Circular Economy: Definitions, Challenges, and Opportunities

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Abstract

Circular Economy (CE) has been suggested by policymakers and industrial practitioners as a way to achieve environmental, social and economic sustainability. However, there is little scientific guidance on how to best implement CE models or evaluate their effectiveness. Process systems engineering is ideally suited to provide the fundamental tools and methods for the transition towards CE, since such a transition requires system level analyses. In this paper we discuss the concept of Circular Economy and the key challenges towards this transition through a Process Systems Engineering lens. Two case studies are presented as motivating examples; one on the circular supply chain of coffee and one on plastic recycling. Opportunities for Process Systems Engineering research are also analyzed.

Keywords

Circular Economy, Process Systems Engineering, Coffee, PET, Sustainability.

Introduction

The extraction of raw materials and the waste generated throughout product supply chains have enormous environmental and socioeconomic impacts, including climate change, biodiversity loss, depletion of natural resources and pollution. Circular economy (CE) is a system-level solution aiming to solve the aforementioned challenges by i) designing out waste and pollution, ii) relying on energy from renewable resources, and iii) building resiliency through diversity (MacArthur et al., 2013). In an ideal CE model, products, components, and materials are kept at their highest utility and value with minimal to non-existent waste, natural processes are supported and emulated, and nature is regenerated (MacArthur et al., 2013). Even though the principles of CE are straightforward, a consistent definition has not been established, creating confusion between researchers, policymakers and practitioners (Homrich et al., 2018). In an attempt to unify different CE definitions and address the ambiguity of the concept of CE, Saidani et al. (2019) proposed the following well accepted definition: *"CE is an economic system that replaces the end-of-life concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro-level (products, companies, consumers), meso-level (eco-industrial parks) and macro-level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations"*

Fig. 1 shows the butterfly diagram that illustrates the view of circular economy by the Ellen McArthur foundation, the NGO that leads the circular economy agenda. The Ellen McArthur foundation divides CE into two distinct areas, the biological cycle and the technical cycle. In both cycles, materials are kept in circulation through different actions, including reusing, recycling and manufacturing in the technical cycle, and reusing, anaerobic digestion, composting and bio-refineries in the biological cycle.

The CE concept shares many of the goals and characteristics of other sustainable development initiatives such as green chemistry, waste management, eco-parks and industrial symbiosis, to name a few. Hence, tools already available to explore, assess and implement the former would be useful for addressing circularity. However, there is no consensus in the literature on which features are similar and which are different among these initiatives. The most fundamental one is perhaps the discussion of whether or not circularity implies sustainability.

Stemming from the definition of Sustainable Development as the one that *"meets the needs of the present without compromising the ability of future generations to meet their own needs"*, the U.S. Chamber of Commerce Founda-

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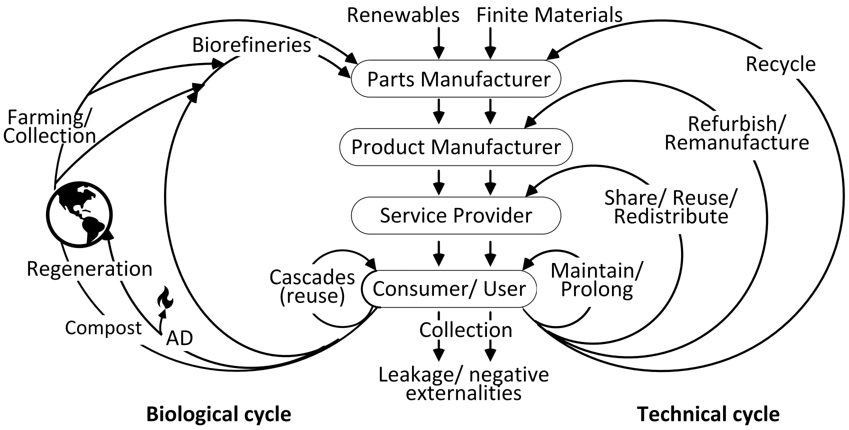

Figure 1: Visualization of the circular economy based on the butterfly diagram by the Ellen Mc Arthur foundation (2013). Right: Technical options for circularity. Left: biological options for circularity; AD= Anaerobic digestion.

tion (2017) argues that circularity lies "under the umbrella" of Sustainable Development providing a way to address the sustainability in the technosphere, i.e. all that has been made or modified by humans. In a similar fashion, the UN Environment programme (2020) and the scope of the journal specialized in CE and Sustainability Springer (2022) refer to CE as a means to promote sustainable development. As "Sustainable Development" lacks implementation specificity and it is open to a wide interpretation, CE gained popularity in the business, governments and the research communities as an operational tool with specific goals as a means to achieve economic, environmental and social sustainability.

Other authors however, consider CE and Sustainability as two different yet interconnected concepts. One such example is Thakker and Bakshi (2021) who introduces the concept of a "Sustainable Circular Economy" implicitly suggesting that circular economy systems - focused on materials and product circulation- may not necessarily be sustainable. In this case, the argument lies in the fact that state of the art CE frameworks focus only on material circulation and the economical aspect, leaving out other environmental and social aspects which are pillars of both sustainable development and Circular Economy.

In any case, it is clear that studies aimed at transitioning towards a CE would benefit from system level analyses, and require assessments beyond material circulation. Process systems engineering (PSE) is ideally suited to provide the fundamental tools and methods for such a transition. In this paper, we first provide motivating examples and present some of the strategies that can be used for circularization. Next, key challenges and opportunities for PSE research are discussed.

Motivating examples & strategies for circularization

The CE has been studied extensively in the past 10 years and many case studies can be found in the literature; the reviews in Homrich et al. (2018) and Bjørnbet et al. (2021) are excellent sources for bibliographic references. The approaches in these studies are generally classified in those that aim at slowing down the loops, those that aim at narrowing the loops and those that aim at closing the loop.Although in principle CE should consider all these three approaches synergistically, many CE initiatives, driven by a business that wants to improve circularity, only focus on one of the strategies, thus lacking the systems level analysis that PSE studies would pursue.

Slowing down the loop refers to those approaches that by design try to extend the life of goods/materials with the rationale that if the same product/material is used for longer, less resources are up-taken from the environment. For consumer products, this approach may be combined with the introduction of service loops that lease, repair, recondition or upgrade the products. Examples that fall in this category are sharing and leasing initiatives (cars, tuxedos/wedding clothes), extended warranty appliances/ electronics vs planned obsolescence, second life initiatives, etc.

Narrowing the loop refers to approaches that focus on using fewer resources per product. It differs from the slowing the loop approach in that it does not influence the speed of flow of products, although both approaches result in lower consumption of resources. An example of this approach can be found in Gallego-Schmid et al. (2016) where a LCA of current vs more energy efficient vacuum cleaners is presented. A critique that is sometimes made to narrowing the loop is that it does not address the time dimension, thus increasing " resource efficiency can easily lead to (...) selling more of a more efficient product" Bocken et al. (2016).

Finally, the closing the loop approach studies processes in between post-use and production (recycle). As the butterfly diagram suggests we can recycle through biological or technological pathways. Most of the work in the PSE community focuses on this approach, many times in combination with the previous ones. Two motivating examples, one representing biological cycles and one representing technical cycles steaming are described bellow.

At the Avraamidou group in University of Wisconsin-Madison, we have been looking at the circular economy of food supply chains. Food loss and waste represent about one-third of the food that is produced, accounting to huge

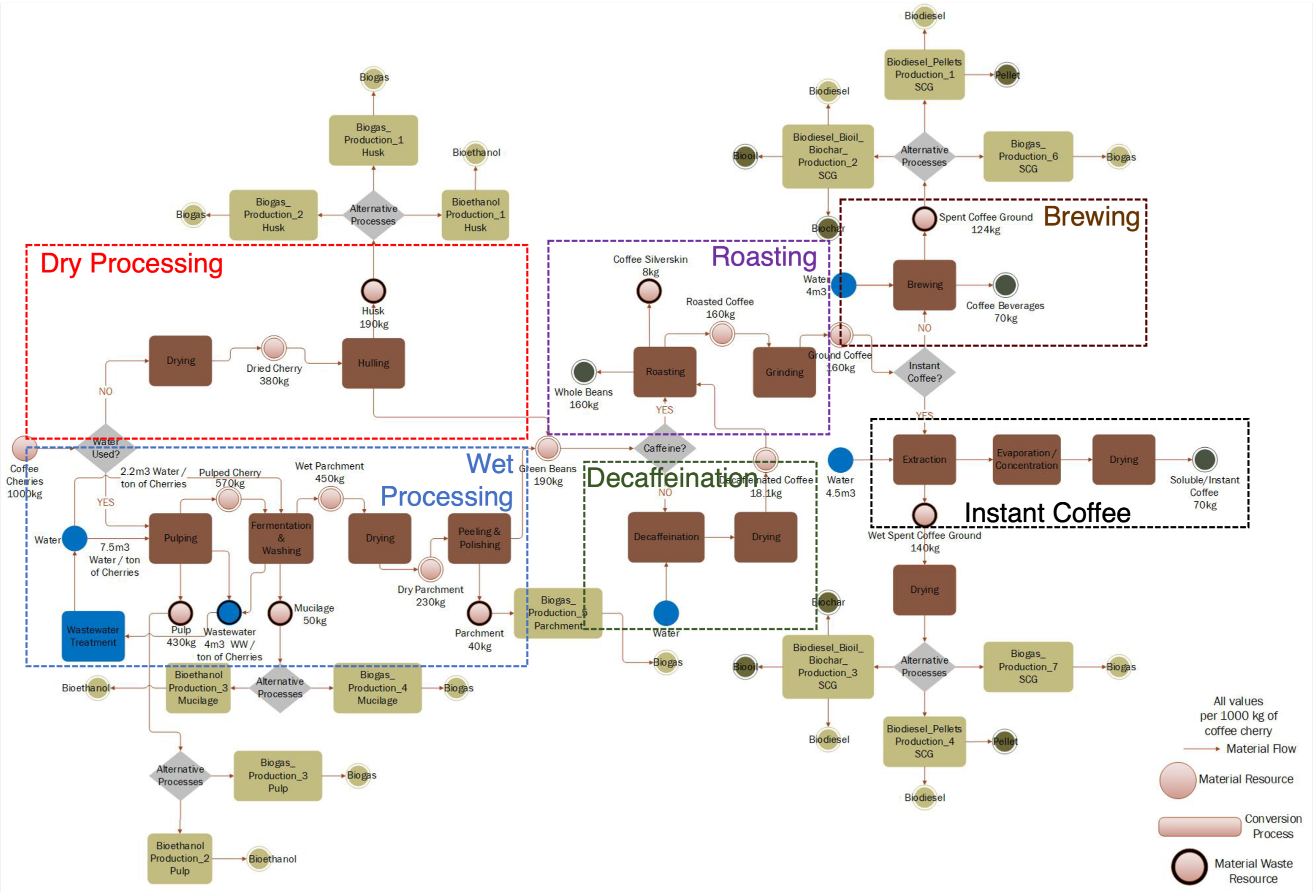

Figure 2: Superstructure representation of different CE pathways for coffee processing and production

environmental, social and economic costs. To this effect we have developed a systems engineering framework for the optimization of food supply chains under circular economy considerations (Baratsas et al., 2021b). One of the food supply chains that we explored is the coffee supply chain (Baratsas et al., 2021a). Coffee is one of the most popular beverages worldwide and it was chosen here to illustrate and communicate the complex issues arising from the transition towards CE and the opportunities for PSE research. The supply chain of coffee produces a lot of organic waste and uses a lot of natural resources, including water, nutrients and energy (mainly from fossil fuels). As the coffee demand and production increases, so does the amount of waste and resources used, aggravating both the waste and energy management problems. This is typical for the case of linear food supply chains. A solution to this problem would be the transition to a circular coffee supply chain where renewable energy resources will be utilized; waste will be collected and used in the production of alternative products and new efficient processing pathways will be implemented. Two main processing methods are widely implemented for the processing and production of coffee beans, the wet and the dry method (Figure 2). Furthermore, different pathways have been proposed by researchers for utilizing the coffee wastes, namely the production of biofuels, fertilizers, cosmetics and antioxidants (Murthy and Naidu, 2012). Apart from the academic research, numerous efforts towards the same direction for circularity and sustainability in the coffee industry have been reported across the industrial and business world, from startups to multi-national corporations.

At the Torres group in Carnegie Mellon, we have been looking at the circular economy of PET waste. PET is the polymer used in plastic bottles, flexible packaging and most of the polyester clothing. The difference between these is the degree of polymerization. Virgin PET is made from ethylene-glycol and terephthalic acid (or dimethyl terephtalate) derived from ethylene and p-xylene. Both of these chemicals can be either obtained from oil or from biomass, so we frequently hear the term “renewable-PET” or “plant based PET”. However, even if made form renewable sources PET is a non-biodegradable polymer, so it cannot be circularized via the biological cycle. Circularization via the technological cycle can be accomplished by different means. Starting with PET-bottles (highest degree of polymerization) these can be mechanically recycled into new bottles (thus slowing down the loop) for a number of times before the reach a degree of degradation that prevents further re-processing without incorporation of virgin material. This recycling method is referred to as primary recycling or up-cycling. After the degree of degradation is such that re-processing as a bottle is not possible, PET can still be mechanically re-processed into lower degree of polymerization products, such as flexible packaging first and fibers for clothing next. This recycling method is referred to as secondary recycling or downcycling. Clothes made with these fibers can be reused and mechanically recycled in a number of ways: second hand clothes, lower requirements textiles such as carpets, filters, etc. Tertiary recycling aimed at recovering the monomers from polymerized PET should ideally be after these two stages. Several depolymerization strategies are available; pyrolysis and gasification are also options that allow to re-enter into the materials loop, although at much earlier stages.

Challenges & opportunities for PSE research

The transition towards CE can be challenging in terms of governance, business models, technology and social aspects. PSE could play a crucial role in providing the required tools and methods for informed decision making through this transition (Avraamidou et al., 2020). This section discusses some of the main challenges that can arise through a PSE lense; along with proposed solutions and research opportunities.

Pathway selection: Navigating, analysing, and identifying the trade-offs of the vast array of pathways for both the coffee and PET supply chains can be a challenge. Given the examples above, it is clear that superstructure based approaches in combination with supply chain analysis are ideally suited for addressing which of the proposed circular pathways is more suitable in different situations. Both superstructure based approaches and supply chain modeling have been extensively addressed by the PSE community; Mencarelli et al. (2020) and Elia and Floudas (2014) are recent contributions reviewing the state of the art in these topics.

Multiple stakeholders: Supply chains are often managed by different companies, governments, and consumers. On one end, we have NGOs and multi-national organisms that would like to optimize the performance of the CE proposals at a macro and global level. On the opposite end, we have the individual actors (industries) that take care of the different parts of the supply chain. For example, the coffee supply chain involves different stakeholders, small and bigger coffee farmers, coffee bean processing industries, exporters and importers, coffee roasting industries, coffee waste management companies, coffee shops, beverage companies, and other vendors along with consumers at different demand centers, different governments, and nations. Similarly, in the PET case it would be reasonable to assume that the actors specialized in mechanical recycling would be different from those specialized in chemical recycling, and different from those taking care of collection and sorting. All of these actors could try to optimize their economic metrics along with their CE metrics. These multiple interconnected stakeholders and their differing or conflicting objectives introduce major challenges in modeling and decision making. It is therefore critical to i) identify ways to coordinate all these decision makers as each individual stakeholder can affect the circularity of the whole supply chain, and ii) reach an agreement on the methodology and metrics that should be used to evaluate circularity. Even after agreeing on the metrics, a pathway that is optimal at the macro level will most probably not be optimal or even acceptable at the micro (individual actor) level. Based on what was learned from the conversion of biomass into chemicals problem Torres and Stephanopoulos (2016), the optimal CE network, defined at the macro level, may be more favorable to some of the actors. This means that, for a certain level of "circularity" of the overall network, some of the actors will be able to claim a largest share for themselves than others. This is a consequence of the conflicting objectives of these individuals, a conflict that emerges when defining the optimal policy for transferring an intermediate between the actors that participate in the optimized network. Hence, a second challenge is understanding possible conflicts and synergies between the actors that participate in the CE network, and building a framework that fairly allocates the costs and benefits of circularization. Multi-agent optimization could be used to guarantee optimal coordination between the actors involved in the CE network and other relevant stakeholders. Contributions helpful in addressing these issues by the PSE community include Torres and Stephanopoulos (2016); Avraamidou et al. (2018); Beykal et al. (2020). Although, the PSE community has focused on solution strategies for problems involving two or three actors (Fischetti et al., 2017; Avraamidou and Pistikopoulos, 2019b,a; Mitsos, 2010), a focus on extending the methodologies developed for problems with more stakeholders is of great importance.

CE assessment metrics: A method for evaluating the circularity of different CE pathways and scenarios is vital for effective decision making. The main tool used to evaluate sustainable development is Life Cycle Assessment (LCA). LCA can quantify all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or services. Despite the availability of sustainability metrics, CE has been mainly measured at national or material levels with the main focus on material flows, while ignoring aspects such as energy, efficiency or durability. A quantitative and holistic circular economy assessment framework has been recently developed by Baratsas et al. (2022). The framework provides a set of indicators and metrics with sector-specific dimensions, and media for data visualization and analysis of CE indicators. Although, this framework can be used for the assessment at the company/micro level, while no metric is currently applicable at the product supply chain level. Therefore efforts for the endorsement and further development of a CE metric that can be effectively used in decision making should be made.

Interconnected supply chains and boundary selection: An additional challenge is the interconnected nature of CE supply chains. Implementing CE closes material loops, but also connects discrete stages of supply chains that are not connected in a linear economy. This can create significant challenges for modeling and decision making. So far, CE case studies have followed an end-of life product driven approach where the focus is a target "problematic" product, and a value chain superstructure is built and designed around *only* this product. However, in a mature CE setting, it is reasonable to expect coincidences in the processes/operations of the CE networks of different end -of-life products. For example a single PET plastic recycling facility may be able to receive, separate and prepare a single product stream from

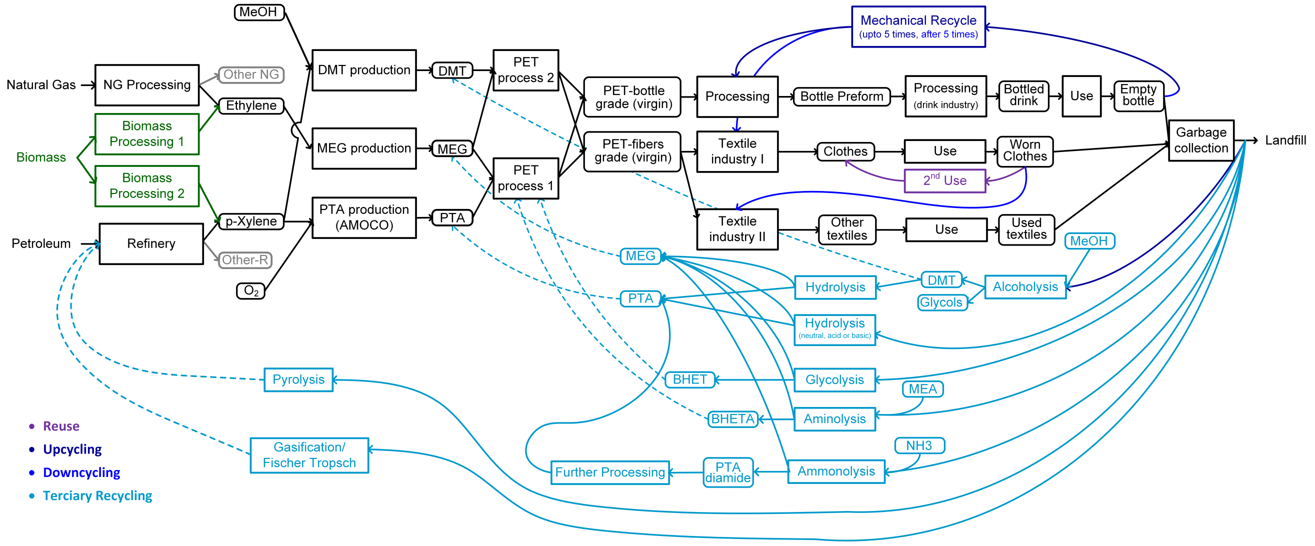

Figure 3: Superstructure representation of current (linear) and CE pathways for PET production and processing. Main current processing pathways in black; renewable biomass based option in green; reuse strategies in purple, mechanical recycle strategies in blue , chemical recycle in light blue.

many end of life PET products; or a refinery can receive organic waste from the coffee supply chain and other organic supply chains. Hence, CE networks should be designed and optimized thinking of possible interlinks. These interlinks make it much harder to define the boundaries of the system. Similarly to LCA studies, the boundary selection can greatly affect the outcomes and solutions for CE supply chain studies. Extending the boundaries could result to more accurate representations of CE systems, but that increases the number of stakeholders involved, could introduce multiple scales, and will result to large-scale mixed-integer problems that can be very challenging to solve. The PSE community has been developing theories, algorithms, and tools able to solve larger and larger problems, but more efficient approaches must be explored.

Social Aspects: Inclusion of the social dimension in sustainability-related studies is still a challenge for the PSE community. On one hand, it is still not clear which social aspects should be included in the analysis, and on the other one, it is not clear how to model (and quantitatively estimate) them from the data that is available at the conceptual design level. As discussed in Barbosa-Póvoa et al. (2018), when reviewing literature on sustainable supply chains, job creation, safety and health are the most used indicators in terms of social aspects. A similar finding is reported by Padilla-Rivera et al. (2020) when reviewing social indicators applied to CE academic studies. However, there is a plethora of social indicators included in the UN Sustainable Development Goals UNS (2022) that are pertinent to CE, can be readily estimated using existing data, and may shift the resulting optimal CE pathways if included as a metric in the objective function/constraints. As an example, CE studies spanning several geographical regions could include metrics such as maximization of the growth rate of real GDP per capita (indicator proposed for SDG 8.1) or number of countries involved in the network (indicator proposed for SDG 12.1) to define where each of the operations should take place. Overall, inclusion of SDG within CE frameworks could be a first step in addressing the social dimension of circularity.

Conclusion

Even though the move towards CE comes with many challenges for decision making, it also presents many research opportunities for PSE. In this work we have discussed some of the decision making challenges and proposed existing tools and research directions for addressing those. A Systems Engineering approach can have a huge impact in understanding more about CE supply chains, their operation and the transition towards them. PSE can provide the tools to facilitate the convergence of different entities towards the common goal of sustainability through CE.

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