



**CIFE** CENTER FOR INTEGRATED FACILITY ENGINEERING

Formalizing Narratives to Better  
Communicate & Integrate  
Sustainable Design  
Processes & Information

By

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# Formalizing narratives to better communicate and integrate sustainable design processes and information.

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***Abstract:** To achieve environmental, economical, and equitable goals, sustainable designers need to ask and answer many questions. To answer each question they often need to ask other questions. A “narrative” of interrelated questions and answers emerges as the design process progresses. In this paper, we illustrate this narrative pattern using a test case, and observe that sustainable designers find it difficult to quickly and accurately communicate and integrate these narratives. We describe a formalism called Narratives that we are designing to help human designers blend their creative and collaborative power with the communicating and integrating power of computers and building information modeling to better communicate, integrate, and thus optimize their design information and processes.<sup>1</sup>*

## 1 Introduction: Sustainable designers need to communicate, integrate and optimize design processes and information.

On each project sustainable designers must satisfy a unique collection of client, occupant, regulatory, community, budget, schedule, resource, environmental, and other goals (Fuller 1981, WCED 1987, McDonough and Braungart 2002). Design is often treated as a subjective and ad-hoc process, but designing for sustainability compels sustainable designers to be more explicit and formal with the goals they pursue, and with the processes and information they use to pursue these goals.

Today sustainable designers often use formal discipline-specific processes (e.g. an energy analysis) and information (e.g. a CAD file) that help them address specific goals (e.g. low energy consumption). However, they lack formal processes with which to formally interrelate and balance these processes and information. Without quick and accurate ways to orchestrate multidisciplinary design processes, cost and aesthetics will remain the primary drivers in project decision-making.

In January 2004 we asked fifteen partners, associates, and designers at sustainable architecture firm William McDonough Partner’s (WMP) to envision how computer technology might help them better design and execute sustainable projects. The WMP team proposed several methods:

- *Pitch the right argument at the right time.*
- *Support the clarity of the ideas as well as the execution of the ideas.*
- *Make the specification and the program come alive.*
- *Show the impact; give form to forces; render the flows visible.*
- *Front-end material specification.*
- *Support certain frame conditions such as raised floor, grass roof, living street.*
- *Respond to world conditions and support anticipatory design.*
- *Enable continuous commissioning.*
- *Support a design process that moves from principles to goals to strategies.*
- *Determine on which projects one should use a raised floor scheme, grass roof, atria.*
- *Design and maintain the intended experience of users.*

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<sup>1</sup> This paper was written in October 2005 in collaboration with Kevin Burke and William McDonough of William McDonough Partners. It was posted as a CIFE Technical Report in November 2008.

- *Design to performance criteria, rather than to a standard program.*

WMP designers found it fairly easy to list these needs, but they have not found computer technologies that adequately address them. First, these designers generally are looking for methods to help them more quickly and accurately *communicate* information and processes amongst stakeholders. For example, in the first four items, they express the need to share their arguments, ideas, specifications, program, and impacts with other project stakeholders. Second, They also need methods to more quickly and accurately *integrate* information and processes amongst stakeholders. For example, in the second four items, they are looking for ways to incorporate specifications, design strategies, world conditions, and performance information throughout their design processes. Finally, they need methods to more quickly and accurately *optimize* their information and processes amongst stakeholders. In the final four items, they are looking to establish goals and use their information and processes to optimally achieve these goals.

It is WMP policy to define goals. One guiding goal for WMP is: “a delightfully diverse, safe, healthy and just world, with clean water, clean air, clean soil and clean power – economically, equitably, ecologically and elegantly designed (McDonough 2004).” On each project, they study local and global conditions and work to define and exceed project specific goals. For example, on one project, a corporate headquarters building in northern California in 1996, WMP set as their goal a project that “combines aesthetic rhyme with architectural reason, environmental sensitivity with operational efficiency, the diverse needs of individual employees with the scale and flexibility required by a growing company (Bay Area Council 2002).”

WMP work towards their goals by asking and answering many questions (McDonough 2004). For example, WMP asks:

“*What is native to this place?*” “*How do we mark the ground?*”  
“*Where does it come from?*” “*Where does it go?*”  
“*How much energy does it consume?*” “*How much energy does it produce?*”  
“*What does it look like?*” “*How long will it take?*” “*How much will it cost?*”  
“*How effective are we with respect to our goals?*”

To answer each question, they often need to ask other questions, and thus a collection of interconnected questions and answers emerges as the project progresses (See Figure 1A). We call this collection a *narrative* from the Oxford English Dictionary definition: “An account of a series of events, facts, etc., ...with the establishing of connections between them.”

Sustainable designers such as WMP iteratively construct and update, or *integrate*, these narratives of questions and answers to help them answer both discipline-specific and multidisciplinary questions as they seek to define and optimize project goals. However using today’s methods they often find it difficult to quickly and accurately communicate and integrate these narrative design processes. As a result, many find it difficult to find optimal multidisciplinary solutions.

In this paper we present a case study from WMP’s design practice that illustrates the narrative structure of a sustainable design process. We describe many of the questions they asked, the answers they constructed for these questions, and the dependencies among these answers. We observe the difficulties they have communicating, integrating, and optimizing their design process using their current methods. We observe that, while AEC projects today often formalize the answers to their questions using formal computer representations, many of the “connections” between answers are not formally represented or managed. Rather, they are stored in the heads of the designers. We propose that with a more complete formalization of these narratives, they would be able to better communicate, integrate, and optimize their design processes and information. We describe our formalization of Narratives (See Figure 1B for a preview), and discuss how sustainable designers might use them to better communicate and integrate their design processes and information, and thus achieve more sustainable and balanced designs. We describe some ongoing implementation and validation efforts with which we are investigating the formalism of Narratives.

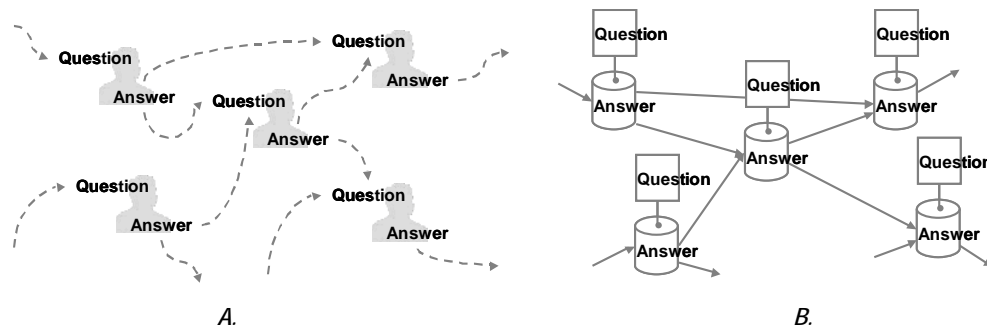


Figure 1: Formalizing sustainable design narratives. *A.* We observe a structure to a sustainable design processes in which sustainable designers ask and answer a collection of related questions. To answer questions, they often ask further questions. A narrative of interrelated questions and answers emerges. The lines are dashed because the information dependencies between these questions and answers are not formally defined and managed in practice today. *B.* A formal Narrative: This paper proposes that if AEC professionals formally define and manage these design processes, they will be able to better communicate and integrate their sustainable designs.

## 2 Case Study: Sustainable designers construct and control narratives

This case study describes a design process by WMP and their consultants for the corporate headquarters building in northern California. We highlight the narrative pattern in their design processes in which they ask about the costs and benefits of employing different sustainable design strategies, such as atria, grass roof, and a raised floor system. We describe and diagram some of the questions the design team and their consultants asked, the answers they constructed for these questions, and the information dependencies among these questions and answers. We reconstructed this case study from interviews and project documents. Actual numbers have been modified and are only representative.

### 2.1 Atria cost-benefit analysis

WMP knows that atria can be an effective way to take advantage of natural light, reduce building energy consumption, and improve the quality of the work environment. However, atria cost money, can cause uncomfortable glare conditions, have

constructability and maintenance issues, and generally result in a bigger building footprint. Therefore, the design team wanted an answer to the question:

**2.1.1 What are the costs and benefits of an atrium?**

The narrative of questions the design team asked, and the information representations they constructed to answer those is illustrated in Figure 2 and described below. During their design process the design team also constructed other narratives related to daylighting and skylights, light shelves, and diffusers, although for brevity a thorough review of those narratives is not presented.

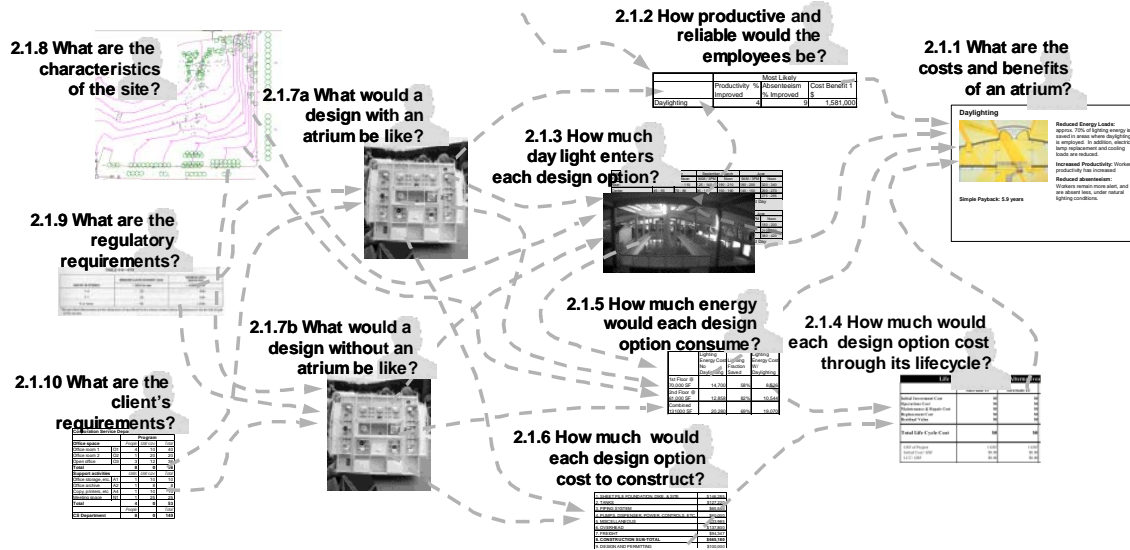


Figure 2: A narrative of questions and answers that comprised the daylighting cost benefit analysis. The arrows between answers and subsequent questions describe the information dependencies, and are shown as dashed because, while implicitly described in their written descriptions, these dependencies were not formally represented in a computer. The numbers next to each question refer to the section in this paper in which the question is discussed.

This building was to house some of the client’s most talented employees, so providing a good and productive work environment was a priority. If the added daylight would appreciably improve the productivity and reliability of their workforce, this would be a compelling argument for the client to invest in atria. This led WMP to ask the question:

**2.1.2 How productive and reliable would the employees be?**

The design team did not have a crystal ball to see into the future, but they did have access to test cases and industry data (i.e., Browning and Romm 1994) that show it is possible to improve the productivity and reliability of a workforce by improving the work environment’s daylighting. These reports and case studies estimate that high quality daylighting solutions can improve worker productivity and reliability by as little as 4 % and as much as 9 % of workers’ annual salaries. Based on a most likely estimated benefit of 7 %, WMP estimated the potential value per year of the daylighting for their client, shown in Figure 3.

	Most Likely		
	Productivity % Improved	Absenteeism % Improved	Cost Benefit \$
Daylighting	4	9	1,581,000

Figure 3: The projected annual productivity and absenteeism benefits of the skylights and atrium (from WMP documentation).

These numbers assume a certain quality of light in the design. To verify this quality, the design team therefore asked the question:

**2.1.3 How well does daylight enter each design option?**

In 1996 adequate computerized daylight simulation and analyses were not available to WMP’s design team. Instead they constructed a physical model of the proposed atrium design (described in section 2.1.6) and analyzed the daylighting performance. The team simulated both clear and cloudy sky conditions and used physical sensors to measure the daylight factors --the ratio of the illuminance at a particular point within the enclosure to the simultaneous unobstructed outdoor illuminance -- in key areas throughout the design (See Figure 4A). They also tested for uncomfortable glare conditions by simulating the path of the sun with a direct beam heliodon test and videotaping the scene to analyze for areas of glare (See Figure 4B). Finally, they converted the Daylight Factors into Illuminance values to give a quantitative estimate to the amount of light at the key areas (see Figure 4C). To analyze the performance of a design without the atrium, the design team modified the atrium design to enclose the atrium, and conducted the same tests. From this information, they were able to say with some confidence that the daylighting with the atrium performs well overall. The WMP team noted that the efficiency of the system might be hampered by excessive light and heat gains unless adequate solar shading strategies are implemented. They modeled light shelves and deflectors into their base physical model and re-did the analysis, finding these features to further improve the quality of the light.

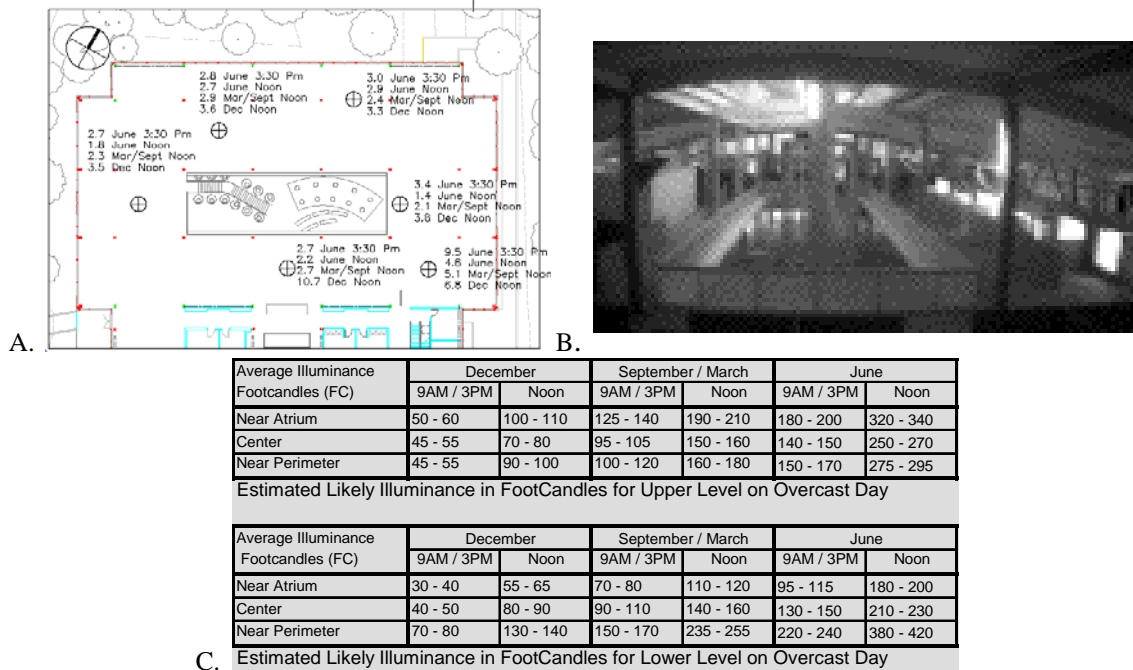


Figure 4: **A.** The amount of daylight at key areas throughout the design at selected times during the year, measured as Daylight Factors. **B.** A screenshot from a videotape of the direct beam heliodon test. **C.** Illuminance values throughout the atrium design (from WMP documentation).

The WMP team was aware that in addition to improving productivity, good daylight can significantly reduce the life cycle costs to operate a facility. The team therefore wanted to know:

**2.1.4 How much would each design option cost throughout its lifecycle?**

To answer this question, the design team needed to calculate how the proposed daylight features would impact the cost to light, heat, and maintain the building each year. Daylighting can reduce the amount of time electric lamps need to be on, so they calculated the amount of energy the building would save in lighting costs (described in section 2.1.5). Reducing electric light usage, reduces the number of times electric lamps need to be replaced, which reduces maintenance costs. Electric lamps also create heat loads on the building; turning off the lights can reduce the need to ventilate and cool the building, so they estimated the reduced HVAC costs. Figure 5 summarizes the expected annual benefits in terms of the cost to light, maintain, and control the temperature of the space with atria.

	Reduced Energy Cost	Reduced Maint. Cost	Reduced HVAC Costs	Net Cost Savings
1st Floor @ 70,000 SF	8,526	635	910	7,925
2nd Floor @ 61,000 SF	10,544	760	1,125	9,495
Combined 131000 SF	19,070	1,395	2,035	22,500

Figure 5: The projected annual cost benefits of the skylights and atrium (from WMP documentation).

In order to calculate how much incorporating daylight could reduce building life cycle costs, they wanted to explicitly know:

**2.1.5 How much energy would each design option consume?**

To answer this question, the design team used the amount of daylight that the atrium design would allow into the design (from section 2.1.3) to calculate the amount of time during normal operating hours that the space would have sufficient daylight to turn off the artificial lighting (69%). This translated into over 2,600 full lighting hours, resulting in a net lighting energy savings of over \$19,000 in annual energy savings over a baseline scheme, shown in Figure 6.

	Lighting Energy Cost No Daylighting	Lighting Fraction Saved	Lighting Energy Cost W/ Daylighting
1st Floor @ 70,000 SF	14,700	58%	8,526
2nd Floor @ 61,000 SF	12,858	82%	10,544
Combined 131000 SF	20,280	69%	19,070

Figure 6: A projection for the cost to light the building with and without the daylighting features (from WMP documentation). *(Note to WMP: Why doesn't "lighting energy cost: no daylighting" add up? Something is not right here...this is from Pg. 17 of Cost Benefit Analysis)*



Another important component of building lifecycle cost is the initial cost. Therefore the design team asked:

### 2.1.6 How much would each design option cost to construct?

To answer this question, the design team performed a cost estimate based on the expected building systems for both the atrium design and the baseline design. From this they were able to determine how much more expensive the atrium design would be. Figure 7 shows the estimated construction costs of design options with and without an atrium.

	No Atrium	Atrium
<b>SITE WORK</b>		
GRADING	750,440	897,325
EXCAVATION	265,030	340,562
OTHER	120,782	145,000
<b>FOUNDATION</b>		
STEEL	1,325,600	1,775,000
ROOF	896,250	1,210,080
HVAC	355,400	420,400
PLUMBING	543,000	520,800
ELECTRICAL	925,000	925,000
DATA/TELECOM	1,150,000	1,150,000
<b>EXTERIOR</b>		
WINDOWS	450,000	450,000
FAÇADE	1,200,387	1,614,779
<b>INTERIOR</b>		
FRAMING/DRYWALL	1,600,000	1,859,000
FLOORING	435,000	512,000
FINISH WORK	290,000	290,000
FITOUT	750,000	750,000
	625,000	625,000
<b>TOTAL</b>	<b>11,681,889</b>	<b>13,484,946</b>
CONTINGENCY	584,094	674,247
<b>TOTAL + CONTINGE</b>	<b>12,265,983</b>	<b>14,159,193</b>

Figure 7: An estimate for the first costs of the two design options (from *WMP, do you still have a cost estimate?* documentation).

To answer these questions of cost, energy consumption, and daylight infiltration, the WMP team needed to ask another question:

### 2.1.7 What would a design with and without an atrium be like?

The design team generated several plans and sections describing a portion of a design with an atrium (see Figure 2 – 2.1.7a). They also built a physical model of this design (see Figure 8). To answer what a design without an atrium would be like, they filled in the atrium in the physical model (see Figure 2 – 2.1.7b).

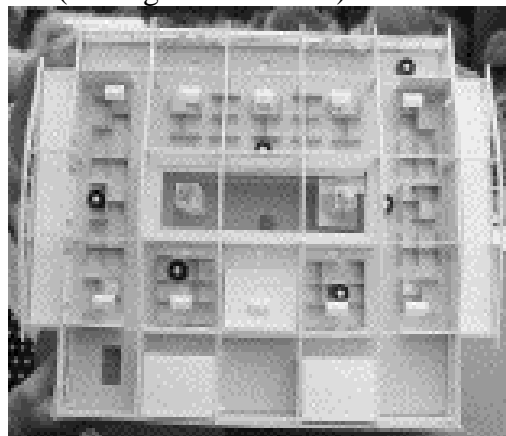


Figure 8: A photograph, from above, of the atrium model, without the roof (from WMP documentation).

To develop these design forms, the team needed to ask other questions about the context of the project. These questions related to the site characteristics and client and regulatory requirements:

### 2.1.8 What are the characteristics of the site?

The project team used survey data to develop a model of the site that showed the contour lines, major vegetation, and vehicular and pedestrian surfaces (see Figure 9). They also observed the site's relationships to the surrounding context, including its proximity to a major freeway and airport.



Figure 9: A site plan describing the existing contours, tree locations, and existing circulation. (from WMP documentation).

Yet to propose a design for this site, the design team also needed to know:

### 2.1.9 What are the regulatory requirements?

To answer this question, the design team conferred with the local and national building codes, including the Uniform Building Code (ICBO 1994), which specifies among other requirements the minimum atrium openings and areas based on building height (See Figure 10). The WMP team needed to assure that the design satisfied these building requirements.

HEIGHT IN STORIES	MINIMUM CLEAR OPENING <sup>1</sup> (feet)	MINIMUM AREA (square feet)
	× 304.8 for mm	× 0.0929 for m <sup>2</sup>
3-4	20	400
5-7	30	900
8 or more	40	1,600

<sup>1</sup>The specified dimensions are the diameters of inscribed circles whose centers fall on a common axis for the full height of the atrium.

Figure 10: A portion of the Uniform Building Code that describes restrictions regarding atria in commercial buildings.

In addition to regulatory requirements, the team obviously also needed to ask:

### 2.1.10 What are the client's requirements?

To answer this question, they (WMP- We need a little color here about how you developed the client requirements ... were they delivered to you, did you do interviews...). Figure 11 shows a partial list of the requirements for the project.

Indoor Environmental Quality		13 Possible Points
<input type="checkbox"/>	Prereq 1 Minimum IAQ Performance	Required
<input type="checkbox"/>	Prereq 2 Environmental Tobacco Smoke (ETS) Control	Required
<input type="checkbox"/>	Prereq 3 Carbon Dioxide (CO <sub>2</sub> ) Monitoring	1
<input type="checkbox"/>	Prereq 4 Ventilation Effectiveness	1
<input type="checkbox"/>	Cond 1.1 Construction IAQ Management Plan During Construction	1
<input type="checkbox"/>	Cond 1.2 Construction IAQ Management Plan Before Occupancy	1
<input type="checkbox"/>	Cond 4.1 Low-Emitting Materials: Adhesives & Sealants	1
<input type="checkbox"/>	Cond 4.2 Low-Emitting Materials: Paints	1
<input type="checkbox"/>	Cond 4.3 Low-Emitting Materials: Carpet	1
<input type="checkbox"/>	Cond 4.4 Low-Emitting Materials: Composite Wood	1
<input type="checkbox"/>	Cond 5 Indoor Chemical & Pollutant Source Control	1
<input type="checkbox"/>	Cond 6.1 Controllability of Systems: Ventilation	1
<input type="checkbox"/>	Cond 6.2 Controllability of Systems: Non-Ventilation	1
<input type="checkbox"/>	Cond 7.1 Thermal Comfort: Group with 90% of 100	1
<input type="checkbox"/>	Cond 7.2 Thermal Comfort: Dissatisfied Occupying System	1
<input type="checkbox"/>	Cond 8.1 Daylight & Views: Daylight 75% of Spaces	1
<input type="checkbox"/>	Cond 8.2 Daylight & Views: Views 75% of Spaces	1
Innovation & Design Process		5 Possible Points
<input type="checkbox"/>	Cond 1.1 Innovation in Design	1
<input type="checkbox"/>	Cond 1.2 Innovation in Design	1


Figure 11: A portion of the client's requirement. (We need a sample of GAP or similar client's requirements?)

### 2.1.11 What are the costs and benefit of an atrium?

The design team used the process described in Figure 2 to help them answer how the added daylight from the atrium design would affect the energy consumption, lifecycle costs, and productivity and reliability of the workforce for each of these designs. They produced a report entitled "Cost Benefit Analysis," which described the design process and explained the expected benefits and the amount of time until the daylighting features paid for themselves.

The chosen design was a building with atria. WMP's post-occupancy summary of the benefits of the design with atria and other daylighting features is shown in Figure 12.

**Daylighting**



**Reduced Energy Loads:**  
approx. 70% of lighting energy is saved in areas where daylighting is employed. In addition, electric lamp replacement and cooling loads are reduced.

**Increased Productivity:** Worker productivity has increased

**Reduced absenteeism:**  
Workers remain more alert, and are absent less, under natural lighting conditions.

**Simple Payback: 5.9 years**

Figure 12: A slide (McDonough 2004) showing the benefits and payback period of the atrium and skylights with respect to a building without these day lighting strategies.

In addition to atria, the design team also explored other sustainable design strategies. The next sections summarize other narratives the WMP team constructed to develop a design that best achieved their goals.

### 2.2 What are the costs and benefits of a raised floor?

Raised floors were a relatively new technology in 1996. They enable designers to think about heating, ventilating, and air-conditioning in new ways. The design team wanted to know if a raised floor system would be an appropriate strategy for this project, and so they constructed a narrative of questions and answers to address the question, illustrated in Figure 13. They asked about the context and requirements for the building. From this information, they asked about potential design forms for the proposed building, looking at raised floor and more conventional solutions. They also asked how these proposals

performed with respect to their requirements, looking at issues such as constructability, maintenance, energy consumption, and worker comfort. Finally, they asked how this performance measured up in terms of costs and benefits. Unlike with the daylight narrative, the project team did not construct a 3D model to run simulations. Rather they used 2D drawings, calculations from consultants, and industry data to calculate the cost and benefits of the raised floor. They also included these answers in a cost-benefit analysis of an overall integrated indoor air quality strategy that also included operable windows and materials chosen for their minimum impact on indoor air quality.

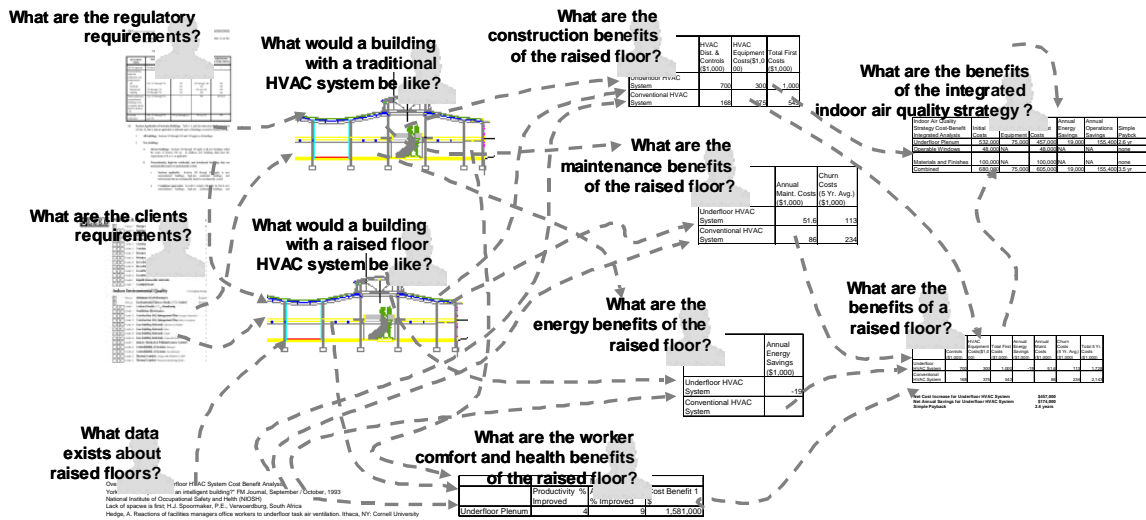


Figure 13: A narrative of interrelated questions and answers that comprised the cost benefit analysis of the raised floor system. The arrows between answers and subsequent questions describe the information dependencies and are shown as dashed because, while implicitly described in their written descriptions, these dependencies were not formally represented in a computer.

Figure 14 shows the calculated costs and benefits of two HVAC systems.


	HVAC Dist. & Controls (\$1,000)	HVAC Equipment Costs (\$1,000)	Total First Costs (\$1,000)	Annual Energy Savings (\$1,000)	Annual Maint. Costs (\$1,000)	Churn Costs (5 Yr. Avg.) (\$1,000)	Total 5 Yr. Costs (\$1,000)
Underfloor HVAC System	700	300	1,000	-19	51.6	113	1,728
Conventional HVAC System	168	375	543		86	234	2,143

Net Cost Increase for Underfloor HVAC System **\$457,000**  
 Net Annual Savings for Underfloor HVAC System **\$174,000**  
 Simple Payback **2.6 years**

Figure 14: The estimated costs and benefits of the raised floor system (from WMP documentation).

The chosen design was the under-floor HVAC system. WMP summarizes the post-occupancy benefits in Figure 15.

**Indoor Air Quality – Raised Floor**



**Under floor HVAC System:**

- Maintains temperature at occupant level, reducing cooling load 20%.
- Provides direct, superior ventilation, total economizer cycle
- Workers have complete control of their environments

**Operable Windows:**

- Allows additional user control as well as possible “free cooling” from ventilation during much of the year.
- Total “churn” flexibility

Simple Payback: 3.5 years  
(2.6 for Plenum)

Figure 15: A slide (McDonough 2004) showing the benefits and payback period of the raised floor HVAC delivery system with respect to a building with a traditional overhead delivery system.

**2.3 What are the costs and benefits of a green roof?**

Taking their cue from surrounding grass-covered hills and the fact that the site is in the noisy flight path of nearby San Francisco International Airport, the design team came upon the idea to cover this project with an insulating roof of grass. The design team wanted to know if a green roof would be an appropriate strategy for this project. They constructed a narrative of questions and answers, illustrated in Figure 16. In this narrative, they asked about the context and requirements for the building; about the form the design would take with a green roof versus a conventional roof; and about how well each design would perform with respect to maintenance, cost, energy, comfort, acoustics, water shed, and aesthetics. To answer these questions, they used 2D drawings, industry data, and calculations from consultants to estimate the cost and benefits of the green roof.

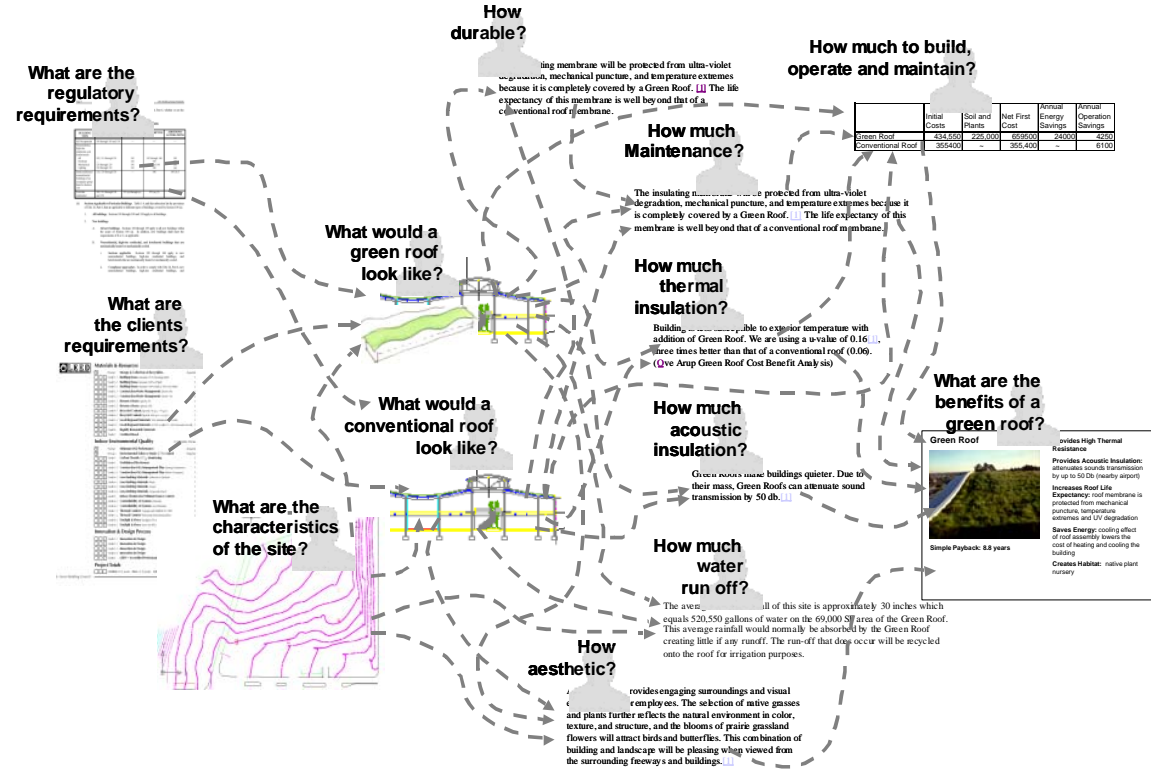


Figure 16: A narrative of questions and answers that comprised the green roof cost benefit analysis


Figure 17 shows the calculated costs for a green and conventional roof.

	Initial Costs	Soil and Plants	Net First Cost	Annual Energy Savings	Annual Operation Savings
Green Roof	434,550	225,000	659,500	24,000	4,250
Conventional Roof	355,400	~	355,400	~	6,100

Figure 17: The estimated costs and benefits of the green roof

The chosen design was the green roof. WMP's post-occupancy summary of the benefits is shown in Figure 18 (from WMP documentation).

**Green Roof**



**Simple Payback: 8.8 years**

**Provides High Thermal Resistance**

**Provides Acoustic Insulation:** attenuates sounds transmission by up to 50 Db (nearby airport)

**Increases Roof Life Expectancy:** roof membrane is protected from mechanical puncture, temperature extremes and UV degradation

**Saves Energy:** cooling effect of roof assembly lowers the cost of heating and cooling the building

**Creates Habitat:** native plant nursery

Figure 18: A slide by William McDonough Partners showing the benefits and payback period of a green roof (with respect to a traditional roof).

## 2.4 Summary: What are the benefits for going green?

The prior three narratives explored the costs and benefits of three specific green strategies. The answers in these narratives also became answers in a more general narrative that the design team constructed to help the owner explore the benefits of going green, illustrated in Figure 19.

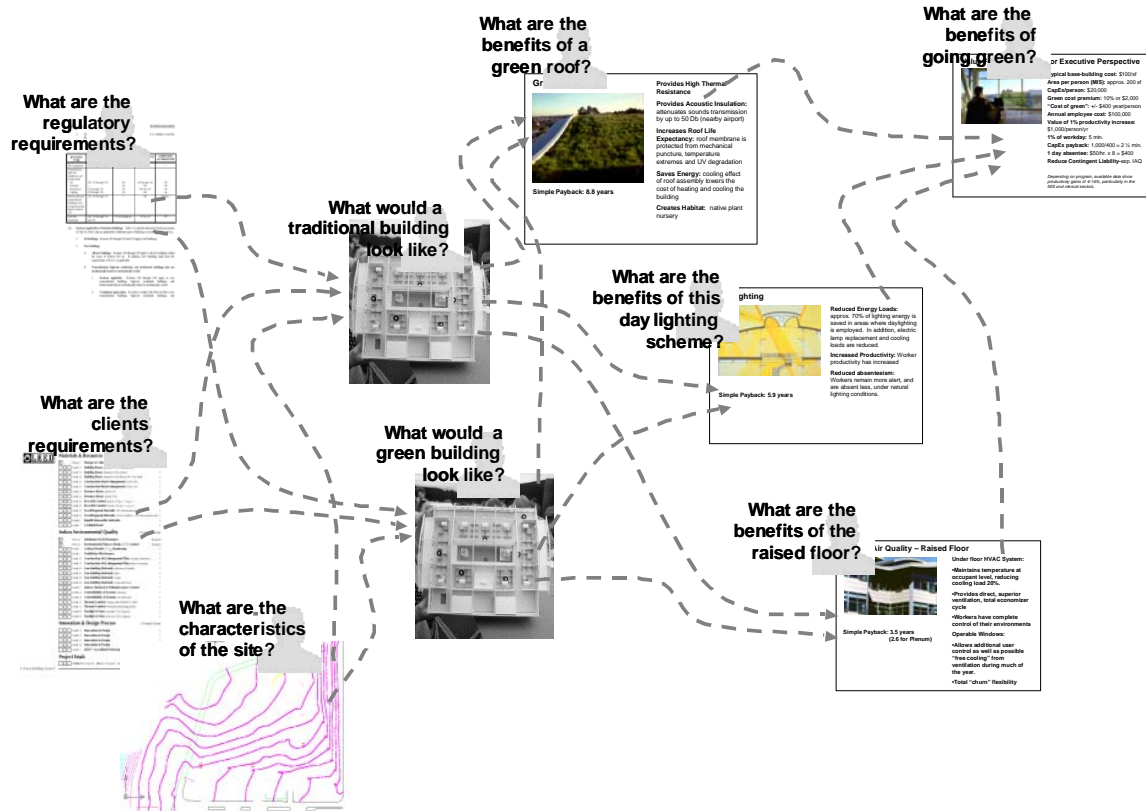



Figure 19: A narrative of questions and answers describing the process by which the project team helped the client decide whether or not to build green

Figure 20 shows WMP's post-occupancy summary of the benefits of going green.

**Value Proposition – Senior Executive Perspective**



- Typical base-building cost: \$100/sf
- Area per person (MIS): approx. 200 sf
- CapEx/person: \$20,000
- Green cost premium: 10% or \$2,000
- "Cost of green": +/- \$400 year/person
- Annual employee cost: \$100,000
- Value of 1% productivity increase: \$1,000/person/yr
- 1% of workday: 5 min.
- CapEx payback: 1,000/400 = 2 ½ min.
- 1 day absentee: \$50/hr. x 8 = \$400
- Reduce Contingent Liability-esp. IAQ

*Depending on program, available data show productivity gains of 4-16%, particularly in the MIS and clerical sectors.*

Figure 20: A slide by William McDonough Partners showing the value proposition of using the recommended green strategies.

## **2.5 Observation: Sustainable designers find it difficult to communicate and integrate their narratives.**

The case study illustrates that in order to set goals, explore options, analyze them, and assess the costs and benefits of these options with respect to their goals, the WMP design team systematically asked and answered a lot of questions. To construct answers to each question, they relied on information constructed as answers to other questions. Although WMP did not explicitly use the terminology, they constructed and integrated a narrative of interrelated questions and answers as the project progressed. By constructing and controlling the integration of their information they were able to develop a building widely recognized as highly innovative and a successful example of sustainable architecture (Leventhal 2001).

However, we have observed that design teams often find it difficult to quickly and accurately communicate and integrate these narrative design processes (Kam and Fischer 2002, Haymaker et al 2004a). For example, on this project the WMP team encountered difficulty:

*Communicating:* The WMP team provided a series of Microsoft Word, Excel, and other documents consisting of over one hundred pages in which they described the results of the process: the costs and benefits of the atrium. However, no diagram such as Figure 2 or other formal description of the process they followed existed for this project. This is a common problem; AEC professionals lack a common, formal method with which to document and broadly communicate their questions, answers, and the connections among questions and answers to project participants, and to AEC professionals on subsequent projects.

*Integrating:* The WMP team manually constructed and controlled the integration of the answers in their narratives. When answers changed; for example, if they wanted to explore a variation on a design option, they needed to manually construct and integrate their analyses, and found it difficult to do so quickly and accurately. In other papers we have documented integration difficulties on AEC projects between discipline-specific information sources; for example, between requirements information and design information (Kiviniemi 2005), between design information and analysis information (Kam and Fischer 2002), between design information and fabrication information (Haymaker et al 2004a), and between analysis information and decision information (Kam, 2004). AEC professionals lack a formal method with which to iteratively ask and answer their questions in a coordinated and integrated way.

Sustainable designers today are limited in their abilities to create the best building possible because they have such difficulty quickly and accurately communicating, and integrating their design processes and information.

## **3 Intuition: Formalize and control the dependency between answers**

To more quickly and accurately communicate and integrate their processes and information, we propose that sustainable designers need to better formalize their



questions, their answers, and the connections between their questions and answers. Figure 21A shows a part of the narrative described in Figure 2. Figure 21B shows the generic formalism for these Narratives (when referring to a formal Narrative, we use a capital N). Figure 21C shows a Narrative that results from applying the generic formalism to the narrative in Figure 21A. Following is a brief discussion of each element that we need to formalize:

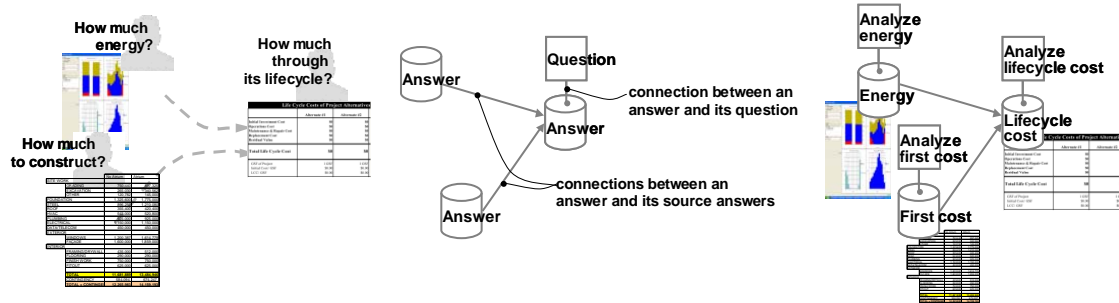


Figure 21: A. Part of a narrative from Figure 2. B. Our formalization of Narrative. C. Our formalization of Narrative applied to the narrative in A.

*Questions:* WMP says sustainable designers need to ask questions (McDonough 2004). Formalizing these questions would enable the computer to communicate them to the project team, and when possible to automatically ask and answer a specific question. Today there are many discipline-specific computer programs that formally ask questions in a way that automatically constructs an answer from information in other answers. For example, it is possible to ask about the energy (Department of Energy 2005), structural (Computers & Structures, 2005), cost (Graphisoft 2005) and other performance of a design option by analyzing a CAD model. Other computer programs such as word processors or CAD provide methods a professional can use to manually ask and answer questions (they too will often construct these answers by consulting information in other answers).

*Answers:* Sustainable designers need answers to their questions. Formalizing these answers enables the computer to communicate them to the project team, help control their integration, and where possible to automatically construct them. Today there are many computerized data structures that AEC professionals can use to formally represent their answers. These include text documents, spreadsheets, and power point slides, as well as CAD drawings and other more semantically rich data structures. Government and industry are establishing standard, non-proprietary, computer interpretable data structures. For example, XML (W3C 2005) provides a structure with which to represent arbitrary types of answers, and the Industry Foundation Classes (IAI 2005) provide a data structure to represent answers specific to AEC building information. In addition to questions and answers, sustainable designers need to represent and manage the connections between these questions and answers.

*Connections between an answer and its question:* Each question results in a corresponding answer. Formalizing this relationship would enable the computer to graphically communicate this relationship to the project team, and to control the integration of answers by re-asking the associated question. Computer operating systems adopt the convention that certain file types, such as \*.doc, or \*.dwg, can be opened by

certain computer programs, enabling a user to click on a Word or AutoCAD document, and have the associated program open this file. However, AEC professionals generally do not explicitly define a connection between a specific question and its associated answer.

*Connections among answers:* Answers to questions often depend on the answers to other questions. Formalizing this relationship would enable the computer to communicate this connection to the project team, and to control the integration of the Narrative by re-asking questions whenever a source answer is modified. Some parametric design systems, such as Revit (Autodesk 2005) do represent the connections among geometric answers. For example the location of a window can be parametrically defined with respect to the location of a wall. However, AEC projects today do not generally define and manage connections between answers and their associated source answers.

*Management Processes:* Today AEC professionals manually manage their narratives. When a particular answer changes, the project team must remember which other answers must be updated, and then manually update those answers. Formalizing management processes would enable the computer to communicate the integration status of current questions, answers, and connections in the Narrative to the project team, and help control the integration of these questions and answers as the project evolves.

Formalizing the above concepts and processes would enable project teams to iteratively and collaboratively specify each question, the answer associated with each question, and the source answers on which each answer depends. The project team could communicate, and iteratively construct and control the integration of their Narratives as the project progresses.

#### **4 Formal Narratives of Questions and Answers**

Haymaker et al 2004b describes the Perspective Approach, which is designed to enable AEC professionals, such as sustainable designers, to construct and control narratives. Using the Perspective Approach, AEC professionals specify and control the sources, status, and nature of the dependency of an information model, called a Perspective, on other Perspectives:

*Sources:* The source Perspectives on which a dependent Perspective depends.

*Status:* Integration status of a Perspective with respect to its source Perspectives.

*Nature:* The reasoning method (automated or manual), called a Perspector, that constructs information in the dependent Perspective from information in the source Perspectives.

Perspectors are generic reasoning. They can embody any type of reasoning, specifying human or automated, off-the-shelf or user-defined reasoning. Perspectors can therefore be used to formalize sustainable designers' questions. Perspectives are generic representations. They can be used to describe any type of information that can be represented in a computer. Perspectives can therefore be used to formalize sustainable designers answers. They can also be used to formalize their connections to source Perspectives (answers), as well as their connections to their question (Perspector). Figure 22A diagrams this formalization of the dependency of a Perspective on source

Perspectives(s). Figure 22B shows that a formal Narrative can emerge from the iterative application of this representation method.

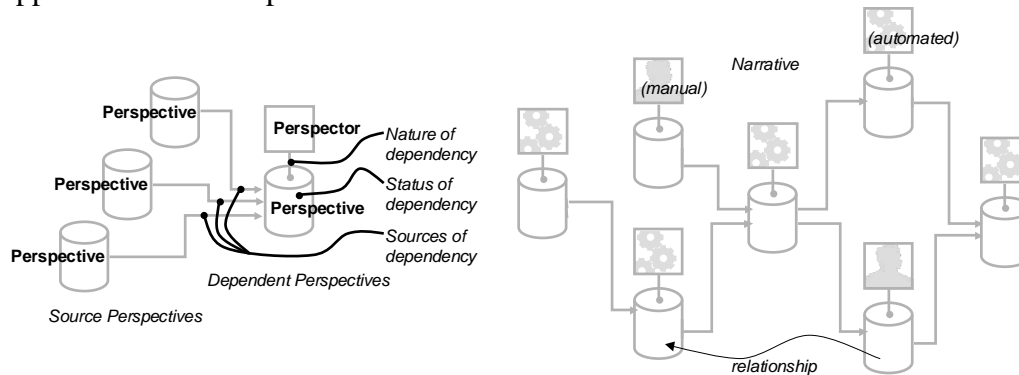


Figure 22: Formalizing the dependency between task-specific information models called Perspectives. **A.** An AEC professional formalizes the sources, nature, and status of the dependency of a Perspective on source Perspectives. A reasoning algorithm, called a Perspector, is used to formalize the nature of the dependency. In other words, the Perspector constructs the information in the dependent Perspectives using the information in the source Perspectives. The status keeps track of a Perspective's integration with respect to its source Perspectives. **B.** A Narrative emerges from the repeated application of the formalism described in A. This Narrative contains both automated and manual Perspectives. Note that the representation in any Perspective can include relationships to information in source Perspectives.

Because a Perspector analyzes information in source Perspectives to produce information in dependent Perspectives, any Perspector can itself be decomposed into a sub-Narrative. Such decomposition aids in the thought process when constructing a Narrative, as well as the readability of a composed Narrative. We provide examples of this decomposition in Figures 24 & 25.

The Perspective Approach also formalizes Management Processes to help AEC professionals control the integration of these Narratives. The first Management Process assures that the dependencies between Perspectives are properly constructed:

*Management Process 1: When constructing a new dependent Perspective, construct a reference to the source Perspective in the dependent Perspective's Source Perspectives list, and place a reference to the dependent Perspective in each source Perspective's Dependent Perspectives list.*

The second Management Process assures that the integration status of all Perspectives is up-to-date with respect to the iteratively modified source Perspectives on which they depend:

*Management Process 2: Before (re)constructing a Perspective, check that each source Perspective's Integration Status is set to Integrated. While (re)constructing a Perspective, set that Perspective's Integration Status to Being\_Integrated. After (re)constructing a Perspective, set that Perspective's Integration Status to Integrated, and recursively set all dependent Perspectives' Integration Status to Not\_Integrated.*

Figure 23 shows our application of the Perspective Approach to the test case. Starting with a Perspective describing the site, client requirements, and regulatory requirements, the Narrative first proposes two building layouts, one with an atrium, and one without

this feature. The Narrative then elaborates on these initial design strategies to generate different alternatives including designs with and without skylights, grass roof, and raised floor. The Narrative then analyzes and compares the atrium, skylight, grass roof, and raised floor alternatives with respect to the more traditional strategies, assesses the costs and benefits of each of these strategies, and finally develops an “executive level” summary of the cost and benefits of each strategy with a recommendation for which strategies make sense given the regulatory, client, and site-specific characteristics of the project.

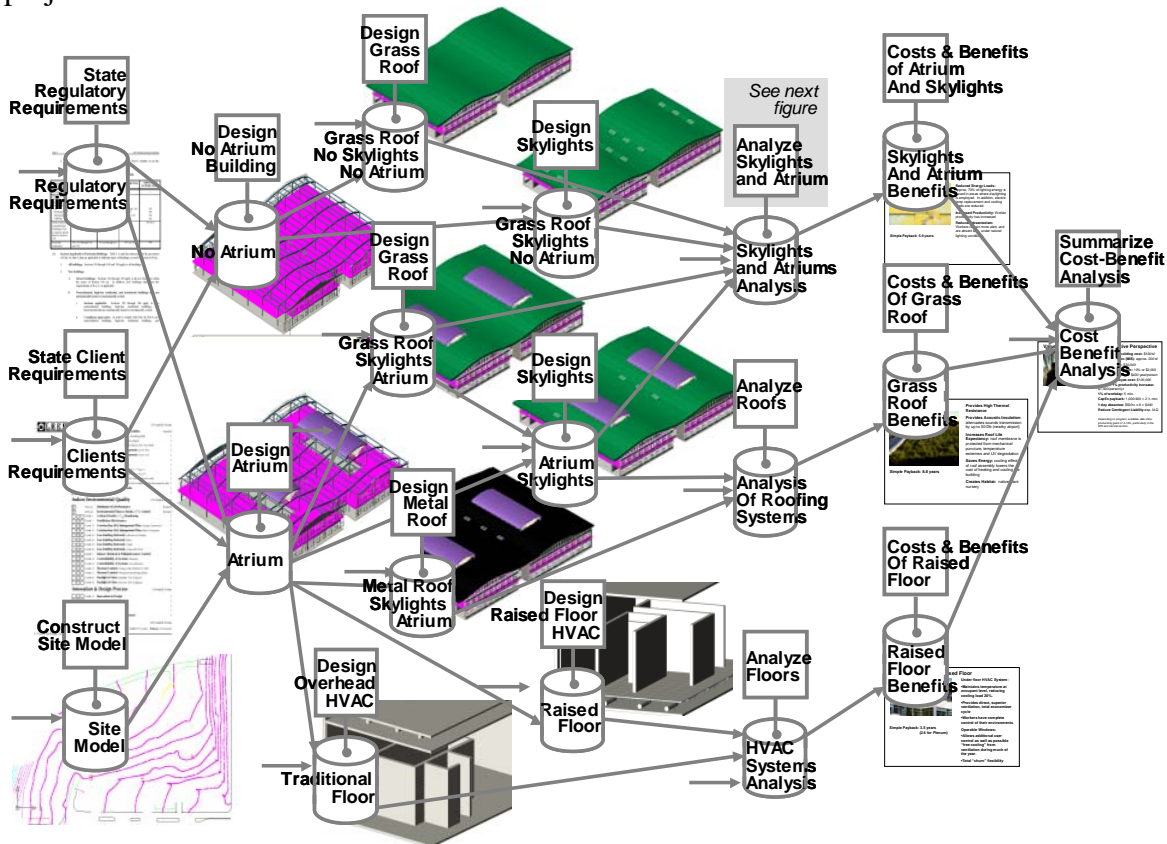


Figure 23: A conceptual Narrative to formalize a cost-benefit analysis described in the test case.

Figure 24 illustrates that any Perspector can itself be defined as a Narrative. The “Analyze Skylights and Atrium” Perspector is decomposed into a Narrative that formalizes this analysis. Starting with Perspectives describing design proposals with and without skylights and atriums, the Narrative performs daylight, energy, constructability, structural, first cost, and lifecycle costs analyses on these proposals, then summarizes these Analyses for use in the higher-level Narrative of Figure 23.

Any of the Perspectives in the Narrative of Figure 24 can also be similarly decomposed. For example Figure 25 shows that the “Analyze and Compare Daylight” Perspector is decomposed into a Narrative that first simulates daylight in each of the four options, then compares the four options in terms of three measurements of the daylight: light contribution, distribution, and adequacy, then summarizes these analyses for use in the higher-level Narrative of Figure 24.

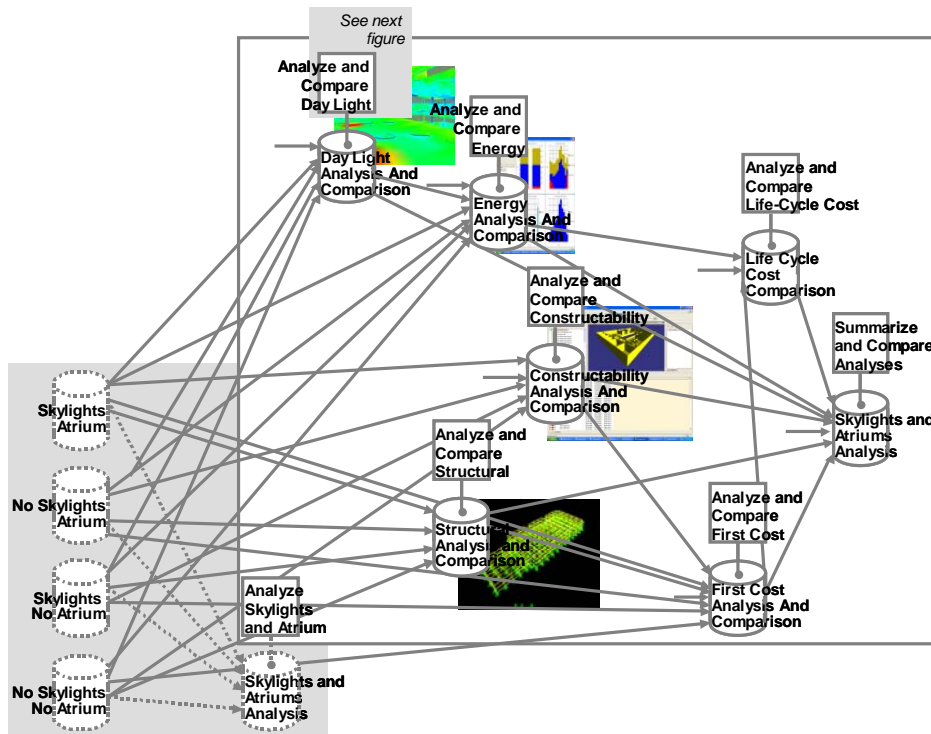


Figure 24: A sub-Narrative that analyzes design options related to skylights and atria in terms of several criteria.

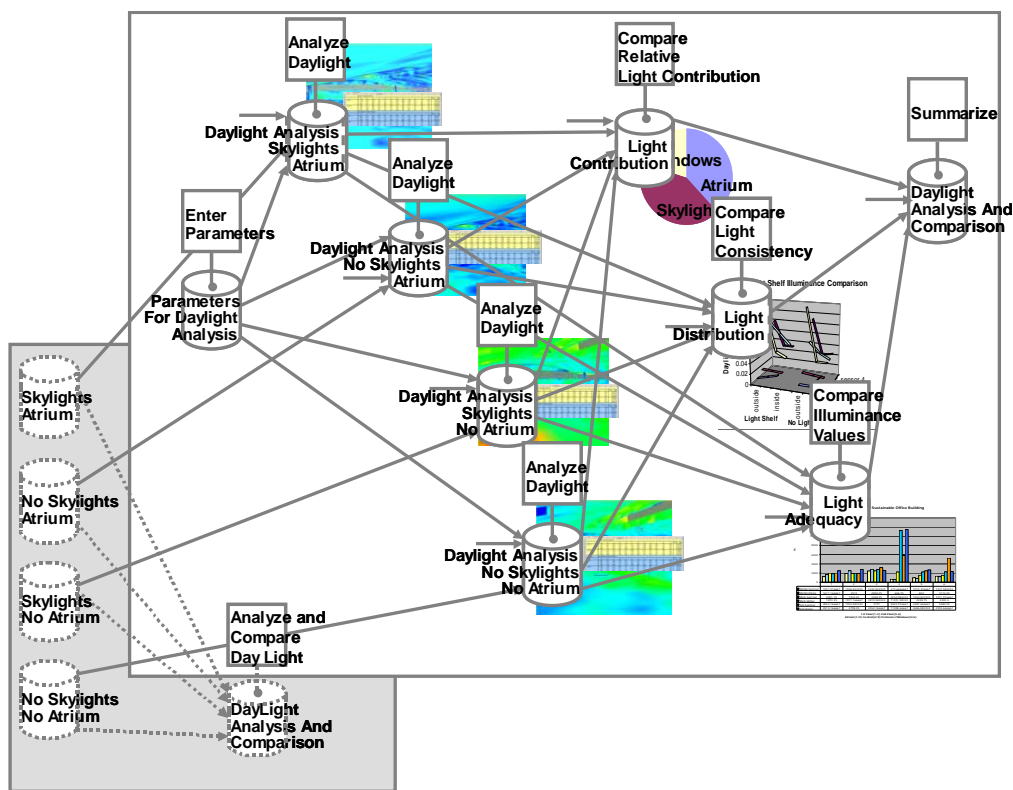


Figure 25: A sub-Narrative to analyze design options related to skylights and atria in terms of daylight, and to compare the results of these analyses in terms of light contribution, distribution, and adequacy.

## 5 Implementing and Validating Narratives

In Haymaker et al 2004b we describe PerspectorApp (see Figure 26A), a computer tool that enables us to iteratively construct, communicate and integrate Narratives of geometric Perspectives and Perspectors on a single desktop computer. In that paper we showed how, from a steel beam Perspective and a concrete slab Perspective, we could automatically construct a Perspective that describes how to attach the slabs to the beams. We also showed how we could control the integration of this deck attachment Perspective as the steel beam and concrete slab Perspectives changed.

We are currently working on next-generation computer tools that we call Narrators. Narrators will enable AEC project teams to collaboratively construct and control Narratives of Perspectives and Perspectors that can conceptually contain and operate on any type of data, and in a more distributed and collaborative fashion. Figure 26B shows a future implementation of a Narrator in an I-Room (Johanson et al 2002). In the figure, the team is iteratively modifying a design of the building (the left screen) as they work to achieve their project goals (represented as a spider diagram on the right screen). The Narrative that evaluates the design to construct the spider diagram is on the center screen.

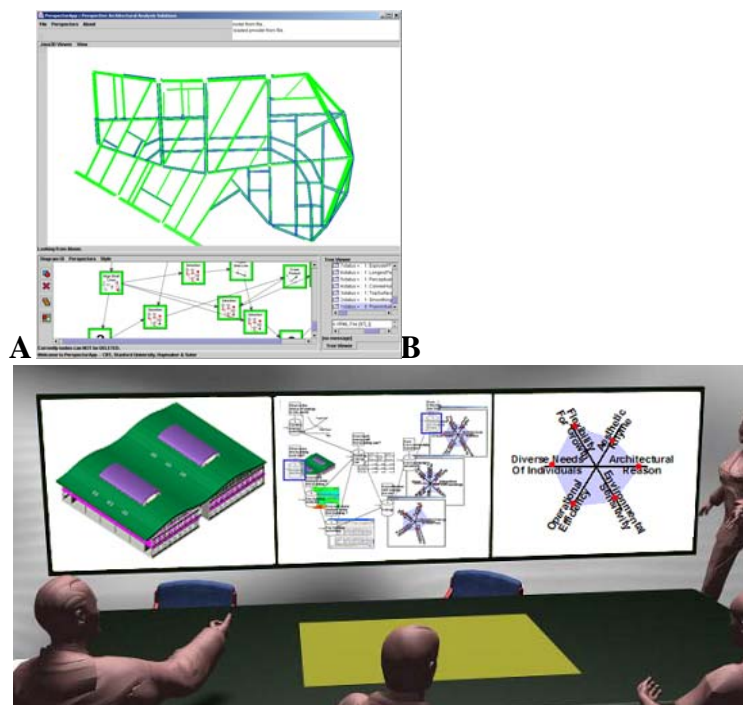
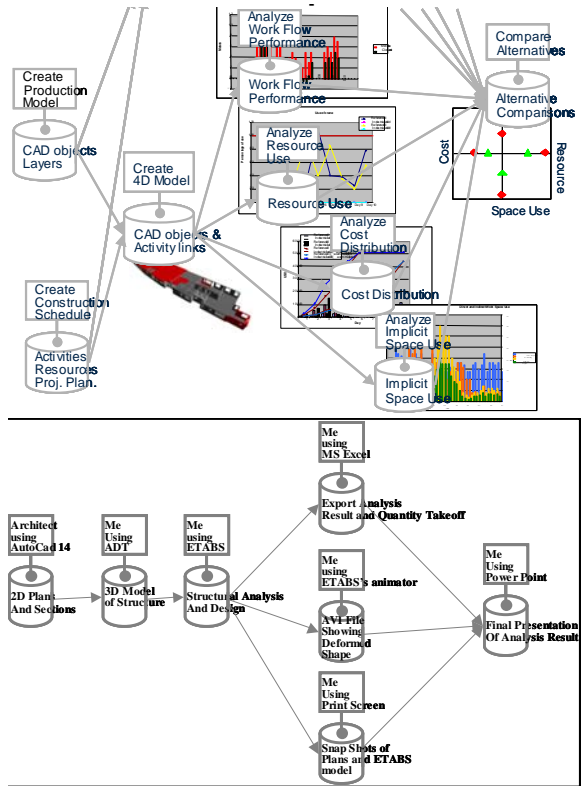


Figure 26: Computer tools called Narrators that enable engineers to quickly connect reasoning and representations into Narratives and control their integration. **A.** Our initial software, PerspectorApp, which constructs and controls geometric Narratives. **B.** A future implementation of the Narrator in the I-Room.

As qualitative evidence for the ability of Narratives to enable *communication*, several Stanford University students and researchers have used them to describe their own design processes. Figure 27 shows and briefly explains a few of these Narratives. To gain more quantitative measures of communication, we are gathering information about the effectiveness of the design process with and without Narratives by keeping track of the

number of agenda items accomplished, the ability for meeting participants to answer questions about the design process, and through a DEEP analyses (Liston 2005) that measure the amount of time a project team spends of Describing, Explaining, Evaluating and Predicting during a design meeting. One idea behind this metric is that Describing and Explaining are potentially less value adding processes compared to Evaluating and Predicting.



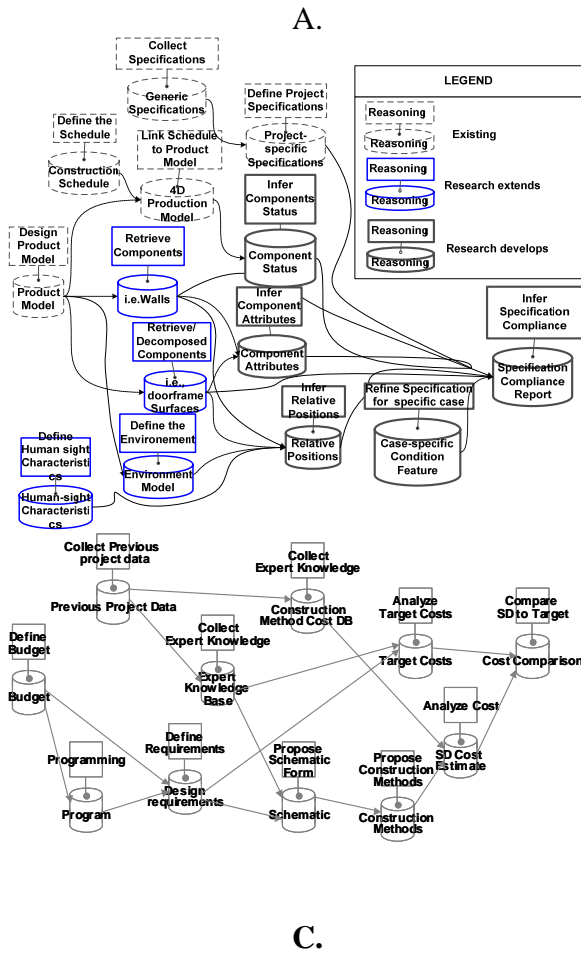


Figure 27: Narratives constructed by other students and researchers that integrate several design representations and computer tools into multidisciplinary processes. **A.** A Narrative that combines building geometry and construction schedule into a 4D model, then analyzes the 4D (3D +time) model for workflow performance, resource use, cost distribution, and space use, and compares the performance of two 4D models against these metrics. **B.** A Narrative that describes a student's process for his class project. He started with 2D drawings constructed by an architect with AutoCAD. He then constructed a 3D model of the building structure using ADT. He then performed a structural design and analysis, using ETABS. He then assembled and formatted the analysis results and quantity takeoffs in Excel. He also created an animation in ETABS to visualize the structure's deformation. He also created a series of screen shots of the structural design and analysis. Finally, he gathered this data into a final presentation of his analysis results. **C.** A Narrative that locates conditions in a building information model that are required to meet certain specification requirements. **D.** A Narrative that compares design costs to target costs that are established earlier in the project.

As qualitative evidence for the ability of Narratives to improve *integration*, Haymaker et al 2004b describes how we used Perspector App to iteratively construct and control the integration of a Narrative of Perspectives and Perspectors on a single desktop. We are gathering more quantitative data from projects with and without Narratives. One measure of integration is latency -- the amount of time for a design change in one representation, or Perspective, to be reflected in a dependent representation, or Perspective. We are also documenting integration errors and resulting costs and delays on projects.



## 6 Conclusions

Because of the communication and integration difficulties, and the time and resource constraints inherent on any project, the WMP team found it difficult to fully explore their design narratives and thus optimize their design. For example, they were unable to explore many different atria options to determine the optimal configuration for the energy, daylight, cost, and other important criteria. William McDonough presented the chart in Figure 28 to illustrate how sustainable designers' goals and methods must continue to evolve both during the project lifecycle and from one project to the next as we continuously learn and evolve towards clearer and more sustainable methods and goals (McDonough 2004).

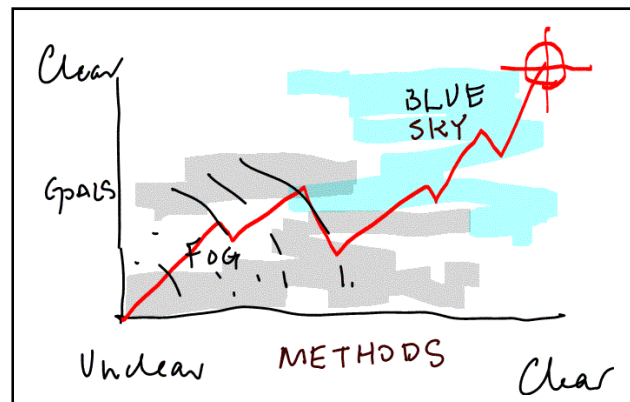


Figure 28: William McDonough asserts that sustainable designers must continually develop clearer methods and goals.

As these methods and goals become more clear, sustainable designer's need simple frameworks to quickly and accurately communicate them to other stakeholders, and to integrate them with the other methods and goals on a project. We are designing Narratives as a flexible framework in which project teams can collaboratively and iteratively communicate, integrate and optimize their design processes as they construct and control Narratives.

Figure 29 is a partial conceptual Narrative that we composed to measure the goals for the project described in the introduction on six axes of a spider diagram. This Narrative consists of interrelated sub Narratives that measure each of these goals. For example, WMP describes environmental sensitivity in terms of several sub goals related to: access to fresh air, indoor air quality, integration with surroundings, energy, site, material flows, water, and access to light. Further sub Narratives would measure each of these sub goals. For example, WMP describes energy efficiency in terms of: embedded energy in materials, building energy use, people and transit, renewable resources, and construction processes. Ultimately, these Narratives interweave other types of representation and reasoning, such as CAD drawings describing design options, analysis data describing energy calculations, and other types of representations. Ideally, the connections between these representations could all be formal. Modifications to any information could propagate through the Narrative, reflecting any changes to the overview of the six goals of the project. When formal, automated connections are not possible, AEC professionals could continue their current practice of using manual connections. For example this

Narrative shows that the measurement of aesthetics could simply involve asking four human design critics for their opinions. The transition to formalized and supported Narratives should be evolutionary and helpful, incorporating today's AEC computer tools; they are not meant to provide constraining meta-solutions that replace individual know-how and creativity. They integrate our greatest advances in information technology with the collaborative human process of design and innovation.

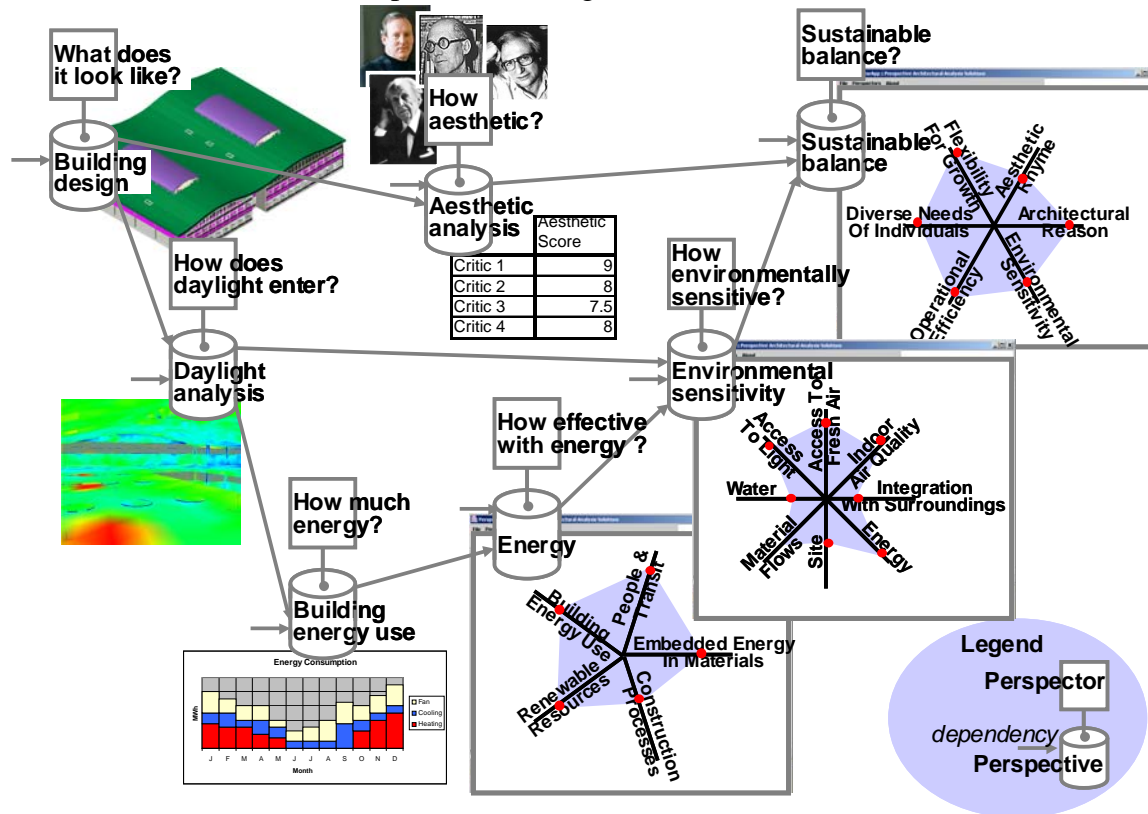


Figure 6: A partial conceptual Narrative to explicitly measure a project in terms of its goals. Starting with information describing the building geometry, and other information (not shown), this Narrative constructs information describing the projected energy performance of the building. From the Building Energy Use representation and from other representations (not shown) the Narrative constructs a representation describing the Energy performance for the entire project. From the Energy representation and from other representations (not shown), the Narrative constructs a representation of the Environmental Sensitivity of the project. From the Environmental Sensitivity Representation, and from other representations (not shown), the Narrative constructs a representation describing the overall Performance in terms of the project's core goals. The project team can iteratively modify the Building Design Perspective while they search for a design that optimally satisfies all their goals.

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