Athens Institute for Education and Research
ATINER

ATINER's Conference Paper Series
ENGEDU2017-2233

Teaching Sustainability in Mechanical Engineering Curriculum

Roy Issa
Associate Professor
West Texas A&M University
USA

An Introduction to ATINER's Conference Paper Series

ATINER started to publish this conference papers series in 2012. It includes only the papers submitted for publication after they were presented at one of the conferences organized by our Institute every year. This paper has been peer reviewed by at least two academic members of ATINER.

Dr. Gregory T. Papanikos
President
Athens Institute for Education and Research

This paper should be cited as follows:

Issa, R. (2017). **“Teaching Sustainability in Mechanical Engineering Curriculum",** Athens: ATINER'S Conference Paper Series, No: **ENGEDU2017-2233.**

Athens Institute for Education and Research
8 Valaoritou Street, Kolonaki, 10671 Athens, Greece
Tel: + 30 210 3634210 Fax: + 30 210 3634209 Email: info@atiner.gr URL: www.atiner.gr
URL Conference Papers Series: www.atiner.gr/papers.htm
Printed in Athens, Greece by the Athens Institute for Education and Research.
ISSN: 2241-2891
14/07/2017

Teaching Sustainability in Mechanical Engineering Curriculum

Roy Issa

Abstract

Sustainability development teaching modules at the senior level were recently introduced into the undergraduate Mechanical Engineering curriculum at West Texas A&M University through the offering of two courses. One of those courses is an elective course that introduces sustainability in engineering design, and examines the eco-aspects of material production, use and disposal at end of life. The course also introduces input-output environmental life cycle assessment (EIO-LCA) as a tool for evaluating the relative impact products have on energy resources and the environment, along with the interaction between the different sectors in the economy. A variety of Eco-Audit and EIO-LCA case studies from the thermal and solid mechanics areas are examined. In the second course offered, a core course on thermal-fluid design, the contents of the course are revised to integrate half a semester worth of teaching material on exergy-based sustainability assessment of thermodynamic cycles. Improvements to the performance of the cycles from the thermal and economics points of view are examined through exergoeconomics studies. A survey administered to students who are taking either or both courses, and to students who have not taken any of these courses reveal the impact these courses have on students' interest and understanding of sustainability in engineering design and analysis.

Keywords: Design, Development, Exergoeconomics, Life Cycle Assessment, Sustainable.

Introduction

Sustainable development is a development that aims at improving human life style and well-being while preserving the natural resources and ecosystems at the same time. During the last decade, many universities across the world started to incorporate sustainability into their curricula (Mintz and Tal, 2014) and into their assessment and reporting by introducing sustainability development to the university's mission and strategic planning (Lozano, 2006). Engineering schools have adopted two approaches for incorporating sustainable development into their curricula, namely through horizontal and vertical integration (Ceulemans and De Prins, 2010). In the horizontal integration, sustainability coursework material is integrated into several courses across the curriculum, while in the vertical integration, new sustainability courses are added into the curriculum. In the horizontal integration, three different approaches are possible (Watson et al., 2013). In the first approach, an existing curriculum course can be revised to include some coverage that is associated with environmental and/or social issues (Thomas, 2004; Paudel and Fraser, 2013). In the second approach, appropriate sustainable development material that matches the nature of the existing course can be interwoven with the original course material (Abdul-Wahab et al., 2003). In the third approach, sustainable development integrated into courses can be offered as a specialization or as a major program at the university (Kamp, 2006; Lozano and Lozano, 2014; von Blottnitz et al., 2015).

The Accreditation Board for Engineering and Technology (ABET), which accredits higher education programs in engineering and engineering technology in the United States and 30 other countries (www.abet.org/about-abet), addresses the need for sustainability in engineering courses through ABET accreditation criteria 3(c) and 3(h). Criterion 3(c) recognizes the need to incorporate sustainability within engineering design. It states that engineering programs must demonstrate that students have (ABET, 2015):

> *"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"*

In addition, Criterion 3(h) states that students should demonstrate (ABET, 2015):

> *"the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context"*

Even though Criterion 3(h) does not mention sustainability by word, it has the three main pillars needed for sustainable development: Economic growth, environmental protection, and social equality (Arrow et al., 2004). This paper reports on the vertical and horizontal approaches for sustainable development that were adopted in the Mechanical Engineering program at West Texas A&M University to introduce sustainability coursework material into the mechanical engineering curriculum through the offering of: 1) an elective course in sustainability, and 2) a core course in thermal-fluid design.

Scope of the Coursework

Elective Course in Sustainability

This engineering elective course examines the eco-aspects of materials, and introduces sustainability in engineering design. Upon the completion of the course, students are expected to:

1. Analyze and understand the multidimensional aspects of sustainable development problems.
2. Examine the damaging impacts of an industrial society on the environment and the ecosystem in which we live.
3. Utilize the tools necessary to analyze and respond to environmental imperatives.
4. Identify the factors used to measure the environmental impacts.
5. Examine the eco-aspects of materials production and use.
6. Apply the economics input-output environmental life cycle assessment (EIO-LCA) method by analyzing a series of case studies using Carnegie Mellon's Green Design Institute's www.eiolca.net software, and
7. Design for sustainability.

Core Course in Thermal-Fluid Design

In this core mechanical engineering course, students are expected to apply heat transfer and fluid mechanics concepts to analyze and design thermal-fluid systems. The course emphasis is on design calculations, component and system modeling, and optimization including economic considerations. An exergy-based sustainability assessment was integrated into the course. Students are expected to:

1. conduct exergy analysis on thermodynamic cycles,
2. apply established guidelines to optimize the thermodynamic effectiveness of the cycles from exergy point of view,
3. conduct exergoeconomics analysis on examined cycles, and
4. perform design evaluation of cycles from exergoeconomics point of view.

Introducing exergy-based sustainability assessment on thermodynamic cycles will help the students establish a deep understanding of:

1. the inefficiencies associated with thermodynamic cycles and the processes causing them,
2. the cost associated with processes and equipment, and the effect of the operating conditions on the equipment cost, and
3. the guidelines for improving the efficiency and the cost effectiveness of thermodynamic cycles.

Design for Sustainable Use

In the sustainability elective course, students work on a variety of case studies focusing on how to design for sustainable use while being eco-informed on the selection of the material. A list of typical studies is shown in Table 1. Examples from thermal-fluids and solid mechanics area are presented. Different evaluation measures ranging from heat transfer, material bending, stiffness, cost, embodied energy, and carbon emissions release are implemented in the selection of the optimal material. The optimization index or the selection of the materials includes evaluation of a combination of material-associated parameters, such as: thermal and mechanical properties, material embodied energy, and material carbon emissions. The optimization index is defined as the parameter or the combination of parameters that need to be maximized or minimized to satisfy the criteria defined by the evaluation measure.

In Table 1, the parameters shown in the optimization indexes are defined as follows: λ is the material thermal conductivity, ρ is the material density, c_p is the material specific heat, σ_y is the material yield strength, E is the material modulus of elasticity, H_m is the material embodied energy per unit mass, H_v is the material embodied energy per unit volume, C_m is the material cost per unit mass, $CO_{2,m}$ is the material embodied carbon emissions per unit mass, $CO_{2,v}$ is the material embodied carbon emissions per unit volume, and L is plate thickness.

Table 1. *Case Studies on Designing for Sustainable Use*

Case Study	Evaluation Measure	Constraints Considered	Optimization Index
Energy efficient furnace	• Minimize furnace total energy consumed	• Wall thickness • Operating temperature	$(\lambda\alpha^{-1/2})_{min}$
Home passive solar heating	• Maximize wall heat capacity • Minimize cost per unit volume	• Heat diffusion time • Wall thickness • Cost	$(\lambda\alpha^{-1/2})_{max}$
Efficient shell& tube heat exchanger	• Maximize heat flow per unit area (minimize volume) • Maximize heat flow per unit mass (minimize mass)	• Tube wall thickness	$(\lambda\sigma_y)_{max}$ $(\lambda\sigma_y^2\rho^{-1})_{max}$
Durable rocket fins	• Minimize surface temperature rise	• Heat diffusion distance • Melting temperature	$(\lambda\rho c_p)_{max}$
Fuel-saving cooking pan	• Minimize thermal resistance • Minimize embodied energy per unit volume • Minimize CO_2 emissions per unit volume	• Base plate thickness • Cost	$(L\lambda^{-1})_{min}$ $(\rho H_m)_{min}$ $(\rho CO_{2,m})_{min}$
Performance refrigerator walls	• Minimize effective thermal conductivity • Maximize flexural modulus	• Wall thickness	$(\lambda_{eff})_{min}$ $(E_{flex,eff})_{max}$
Durable carbonated water bottles	• Minimize embodied energy per unit area • Minimize cost per unit per area	• Wall thickness	$(H_m\rho\sigma_y^{-1})_{min}$ $(C_m\rho\sigma_y^{-1})_{min}$
Eco friendly drink containers	• Minimize embodied energy per unit volume • Minimize CO_2 emissions per unit volume	• Corrosion resistant • Formable • Recyclable	$(H_v)_{min}$ $(CO_{2,v})_{min}$
Eco friendly crash barriers & car bumpers	• Minimize mass for given bending strength(bumpers) • Minimize embodied energy for given bending strength (crash barriers)	• High strength • Recyclable	$(\rho\sigma_y^{2/3})_{min}$ $(\rho H_m\sigma_y^{2/3})_{min}$
Durable Table Top (stiffest top)	• Minimize the mass • Minimize the embodied energy • Minimize the CO_2 emissions	• High stiffness	$(\rho E^{1/3})_{min}$ $(\rho H_m E^{1/3})_{min}$ $(\rho CO_{2,m}E^{1/3})_{min}$

Application of Economic Input-Output Life Cycle Assessment (EIO-LCA) Method in Sustainability Course

Wassily Leontief, Harvard University economist, developed input-output models of the U.S. economy (Leontief, 1936) for which he received the Nobel Prize in economics in 1973. His models identify the different inputs needed to generate a unit of output in each economic sector. By assembling all the sectors in the economy, Leontief traced all the direct and indirect inputs required to produce outputs in each sector. The economic input-output model is a linear model such that any increase in the output of goods and services from any sector will result in a proportional increase in each input received from all the other sectors in the economy. Leontief's models divide the entire economy into distinct sectors, and can be visualized as a matrix of n rows by n columns (where n stands for the number of sectors). The required economic purchases, $\vec{x}$, in all economic sectors required to make a vector of desired output $\vec{y}$ can be calculated as follows:

$$\begin{aligned}\vec{x} &= [I + A + AxA + AxAxA + ...]\vec{y} \\ &= [I - A]^{-1}\vec{y}\end{aligned} \quad (1)$$

where $[A]$ is the input-output direct requirement matrix, and $[I]$ is an identity matrix. The environmental outputs such as hazardous wastes (air, water, land, and underground releases), air pollutants (SO_2, CO, NOx, VOC, Pb, PM10, PM2.5), and greenhouse gases (CO_2, CH_4, N_2O, CFCs) associated with the economic purchases (process stage), $\vec{b}$, can be calculated as:

$$\vec{b} = [R]\vec{x} \quad (2)$$

where $[R]$ is a diagonal matrix whose elements represent the environmental impact per dollar of output for each process.

A sample of the EIO-LCA cases studies that the students work on in the sustainability elective course is shown in Table 2. These case studies are based on Carnegie Mellon University EIO-LCA model of the U.S. economy.

Table 2. *EIO-LCA Case Studies*

Case Study	Objective/ Evaluation Measures	Cost Evaluation
Plastic vs. Paper Bags	Use the cost values of the bags as inputs into EIO-LCA to estimate the relative energy consumption and greenhouse gas emission.	cost = bag purchase cost
Alternative Light Bulbs	Assess the energy consumption and greenhouse gas emissions over the lifetimes of the two alternatives light bulbs: 13 W compact fluorescent bulb, 60 W incandescent bulb.	cost = bulb manufacturing + electric operation cost
Alternative Washing Machines	Assess the energy consumption and greenhouse gas emissions over the lifetimes of two alternative washing machines: standard machine, eco-friendly machine.	cost = purchase + electric operation + water cost
2002 Ford Taurus LX	Perform: economic, energy, and environmental impact analysis of the stages of the life cycle for 2002 Ford Taurus LX (typical midsize domestic spark-ignition port-fuel-injection automobile). The analysis is to consider the automobile manufacturing, over the vehicle lifetime purchase of fuel, maintenance and service, and fixed costs (insurance).	cost = manufacturing + petroleum refining + maintenance + repair + insurance cost
Steel vs. Plastic Fuel Tank Systems	Compare the life cycle energy and environmental performance of steel and plastic automobile fuel tank systems: traditional steel fuel tank system on the Chevrolet 1996 GMT 600 vehicle line of vans with HDPE plastic tank system that General Motors uses on select models.	cost = input to manufacturing + tank manufacturing steps + use phase
Mid-Size Passenger Vehicle vs. Tramway (City of Graz)	LCA of a passenger vehicle transportation is compared to the tram in the city of Graz, Austria, based on their overall cost, energy consumption and greenhouse gas emissions	for tram: cost = tram cost + rail cost + elec. cost + maint. cost

Case Study 1: Steel versus Plastic Automobile Fuel Tanks

The following is a typical case study the students in the sustainability elective course worked on using the online EIO-LCA model by Carnegie Mellon University of the U.S. economy. In this particular case, students analyzed the life cycle energy and environmental performance of steel and plastic automobile fuel tank systems. A traditional steel fuel tank on the Chevrolet 1996 GMT 600 vehicle line of vans was compared with the high-density polyethylene (HDPE) plastic fuel tank introduced by General Motors on select models. Figures 1a and 1b show the steel and HDPE fuel tanks.

Figure 1a. *Steel Fuel Tank (31 Gallons, 21.92 kg Empty Mass)*

Figure 1b. *HDPE Fuel Tank (34.5 Gallons, 14.07 kg Empty Mass)*

Two life phases of the automobile fuel tank system were analyzed in the EIO-LCA study: the manufacturing and the use phases of the fuel tank (shown in Figure 2). Tables 3a and 3b show the different input to the manufacturing and the use phases of the steel and plastic fuel tanks. The figures also identify the sectors of the 1997 U.S. economy associated with these inputs. The input value in U.S. dollars to each EIO sector is the demand from that particular sector of the economy.

Figure 2. *Automobile Fuel Tank Manufacturing and Use Life Phases*

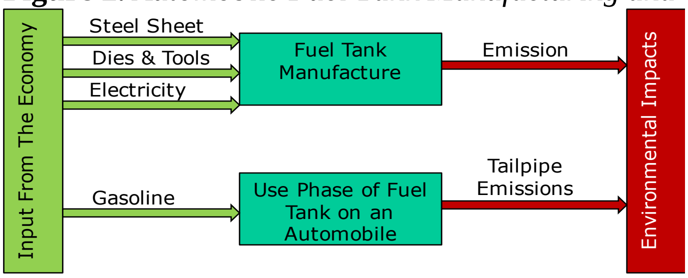


Table 3a. *EIO Sectors for the Manufacturing and Use Phases for the Steel Fuel Tank*

INPUT	EIO SECTOR	INPUT VALUE/TANK ($)
Steel Tank Manufacturing		
Carbon steel sheet	Blast furnaces & steel mill products	27.18
HDPE shield material	Plastics & resins	2.46
Stamping, trimming dies	Dies, tools, & machine accessories	3.75
Transportation of finished tanks	Motor freight transportation	1.32
Electricity	Electric utilities	1.06
Transportation of raw materials	Railroad transportation	0.31
Galvanizing & coating	Plating & polishing services	0.32
Natural gas for boilers	Gas distribution	0.22
Packing materials	Paper & paper board containers	0.21
Paints	Paints & allied products	0.16
Bearings & other repairs	Ball & roller bearings	0.14
Detergents for washing tanks	Soaps & detergents	0.02
Lubricants & coolants	Lubricants & greases	0.02
Steel Tank Use Phase		
Gasoline	Petroleum refining	16.63

Table 3b. *EIO Sectors for the Manufacturing and Use Phases for the HDPE Fuel Tank*

INPUT	EIO SECTOR	INPUT VALUE/TANK ($)
HDPE Tank Manufacturing		
HDPE, PVC, EVOH	Plastics and resins	9.62
Steel straps & shield	Automotive stampings	4.00
Electricity	Electric utilities	1.71
Glycol & other supplies	Industrial org. & inorg. chemicals	1.31
Natural gas	Gas distribution	0.22
Packing materials	Paper & paper board containers	0.87
Molder spare parts	Special industry machinery parts	0.31
Carbon black	Carbon black	0.14
Adhesive layer material	Adhesives & sealants	0.21
HDPE Use Phase		
Gasoline	Petroleum refining	10.67

Energy and environmental burdens associated with the economic demand from the input to the manufacturing and use sectors are calculated using the EIO-LCA model. The results are shown in Tables 4a and 4b for the fuel tanks.

Table 4a. *Energy and Environmental Burdens Associated with Steel Tank Input to Manufacturing and Use Phases*

EIO SECTOR	INPUT VALUE/ TANK ($)	ELEC. USED (KWH)	ENERGY CONSUMED (MJ)	GREENHOUSE GAS EMISSION, $CO_{2,E}$ (KG)	TOTAL TOXIC RELEASES (G)
Input to Steel Tank Manufacturing		***42.15***	***980.94***	***90.13***	***143.87***
Blast furnaces & steel mill products (#331111)	27.18	37.51	818.12	74.75	132.09
Plastics & resins (#325211)	2.46	2.21	55.84	4.08	5.54
Dies, tools, & machine accessories (#333514)	3.75	1.36	21.60	1.85	3.33
Motor freight transportation (#484121)	1.32	0.24	22.18	2.80	0.33
Electric utilities (S00202)	1.06	0.14	42.29	4.88	0.17
Railroad transportation (#48211)	0.31	0.05	5.49	0.35	0.11
Plating & polishing services (#332813)	0.32	0.21	3.87	0.30	1.19
Gas distribution (#221210)	0.22	0.09	3.04	0.49	0.07
Paper & paper board containers (#32221)	0.21	0.15	3.32	0.25	0.28
Paints & allied products (#325510)	0.16	0.09	2.59	0.19	0.59
Ball & roller bearings (#332991)	0.14	0.08	1.15	0.09	0.13
Soaps & detergents (#325611)	0.02	0.01	0.22	0.02	0.02
Lubricants & greases (#324191)	0.02	0.01	1.23	0.08	0.02
Input to Steel Tank Use Phase		***11.87***	***409.10***	***36.59***	***13.29***
Petroleum refining (#324110)	16.63	11.87	409.10	36.59	13.29

Table 4b. *Energy and Environmental Burdens Associated with HDPE Tank Input to Manufacturing and Use Phases*

EIO Sector	Input Value/ Tank ($)	Elec. Used (kWh)	Energy Consumed (MJ)	Greenhouse Gas Emission, $CO_{2,E}$ (kg)	Total Toxic Releases (g)
Input to HDPE Tank Manufacturing		***13.47***	***371.67***	***30.41***	***33.92***
Plastics and resins (#325211)	9.62	8.65	218.37	15.97	21.65
Automotive stampings (333513)	4.00	1.32	24.24	1.95	3.39
Electric utilities (S00202)	1.71	0.22	68.23	7.87	0.28
Industrial organic (#325199) & inorganic (#325188) Chemicals	1.31	2.19	37.86	2.62	6.73
Gas distribution (#221210)	0.22	0.09	3.04	0.49	0.07
Paper & paper board containers (#32221)	0.87	0.64	13.75	1.04	1.17
Special industry machinery parts (#333514)	0.31	0.11	1.79	0.15	0.28
Carbon black (#335991)	0.14	0.13	1.74	0.12	0.10
Adhesives (#325520) & sealants (#339991)	0.21	0.12	2.65	0.20	0.25
Input to HDPE Use Phase		***7.62***	***262.48***	***23.47***	***8.53***
Petroleum refining (#324110)	10.67	7.62	262.48	23.47	8.53

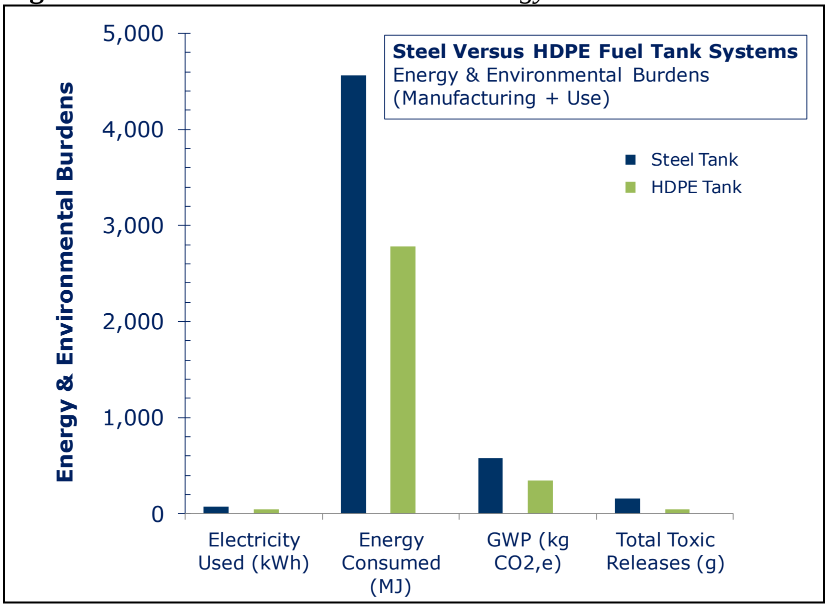
The energy requirements for the tanks manufacturing processes were based on the estimates provided by Sullivan et al. (2010) and Ashby (2013). For a steel tank, the major processes are stamping (5.1 MJ/kg), gas welding (1.9 MJ/m), electric welding (2.6 MJ/m), and machining (2.0 MJ/kg). For HDPE tank, the major processes are blow molding (19.7 MJ/kg) and extrusion (7.0 MJ/kg). The environmental burdens of the tanks manufacturing processes, the contribution of the fuel tank system to the vehicle fuel consumption (i.e. its use), and the contribution of the fuel tank to the total vehicle air emissions (direct function of the total fuel consumption allocated to the tank) were estimated based on correlations provided by Keoleian et al. (1998).

Summarizing the energy and environmental burdens associated with the following life phases of the fuel tanks: input to the manufacturing sector, input to the use phase, manufacturing phase, and use phase, the results can be seen in both Table 5 and Figure 3. Compared to a steel tank, HDPE fuel tank reduces the electricity demand, consumed energy, and global warming potential (GWP) by approximately 40% for the above listed life phases, and the total toxic releases by about 73%.

Table 5. *Steel and HDPE Fuel Tanks Energy and Environmental Burdens*

Fuel Tank System	Electricity Used (kWh)	Energy Consumed (MJ)	GWP/Green-house $CO_{2,e}$ (kg)	Total Toxic Releases (g)
Input to Manufacturing				
Steel Tank	42.2	980.9	90.1	143.9
HDPE Tank	13.5	371.7	30.4	33.9
Input to Use Phase				
Steel Tank	11.9	409.1	36.6	13.3
HDPE Tank	7.6	262.5	23.5	8.5
Manufacturing Phase				
Steel Tank	18.0	74.0	4.0	0.3
HDPE Tank	23.0	160.0	4.0	0.5
Use Phase				
Steel Tank	---	3,101.0	449.0	---
HDPE Tank	---	1,988.0	289.0	---
Total (Manufacturing + Use)				
Steel Tank	**72.1**	**4,565.0**	**579.7**	**157.5**
HDPE Tank	**44.1**	**2,782.2**	**346.9**	**42.9**
HDPE/Steel (Reduction)	**39%**	**39%**	**40%**	**73%**

Figure 3. *Steel and HDPE Fuel Tanks Energy and Environmental Burdens*



Case Study 2: Tramways versus Automobiles

In this project, students performed life cycle assessment study on the tramway transportation system for the city of Graz, Austria and compared that to automobile transportation based on their overall cost, energy consumption and carbon footprint on the environment. The analysis focused on a single tram (manufacturer: Stadler, Figure 4a) with its riders replace it with passenger vehicles for city commuting. The car of choice selected was Volkswagen Golf (Figure 4b). It was estimated that approximately 3,289 passengers in Graz will ride on a single tram every day. The life span of the Stadler tram was estimated to be 50 years, and of that of the Volkswagen Golf to be 16.1 years. The analysis then encompassed 50 years' worth of cars (roughly 10,214 cars) and car related expenses. The analysis assumed the vehicles market price did not change over the 50 years period.

Figure 4a. Graz Stadler Tram

Figure 4b. *Volkswagen Golf*

Table 6 shows the tram specifications in addition to its cost and its other related expenses such as the cost associated with the railway length for the tram line, the cost of the electric power usage for the operation of the tram, and the tram maintenance expenses (Railway Gazette, 2007; https://melbpt.wordpress.com; www.stadlerrail.com). Table 7 shows the vehicle specifications for the Volkswagen Golf along with its cost and its estimated operation expenses such as its fuel usage and cost, maintenance, and insurance expenses (https://volkswagen.com.au; www.insurance-austria.at).

Table 6. *Tram Specifications*

Specification	Value
Tram cost	2.16 €m
Tram lifespan	50 years
Rail cost	12.7 €m/km
Energy usage	0.211 kWh/km
Avg. distance travelled per rider	11.7 km/day
No. Of riders	3,289 people/day
Cost of track	12.7 €m/km
Electricity cost	0.211 €/kWh
Electricity usage	1.84 kWh/km
Maintenance cost	0.9 €m/yr

Table 7. *Golf Specifications*

Specifications	Value
Car cost	16,990 €
Car lifespan	16.1 yrs
Fuel mileage	10.5 km/L
Curb weight	1,316 kg
Avg. distance driven per person per day	11.7 km/day
Fuel cost	~1.0 €/L
% of fuel cost that is tax	~60%
Maintenance cost	~600 €/yr
Insurance cost	~1,620 €/yr

The study was conducted using the EIO-LCA online model by Carnegie Mellon University for the 1995 German economy. Since the model uses the Marks currency for Germany that existed during that time, all expenditures were converted from the Euro currency to the Marks currency using a fixed currency conversion rate of 1.9558 Marks per Euro. The current costs were adjusted by an inflation rate of 134% from current prices to the 1995 German economy prices (https://www.statbureau.org).

Figure 5 shows a breakdown summary of the greenhouse emissions associated with different processes for a single tramway over a 50-year lifetime period and for 3,289 daily riders, while Figure 6 shows the greenhouse emissions associated with the use of 10,214 Volkswagen Golfs by the same number of daily riders over the 50-year period instead of using the tram system. The results show the total carbon footprint from a single tram over the 50-year period is 47,971 metric tons of equivalent CO_2, while that associated with 10,214 Volkswagen Golfs is 201,853 metric tons of equivalent CO_2. Based on this study, the tram is show to decrease the carbon emissions by approximately 76%.

Figure 5. *Greenhouse Gas Summary for a Single Tram over a 50-year Period*

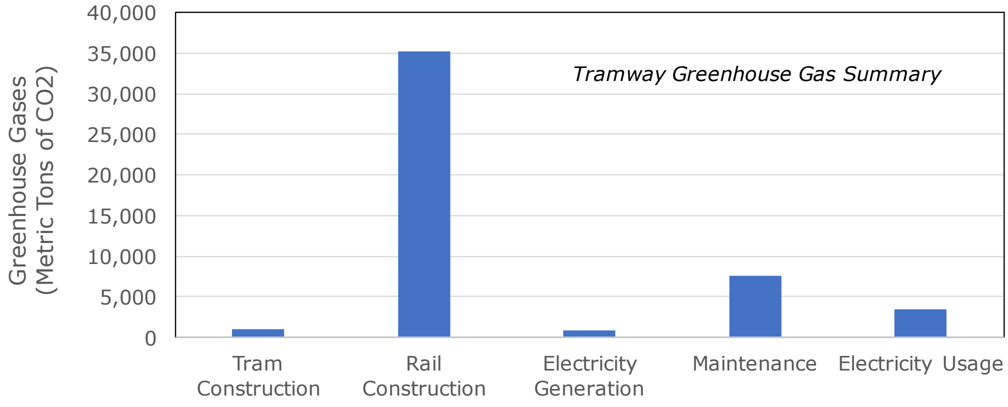
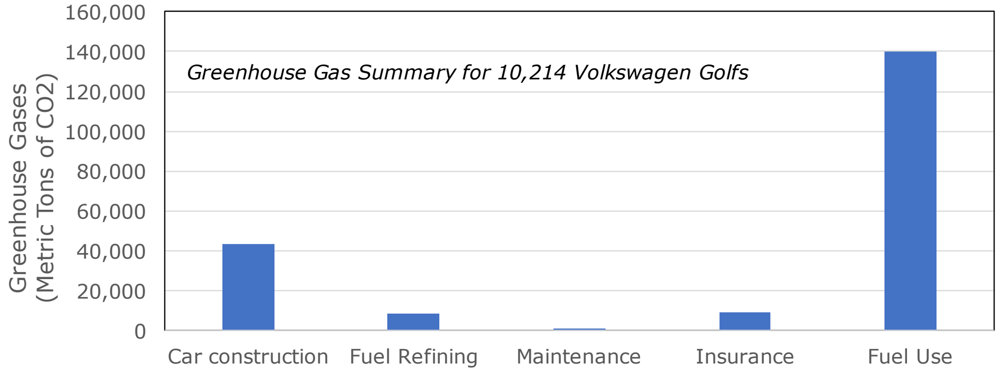


Figure 6. *Greenhouse Gas Summary for a 10,214 Volkswagen Golfs over a 50-Year Period*



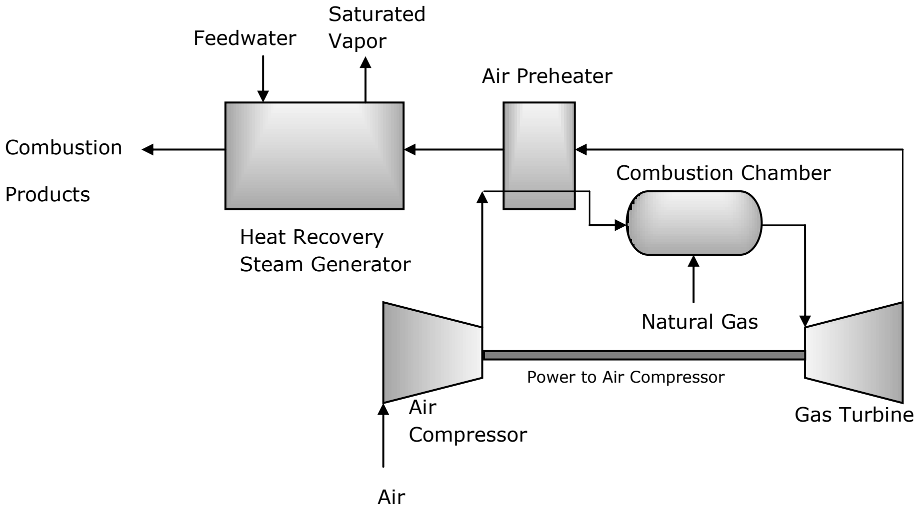
Exergy as a Sustainability Measure

Exergy is defined as the maximum useful work potential attainable from an energy conversion system as the system is brought into thermal equilibrium with the environment it is interacting with. Unlike energy, exergy can be destroyed due to the irreversibilities present in the system. Because of that, energy analysis which is based on the first law of thermodynamics, is unable of identifying the quality of various forms of energy. However, exergy analysis is capable of quantifying the types, magnitudes of wastes, destructions and losses of energy in a system (Bejan et al., 1996). Exergoeconomics consists of an exergy analysis, economics analysis, and an exergoeconomic evaluation (Bakshi et al., 2012). Exergoeconomics identifies the location, magnitude, causes and costs of thermodynamic inefficiencies such as exergy destruction and exergy loss in a system. Because exergoeconomics is conducted at the component level, it identifies the relative cost importance of each component.

Case Study 3: Gas Turbine Cogeneration System

In the thermal-fluid design course, students conduct exergy and exergoeconomics analyses on major thermodynamic cycles such as the system shown in Figure 7. The depicted system is a gas turbine cogeneration cycle.

Figure 7. *Gas Turbine Cogeneration System*



For the case of a net output power demand of 30 MW, compression ratio of 10, air preheat temperature of 850 K, combustion temperature of 1520 K, feed water mass flow rate of 14 kg/s at 20 bars pressure, and turbine and compressor isentropic efficiency of 86%, the exergy destruction and exergy losses associated with the various system components are then calculated. The results are shown in Table 8. The results indicate that the combustion chamber and the heat recovery steam generator have the highest exergy destruction and lowest exergetic efficiencies. According to these results, the efforts to improve the thermodynamic efficiency of the cycle rest on these components.

Table 8. *Exergetic Analysis for the Gas Turbine Cogeneration Cycle*

Order of Concern	System Component, k	Exergy Loss, $\dot{E}_L$ (MW)	Exergy Destruction, $\dot{E}_D$ (MW)	Exergy Destruction Percentile (%)	Exergetic Efficiency, ϵ_k (%)
1	Combustion Chamber		25.3	64.3	80.1
2	Heat Recovery Steam Generator		6.2	15.8	67.3
3	Gas Turbine		3.0	7.7	95.2
4	Air Pre-Heater		2.6	6.6	84.8
5	Air Compressor		2.2	5.6	92.6
6	Flue Gas	2.81			
	Overall System	2.81	39.3	100	50.4

In order to identify the costs associated with the thermodynamic inefficiencies, the cycle needs to be analyzed from exergoeconomics point of view as well. Table 9 summarizes the results of the exergoeconomics analysis of the cogeneration cycle. The combustion chamber, gas turbine, and air compressor are shown to have the highest values for the combination of investment and exergy destruction cost rates. Therefore, they are the most system components to consider from a thermo-economics point of view. The low value of exergoecomonic factor for the combustion chamber shows the costs associated with the combustion chamber are almost due to exergy destruction. This exergy destruction can be reduced by: preheating the reactants, reducing the heat loss, and reducing the excess air. Excess air can be reduced by increasing the combustion products temperature at the inlet of the turbine. However, this will cause an increase in the capital investment cost for the turbine. Since the gas turbine already has the second highest combination of investment and exergy destruction cost rates, this option is not feasible. Its capital investment cost can be reduced by reducing the pressure ratio or its isentropic efficiency. Since the air compressor has the highest exergoeconomic factor value, and the second highest relative cost difference, the cost effectiveness of the entire system could also be improved by decreasing the air compressor investment cost. This is achieved by decreasing the compressor pressure ratio or its isentropic efficiency. The final conclusion on where the modifications in the cycle can be made in order to improve its performance from a thermo-economics point of view then lies with a single or combination of decisions: increasing the air preheat temperature to the combustion chamber, decreasing the pressures and isentropic efficiencies in the gas turbine and air compressor.

Table 9. *Exergoeconomics Analysis for the Gas Turbine Cogeneration Cycle*

System Component	Investment Cost Rate, $\dot{Z}_k$($/h)	Exergy Destruction Cost Rate, $\dot{C}_{D,k}$ ($/h)	$\dot{Z}_k + \dot{C}_{D,k}$ ($/h)	Cost per Unit of Exergy for Fuel, $c_{F,k}$ ($/GJ)	Cost per Unit of Exergy for Product, $c_{P,k}$ ($/GJ)	Relative Cost Difference, $r_k = \frac{c_{P,k}-c_{F,k}}{c_{F,k}}$	Exergoeconomic Factor $f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}}$
Combustion Chamber	68.0	1,045.0	1,113.0	11.5	14.5	26.5	6.1
Gas Turbine	754.0	159.0	913.0	14.5	19.7	29.3	82.6
Air Compressor	753.5	147.7	901.2	18.8	27.9	48.5	83.6
Heat Recovery Steam Generator	264.2	323.8	587.9	14.5	30.3	88.3	44.9
Air Pre-Heater	188.8	135.8	324.6	14.5	20.8	43.0	58.2

Students Feedback

Two surveys were administered to two groups of mechanical engineering students at the senior level to assess the impact these courses have on students' interest and understanding of sustainability in engineering. One of the groups consisted of students who were taking one or both sustainability courses, while the other group consisted of students who had not taken any of those courses yet. The first survey was administered one month after the start of the 2016 fall semester, while the second survey was administered at the end of the semester.

Students Questions on Survey No. 1

The questions students were asked in *Survey No. 1* were the following:
Q1: What is sustainability?
Q2: How do you design for sustainability?
Q3: How do products make environmental impact?
Q4: What factors are used to measure environmental impact?

Students Questions on Survey No. 2

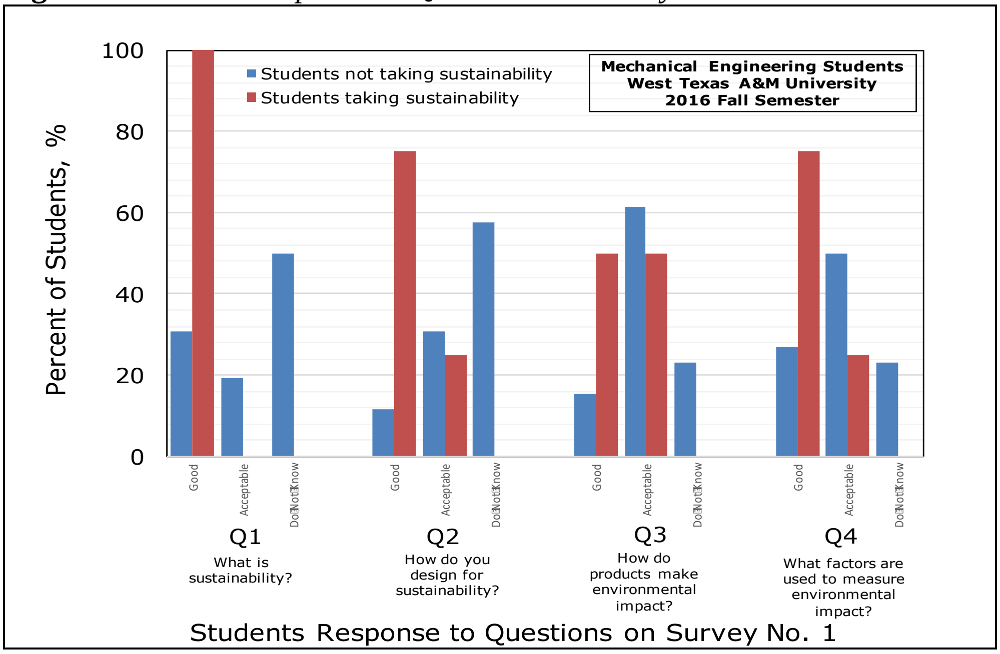
In *Survey No. 2*, students were asked to reflect on the following:

Q1: Participating in the sustainability modules helped me learn about sustainable design.
Q2: Engineering department at West Texas A&M University should provide more opportunities for students to discuss sustainability topics.
Q3: I will strive to engage in sustainable design as a practicing engineer.
Q4: Human destruction of the natural environment has been greatly exaggerated.

Assessment of Students Feedback on Survey No. 1

Figure 8 shows the students response to questions asked on *Survey No. 1*. For students who have not taken either course, approximately 30% of them were able to define sustainability very clearly, only 12% of the students had good understanding of how to design for sustainability, 15% had a strong grasp of the environmental impact associated with the life cycle of a product, and 26% could very clearly identify factors to measure the environmental impact. For students with one month of exposure to either or both courses, the survey showed the entire group had good understanding of sustainability, 75% had very clear idea on how to design for sustainability, 50% had a strong grasp of how products make environmental impact, and 75% were able to distinctly pinpoint factors that measure environmental impact. It is clearly evident the positive impact these two courses had on the students increased level of understanding of sustainability and its application in engineering.

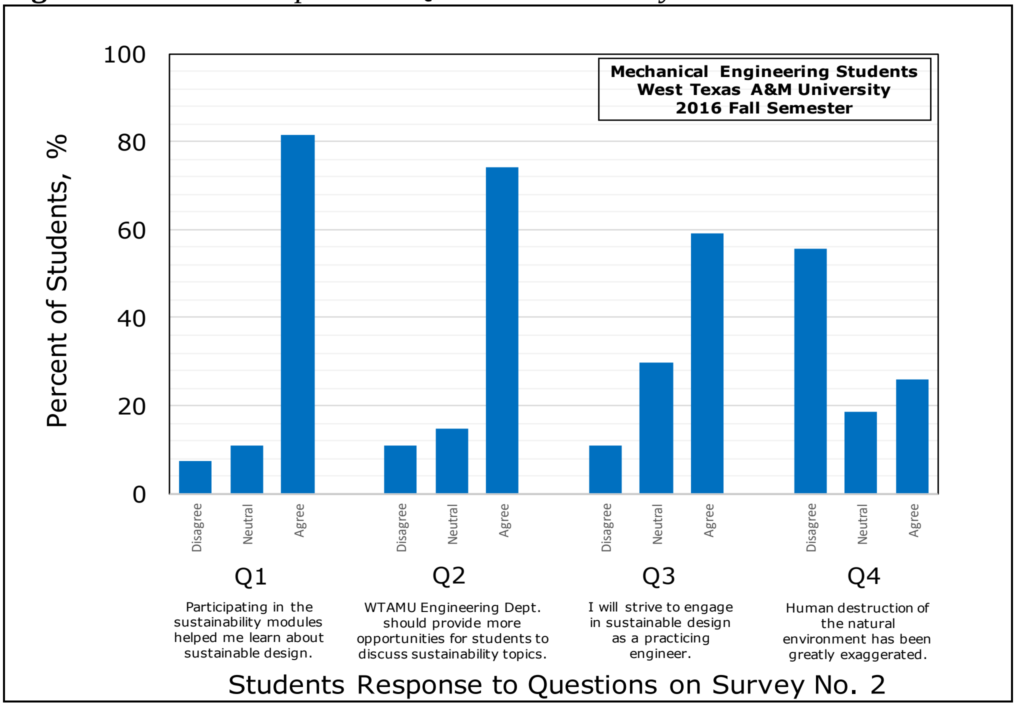
Figure 8. *Students Response to Questions on Survey no. 1*



Assessment of Students Feedback on Survey No. 2

Students response to questions on *Survey No. 2* are shown in Figure 9. It was interesting to find out at the end of the semester that over 80% of the surveyed students agreed that participating in the sustainability modules helped them learn about sustainable design. Also, approximately 74% of them wanted the engineering department at West Texas A&M University to provide more opportunities for the students to discuss sustainability topics during their 4-years academic program. However, when asked about who will strive to engage in sustainable design as a practicing engineer (Q3), only 59% of the students promised to do so, while 30% stayed neutral in their answer. Their reflection on the statement that human destruction of the natural environment has been greatly exaggerated (Q4), 26% of the students agreed with that and 19% stayed neutral. It should be noted that the students' response to question 3 was a bit surprising to the author. The author has thought that a much higher percentage of his students would strive to engage in sustainable design as practicing engineers especially after they have spent more than half a semester participating in the sustainability modules. It is possible that the difficulty the students experienced in understanding Exergoeconomics and in applying EIO-LCA to complex systems at the undergraduate level may have contributed to this. Apparently, more sustainability teaching modules have to be developed in future and offered in a larger variety of engineering courses at different academic levels to introduce the students to these news concepts. Since this pedagogical development is still at a very early stage, future assessment data still need to be gathered and analyzed.

Figure 9. *Students Response to Questions on Survey no. 2*



Conclusions

With the overcrowded mechanical engineering curriculum at West Texas A&M University, it was possible to introduce sustainability coursework material through the offering of an elective course and through the integration of sustainability teaching material with the original material of a core mechanical engineering course. The elective course focused primarily on the eco-aspects of materials in engineering design and on conducting economic input-output life cycle assessment studies through the use of the online U.S. economy models provided by the Green Design Institute at Carnegie Mellon University. The sustainability material that was interwoven into the core course focused on introducing exergoeconomic studies in the thermal-fluid design course. Student learning outcome was evaluated one month into the courses and also upon the completion of the courses. One month into the courses, the results of the first survey showed a sufficiently large number of students had gained considerable knowledge of what sustainability is and how to design for sustainability compared to students who had not taken either course. The results of the second survey showed the sustainability teaching modules had a positive impact on the overwhelming majority of the students who also wanted the engineering department to provide more opportunities for them to discuss sustainability topics. Their responses showed a mature understanding to the importance of incorporating sustainability considerations during the design phase of a project. However, when asked about who will strive to engage in sustainable design as a practicing engineer, an anemic 59% of the students promised to do so. Such a percentage was a bit surprising to the author. However, it also shows that more work needs to be done on sustainability developments and on incorporating sustainability teaching modules in a larger variety of engineering courses not only at the senior level but at different academic levels.

References

Abdul-Wahab, S. A., Abdulraheem, M. Y and Hutchinson, M. 2003. The Need for Inclusion of Environmental Education in Undergraduate Engineering Curricula. *Int. J. Sustain. High. Educ*. 4, 2, 126-137.

"About ABET". ABET. Retrieved 07-03-2017. (Website Address: www.abet.org/about-abet).

ABET Engineering Accreditation Commission. 2015. Criteria for Engineering Programs: Effective for Evaluation during the 2016-2017 Accreditation Cycle. (Website Address: www.abet.org).

Arrow, K., Dasgupta, P., Goulder, L., Daily, G., Ehrlich, P., Heal, G., Levin, S., Maler, K., Schneider, S., Starrett, D., and Walker, B. 2004. Are we consuming too much? *J. Econ. Perspect*. 18, 3, 147-172.

Ashby, M. F. 2013. Materials and the Environment. Second Edition, Elsevier.

Bakshi, B. R., Gutowski, T. G., Sekulic, D. P. 2012. Thermodynamics and the Destruction of Resources. Cambridge University Press.

Bejan, A., Tsatsaronis, G. and Moran, M. 1996. Thermal Design and Optimization. John Wiley and Sons.

Car Insurance in Austria. Retrieved 10-01-2016. (Website Address: www.insurance-austria.at/car-insurance-austria)

Ceulemans, K. and De Prins, M. 2010. Teacher's Manual and Method for SD Integration in Curricula. *J. Clean. Prod*. 18, 7, 645-651.

Germany Inflation Calculators. Retrieved 10-01-2016. (Website Address: https://www.statbureau.org/en/germany/inflation-calculators).

"Graz Tenders Follow Trams". Nov. 5, 2007. *Railway Gazette*. Retrieved 10-01-2016. (Website Address: http://bit.ly/2thKQJh).

Kamp, L. 2006. Engineering Education in Sustainable Development at Delft University of Technology. *J. Clean. Prod*. 14, 928-931.

Keoleian, A., Spatari, S. and Beal, R. 1998. Life Cycle Design of a Fuel Tank System. General Motors Demonstration Project, EPA 600/R-97-118.

Leontief, W. 1936. Quantitative Input and Output Relations in the Economic System of the United States. *Rev. Econ. Stat*. 18, 3, 105-125.

"Low-Floor Tramway, Type Variobahn for the Graz AG, Austria". Retrieved 10-01-2016. (Website Address: www.stadlerrail.com).

Lozano, R. 2006. A Tool for a Graphical Assessment of Sustainability in Universities. *J. Clean. Prod*. 14, 963-972.

Lozano, F. J. and Lozano, R. 2014. Developing the Curriculum for a New Bachelor's Degree in Engineering for Sustainable Development. *J. Clean. Prod*.64, 136-146.

Mintz, K. and Tal, T. 2014. Sustainability in Higher Education Courses: Multiple Learning Outcomes. *Stud. Educ. Eval*. 41, 113-123.

Paudel, A. M., and Fraser, J. M. 2013. Teaching Sustainability in an Engineering Graphics Class with Solid Modeling Tool. *120th ASEE Annu. Conf. Expos.*, Atlanta.

Sullivan, J. L., Burnham, A. and Wang, M. 2010. Energy Consumption and Carbon Emission Analysis of Vehicle and Component Manufacturing. Report no. ANL/ESD/10-6, Argonne National Laboratory.

Thomas, I. 2004. Sustainability in Tertiary Curricula: What is stopping it happening? *Int. J. Sustain.High. Educ*. 5, 1, 33-47.

"Tram Construction and Operating Costs". Melbourne Public Transport Blog. Retrieved 10-01-2016. (Website Address: https://melbpt.wordpress.com/tram-construction-costs/).

Volkswagen New Golf. Retrieved 10-01-2016. (Website Address: http://bit.ly/2sTnbz9).

Von Blottnitz, H., Case, J. M. and Fraser, D. M. 2015. Sustainable Development at the Core of Undergraduate Engineering Curriculum Reform: A New Introductory Course in Chemical Engineering. *J. Clean. Prod*. 106, 300-307.

Watson, M. K., Lozano, R., Noyes, C. and Rodgers, M. 2013. Assessing Curricula Contribution to Sustainability more Holistically: Experiences from the Integration of Curricula Assessment and Students' Perceptions at the Georgia Institute of Technology. *J. Clean. Prod*. 61, 106-116.