86. Sustainability Integrated throughout Rowan's Chemical Engineering Curriculum

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Abstract

This paper summarizes the pedagogical activities and course work in the area of sustainability in the Chemical Engineering Department at Rowan University. Rowan Engineering features a unique sequence of eight semesters of project-based learning. These "clinic" courses are required for all engineering majors and constitute the hallmark of Rowan's engineering programs. Students are engaged in experiential and PBL from freshman to senior year. The Chemical Engineering Program has successfully implemented a series of modules that gradually introduces students to sustainable design. In the first year, they learn about life cycle assessment (LCA) through the comparison of the carbon footprint in the production and use of diesel fuels: petroleum diesel, biodiesel from new vegetable oil, and biodiesel from waste vegetable oil. Students produce their own biodiesel from these different raw materials, and then they test the final product in a generator and measure actual emissions and use those emissions in the final calculations of the cradle-to-gate LCA. During sophomore year students are introduced to the basic steps of microalgae production for the manufacturing of biodiesel. Student-teams run small photo-bioreactors in the laboratory during this semester-long project. They study growth factors such as nutrients and light availability, light intensity, CO_2 transport, and agitation. In the junior and senior year, students are teamed-up in clinic project that are usually externally-funded through government grants and industrial partnerships. For almost ten years now, juniors and seniors have been working in real-life projects related to the sustainable design of active pharmaceutical ingredients using tools such as ASPEN Plus®, SimaPro®, and Ecosolvent®. The projects vary in nature and complexity, from comparing the LCA of different manufacturing routes of an API to the designing of the optimal organic solvent recovery system for a particular production route. Formal assessment of the freshman engineering student has been conducted, and data show a significant increase in conceptual understanding of the steps in life cycle assessment and an average gain of over 55% in overall knowledge of this tool. Junior and Senior Engineering clinic projects provide industry with guidance and solutions based on the best sustainable process design strategies, and students benefit from the close interaction with industrial mentors.

1 Introduction

The Chemical Engineering Department at Rowan University is committed to deliver first class undergraduate engineering education. The "hands-on," "minds-on" curricular approach has proven highly effective in producing quality engineers.

Safety and sustainability are key topics and are fully integrated in traditional courses (Slater & Hesketh, 2004, Slater *et al*., 2007) as well as in Rowan's engineering clinics. The eight-semester sequence of clinics provides students with a wide range of experiential learning where green engineering topics, sustainability, and life cycle understanding are incorporated. Life cycle thinking and the use of assessment tools are important elements in the preparation of future chemical engineers.

In the last decade, alternative liquid fuels such as biodiesel and bioethanol have received significant attention as scientists and engineers seek out renewable and nontoxic replacements to petroleum-based transportation fuels (Balat, 2010, Varanda, 2011). One of the key elements of the ongoing discussion centers on the energy required to produce these fuels and their cradle-to-grave carbon footprint. With this idea in mind, a freshman engineering clinic has been designed to introduce students to the manufacturing of biodiesel and LCA. This semester-long project provides students with an understanding of the manufacturing steps, the desired product specifications, and it concludes with quality and performance testing (Farrell & Cavanagh, 2013). Additionally, students learn how to perform life cycle assessment calculations for their own produced biodiesel and to compare the LCA with published data for commercial biodiesel.

Freshman Clinic is a two-semester introductory course that focuses on multidisciplinary education through collaborative teamwork in the laboratory and in the classroom. Students are also introduced to state-of-the-art equipment and software tools commonly used by practicing engineers. This two-credit course meets twice per week: the first meeting is one 50-minute class that is followed by one 3-hour laboratory meeting later in the week. Several publications offer more details and insight on this course (Farrell *et al*., 2005, 2004, 2002, Slater *et al*., 2005).

During the second year of the engineering clinic sequence, students are introduced to the production of algae-derived biofuels. This laboratory project allows students to learn the fundamental of bio derived oils from algae and crop plants, required nutrients and growth efficiencies, carbon dioxide mitigation, and the use of inexpensive industrial and municipal waste streams such as flue gas and wastewater. Additionally, students gain an understanding of resources use and the importance of producing biodiesel from raw materials other than food sources. In the laboratory, students explore the use of different algae species, the optimal growth conditions, and lipid productivity of said species. One of the main objectives of this semester-long project is to obtain an understanding of the optimization of algae growth as relates to an increase in lipid yield. Students test different high-lipid content algae species and make recommendations of species that could make algae-derived biodiesel an economically viable alternative to traditional fuels. This class is specially designed for engineering students as it integrates a traditional composition class with an engineering laboratory experience. The course is taught by a team of writing and engineering faculty. Students meet twice a week for 75-minutes lectures and once for a 150-min lab. The composition faculty teach technical writing and also critique student's laboratory reports. The second semester of sophomore engineering clinic emphasizes the development of oral communication skills, and it is taught by a team that includes public speaking faculty.

In the upper level curriculum, students participate in open-ended, real-life projects. The green engineering projects are typically funded by competitive grants from government agencies and/or from Rowan's industrial partners. These projects are multidisciplinary in nature and integrate junior and senior level engineering students; however, the project may also include chemistry and biology majors as needed to accomplish the objectives of the proposed problem. These projects provide a good example of the possible interactions between academia, industry, and government agencies to assist with regional and global needs in the area of sustainable engineering and manufacturing.

This paper summarizes the Junior and Senior Engineering Clinic projects that have focused on pollution prevention and sustainable design in pharmaceutical manufacturing. Rowan University is located in a geographical region that also houses a significant number of pharmaceutical companies, a fact that makes an imperative to prepare the next generation of engineers with the skill-set required by their future employers.

2 Methods and Implementation

The eight-semester engineering clinic sequence is part of the required courses in all of Rowan engineering programs. Junior and senior clinics are two-credit courses that meet twice a week for 150 minutes. These time slots allow for all engineering students to be available and work together. In addition, once a week the student teams meet with their faculty advisor to review the task completed and to set up action items for the incoming work week. At the beginning of each semester, faculty present the selection of projects to be staffed. Students are given the opportunity to select up to three projects and rank them in order of their interest. Then, students are placed into projects based on their indicated preference and possible prior experience. Faculty meet and advise the teams on a regular basis; these meeting may include the industrial liaison, depending on the company's preference. It is also possible that the nature of the project may require more than one faculty member to provide with adequate professional expertise.

After the first week and once the clinic teams have been formed, students are presented with the problem statement, usually in a kickoff meeting lead by the industrial partner. In this meeting, the students learn about the engineering aspects of the project, the objectives to be completed in the allotted time, typically two semesters, and other pertinent information that helps the team establish a timeline of activities and deliverables.

The clinic team is then charged with writing the outcome of the meeting and the outline of the semester task along with a Gann chart, and a comprehensive literature search is initiated. This literature review provides the students with the opportunity to familiarize themselves with the pertinent search engines and research protocols.

Once they have completed and properly documented the literature search, students are expected to present the faculty advisor and the industrial liaison with a synopsis of the current state of the art in the area of interest, technology options, and feasible and sustainable design alternatives. This process could occur in writing through a short white paper, a formal oral presentation, or both. At this point, the industrial partner offers advice and insight on financial, geographical, or environmental business constrains, and regulations such as the U.S. Food & Drug Administration Current Good Manufacturing Practices (FDA cGMP).

Part of the pedagogical objectives of "clinic" is to improve written and oral communication skills; therefore, students are required to produce weekly meeting agendas and minutes, written mid-term progress and final reports, a final oral presentation in the fall semester, and a poster presentation in the spring semester. These presentations are intended for peers and faculty and may present limited content, leaving out any information that might be deemed as confidential by the industrial partner. Even though these presentations fulfil the courses requirement;

students are also expected to present their results to the industrial partner during semester breaks - at an R&D or manufacturing facility of the sponsoring company. Additionally, students are also encouraged to present at conferences of professional societies such as the American Chemical Society and the American Institute of Chemical Engineers.

During the early stages of the project, the student teams are introduced to concepts of life cycle assessment and to the software that the University currently licenses, SimaPro® 7.3 (PRé Consultants, Amersfoort, Netherlands) and EcoSolvent® (Safety and Environmental Group, Zurich, Switzerland). First and through complete material and energy balances, students determine and quantify raw materials, energy types and sources (steam, liquid fuel, electricity, etc), and waste streams. Then, they create life cycle inventories for all materials and energy sources using SimaPro®, and waste disposal emissions are estimated using EcoSolvent®. Finally, the team calculates the carbon footprint or environmental impact of the modified or alternative route for the API manufacturing process. They perform this analysis for the complete life cycle as shown in Figure 1.

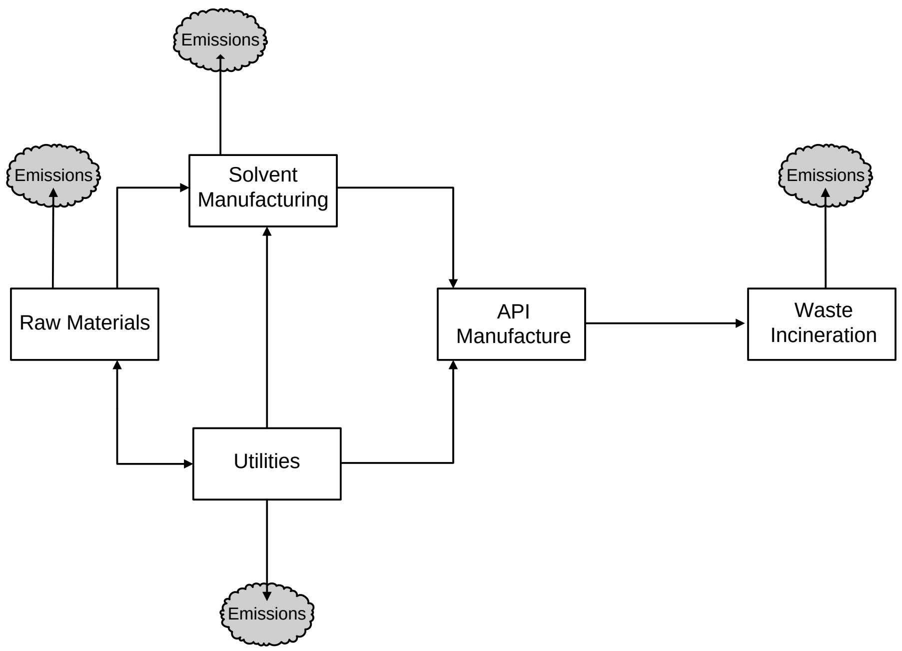

Figure 1: Emissions sources in the life cycle of solvent used in pharmaceutical manufacturing (Adapted from Slater and Savelski, 2009).

At the final oral presentation, students introduce the proposed green alternative solution(s) to the problem or design. They explain the calculated environmental impact of the anticipated solution and, in cases where the process already exists, how the proposed alternative compares to the existing company "base case." The student team presents a comprehensive LCA of all alternative processes and an assessment for the base case; the team also uses the LCAs to examine and rank the alternative routes and to present the industrial partner with more sustainable options. In most cases, the life cycle analysis of the manufacturing processes are performed on a "cradle" to "grave" format, and they are accompanied by an in-depth cost analysis that also guides the decision making process.

3 Results and Discussion

For almost a decade now, our research team has been engaged in projects with pharmaceutical companies. These projects have mostly centered on organic solvent reduction strategies in the production of active pharmaceutical ingredients (APIs) because pharmaceutical manufacturing has one of the largest waste generations in industry when measured as kg of waste per kg of API produced. This is quantified using the so called E-factor (Sheldon, 1997). Table 1 shows typical E-factors for different industrial sectors. Therefore, waste reductions through process optimization and solvent recovery strategies are paramount in reducing the carbon footprint and energy expenditures in pharmaceutical processes.

Table 1: Industrial E-factors, adapted from Sheldon (1997).

Industry segment	**Product tonnage**	**kg of waste/kg of product**
Oil refining	$10^5 – 10^8$	<0.1
Bulk chemicals	$10^4 – 10^6$	<1-5
Fine chemicals	$10^2 – 10^4$	5→50
Pharmaceuticals	$10 – 10^3$	25→100

A very enlightening way of assessing the overall impact of waste reduction is though comprehensive life cycle analysis of solvent use and disposal in API manufacturing (Slater & Savelski, 2007, Slater *et al.*, 2010, Raymond *et al.*, 2010).

In 2005, we have our first project with Bristol-Myers Squibb (New Brunswick, New Jersey). Since then, we have also had projects with Novartis (East Hanover, New Jersey), and Pfizer (Peapack, New Jersey; New York; Barceloneta, Puerto Rico; and Kalamazoo, Michigan). A brief description of some of these projects and their objectives and outcomes are described in the following section.

Our project with Bristol-Myers Squibb examined carbon footprint reduction alternatives by recovering tetrahydrofuran in the manufacturing of a new oncology drug. The proposed engineering solution took advantage of a hybrid pervaporation-constant volume distillation operation (Slater *et al.*, 2007, Taylor *et al.*, 2007).

The project with Novartis studied the use of a fixed bed adsorption process to reduce methanol and water usage in a Heck coupling reaction step in a drug synthesis (Slater *et al.*, 2008).

Several projects were sponsored by Pfizer. The first one investigated the use of traditional distillation followed by pervaporation to dehydrate isopropanol and possibly recycle and reuse the solvent. The spent solvent waste streams were being generated in the manufacturing of celecoxib, the API in Celebrex®, which is used to treat arthritis pain (Savelski, *et al.*, 2008a,b, Slater *et al.*, 2008).

A second project with Pfizer examined the recovery of acetone, acetonitrile, and toluene using a multi-purpose, stand-alone distillation system (Quigley, 2010). In all these projects, the carbon footprint of the green design alternatives were compared to the emissions generated if solvents were not recovered and instead incinerated. This work showed significant reductions in solvent use and green house emissions determined using life cycle assessment.

In summary, Rowan Engineering Junior/Senior Clinics offer undergraduate students with the unique opportunity to learn about sustainable engineering practices, to acquire professional skills using high profile software tools, understand the problems and constrains of an industrial sector, and to be involved in seeking sustainable design alternatives for pressing industrial environmental problems. The clinics rely heavily in strong partnerships between academia, industry, and government agencies like US EPA and FDA. In addition, sufficient funding and resources, as well as realistic goals and timelines achievable with undergraduate student teams, are key elements of the success of this model.

Finally, the projects should be able to be “mapped” to academic department goals and objectives, and accreditation needs. As an ABET-accredited engineering program in the United States of America, we find these projects as excellent vehicles to evaluate student outcomes in several of the criterion.

4 Conclusions

The Rowan University Engineering Clinic program provides eight consecutive semesters of project-based learning that serves as venue to introduce green chemistry and engineering as well as topics of sustainability in engineering design. Freshman and sophomore clinics are more structured courses, so they include formal instruction on topics like renewal fuels production and life cycle assessment. In junior and senior clinic, real-world projects present the students with challenging problems and real industrial needs as well as with the opportunity to learn advanced simulation tools and specialized software. Students also benefit from direct mentoring and interaction with the scientists and engineers of the industrial partner. In addition, the companies involved in our program benefit from the experience as the clinic teams provide recommendations that improve the carbon footprint of pharmaceutical syntheses by reducing solvent use. Our recommendations in the above mentioned projects resulted, upon implementation, in the reduction of 2.01×10^7 kg/yr emissions of which 1.81×10^7 kg/yr are of CO2 and save 7.56×10^6 USD/yr.

In conclusion, Rowan engineers are graduating students with knowledge in green engineering practices and tools and ready to apply them to an industrial setting. The College of Engineering and the Chemical Engineering Department are fulfilling the important mission of educating the next generation of engineers and preparing them to assist their future employers and community in creating sustainable economic growth and development.

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