Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
Paper ID #48274

WIP: Introducing Engineering for Sustainable Development. The Circular Design Thinking Approach to First Year Engineering.

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Abstract

This work-in-progress paper describes developing and assessing a short introductory course on the Circular Design thinking approach to Engineering for Sustainable Development for first-year engineering students at a large University in the Southwest. The course focuses on how sustainable circular engineering designs are developed to fit into a functional Circular Economy. Engineers realize that the world is becoming unsustainable mainly because humans misuse technology. The societal expectations to resolve the increasing side effects of our unsustainability, like the environmental effects of pernicious global warming and its economic consequences, motivate engineering educators to explore how to redirect engineering curricula to sustainable technology development.
The learning objectives for the training session are tailored according to the outcomes of a comprehensive questionnaire that explores knowledge of the basics of sustainable circular engineering design and the circular pedagogical methodology used. Of special significance is the students' interest shown after this short training in learning the more advanced engineering courses that will equip them to apply their technical knowledge to technology developments designed towards a better world, not only for future generations but also for the present.

Introduction

The paradigms of sustainability and the circular economy (CE) are creating new constraints on the design and development of products for everyday use [1],[2],[3]. The circular economy promotes a restorative and regenerative system capable of minimizing waste, optimizing resource use, and enhancing product lifecycles. The global economy is estimated to consume approximately 100 billion tons of materials annually. However, only 8.6% of those materials undergo recycling back into use [4], creating resource depletion, environmental degradation, and greenhouse gas emissions [5]. Transitioning from a linear to a circular economy is critical to achieving global sustainability.

The current and traditional linear extract-produce-use-dump material and energy flow model of the modern economic system is unsustainable [6]. A circular economy provides the financial system with a cyclical alternative flow model [7]. The materials cycle concept has existed since the dawn of industrialization. The idea has also been practiced, accompanied by the argument that it reduces negative environmental impacts and stimulates new business opportunities during industrialization [8]. However, the linear flow model has dominated the development, causing serious environmental harm. Unlike traditional recycling, the practical policy and business-oriented circular economy approach emphasizes product, component, and material reuse, remanufacturing, refurbishment, repair, cascading, and upgrading, as well as solar, wind, biomass, and waste-derived energy utilization throughout the product value chain and cradle-to-cradle life cycle [9].

A circular economy is based on eliminating waste and pollution, promoting the circularity of products and materials in use, and regenerating ecosystems as much as possible. It has proven to be a sound system for business, people, and the environment. [10].

Historically, a transformation in our ability to make things has changed society. In 1684, Thomas Savery invented the steam engine, which changed everything. It kick-started the Industrial Revolution, transforming our ability to make things. Raw materials and energy were seemingly infinite, and labor was readily available. For the first time in history, goods were mass-produced. The Industrial Revolution laid the foundation for how the economy of today operates. We turn resources into an extraordinary number of products. Since the Industrial Revolution, the rapid pace of technological progress has continued. The resulting innovations mean that many now have access to affordable products from all over the world. These products have brought many of us levels of material comfort unimaginable to previous generations [9].

However, our vibrant life is based on a linear economy—an economy based on our ability to use raw materials, transform them into valuable, marketable items, use them, and dispose of them in the most profitable transaction. Our way of doing things has, however, reached its limits. At one point, it was recorded that the equivalent of one garbage truck of textiles was landfilled or burned every second. This practice is unsustainable. The linear economy has to change [9].

We must transform all the elements of the take-make-waste system: how we manage resources, make and use products, and what we do with the materials afterward. Only then can we create a thriving economy that can benefit everyone within the limits of our planet. We must disrupt the linear economic system [10].

The scale of our design has shifted from products to companies to economic systems. Who engineers are developing technology for has expanded from a solitary user to an intimately connected web of people spanning the globe. New tools such as artificial intelligence, the internet of things, and biomimicry (design products or materials, structures, and systems modeled by biological entities) mean that engineers' imagination limits their design ambitions. Meanwhile, creativity has never been more critical. The global economy is stuttering, and disruptive technologies challenge established business models. The next big thing in design is circular.

Now, we have the knowledge and tools to build an economy fit for the 21st Century. A new mindset for business is emerging. Just in its beginning, it is estimated to be worth around a trillion dollars; it will drive innovation in tomorrow's companies and reshape every part of our lives. We are living the birth of a radical, restorative, regenerative approach to business. But making the shift isn't easy. Innovators must create more elegant, practical, and creative solutions for the circular economy. Solutions that are invaluable for people give businesses a competitive advantage and are regenerative for our world. Because companies and business organizations primarily operate around profit as the end objective, we will question the health of our organizations, social systems, and business models with design thinking in the circular economy.

The design thinking approach allows engineers to explore new ways to create sustainable, resilient, long-lasting value in the circular economy. It gives engineers the creative confidence to redesign the world. Design thinking is a restorative and regenerative approach to creating technology.

This is an emerging new mindset for business. It will drive innovation in tomorrow's companies and reshape every part of our lives.

The circular design principle.

The framework of design for the circular economy is increasingly used in industry to improve product sustainability and decrease costs. Various models have been developed in academia to guide circular design [11]. At its core, a circular economy means that products no longer have a life cycle with a beginning, middle, and end. Circular engineering design will help us to understand the different ways to shift technologies to be more circular [12][13]. The way to get started designing for the circular economy is to understand circular flows of mass and energy so that the circular designs contribute less waste and can add value to their ecosystem. When materials stop being used because the technology has reached the end of its life cycle, they should return to a proper cycle, activating the circular economy.

The engineering design process

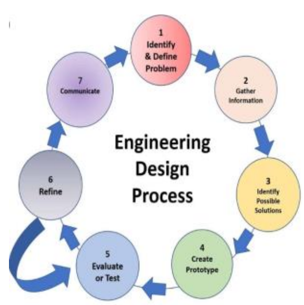

Figure 1. The traditional step-by-step design process.

The need is identified in the traditional engineering design process depicted in Figure 1, followed by the analytical method of gathering as much technical information as possible. By applying scientific engineering knowledge, the solution to the problem is identified, and a prototype is created next. After the experimental demonstration that the technology works, it is passed through refining the product. The technology is finally deployed to the market for profit. The technology is disposed to waste at the end of the life cycle.

Figure 2. is a graphical representation of a conventional butterfly diagram for the circular economy. The right-hand side, highlighted in blue, is the most common circularity for an industrial process, whereas the left side of the diagram, highlighted in green, represents a biological cycle.

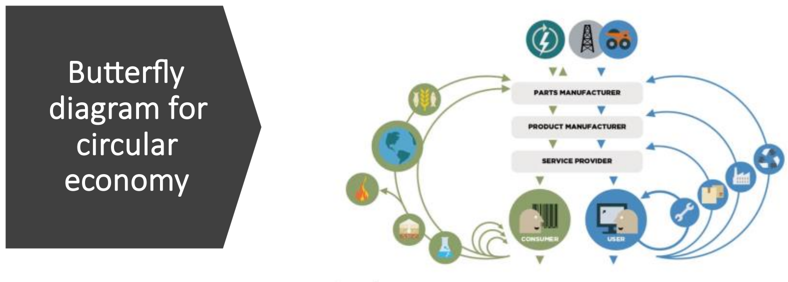

Figure 2. Butterfly diagram of Circular Economy for biological and industrial cycles.

(Adapted from EMF (2013-14)).

Worksheet for Circular Flows. The engineer gets acquainted with the different ways of being circular by using circular flow worksheets. Initially, there was a focus on the historical development of a circular economy and value retention options (ROs) for products and materials, aiming for increased circularity [14]. Figure 2 helps to observe which of these loops is most relevant or achievable for what engineers are designing, because there are many ways to design for circularity. For instance, the left side represents when the design will work on a biological cycle. In contrast, the right side represents when the design is for a technical cycle, meaning man-made materials. At some point in the design, it is essential to identify what materials will be used. Here, it is vital to remember the five critical materials that produce the most industrial carbon emissions globally because they are highly energy-intensive.

Once the first draft of the design is complete, the engineer can evaluate the Life Cycle Assessment (LCA) of the Engineering Designs. LCA is a detailed analysis that provides information on how to make the most environmentally and economically friendly decisions throughout product design [15]. The energy and material analysis looks at a product's life, encompassing ore extraction, material production, manufacturing, product use, end-of-life disposal, and all transportation between these stages. Life cycle engineering (LCE) was introduced in the early 1990s with a focus on eco-efficiency. Hence, LCE designs products to reduce their environmental impact over their life cycle while maintaining or increasing the value created [16]. In a broad sense, the Life Cycle Assessment (LCA) of Engineering Designs will re-evaluate ore extraction, material production, manufacturing, product use, end-of-life disposal, and all transportation between these stages. The importance of the life cycle assessment in the engineering design process warrants a detailed separate presentation.

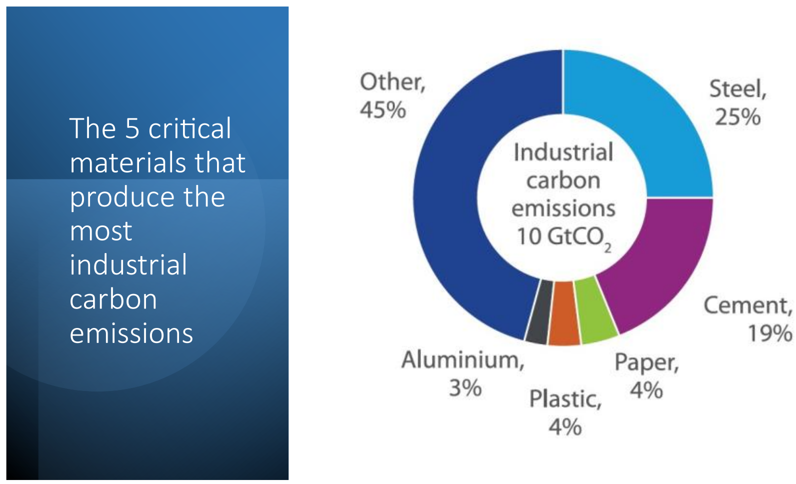

Figure 3. The five most critical materials that, because of their energy density, produce the most industrial carbon emissions [15].

The main objective of a technical cycle is to maintain the embedded material value and energy required for manufacture. Initially, the engineering team will brainstorm the cycles for which the product (design) could be designed. This stage can be performed in four cycles [9]:

Cycle 1. It gets reused. Here, how long a product or material stays in use can be identified. This might mean offering a product as a service after its life cycle, such as car-sharing schemes. To explore as many ideas as possible, the engineering team can evaluate: a) How might this be possible for the product? b) What would be needed, or is standing in its way?

Cycle 2: It gets refurbished. The engineering team intends to design a product that can be easily repaired or upgraded to prolong its use. Exploring ideas, the engineering team evaluates: a) How might this be possible for the product? b) What would be needed, or is standing in its way?

Cycle 3: It gets remanufactured. After use, the product is returned to the manufacturer to have any necessary components replaced (improved) before reentering the market. Exploring ideas, the engineering team evaluates: a) How might this be possible for the product? b) What would be needed, or is standing in its way?

Cycle 4. It gets recycled. The engineering team designs a product made from raw materials, standardized to be recycled, and returned to a raw, natural state. Exploring ideas, the engineering team evaluates: a) How might this be possible for the product? b) What would be needed, or is standing in its way?

Notice that on the technical side of the butterfly diagram of Figure 3, the inner loops are more in control, and the outer loops are less in control: Reused goes directly back to your users. Refurbished comes back to you (as the service provider). Remanufactured goes through the manufacturing process. Recycled goes back to the materials processor.

Pushing the frontiers. Transforming the organization's established linear business model to a circular business model perspective is challenging. The engineering team must reinvent the organization’s business model, capturing value for customers, key partnerships, resources, and distribution models. Expand a new perspective to the broader system and set the business up for success in an interconnected world. There is no rigid start and end point. Circular design thinking is an iterative process of continuous learning, prototyping, and feedback loops. The engineering team continuously returns to the user(s) as their perspectives fit within the system and iterates on this business model. They will have to adapt as needed and continue to reference this as it iterates on the best possible solution.

A discretionary business model. Osterwalder & Pigneur [20] developed this Circular Business Model Canvas for Circular Designs:

Key Partnerships. How might the engineering team strengthen its partnerships with organizations across the value chain to benefit from the system's circularity (flows of materials, information, and capital)? What new or unexpected alliances can be formed to grow circularity within the organization and the system?

Key Activities. What activities might best help to achieve the value proposition? What might be the activities' positive externalities (i.e., consequences of the actions on others)? And how might it be monitored and designed without any negative externalities? How might new human, natural, and financial capital be created?

Key Resources. How might a multidisciplinary team within or across organizations be built to create value in a circular economy? How might connectivity be embraced? What capabilities are needed to enable circular flows and feedback mechanisms and run the organization successfully in the short and long term? Where will the resources come from (renewable or finite source), and what will happen to them after use?

Customer relationships. What feedback loops will be built into the customers to become nimbler and more adaptable to their feedback? How might customers be connected with other parts of the journey of the product/service or materials?

Customer Segments. Who will be the main customers or users of engineering design? Who else might benefit from or be affected by the design materials? Beneficiaries beyond the immediate value chain and industry should also be considered.

Channels. How might the relationship with the supply chain be redesigned? How can feedback be incorporated into the engineering design to allow for the identification of new opportunities? What role will the engineering team play in the reverse logistics chain?

Costs. Which costs could be shared or lowered through other users or partners? Could the engineering team shift from an ownership model of underutilized assets to payment for access and usage? How can cost volatility and dependence on finite resources be reduced? What can be done to mitigate risk?

Revenues. How might opportunities be diversified to increase resilience, growth, and innovation? How might growth through value creation elsewhere in the system favorably impact the future success planned? How might the business model help create other types of value? Like human, social, or natural capital? How might new complementary technologies increase revenues from existing technologies, products, assets, or the new delivery system?

Smart material choices are critical [17]. Materials play an essential role in a circular economy, so the engineering design needs to be made of safe ingredients that can be continuously cycled. Better decisions about what materials go into the new design and their impact on the broader system are essential. By designing products with materials that come from and safely flow into their respective nutrient cycles, you can contribute to creating an optimized materials economy that eliminates the concept of waste. The Smart Material Choices Worksheet developed by the Ellen Mac Arthur Foundation [18] will help create a list of the raw materials and components required to build or manufacture the new product. If any material(s) are not yet fit for the circular economy, the engineering team should evaluate alternatives without wasteful materials. The Cradle-to-Cradle Certified Materials for Designers resource [19] is valuable for choosing materials assessed for material health, re-utilization, renewable energy, water stewardship, and social fairness.

Academic assessment.
The authors followed the ADDIE model [21] for the course's overall development to consolidate the connectivity and dependency of circular designs and circular economy. They started with a modular approach, explaining the circular economy concept, which was broken down into shorter topical modules that derived the idea of circular designs and the dependence of these critical principles on the sustainable development theory. This process follows the systems thinking principle incorporated in the sustainable development theory. We conducted a direct assessment of each defined learning outcome for the course. Each module has an assessment that is aligned with the learning outcome identified. For that module, the student performance on each evaluation is translated into the defined learning outcomes for the short course. The learning objectives were translated into a PowerPoint presentation and a brief Q&A session, followed by the second questionnaire assessment. Using the Canvas Learning Managing System numerical outcomes, the authors identified the student performance, as shown in Figure 4.

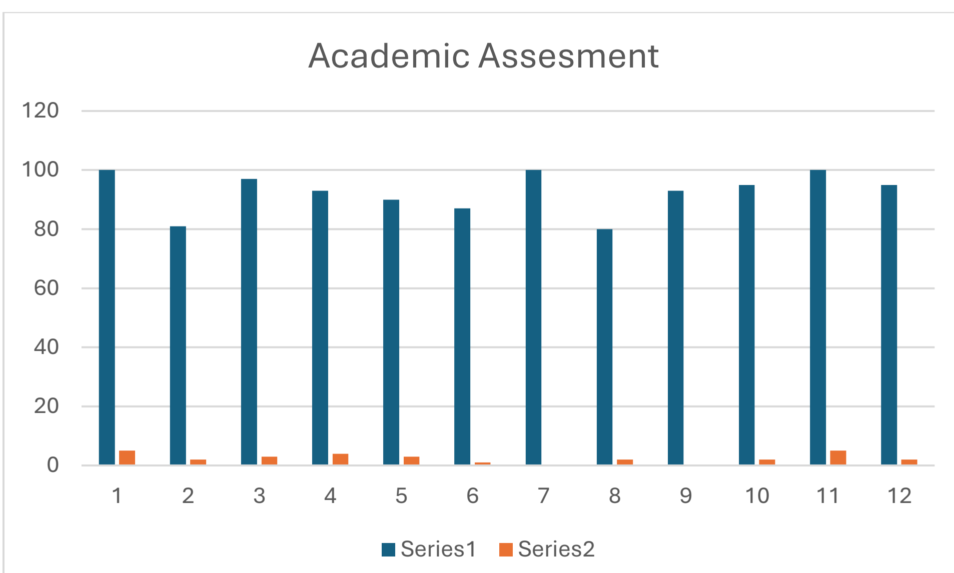

Figure 4. A 12-question assessment questionnaire was given to 221 first-year engineering students of ENGR 102 (Introduction to Engineering) in the Fall semester of 2024. Orange bars (series 2) show correct responses before training (Pre-assessment). Blue bars (series 1) show correct responses after 2 hours of training. The horizontal axis is for the questionnaire; the vertical axis depicts the student performance given in (%). 100% indicates that all students responded correctly to the particular question.

Table 1 shows the questionnaire given to 221 first-year engineering students before and after the 2-hour training. The authors followed the methodology described by Hake [22] to measure conceptual circular design thinking for a circular economy.

Question	**Question**
1. *What are the three fundamental dimensions of sustainability?*	*7. What are the five most critical materials that produce the most industrial carbon emissions in the world?*
2. *What are circular engineering designs?*	*8. Describe the discretionary steps of the circular flow sheet. You can get acquainted with the different ways your design can be circular.*
3. *What is a linear economy?*	*9. What is the core objective of circular designs?*
4. *What is a circular economy?*	*10. What will you brainstorm for in each circularity cycle during your engineering design?*
5. *What is an Engineering Design Life Cycle Assessment (LCA)?*	*11. Name the key components of the circular business model for your new circular design.*
6. *How do you perform an energy and material analysis in a life cycle assessment of a new technology?*	*12. Name the steps you can follow in your circular design's innovative materials decision tree.*

Table 2.1

The same 12-question questionnaire was given before and after the training session. The outcomes are eloquent. Of special significance is the students' interest shown after this short training in learning the more advanced engineering courses that will equip them to apply their technical knowledge to technology developments designed for a better world, not only for future generations but also for the present.

Conclusion.

The authors successfully executed a quasi-experimental methodology on 221 first-year engineering students to measure the effectiveness of the short training course on Circular design for a circular economy applied to engineering for sustainable development theory. The promising outcomes indicate the possibility of introducing more of these vital concepts into the engineering curricula at an earlier stage than what is done now. The authors are committed to developing similar works incorporating engineering concepts for sustainable development, such as the life-cycle analysis of newer technologies, into first-year engineering programs. This practice will help create new mentalities in the engineering workforce and develop newer, more sustainable technologies for future generations.

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