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Engineering Sustainable Construction Materials for the Developing World: a Meta-discipline Approach to Engineering Education*

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In order for society to achieve a sustainable future, engineers must equally consider issues of the environment, society, and economy. For years engineering education has taken a behaviourist approach, assuming a student's mind is an empty slate that needs to be filled with a finite amount of knowledge, transmitted from teacher to student. Here we demonstrate how a team of engineering and public policy students can construct their own knowledge while developing sustainable construction materials that could be used in the developing world. Our education model is assessed by several direct and indirect methods; including evaluation of course deliverables, student surveys and comparison to more traditional design projects.

Keywords: constructivist education; engineering; social science; public policy; sustainable development; pozzolan; cement; developing world

INTRODUCTION

SCHOOLS OF ENGINEERING have for years taken a behaviourist approach to education. The traditional method of three lectures per week, three homework problems per lecture and three tests per semester is objective and limits engineering solutions to right and wrong answers facilitated by 'number crunching' [1]. Behaviourist education assumes the mind is a *tabula rasa*, or an empty slate needing to be filled with a finite amount of knowledge that is transmitted from teacher to student. This assumption leads to the traditional teacher centred lectures characterized by professors scribing notes and talking to blackboards while students rush to keep up in their notebooks. This manner of learning is one-sided and void of discussion, independent thought and social interaction.

At a recent meeting of the US National Science Foundation in Washington, DC, guest speaker Dr Alan A. Leshner of the American Association for the Advancement of Science (AAAS) stated 'Today's scientists need to be trained in a way that will allow them to learn new categories of knowledge at an astounding rate'. For this task to be accomplished, higher education must move from the traditional behaviourist approach toward a constructivist approach where students are able to construct their own knowledge through experience while using preconceptions as a foundation. Constructivism may take on different meanings but generally implies that learning is a continual process that takes the findings of new experiences and refines, modifies or rejects existing interpretations of reality [2]. This theory of learning takes a more cognitive approach by viewing learning as the activation of prior knowledge through retrieval and construction that when well integrated becomes meaningful and useful [3, 4]. In this setting the professor becomes a facilitator in the learning process by guiding decision making and providing appropriate evaluation and feedback. Students create their knowledge through discovery, social interaction and active dialogue. Previous research shows that students in Schools of Engineering, Social Sciences, Humanities and Administration and Business Management prefer cognitive instruction to behaviourist instruction [5].

What does constructivist education look like in an engineering context? We believe that a meta-disciplinary approach to engineering education, framed in the context of sustainable development, allows students to engage engineering principles and fundamentals in a way that is useful and meaningful and more accurately reflects professional practice. A meta-disciplinary study combines the information from multiple lines of inquiry to yield insights and perspectives not achievable with any one alone [6].

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It differs from interdisciplinary approaches that focus on activities at the interface between disciplines and multidisciplinary approaches that utilize knowledge from several disciplines.

We applied this concept in a project that brought Engineering students from Michigan Technological University together with Public Policy students from Southern University and A&M College to evaluate and develop sustainable construction materials for the developing world. The topic of sustainability is conducive to this approach, as it requires a holistic approach that engineering solutions cannot cover alone and is an emerging metadisciplinary field.

Traditional engineering education that resides in the technical realm does not prepare students to integrate socio-economic and environmental concerns, necessitating an evolution in curricula design [7]. Some sustainability researchers view 'goal oriented multidisciplinarity' as the adding together of results from different disciplines with little interaction between disciplines [8]. To the contrary, the nature of the course project described here required Engineering and Public Policy students to be able to discuss concepts from their respective disciplines while simultaneously learning concepts from the other. This allowed students to construct their own knowledge of the problem and solution. The final product reflects a metadisciplinary approach. Importantly, a metadisciplinary approach is a significantly feasible approach in respect to the time considerations of most engineering courses.

Of greater concern to the evaluation of the usefulness of the educational experience is the manner in which it would be assessed to determine whether the students developed significant additional skills that would not be realized in a more traditional approach. Because it is difficult to determine the many variables involved in improving instruction validation and '. . . one is frequently reduced to reliance on intuition, subjective intellectual taste, and imprecise observational tools in deciding whether a certain change is expected to or has in fact improved the quality of instruction' [9] we assessed our model through evaluation of course deliverables, student surveys, and through the comparison of similar projects produced by more traditional engineering design teams.

THEORY

Society, the environment and economic/industrial development—the 'triple bottom line'—are inherently interconnected. Mihelcic et al. [6] have written in the past about the emergence of the new metadiscipline of sustainability science and engineering. Unlike interdisciplinary approaches that focus on activities at the interface between disciplines, we called this new field a metadiscipline approach because it provides an over-arching framework for adopting and incorporating knowledge across many fields of study to improve human and environmental development and quality [6, 10]. Here, sustainable development is defined as:

> . . . the design of human and industrial systems to ensure that humankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health, and the environment [6].

The World Federation of Engineering Organizations has stated 'engineers play a crucial role in improving living standards throughout the world. As a result, engineers can have a significant impact on progress towards sustainable development' [11]. Accordingly, we have previously discussed the need to educate engineers with a global perspective so they understand how to place engineering into practice while taking into consideration the social, economic and environmental limitations of the developing (and industrialized) world [10, 12, 13]. Figure 1 shows how this approach (that we term the *sustainable futures model)* will require faculty and students to consider sustainable development in the context of the environment, society, and economy/industry if the world is to achieve a sustainable future.

Currently in the US, accredited engineering programmes must demonstrate that graduates attain a list of ten skills, knowledge and behaviours. Specific to the sustainable futures model, graduates must demonstrate:

1) the ability to function on multi-disciplinary teams;
2) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental and societal context;
3) knowledge of contemporary issues;
4) an ability to design a system, component or process to meet desired needs *within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability and sustainability* (the language in italics was added for the 2005–2006 accreditation cycle).

In addition, the engineering design experience not only must integrate knowledge from engineering, maths and science, but also from the humanities and social sciences [14]. The sustainable futures model (shown in Figure 1) provides the integrated framework that is required if educators are to achieve more realistic engineering design experiences. One aspect of this approach is that it places equal weight on each part of the sustainability triangle. Gravander et al. have discussed how integration is an essential component of a successful engineering project and how integrated approaches provide a more real world experience, recognize that all accreditation requirements are equally important and that the final solution is greater than the sum of the individual parts.

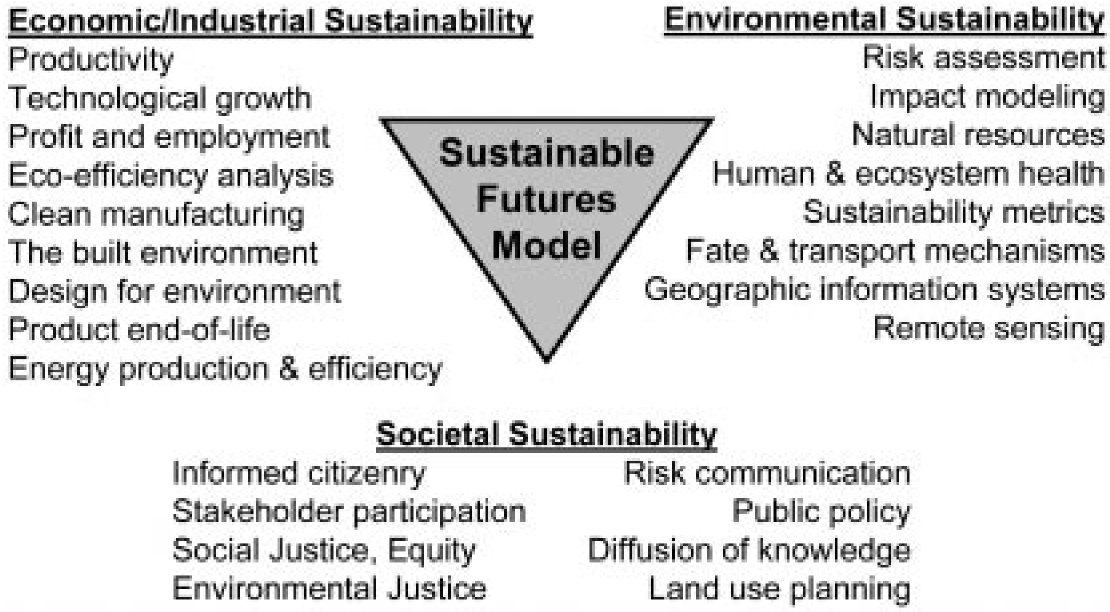

Fig. 1. Sustainability triangle showing the three facets of the metadisciplinary approach for solving environmental problems [10].

Others have pointed out that students need to understand science, technology and policy associated with issues of environmental literacy [15]. However, this is not always the case in engineering education. For example, in a survey of capstone engineering courses in North America that allow multidisciplinary participation by students outside the lead department, it was found that the frequency of social science students was only 1% and business students 4% [16]. In fact, most multidisciplinary participation identified in that study was from other departments already focused on design and manufacturing. In addition, engineering education does not do a good job of integrating technological development with development that is compatible with society and the environment [17] and rarely have engineering courses attempted to obtain and utilize information about the impact that technology has on human, societal and environmental systems [18]. Furthermore, in a workshop that investigated the social dimensions of engineering design, workshop participants agreed that 'good design requires bringing in perspectives of the humanities and social sciences' and there was a need for more multidisciplinary collaboration [19].

Accordingly, the objectives of this manuscript are to demonstrate how an engineering design project can fit into the sustainable futures model and provide a global perspective, and how a team of engineering and public policy students can be organized so after they graduate, students realize this team composition is the standard method to solve problems of sustainable development. We then assess our model through examination of student deliverables, student surveys and through the comparison of similar projects produced by more traditional design teams.

To accomplish this we involved four engineering students at Michigan Technological University (USA) and four public policy students at Southern University and A&M College (USA) in a two-semester design project. Of the four public policy students, three have a first degree in engineering and the fourth a graduate degree in environmental science. The design project determined the feasibility of substituting natural pozzolans (i.e. volcanic ash, rice husk ash) for Portland cement in the construction of engineering infrastructure in the developing world. The evaluation criteria that were selected included: workability and strength, availability, economic and societal issues, environmental impact, and community concerns of the developing world.

The use of natural pozzolans for hydraulic cement began in prehistoric times, and was abandoned for western-based Portland cement concrete technology in the early 1900s. Pozzolans are cementations materials that supplement Portland cement in the concrete mixture. The word pozzolan comes from an Italian word pozzolana meaning 'earth of Pozzuloli', which is the name of a town near Naples, Italy. During the hydration of Portland cement, pozzolans chemically react with calcium hydroxide ($Ca(OH)_2$) to form calcium silicate hydrates (CSHs). CSHs are the strong binders that harden concrete. In the developed world, industrial by-products such as fly ash and blast furnace slag are currently used by the cement industry. For example, coal fly ash has become a common substitute for up to 50% of Portland cement in concrete that is manufactured in the United States [20]. Naturally occurring pozzolans such as rice husk ash, diatomaceous earth and volcanic ash are also an option, but are not utilized as frequently.

Table 1. Composition of sustainable construction materials for the developing world student team.

Number of Students	Percentage Female	Percentage Underrepresented Minority	Breakdown of Academic Discipline	Breakdown of Education Level
8	38%	38%	Civil Engineering, Environmental Engineering, Public Policy	Two baccalaureate; one master level, five doctoral

APPLICATION

Michigan Technological University's Sustainable Futures Institute (SFI) has been collaborating with Southern University and A&M College's Nelson Mandela School of Public Policy and Urban Affairs on several education and research initiatives. Michigan Technological University offers a Ph.D. in several national-ranked engineering disciplines, but does not currently offer a doctoral degree in public policy. On the other hand, Southern University offers a doctoral degree in public policy, but no doctoral degree in engineering. In addition, the partnership between the schools has broadened the cultural, technical and worldviews that each can offer individually.

Table 1 shows the composition of our eight-person student team. Note that we were able to assemble a team that was diverse in terms of education level, academic discipline, race and gender. Students were located at two universities separated by 2,170 km. Students communicated by: weekly telephone conversations when both university calendars allowed; face-to-face video-conferences using distance education technology, email and a shared website were used to post information. In an implementation phase, students were partnering with 24 sanitary engineering students at Partido State University (Philippines). Partido State is not only located in an area sandwiched between three volcanoes (Mt Isarog, Mt Asug and Mt Mayon, of which Mt. Mayon is still active) but in addition, the Philippines ranks eighth in the world in terms of rice production (8.3 million tons) and consumption (9.1 million tons). Faculty members at the three universities worked as facilitators and thus allowed the students to independently develop the direction of their project.

TECHNICAL ANALYSIS

Three natural pozzolans were evaluated in this study: volcanic ash, diatomaceous earth, and rice husk ash. The Portland cement used was LaFarge Type I. Laboratory results demonstrated that these natural pozzolans may be substituted for Portland cement at percentages listed in Table 2.

Students performed all mixing and testing in accordance with appropriate ASTM standards. For example, all unit weight tests were performed in accordance to ASTM Standard C138 [21]; slump testing was performed in accordance to ASTM Standard C143 [22], concrete cylinders were made in accordance with ASTM standard C192 [23]; and compressive strength tests were performed in accordance to ASTM Standard C39 [24]. Observations of each pozzolan were made using a scanning electron microscope (JEOL 6400, Peabody MA) and data on the mineral composition of each pozzolan were obtained using X-ray diffraction (Scintag XDS-2000 Cupertino, CA).

The properties of volcanic ash, such as angularity, surface area, and porosity are similar to Portland cement, which explain why a 0.5 water-to-cement ratio (w/c) could be used for mixing. It was necessary to alter the mix design for diatomaceous earth in order to improve the workability. The high surface area and porosity of diatomaceous earth required additional water. Cylinders that were made with a lower w/c produced honeycombing due to poor consolidation, which is an undesirable property. The diatomaceous earth cylinders also did not break on 45-degree fracture planes. When stressed the cylinders crumbled apart. After the cylinder failed, observations showed the area where the failure occurred seemed to be very powdery. It is also worthy to note that when these cylinders were taken out of their moulds, the surface seemed soft. This could be due to the large amounts of diatomaceous earth not having enough time to hydrate and form its strength. The rice husk ash mix of 12.5% substitution had a tolerable workability. When the 25% mix was performed at the 0.5 w/c, the concrete was noticeably stiffer and harder to work with.

Students determined compressive strength for all pozzolans and substitutions (data not shown). As one example, the resulting compressive strengths using the volcanic ash were relatively consistent. The 25% mix produced satisfactory results at both the 7-day and 28-day breaks resulting in compres-

Table 2. Recommended percent substitution of natural pozzolans for Portland cement in the manufacture of concrete.

Natural Pozzolan Tested	Highest Per cent Substitution Recommended in this Study (% by wt.)
Volcanic Ash	25
Diatomaceous Earth	6.25
Rice Husk Ash	25

sive strength values greater than 3,000 psi at 28 days. The volcanic ash cylinders did have a strength gain between its 7-day and 28-day breaks of about 1000 psi. The 50% mix produced compressive strengths that were significantly below the controls. This mix did not meet predicted strength expectations and therefore is not recommended for use in construction.

ENVIRONMENTAL, ECONOMIC AND SOCIETAL ANALYSIS

The use of cement is a major contributor to worldwide CO_2 production. The 1.45 billion Mg of global cement production account for 2% of global primary energy use and 5% of anthropogenic CO_2 emissions. On average, manufacturing 1 kg of cement produces 1 kg of CO_2 [20]. The CO_2 emissions associated with the energy used for heating the kiln account for approximately 0.47 tons of CO_2 per ton of clinker manufacturing [25, 26]. While many engineering students are prepared to analyze environmental consequences of their engineering solutions, they are less prepared to integrate detailed economic and societal analysis.

Sustainable development may be viewed with overlapping domains: environmental, economic and social [6, 27]. Development in this conceptual framework means change without growth. In this sense, substitution of a key ingredient for manufacturing concrete, that is; using natural pozzolans, is change without growth. What is essential is internalization of social costs. The production of Portland cement generates unwanted by-products, including greenhouse gases that degrade the global environment and particulate matter that adversely impacts human health. Such negative externalities are third-party effects. That is, engineers do not consider these undesirable effects when selecting Portland cement as a material choice. Externalities are 'market failures' in economic parlance, meaning that individuals acting rationally will not change their behaviour, even when they are made worse off as groups. This is justification for social (i.e. government) intervention in the marketplace, such as public policy making. While policy instruments can often correct negative externalities, we must choose the best solution for all, even when that includes doing nothing at all.

The social context of sustainable development is viewed as a constraint set for possible solutions to problems offered by technology. For engineering students, this means exogenous determinants: looking outside the black box when solving problems. Pedagogically, the overlapping domains define the realm of permissible approaches to resolving perceived problems. Such exogenous forces are an important consideration for design and production. Problem identification may be social. Public awareness or third-party complaints are setting the agenda for investigation and for feasible solutions. Feasible solutions to engineering problems are ones that navigate the domains defined by sustainability. Sustainability often refers to a class of problems: requiring collective action [28]. Collective action problems, such as market failures, may be fixed with selective incentives. For Portland cement producers and consumers, students need to consider what can be done to change their behaviour and what selective incentives can be provided.

In the environmental domain, students posited a technical solution to a global problem that would hopefully reduce environmental degradation. In the economic domain, students proposed natural pozzolans as a cost-effective substitute ingredient for manufacturing concrete; that fits into existent global life cycles for volcanic deposits and the by-products of rice consumption. Hence, their solution may conserve natural capital and create social capital simultaneously while also reducing environmental degradation and poverty with lower cost Portland cement. Students were challenged to determine if there was a market for so-called 'green' cement? If so, then will social institutions allow this green cement to be utilized? Such are the 'out of the box' design considerations. Solutions to problems may be technically possible from an engineering 'point of view', but not feasible or viable in a given social context. For example, although the perfect widget may exist, social choice requires that only sprockets be made. Inefficiency may result where markets dominate social values and fail to provide solutions to problems. Globalization may exacerbate problems where international trade ignores boundaries and territories. Markets may be unregulated. While world-governing bodies may exist, they often lack teeth for enforcing market conditions, which could reduce externalities [29].

Students began this project with the naïve notion that they could transfer technology from a developed country to less developed countries, thereby benefiting society. By using natural pozzolans, they hoped to reduce cement-purchasing costs by up to 25% (see Table 1 results), saving funds for other purposes in the developing world and reducing global CO_2 emissions. Students considered a model for policy innovation and diffusion [30] for this purpose. Technology adoption must be considered socially and technically, because engineering is bounded by social context. For example, scientific standards that facilitate technical solutions to problems are the product of voluntary institutions in certain fields or maybe generated by government intervention in others. Such rules for design are not neutral. They might not even be optimal, in an engineering perspective.

GLOBAL PERSPECTIVE

As an example of the global availability of natural pozzolans, students were required to identify whether there was global availability of the natural pozzolans. The results (data not shown) suggested there is widespread availability of these natural pozzolans. United Nations Millennium Development Goal Number 1 is to 'eradicate extreme poverty and hunger'. Since more than a billion people still live on less than US$1 a day, there is a need for low cost and locally available substitutes for Portland cement. Natural pozzolans will most likely be free to local communities, like sand and gravel currently are. If a community obtains materials locally, their labour is typically considered as an in-kind cost to a project's sponsors. Millennium Development Goal Number 7 is to 'ensure environmental sustainability' with one target for year 2015 to reduce by half the proportion of people without access to safe drinking water. Water supply projects are one aspect of engineering infrastructure where use of natural pozzolans may be feasible.

As an extension of the overall goal of the project, an attempt was made to quantify the real-world contributions that the implications of the project could entail. Specifically, the potential economic savings and reduction of anthropogenic CO_2 emissions were estimated with the assumption that these natural pozzolans would be utilized on a global basis, to their fullest extent as determined in this study's compressive strength tests. It was also assumed that the pozzolans would be applied in the construction of either spring-boxes or gravity fed water systems within areas of the developing world that lack access to safe drinking water. The estimations were based on material lists obtained from previous research studies conducted by graduate students who performed their research in the Dominican Republic [31] and Cameroon [32].

The results suggest that if the natural pozzolans investigated in this study were used to construct spring boxes or gravity fed water systems for the billion people worldwide that do not have access to safe drinking water, $US141 to $US451 million could be saved if volcanic ash or rice husk ash were substituted for Portland cement at a 25% level, and $US37 to $US102 million could be saved if diatomaceous earth was substituted for Portland cement at 6.25%.

As mentioned previously, the use of cement is also a major contributor to worldwide CO_2 production. It was estimated that if natural pozzolans were used to construct spring boxes or gravity fed water systems for the 1 billion people worldwide that do not have access to safe drinking water, the total anthropogenic CO_2 emissions could be decreased by 0.95 to 3.8 million tons if volcanic ash or rice husk ash were substituted for Portland cement at a 25% level, and by 240,000 to 874,000 tons if diatomaceous earth was substituted for Portland cement at 6.25%.

The partnership with Partido State University is now providing students with an opportunity to understand the complexity of issues associated with implementation of their solution in communities of the developing world.

ASSESSMENT

Indirect and direct measurement techniques are commonly used to assess student learning. Effective assessment should use direct measures and then complement the results with indirect measures. Direct measures include observations and student portfolios. Indirect measures include surveys that measure a student's perception of what they learned.

We reviewed the slides from oral presentations, number of pages in a final report, and subject areas devoted in a poster presentation in order to assess student valuation of each component of the sustainability triangle. These direct measures of assessment indicated that students used the sustainable futures model successfully, and placed equal weighting on the three components of the sustainability triangle depicted in Figure 1 (economic, social, environmental). Partnering with a university in the Philippines to make students think about the community implementation of their proposed solution, and requiring students to frame their work in context of the UN Millennium Development Goals appear to have allowed the students to place their work in a global and community context.

For indirect assessment we conducted a post-course survey that measured each student's perception of the importance for what they learned. The results are presented in Tables 3a, 3b, 3c, and 3d. They suggest that students completed the course in strong agreement on the equal importance of the components of the sustainable futures model. In addition, though the sample size is small, it does not appear there is a difference between the engineering and public policy students in their perceived importance of any aspect of the sustainable futures model. Engineering and public policy students were both in agreement that a team that was to solve problems of sustainability must incorporate individuals with expertise in societal issues (Table 3a) and they also responded that the societal component was very important to successful solutions to a sustainability problem (Table 3b).

When asked to rate their improvement in understanding several components of sustainable development, the greatest average perceived improvement of the class was reported in the area of 'societal' (Table 3c). After the course, the students also viewed the UN Millennium Development Goals as very important to their professional disciplines (Table 3d). As one civil engineering student reported 'I would not have known about the U.N. Millennium Development Goals if this class did not address them. Now that I understand what these goals are I will be able to work towards them'. This student also commented that 'they learned through the teamwork that the social aspect was the most important' and when asked if this experience was valuable (or not valuable) for future work in their profession that 'It has made me realize for a given task that I need

Table 3a. Students were asked 'how important do you feel the following disciplines are if one is to create a team to solve sustainability issues'? 0 (not important) to 10 (very important). Students 1–4 are enrolled in public policy and students 5–8 are enrolled in engineering.

	1	2	3	4	5	6	7	8	Average
Engineering	10	6	10	10	10	10	10	10	9.5
Business/economics	10	8	7.5	10	10	10	8	10	9.2
Social sciences and public policy	10	9	10	10	10	10	10	10	9.9

Table 3b. Students were asked 'how important to you feel each of the following components are to developing a successful solution to a sustainability problem'? 0 (not important) to 10 (very important). Students 1–4 are enrolled in public policy and students 5–8 are enrolled in engineering.

	1	2	3	4	5	6	7	8	Average
Societal	10	7	10	10	10	10	10	8	9.4
Environmental	10	7	10	10	10	7	10	8	9.0
Economic	10	7	8	10	10	9	8	6	8.5
Global perspective	10	7	10	10	10	7	10	5	8.6

Table 3c. Students were asked to 'rate your improvement over the past academic year (two semesters) in understanding each of the following components of sustainable development'. 0 (no improvement) to 10 (great improvement). Students 1–4 are enrolled in public policy and students 5–8 are enrolled in engineering.

	1	2	3	4	5	6	7	8	Average
Societal	9	9	3	9	7	7	10	10	8.0
Environmental	5	9	2	7	8	6	10	6	6.6
Economic	5	9	7	8	7	8	10	8	7.8
Global perspective	5	9	3	7	9	9	10	5	7.1

Table 3d. Students were asked to rate the following statement 'The U.N. Millennium Development Goals are important to my professional discipline'. 0 (not important) to 10 (very important). Students 1–4 are enrolled in public policy and students 5–8 are enrolled in engineering.

	1	2	3	4	5	6	7	8	Average
	10	8	10	8	9	8	10	Not reported	9.0

to ask myself the 'what if" questions, and to see where we are going, not for my own benefit, but for the benefit of those that are in need'.

Students were also asked what additional skills they developed over the course. Several students commented that they had a better understanding of how engineering practices impact society, the environment and the economy. One student commented on how they were able to apply GIS skills to not just the environment, but also economic and social issues. Several students commented how they now had a better understanding of how governmental structures perpetuate poor housing, poverty and hunger. An engineering student commented that seeing the 'big' picture was a new skill they found valuable when evaluating the feasibility of scientific applications. Several students also commented on how they learned to work without supervision, learned about sustainability and also about the needs of the developing world. These comments support our theory that a constructivist approach provides a framework where students are able to construct their own knowledge through experience while using preconceptions as a foundation. Written student comments also suggested that the learning experience was meaningful and useful.

In order to further validate the usefulness of the sustainable futures model, we assessed whether incorporating public policy into engineering design projects would decrease the value of the overall project in the eyes of an outside review panel of practitioners. For this we compared our project to other student projects that were focused on sustainable development, had an engineering focus and had been entered in either a US or international design competition. For this evaluation, we used two methods. First, the sustainable construction material team entered their project in the Mondialogo Worldwide Engineering Award. Mondialgo is a partnership between Daimler Chrylser and UNESCO and has the support of the World Federation of Engineering Organizations (WFEO). The overall goal of Mondialogo is to promote intercultural dialogue between students located on different continents. Students were challenged to produce engineering proposals to reduce world poverty and promote sustainable development in developing countries. An international jury assessed the project ideas for sustainability, feasibility and quality of intercultural dialogue within the project teams. A total of 1,700 students from 79 nations registered for the contest, forming 412 international teams. Our sustainable construction materials team was one of final 21 awardees, of which only four appear to have directly addressed public policy issues (based on a review of abstracts posted on the Mondialogo web site, www.mondialogo.org).

In addition, our student team was also considered as a finalist for the US Environmental Protection Agency's People, Prosperity, and the Planet (P3) award. Of 65 finalist teams, a total of 21 (including our team) received either a financial award or an honourable mention. In this competition, projects were reviewed by judging teams comprised primarily of members from the US National Academy of Sciences. Based on a review of abstracts posted on the P3 web site (www.epa.gov/P3), two projects out of 21 appear to have directly addressed issues of public policy. Accordingly, it appears that inclusion of public policy into an engineering design project that incorporated the sustainable futures model did not 'lessen' the project in the eyes of engineering and scientific practitioners who evaluated the project for the two student design competitions.

CONCLUSIONS

For years engineering education has taken a behaviourist approach, assuming a student's mind is an empty slate needing to be filled with a finite amount of knowledge, transmitted from teacher to student. In this article we demonstrate how a constructivist approach is a better method to teach concepts of sustainable development and engineering design. In this case the professor becomes a facilitator in the learning process by guiding decision making and providing appropriate evaluation and feedback. For this project, a team of engineering students from Michigan Technological University (USA) and public policy students from Southern University and A&M College (USA) determined the feasibility of substituting natural pozzolans (i.e. volcanic ash, rice husk ash) for Portland cement in the construction of engineering infrastructure in the developing world. The evaluation criteria that were selected included: workability and strength, availability, economic and societal issues, environmental impact and community concerns. The results of our project demonstrated the feasibility of substituting natural pozzolans for Portland cement in the developing world. Assessment showed that incorporating public policy and the sustainable futures model into an engineering design project not only resulted in a metadisciplinary learning environment for students, but also did not diminish the overall perception of the engineering project by a team of outside practitioners.

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