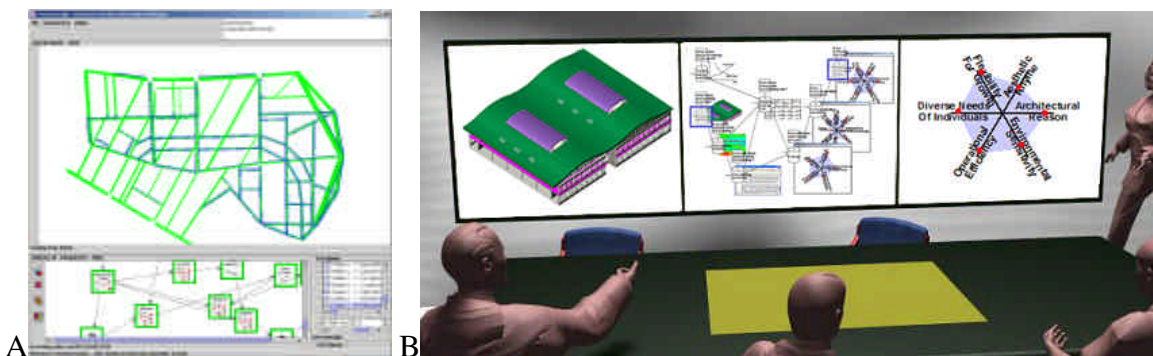

Figure 7: Implementations of a *Narrator* that enables engineers to quickly connect reasoning and representations into MDA Narratives. **A.** Our initial software, which implemented the deck attachment test case. **B.** A future implementation of the Narrator mocked-up for the I-Room. In this scenario, the team is iteratively modifying a design of the building (the left screen) as they work to achieve their project goals (right screen). The Narrative is on the center screen.

Design and Build a Framework:

Figure 7A shows an initial framework, described in Haymaker et al 2004b in which AEC professionals can quickly construct and relate representation and reasoning into MDA Narratives. The current implementation runs on a single machine and handles only geometric representations and reasoning. We are currently working to construct a new implementation, called the Narrator that addresses these limitations. Specifically, the Narrator will be deployed in an I-Room setting, and enable distributed and arbitrary representation and reasoning. See Figure 7B.

Validation:

Enabling project teams to define, communicate, integrate, and automate their design processes better than current methods allow. As illustrated in Figures 5 and 6, we find the Narrative diagrams to be effective ways to define and communicate a design process. Future work will use the DEEPAND system (Garcia et al 2003) developed for measuring meeting effectiveness. This approach measures the time spent in a meeting Describing, Explaining, Evaluating, Predicting, Analyzing, Negotiating, and Deciding. The main hypothesis for measuring meetings in this way is that certain activities (i.e., Describing,

Explaining) are less value adding than others, (i.e., Predicting, Analyzing).

The deck attachment case provides evidence that it is possible to better control the integration of information from multiple disciplines than was possible on a state-of-the-art-project (Haymaker et al 2004 b & c). Future work will measure the latency from the time a change occurs in a source representation; to the time the corresponding dependent representations are integrated. In Haymaker et al 2004 c we showed that we were able to effectively automate the design of 84 of the 86 deck attachments that were required, but were field welded, in an area of the WDCH project. Future work will measure the number of design alternatives explored, the amount of time required per alternative, and the accuracy and completeness of automated representations compared to current practice.

CONCLUSION: A POWERFUL AND GENERAL MODEL FOR MDA

AEC professionals need a simple, formal, expressive, generic set of methods to help them communicate, integrate, and automate their design processes; they must be flexible enough to evolve with practice, yet powerful enough to provide them with the information they need. We propose that Narratives can provide this power and flexibility. With adequate adoption and support, Narratives could transform the way the AEC industry practices design and construction. We seek methods that will enable AEC professionals to weave together Narratives that quickly, accurately, and where desired persistently, communicate, integrate, and automate their MDA processes.

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