**Proceedings of the ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference**
**IDETC/CIE 2012**
**August 12-15, 2012, Chicago, Illinois, USA**

# DETC2012-70461

# DESIGNING-IN SUSTAINABILITY BY LINKING ENGINEERING CURRICULA WITH K-12 SCIENCE PROJECTS

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## ABSTRACT

*In light of society's increasing awareness with regards to the health of the environment, many engineering firms are hiring recent engineering graduates with project- (or course-) based experience in environmental sustainability. Currently engineering schools at the collegiate level have addressed this need by modifying their curricula by including additional coursework on sustainability related subjects. The next step of adaptation calls for a holistic treatment of sustainability concepts by integrating them within traditional coursework. Engineering schools have not yet addressed the best way to accomplish this integration due to the concerns stemming from the increase in cognitive load and scheduling pressure. Additionally, it has been shown that K-12 curricula also lack exposure to sustainable thinking. As a result, incoming freshmen are not aware of the inherent correlations between engineering principles, e.g. heat transfer, and environmental sustainability. To prepare the next generation of innovative thinkers to solve these complex, interdisciplinary issues, engineering principles must be contextualized in terms of sustainable design at both the K-12 and undergraduate levels. To meet this need, the authors developed a general framework for introducing sustainable design thinking into K-12 student projects. A pilot case is presented to illustrate a particular student's (listed as a co-author) growth through a newly gained understanding of environmental sustainability through experimentation. The project specifically addresses various insulation materials for residential buildings by judging their individual environmental advantages and economic feasibility. The main outcome of this project is the extensive redesign of an existing undergraduate heat and mass transfer lab experiment.*

Keywords: Engineering Education, Environmental Sustainability, K-12 Science Projects, Project Based Learning

## INTRODUCTION & MOTIVATION

According to a recent article in the *Harvard Business Review*, environmental sustainability has become a cornerstone of innovative thinking [1]. This trend has been evident throughout design consulting firms (e.g. IDEO [2]) and academic programs (e.g. the d.school at Stanford [3]). Additionally, there has been a recent influx of literature focusing on the emergence of sustainability-inspired teaching within undergraduate and graduate engineering programs both in the US and throughout European communities [4]. This work can be divided into two main categories: (1) curriculum reform (e.g. [5]) and (2) intra-course integration mostly through problem-based learning (PBL) projects (e.g. the authors' previous work [6]). Many of these efforts cite the interdisciplinary nature of sustainable technologies as an enabler for disseminating relevant concepts into the classroom. Though much of this work has produced positive learning outcomes, it has also uncovered a significant amount of undergraduate engineering students lacking general awareness of key global issues related to environmental sustainability [7]. Students' misconceptions can be caused by a number of societal influences, including media outlets and political tendencies [8], from a very young age. Thus, to increase student awareness

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related to environmental sustainability, it is vital to reach K-12 students early with tools and methods incorporating sufficient technical merit backed by science, technology, engineering and mathematics (STEM). Additionally, the authors hypothesize that disseminating STEM topics coupled with environmental issues into K-12 will also provide a learning platform for which educators can implement at the undergraduate level.

Exposing pre-collegiate students to engineering-related problems has been shown to help stimulate their interest in STEM-related areas [9, 10]. It has also been argued that introducing key STEM concepts is necessary to keep pace with the evolving engineering community [11, 12]. The introduction of engineering concepts can be done through many different mediums. As an example, K-12 design competitions have been used for years to promote talented students' interest in studying engineering at the next level. In recent years, these national-level design competitions have used this forum to disseminate concepts related to sustainable engineering. In 2011, the theme of the well-known JETS (Junior Engineering Technical Society) high school competition was "Smarter Energy, Cleaner Planet". Under this theme, JETS participants were challenged to consider the US current resource dependencies, identify environmentally efficient technologies, and brainstorm ideas related to preserving a clean and safe environment [13]. Acceptable submissions from student teams required considerable technical content to back any claims regarding their solution's environmental benefits.

Other K-12 programs focus on the dissemination of educational material within the classroom itself. One notable effort is The Cloud Institute for Sustainability Education, founded in 1995, which has based its mission on ensuring "the viability of sustainable communities by leveraging changes in K-12 school systems to prepare young people for the shift toward a sustainable future" [14]. The Cloud Institute initiatives focus on behavioral reformation to ensure participating K-12 programs produce environmentally-conscious students. This institute focuses on school-level programs. One example is a custom educational program specifically for K-12 instructors. Additionally, the Cloud Institute offers services for custom curriculum design and specific in-class exercises at various grade levels (i.e. grades K-2, grades 3-5, grades 6-8, and grades 9-12). Though this specific program provides a relevant framework for introducing students to cradle-to-cradle design thinking [15], it still lacks the inclusion of technical work, e.g. engineering principles and measurement science.

This inherent gap in incorporating early engineering education with concepts related to environmental sustainability has been identified as a national concern by government funding agencies. For example, the US National Science Foundation (NSF) has granted a number of research awards, e.g. [16, 17] to K-12 dissemination programs through its NSF Engineering Education and Centers (EEC) program [18]. Furthermore, the NSF has stated throughout their program solicitation of "Discovery Research K-12" that environmental sustainability is a cross-disciplinary topic that requires more cutting-edge teaching approaches at the pre-collegiate level [19]. Additionally, the US Department of Energy (DOE) urges all their grant awardees to design educational platforms to educate K-12 students in regards to challenges critical for national societal development, such as renewable energy technologies [20].

These funding programs have led to considerable work in K-12 program development. In 2009, the National Academy of Engineering (NAE) released an extensive review outlining the current state of STEM-related projects in the K-12 realm. One relevant initiative outlined by the report was developed by the National Center for Technological Literacy Museum of Science, titled "Engineering the Future". This program is designed to be an entire high school course divided into four units incorporating undergraduate level engineering principles, such as processing technologies, thermodynamics, life cycle analysis and general measurement science [21]. This comprehensive program outlines an impressive collection of salient student skills as outcomes. It does, however, require considerable school funding for textbooks and other course material as well as significant time, i.e. at least a full school year, in order to complete the curriculum.

Each of these K-12 dissemination methodologies described is valuable. However, the ideas conveyed, and more importantly discovered through experimentation is particularly rewarding to each student. In an authors' previous study, lessons related to sustainability was enabled through a project-based critique scenario at the undergraduate level. In this case, experts critiqued each project team's design project from an environmental sustainability perspective without warning to the students and coached them through specific redesign scenarios. The 'shock value' of realizing their mistakes proved as an effective learning medium [6].

In this paper, a pilot study is presented in which a lab assignment from an undergraduate heat and mass transfer course (ME315) at Purdue University is provided to a 6$^{th}$ grade student, listed as a co-author on this paper, in order to assess its applicability at the K-12 level. The deep thinking conducted by the student motivated the redefinition of ME315 in a more holistic context based on sustainable design of buildings, materials and processes. In this context, the lessons learned at the K-12 level will later push the undergraduate lab forward, adding relevant learning objectives, e.g. energy efficiency in insulation materials and environmental impacts related to different stages of a building's lifecycle. Thus, the impact of this pilot study is twofold, i.e. at both the K-12 and undergraduate levels. The authors plan to use the study's results in order to prepare more appropriate materials for a K-12 exercise encompassing concepts related to heat and mass transfer along with environmental sustainability. Additionally, the authors also plan to move forward with an additional learning module added to the ME315 lab experiment, focusing on multi criteria decision making to overcome tradeoffs between performance, economics and environmental impacts.

 

It should be noted that this pilot study is not part of the engineering curriculum at Purdue. The participating student chose to pursue a modification of this specific project due to its relevance with regards to an everyday issue, i.e. energy efficiency in residential buildings. There was no incentive for the student's participation, other than his own received accolades in an Indiana-statewide science project contest. The student subject can be considered representative of talented, STEM-interested students attending public middle schools in the United States.

The next section more specifically details the contents of the project.

## CASE STUDY: ASSESSING INSULATION MATERIALS FOR ECO-EFFICIENT BUILDINGS

With newly developed 'clean' technologies, there exist difficult decision (design) tradeoffs between performance, economic and environmental factors. It turns out that many purely environmentally sustainable systems do not meet existing system requirements form a triple-bottom-line (TBL) perspective. Streamlined life cycle assessment (LCA) data enables decision makers to overcome these complex tradeoffs early in the design process (e.g. material selection) [22].

Though K-12 programs have been implemented throughout the nation in order to teach students the importance of environmentally efficient behavior as described in the previous section, there has been little use of actual streamlined LCA data for science-related projects. The primary reason is the complexity of fully defined LCAs, which deters educators from incorporating such data. However, it is still possible to use simpler LCA metrics (e.g. carbon footprint of specified materials) in order to introduce novice designers to the general idea of design decision tradeoffs. Another benefit for material-centric projects at the K-12 level is that it simulates a real-world engineering problem. Material selection has always been a key step in the design process [23]. As design groups become more cognizant of the use of environmentally damaging materials, engineering designers are facing complex multi-criteria decisions when developing actual products. As a result, to be a successful designer, it is necessary to be able to cognitively juggle multiple design criteria at once. Creating a learning module applicable at both the pre-collegiate and undergraduate levels would help build these kinds of decision making skills to enable success in STEM related areas. One goal of this particular project is to design a learning module that engages both K-12 and undergraduate students in these complex tradeoffs and allows students to develop their own means to overcome these intra-design compromises. The applied focus of the project is in regards to assessing different insulation materials for eco-efficient materials.

This project is directly related to and significantly reframes an existing course-lab project in ME315, Heat and Mass Transfer, taught by Prof. Xiulin Ruan, an Assistant Professor in the School of Mechanical Engineering at Purdue University. It should be noted that the objective of the original lab was to calculate given materials' thermal conductivities by measuring the temperature gradients across materials in a controlled environment. The original lab assignment contained no specific application domain (e.g. building construction), nor did it provide a multi-criteria decision tradeoff perspective for the students. Also, the lab experiment did not provide insight into a material's microstructure's effect on its k-value. These aspects are incorporated into the modified project through the pilot study and will later be included in the modified lab assignment.

In the modified version of the experiment, material use within the construction of buildings is used as a pilot case study due to its widespread environmental implications. Buildings account for a significant portion of the total energy use and carbon footprint in the US, some 39% and 38% respectively, according to the US DOE [24]. The use phase of these buildings dominates the total energy and carbon footprint of the buildings lifecycle, as with many complex systems with a considerably long useful lifetime. One area of focus in mitigating the energy consumed by buildings lies within insulation material advancement. Organizations have filled these niche markets from several different perspectives, e.g. high performance materials, recycled/organic/natural materials, and hybrid materials.

One particular material of interest in this study is Greensulate™, a fungus-based material. Ecovative™, the producer of Greensulate™, has procured significant funding from national agencies (e.g. NYSERDA, NSF, USDA) due to its promise and preliminary performance results [25]. The material's advantages lie in its lesser environmental impact at the material processing stages (i.e. $CO_2$ emissions) compared against traditional insulation materials, such as fiberglass. However, the natural material exhibits a significant performance loss compared with traditional insulation materials, which can be directly correlated with its greater impact during the use phase. Another major obstacle for Ecovative™ lies within its selling point. Because there is a significant upstream undertaking in growing the fungi itself, there exists a substantial upfront cost to Greensulate™. This motivates a holistic outlook of the product's feasibility versus traditional building materials from multiple perspectives (i.e. environmental vs. economic constraints). Again, overcoming these complex tradeoffs is a point of focus for the student's project. Observing how exactly the student develops his own methods to make a final decision will be used to improve the ME315 lab framework.

In the current study, the authors (1) evaluated the usefulness of embedding a sustainability-related element to the existing ME315 lab (2) observed the K-12 student's technique in performing decision tradeoffs between performance and environmental metrics and (3) assessed the student's educational growth in regards to his gained understanding of fundamental engineering principles in a simulated real-world type problem in which streamlined LCA data was provided. This context provided an environment in which design decision tradeoffs can be made at different abstraction levels. Though LCA is a complex method, inclusion of basic concepts into a K-

12 level would provide a basis of understanding that should be valuable to students later in their academic career. The next section outlines the project in detail, describing the steps of 'doing' and 'thinking' by the student.

## PROJECT IMPLEMENTATION

The fundamental purpose of this experiment is to measure the insulating capacity of several types of materials. Below is the outline of the procedural steps of the experiment.

1) Two equal sized foam blocks were prepared using a knife.
2) A window was opened to allow the material blocks to fit snuggly between the space of the bottom of the window and the window sill. Space between the two blocks was left to ensure that the insulator could be placed.
3) Each configuration of material was cut at the same thickness and shape using a Vernier caliper.
    a. For the fiberglass samples, four different thicknesses (i.e. 1, 2, 3, and 4 inches) were compressed to the prescribed thickness to study the effect of utilizing less air with regards to the insulating capacity.
4) The studied insulator was fit between the two foam blocks with as little space between them as possible.
5) The student waited several minutes to allow the inside and outside surface temperature of the studied material to reach a steady state. An infra-red measurement gun was used to take temperature readings, as shown in Figure 1. Five measurements on different regions of the surface were taken and then averaged later.
6) Steps 1-5 were repeated for each insulating material. It should be noted that all measurements were conducted one after the other to ensure there was consistency in the ambient temperature. The heating/air-conditioning system of the house was also turned off during the experiment.

Figure 1: Infra-red measurement gun is shown here recording temperatures during student's experiment.

The student procured all the necessary materials and conducted the experiment at his home. He chose to study five different thicknesses of open-cell and closed-cell polystyrene, four different densities of fiberglass, and three types of the Greensulate™ material. The purpose of testing different thicknesses of the same material was to illustrate that the thermal conductivity is a property of the material itself. The student measured the temperature on each face of the material as described in the procedural steps above. After the experiment was conducted, aided by Professor Ruan, the student completed a simple heat transfer diagram, as shown in Figure 2. As seen in the figure, the main goal of the experiment is to calculate the temperature gradient across the material. The diagram shows that the temperature outside the house is considerably lower than the inside temperature. Describing the experiment from a modeling perspective provided a context for the student to make theoretical observations. Through simple algebra, he realized that the temperature gradient found is directly correlated with the thermal conductivity. He then used the temperature gradient as an indicator for the performance of each insulation material. The student observed that the temperature differences were different for different thicknesses of the same material, but realized that the temperature gradient, as he defined as the change in temperature across the insulation divided by the thickness, was similar for each material.

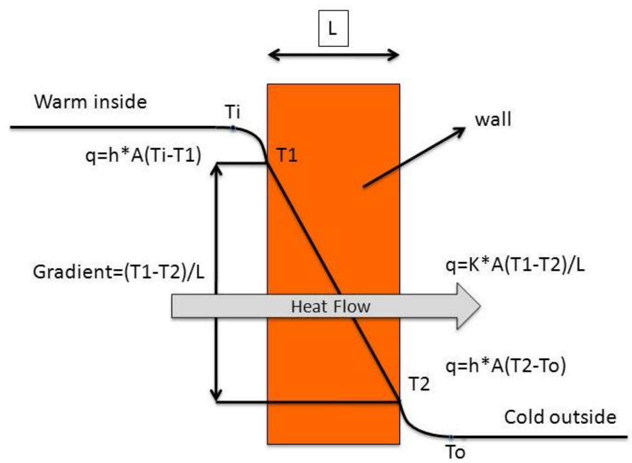


Figure 2: Heat transfer diagram for the student's experiment. This diagram was sketched out by the student himself.

Supplemental to conducting the thermal conductivity experiment, the student also used a microscope to observe the microstructure of each material and their respective thickness differences. Some of the student's photographs can be seen in Figure 3. It should be noted that an alternative learning objective of the experiment was for the student to understand the role of air as an insulator in the studied materials. After examining the microstructure of each material, the student realized the difference between open-cell polystyrene (Figure 3-F) and its closed-cell counterpart (Figure 3-G). In order to assess the student's level of learning and gained understanding of related principles, an informal interview with open-ended questions was conducted. This insight is shown below in the student's own words.

*"I found that the open- cell foam's cells are all connected so air can flow through. Also, the spaces between the cells are connected. This is why it's very soft. The closed- cell foam's cells aren't connected which is why it's hard."*

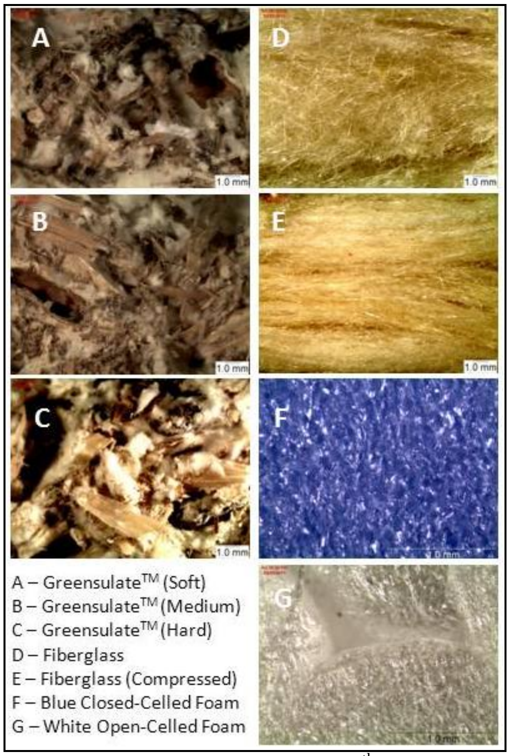


Figure 3: Microscopic images taken by the $6^{th}$ grade student of each studied insulation material.

The student then measured the mass and volume of each material, and then calculated the amount of air 'trapped' within each material. To the student's surprise, air contributed to the vast majority of the insulator, in some cases, contributing 98% of the total insulator. Furthermore, the student realized that the tightly packed fiberglass outperformed the lightly packed fiberglass pieces. He explained this phenomena by realizing that the smaller the pores within the material the higher the insulating capacity. This illustrated the key concept that air itself is a very effective insulator. Interestingly, the student coined a new term, *trapped air*, in order to describe the air that was acting as an insulator.

After all measurements were recorded and averaged, the student used the heat transfer diagram and its governing equations to calculate the thermal conductivity for each material. It should be noted that this is the final deliverable of the lab experiment in ME315. In the past, ME315 students, based on each material's k-value, would recommend a material. Within the modified project, one of the main objectives was to provide a context for conducting multi-criteria decision analysis (MCDA) through a concise medium. Hence, the student was provided a data sheet of carbon footprints, extracted from CES Material Database 2011, software developed from Cambridge University that offers an extensive archive of properties of engineering materials [26]. It should be noted that data for Greensulate™ was found on the Ecovative website [25]. A version of the used datasheet for the carbon footprints of each material can be seen below in Table 1.

Table 1: Carbon footprints of material acquisition and processing for studied materials, extracted from CES Edupack 2011.

| |
|---|
| *Polyurethane foam (flexible, closed cell)*<br>Primary Material Production: 6.35-7.01 $CO_2$ lb/lb<br>Polymer Molding: 1.36-1.50 $CO_2$ lb/lb<br>Polymer Extrusion: 0.531 $CO_2$ lb/lb |
| *Polyurethane foam (elastomeric, open cell)*<br>Primary Material Production: 4.91-5.43 $CO_2$ lb/lb<br>Polymer Molding: 1.27-1.40 $CO_2$ lb/lb<br>Polymer Extrusion: 0.498 $CO_2$ lb/lb |
| *Glass Fiber*<br>Primary Material Production: 4.26-4.71 $CO_2$ lb/lb<br>Composite Molding: 0.901-0.994 $CO_2$ lb/lb |
| *Greensulate™*<br>Primary Material Production: 13.0 $CO_2$ kg/$m^3$<br>Material Processing: 13.0 $CO_2$ kg/$m^3$ |

At this stage, the student has access to performance-related metrics, the material price, and the carbon footprint associated with processing each material (from the resource acquisition stage through manufacturing a useful product). No instruction was given as to exactly how to converge to one solution for an insulation material. Interestingly, the student overcame this tradeoff through two simple calculations that produced multi-criteria metrics he called the material's 'green number' and the materials 'functional environmental economic' (FEE) number. The student's own words are provided below to illustrate his thinking.

*"I wanted to find a way to compare the material's insulating capacity and its carbon footprint to other materials so I could determine which material has a better overall performance."*

Before fully defining these two metrics, the student identified the material properties that would be appropriate to maximize as well as which ones should be minimized. The student targeted the temperature gradient (ΔT/L) as a variable in which was most appropriate to maximize, while he identified carbon footprint (CF) and material price (MP) as attributes to minimize. First, he attempted to overcome the tradeoff of environmental and functional performance through his "green number" (GN), as defined below in Eq. 1.

$$GN = \frac{\Delta T/L}{CF} \qquad \text{(Eq. 1)}$$

Even though this is a simple calculation, it demonstrates a great deal of student engagement and learning, especially considering the student's $6^{th}$ grade level. Next, he defined an additional metric, which included the economic aspect of the tradeoff problem, the FEE number, which is defined below in Eq. 2.

$$FEE = \frac{GN}{MP} \qquad \text{(Eq. 2)}$$

The student calculated the 'green number' and FEE number for each material and graphed the results. It should be noted that the results of the student's work were normalized in order to show each metric on the same scale in Figure 4. It can be seen that for each comparison a different material dominates each metric. From a functional performance perspective, the closed-cell polystyrene outperforms the rest, while Greensulate™ shows the best performance for the 'green number' due to its lower carbon footprint. Interestingly, the open-cell polystyrene outperforms the other material choices in regards to the FEE number. This is due to the fact of its significantly low selling point and its lesser carbon footprint compared with closed-cell polystyrene. The results led the student to recommend open-cell polystyrene as an insulation material if it were to be used in his own home. However, the 6th grader suggested that if the natural material, Greensulate™, could be produced at higher volumes it could lower its price and make it a more feasible option for residential and even commercial use. Additionally, he concluded that a possible future direction for the Greensulate™ developers is to design new material configurations in order to maximize the use of air as an insulator.

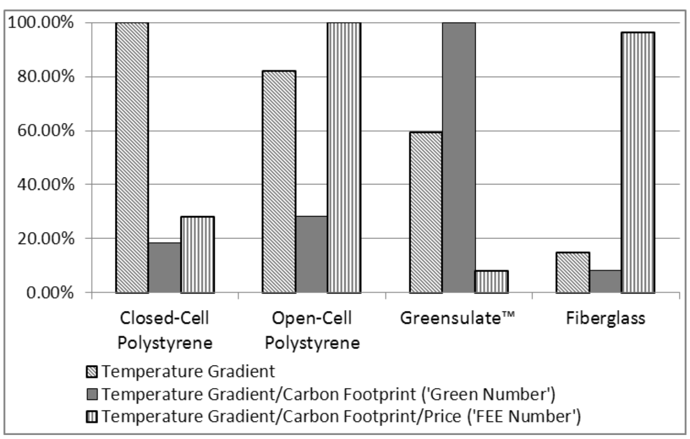


Figure 4: Results from student project with self-described metrics, green number and FEE number.

It can be seen throughout the student's work and words that this exercise was significantly beneficial to the student. There is little doubt to the authors that integrating the economic and environmental components to the original lab experiment will have a positive effect on a larger student population. One benefit of the proposed modifications for the undergraduate assignment is that no significant additional resources are required for implementing the additional learning modules.

The outcomes of the pilot study also show promise for further K-12 outreach projects. Though it is obvious that the particular student studied has impressive mastery of middle-school-level mathematics and science for his grade level, portions of the experiment can be redesigned to be relevant across a full spectrum of K-12 students. The authors plan to develop different versions of the project in order to implement the exercise across multiple grade levels. One example of a possible design for a K-12 project would be a simplified assignment in which students measure the thermal conductivity using an infrared measurement gun, as described above, and calculate an energy efficiency coefficient along with several more simple calculations based on each material's carbon estimated carbon footprint and price. This hypothetical project would most likely be suited for students at the high school level. This would be an easy-to-implement approach for introducing students to multi-criteria decision making, measurement science, and the importance of environmentally efficient decisions. The study could also include the investigating of material microstructure if microscopes are readily available. Other modifications could be made, e.g. with results provided, in order to make this project appropriate for grades of lower levels.

This student project presented also encompasses sufficient engineering aspects, e.g. material microstructure and economics, and their relationship with heat and mass transfer. This has provided significant insight into how exactly to modify the ME315 lab experiment centered on finding materials' thermal conductivities. An overview of the changes to be made can be found in Table 2. As shown, the authors plan to incorporate principles related to economics and environmental sustainability that were previously lacking. Additionally, a more comprehensive list of learning objectives related to heat and mass transfer (e.g. application domain specific optimization and microstructure investigation) will be included.

Table 2: Overview of planned modifications for the ME315 lab.

| | ME315 Original Lab Experiment | ME315 Modified Lab Experiment |
|---|---|---|
| ***Heat and Mass Transfer Principles*** | | |
| Thermal Conductivity (k-value) Calculation | X | X |
| Experimental Design | X | X |
| Application Specific Optimization | | X |
| Microstructure Investigation | | X |
| ***Economics Principles*** | | |
| Material Price | | X |
| Tradeoff Perspective (functional, economic) | | X |
| ***Environmental Sustainability Principles*** | | |
| Material Carbon Footprint | | X |
| Triple Bottom Line Perspective | | X |

## CONCLUSION & FUTURE DIRECTIONS

Current K-12 curricula do not sufficiently expose students to elementary concepts related to environmental sustainability.

As a result, undergraduate students may need to devote an entire course to learn and apply these concepts to projects in traditional engineering courses. Most undergraduate curricula cannot afford this extra course and thus a small portion of engineers at this level are trained in principles of sustainable design and manufacturing, as a specialty. An additional consequence is that more complex concepts such as life cycle inventory analysis and design theories in sustainable product realization are often dealt with only at a graduate level. In order to overcome the above limitations within curricula, this paper presents a case for embedding environmental sustainability as a consideration within K-12 level student science projects as well as within an undergraduate level lab experiment at Purdue University. A pilot study was presented and tested for a 6th grade student. The motivation for this pilot case was twofold: 1) assessing how engineering institutions can disseminate their engineering expertise within a framework that can be applied at the K-12 level and 2) estimating changes in undergraduate curricula in order to incorporate subject relevant sustainability metrics. The overarching goal is to ensure that every engineer has adequate training to work within the context of a complex problem and incorporate intelligent sustainable design.

Although a large-scale study is necessary to assess the benefits of extending sustainability relevant science projects to K-12 projects, the current case has proved to be a valuable learning experience for the involved student as well as the educators. The individual student's case also resulted in a first-place award at the 2011 Hoosier Science and Engineering Fair [27]. This makes a strong case for scaling up the current study to include a comprehensive cohort of K-12 students. The authors plan to develop custom projects and seminars for disseminating engineering based science exercise throughout multiple K-12 levels. Examples of these include teaching measurement sciences through a 'Energy/Water metering project' as well as a demand and supply based comparison of different modes of renewable energy production, i.e solar, wind, and/or hydroelectric energy sources. These projects will aid in mass dissemination of concepts related to engineering and sustainability into K-12 groups, similar to [28, 29]. The authors hope that such endeavors will boost student interest in STEM disciplines and concurrently engage them in promoting environmental sustainability.

Immediate impact of this study will be seen through the incorporation of several key modules into the undergraduate lab experiment within ME315 beginning in the Fall 2012 semester. As stated in the above section, a more rigorous comparison of the environmental and economic benefits of each studied material will provide a MCDA type platform in which students will learn to overcome complex tradeoffs related to environmentally efficient materials. Furthermore, the authors plan to include an additional module to the lab exercise related to microstructure investigation in order to promote the students' understanding of the role of air in regards to insulation materials. The authors hypothesize that all discussed additions and modifications to the lab experiment will help better contextualize the learning objectives of the original lab and provide a unique learning medium related to triple-bottom-line thinking for undergraduate students.

## ACKNOWLEDGMENTS

The authors would like to especially thank Sherry Anderson, Arjun Ramani's 6th grade teacher at Happy Hollow Elementary School, for her instrumental guidance to the student during his project. This work was partially supported by the NSF under the grants EEC-0935074 and CMMI-1100619. This paper does not necessarily reflect the views or opinions of the agency.

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