Circular Economy Systems Engineering for Food Supply Chains: A Case Study on the Coffee Supply Chain

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Abstract

Food supply chains rely heavily on the extraction of finite natural resources, including phosphorus, potassium, and fossil fuels. Population growth, welfare growth, and the constant need for an increasing standard of living increase the demand for food, leading to natural resource degradation, increased landfill wastes, water contamination, and increased greenhouse gas emissions. Circular Economy (CE) can be a solution for the transition of food supply chains to a more sustainable and regenerative future. A holistic systems engineering approach is clearly needed to navigate the multi-scale, multi-faceted, and interconnected CE food supply chain, identify opportunities for synergistic benefits and systematically explore interactions and trade-offs. In this work, we present the foundations of a systems engineering framework and quantitative decision-making tools for the analysis and trade-off optimization of interconnected food supply chains. We focus on the supply chain of coffee, as coffee is one of the most popular beverages worldwide. A superstructure representation of the supply chain of coffee is presented.

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 standard of living requirements mean that more and better goods are in demand, which in turn require more natural resources and manufacturing activity.

More specifically, food supply chains rely heavily on the extraction of finite natural resources, including phosphorus, potassium, and fossil fuels. The increase in the demand for food, is leading to natural resource degradation, increasing landfill wastes, water contamination, and increasing greenhouse gas emissions.

Circular Economy (CE) can be a solution for the transition of food supply chains to a more sustainable and regenerative future [MacArthur and Waughray (2016)]. 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. CE will contribute to all dimensions of sustainable development: economic, environmental, and social; operating at three levels – the micro level (products, companies, consumers), meso level (eco-industrial parks), and macro level (city, region, nation and beyond). Businesses and policymakers initially developed the concept of CE, but there is little scientific guidance about how to best implement it or evaluate its effectiveness. To achieve CE, four areas of system improvements have been suggested: reuse, repair, remanufacturing, 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.

In general, 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 are summarized as follows:

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 in direct emissions/pollutants.
5. *Increase the value durability of products:* Extension of product lifetime through the redesign of products and high-quality recycling.

Fulfilling these goals and implementing a holistic approach for the CE is a challenging task. Governments, industry and academia over the recent years have shown an increasing attention towards CE, however we are still at an early stage. Innovation for circularity and sustainability have become not only a necessity due to climate change and economic environment but a fundamental for all involved parties to maintain and/or improve their competitive advantage in the 21st century. The intrinsic complexity and comprehensive nature of CE mandates multidisciplinary and collaborative efforts. Process systems engineering (PSE) accompanied by environmental engineering and horticultural sciences could play a crucial role in providing the required tools towards the transition to CE food supply chains. In particular, our recent work showed a clear overlap between the objectives that have been explored by the PSE community and the CE reported goals [Avraamidou, Baratsas et al. (2020)].

While most work on CE emphasizes the macro level, it is clear that a holistic systems engineering approach is needed to navigate and fully consider the multi-scale, multi-faceted and interconnected CE supply chain, identify opportunities for beneficial improvement, and systematically explore interactions and trade-offs [Avraamidou, Baratsas et al. (2020)].

In this work, we present the foundations of a systems engineering framework and quantitative decision-making tools for the analysis and trade-off optimization of interconnected food supply chains. The framework combines data analytics and mixed-integer modeling & optimization methods to establish the interconnections between different stages of the circular food supply chains. The analysis of the trade-offs is empowered by the introduction of composite metrics for CE that include waste, energy, and resource use minimization, as means to facilitate decision making and compare alternative processes, materials, resources, and technological options. To illustrate the applicability of the proposed framework we focus on the supply chain of coffee.

2. Coffee Supply Chain

Coffee is one of the most popular beverages globally with more than 155 million 60-kg bags of coffee being consumed yearly worldwide [Samoggia and Riedel (2018), ICO (2017)]. The global coffee sector has expanded significantly over the last decades, with the production being increased by 65% since 1990, driven mainly by the rising demand in the consuming countries (ICO 2019). The global coffee supply chain creates an estimated 23 million tons of organic coffee waste per year [Pauli (2010)] in the form of coffee pulp (CP), coffee husk (CH), coffee silver skin (SS), and spent coffee ground (SC) based on the processing method that was chosen. Along with the organic waste, the coffee supply chain also creates a large amound of single use plastic, used for packaging, capsules, cups, straws and stirrers. Moreover, large amounts of water and energy are used, and in return a lot of Green Hounse Gas (GHG) emmisions are released (Figure 1, Figure 2). However, a small fraction of the residues and wastes are reused even though there are plenty of studies demonstrating sustainable, and circular applications, namely biofuels, fertilizers, livestock feed, compost, food production and other value-added products such as pharmaceuticals, cosmetics, antioxidants etc. [Murthy and Naidu (2012), Figueroa, Homann et al. (2016)].

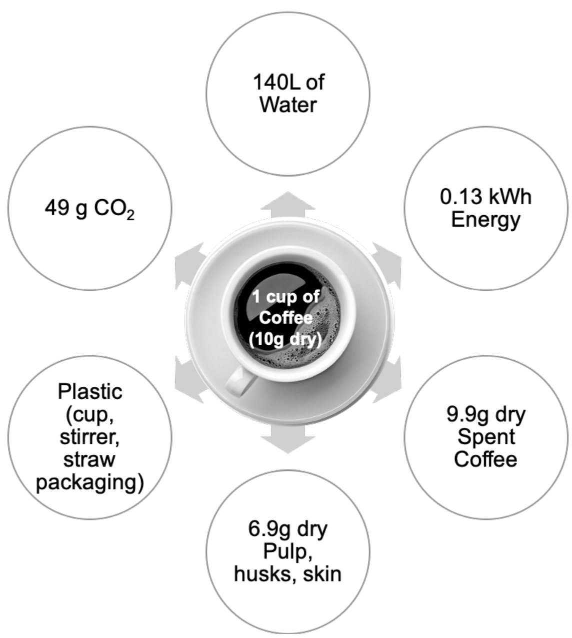

Figure 1 Waste generated just from one cup of coffee through its supply chain [(Chapagain and Hoekstra 2003),Okada, Rao et al. (1980),Murthy and Naidu (2012),Hassard, Couch et al. (2014)]

As the coffee consumption increases, so does the amount of organic coffee waste and the amount of resources used, aggravating both the waste and energy management problems. This is typical for the case of a linear supply chain where energy produced from fossil fuels is consumed in every process of the supply chain, while water is used and contaminated in many different processes, depending greatly on the processing method. A simplified linear supply chain of coffee is illustrated in Figure 2, showing the different flows and the wastes that are produced.

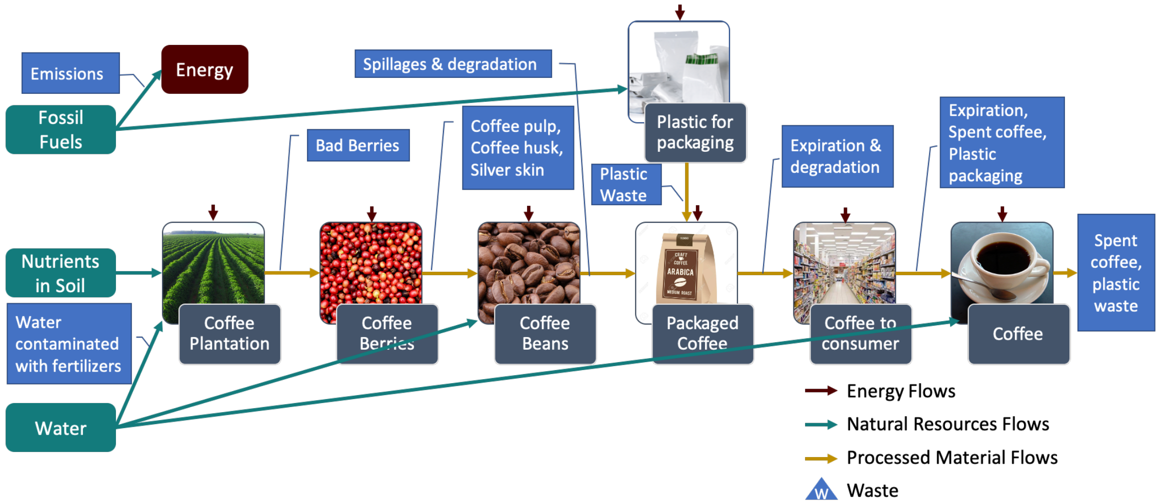

Figure 2 Linear Economy based Coffee Supply Chain

A solution to this problem would be the transition to a circular supply chain where renewable energy resources will be utilized; alternative and efficient products will be produced from the waste and reusable packaging materials will be used. The aim would be to open the loops of the energy flows, and close the loops of the resources and material flows of the supply chain. Figure 3 illustrates such a circular coffee supply chain.

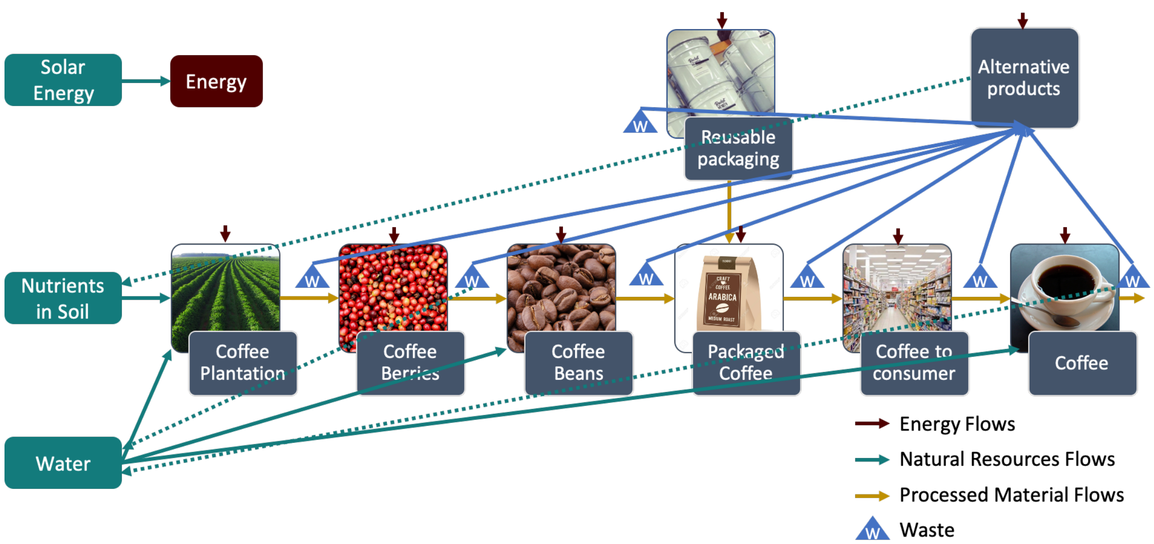

Figure 3 Circular Economy based Coffee Supply Chain

3. Coffee by-products

This transition of the supply chain from a linear to a circular coffee supply chain requires to overcome many challenges. First, we have to identify and evaluate the alternative

pathways. Thus, a superstructure representation of the supply chain of coffee is presented, which involves alternative pathways for coffee harvesting and processing, waste utilization, product distribution, and the introduction of new/alternative products. This type of analysis, in conjunction with feedback from experimentalists, can led to the identification of the optimum CE supply chain for coffee.
Following the cultivation of the coffee trees which takes about 5 years for the first full crop of beans, the fresh coffee cherries are collected from the coffee trees through selective harvesting (picking only the ripe fruits by hand) or strip harvesting (fruits striped at once with different maturity levels) [Chala, Oechsner et al. (2018)]. Then, the raw coffee fruit is converted into liquid coffee either through wet, semi-dried or dry processing methods, which vary in complexity, in quality as well as on the resultant by-products (Figure 4).

Pre-roasting by-products are coffee cherry husks from the dry processing method, and coffee pulp and mucilage from the wet processing method. Figure 4 illustrates the different steps and the resulted by-products of the processing methods. In particular, one ton of fresh coffee cherries processed through the dry method, produces around 150-200 kg of commercial green coffee, [Blinová, Sirotiak et al. (2017)] and around 180kg of husk [Adams and Dougan (1981)].

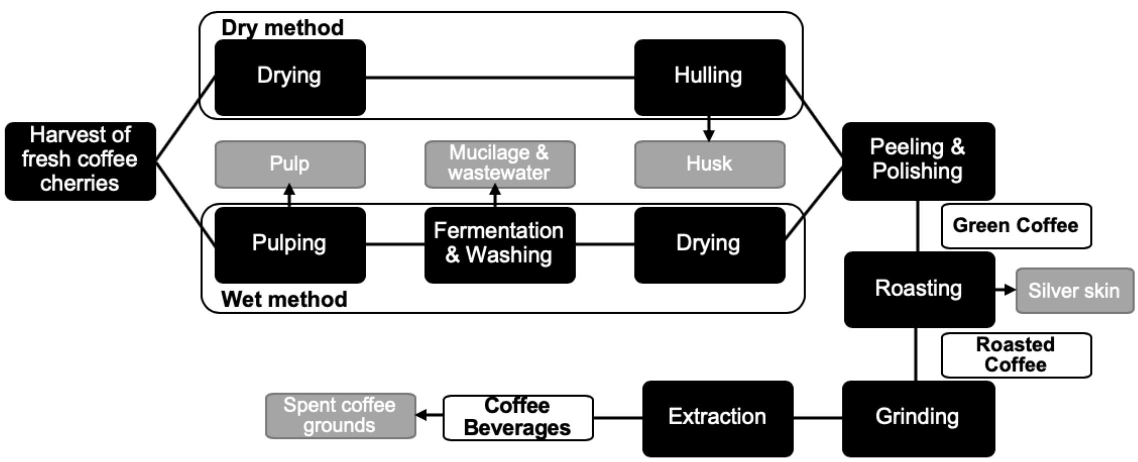

Figure 4 Dry and Wet Processing methods products and by-products (*Black:* Processing Steps, *White*: products, *Gray*: by-products)

On the contrary, 290kg of coffee pulp and 580kg of commercial green coffee are generated through the wet or semi-dry processing method for every ton of fresh coffee cherries [Blinová, Sirotiak et al. (2017)]. In addition to the enhanced productivity, the green coffee beans from the wet processing method are considered of superior quality, with greater aroma and are generally sold at higher prices. On the downside though, the wet processing method is water intensive requiring about 80 liters of water per kg of green bean [Esquivel and Jiménez (2012)].
Post roasting coffee by-products include the coffee silver skin (SS) which is released during roasting, and the spent coffee grounds (SCG) which are the by-products of the brewing process. Coffee silver skin is the least environmentally harmful by-product due to its composition (mainly dietary fibers and phenolic compounds), while on the contrary spent coffee grounds are the main source of coffee waste. According to Banu, Kavitha et al. (2020), 650kg of spent coffee grounds are generated for every ton of green coffee bean, while Dugmore (2014) and Blinová, Sirotiak et al. (2017) state that 910kg of spent

coffee grounds are released from 1 ton of ground coffee, and about 2 tons of wet spent coffee grounds are obtained per each ton of soluble coffee [Pfluger (1975)]

4. Coffee by-products utilization and management

Different pathways have been proposed by researchers for utilizing the coffee wastes and by-products and treating the contaminated waste waters. Extended reviews in the subject have been conducted by Murthy and Naidu (2012), Murthy and Naidu (2012), Hughes, López-Núñez et al. (2014), Rattan, Parande et al. (2015), Figueroa, Homann et al. (2016), Blinová, Sirotiak et al. (2017) who presented a variety of alternative pathways. 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. Bio-bean (https://www.bio-bean.com/) is such an example that offers coffee collection services and industrial scale coffee recycling, which turns coffee waste to biofuels, coffee logs, pellets, or even natural flavors and cosmetics, while at the same time provides significant environmental savings in the form of reduced CO2 emissions in comparison to the traditional methods of landfill (about 80% less CO2e emissions) or anaerobic digestion (about 70% less CO2e emissions).

The production of biogas utilizing the coffee by-products of husk, pulp, parchment, and mucilage which are generated through the wet and the dry processing methods are presented here. The reported values are based on the findings from Chala, Oechsner et al. (2018). In particular, wet method generated 0.6kg of pulp and 0.103kg of mucilage for each kg of produced coffee beans, while dry method generated 0.933kg of husk for each kg of produced coffee beans. The specific methane yields (SMY) of the coffee by-products are found to be comparable with those of commonly used agricultural residues and crops, with mucilage having the highest value, followed by pulp and husk, while parchment found to be unsuitable for anaerobic conversion (Table 1). Thus, anaerobic fermentation of the coffee by-products has the potential to generate significant amounts of energy either in the form of thermal energy or electricity which can be produced and consumed at the processing facilities, closing the loop and enabling circularity.

Table 1

Substrate	SMY (L/kg VS[1])	Methane Content (%)	Methane Energy (MJ/kg VS)	Energy Recovery (%)
Husk	159	51.5	6.33	33.7
Pulp	245	56.8	9.75	56.1
Mucilage	294	55.5	11.7	66.1

5. Conclusion

The transition towards a circular economy model for the food supply chain can result in many challenges. In this work we have presented a building blocks of a systems engineering framework for the analysis and trade-off optimization of interconnected food supply chains. In conclusion, it was illustrated that a Systems Engineering approach can have a big impact on the understanding, analysis, and optimization of Circular Economy

[1] Volatile solid

Food Supply Chains, and the convergence of different disciplines towards a common vision of Circular Economy.

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