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Integrating Eco-Design in Manufacturing Materials and Processes Related Courses - Material Selection for Sustainable Design using CES Package

Dr. Yalcin Ertekin, Drexel University (Tech.)

Yalcin Ertekin received his Ph.D. degree in mechanical Engineering from Missouri University of Science and Technology (formerly The University of Missouri-Rolla). He is a Certified Quality Engineer (CQE) and Certified Manufacturing Engineer (CMfgE). His teaching responsibilities include Computer Numerical Control, manufacturing processes, applied quality control, mechanical design, and applied mechanics, manufacturing information management systems, introduction to technology and graphical communication as well as senior design courses. He developed two online graduate courses: rapid prototyping and product design and lean manufacturing principles for MSET program. Dr. Ertekin has over six years of industrial experience related to quality and design engineering mostly in automotive industry. He worked for Toyota Motor Corporation as a quality assurance engineer for two years and lived in Toyota City, Japan. His area of expertise is in CAD/CAM, manufacturing processes, machine design with CAE methods, rapid prototyping, CNC machining and quality control. His research interest includes sensor based condition monitoring of machining processes, machine tool accuracy characterization and enhancement, non-invasive surgical tool design and bio-materials applications. During his career, Dr. Ertekin published papers in referred journals and in conference proceedings in his area of research interest. He has also been PI for various NSF research projects including NSF-TUES and MRI programs. Dr. Ertekin is an active member in the Society of Manufacturing Engineers (SME), and currently serves as a chair of Philadelphia SME Chapter-15.

Dr. Irina Nicoleta Ciobanescu Husanu, Drexel University (Tech.)
Dr. Richard Chiou, Drexel University (Eng.)

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Abstract

Responsible design aims to provide safe, affordable services while minimizing the drain on resources and the release of unwanted emissions. This can be accomplished by performing an ongoing eco-audit of the design (or redesign) as it progresses. As we teach engineering materials and manufacturing process courses prior to capstone senior design projects, it is imperative to introduce Engineering Technology (ET) students to advanced tools to impart skills that will guide design decisions that minimize or eliminate adverse eco-impact. Embodied energy and carbon footprint, recycle fraction and toxicity have obvious eco- connections that require careful considerations for Product Lifecycle Assessment (PLA) combined with mechanical, thermal, and electrical properties that have the greatest role in design to minimize eco-impact. Several courses in ET curricula have been used during the past Academic Year (AY) to infuse sustainability, eco design and green energy production teaching materials and projects into Mechanical Engineering Technology courses such as Materials, Mechanical Design, Manufacturing Processes and Senior Design Capstone course sequence.

This investigation aims to evaluate from student learning perspective the benefits of incorporating software based eco-design team projects into main required courses in our Engineering Technology curricula. The benefits are assessed based on several tools ranging from questionnaires administered to students to assessment of students' knowledge and expertise demonstrated in the student-led projects. Questionnaires are also based on evaluating the level of practical knowledge gained by the students during the development of such projects on one hand and on whether the project has a multidisciplinary character and to what extent. Another aspect included in this research is the students' involvement in evaluating the outcomes of fellow students' projects.

During the past AY authors used two software packages: Cambridge Engineering Selector (CES-EduPack 2013) and our existing SolidWorks® 2013 package with Sustainability "**addin**" function invoked to provide tools to meet complex product and process design requirements, helping students to explore and learn the underlying science of eco-design in a sustainable environment. While CES EduPack Sustainability database package provides a computer-based resource for assessing articulations of sustainable technology and the place of materials in them, SolidWorks sustainability evaluates the environmental impact of a design throughout the life cycle of a product. Students are required to compare results from different designs to ensure a sustainable solution for the product and the environment.

These approaches have been studied by the authors since AY 2012-2013 and have been successfully implemented in most of the courses taught by them. As a general outcome, students became more involved during class time and also they shown interest in sustainable eco-design areas, being involved in more advanced course research activities. Several students also elected to develop their own ideas during team projects and undertook projects of a wider PLA scope.

Background

The characteristics of postsecondary education in engineering are dynamic; thus colleges and universities need to be in continuous review of their expected outcomes to ensure they are educating the student to be prepared in the current global environment. The qualities that a current engineering program should possess include: global and local focus, innovative, collaborative, transparent, flexible, market-driven and accountable.[1] The global focus ensures that the skills acquired are internationally benchmarked while the local focus makes certain that the needs of the regional economy are understood. Flexibility in curricula will allow for quick change to adapt to current situations and make the process transparent.

In Drexel University's College of Engineering-Engineering Technology (ET) department, many courses related to design, manufacturing processes, green manufacturing and engineering materials are offered to the students in the Bachelor of Science in Engineering Technology. Courses such as Robotics and Mechatronics, Quality Control, Manufacturing Materials, Microcontrollers, and Applied Mechanics can benefit from the laboratory experience in applications of sustainability and eco design as well as material and processes selection. As well as helping in the teaching of various courses, such experience benefits students who are pursuing degrees in the engineering field. Students in the Mechanical, Electrical, Industrial and Biomedical fields along with many others can learn many new skills from case study projects such as designing and fabricating various consumer products, machines and equipment. Such projects show students how to use different types of technology, and demonstrate how advanced technology can be used in an actual application. This project talks about instilling future engineers and technologists with various advanced skills and tools that can be used in their careers. Overall, many different fields of engineering can benefit from the modern tools and applications, enabling the development of skill and knowledge in many different engineering aspects and processes.

Current curricula methodology teaches engineering concepts distinctly from sustainability concepts. These functional silos are a thing of the past in industry and students must be able to succeed in a multi-disciplinary environment that necessitates systems approach. While courses such as "green manufacturing" and "green/renewable energy manufacturing" exist in ET curricula, students are not taught to look at the environmental impacts of decisions in a traditional engineering course. Additionally, many public colleges and universities are not providing all of their graduates with the critical thinking, problem-solving, and adaptive skills, including science, technology, engineering, and math (STEM) competencies, required to meet the needs of employers. In order for companies to compete in the global marketplace, employers in the 21st century will require their engineers couple the traditional engineering design skills with new and modern skills in sustainability, eco design and audit as well as the ability to function in multi-disciplinary teams.

This project proposes to address the characteristics needed by current engineering technology curricula by seamlessly integrating sustainability concepts within the mechanical and Industrial Engineering laboratory course work. In particular, the junior and senior level courses will each have revised modules, each spanning multiple weeks and covering a broad range of sustainability and eco design topics using Cambridge Engineering Selector EduPack software (CES EduPack

). The traditional materials and manufacturing skills will be taught, and consequently, the sustainable impact of the decision related to materials and processes will be investigated. Working in teams with greedy members in term projects, students will come to a rational, unified group decision, with the intent of exposing students to more enhanced decision-making skills using modern tools in a multi- disciplinary, team environment.

Sustainability and Decision Making in Engineering Education

In the last one to two decades, there has been substantial attention of sustainable products and programs from consumers, industries and governments globally. While price, functionality, convenience are the traditional deciding factors in an engineering decision, it has been reported that 65% of Americans and approximately 25% of Europeans are willing to pay a premium for a more sustainable solution.[2] Emphasis is on designing products that are sustainable in a setting that will not compromise the environment for future generations. Society now looks to engineers to address the short and long-term issues dealing with sustainable development, prototyping, and manufacturing. Within the last decade, companies have been called upon to perform such tasks as mitigation of gas emissions, and reduction of carbon footprint[3]. Over the last few years in particular, there have been unprecedented calls for society to both mitigate greenhouse gas emissions, and to adapt to an altered climate regime, the nature of which will be dependent on the extent of mitigation[4]. During the 2007 Global Sustainability Forum on the future for engineering education it was acknowledged that "The business as usual model, where profits come before sustainability, is absolutely finished. We now have a window of ten to 15 years to adopt a sustainable approach before we reach a global tipping point, the point at which mankind loses the ability to command growth and development ." [3]

One of the major United States initiatives promoting energy efficient products and practices, Energy Star, was introduced in 1992 by the Environmental Protection Agency to protect the environment by encouraging the use of energy efficient products, enabling both energy use and cost reduction. [5] In 2007, the program was estimated to have saved $16 billion. The European Union (EU), in 2001, developed broad strategic directives with the aim of addressing climate change and energy, transportation, production, and protection of natural resources. Some of the directives stemming from this initiative include the Waste Electrical and Electronic Equipment initiative in which each nation had to set target points for collection, recycling and recovery of electronic products. In 2005, the Eco-design of Energy-using Products directive established guidelines for eco-design to facilitate trade within EU countries without regulations becoming a barrier.

However, this current trend often creates situations that produce conflicting attributes. For example, the effects of preserving fuel economy and creating recyclability often conflict with traditional desired product attributes such as material consistency, convenience and performance.[6] One particular concern is cost; many customers opt for products with low environmental quality due to cost considerations. Additionally, designing these new eco-friendly, green products involves a large investment in research and design, and even then, the outcome is still uncertain.

As engineering educators, we are aware that the ability to function in an interdisciplinary environment is an important concept to impart among our students. Therefore, a lot of attention has been given to team-building activities, and collaborative learning in the classrooms. It is such a critical topic, that the Accreditation Board of Engineering Technologies, (ABET)[7], strongly encourages teamwork in the curricula. ABET-ETAC requires that engineering technology programs demonstrate that graduates are able to design a system, component, or process to meet desired needs and an ability to function on multi-disciplinary teams (ABET outcomes d and e). Additionally, ABET recognizes that this cannot be taught in one course; it is an experience that must grow with the students development.[7, 8]

Even when students are prepared to enter industry and perform efficiently in a team environment, they are not necessarily prepared to work in a multi-disciplinary environment. The aim of this curricula improvement is to raise student awareness of sustainability & Eco-design concepts as they relate to the ET curricula and facilitate student growth with regards to multi-attribute decision making and working in a team environment.

Impact on Continuous Improvement of ET Program: Integrating Sustainability into ET Curricula

Going forward, engineering decisions that need to be made with regards to design, development and implementation will involve high levels of uncertainty. The decision-making process is not linear, and often involves iterations, feedback and compromises to arrive at a favorable conclusion. When faced with this uncertainty, typical engineers rely on past experience since they lack the training required to make effective decisions.[9]

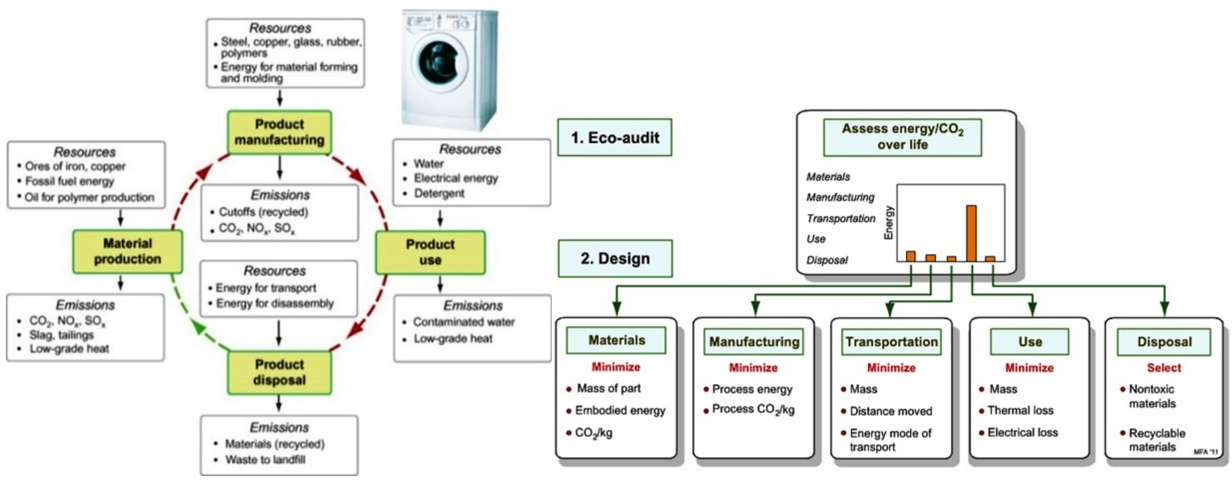
Integrating sustainability issues into a traditional Engineering Technology courses requires that students incorporate sustainability issues into their problem solving skills while considering the wider issues such as safety, target costing, engineering standards and economic justification. ET program should provide access to the technological knowledge but also have students' afforded the opportunity to apply this in designing hard solutions. The next generation of engineers needs to rethink their fundamental attitudes towards a broader, multiple perspective approach in which problem formulation and context setting play a vital role in reaching consensual solutions[10].

Traditional undergraduate engineering programs are over 130 credit hours and are not designed to handle any additional credit hour increase that would be required by integrating new curricula components regarding sustainability aspects. Students will graduate armed with the technical competence necessary to succeed in their field as well as the business acumen and skills necessary to work effectively with other team members.

Sustainability and Eco Design

Responsible design aims to provide safe, affordable services while minimizing the drain on resources and the release of unwanted emissions. This can be accomplished by performing an ongoing eco-audit of the design (or redesign) as it progresses. This audit must be fast, allowing "what if?" type exploration of the consequences of alternative choices of material, use pattern, and end-of-life scenarios. The currently used full "Life Cycle Assessment (LCA)" is not well adapted for this task (slow and expensive). One way to tackle these issues is to focus on analysis of the main culprits as a pair resource-emission: *one resource—energy—and one emission—carbon dioxide, CO_2.*

The idea of a life cycle has its roots in the biological sciences. In product design life cycle concepts rely on the interaction of products with the natural, social, and business environments. Concerns about resource depletion, the oil crisis of the early 1970s, followed by the first evidence of carbon-induced global warming, focused attention on the life cycle of manufactured products and their interaction with the natural environment. The study of a product and its associated material life cycle involves assessing the environmental impacts associated with its life, from the extraction of raw materials to their return to the ecosphere as "waste"-from birth to death. Figure 1a is a schematic of the start of an inventory analysis – an example of the identification of the main resources and emissions for a washing machine.



(a) (b)

Figure 1. (a) The material life cycle and the principal resource emissions associated with the lifecycle of a washing machine (b) Rational approaches to the eco-design of products start with an analysis of the phase of life to be targeted.[11, 12]

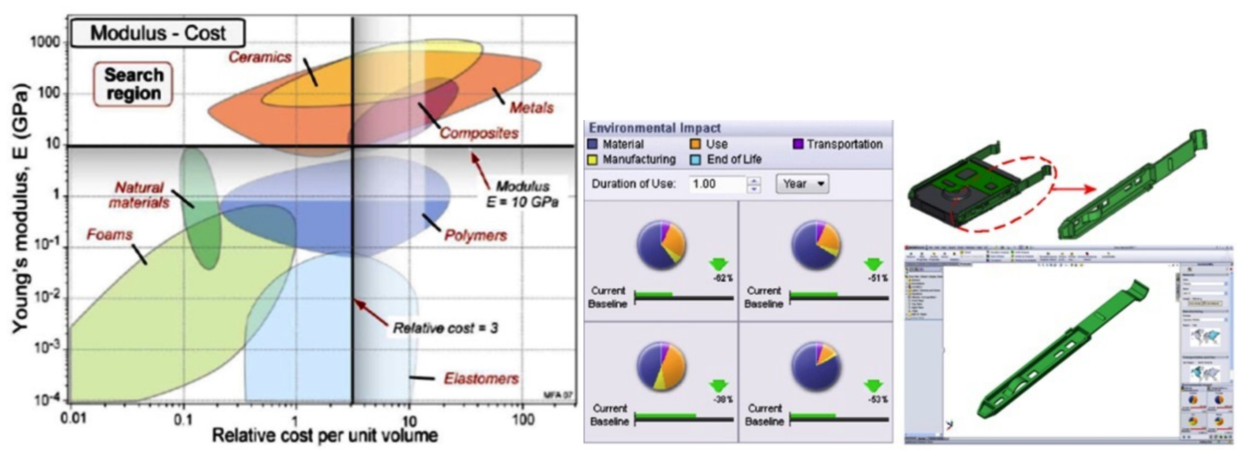
Figure 1b above suggests how the Life Cycle Assessment (LCA) strategy can be implemented. If material production is the dominant phase, then the logical way forward is to choose materials with low embodied energy and to minimize the amount of it that is used. If manufacturing is an important energy-using phase of life, reducing processing energies becomes the prime target. If transportation makes a large contribution, then seeking a more efficient transportation mode or reducing transportation distance becomes the first priority.

Integration of CES EduPack and SolidWorks Sustainability to ET Courses

As we teach engineering materials and manufacturing process courses prior to capstone senior design projects, it is imperative to introduce ET students with advanced tools to impart skills that will guide design decisions that minimize or eliminate adverse eco-impact. Embodied energy and carbon footprint, recycle fraction and toxicity have obvious eco- connections that require careful

considerations for Product Lifecycle Assessment (PLA). combined with mechanical, thermal, and electrical properties that have the greatest role in design to minimize eco-impact.
This project aims to develop a pilot course materials and modules that will help bridge the gap between the Industrial Engineering Technology (IET) and Mechanical Engineering Technology (MET) concentration curriculum, collaborative decision-making and sustainability: all necessities in today's engineering education. The main focus of the changes would be to embed and integrate sustainability concepts in both IET and MET curricula, in the beginning using representative courses for both concentrations (such as MHT 401-mechanical design, MET 407-manufacturing processes and MET 4XX-Senior Design Capstone sequence). *This approach will combine the skills necessary to succeed in today's engineering business world: engineering concepts, a sustainable focus, team skills and multi-attribute decision making skills.* Students will learn to think globally by addressing the larger-scale sustainable issues of their decisions. Decisions will be made both independently and in a group setting, thus enabling students to develop collaborative decision-making skills. Thus the curriculum changes have the following objectives: (1) Integrate sustainability concepts within the framework of Industrial & Mechanical Engineering Technology curriculum and emphasizing the dichotomy which exists between sustainable and economic-based decisions; (2) Embed decision-making approaches within student-led team environment; (3) Enable students to make decisions under uncertainty with open ended what if scenarios simulating a real-world situation – integrate sustainability with creativity and innovation.

The success of the curricula improvement in an education and research-oriented facility will advance the state of art of engineering technology education, specifically in the areas of manufacturing material and process selection, sustainability and green design of products and problem solving.



(a) (b)

Figure 2. (a) Constraints of modulus greater than 10 GPa and relative cost less than 3 plotted on a graph, (b) SolidWorks Sustainability analysis using a plastic part.

The sustainability and eco design teaching materials and projects are being integrated into Mechanical Engineering Technology courses (MET 101, MHT 401, MET 407 and MET 4XX-Senior Design). The starting point of achieving our project goals would be attained using two software packages specifically Cambridge Engineering Selector (CES EduPack ™ 2013) using our existing SolidWorks2013 with Sustainability addin/ function invoked. The CES EduPack™ software provides tools to meet complex design requirements, helping students to explore and learn the underlying science of eco-design in a sustainable environment. Figure 2a depicts the functionality of this package and how it serves the purpose of this project. SolidWorks sustainability (Figure 2b) evaluates the environmental impact of a design throughout the life cycle of a product. Design engineer can compare results from different designs to ensure a sustainable solution for the product and the environment.

We are developing the specific assessment instruments, their types, and structure, some of which can be developed only during the course offerings, depending upon intermediate outcomes. Formative assessment will be performed through tests and questionnaires by systematically collecting feedback from students. Improving learning through formative assessment depends basically on three key factors (1) effective feedback to students; (2) active involvement of students in their own learning; and (3) adjusting teaching to take into account the results of assessment. In exams for all course offerings, an entering knowledge test on sustainability and eco design will measure what students are expected to know prior to taking the course, while the final exam will reflect content objectives and expected student knowledge acquisition from the course. The predetermined assessment criteria will be communicated to students at the beginning of the instructional period. A Likert type scale questionnaire will measure how students feel about aspects of the technology tools such as CES-EduPack and SolidWorks.

Example Case Studies to be used in Course Module Development

Design in general, and mechanical design in particular are iterative activities. Iteration, looping back to explore alternatives, is an essential part of the design process.[14, 15] Iterating is, of course, time consuming and costly, but a systematic search for creative solutions early on in the process is not, either extremely costly or terribly time consuming and is fundamental to the design of innovative products. Therefore, in this project, the students learned what engineers have to deal with and how to look at a problem and taking the steps to fix it. The CES EduPack ™ software provides tools to meet complex product and process design requirements, helping students to explore and learn the underlying science of eco-design in a sustainable environment. The CES EduPack ™ sustainability database package provides a computer-based resource for assessing articulations of sustainable technology and the place of materials in them. SolidWorks sustainability evaluates the environmental impact of a design throughout the life cycle of a product. Design engineer can compare results from different designs to ensure a sustainable solution for the product and the environment. The students can access the software using Windows remote desktop accessory since the software is installed in a virtual lab server. This is very convenient for the students making the tool available anytime and anywhere with internet connection.

Material Selection Exercise Case Study: "Hot Air Balloon Basket Floor"
(Case study provided by Dr. Ronald Kander of Philadelphia University) [16]
The floor of a hot air balloon basket has to meet a complex set of design requirements in order to function safely and effectively. In this exercise you are asked to select a material for this application using the CES EduPack software. **Use the CES Level 2 database "materials with eco and durability properties" to perform your analysis.** In this exercise, you are working as

a consultant for a company that is considering a business opportunity to manufacture and sell hot air balloon baskets. Our client has identified several constraints and objectives that they have determined are important in this market. They want you to use these constraints and objectives (and any other considerations you think are important to take into account) to suggest several of the best material for them to consider in making the floors of their hot air balloon baskets. First, you determine that the panel making up the floor of the hot air balloon basket is a stiffness-limited design that essentially functions as a flat plate loaded in bending.

Here are the properties your client has identified that the basket floor must have:

- Since the basket floor will be used outdoors, it must be durable in the presence of water. *You can interpret this need as requiring excellent or acceptable durability in fresh water.*
- Also, since the basket will be stored outdoors, it must be resistant to long-term sunlight exposure. *You can interpret this need as requiring excellent or good durability in UV radiation (sunlight).*
- Since a fracturing of the floor would have catastrophic consequences, it must also be reasonably resistant to fracture. *You can interpret this need as requiring a fracture toughness greater than 5* $MPa*m^{1/2}$.

Given these properties, your client would like to optimize their design based on two stiffness-limited design strategies. The client would like to consider materials that are:

- as stiff-and-light as possible, since extra weight means less paying passengers on the balloon ride.
- as stiff-and-cheap as possible, allowing them to lower their investment and therefore lower the price charged for the balloon ride.

Given the function and constraints in this application, use the CES software to systematically select a few top materials that you would recommend to the client for each of the two strategies listed above.

Combine the information from these two scenarios to recommend several different material options that would be the overall "best" choices, with reasons why each option might be a good choice.

After making these recommendations to your client, they begin to question your assumption about modeling the requirement of durability in the presence of water by allowing excellent or acceptable durability in fresh water. The client would like more rigorous water durability. Repeat your analysis by allowing only excellent durability in fresh water and report how your previous recommendations would change.

Material Selection & Eco-audit Exercise Case Study: "Automobile Bumper Beam"

(Case study provided by Dr. Ronald Kander of Philadelphia University) [16]

The company you work for would like to manufacture and sell a lightweight automobile bumper beam for a typical gasoline-powered family car. They have found many incumbent products on the market that are made from steel. The idea is to make a bumper beam from a lighter weight material that will save gasoline, compared to heavier beams, when mounted on a car. You are asked to determine if a bumper beam made from a lighter, but more expensive, material would save money, in the long run, compared with a heavier, but cheaper, beam made from steel. You have already done some background research and determined that a typical steel bumper beam is made from "low alloy steel" that is manufactured by a forging process. A steel beam typically weights about 8 kilograms. You also gather the following information from the design team manager:

- The company would like to make the new, lighter, beam from either a metal or a composite material.
- The selected material must have a fracture toughness greater than 10 MPa*m$^{1/2}$.
- The bumper beam is essentially a "strength-limited design" and essentially functions as a "beam loaded in bending" with the "load, length and shape specified and the section area free".

Use the CES software to perform the following two selection exercises:

- Select the best few materials by using the appropriate material index for the strongest material at minimum mass (strong-and-light).
- Select the best few materials by using the appropriate material index for the strongest material at minimum price (strong-and-cheap).
- Compare "strong-and-light" performance with "strong-and-cheap" performance to generate a "tradeoff line" to identify several good material choices for this application.

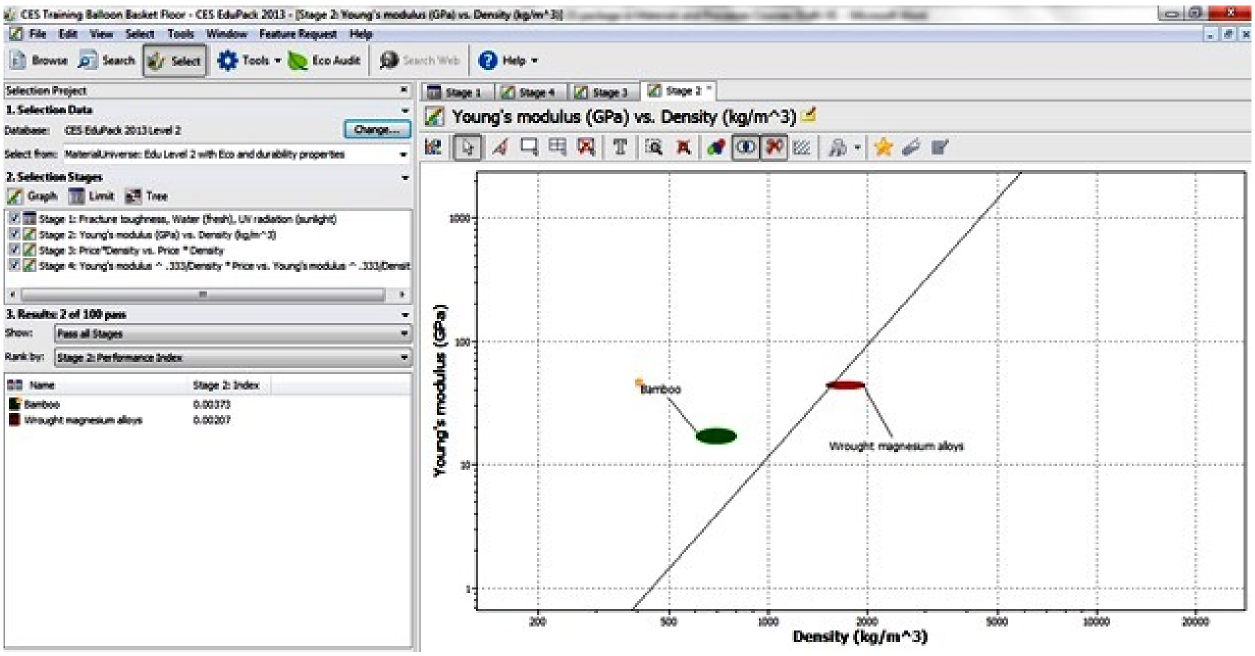


Figure 3. Possible CES solution for the “Hot Air Balloon Basket Floor” case study.

Next, estimate the **mass** and **material cost** for bumper beams made from your proposed material recommendations by following this procedure (we will do this together as a class):

- Calculate the average "strong-and-light" material index for each of your material recommendations and for low alloy steel (the incumbent material).
- Use the ratios of these indices to estimate the mass of the beams made from each material based on the known mass of the steel beam (given earlier in this problem statement).
- Use these masses and the prices per unit mass in the CES database to estimate the price of the beams made from your materials and compare these to the price of the incumbent steel beam.

Finally, enter your material options (and the steel option) into the Eco-Audit part of the CES software to determine how much energy (and, therefore, how much money) it will cost to carry the bumper beam on a typical gasoline-powered family car over its lifetime (from the "use" section of the eco-audit). Make the following assumptions:

- The beam is mounted on a typical gasoline-powered family car for 10 years.
- The car is used, on average, 350 days per year and is driven, on average, 75 kilometers per day.
- The cost of energy to run the car is, on average, about $0.02 per MJ.

Now, compare the initial price of the bumper beam materials to the cost of energy attributed to the beam over its life cycle to determine if the idea of producing a lighter, but more expensive, "fuel efficient" bumper beam is a good one.

What other issues have we not taken into account in this analysis that would be important to consider in making this decision?

Use "CES EduPack Level 2: Materials With Eco and Durability Properties" in working on this design problem.

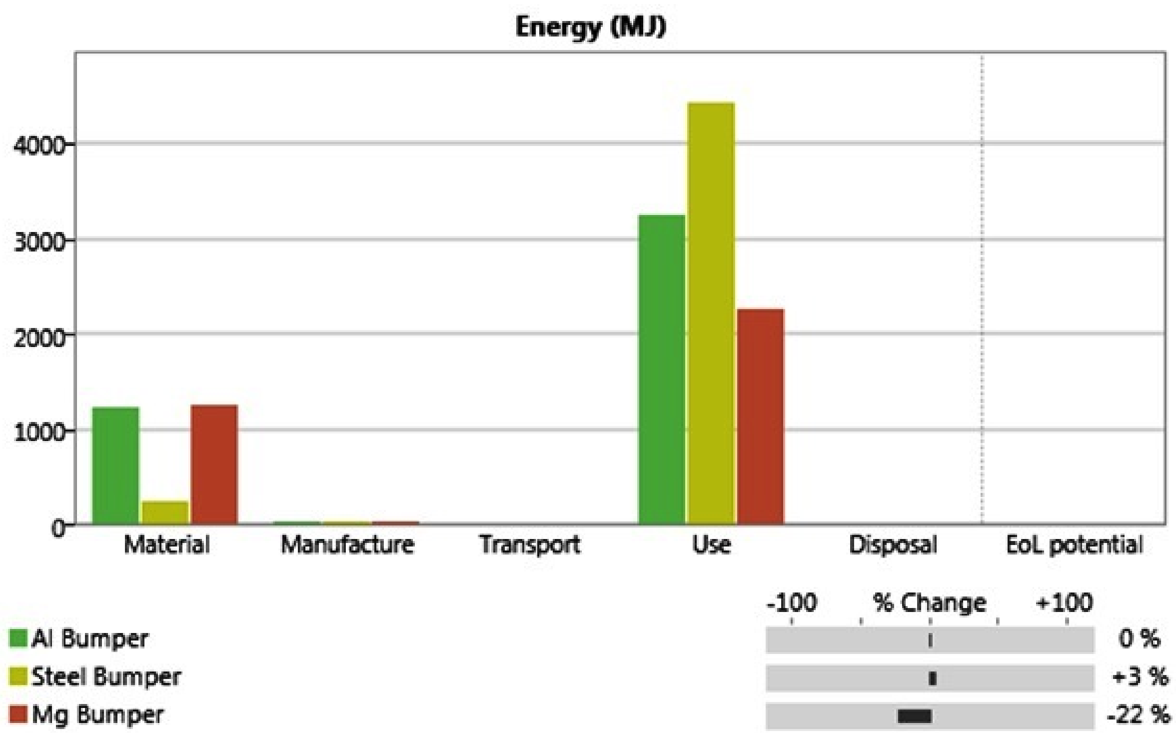


Figure 4. Possible CES Eco-audit for the "Automobile Bumper Beam" case study.

Conclusions

Teaching sustainable and eco-design methodologies accompanied by real system's data will increase the comfort, competitiveness, and confidence of the students not only qualitatively, but also quantitatively. It was also observed a positive impact on student's simulation skills. The design as well as material and process selection experience develops the students' lifelong learning skills, self-evaluations, self-discovery, and peer instruction in the design's creation, critique, and justification. Students learn to understand the data bases and sheets, application notes, and technical manuals and component specifications. The experience of teamwork gives the students a sense of satisfaction and accomplishment that is often lacking in many engineering courses, not including projects. Furthermore, the eco-design experience motivates student learning and develops skills required in industry. The students will able to make more accurate and satisfactory estimations and calculations of these projects. We hope to see that their project and case study results reflect that they have understood well all the basic ingredients of the sustainable and eco-design of the engineering systems.

Acknowledgement

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