

Circular Economy - a challenge and an opportunity for Process Systems Engineering[☆]

Styliani Avraamidou, Stefanos G. Baratsas, Yuhe Tian, Efstratios N.
Pistikopoulos*

styliana@tamu.edu, sbaratsas@tamu.edu, ytian@tamu.edu, stratos@tamu.edu

Abstract

Rising populations put huge stresses on natural resources. Extraction and depletion of raw materials and waste created throughout the supply chain of products have enormous environmental and socioeconomic impacts. One way to reduce these impacts is through the move towards the circular economy (CE). CE aims to solve resource, waste, and emission challenges confronting society by creating a production-to-consumption total supply chain that is restorative, regenerative, and environmentally benign. This article highlights research challenges and identifies process systems engineering (PSE) research opportunities to assist in the understanding, analysis and optimization of CE supply chains. A motivating example on the supply chain of coffee is introduced to illustrate the challenges of the transition towards a CE and propose PSE research opportunities.

Keywords: Circular Economy, Process Systems Engineering, Sustainability

[☆]In honor and memory of Professor Roger H. W. Sargent, the ‘patriarch’ and intellectual leader of process systems engineering, who was always pushing the boundaries of this field.

*Corresponding author

1. Introduction

Natural resources, the environmental impact of manufacturing, and the economics of production play critical roles in the development and wealth of societies. Preservation, impact reduction, and economic efficiency are vital for the provision of manufactured goods, energy, food, shelter, transport, and – more generally – almost all basic functions of society. Population growth, economic growth, and increasing requirements for the standard of living mean that more and better goods are in demand, which in turn require more natural resources and manufacturing activity. Such developments, if not carefully designed, can lead to resource depletion/degradation, more landfill waste, higher levels of pollutants, and increased environmental impacts, such as climate change.

The concept of "Sustainability" has been gaining traction as climate change, resource depletion and biodiversity loss are becoming more and more evident. Even though this term is highly used by businesses, governments and the research community, it lacks implementation specificity as it is open to a wide interpretation. This has led to vagueness of the term, while Circular Economy (CE) can be viewed as an operational tool with specific goals, aimed for businesses as a means to achieve economic, environmental and social sustainability.

CE aims to solve resource, waste, and emission challenges confronting society by creating a production-to-consumption total supply chain that is restorative, regenerative, and environmentally benign. It does this by keeping products, components, and materials at their highest utility and value with minimal to non-existent waste at all times.

1.1. Origin and Definition of CE

The origins of the CE concept cannot be easily traced back to a single author or date, but due to its potential applications to the modern economic and industrial world, the concept has gained momentum since the 1970s (Ellen MacArthur Foundation, 2013). In the same report, Ellen MacArthur Foundation (2013), claims that CE is based on 3 principles: a) design out waste, b) build resilience through diversity, c) rely on energy from renewable sources. However, and despite the fact that it seems a rather straight forward and easy to conceive term, in reality, it creates confusion among the involved parties including researchers, policymakers and practitioners. In particular, Kirchherr et al. (2017) reviewed 114 definitions for CE revealing ambiguity on the framework and the principles which if not addressed promptly could potentially crash the concept. To this respect and based on their findings, they proposed a definition of CE based on the semantic sample. Similar findings were reported in a review of 327 articles, where Homrich et al. (2018) pointed out a lack of consensus and convergence on the terminologies and definitions. In the same review, an analysis of a sample of 35 definitions was presented and a “CE sample-based definition” was proposed. In an attempt to unify these definitions, Saidani et al. (2018) proposed the following:

“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 qual-

ity, economic prosperity and social equity, to the benefit of current and future generations”.

1.2. Key characteristics and goals of CE

The goals and characteristics of a CE can differ for different systems (e.g. organic vs non-organic cycles), but similar principles can be applied. The key characteristics of a CE have been recently identified by Reichel et al. (2016) and are listed below along with a description:

1. *Reduction of material losses/residuals*: Waste and pollutants minimization through the recovery and recycle of materials and products.
2. *Reduction of input and use of natural resources*: The reduction of the stresses posed on natural resources through the efficient use of natural resources (e.g. water, land, and raw materials).
3. *Increase in the share of renewable resources and energy*: Replacement of non-renewable resources with renewable ones, limiting the use of virgin materials.
4. *Reduction of emission levels*: The reduction in direct and indirect emissions/pollutants.
5. *Increase the value durability of products*: Extension of product lifetime through the redesign of products and high-quality recycling.

Even though the economic and financial aspects do not appear as one of the main goals of the CE, the transition to such an economic model is expected to be economically sustainable. The elimination of waste could lead to significant cost savings in the production processes, create new sources

of revenue from the distribution of the waste to new markets, as well as reduction in the resource dependency.

Moreover, the economic and financial objectives are not limited to the traditional approach of the cost minimization or profit maximization but has a wider and holistic objective. As per Ellen MacArthur Foundation (2013), the transition to circularity has the potential to reveal an economic opportunity with a positive impact to all involved parties i.e. economies, companies, consumers and customers. In particular, the significant net material and energy cost savings, the effective implementation of recycling that will reduce the volatility between the supply and demand and the relevant risks, along with the resilient economic growth through the minimization of the externalities will greatly benefit the economies. Similarly, the companies will benefit from new profit pools in the reverse value cycles, the improved logistic services that put high emphasis in the material recycling systems and refurbishment of products as well as the new venues of financing and capital that will be required from the shift towards the tertiary sector. The transition to the circular economy will force the improvement of service quality, durability and reliability of the products which would eventually assist the appearance of new emerging trends of sharing, lending, swapping etc. that will benefit the end users and consumers. At the same time, increasing competitiveness among the companies will lead to greater variety of products and services, less hassles from obsolescence, as well as an overall improved company - customer interaction and loyalty that will benefit both of them.

To achieve CE, four areas of system improvements have been suggested: reuse, repair, re-manufacturing, and recycling. While these actions help close loops and connect discrete stages of the supply chain, interconnections among the diverse supply chain elements, stakeholders, and regulatory environments create significant challenges for decision making. Moreover, in addition to these strategic actions and goals, there is still a lack of quantitative metrics to define the targets of CE. For example, what is a proper baseline metric for waste recovery rate achieved via CE given the latest available recovery rate is 34.7% in 2015 regarding municipal solid waste (United States Environmental Protection Agency, 2019), and also how to define the assessment of waste recovery rate, e.g. based on available wastes or their re-usability factor. Thus, it is clear that a holistic systems engineering approach is needed to quantitatively navigate and fully consider the multi-scale, multi-faceted and interconnected CE supply chain, to identify opportunities for beneficial improvement, to systematically explore interactions and trade-offs, as well as to assist quantitative assessment and decision making.

This article highlights research challenges and identifies process systems engineering (PSE) research opportunities to assist in the understanding, analysis, and optimization of CE supply chains. A literature review on PSE tools and research areas focusing on achieving the objectives of CE is presented in Section 2, while Section 3 discusses the challenges and research gaps arising in CE research. A motivating example on the supply chain of coffee is introduced in Section 4 to illustrate the challenges and opportunities that arise due to the move from a linear to a circular coffee supply chain. Finally, Section

5 concludes this work with a discussion on PSE research opportunities.

2. PSE and CE - Literature review

The concept of circular economy (CE) has captured the interest of governmental and inter-governmental organizations, decisions makers, academia and industry during the last years, however a recent review of over 114 definitions for CE illustrates a vagueness with regards to the definition as well as with regards to the actual perception of people working on this concept (Kirchherr et al., 2017). The same review highlights that only 40% of the CE definitions use a systems perspective to conceptualize it while another review suggests that a non-holistic approach could lead to ambiguous and contradicting conclusions (Iacovidou et al., 2017). Similar findings were made from another review which considers CE as an evolving as well as an umbrella concept which needs to unify definitions, principles, and boundaries (Merli et al., 2018) as well as metrics for monitoring framework (Parchomenko et al., 2019). This fact could explain the lack of robust mathematical and engineering methodology, even though someone would expect that such an approach is indispensable not only for the transformation of the corresponding processes and business models but also for the effective evaluation towards CE implementation/fulfillment.

Process engineering could play a crucial role in providing the required tools and methods for the transition towards CE. There is a large overlap between the objectives widely explored by the PSE community and the CE reported goals (Reichel et al., 2016; Elia et al., 2017). Figure 1 illustrates this overlap, showing that most of the CE reported goals have been explored

by the PSE community. Even though these objectives have not been tackled holistically, or at the scale to be directly applicable for CE, the methodologies and tools developed by the PSE community for them (Figure 2) have the potential to assist decision-makers for the transition towards a CE.

This section focuses on tools and methods developed or widely used in the PSE community, such as modeling & optimization, life cycle assessment, and process integration and intensification and their potential in assisting in the transition from linear to circular supply chains. The goal of this section is to highlight the relevant literature and identify research gaps and possible PSE opportunities for PSE research.

Tables 1 to 5 include indicative contributions by the PSE community for the achievement of different CE goals as reported in Reichel et al. (2016) and Elia et al. (2017). From these tables, it is clear that different PSE approaches have already been applied for decision making regarding most of the goals of CE. It is also evident that the PSE community has a lot of expertise in some areas and goals of CE, even though these were not undressed holistically and their original intent was not explicitly for CE. But, to our knowledge, no effort or developments have been reported by the PSE community for the maximization of the durability and reliability of the products, that is a key goal of CE - even though many PSE tools can have the potential to include this consideration (Figure 2). This consist an obvious gap in PSE research and exploring this can have a high impact towards the transition to CE.

A selection of some of the most important tools and methods from PSE for CE are chosen for more detailed discussion in the following section.

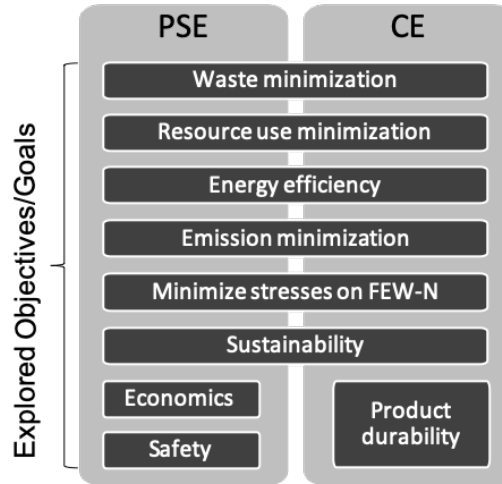


Figure 1: Explored objectives in Process Systems Engineering and set goals of Circular Economy

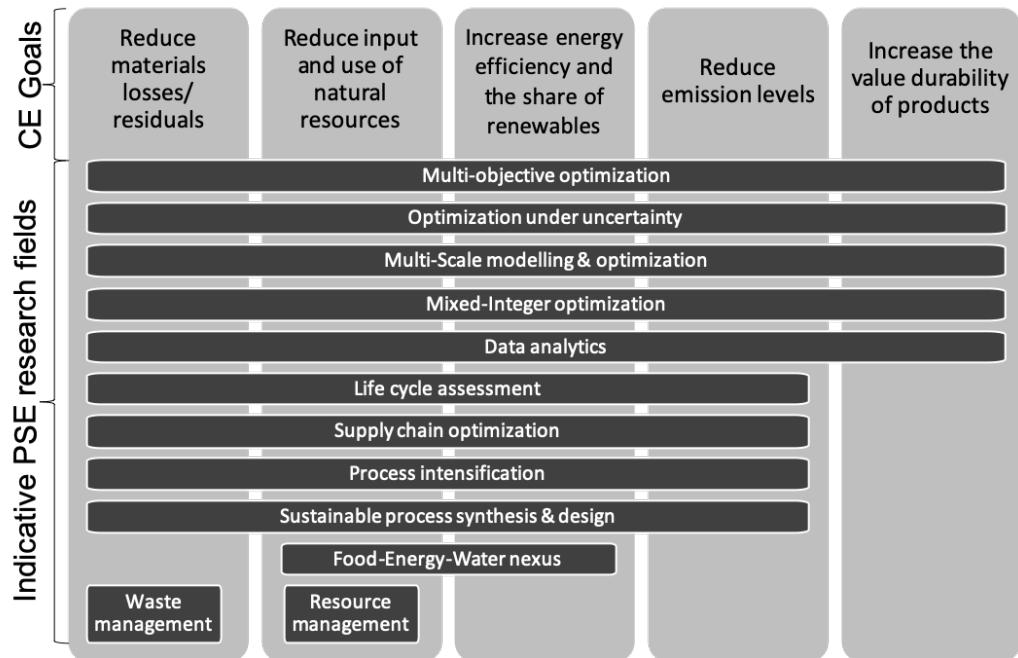


Figure 2: Indicative PSE research fields with potential use in achieving different CE goals

2.1. Tools and Methods from PSE for CE

2.1.1. Multi-Scale Modeling

CE supply chains are multi-spacial and multi-temporal (Section 3.1), similar to other problems encountered by the PSE community. Process engineering could play a significant role in the growing circular economy, by utilizing in a multi-scale approach its key principles i.e. basic laws of mass and energy, entropy, mathematics, and system science, towards an integrated environmental, economic and social sustainable plan (Reh, 2013). To this respect, Floudas et al. (2016) demonstrated the positive impact from the usage of multi-scale systems engineering into energy and environment, without though referring to the CE term. A more recent study presents a multi-scale framework for the optimized production of bio-gas and fertilizer from residues conducting a techno-economic as well as a supply chain network evaluation (Taifouris and Martin, 2018). Walmsley et al. (2019), proposed the concept of Circular Integration as a unified methodology towards the sustainable development of processes, industries, and economies by applying a multi-dimensional, multi-scale approach for the minimization of the resource and energy consumption. The social aspect of the CE should not be overlooked and must be integrated along with economic and ecological dimensions. Such an attempt was conducted through a multi-scale integrated analysis of societal metabolism in China, revealing a need for a more balanced development strategy and sector structure combining the economic progress with the social welfare of the people (Geng et al., 2011). This result is of particular interest since China was one of the pioneers in adopting and promoting the CE terminology.

Table 1: Indicative PSE contributions for achieving different CE goals:
1-Reduce material losses/residuals, **2**-Reduce input and use of natural resources, **3**-Increase energy efficiency and the share of renewable, **4**-Reduce emission levels, **5**-Increase the value durability of products

PSE field	Circular Economy Goal				
	1	2	3	4	5
Multi-objective Optimization	Nie et al. (2019); Ahmetovic et al. (2010)	Hugo and Pistikopoulos (2005); Nie et al. (2019); Gao and You (2015); Ahmetovic et al. (2010); Bernardi et al. (2012); Garcia and You (2015a); Kursun et al. (2015)	Nie et al. (2019); Dahdah and Mitsos (2014); Ahmetovic et al. (2010); Garcia and You (2015a); Kursun et al. (2015)	Hugo and Pistikopoulos (2005); Cadavid-Giraldo et al. (2016); Santibañez-Aguilar et al. (2014); Krajanja and Čuček (2013); Nie et al. (2019); Li and Guo (2014); Bernardi et al. (2012); Čuček et al. (2012); Kursun et al. (2015)	
Multi-scale Modeling and Opt.	Taifouris and Martin (2018)	Walmsley et al. (2019)	Walmsley et al. (2019)		

Table 2: Indicative PSE contributions for achieving different CE goals:
1-Reduce material losses/residuals, **2**-Reduce input and use of natural resources, **3**-Increase energy efficiency and the share of renewable, **4**-Reduce emission levels, **5**-Increase the value durability of products

PSE field	Circular Economy Goal				
	1	2	3	4	5
Supply Chain Optimization	Nikolopoulou and Ierapetritou (2012); Santibañez-Aguilar et al. (2013); Niziolek et al. (2018)	Hugo and Pistikopoulos (2005); Gao and You (2015); Aviso et al. (2011); Bernardi et al. (2012)	Nikolopoulou and Ierapetritou (2012); Vance et al. (2012)	Hugo and Pistikopoulos (2005); Cadavid-Giraldo et al. (2016); Nikolopoulou and Ierapetritou (2012); Vance et al. (2012); Santibañez-Aguilar et al. (2014); Kravanja and Čuček (2013); Bernardi et al. (2012); Čuček et al. (2012)	
Optimization under uncertainty	Nemet et al. (2015)	Lira-Barragan et al. (2016); Paul et al. (2000); Aviso et al. (2011)	Wang et al. (2018)	Li and Guo (2014); Wang et al. (2018)	

Table 3: Indicative PSE contributions for achieving different CE goals:

PSE field	Circular Economy Goal				
	1	2	3	4	5
Mixed-Integer Optimization	Nikolopoulou and Ierapetritou (2012); Bieber et al. (2018); Papalexandri et al. (1994); Santibañez-Aguilar et al. (2013); Reaff et al. (1999); Nie et al. (2019); Demirel et al. (2017a); Niziolek et al. (2018)	Hugo and Pistikopoulos (2005); Nikolopoulou and Ierapetritou (2012); Bieber et al. (2018); Nie et al. (2019); Gao and You (2015a); Bernardi et al. (2012); Garcia and You (2015a)	Nikolopoulou and Ierapetritou (2012); Nie et al. (2019); Garcia and You (2015a); Proios and Pistikopoulos (2005a); Demirel et al. (2017a)	Hugo and Pistikopoulos (2005); Cadavid-Giraldo et al. (2016); Nikolopoulou and Ierapetritou (2012); Santibañez-Aguilar et al. (2014); Bieber et al. (2018); Kravanja and Čuček (2013); Nie et al. (2019); Bernardi et al. (2012); Čuček et al. (2017a)	
Resource Management	Bieber et al. (2018); Haque et al. (2000); Nelen et al. (2014)	Bieber et al. (2018); Haque et al. (2000)		Bieber et al. (2018)	

Table 4: Indicative PSE contributions for achieving different CE goals:
1-Reduce material losses/residuals, **2**-Reduce input and use of natural resources, **3**-Increase energy efficiency and the share of renewable, **4**-Reduce emission levels, **5**-Increase the value durability of products

PSE field	Circular Economy Goal				
	1	2	3	4	5
Food-Energy-Water Nexus	Bieber et al. (2018); Garcia and You (2017); Nie et al. (2019)	Bieber et al. (2018); Garcia and You (2016); Nie et al. (2019); Gao and You (2015); Garcia and You (2015a)	Garcia and You (2016); Nie et al. (2019); Garcia and You (2015a)	Bieber et al. (2018); Nie et al. (2019)	
Process Integration and Intensification	Tula et al. (2017); Demirel et al. (2017a); Ponce-Ortega et al. (2012); Lam et al. (2011); Kravanja et al. (2015)	Tula et al. (2017); Ponce-Ortega et al. (2012)	Proios and Pistikopoulos (2005a); Demirel et al. (2017a); Yan et al. (2018); Lam et al. (2011); Kravanja et al. (2015)	Tula et al. (2017); Ponce-Ortega et al. (2010); Demirel et al. (2017a); Agarwal et al. (2010a); Portha et al. (2014); Lam et al. (2011); Kravanja et al. (2015)	

Table 5: Indicative PSE contributions for achieving different CE goals:
1-Reduce material losses/residuals, **2**-Reduce input and use of natural resources, **3**-Increase energy efficiency and the share of renewable, **4**-Reduce emission levels, **5**-Increase the value durability of products

PSE field	Circular Economy Goal				
	1	2	3	4	5
Sustainable process synthesis and design	Tula et al. (2017); Nikolopoulou and Ierapetritou (2012)	Tula et al. (2017); Nikolopoulou and Ierapetritou (2012)	Nikolopoulou and Ierapetritou (2012); Vance et al. (2012); Kravanja and Čuček (2013); Bertran et al. (2017)	Nikolopoulou and Ierapetritou (2012); Vance et al. (2012); Kravanja and Čuček (2013); Bertran et al. (2017)	Nikolopoulou and Ierapetritou (2012); Vance et al. (2012); Kravanja and Čuček (2013); Bertran et al. (2017)
LCA	Tula et al. (2017); Carvalho et al. (2013); Nikolopoulou and Ierapetritou (2012); Cristóbal et al. (2016)	Tula et al. (2017); Carvalho et al. (2013); Hugo and Pistikopoulos (2005); Nikolopoulou and Ierapetritou (2012); Kursun et al. (2015)	Carvalho et al. (2013); Nikolopoulou and Ierapetritou (2012); Kursun et al. (2015)	Hugo and Pistikopoulos (2005); Nikolopoulou and Ierapetritou (2012); Santibañez-Aguilar et al. (2014); Čuček et al. (2012); Kursun et al. (2015)	Carvalho et al. (2013); Hugo and Pistikopoulos (2005); Nikolopoulou and Ierapetritou (2012); Santibañez-Aguilar et al. (2014); Čuček et al. (2012); Kursun et al. (2015)

2.1.2. Life Cycle Assessment (LCA)

Any attempt towards analysis, modeling, implementation and/or assessment of the CE requires a holistic and structured approach that has Life Cycle Assessment (LCA) as an inherent attribute. Being an internationally standardized method, LCA quantifies 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 (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010) and has recently emerged as the main tool to evaluate sustainable development. Toxopeus et al. (2015) and Neugebauer et al. (2015), model processes and properly judge different options towards the implementation of CE (Sauvé et al., 2016). As illustrated in Table 5, the PSE community has been using LCA approaches extensively and has been developing tools and methodologies around it. Extensions that would allow the consideration of the value durability of products in an LCA assessment would make this tool extremely useful for CE decision making and assessment.

2.1.3. Process Intensification

Process intensification (PI) have been gaining increasing momentum from the chemical engineering research community and the chemical/energy industry during the past several decades (Stankiewicz and Moulijn, 2000; Van Gerwen and Stankiewicz, 2009). Although there is also a significant lack of clarity on the scope and definitions of PI (see Keil (2018) and Tian et al. (2018) for the summary and evolution of PI definitions), we can still gain insights on the synergy between circular economy and process integration and intensification through some representative definitions. One of the early definitions

for PI given by Cross and Ramshaw (1986) defined PI as a methodology for making remarkable reductions in equipment size, energy consumption, or waste generation while achieving a given production goal. In another well-accepted definition, Stankiewicz and Moulijn (2000) recognized PI as the development of novel apparatuses and techniques that are expected to bring dramatic improvements in manufacturing and processing, substantially decreasing equipment-size/production-capacity ratio, energy consumption, or waste production, and ultimately resulting in cheaper, sustainable technologies. From these definitions, it is obvious that process integration and intensification along with the circular economy share commonalities in reducing energy consumption, minimizing waste production, improving sustainability performance, reducing capital/operating costs, etc. Moreover, PI aims to substantially improve chemical processes. For example, one of the evaluation metrics for the intensified process modules currently under development, set by the Rapid Advancement in Process Intensification Deployment (RAPID) Manufacturing Institute (<https://www.aiche.org/rapid>), is to achieve 10x reduction in capital cost, 20% improvement in energy efficiency, and 20% lower emissions/waste related to commercial state of the art. It is also worth noting the unique nature of process integration and intensification for innovation (i.e., novel process schemes and equipment), which renders PI an enriched design space to discover out-of-the-box process solutions (Bielenberg and Palou-Rivera, 2019). Specifically from process systems engineering (PSE) perspective, the development of systematic strategies and advanced computer-aided tools to assist quantitative decision making in PI applications has been the topic of many academic works, with considerations on

energy savings (Proios and Pistikopoulos, 2005b), sustainability (Tula et al., 2017), waste minimization (Demirel et al., 2017b), emission reduction (Agarwal et al., 2010b), and etc. For detailed state-of-the-art advances in these areas, readers are referred to the extensive reviews given by Tian et al. (2018); Moulijn et al. (2008); Lutze et al. (2010); Sitter et al. (2019); Tian and Pistikopoulos (2018); Demirel et al. (2019).

3. Scientific needs and challenges in Circular Economy research

Several challenges and scientific needs for PSE to assist in the convergence towards a CE have been identified. Major challenges arise in the modeling, optimization and decision making for supply chains and their transition from a linear to a circular economy. These challenges include: i) interconnected supply chains, ii) boundary selection, iii) multi-scale issues, iv) multiple stakeholders and objectives, v) uncertain and dynamic conditions and vi) no widely accepted assessment criteria among others. This section is focused on the discussion of some of those challenges.

3.1. Interconnected supply chains, boundary selection, and multi-scale issues

Product supply chains are highly interconnected making the selection of system boundary conditions very challenging. Similarly to LCA studies, system boundary definition plays a critical role in the context of the results from such an analysis. Circularity, in terms of CE, is a property of entire interconnected supply chain that includes the micro (consumers, companies), the meso (eco-industrial parks) and macro (city, nation) levels, therefore system boundaries should be greatly expanded beyond the traditional process boundaries the PSE community is currently exploring.

The extension of the boundaries introduces multiple scales, both spatial and temporal, with each level having the potential to impact the rest of the levels. For example, the operation of an industrial process unit (e.g. reactor, separator, etc.) can impact the operation of the whole industrial plant, and sequentially any other industry or consumer down the supply chain using the products of the first plant. The interaction between the different special and temporal scales introduces high complexities in the modeling and optimization of CE supply chains. Modeling and optimization of some of the individual scales have been widely explored by the PSE community (e.g. process units and industrial plants), although the consideration of individual levels neglects the connectivity between them and can lead to sub-optimal or even infeasible solutions.

Although multi-scale approaches have been developed in the PSE community (Section 2.1.1.), they were mainly applied to industrial case studies, that did not involve all scales relevant to CE, such as consumers at the household level or diplomatic relations at the global scale. Gaining knowledge for the modeling of such scales that have not yet being explored by the PSE community is a vital step for multi-scale modeling and optimization of CE supply chains.

Furthermore, highly interconnected CE supply chains, with expanded boundaries and multiple scales would consist of large-scale mixed-integer problems that are challenging to solve. Even though many tools and algorithms have been proposed for the solution of this class of problems (Papageorgiou, 2009; You and Grossmann, 2008; Garcia and You, 2015b) more efficient approaches must be explored.

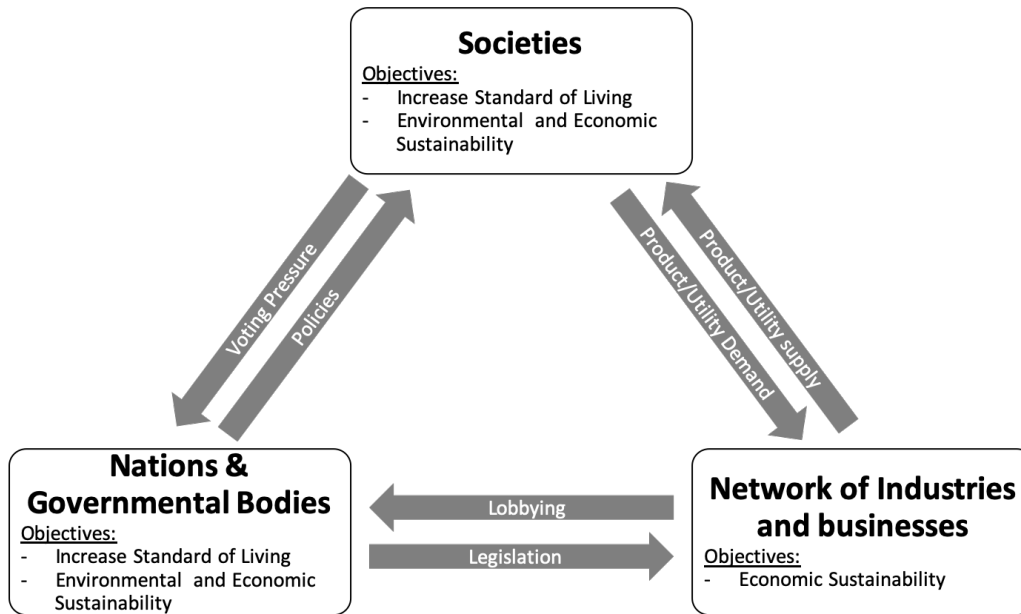


Figure 3: CE stakeholders, their interconnections and conflicting objectives

3.2. Multiple players and objectives

Product supply chains are often managed by different companies, governments, and consumers. Figure 3 shows that different stakeholders in a CE supply chain have competing interest and objectives. Furthermore, each entity can affect the actions and outcomes of the other entities; for example, a governmental policy can change the behavior of societies, such as their energy consumption patterns or diet preferences, affecting the demand of these utilities and products, and subsequently affecting the industries and businesses supplying those. In turn, the industries can lobby against these new policies and affect the governmental decision-making process. These multiple interconnected stakeholders and their differing or conflicting objectives introduce major challenges in modeling and decision making, requiring game

theoretic approaches, such as multi-agent hierarchical optimization, that require a Stackelberg equilibrium for their solution (Geissdoerfer et al., 2018; Avraamidou et al., 2018; Brauers, 2013).

Even though the economic objectives of companies have been widely studied by the PSE community, the consideration of the interest of the wider range of the stakeholders involved in a CE supply chain, such as consumers, regulators and local authorities has not being yet explored by the PSE community, making the modeling of such supply chains even more challenging.

3.3. Dynamic and Uncertain conditions

In the existing unstable environment, with constantly changing market conditions and customer needs and expectations along with climate change, it is of high importance to consider the effect of uncertainties when modeling a CE supply chain. Sources of uncertainty in a CE supply chain may include variations in processing rates, canceled or rushed orders, equipment failure, raw material, final product or utility price fluctuations, demand variations and climate changes (Gupta and Maranas, 2003). Failure to consider these uncertainties can lead to unsatisfied customer's demands and loss of market share by the industries and businesses involved along with environmental costs. Therefore considering these uncertainties and their effect appropriately in the modeling of CE supply chains is critical but can result in new technical challenges as the size and complexity of the models is increased.

A number of publications have been devoted to studying supply chain planning under demand uncertainty or price fluctuations in the PSE community (Guillen et al., 2005; Gupta and Maranas, 2003; Santoso et al., 2005; Avraamidou and Pistikopoulos, 2017), although not the same attention has

been given for other sources of uncertainties, such as population growth or raw material depletion. Climate change has also received a lot of attention as many researchers are focusing on the development of inherently safer process and network designs that can withstand extreme weather events, therefore reducing the human and economic, and environmental costs (Gupta and Edwards, 2002; Panteli and Mancarella, 2015).

Key methodologies behind the approaches listed above are robust and stochastic programming (Li et al., 2011; Birge and Louveaux, 2011). These fields have been widely explored by PSE and other communities with the development of approaches for the solution of different classes of optimization problems under uncertainty such as adjustable robust optimization (Avraami-dou and Pistikopoulos; Lappas and Gounaris, 2016; Bertsimas and Georghiou, 2018), and multi-stage stochastic optimization (Allen et al., 2019; Balsa-Canto et al., 2005).

3.4. Assessment Criteria

A method for evaluating and comparing different circular economy pathways and scenarios is vital for effective decision making. A selection of metrics relevant to CE has been collected and evaluated by Parchomenko et al. (2019). These metrics were developed for measuring different aspects of CE but not CE holistically. Furthermore, an approach for the development of a CE metric limited to the flow of materials has been developed by Garcia-Barragan et al. (2019). Tools have also been developed that can be used to track the transition of nations towards CE and circularity of materials (Edgerton et al., 2018; Cayzer et al., 2017; Saidani et al., 2017; Ellen MacArthur Foundation and Grata Design, 2015; Haupt et al., 2017; Linder

et al., 2017). Despite the availability of metrics, CE has only been measured at national or material levels with the main focus on material flows, while no metric is currently applicable at the product supply chain level or company level, therefore efforts for the development of a CE metric that can be effectively used in decision making should be made.

4. Motivating Case Study - The Supply Chain of Coffee

This section is focusing on the illustration of the aforementioned challenges and opportunities through the coffee supply chain.

Coffee is one of the most popular beverages worldwide with more than 155 million 60-kg bags of coffee being consumed yearly worldwide (Samoggia and Riedel, 2018; ICO, 2017). The global coffee supply chain creates an estimated 23 million tons of organic coffee waste per year (Pauli, 2010). In fact just one cup of coffee (containing about 10g dry coffee), produces through its entire supply chain about 49g of CO_2 emissions (Hassard et al., 2014), 9.9g of dry spend coffee waste, 6.9g of dry coffee pulp, husk and skin waste (Murthy and Naidu, 2012) and plastic used for packaging, cups, straws and stirrers. Furthermore, just for one cup, 140L of water (mainly for irrigation) (Chapagain and Hoekstra, 2003) and 0.13 kWh of energy (Hassard et al., 2014) is needed.

As the coffee supply chain produces a lot of waste and uses a lot of resources, it is highly relevant for the transition towards a CE and easily understandable, therefore it was chosen here to illustrate and communicate the complex issues arising from the transition towards CE and opportunities for PSE.

The following subsections present the linear and circular coffee supply chain, discuss the challenges that arise from the transition and the opportunities for PSE to assist in this transition.

4.1. The transition from a linear to a circular coffee supply chain

The wastes produced and the resources used can be minimized when the linear economy structure of the coffee supply chain evolves into a circular economy structure. Figure 4 illustrates a simplified coffee supply chain. Energy (mainly from fossil fuels) is used for every process in the supply chain, while water is used and contaminated in many processes (highly based on the coffee processing methods). Furthermore, waste is created at every stage; **W1** corresponds to the wastes and emissions created when fossil fuels are used for the generation of energy, **W2** corresponds to the water contaminated with fertilizers during irrigation processes, **W3** are bad coffee berries collected during harvesting, **W4** are berries parts (the coffee pulp, coffee husk, and silver skin) that are discarded during processing, **W5** corresponds to spillages and degradation during packaging, **W6** corresponds to plastic waste, **W7** corresponds to expired and degraded packaged coffee, **W8** corresponds to expired coffee, spent coffee and plastic packaging and **W9** corresponds to the plastic cups, straws, and stirrers.

The transition towards a circular economy coffee supply chain (Figure 5) would require the transition to renewable energy resources and reusable packaging solutions. Processes that are more energy efficient, produce less waste and contaminate less water will need to be chosen. It would also require the collection of all created waste and their processing to produce alternative products. Furthermore, natural resources (water and nutrients) need to be

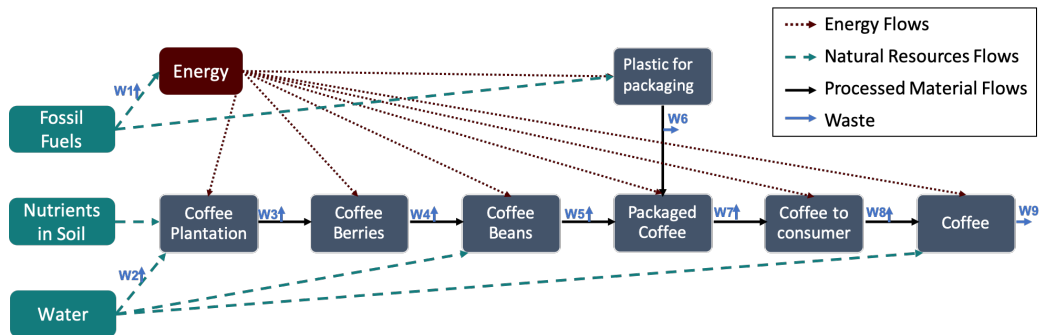


Figure 4: Supply chain of coffee in a **linear** economy

returned to their source, therefore, closing the loops and creating a circular economy that is closed in terms of material flows and open in terms of energy flows.

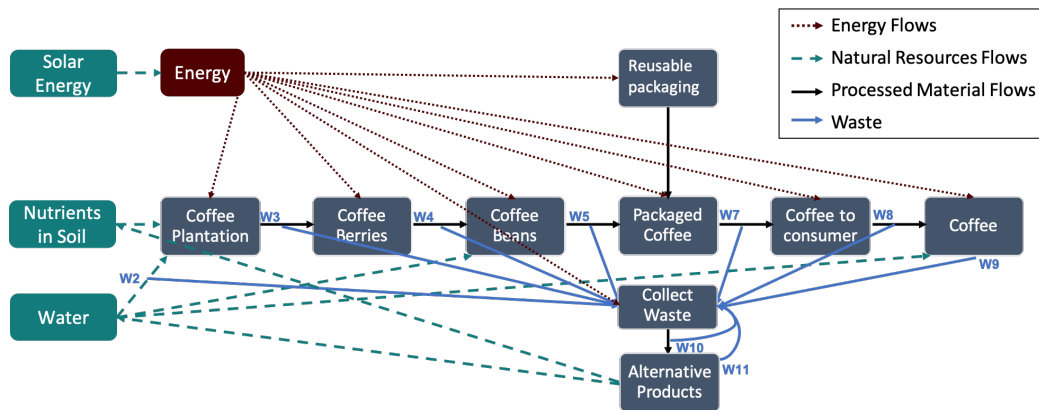


Figure 5: Supply chain of coffee in a **circular** economy

4.1.1. Coffee organic wastes and alternative waste management pathways

Coffee production generates waste from the coffee berries amounting to more than 50% of the fruit mass (Tsai et al., 2012), while spent coffee (the residue obtained during the brewing process) constitutes about 99% of the

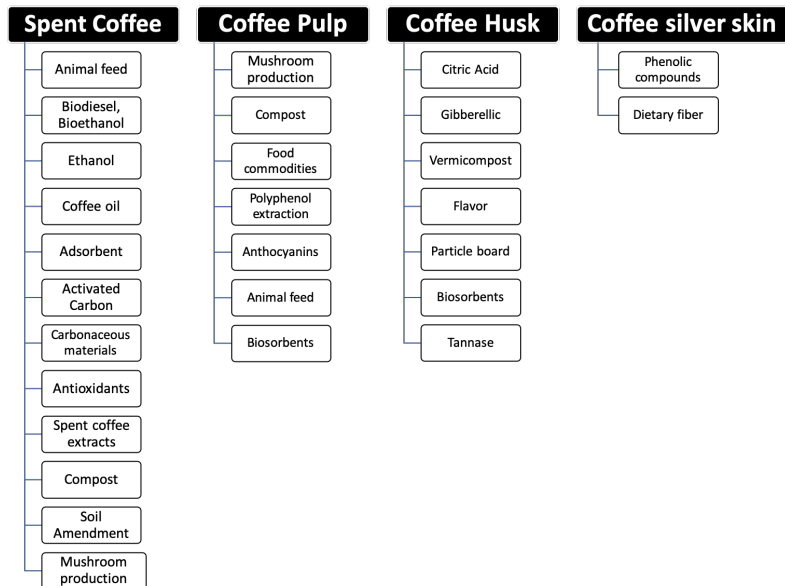


Figure 6: Alternative product pathways from organic coffee waste (Murthy and Naidu, 2012; Karmee, 2017)

dried roasted coffee bean. In most of the soluble coffee producing industries, the waste is collected at a cost and disposed or, in limited cases, it is used as a raw material for different purposes. A selection of the different products that can be produced from organic coffee waste is illustrated in Figure 6. These different pathways can reduce not only the economic and environmental costs of disposal but also generate revenue from an undervalued material.

4.1.2. Challenges and opportunities for PSE

The transition of the coffee supply chain from a linear to a circular economy consists of many challenges but at the same time many opportunities for PSE. This section summarizes some of these challenges and the corresponding research opportunities for PSE.

Assessment of multiple pathways. As discussed in section 4.1.1., there are a lot of different pathways developed for the utilization of organic waste created along the supply chain of coffee (Figure 6). The huge amount of waste generated annually in the production of coffee along with the large number of alternative pathways available for waste utilization requires sophisticated waste management plans for optimal operation. Furthermore, many of the illustrated pathways have been reviewed and demonstrated mainly at a lab scale (Murthy and Naidu, 2012; Karmee, 2017; McNutt and He, 2019), making them not reliable on a larger meaningful scale. Modeling and optimization can be used to predict the technical and economic feasibility of these pathways at a larger scale. A techno-economic analysis of the different pathways will require collaborative work between PSE and experimental scientist working on the different utilization pathways, in conjunction with industry to identify which of these processes are technically and economically viable and can add value to both the industries and the environment.

Similarly to waste management, there are different pathways for coffee harvesting, processing, and packaging. Process integration and intensification may be able to develop further integrated and intensified processes for the processing of coffee that are more energy and resource efficient. A methodology to holistically evaluate these different pathways is of great importance. CE assessment metrics along with superstructure representations and optimization of the alternative coffee supply pathways would be necessary tools for preliminary screening of the different technologies. Using these as the first step, more detailed models can be built for further and more reliable assessment of the most promising coffee supply chain pathways.

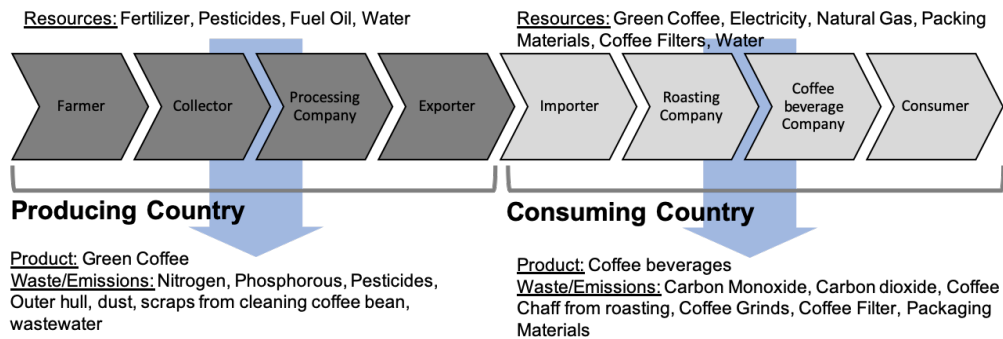


Figure 7: Example of the chain of stakeholders in a coffee supply chain

Multiple stakeholders. 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 (Figure 7). Farmers and industries are focusing on increasing their profits, while regulators and policymakers can have multiple objectives including the minimization of environmental impact in their nation, the cost of coffee for their societies and the maximization of profit for their farmers and industries (Figure 3). Consumers, on the other hand, are focusing on enjoying the best cup of coffee at the most ‘reasonable’ price, although the brand loyalty should not be overlooked. Studies in different industries have shown that loyal customers are less price sensitive, they are frequent buyers of current products and willing to try new products and services, while at the same time they bring in new customers (Tu et al., 2012). Reichheld and Sasser (1990) revealed that loyal customers can boost company’s revenues since a 5 percent increase in customers retention leads to a surge of 25-75 percent in profit.

Moreover, Wills (2009) indicated that the cost to attract a new customer is 5 times higher than to maintain an existing one. In the coffee industry, the brand loyalty has emerged as a crucial factor for the sustainability and growth of the coffee organizations in today's extremely competitive, international business environment. In particular, brand satisfaction was indicated as the most important contributor to building brand loyalty, while cognitive and affective factors such as brand awareness, brand image, pleasure and arousal, along with relationship commitment are the rest of the key drivers towards building brand's loyalty.

Furthermore, there is a hierarchy in the decisions taken by the different stakeholders, for example, policymakers can come up with a new policy on the type of fertilizers allowed for coffee farming, the farmers then can increase the price of the coffee beans if the new fertilizers are more expensive, this change in coffee bean price will gradually climb up the ladder, potentially reaching the consumers. Importers might choose to import more coffee from another nation that has cheaper coffee beans. Coffee brands might not be willing to switch to different coffee beans unless it becomes absolutely mandatory since this is going to affect their final product and potential harm their brand loyalty. Consumers might potentially not like the new coffee or do not want to pay more for the coffee they were used to having, therefore the fluctuating demand for the different types of coffee will affect all stakeholders involved. Consequently, a global shift from the current linear, throwaway model to a circular, restorative/recycle model is necessary and shall be viewed from all parties involved as a pioneering and rewarding opportunity in the 21st century. The scarcity of resources and the environmental standards have

become a reality and will continue to be on the top of the agenda. At the same time we have already witnessed a shift in the consumers' behavior in the direction of a greener and more environmentally friendly ecosystem of products and services.

Both public and private sectors though should closely collaborate making this a smooth transition. Governments and policy makers shall adjust the rules, advance the taxation and regulatory environment, setting the direction to a circular and international model and at the same time provide incentives that promote innovation and entrepreneurship. On the other hand, the private firms shall take advantage of the quickly altering business environment, and advance their recycling technologies, redesign their business models, optimize their supply chain networks, minimize their dependence in depleted resources, re-brand their products and services so as to attract new customers and eventually re-position themselves in the global market (Ellen MacArthur Foundation, 2013). In a recent report, the U.S. Chamber of Commerce Foundation Corporate Citizenship Center along with the Ellen MacArthur Foundation illustrated an extensive list of companies that utilize the principles of circular economy in a profitable and rewarding way (US Chamber of Commerce Foundation, 2015). Apparently, the adoption and incorporation of the circular economy could generate an estimated of over 1 trillion US dollar annually by 2025, create 100,000 new jobs and prevent 100 million tonnes of materials waste within five years (World Economic Forum, 2014).

Therefore, hierarchical and multi-objective optimization will be needed to model this highly interconnected supply chain. Such formulations would

make both modeling and solving the coffee supply chain problem very challenging. Multi-objective strategies developed and used in the PSE community can be directly applied to this problem. Moreover, the PSE community has focused on the solution of two or three level hierarchical optimization systems (Mitsos, 2010; Avraamidou and Pistikopoulos, 2018b,a, 2019), therefore a focus on extending the methodologies developed for problems with more hierarchical levels and decision players is of great importance.

Multi-scale modeling. The coffee supply chain is spanning different countries as most of the coffee in the market is produced in a different country than the one that it is consumed (Figure 7). Based on the UN Comtrade Database, in 2017 more than 30% of the total production of coffee was produced in Brazil and it was exported and consumed in 108 different countries.

The multi-spacial and multi-temporal nature of the coffee supply chain introduces challenges in modeling and optimization. Multi-scale modeling approaches that would allow multi-spacial and multi-temporal considerations in supply chain modeling need to be further developed. Effective decomposition methods for the large scale models that will be created will also be vital for the solution of the optimization problems.

5. Conclusion

Circular economy (CE) is considered as an approach that effectively matches the economic growth with sustainable economic, environmental and social development, providing an alternative, cyclical flow model to the conventional linear economy models (Ellen MacArthur Foundation and Grata

Design, 2015). The move towards such an economy model can result in many challenges but also many opportunities for PSE.

In this work we have presented a literature review listing PSE approaches that have been developed and can be used to facilitate the transition towards CE. PSE literature gaps, such as the exploration of the objectives of different stakeholders, were identified and areas with great potential that PSE community should explore have been suggested.

In conclusion, it was illustrated that a Systems Engineering approach can have a big impact on the understanding, analysis, and optimization of Circular Economy Supply Chains, and the convergence of different disciplines towards a common vision of Circular Economy.

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