AC 2007-689: OPTIMIZATION OF GREEN ROOF SYSTEMS FOR MULTIFUNCTIONAL BUILDINGS: A THREE-YEAR INTEGRATED CIVIL AND ENVIRONMENTAL ENGINEERING DESIGN COURSE EXPERIENCE

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Optimization of Green Roof Systems for Multifunctional Buildings: A Three-Year Integrated Civil and Environmental Engineering Design Course Experience

Course Motivation and Objective

Every year, the instructors of the senior design course for Civil and Environmental Engineering develop course materials and projects to illustrate the various professional life aspects of practicing engineers, including successful project proposal writing, development of status reports, and final project delivery, analysis of ethics issues, and economics. The students are expected to work in multi-disciplinary teams to successfully complete a civil/environmental project need. Defining the technology opportunity space, a compelling practical need, and a project that capitalizes on the backgrounds of students in structures and materials, construction, geotechnical engineering, and construction management is challenging, as is the means by which the project results are communicated across disciplines and to the lay public.

It has been four years since I volunteered as a faculty advisor in engineering to a student project in the Tauber Manufacturing Institute (TMI), which is founded at the interface between engineering and the business school. Funded by major endowments from industry and individual donors, the two-year TMI educational program trains business and engineering students, culminating in a combined MBA-MEng degree. As part of the program, the students are required to work in teams on industry-proposed projects related to manufacturing. I was interested in a project proposed by Alcoa Corporation through its Technical Center in Pittsburgh, PA to make the business case for a cost-effective stormwater management technology for industrial applications. Specifically, Alcoa was interested in the implementation of green (or vegetated) roofs as a means to reduce and delay peak stormwater discharges, and clean up contaminants in runoff. The basic features of a vegetated roof are outlined in Figure 1, and include, aside from the structural support, a roofing membrane, root barrier, a drainage system, the growth medium and vegetation. Depending on the configuration, growth medium thickness, and functionality, the average added weight per square foot of roof surface is on the order of 17 to 80 lbs wet weight.

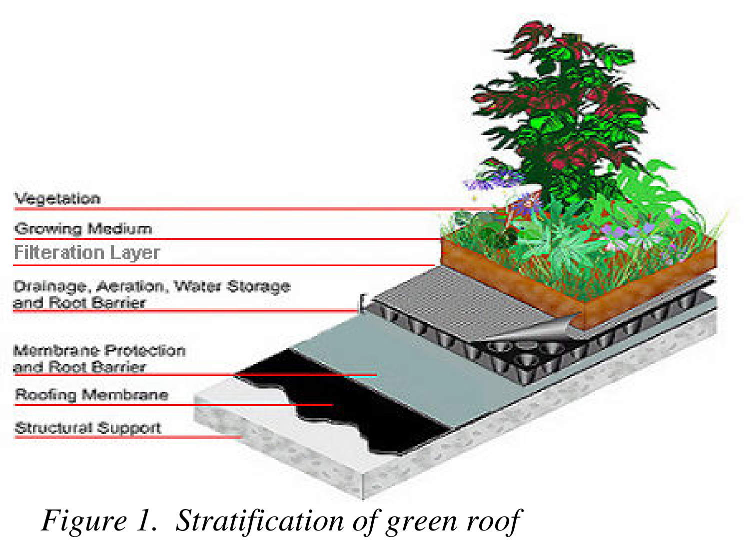

Figure 1. Stratification of green roof

At that time my knowledge of green roof technology and designs, or their cost-benefit analysis was limited, as it was for my colleague in the Business School, Professor Brian Talbot. The team was made up of two business students, one engineering student and a student from the Corporate Environmental Management Program (CEMP). The latter is a joint program between the Business School and the School for Natural Resources and Environment. To help the team become experts in the technology, Alcoa sponsored all of us to go to the First North American Green Roof Conference in Chicago, to the World's cleanest smelter (Alcan) on the St. Lawrence River (in Quebec, Canada), and to a meeting with DuPont in Delaware to discuss synergies with Alcoa's product line and to explore strategic partnerships. In addition, the students spent one month in Germany, which is the seat for green roof technology with forty years of experience. After five months of study and meetings, a presentation was made to Alcoa's corporate board, including Alcoa's Vice President for Environment. It was decided that the technology would be implemented on all the buildings of the Fjardaal smelter, except for on the smelter 'pot room' itself due to the incompatibility between hydrofluoric acid emissions and plant growth.

As a professor in CEE, the experience opened my eyes to corporate decision-making, and business culture, and helped me realize that this technology implementation was dominated by architects in cooperation with executive officers at Alcoa, with little or no input from engineering, aside from structural calculations. Yet, the technology touches many aspects which are our bread and butter: structural analysis, stormwater management, and contaminant fate and transport (see also Figure 2. The green roof stormwater control strategy capitalizes on the expertise of civil engineers in the building design and construction for appropriate roof load capacity under various climatological conditions for new and refurbished (e.g. Brownfields) facilities (residential, commercial, and industrial). Environmental engineering expertise is required to evaluate the impact of green roof designs on permitting, design of retention facilities, and stormwater runoff. When the opportunity presented itself to teach the senior design course, I decided to focus on green roof technology as an example of green infrastructure design, and an opportunity to enable the civil and environmental engineering undergraduates to work together on a single project, rather than on separate projects.

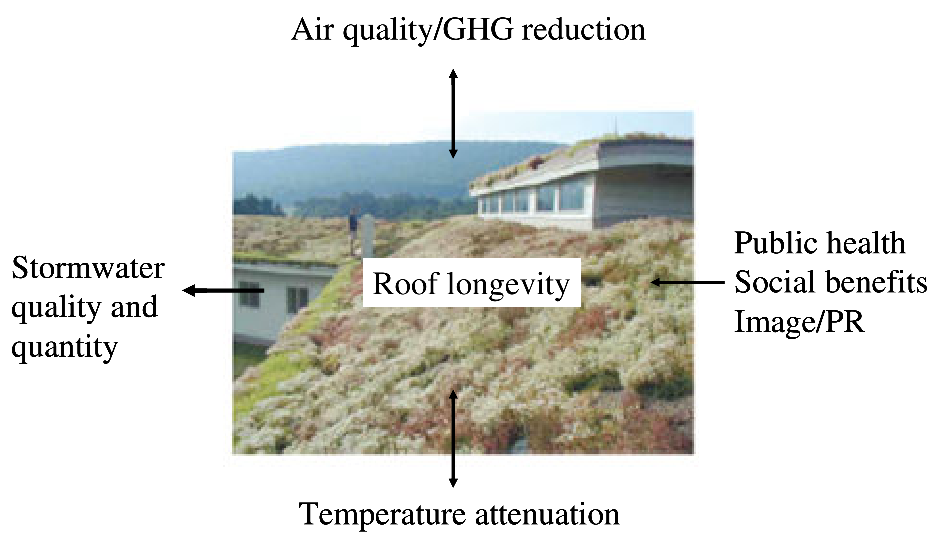

Figure 2. Benefits of green roofs (GHG, greenhouse gas)

The objective of this design course is for the students to capitalize on their specialized knowledge in CEE program areas, and leverage this into a project of high visibility and translational potential to practice.

Student Background and Course Metrics

When the students enter the course, they have had varied exposures to coursework pertaining to structures and structural analysis, water treatment and hydrology, typically constituting a sequence of two to three courses in their focus area of choice. Moreover they have been exposed to technical communications and team work requirements, as well as to pre-specified design projects. This not a 'classical' design course where the variables and objectives are predestined at the beginning of class. Rather, we have intended to convey the reality of practical problem solving by simulating the process between problem owner (client), procurer of engineering services and engineering consultants. This requires the student teams to have to identify the important drivers, including economic sensitivities to meet the client's expectations in terms of dollar and time budget. Hence, the objective is to develop a preliminary design sufficient for the problem owner to make a decision as to whether the green roof is a good investment – NOT necessarily to come up with a buildable design.

Professional growth is measured by way of ten (10) course milestones (Table 1), emphasizing both individual and team-based deliverables over a semester (14 week) timeframe

Table 1. Tasks, Deliverables and Grading Structure

Task	Deliverable	Evaluation	Timeframe	Grade (%)
1. Technical and Cost Proposal	Proposal and short presentation	Team	Week 3	20
2. Homework 1 Economics	Engineering economics solutions	Individual	Week 4	1/3rd of 20
3. Homework 2	Load calculations	Individual	Week 5	1/3rd of 20
4. Homework 3	Stormwater hydrology	Individual	Week 6	1/3rd of 20
5. Interim Report 1	30% review – loads and rainfall data	Team	Week 6	1/3rd of 20
6. Ethics essay	1-2 page descriptive solution to case study	Individual	Week 7	10
7. Interim Report 2	60% review – structural analysis	Team	Week 8	1/3rd of 20
8. Interim Report 3	90% review – cost/benefit analysis and optimization	Team	Week 11	1/3rd of 20
9. Draft Design Report	Executive summary (5p), Appendices (Figures, Structural and environmental calculations, Economics)	Team	Week 12	20 (prelim grade)*
10. Project Presentation	20 min PowerPoint	Team	Week 13	10
11. Public presentation	3D or virtual displays	Team	Week 13	0
12. Final Design Report	Fully updated and corrected report.	Team	Week 14	30 (final grade)

**Preliminary grade: The students receive a grade for their draft reports, which can be adjusted by up to half a letter grade if they incorporate the instructors' comments in the final submission.*

Since the engineering consultancy is essentially an iterative process, communication is of the essence to understand the client's needs and goals, and to propose solutions addressing these needs. It is important to note that as an engineering consultant and design engineer, they need to help the client understand the open-ended solutions to his problem or desired project, and the variables that may impact his/her decision. Hence, the student learns the professional evolution of a project, rather than 'plug-and-chug' solutions to specified problems. Since each student team essentially forms its own engineering firm, they have to internally appropriate expertise and exchange information on how the structural features impact the environmental endpoints and *vice versa*. To formalize the link of engineering design to practice, two to three consultants from the environmental and construction industries are engaged to participate two hours per week to guide the student teams through their design project. In addition, to ensure that the engineering communication component of the course is satisfied, a technical communications representative is engaged to work with the cognizant faculty member and the consultants on the project design.

Three features allow the student teams to benchmark themselves in their learning experience.

1. <u>The technical and cost proposal</u>. The importance of a professional response to a request for proposals is the focus of this objective. This requires being responsive to the client's requests and making the case for an appropriate design approach. The student team develops a draft proposal, which is presented to the practicing engineers, the course instructor, and the technical communications representative. The proposal and its presentation receive a preliminary grade which can be improved by half a grade if the team responds to the comments in the final proposal. The final product is measurably improved over the draft.

2. <u>Engineering economics</u>. This objective teaches the student of the interaction between design requirements and economic constraints to make the business case for a design project. The growth in this objective starts with one week of lectures on engineering economics, and the importance of various assumptions in net present value projections, followed by a comprehensive homework assignment emphasizing the value of economic sensitivity analysis and how it impacts a design exercise. The teams are then told to check the implications of their engineering assumptions on cost as their design project evolves. The teams submit a preliminary report on the design metrics as influenced by economic considerations, conduct an in-class report out on design sensitivities which is queried by the instructors. Finally, the net present value analysis (over 40 years) for investment in the green roof is included in the final design report.

3. <u>Final design report and communications</u>. The final report is the culmination of approximately two and half (2.5) months of research and design, including two interim reports (aimed at benchmarking progress). The students again have the opportunity to submit a draft project report for a preliminary grade, which can be improved upon by incorporating comments from all four lecturers. The final projects are presented to a professional audience, including UM plant operations, UM facilities planning, and the adjunct lecturers from industry (consultants). Communication incorporates the following elements: technical presentations, public presentations, technical reports, and essay.

Course Content and Illustrative Examples

Over the last three years, up to sixteen teams of four students (each composed of a mix of structural, geotechnical and environmental engineering majors) worked on a number of buildings capturing public and private facilities with multiple functionalities. The *a priori* opportunity space and design criteria as well as the scale are provided in Table 2 for the 2006 version of the course; the criteria have changed from year to year depending on client requirements. The opportunities were chosen based on stakeholder interest, public priorities or city/district wide policies, and the design criteria were either artificially imposed or set by the stakeholder. The objective was for the student teams to work through structural, environmental, and economic issues to achieve an optimized solution to the problem. To accommodate this objective and the varied deliverables for the course, the class was structured to include two meeting periods per week, divided between external testimonials or high profile green roof case discussions on the one hand, and in-class discussions/feedback with the four instructors on the other hand.

Table 2. Green Building Functionality, Design Criteria, and Scale

Building	Functionality	Design Criteria	Scale (sq. m)
Walmart facility	Single storey retail	Capture 10 year storm event; ROI < 20 years	10,000
Environmental and Water Resources Engineering – University campus	Multiple storey administrative and research	Capture 10 year storm event; ROI< 20 years	1,000
Art and Architecture Building – University campus	Multiple storey administrative and research	Capture 10 year storm event; ROI < 20 years	8,000
Public Hospital	Multiple storey administrative and services	Capture 10 year storm event; ROI < 20 years	6,000
Private Hospital	Multiple Storey administrative and services	Maximum stormwater retention; incorporation of playground; two roofs	12,000
Industrial Facility	Single storey, heavy manufacturing	Capture 10 year storm event; cool process water to 20ºC for discharge	125,000
Office building	Multiple storey, administrative	Capture maximum storm event without structural reinforcement; emphasis on city-wide scalability	6,000

Note: ROI, Return on Investment

To address the problem, the students were provided engineering drawings, log borings (when available), existing storm water infrastructure, current energy expenditures for heating and cooling, live/dead loads to be taken into account, and access to current guidelines[1-5]. The students are expected to do their own research pertaining to climatological conditions, storm water capture and insulation requirements, and structural needs/costs for reinforcement (if required). For the public communication requirement, the students were provided a series of three workshops on software training, building scaling, and continued access to expert consultancy from the 3D imaging laboratory. For illustrative purposes, the design of two green roof systems will be described in this manuscript.

Case Study 1. Art and Architecture Building
The first case study is represented by a campus building (Figure 3, left). The building was constructed in 1974, and the roofing membrane has been replaced in sections as needed. The existing roofing membrane is scheduled for replacement within the next two years. The client required a green roof design for the Art & Architecture building which is optimized with respect to structural needs, environmental benefits, and economic constraints. The goal outlined in the request for proposals stressed that the design should adhere to the principles of sustainable design, and provide an optimized building envelope solution, where economic savings result from environmental benefits. There was a constraint of a seven year break even point for expenditures associated with energy improvements. To optimize a green roof system, two designs were considered. The first design must capture approximately 1" of rainfall, and the second must capture approximately 3" of water. For each design, the structural implications associated with placing the additional weight on the roof, and design reinforcements needed to be considered as necessary. The differences in energy costs associated with the green roofs as compared to the existing roof needed to be determined using a cost benefit life cycle economic analysis.

Since the roof was designed as one way slab, a load pattern was assumed, in which the load is transferred from the deck, to the beams, girders, columns, and then to the footings. The current structure was analyzed with existing dead loads and live loads for deck, beams, girders, columns, and footings (Figure 3, right). The same members were then analyzed again for 4" and 8"thick green roof designs. The calculations indicated that the current structure must be increased in capacity by reinforcing the beams to be able carry additional dead load of the green roof.

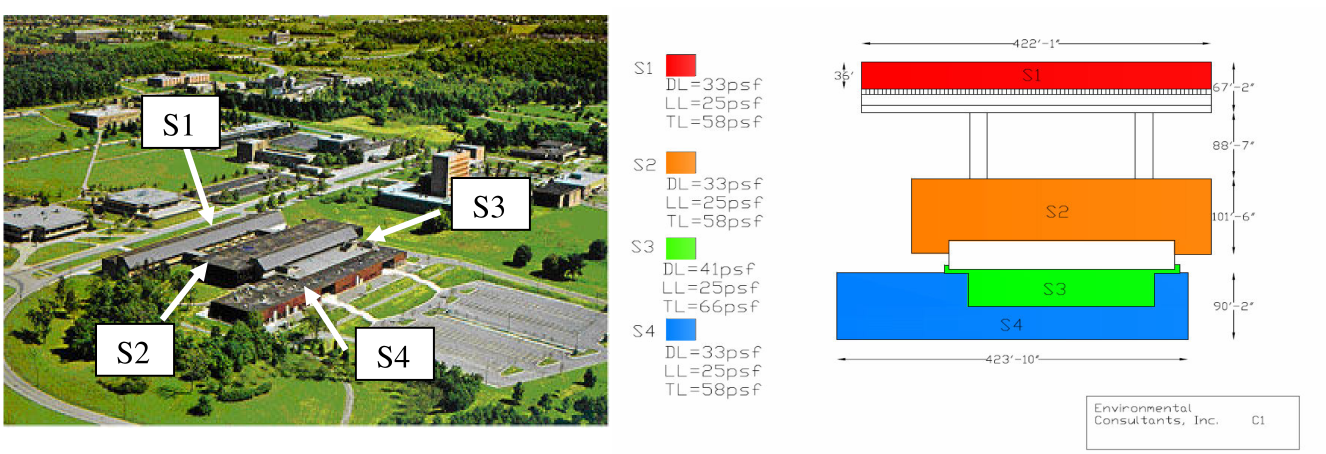

Figure 3. Aerial photograph and load analysis of the current roof of the A&A building (DL, dead load; LL, live load; TL, total load). Designations S1-S4 represent the roof sections considered in the design analysis; hence, section S1 in the aerial photo refers to the top roof section in the load diagram.

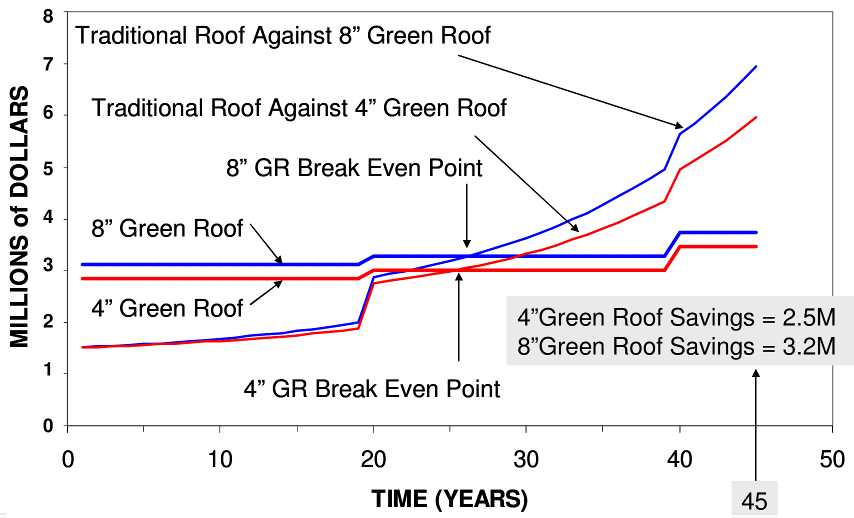

Figure 4. Lifecycle cost analysis of two green roof designs

Some basic assumptions that were made in dead load calculations are: Insulators:1 psf, roofing:10 psf, deck and lightweight gypsum concrete: 15 psf, HVAC and lighting: 5 psf, ceiling: 2 psf, Skylight and frame:15 psf, membrane: 1 psf. The saturated dead load of the 8" green roof was given by the manufacturer (28 psf) and the saturated dead load of the 4" green roof was given as 15 psf. The live load was considered as the 25 psf snow load.

The net present worth of the 4" extensive, 8" intensive, and traditional roof system were calculated using a spreadsheet analysis tool (Figure 4). Assumptions included that the waterproof membrane is replaced before installing a green roof. We modeled a variety of situations by varying what we identified as the most significant parameters to produce a reasonable range of break even times corresponding to each situation. The energy inflation rate and cost of structural reinforcements are the most significant uncertain factors affecting the break even points of each green roof system. Energy calculations were based on heat flux analysis in traditional versus green roofs. Since green roofs impart insulation value to the roof (R values of up to 2 for every inch of green roof), there are associated energy savings from heating and cooling. The reduction in storm water runoff will be accomplished through the water retention capacity of the green roof and the reduction in peak runoff rate. The combined effects will significantly reduce the required capacity of the detention pond that serves the area. The results in Figure 4 show the costs and benefits of the 4" and 8" green roof. Over time, the net present value calculations indicate that the green roof (reinforcement included) premium investment will be recovered after 25-26 years, with savings of $2.5-3.2 M over 45 years (the presumed lifetime of a green roof). It was assumed that the traditional roof needs to be replaced every 18 years.

Case Study 2. Office Building Washington DC

The second case represents a typical multi-storey office building in the Nation's capital. The client in this case was DC Green Roof Allies, which includes developers, policymakers, and NGOs dedicated to the promulgation of green roofs in the Nation's capital, and represents a strong proponent of the 20-20-20 objective for the District of Columbia. This objective, currently being considered by the District and EPA, is to green 20 million square feet of roof surface covering approximately 20% of office buildings by 2020. The main driver for this alliance is to provide multiple benefits to the city, such as: (i) Improving air and water quality and public health, (ii) Reducing asthma rates in children, (iii) Providing public green spaces, (iv) Lessening urban heat island effects. DC Green Roof Allies has already collaborated with EPA and Washington DC to demonstrate the ability of green roofs to reduce storm water runoff in both the combined sewer system and the storm sewer system. However, these storm water and water quality benefits are secondary to developers and not sufficiently persuasive in their own

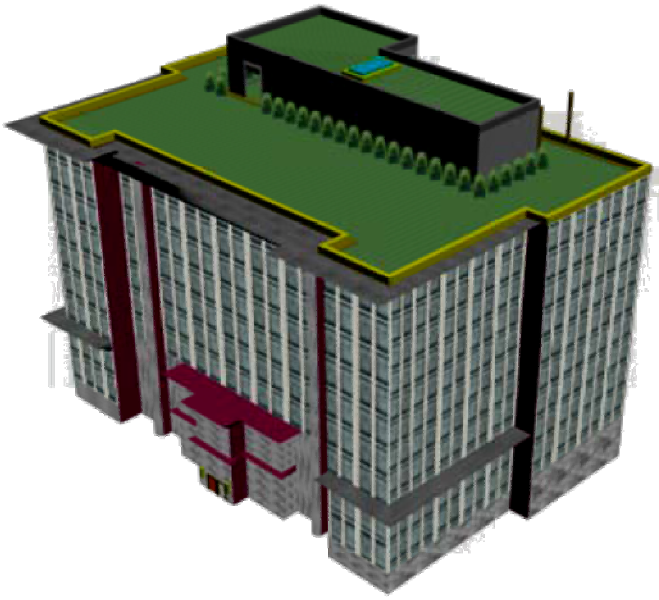

Figure 5. A representative DC office building and artistic rendition of an intensive (public access) and extensive (only maintenance access) green roof system

right to spur green roof development. Hence, economic incentives will be necessary to meet the 20-20-20 objective. In order to encourage developers in the District of Columbia to install green roofs, these benefits have to be quantified for a typical or traditional building design. The student teams were asked to provide a recommendation for a green roof design which provides the best balance of storm water storage, energy saving, and economic advantages.

The typical DC office building for this study was located at 700 Sixth Street, NW, about a half mile northeast of the White House. Aerial views show the building footprint to be in the heart of the Washington, DC business district. The building is currently in the design stage, and is planned to consist of twelve floors with a penthouse containing mechanical equipment (Figure 5, left). The design team designed and evaluated the benefits and costs of an extensive green roof to capture a one year, thirty minute storm and an intensive green roof (Figure 5, right) to capture a one year, twenty-four hour storm, as requested by the client.

The structural features of typical DC building include (i) reinforced concrete construction, and (ii) two-way and one-way slab systems. Similar load calculations were performed as in the previous case, except for that the weakest member analysis indicated that not structural reinforcement was required. Hence, no load transfer analysis to the girders, columns and footings was performed. Energy and storm water calculations were as before, resulting in the following economics of these designs (Figure 6): (i) the break-even point of an extensive green roof is at 20 years, when the conventional roof needs to be replaced; (ii) the insive green roof breaks even after 40 years; (iii) the energy savings are in the $1,000-8,000 per year, depending on scale; (iv) the total NPV over 40 years for intensive roofs is $45,000 representing 10% of the premium cost. Further benefits (not shown) were calculated based on the scalability of storm water reductions on a city-wide basis (20-20-20); stormwater infrastructure savings amount to millions of dollars in construction.

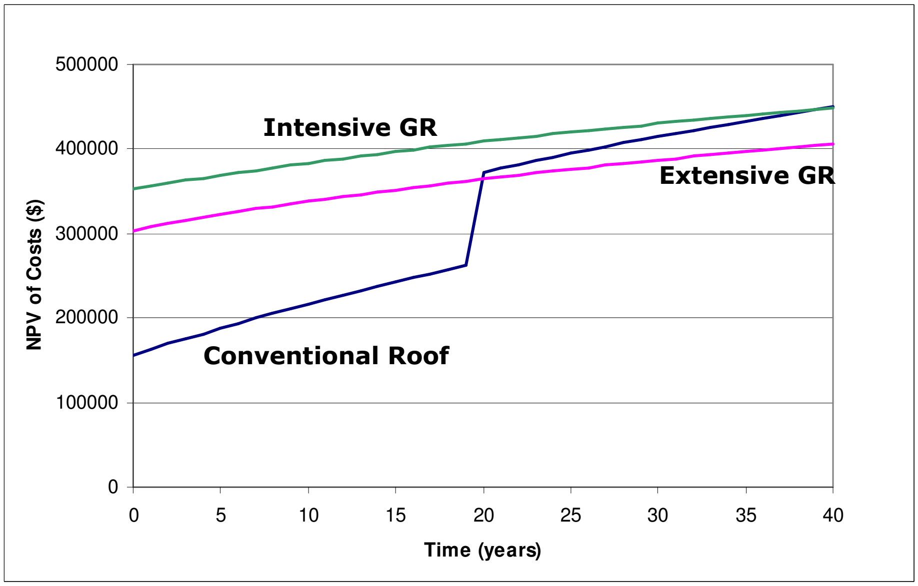

Figure 6. Net present value (NPV) evolution over 40 years

Student Assessment

Student feedback during the three-year pilot has been increasingly positive as to the design challenge and requirements. A formatted response (here, the 2005 AY) is represented in Table 3, for a student response of 35 out of 58, based on course objectives capturing the design experience and exposure to required course elements in a capstone design course.

Table 3. Course evaluations vs. course objectives (AY 2005)

		To what degree has this objective been met				
Course Objective	**Strong**	**Fair**	**Weak**	**None**	**No Response**	**Total**
1. To provide an exposure to project design.	31%	43%	20%	3%	3%	100%
2. To provide an exposure to proposal writing and final report preparation.	83%	17%	0%	0%	0%	100%
3. To provide exposure to economic analysis of engineering projects.	40%	51%	9%	0%	0%	100%
4. To provide exposure to regulatory issues.	9%	31%	57%	3%	0%	100%
5. To provide an exposure to engineering ethics and the role of professional code of ethics in decision making.	26%	63%	11%	0%	0%	100%

As a department policy, it is argued that no corrective action to the course is required if the combined strong and fair responses total 75%; in this case, exposure to regulatory issues was viewed as being inadequate by the students, and hence, was corrected in 2006. A more informal debriefing at the end of class indicates that the students appreciate the multi-disciplinary approach and open-ended solutions space, and the opportunity to translate the designs into virtual visualizations. However, by attempting to design a course for the entire department, the students are conflicted over whether all the projects (i.e. choice of buildings and available information to complete the design) provide equal opportunity for all CEE program areas (structures, geotechnical, environmental, construction engineering and management) to apply their skills during the project. The perceived value of the remedial homework and lectures was also mixed, considering that some students are taking relevant courses during the same term as the design course. Finally, there may be a need for curriculum adjustment with the end-goal in mind. If the students will be required to be able to take engineering drawings and interpret them to enable the design of green buildings within an engineering economics framework, what should the content of supporting courses be to allow them to take on this task? The nature of the final project designs change as a function of cognizant faculty interest, external consultant expertise, and project availability. The challenge is to find an appropriate curriculum that would allow the students to move between projects, which at the same time adhere to suggested design course requirements including exposure to ethics, economics, the regulatory environment, team work and communications.

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