Closing the Circularity Gap Via Engineering Education for Circularity with a Whole Systems and Biomimetic Perspective

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Abstract

As reported at the World Economic Forum in Davos, Switzerland in January of 2019 only 9% of the world is circular (defined as the annual percentage of materials that are returned to the system vs. discarded as waste). It is estimated that the 91% that is not circular contributes to over 60% of global greenhouse gas (GHG) emissions along with an estimated 8 million tons of waste entering our oceans each year.

Villanova's focus on circularity in engineering education includes three graduate level courses: Sustainable Materials and Design, Biomimicry (defined as engineering solutions inspired by nature), and Sustainable Supply Chain, along with industry and grant sponsored class projects, MS and PhD level research. Four key fundamental learning themes emphasized include a whole systems STEEP (social, technical, environmental, economic and political) perspective; assurance that the performance and cost benefits of the incumbent linear solutions are understood, quantified, and rivalled in the circular solution; engaging the right subject matter experts, cross disciplines and stake holders; and ensuring that the right metrics are in place for the final recommended more circular systems.

Specific examples in this paper will include highlight projects from the above mentioned courses, circularity focused industry-sponsored class projects, Master's level research developing a closed loop system for converting food waste to a hydrochar material that re-enters the system for energy and other higher value uses, and PhD research on renewably sourced polymers for aircraft composites.

The challenges we face to move towards the circular economy from our current linear economy are daunting. We believe, however, that through the described collaborative engineering educational learning experiences for today's future leaders we will be able to make a significant impact.

1 Introduction

1.1 Background

The need to close the circularity gap was clearly articulated in the second Circularity Gap Report (Wit *et al*., 2019) where at 9.1%, no significant progress had been made since the first report in 2018 (Wit *et al*., 2018). In fact, this report went on to conclude that it would not be possible to achieve the Paris Agreement goal of limiting global warming rise to 1.5 degrees Celsius from pre-Industrial levels without closing this gap. At the World Economic Forum in Davos, Switzerland, in January of 2019, there was a focus on how to reverse the trend and close the 91% circularity gap to stop the >60% of greenhouse gas (GHG) emissions and over 8 billion tons of plastic leaking into oceans. This resulted in several initiatives including eliminating electronic waste, stopping plastic pollution, and establishing a new system for reusing packaging (WORLD ECONOMIC FORUM, 2019). At Villanova, we challenged ourselves to ensure that our graduate program in Sustainable Engineering provided the education and tools needed for our students to do their part in closing this gap as future leaders for sustainable engineering solutions.

1.2 Approach

Develop the skills and capabilities needed to create more circular whole system solutions by analyzing both the benefits and issues with our current linear system and assessing and synthesizing more circular alternatives across a whole systems social, technical, environmental, economic and political (STEEP) perspective (Schmidt *et al.*, 2015) via curricula, company sponsored class projects and research (Lee, 2018). Specific examples in each of these areas will be described in the sections that follow. Pedagogic evidence for effectiveness has been provided by annual internal surveys that rate the elements in each area on a scale of 1 to 5 (5 highest). Scores for 2.1 and 2.2 consistently rank between 4 and 5 confirming their effectiveness and consistent with cited external examples of effectiveness. In sections 2.3 and 3, less rigorous assessments have confirmed effectiveness via student and company feedback of application to the circular economy.

2 Sustainable Engineering Graduate Courses that Drive Circularity

2.1 Course Title: **Sustainable Materials and Design**

2.11 Key Elements that Drive Circularity:

- **Individual Project Based Learning**: In this project based course, each student picks a material intensive area of livelihood that they are passionate about and would like to see an improvement in circularity and sustainability. Three individual projects, equally spaced throughout the semester and culminating in a 12 to 15 detailed and footnoted slide presentation, are then completed. The high internal survey rating for this area (section 1.2) is consistent with external reports (e.g. Blumenthal *et al*., 1991) that affirm the improved learning experience from individual projects that students have a keen interest and passion in.
- **Understanding the Functional Benefits of the Incumbent Materials**: The first section of the course focuses on the functional benefits and issues with existing materials. This is a key element that differentiates this approach to sustainable materials and circularity. Typically, courses focus first on the need and then on potential ways to achieve circularity (e.g. COURSERA, 2020) without a detailed analysis of the performance that must be achieved to rival the linear take-make-waste incumbent. In their comprehensive report on the Circular Economy, the Ellen MacArthur Foundation and McKinsey recognize that closing the functional gap between circular and linear materials is a critical innovation need, not only for future material suppliers, but also for the institutions conducting the research and education (EMAF, 2012). This first section focuses on the established performance of the materials that are part of our linear system today from a whole systems STEEP perspective (see below) both in the lecture content and in the first project assignment. For example, the awesome process capability to achieve 300 nm thick free-standing polyethylene napthalate film is demonstrated in class by providing a sample and describing the biaxial stretching process capability of today's polyester film industry that enabled this achievement (Forrest *et al.*, 1998, Gardner *et al.*, 1999. see Figure 1).

It is only by thoroughly understanding the value and performance of the incumbents that alternatives for circular systems can be selected or designed with any hope of displacement.

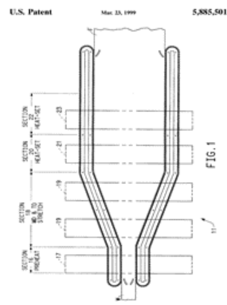


Figure 1 Schematic of Linear Motor Accelerated Simultaneous Biaxial Ultra-Thin Film Stretching

- **Whole Systems STEEP Assessments for More Circular Alternatives and Designs**: The second section of the course focuses on understanding more circular and sustainable alternatives and the third section focuses on designing new circular and more sustainable material solutions. All of the alternatives and new designs are assessed from a whole systems, STEEP perspective (Schmidt *et al*., 2015) that includes the social (especially producer and user safety and health), technical (especially functional performance as mentioned above), economic (especially the ability to achieve cost parity with the incumbent), environmental (including quantitative estimates of the net environmental benefits (e.g. reduced GHG, waste, pollution, water use, etc.) and political (e.g. regulatory drivers such as REACH and TSCA) dimensions. Circularity knowledge, skills and capabilities are developed through assessing these whole system dimensions for renewably sourced, biodegradable, recyclable or durably reusable more circular and sustainable alternatives and designs, and comparing them with the whole systems STEEP assessment of the incumbent material or material system. Examples of commercially viable circular materials and circular material designs are provided via class lecturers including the production of 1,3 propane diol from glucose for renewably sourced and recyclable carpets (DuPont, 2020) and the production of a renewably sourced and biodegradable thermoplastic starch to displace polystyrene in chocolate trays (Plantic, 2020).

2.12 Sustainable Materials and Design Student Project Example: Figures 2 thru 4 show slides from a student project that assessed a more circular material solution for personal care packaging based on renewably sourced bamboo and PLA. Note the use of Ashby plots comparing material performance in two dimensions via the CES EduPack software tool by Granta Design (CES EduPack, 2019), the whole systems STEEP analysis, and the conclusion that recognizes the trade-offs and what must be done to achieve the more circular solution.

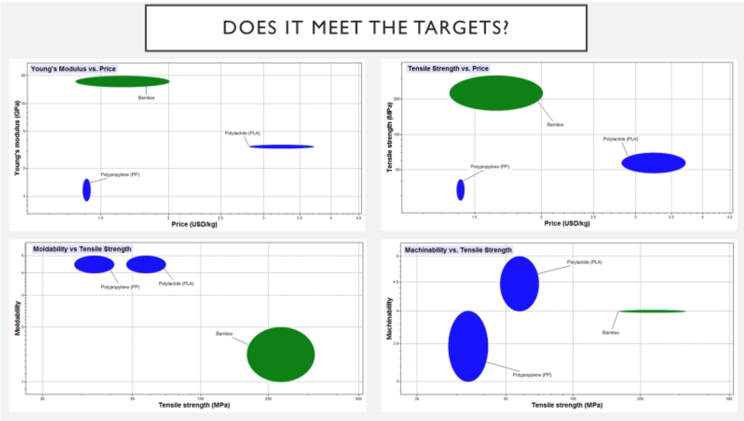
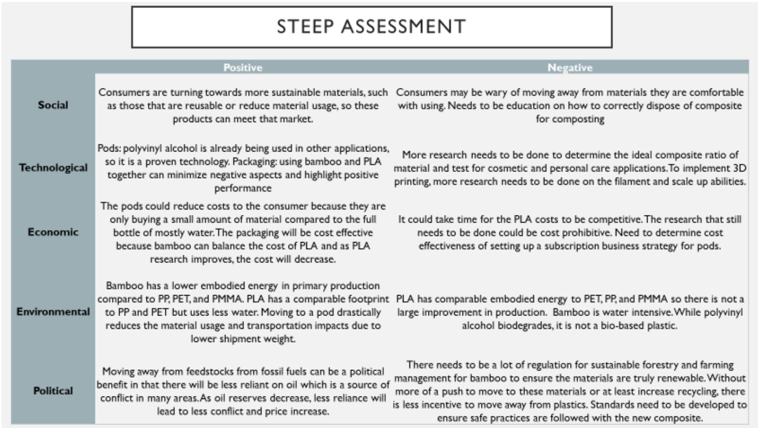


Figure 2



STEEP ASSESSMENT

	Positive	Negative
Social	Consumers are turning towards more sustainable materials, such as those that are reusable or reduce material usage, so these products can meet that market.	Consumers may be wary of moving away from materials they are comfortable with using. Needs to be education on how to correctly dispose of composite for composting
Technological	Pods: polyvinyl alcohol is already being used in other applications, so it is a proven technology. Packaging: using bamboo and PLA together can minimize negative aspects and highlight positive performance	More research needs to be done to determine the ideal composite ratio of material and test for cosmetic and personal care applications. To implement 3D printing, more research needs to be done on the filament and scale up abilities.
Economic	The pods could reduce costs to the consumer because they are only buying a small amount of material compared to the full bottle of mostly water. The packaging will be cost effective because bamboo can balance the cost of PLA and as PLA research improves, the cost will decrease.	It could take time for the PLA costs to be competitive. The research that still needs to be done could be cost prohibitive. Need to determine cost effectiveness of setting up a subscription business strategy for pods.
Environmental	Bamboo has a lower embodied energy in primary production compared to PP, PET, and PMMA. PLA has a comparable footprint to PP and PET but uses less water. Moving to a pod drastically reduces the material usage and transportation impacts due to lower shipment weight.	PLA has comparable embodied energy to PET, PP, and PMMA so there is not a large improvement in production. Bamboo is water intensive. While polyvinyl alcohol biodegrades, it is not a bio-based plastic.
Political	Moving away from feedstocks from fossil fuels can be a political benefit in that there will be less reliant on oil which is a source of conflict in many areas. As oil reserves decrease, less reliance will lead to less conflict and price increase.	There needs to be a lot of regulation for sustainable forestry and farming management for bamboo to ensure the materials are truly renewable. Without more of a push to move to these materials or at least increase recycling, there is less incentive to move away from plastics. Standards need to be developed to ensure safe practices are followed with the new composite.

Figure 3

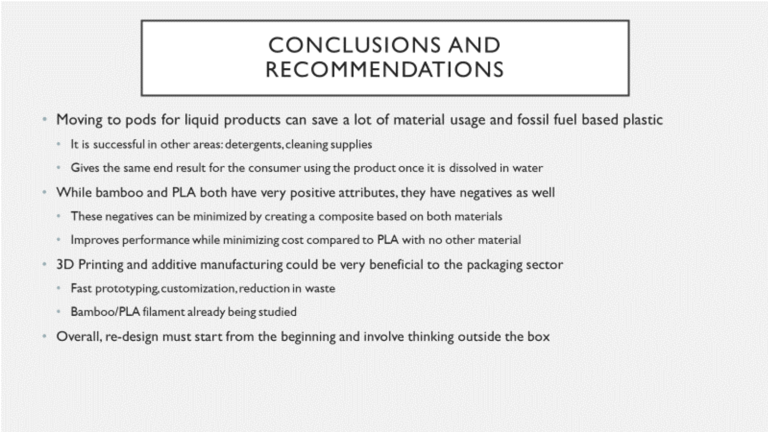


Figure 4

2.20 *Course Title:* **Biomimicry**

2.21 Key Elements That Drive Circularity

- This course is organized in exactly the same manner as the Sustainable Materials and Design course and includes the same elements of:
    - **Three individual equally spaced projects** – but in this case students choose from thirteen service systems of life (Spohrer, 2014) and pick one that they are most passionate about improving.
    - **Understanding the good and the bad -** The focus in the first project and first part of the course is again on understanding the awesome benefits of today's systems that must be preserved as well as the issues that must be changed from a whole systems STEEP perspective.
- **Applying learnings from nature:** The second and third parts of this course focus on learning from nature's circular systems and applying those learnings to create more circular and sustainable biomimetic system designs. To accomplish this, students are taken on field trips to the Philadelphia Zoo and to Longwood Gardens to see first-hand how nature provides solutions. In preparation for this a workshop on form vs. function (Kleinke, 2012) and TRIZ (Weaver, 2012) is conducted to provide the tools to understand the current and natural systems in terms of the key functional performance needed and how that is achieved in nature. Lectures focus on understanding how nature provides ecosystem services, materials, energy, information storage, etc. Examples of implemented commercial biomimetic systems are also presented. The final student project provides a more circular and sustainable biomimetic system design assessed from a whole systems STEEP perspective to show the net impacts and implementation strategy.

2.22 *Biomimicry Student Example* The student project shown below focused on developing a more sustainable and circular biomimetic solution to heat and cool buildings. Building from how termite mounds keep a constant temperature and also finding that bricks can be comprised of natural materials (even waste) the student designed a biomimetic system to improve energy efficiency and reduce waste. Figure 5 shows her proposed solution and Figure 6 highlights her comprehensive STEEP assessment of the benefits.

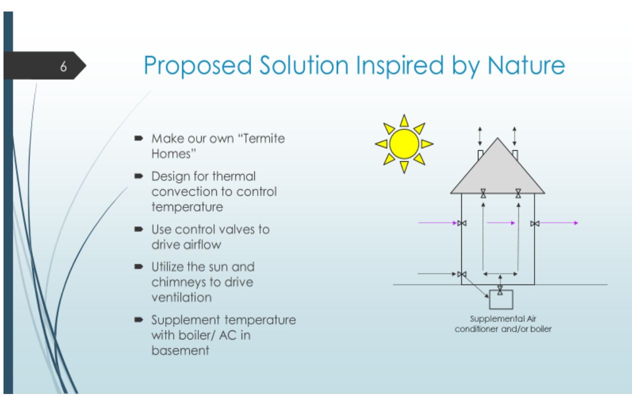


Figure 5 Proposed Solution

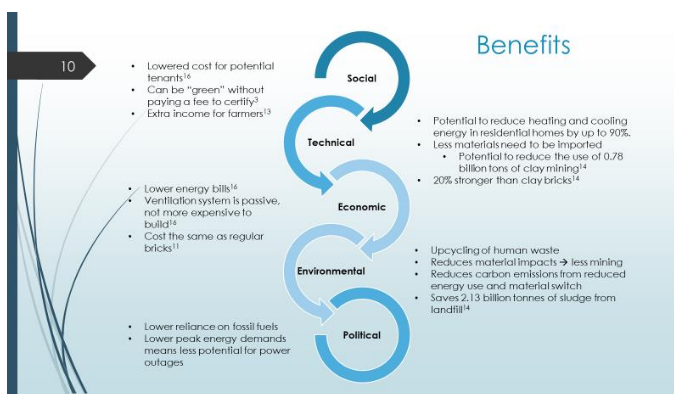


Figure 6 STEEP Assessment

2.3 Course Title: **Sustainable Supply Chain**

2.31 Elements that Drive Circularity

We explore circular economy sustainability principles and practices through a supply chain management perspective. The focus is on how companies design, build and implement their supply chains to deliver products and/or services while seeking to optimally balance organizational and performance outcomes across economic, environmental and social criteria. The curriculum follows the Supply Chain Operations Reference model (SCOR) (ASCM, 2020) including Plan, Source, Make, Deliver, and Return and addresses "upstream" suppliers, planners, manufacturers, distributors through "downstream" customers. Application of practical tools, case studies, group projects as well as lectures by industry practitioners are used to foster better understanding of this growing global business topic.

Key circular economy principles highlighted include:

- Design out waste by identifying and designing out negative externalities, such as water, air, and noise pollution, extraneous packaging materials
- Shift to renewable energy resources away from fossil-fuel based sources
- Use systems thinking concepts to preserve and enhance natural capital **-** by controlling finite stocks and balancing renewable resource flows
- Move toward eco-effectiveness (from one-way linear flow of materials to cyclic, cascading steps by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles)

Using these design principles, students apply a businss model framework (Accenture, 2014) outlined in Figure 7 to case study supply chain projects where they recommend improvements. The recommended alternatives and new designs are also assessed from a whole systems, STEEP perspective (Schmidt *et al.*, 2015). External reports (Moraga, G., *et al.*, 2019) have affirmed the importance of holistic measurement evaluation (i.e. STEEP framework) to address Circular Economy systems, rather than a separate metric.

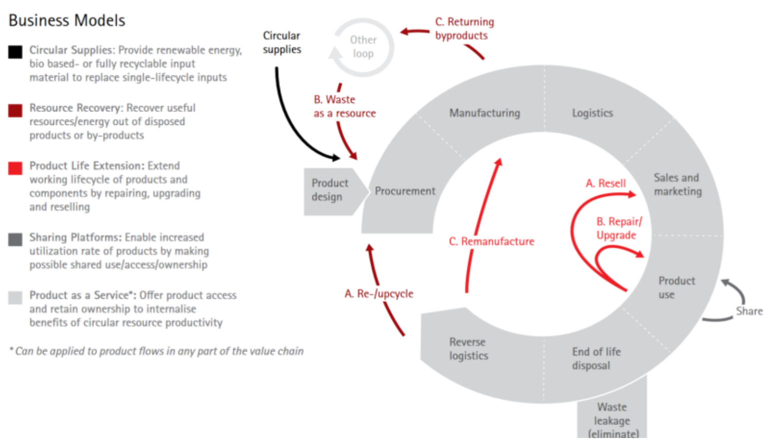


Figure 7 Circular Economy Models for Sustainable Supply Chains (from Accenture, 2014)

3. Research Examples. As reported previously, (Lee, 2018), circularity, renewably sourced energy and sustainable materials are three of the top five areas of sustainable engineering research focus. Figure 8 shows over 30 past and current company sponsored class, Master thesis and PhD research projects on closing the circularity gap. Highlighted in the circles are examples that include a class project to help a raw

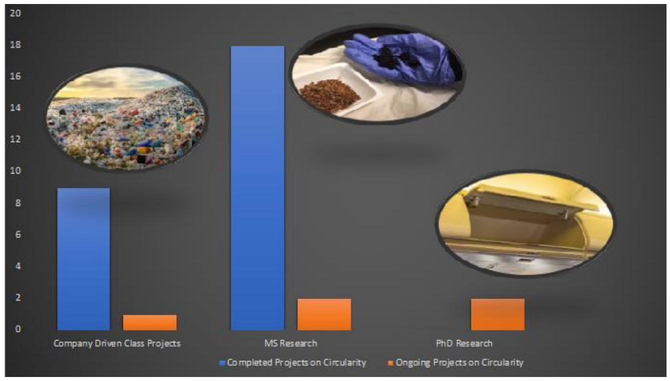


Figure 8. Research Examples

material provider improve recycling, a master thesis project to convert food waste into a hydrochar product for energy recovery or higher value use, and a PhD project to renewably source composites.

4. Conclusion. Our educational processes to provide the knowledge skills and capabilities in our graduate students to best equip them as future leaders to close the circularity gap can best be summed up as:

- Having students pick areas they are passionate about and focus first on understanding the benefits that must be preserved and rivalled by the more circular solution
- Assessing alternatives and more circular and sustainable designs from a whole systems STEEP perspective to ensure that the improved solution provides an overall net benefit across all these dimensions
- Engaging the right subject matter experts, disciplines, collaborators and stakeholders in classes, projects and research to achieve the highest quality outcome and richest learning experience**.**

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