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Development of a Green Building Decision Support Tool: A Collaborative Process

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In this paper, we discuss a collaborative process for developing a decision tool to support decisions around investment in green energy technologies. Our tool was developed specifically for the Hitchcock Center for the Environment, a local environmental education organization, and the development process began as an undergraduate student service learning project. Building on the student projects, we developed an Excel-based tool that allows users to select various combinations of technologies and instantly see the financial, environmental, and educational impacts of their choice. Given our initial parameters and the preferences of the Hitchcock Center staff, the optimal configuration included installing a biomass heating system and a composting toilet, but avoiding investment in other green technologies, yielding an annualized preference-adjusted cost of $5,252.58. Sensitivity analysis indicated that the optimal choice was not sensitive to environmental valuations, and only slightly sensitive to educational values. All participants in the process found the concept and practice of value elicitation to be useful and illuminating.

Key words: environment; green building; decision analysis; energy
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1. Introduction

The Hitchcock Center for the Environment (HC) is an environmental education center located in Amherst, Massachusetts. The mission of the HC is to "foster a greater understanding and awareness of our natural world and to develop environmentally literate citizens." Because of increasing program attendance and the size restrictions of their current facility, the HC has recently received funding for expansion. This expansion could take the form of renovations to the current building or the construction of an entirely new building. As part of this expansion, the HC wants to consider the implementation of various "green" technologies. In this paper, we discuss a decision-making tool developed to help the HC decide in which technologies to invest.

This was a collaborative process with an educational focus. We had multiple goals in this project, including educating students and the public, as well as delivering a decision tool. The first part of the project involved a service learning project for undergraduate students in an engineering economics class. The students gathered data and calculated the annualized costs and the carbon emissions for a range of technologies. The goals were to allow them to get a real-world application of engineering economic evaluation, to learn about a range of currently available "green" technologies, to deepen their involvement in the local community through working with and learning about a local nonprofit, and to introduce them to the decision analysis (DA) process.

The students and the research team worked closely with the teachers, the building committee, and the board of directors of the HC. We elicited preferences from the HC building committee and teachers and presented the results of our analysis at a number of public meetings. Our goals from this interaction were to introduce them to a formal decision-making process, including elicitations of preferences and quantifying the costs and benefits of alternative technologies. The product of the process is a decision tool that the HC can use for both designing and constructing their new building. Finally, the HC intends to pass on what they have learned and educate the public about ways to evaluate green building choices.

The decision analysis process is relevant to green building decisions (as well as similar environmental decision problems) because these decisions often involve multiple criteria, multiple stakeholders, and significant trade-offs between near-term investment and long-term payoffs. Explicitly quantifying multiple criteria in monetary terms allows multiple stakeholders to communicate their values with each other. Combining the quantified criteria with engineering economic models allows stakeholders to compare their preconceived ideas about attractive alternatives with a quantitative analysis, which often inspires significant reevaluation.

In fact, the results of the process indicated that the Hitchcock Center's stated goals did not match closely with their elicited preferences. The goals behind the expansion of the HC are numerous and aggressive. The overarching goal is to transform the existing building into a high-performance sustainable building that is healthy, resource efficient, adaptable, and educational. To this end, the building committee hopes to work toward Leadership in Energy and Environmental Design (LEED) certification, reduce their ecological footprint, reduce their net energy use to zero, and reduce their wastewater discharge to zero. They also hope to use their building as a teaching tool that can be used to demonstrate feasible ways for visitors to introduce green technologies into their own lives. However, the values that we elicited from them, and the data we collected, were not consistent with such extreme goals. Instead, we found that their current means of providing heat and electricity to their building proved to be near optimal, even considering environmental externalities. Of all the green technologies under consideration, the optimal selection included the implementation of a biomass heater and a composting toilet. The first result is driven by financial and environmental considerations; the second result is driven by educational value. The emissions reductions associated with other technologies were not significant enough to offset the high initial costs of these technologies. The small role played by environmental values stems from the relatively low amount of carbon dioxide (CO_2) and wastewater produced by the HC, and hence the relatively small savings that can be gained by reducing these emissions.

The most useful part of the process for all parties involved was introducing them to the idea of explicitly "thinking about values" (Keeney 1992). Although most participants could generally discuss what was important to them, the idea of *quantifying* values (as opposed to simply quantifying costs) was new, and many participants noted that this provided them with a new way of approaching decision problems.

Section 2 of this paper provides a literature review relating our work to that done in the past. In §3 we discuss the collaborative process, involving an undergraduate engineering economics class and the HC building committee and teachers. This process includes the development of the technology alternatives considered in our tool and the process of eliciting the HC's preferences and establishing base values for tool parameters. In §4 we describe the resulting decision tool. We then present the initial results and sensitivity analysis in §5, and conclude in §6.

2. Literature Review

A rich body of work exists in the area of using decision analysis and decision-aiding tools for decision making within the energy industry. These applications include the determination of the price of an oil refinery (Keefer 1995), the negotiation of the construction of a major transmission line (Borison 1995), the scheduling of refueling for a nuclear power plant (Dunning et al. 2001), and strategic managerial planning at a hydro power plant (Keeney and McDaniels 1992). We also see many instances of DA being applied to the energy sector relating to environmental sustainability and policy (Merkhofer 1987, National Research Council 1990). These works describe the fundamentals of decision-aiding techniques, including the use of modeling to decompose difficult problems. Also discussed are the moral valuation of environmental impacts (clean air and water, human health, etc.) for policy evaluation purposes, and the concept of making environmental decisions when faced with uncertainty in parameters. Specific environmental examples from the literature include the development of a support tool to arrive at the optimal portfolio of technologies for waste site remediation (Jackson et al. 1999), the management of the economic and environmental risks posed to utilities by use of potentially hazardous chemicals (Balson et al. 1992), and the assessment of values of multiple stakeholders as related to potential actions for watershed improvement (Merrick et al. 2005). A complete review of DA and its application to energy and the environment can be found in Keefer et al. (2004).

One subset of research involves the application of outranking methodologies to renewable energy issues. These methodologies rely on pairwise comparisons of potential actions, and two specific methodologies are prevalent in the literature: the preference ranking organization method for enrichment evaluation (PROMETHEE) and the elimination and choice translating reality (ELECTRE). PROMETHEE has been applied to the specific problem of developing geothermal energy resources in the island of Chios, Greece (Haralambopoulos and Polatidis 2003). ELECTRE is used in a variety of decision analysis problems, including implementing renewable energy technologies in Crete (Georgopoulou et al. 1997), Sardinia (Beccali et al. 2003) and Turkey (Topcu and Ulengin 2004), as well as greenhouse gas emission strategies (Georgopoulou et al. 2003). We also find outranking methodologies used to evaluate wind turbine siting decisions (Hansen 2005, Ramirez-Rosado et al. 2008). These methods are generally applied to decisions with multiple sets of stakeholders with conflicting priorities to find the solution most satisfactory to all groups. They are time consuming and computationally intensive; thus, they are not applicable to the decision problem faced by the HC, which has a small, relatively unified number of stakeholders.

We aim to create a decision-aid tool that will allow the HC to quickly and effectively evaluate different renewable energy alternative options to arrive at the investment decisions that will allow them to best meet their stated goals. A well-established body of work exists regarding the development of similar tools. Feng and Keller (2006) present a tool in their work on a potassium iodide distribution decision problem. These authors utilize a spreadsheet that allows the user to assign weights to a variety of objectives, and also rate the degree to which each alternative meets each objective. They therefore provide a framework for comparing different alternatives, as well as easily performing sensitivity analysis of the results. Von Winterfeldt and O'Sullivan (2006) build an Excel-based model to analyze the effectiveness of taking countermeasures against missile attacks on airplanes. They examine a number of consequences, including lives lost, economic losses, and the costs of the countermeasures, based on a parameterized model that allows users to see and alter the parameters. Caccavelli and Guergli (2002) describe the development of a software tool used by engineers and architects to make decisions about energy efficiency building retrofits. This tool allows the user to select from a variety of building improvements and see projected impacts on energy use, environmental comfort for residents, and budgetary constraints. Our work is similar to the first two tools mentioned in that we include metrics that are difficult to quantify (environmental impact, educational effectiveness), whereas the third tool relies on easily quantifiable metrics. Little work exists, however, that deals with this renewable technology investment decision, particularly from the perspective of nonexpert home or business owners.

In addition to providing a useful tool, we hope to educate members of the public on the principles of decision analysis to get them to think more about the way they make decisions. Guikema and Milke (1999) provide descriptions of quantitative methodologies and tools that state agencies in various nations use to tackle decision problems involving investment in wildlife conservation programs. They aim to educate decision makers on decision analysis concepts, including structuring objectives and developing attributes, utility functions, and weightings to improve decision-making behavior. Through working with the New Zealand Department of Conservation, the authors found that the decision makers felt that DA techniques were helpful in clarifying their own objectives and values but had concerns over the difficulty of implementing these techniques in their organizations. Kasemir et al. (2000) researched the importance of removing disconnects between the public's views on climate change and energy issues and those of experts and decision makers. They studied focus groups' perspectives on climate change both with and without interaction with experts and exposure to climate models. This research was used to draw out average citizen's concerns on these issues, which were generally ethical rather than economical, to allow policymakers the opportunity to make decisions that would meet with public approval. Although our work deals with decision making on a much smaller scale, we see the value gained through education about the decision-making process and developing concordance among stakeholders.

In our work, we make use of value elicitation to place quantifiable values on the qualitative characteristics of educational value and environmental impact. A similar method is presented to evaluate the efficacy of tasks required of army recruits during basic training (Klimack and Kloeber 2006). McDaniels and Roessler (1998) performed another value elicitation to place dollar values on qualitative aspects of wildlife preservation. Subjects were asked to place dollar values on various levels of preservation through guided discussion and argument amongst themselves. They found a general consensus that preservation was favored, but also resulted with a wide range of valuations of this preservation. They note that subjects found the "explicit treatment of distinct values helped focus their thinking" (p. 308). We found the value elicitation process to be the most valuable part of the project for the HC staff. By asking them to consider the value they place on subjective properties, and working through the decision tool development process with them, we provided them with a new perspective from which to consider decision problems.

3. An Educational Collaborative Process

Our project had two goals: to support the decision-making process of the client, the HC, and to educate students and the public about the decision analysis process and the benefits it can bring to decision-making processes. Because the HC is an educational organization, they were fully supportive of both goals. In support of these goals, we integrated the project into the undergraduate engineering curriculum and worked with a broad selection of stakeholders at the HC. The following subsections outline the key steps in this process: introduction of the students to the decision problem faced by the HC; the students' development of the engineering economic models; elicitation of the environmental values from the HC building committee; and elicitation of the educational values from the teaching staff. The development of the decision tool is discussed in §4.

3.1. Introduction of Students to Decision Problem

The first step in any decision-making process is to perform an analysis of the values that drive the decision and develop alternatives based on these values (Keeney 1992). To this end, we had an Economic Decision Making class of mechanical and industrial engineering undergraduates meet with the executive director and several board members of the HC to discuss their values relative to this decision problem. Through discussion between the students, the HC members, and the analysts, the three key evaluation criteria of concern to the HC were found to be the environmental impact of the center, the educational effectiveness of the center, and the financial costs to the center.

3.2. Engineering Economic Models

Given these criteria, the students divided into four groups, performed initial research, and arrived at ideas for different areas of improvement that they felt might reinforce the HC's values. These selections were discussed with the HC director, and it was agreed that the technologies under consideration were in line with the HC's goals. The four areas of technology considered were daylighting, photovoltaics, heating, and wastewater. The student groups each developed an engineering economic analysis comparing alternatives for each technology group, including the net present value (NPV) of costs plus data on emissions and other issues relevant to the topic, such as concerns about bird deaths with daylighting.

3.3. Development of the Alternatives

Within each category, a variety of technologies were considered. In researching these technologies, the students considered two construction options available to the HC: either to renovate the current building or construct a new building. The primary difference between these two options is size, with the new building under consideration being larger than the current one. Thus, we assume the new building will have greater heating and electricity requirements than the current building. It is also important to consider any additional costs of retrofitting a technology to the current building as opposed to including it in the construction of the new building. Daylighting falls into this category, due to the additional cost of removing old windows and installing new, larger windows at the current facility. Below we briefly describe each technology.

3.3.1. Daylighting. Daylighting is simply the use of additional or expanded windows, carefully placed to increase the amount of natural light allowed into a building without creating glare. This increase in natural light is generally coupled with electric lighting controls, which monitor the level of light in a room and adjust the level of illumination accordingly. Thus, instead of having electric lights turned on all day, the lights will be dimmed or off during peak daylight illumination hours and then gradually increased as the sun sets. This reduction in electricity use leads to both a financial savings and a reduction in the HC's carbon footprint. We consider four alternatives for daylighting technologies: continued use of current windows or implementation of electric lighting controls with either double-pane clear glass windows, double-pane tinted glass windows, or double-pane low-emissivity glass windows. These window types vary in price and insulating effectiveness (Nicklas and Bailey 1996). We assume a 10% electricity savings from daylighting in the current building, and a 15% savings in the new building. This difference results from the fact that the new building could be designed with daylighting in mind. We also assume a $5/ft^2 reconstruction cost for the current building, which is absent from the new building.

3.3.2. Solar Photovoltaics. Photovoltaic (PV) technology takes energy from the sun and transforms it into useable electricity. PV panels work by absorbing photons from the sun's rays and using these photons to force the movement of electrons within the panel, thus generating electricity. The ability of a PV panel to produce electricity depends greatly on the siting of the panel (south facing in the northern hemisphere; free of obstructions by shadow casting objects) and the sunlight conditions of the environment (typically sunny, cloudy, etc.). Although many types of photovoltaic solar panels are currently available to consumers, we choose to focus on two of the more prevalent types of silicon-based panels: monocrystalline silicon panels and noncrystalline triple-junction panels. These two types differ in efficiency and cost (Solarbuzz 2008). We also consider two scenarios to address treatment of excess electricity generated from panels. Under the "no buyback" scenario, excess electricity simply goes to waste. Under the "buyback" scenario, excess electricity is sold back to the utility at the retail rate.

3.3.3. Heating. Four distinct alternatives were considered within the heating category. Propane-based heat is currently used in the HC, and is the first alternative. For our analysis, we consider continued use of the current propane heater for the current building, and the purchase of a new propane heater for the new building. The remaining useful life of the current heating system is difficult to determine because the system is comprised of four distinct propane units that were bought at different points in the history of the HC. For our analysis, we simply discount the value of the current system as if it were a new one. This practice will overvalue the current system; however, because propane is never shown as optimal, this does not impact the results of our model. We also considered heating with biodiesel and biomass furnaces. Biodiesel is a diesel fuel made from vegetable oil and produces lower carbon emissions than fossil fuels. Biomass furnaces simply burn wood or corn to generate heat, again producing lower carbon emissions than fossil fuels. For our analysis, we will calculate the carbon emissions of biomass as equivalent to the amount of carbon held within the fuel. The final heating alternative considered is geothermal heating, which involves digging a well to access heat below the earth's surface. Electric pumps bring the heat to the surface. Geothermal heating has the benefit of not directly requiring the combustion of any carbon-based fuel, but does have significant excavation, installation, and equipment costs. Geothermal heating also requires the use of electricity to run the heat pumps.

3.3.4. Wastewater. The wastewater reduction category was broken into four possible alternatives. The first involves no changes to current water-using appliances; this is the "do nothing" alternative. The second alternative involves the installation of waterless urinals. These have a low initial cost and would be a useful way of reducing water usage from flushing the toilet. The third alternative is the installation of a composting toilet, which has higher costs associated with purchase, installation, and maintenance, but uses no water and would also provide

Table 1 Example of Alternative Sets

	Current building		New building		
	Optimal	Low Carbon	Optimal	Low Carbon	Status Quo
Daylighting	No daylighting	Double pane clear	Double pane clear	Double pane clear	No daylighting
Solar	No solar	Triple-junction 48 full buyback	No solar	Triple-junction 72 full buyback	No solar
Wastewater	Compost toilet	Living machine	Compost toilet	Living machine	Town water
Heating	Biomass	Biomass	Biomass	Biomass	Propane

the HC with useful compost. The final wastewater reduction alternative is the implementation of a system known as the living machine. The living machine consists of a series of tanks, each containing organisms that break down biological waste and cleanse the water. Wastewater is gradually moved from tank to tank, becoming successively cleaner, until it can finally be reintroduced back into the system as toilet water. The living machine requires the construction of a greenhouse, which could yield potential heating benefits for the HC (estimated at 23% savings of total heat use).

The decision tool we develop allows for the selection of a single option from each of these four categories. The term "alternative set" used throughout this paper refers to a given combination of one of each of the daylighting, solar, heating, and water options. Table 1 provides examples of alternative sets, which are evaluated in this paper.

3.4. Value Elicitation I: Environmental Values and Discount Rate

While students developed alternatives, NPVs, and emissions data, analysts met with the HC building committee, explained the DA process and the aim of the tool, and elicited values for environmental impacts (CO_2, SO_x, and NO_x emissions and water use) and a discount rate. The students then used these values in their final analysis. To effectively evaluate the relative worth of different combinations of alternatives, we needed to develop metrics for the three key evaluation criteria: financial cost, environmental impact, and educational value. Whereas the financial costs associated with each alternative are easily quantified in terms of dollars, the same cannot be said of environmental impact and educational value. We chose to represent these two metrics in dollar values for two reasons. First, although the members of the building committee were not familiar with DA or value elicitations, they were, as Howard and Abbas (2010) argue, familiar with "using monetary measure in valuation." Second, it allows us to potentially calculate the value of information. Using a willingness-to-pay technique for eliciting a value for the cost of emissions damages is reasonable, because both criteria for effective use of willingness to pay are met (Keeney and Raiffa 1993). First, the amount of CO_2 emitted by an alternative is independent of the other attributes of that alternative (price, educational value). Second, the marginal rate of substitution between money and other attributes does not functionally depend on the monetary level. Here we see that the monetary level associated with an alternative does not impact the rate at which money can be substituted for attributes (like CO_2 emissions). Thus, we worked with the HC building committee to determine dollar values for these metrics that reflected their core values. It should be noted that Phillips and Costa's (2007) application of multiple-criteria decision analysis combined with decision conferencing is an alternative method to placing monetary values on environmental damages and educational benefits.

We focus on measuring the environmental damage through determining the amount of CO_2 released into the atmosphere by each alternative. CO_2 is the most prevalent greenhouse gas and one of the biggest contributors to global warming. We asked the HC to put a value on the costs of environmental damages incurred by emission of a single ton of CO_2 in the present. Note that one approach would look at the costs of environmental damages as *information* rather than *preferences*. There is, in fact, a great deal of uncertainty involved in such a valuation. Scientists are

Table 2 Valuations of Damages from CO_2 Emissions

Study	\$/ton CO_2
Leach et al. 1997 (low value)	2
Lomborg 2007	2
IPCC 2008 (low value)	6
Tol 2005 (median value)	8
Tol 2005 (mean value)	18
Leach et al. 1997 (high value)	51
IPCC 2008 (high value)	138
Tol 2005 (90th percentile value)	385

Table 3 Estimates of Costs of Damages from SO_2 and NO_x

Emission	Study	\$/ton	\$/ton CO_2
SO_2	Wang and Santini 1995	341	0.98
	Leach et al. 1997	1,450	4.15
	Wang and Santini 1995	9,041	25.85
	Leach et al. 1997	24,670	70.56
NO_x	Wang and Santini 1995	256	0.28
	Leach et al. 1997	1,450	1.56
	Wang and Santini 1995	17,635	18.96
	Leach et al. 1997	33,378	35.88

uncertain about the degree to which global warming is impacted by human emissions; they are uncertain about how the stock of emissions in the atmosphere relates to global mean temperature; they are uncertain about how global mean temperature relates to local climate variables such as rainfall, temperature, and extreme storms. Finally, there is disagreement about how to value impacts on varying populations, species, and locales. To simplify the process, we represented both the beliefs (about the likelihood of various events) and the preferences (about the value of ecosystems, for example) in a single parameter, elicited as a preference.

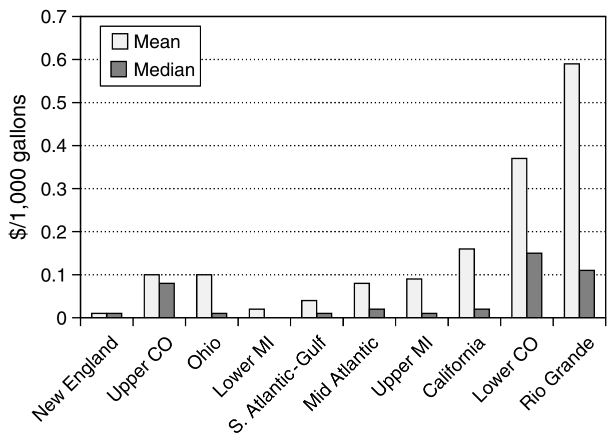
To support the HC in making this value judgment, we performed a literature review and collected an assortment of estimates of the marginal damages from climate change. The values ranged from as little as \$2/ton CO_2 (Leach et al. 1997, Lomborg 2007) to as high as \$385/ton CO_2 (Tol 2005). This high value represents the 90th percentile value from an analysis of 28 studies on the subject compiled by Tol (2005). We present the range of values in Table 2. We also wanted to consider damage from emissions other than CO_2, with the two primary pollutants being SO_2 and NO_x. Although these two gases are released in much lower quantities than CO_2, they have significant environmental impacts, including contributions to both acid rain and climate change. To simplify our calculations, we estimated the approximate amount of emissions of these two gasses for every ton of CO_2 emitted. In reality, these values will vary depending on the type of fuel used and the quality of the facility in which it is burned. Emissions from electricity generation in Massachusetts for these two pollutants were calculated to be 5.72 lbs SO_2/ton CO_2 and 2.15 lbs NO_x/ton CO_2 (U.S. Environmental Protection Agency 2007).

Data collection revealed highly variable estimates of the marginal costs of damages due to these two pollutants, ranging between \$341 per ton (Wang and Santini 1995) and \$24,670 per ton (Leach et al. 1997) for SO_2, and \$256 per ton (Wang and Santini 1995) and \$33,378 per ton (Leach et al. 1997) for NO_x. We then translated these into an extra cost for a ton of CO_2. For instance, \$341/ton $SO_2 * 1$ ton SO_2/2,000 lbs $SO_2 * 5.72$ lbs SO_2/ton CO_2 yields \$0.98/ton CO_2. The values are displayed in Table 3.

We presented these values to the HC building committee and discussed how their own environmental beliefs compared with those of the authors of the various studies. The committee noted that, even though it is an environmental center, they did not necessarily want to simply choose the most extreme number available. Part of the intention of the Green Building Project is to educate the public about the green alternatives that are available in the hopes that more people will implement them. If the HC chose an extreme value, they would be likely to lose much of the public. After some discussion they decided that they would use the high valuation from the Intergovernmental Panel on Climate Change (IPCC). They felt that the IPCC was a respected and valid resource, and that the higher valuation was appropriate because the HC has a firm commitment to protecting the environment; therefore, their members would tend to fall on the high end of valuations for ecosystem services. They combined the IPCC's high estimate of \$138/ton CO_2 (IPCC 2008) with the valuations of \$25.85/ton CO_2 for SO_2 and \$18.96/ton CO_2 for NO_x (Wang and Santini 1995) for a total of \$183.

A similar method was used to put a value on water usage, though this was somewhat less subjective because water prices are readily available. However,

Figure 1 U.S. Freshwater Valuation by Region



the HC building committee felt it important to value the impact of water use at more than simply its market price. To help them arrive at a reasonable valuation, we first presented them with a study assessing national freshwater valuation by region (Frederick et al. 1996). As seen in Figure 1, New England has some of the lowest valuations of any region in the nation.

We also examined local water and sewer prices, adjusted them for inflation, and made linear price projections. These projections indicate that the cost of water in Amherst has been steadily increasing over time. The current cost of water services is $1.50/1,000 gallons, and sewer services cost $1.50/1,000 gallons as well. This results in a total financial cost of $3/1,000 gallons of water used.

After examining local water and sewer prices, linear projections of the future prices, and national water availability/scarcity data, the building committee agreed to value water use generously at $3/1,000 gallons for utility and another $3/1,000 gallons for environmental impact, for a total valuation of $6/1,000 gallons of water used. This is a relatively high value for what is generally considered to be a low-valued commodity, and reflects the HC's high level of concern for the future condition of the environment.

Finally, the HC building committee was asked to choose their discount rate, to be used in the tool to perform calculations incorporating the time value of money for each investment. The HC building committee agreed upon a discount rate of 3%, which is what is suggested by the National Oceanic and Atmospheric Administration (2008) for public goods projects. This relatively low value reflects the high level of importance the HC places on the future.

3.5. Value Elicitation II: Educational Values

The members of the building committee did not feel qualified to comment on the educational value of the alternatives. Instead, we met with HC teachers to elicit values for educational value. The HC director, present at both meetings, made sure there was some consistency between the two groups.

Our first step in performing the elicitation of the educational value of different technologies was to explain the purpose of our work to the teachers. We provided descriptions of each of the technologies to ensure everyone understood their functionalities and applications. We then explained that we were interested in eliciting purely educational values for the technologies in question. We asked them to exclude factors like cost or electrical or heating savings; instead, we asked them to think about the value of the technology for use purely as a teaching tool. To help them, we framed our questions as, "How much would you be willing to pay to have a solar array at the HC to use in your lesson planning, even if that solar array provided no usable electricity?"

We then displayed a list of all the technologies found in the tool, and asked the teachers to rank them in order of highest educational value to lowest educational value. After establishing this order, we started our value elicitation with the highest-ranking technology, the living machine. It was initially difficult for the teachers to place a dollar value on a concept like educational value. They kept including conventional methods for valuing items, worrying about cost, and other factors. Guidance from the analysts combined with group discussion, however, eventually led to placing an educational value of $10,000 on the living machine. Having crossed this first hurdle, the remaining technologies were easier for the group to value. Often different teachers would suggest strikingly different values for the same technology. When this occurred, a discussion of the merits of the technology for teaching ensued. For instance, some teachers placed a much higher value on heating systems like geothermal and biodiesel than other teachers. Some felt that having the technologies on site would

Table 4 Educational Value Elicitation

Technology	Educational value ($)
Living machine	10,000
Composting toilet	9,000
Solar PV	8,000
Daylighting	8,000
Geothermal	5,000
Biomass	100
Biodiesel	100
Waterless urinal	0

be very useful, whereas others felt that because these heaters were quite similar in appearance to standard heaters, that it would be just as easy to teach the principles they represent using models or books. Lesson planning ideas and other educational uses for the technologies were discussed until finally a consensus was reached. In this manner, we placed educational values on all considered technologies, with results as shown in Table 4. The values we elicited in this process were given in terms of lump sum amounts. Thus, for use within the tool, we annualize them over the lifespan of a technology.

Upon completing the value elicitations, the teachers commented that it had been an interesting process and had required that they think about their values in an unconventional manner. In general, most felt that it had been a very useful process.

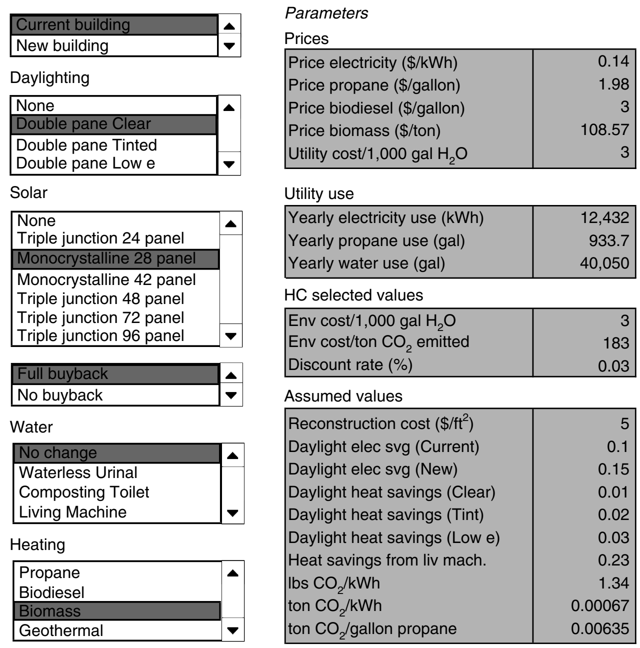
4. Decision Tool Description

The decision-aid tool created for the HC takes the form of a Microsoft Excel workbook, because Excel has the capabilities to perform all necessary calculations and is common enough that most people are familiar with it. The tool contains one tab on which users can select alternatives, change parameters, and view results, as well as several other tabs that hold the relevant data for various calculations. The tool output is a numerical and graphical display of the metrics associated with a selected alternative set, including the annualized values of financial cost, carbon emissions, educational value, and overall preference-adjusted cost.

4.1. Decision Tool Inputs

The inputs to the tool are twofold. The user is required to point and click on selection boxes, which hold the various alternatives under each category of alternatives. They must first select whether they will be considering the current building or a new building, and then select the desired daylighting, solar (with or without buyback), wastewater, and heating options. Having selected these inputs, they also have the opportunity to change any of the many parameters used in performing the calculations. These parameters include items such as the annual utility use of the HC, damages from emissions, and heat savings from various technologies. These values can be changed by the user. A complete view of the selection menus and parameters available to the user is displayed in Figure 2.

Figure 2 Selection Menus and Parameters



4.2. Model Output

The outputs of the tool are both numerical and graphical. The annualized financial cost for each alternative is displayed, and all annualized financial costs are summed to yield the total annualized cost of the selected alternative set. The utility use and associated environmental costs are also displayed and summed, showing the user how many tons of CO_2 and gallons of water they will be using, and what the overall annual cost is for this use. The annualized

Table 5 Numerical Output of Decision Tool

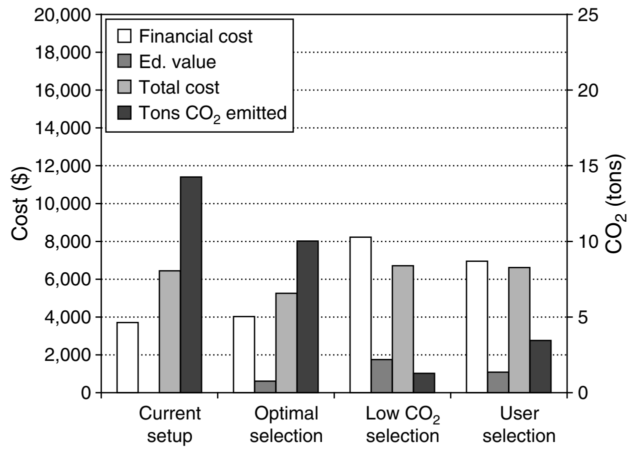
	Daylighting	Electricity	Water	Heating	Total
Ann. fin. cost ($)	0.00	1,740.48	120.52	1,998.97	3,859.97
Utility use		12,432 kWh	40,050 gal	85.9 MMBtu	
Fuel used				7 ton biomass	
Tons CO_2		8.33		1.69	10.02
Ann. env. cost ($)		1,524.29	120.15	310.00	1,954.44
Ann. ed. value ($)	0.00	0.00	0.00	6.72	6.72
Total annual cost ($)					5, 807.69

Note. Ann., annual; fin., financial; env., environmental; ed., educational.

educational values of selected alternatives are displayed as well. The total preference-adjusted annual cost of the selected alternative set is displayed, combining the financial and environmental costs, and educational values. Table 5 shows the numerical display seen by the user given a selection of the current building, no daylighting, no solar, town water, and biomass heating.

We designed a graphical display that allows the user to compare their selection directly to three other alternative sets. This was done with a simple bar graph, with four bars for each set. Beginning on the left, the first bar represents the financial cost of the set, the second bar represents the educational value of the set, the third bar represents the preference adjusted cost of the set, and the fourth (rightmost) bar represents the tons of CO_2 released by the set (as measured on the right-hand axis). Four alternative sets are displayed on the graph: the Status Quo, Optimal, and Low-Carbon sets, as well as the set the user has currently selected. These different sets are further explained in the Results section. The User Selection set of bars will change as the user changes her selected technologies. Any change made by the user to the parameters of the tool will be reflected in all four of the displayed alternative sets. Figure 3 displays the Current, Optimal, and Low-Carbon alternative sets for the construction of a new building. The User Selection in this instance is an alternative set comprised of double-pane clear daylighting, a 28-panel monocrystalline solar array with buyback, town water, and biomass heating. Note that this alternative set has a lower total preference-adjusted cost than the status quo and much lower carbon emissions, but higher financial cost.

Figure 3 Sample of Graphical Model Output: Alternative Combination Comparison



5. Results and Sensitivity Analysis

The model allowed us to find the set of alternatives for the default parameter settings that has the lowest preference-adjusted cost (including financial and environmental costs and educational values). We define this set as the Optimal set. Holding all parameters at their default values, this set of alternatives is the optimal choice for the HC. The Optimal set for the current building is comprised of no daylighting, no solar array, a composting toilet, and a biomass heater, as indicated in Table 6. It is important to note that under the assumption of carbon neutrality for biomass, this set is even more preferred. The Optimal set has an annual financial cost of $4,026.93, a total preference-adjusted annual cost of $5,252.56, and releases 10.02 tons of CO_2 per year. The Optimal set for the new building is similar, but includes daylighting. It has an annual financial cost of $5,617.11, a total preference-adjusted annual cost of $6,729.19, and releases 12.34 tons of CO_2 per year. For comparison purposes, we also consider a Low-Carbon set of alternatives. This set has higher overall costs but very low emissions. Table 6 displays the alternatives that make up each of these sets for both the current building and a new building, along with key values associated with these sets.

All stakeholders felt that the value elicitations were very difficult, and were concerned that if a specific value was decisive they would like to revisit it. Moreover, individuals among the stakeholders may hold

Table 6 Alternative Sets

	Current building		New building		
	Optimal	Low Carbon	Optimal	Low Carbon	Status Quo
Daylighting	No daylighting	Double pane clear	Double pane clear	Double pane clear	No daylighting
Solar	No solar	Triple-junction 48 full buyback	No solar	Triple-junction 72 full buyback	No solar
Wastewater	Compost toilet	Living machine	Compost toilet	Living machine	Town water
Heating	Biomass	Biomass	Biomass	Biomass	Propane
Financial cost ($)	4, 026.93	8, 227.11	5, 617.11	9, 729.70	3, 713.45
Carbon emissions (tons)	10.02	1.28	12.34	1.82	14.26
Educational value ($)	611.66	1, 754.33	1, 149.39	1, 754.33	0.00
Pref. adj. cost ($)	5, 252.56	6, 709.75	6, 729.19	8, 309.76	6, 442.90

Note. Pref., preferred; adj., adjusted.

personal values that diverged from the value agreed upon by the group. Thus, we paid special attention to the value of environmental damage caused from climate change, educational value, and the discount rate.

To perform this sensitivity analysis, we take individual parameters and graph the change in overall cost to the HC resulting from a change in each parameter for several alternative sets (Clemen and Reilly 2001).

First, we examine how the results would change if only financial costs were considered. The result (for both buildings) is that the Status Quo set is preferred; that is, with no emissions costs or educational values, the HC is currently doing the best they can. Including only costs of emissions results in a preference for the Optimal set using town water in place of the composting toilet. For comparison purposes, we include these alternative sets in our sensitivity analysis.

We now look at the sensitivity of our results to the cost of environmental damage associated with emissions. Holding all other parameters constant, we vary this cost for several alternative sets. Figure 4 shows the results of this analysis for the current building. Results for the new building are nearly identical, and are thus omitted. The first insight derived from this figure is that even when the cost of damages from emissions is set to zero, the full Optimal set, including the composting toilet, performs better than the Status Quo. This is driven largely by the educational value placed on this technology. We also see that the Optimal set remains preferred until the cost of damages increases to $350/ton CO_2, at which point the Low-Carbon set is best. This represents a significant increase over the $183/ton CO_2 we use initially, indicating that our results for the cost of emissions damages are robust.

We also examined sensitivity to the educational value placed on technologies. We first examine the educational value placed on the composting toilet, because this technology was valued very highly by the HC teachers and is included in the Optimal set. We vary the educational value of the composting toilet, and compare four sets of alternatives: Optimal, Optimal using town water, Optimal using the living

Figure 4 Marginal Cost of Carbon Damages Sensitivity Analysis (Current Building)

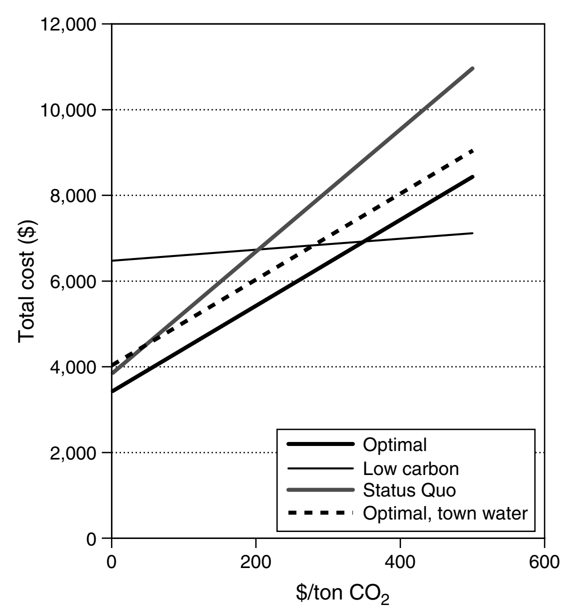


Figure 5 **Sensitivity to Composting Toilet Educational Value (Current Building)**

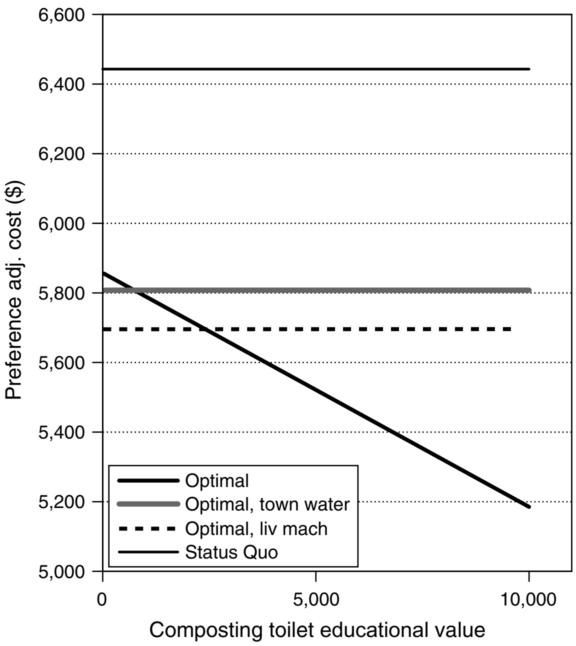
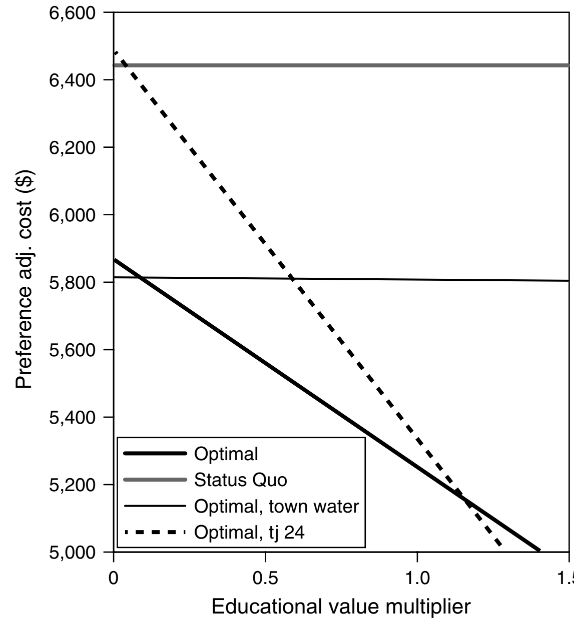


Figure 6 **Sensitivity to Changes in Elicited Educational Values (Current Building)**



machine, and the Status Quo. Our results are displayed in Figure 5. Holding all else constant, we see that an educational value of $1,000 must be placed on the composting toilet to make the Optimal set preferred to the Optimal set using town water. This value must increase to $2,600 to make the Optimal set preferred to the Optimal set using the living machine. This is compared to the $9,000 value that the teachers assigned to it. Thus, we see that the HC educators would have to dramatically lower their valuation of the composting toilet to make the Optimal set not preferred. Therefore, the inclusion of the composting toilet in the Optimal set is quite robust.

An early step in the elicitation of educational values was to establish an ordering over the relative educational value of the technologies. We additionally test the sensitivity of our results to the educational values elicited by maintaining this ordering of technologies, but adjusting the elicited values by a multiplier. The results for the current building are seen in Figure 6. The overall educational values would need to be reduced by nearly 90% before the use of the composting toilets would become suboptimal. On the other hand, if educational value was increased by 20% across the board, a set that includes biomass, the composting toilet, and a 24-panel triple-junction solar array would become preferred to the Optimal set. Thus, we see there exists a broad range of educational values within which the Optimal set will remain preferred by the HC.

Finally, we examined sensitivity of our results to the discount rate selected by the HC and found that it does not play a strong role in our results; in fact, the Optimal set is always best, regardless of discount rate.

6. Conclusion and Insights from the Project

In this paper, we discuss the process of developing a decision-making model to support investment choices in green energy technologies. Based on the metrics of environmental sustainability, educational applicability, and cost, student researchers gathered data in four areas of technology suited to the Hitchcock Center's goals. This research was consolidated into an Excel-based decision tool that allows users to select different technologies and view the resulting costs and impacts. Using the tool, we were able to find the lowest cost alternative set, which for the current building included no daylighting, no solar array, a composting toilet, and the installation of a biomass heater, yielding a preference-adjusted annual cost of \$5,252.58. We also performed a sensitivity analysis showing how the optimal choices will change with changing parameters.

This collaborative process had educational value for the undergraduate students and for members of the HC community. The students gained perspective from participating in a real project, including the difficulties in finding data and in choosing preference parameters such as the discount rate. They were introduced to the concepts of value-focused thinking and multi-objective DA as they implemented the HC's valuation of CO_2 reduction. Moreover, the students got involved in the community, learning about a local nonprofit and ways in which engineering professionals can contribute to the greater good. This project is consistent with the new Carnegie Foundation (Sheppard et al. 2009) recommendations for engineering education, allowing the students to integrate knowledge and skills in a real-world application.

Members of the HC community were very interested in the process. Most of the people we worked with had no exposure to quantitative-based decision making. They found the process of choosing CO_2 and educational values daunting but illuminating. They were used to considering the price or cost of alternatives, but not their personal values. Although they were somewhat comfortable with the idea of ranking preferences, they found making specific trade-offs quite radical. They agreed that they enjoyed the experience, discussed values heartily, and generally came to a consensus about values. They appreciated the idea that they can revisit their values as they have time to reflect and further discuss them. They are very interested in making the decision tool and the process of preference elicitation part of their educational arsenal—they want to help people make better decisions about green technologies.

Direct comparisons can be made between the results of our work and others from the literature. Our initial meetings with the HC director and building committee ensured that we met the conditions for completeness of Gregory et al. (2005), which call for the key values of all stakeholders to be included. Our elicitations and modeling ease the cognitive load on decision makers, providing comprehensiveness to the decision-making process, and our results were appropriately informative through making full use of the participants preferences. Schilling et al. (2007) detail metrics upon which the quality of a decision process and output can be measured. Although we performed no specific analysis of the quality of our process, many of our methods are in line with the metrics described. From the standpoint of process effectiveness, our work included adequate empirical information, creativity on the part of students and committee members, and sufficient participation from stakeholders. Schilling et al. (2007) measure output in terms of group alignment. We found that HC committee members' values surrounding their decision are certainly more aligned now than they were prior to working with us on elicitations and using the decision tool.

In summary, this project indicates that perhaps the single greatest service we can do is to get people thinking about values. The development of decision tools like ours are useful in that they give stakeholders a clear incentive to go through the process of value elicitation and allow them to explicitly and transparently test the impact of their elicited values. Providing a visual representation, allowing stakeholders to compare multiple alternatives across multiple criteria, was a particularly useful aspect of the project.

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