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Synthesis of Renewable-Based Supply Networks with Closed Loops of Energy and Emissions

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This paper describes the development of a circularity model for the synthesis of supply networks for the production of energy and food, mostly from renewables, and the use of suitable sustainability measurements in order to promote sustainable designs. The model includes options for closed loops of energy, material, and emissions. For assessment of its circularity, Material Circularity Indicator (MCI) was used; however, in order to promote other sustainability measures, including economic, environmental and social ones, a recently proposed Sustainability Profit (SP) model was applied and its designs compared to those obtained by MCI. The concepts and model were demonstrated in a case study of a regional-scale renewable-based energy supply network for the production of food, biofuels, and electricity from photovoltaics, wind turbines, and binary cycle geothermal plants. The designs indicate that by maximization of SP, a similar level of circularity, but with higher economic profit, can be obtained than with MCI.

1. Introduction

In recent decades, more and more attention has been given to preserving the environment and natural resources, as well as sustainable development in general. Besides environmental issues, the social aspect of sustainability has become increasingly important as a result of high unemployment, increasing numbers of people living below the poverty line and other problems (Gontkovićova et al., 2015). Environmentally and socially sustainable operations have become an important topic in operations management literature in the last decade (Miao et al., 2016). In addition, consumers and governments have started pressuring companies to compromise some of their profitability in order to increase their sustainability (Tang and Zhou, 2012). Remanufacturing is playing important role in sustainable operations because of its significant value in recovering used products. By replacing or reprocessing used components from used products to produce “new” ones, remanufacturing can reduce the use of natural resources and the production of emissions and waste in the manufacturing process, which helps to enhance the environmental performance of companies (Miao et al., 2016). Closed-loop production systems strive for sustainability by improving economic and environmental goals simultaneously. In order to design such closed-loop production systems, the best option is in the form of sustainable supply chain networks (Winkler, 2011).

Supply chain networks can close the links between companies and waste production/consumption and thus improve sustainability. The closed-loop approach can valorize excess and waste energy and emissions through a cascade of processes addressing circular economy or cradle-to-cradle systems (Venkata Mohan et al., 2016). Recently, the need for increased product life-spans, material reuse, recycling, resource recovery, and industrial symbiosis leading to closed-loop processes (Figure 1) has been stressed (European Commission, 2013). For assessment of closed loop and circular economies, several indicators have been developed in recent years; one of these is the Material Circularity Indicator with all of its sub-indicators (Ellen MacArthur Foundation et al., 2015). Although the existing material, emissions, waste, and energy indicators are suitable for promoting closed loop systems and circular economies, unfortunately, they suffer from a lack of the economic and social components of sustainability. In order to assure that new designs are sustainable with respect to all of the economic, environmental and social pillars of sustainability, the sustainability criteria Sustainability Profit (Zore et al., 2017) and more recently the Sustainability Net Present Value were developed; both of these can be used successfully for the promotion of closed loop and circular systems.

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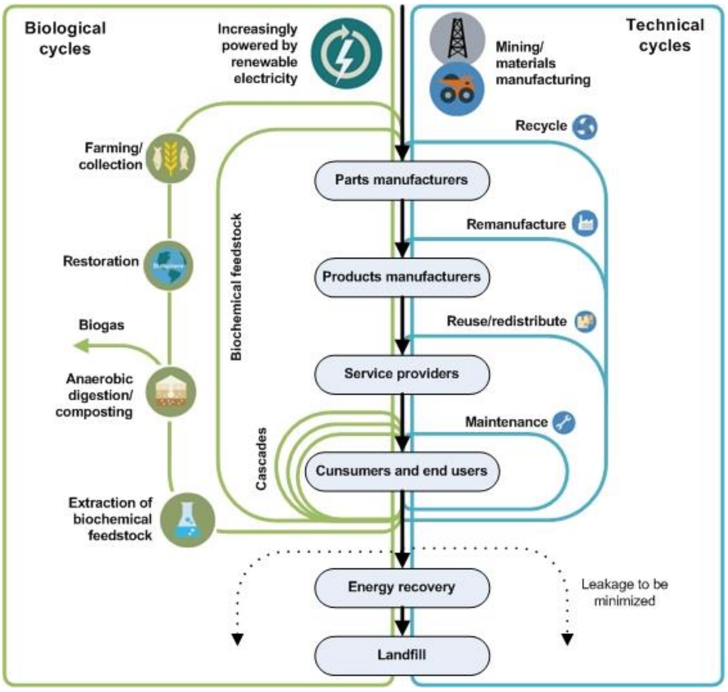

Figure 1: Circular economy – an industrial system that is restorative by design (after Ellen MacArthur Foundation et al., 2015)

This paper shows that with the use of sustainability criteria such as Sustainability Profit, we can obtain similar results from environmental studies as from those performed with circularity indicators. The multi-objective optimization approach is applied by using selected measurements as objectives that generate efficient and sustainable process solutions to manufacturing problems. In order to perform a multi-objective synthesis of renewable-based supply networks, a model based on four layers (Čuček et al., 2014a) and composite sustainability criteria (Zore et al., 2017) was applied.

2. Sustainability indicators and circular economy

Sustainability profit (SP) is a composite criterion of economic, environmental and social efficiency expressed in monetary terms and defined as the sum of Economic (P^{Economic}), Eco- (P^{Eco}) and Social Profit (P^{Social}) (Zore et al., 2017). As all the three basic components are monetary based, SP is intuitive and can be easily understood by the wider public. A higher value of SP and its components - economic, eco- and social profit - means that the design is more sustainable. With different combinations of the basic components (Economic, Eco- and Social Profit) we gain Viable profit (P^{Economic} and P^{Eco}), Equitable profit (P^{Economic} and P^{Social}) or Bearable profit (P^{Eco} and P^{Social}). Eq. (1) shows general and detailed representations for calculating SP, where weights w^a, w^b and w^c can take values between 0 and 1. If all coefficients have values of 1, Eq (1) resembles SP and the designs obtained are the most sustainable with the highest SP values.
In Eq. (1) the P^{Economic} is calculated with yearly revenue (R), expenditures (E) and depreciation (D). In P^{Eco} q_{m} represents mass flow rates and ($c_{i,t}$) and ($c_{j,t}$) eco-cost coefficients for raw materials and products, respectively, for technology t. Note that eco-cost coefficients represent marginal investments to avoid burdening the environment (Vogtländer et al. 2010). The investment in zero-waste is calculated by multiplying those coefficients with mass flow rates, which is called Eco-cost. An opposite case is Eco-benefit, which presents unburdening of the environment, as when waste is used as raw material rather than being dumped or when green products are produced instead of environmentally harmful ones. It is calculated the same way as Eco-cost; however, now it represents the decrease of the zero-waste investment. P^{Eco} is then defined as a surplus of Eco-benefit over Eco-cost. In this way, it considers both burdening and unburdening effects for raw materials (R^{B} and R^{UNB}) and products (P^{B} and P^{UNB}). Note that f denotes substitution ratio between amounts of previously used products (S) and currently substituted green products (P^{UNB}) (Čuček et al., 2012). P^{Social} is calculated regarding number of jobs created N_t^{Jobs}. For every job created there are average gross (s_t^{Gross}) and net salary (s_t^{Net}) in the production sector, for technology t. The state provides social transfers for unemployed ($c_{\mathrm{s}}^{\mathrm{UNE}}$) and employed people ($c_{\mathrm{s}}^{\mathrm{EMP}}$), and companies pay some social charge ($c_{\mathrm{s}}^{\mathrm{Company}}$) for improving the social status of

employed people (Zore et al., 2017). Because typically the intention is to maximize gains rather than to minimize losses, the term profit is used and the objective now is to maximize Sustainability Profit, thus simultaneously maximizing economic, eco and social profits.

$$
\begin{aligned}
SP &= w^a \cdot P^{\text{Economic}} + w^b \cdot P^{\text{Eco}} + w^c \cdot P^{\text{Social}} \\
&= w^a \cdot \left(R - E - D\right) && \mathrm{P}^{\text{Economic}} \\
&+ w^b \cdot \left(\begin{array}{l} \left(\sum\limits_{t\in T} \sum\limits_{i\in R_{\text{UNB}}} q_{m_i}^{\text{R}_{\text{UNB}}} \cdot c_{i,t}^{\text{R}_{\text{UNB}}} + \sum\limits_{t\in T} \sum\limits_{j\in P_{\text{UNB}}} q_{m_j}^{\text{P}_{\text{UNB}}} \cdot f_j^{\text{S/P}_{\text{UNB}}} \cdot c_{j,t}^{\text{S}} \right) \\ -\left(\sum\limits_{t\in T} \sum\limits_{i\in R_{\text{B}}} q_{m_i}^{\text{R}_{\text{B}}} \cdot c_{i,t}^{\text{R}_{\text{B}}} + \sum\limits_{t\in T} \sum\limits_{j\in P_{\text{B}}} q_{m_j}^{\text{P}_{\text{B}}} \cdot c_{j,t}^{\text{P}_{\text{B}}} \right) \end{array} \right) && \mathrm{P}^{\text{Eco}} \qquad (1) \\
&+ w^c \cdot \left(\sum_{t\in T} N_t^{\text{Jobs}} \left(s_t^{\text{Gross}} - s_t^{\text{Net}} \right) + \sum_{t\in T} N_t^{\text{Jobs}} \cdot c_s^{\text{UNE, State}} - \sum_{t\in T} N_t^{\text{Jobs}} \cdot \left(c_s^{\text{EMP, State}} + c_s^{\text{Company}} \right) \right) && \mathrm{P}^{\text{Social}}
\end{aligned}
$$

However, when only burdening was considered and terms for benefit were left out. Eq. (1) would represent Sustainability Cost; similarly, the sub-metrics would be reduced to bearability, viability, and equitability cost, and elemental-metrics to economic, eco- and social cost.

The Material Circularity Indicator (MCI) measures how restorative the material flows of a product or company are. MCI is the main circularity index and is typically used with complementary indicators that allow additional impacts and risks to be taken into account. The indicator can be used as a decision-making tool for designers, but may also be used for several other purposes including internal reporting, procurement decisions and the evaluation or rating of companies. The MCI can be calculated for each product or for a whole assortment of products at the company level. The MCI gives a value between 0 and 1, where a higher value indicates a higher circularity.

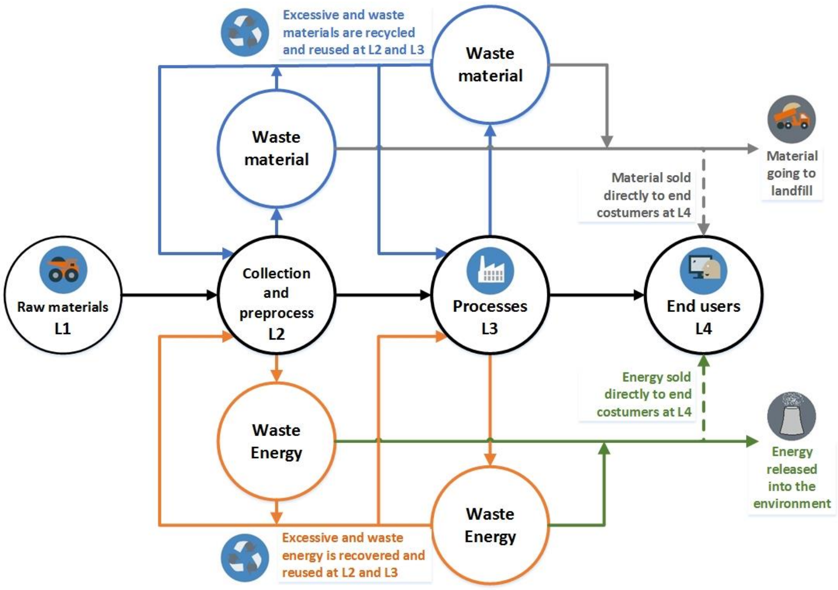

Figure 2: Circularity of material taken into account in a four-layer supply chain based on Čuček et al. (2014a) and Circularity Indicators from Ellen MacArthur Foundation et al. (2015)

The MCI is composed of sub-metrics that calculate input in a production process, utility during use phase, destination after use, and efficiency of recycling. The input of the production process is determined according to its fractions supplied from virgin and recycled materials and reused components. How long and intensely the product is used, compared to an industry average product of similar type, is considered in utility. This takes into account the increased durability of products, but also repair/maintenance and shared consumption business models. Destination after the use is determined by how much of the material goes into landfill (or energy recovery), how much is collected for recycling and which components are collected for reuse. The efficiency of recycling evaluates the efficiency of the recycling processes used to produce recycled input and to recycle material after use (Ellen MacArthur Foundation at al., 2015).

Because of the complexity of the data needed to calculate MCI, for a larger supply chain the focus is on material and energy circularity. The integration of the circularity concept into the four-layer supply network for the production/supply of energy by Čuček et al. (2014a) is shown in Figure 2. The circularity in the supply chain is defined by Eq. (2). The intention is to obtain designs with the highest fraction of recycled, reused and recovered excessive and waste materials, Fi, in processing plant i. Other symbols in Eq. (2) are virgin feedstock for the process, $q_{m_i}^{\text{Total}}$, and total mass of the material, $q_{m_i}^{R}$.

$$\sum_{i \in R} q_{m_i}^{R} = \sum_{i \in R} q_{m_i}^{\text{Total}} (1 - F_i) \tag{2}$$

Note that the fraction can represent circulating energy, such as utilities, medium pressure steam, cooling water and others. If the waste or emissions from one process are used as feedstocks for other processes, we are dealing with the circularity of waste and emissions. Excessive and waste materials and energy, if there is some market demand, can be sold to customers instead of being released into the environment or landfilled. Note that today, perfect closed-looping of material, energy, waste, and emissions is still not possible, but with newly developed, advanced technologies, it will become more and more likely.

3. Case study

The case study presents an upgraded multi-period mixed-integer linear programming (MILP) optimization model (Čuček et al., 2014b) of a regional-scale renewable-based energy supply network (Čuček et al., 2014a) with the addition of electricity production and circularity of materials and utilities (Figure 2). To incorporate electricity production from renewable sources, the usable land in the region taken into an account is enlarged for the production of food, biofuels, and electricity from 10 % to 11 %.

Electricity can be produced from three different technologies and sources, photovoltaics for solar power, wind turbines for wind power and binary cycle geothermal plants for geothermal energy. If there is not enough electricity produced, the deficit can be bought in the market. Even though thermal energy can also be produced, only the production of electricity is considered based on estimated data for investment, fixed maintenance and operating cost (U.S. EIA, 2013). In the model are some restrictions: all food demand and electricity should be satisfied, and at least 10 % of fuel demand should be satisfied.

The model considers monthly time periods for less-intermittent sources and products (biomass, food, and biofuels), and hourly time periods for more intermittent sources and products (solar, wind, geothermal and electricity) (Čuček et al., 2016). In the latter case, 6 periods were taken per month and 4 periods/d in order to reduce the model size. For comparison, we ran optimization with different objectives, maximal P^{Economic}, SP, and F – a fraction of reused materials and energy from a macroeconomic perspective that combines companies' and governments perspective. We ran the optimization with the circularity of materials and energy disabled and enabled. Results are presented in Table 1 and solved with a 5 % optimality gap.

Table 1: Different profits and fractions of regional supply network with circularity enabled and disabled

Profits and fractions	Maximization criteria				
	P^{Economic}	SP	P^{Economic}	SP	F
	Circularity disabled		*Circularity enabled*		
P^{Economic} (M€/y)	**5,956**	-407	**6,596**	974	974
*P^{Economic} (M€/y)	10,389	1,991	11,122	3,975	3,975
P^{Eco} (M€/y)	1,231	18,030	1,130	18,111	18,011
P^{Social} (M€/y)	87	516	88	525	525
SP (M€/y)	7,275	**18,139**	7,815	**19,610**	19,510
Fraction of renewable electricity (%)	12.6	54.3	12.6	54.3	54.3
F (%)	-	-	17.5	19.4	**19.4**

*P^{Economic} – economic profit from only companies' perspective, including subsidies and taxes

Table 1 shows the results regarding different measures obtained for the supply network when maximizing different objectives with the circularity of materials being disabled and enabled. The objective values in the corresponding columns are shown in bold. As expected, maximizing SP favors circulating materials in the supply chain more than maximizing P^{Economic} (19.40 vs. 17.50). SP also produces 54.3 % of electricity from renewable sources, whilst P^{Economic} only 12.6 %. Note that when the circularity of the materials is enabled, designs obtained have better overall sustainability performance for both objectives P^{Economic} and SP. As in the circulation there are steam and cooling water, we also have circular energy. Note that when maximizing circularity of materials, energy, and waste, we obtained the same fraction of reused and recycled materials and energy as when maximizing SP with circularity enabled.

Table 2: Detailed results from optimization of regional supply network with circularity enabled and disabled

Technical items	$P^{Economic}$	SP	$P^{Economic}$	SP	*F*
	Maximization criteria				
	Circularity disabled		*Circularity enabled*		
Area used (%)	11.00	11.00	11.00	11.00	11.00
- afforested (%)	-	2.61	-	1.88	1.88
Demand for fuel (%)					
- gasoline	64.32	37.47	68.19	45.41	45.41
- diesel	19.44	11.15	17.13	13.63	13.63
Demand for electricity (%)					
- wind	12.60	-	12.60	39.73	39.73
- solar PV	-	-	-	14.61	14.61
- geothermal	-	-	-	-	-
- coal	87.40	100.00	87.40	45.66	45.66
Raw materials (Mt/y)					
- corn grain	5,807	5,807	5,807	5,808	5,808
- corn stover	3,484	3,484	3,484	3,485	3,485
- wheat	8,904	8,905	8,903	8,904	8,904
- wheat straw	9,082	9,083	9,081	9,082	9,082
- miscanthus	18,414	4,906	18,486	8,710	8,710
- forest residue		91		70	70
- algae					
- cooking oil					
Technologies*:					
- hydrogen	●		●		
- dry-grind process					
- syngas fermentation	●	●	●	●	●
- catalytic synthesis					
- FT synthesis	●	●	●	●	●
- cooking oil methanol					
- cooking oil ethanol					
- algae methanol					
- algae ethanol					
Biofuels (Mt/y)					
- ethanol	4,844	2,832	5,332	3,425	3,425
- green gasoline	688	395	606	482	482
- et-diesel**				-	-
- me-diesel***				-	-
- FT diesel	2,588	1,485	2,280	1,815	1,815
- hydrogen	397	300	383	342	342
Number of employees	14,863	85,729	14,983	87,226	87,226

***biodiesel produced using ethanol, ***biodiesel produced using methanol*

Table 2 shows that the demands for food (100 % of corn and wheat) and fuels (10 % of gasoline and diesel substitutes by biofuels) are satisfied in all cases. When SP is maximized, the renewable sourced electricity is all from wind turbines. However, the items are very different when circularity is dis(en)abled.

a) Circularity is disabled: At both $P^{Economic}$ and SP objectives, fewer gasoline substitutes are produced (64.32 % and 19.44 %), and fewer diesel substitutes when SP is maximized and more of them when $P^{Economic}$ is maximized. Note that the difference for the production of substitutes when circularity is enabled or disabled are higher when SP is maximized. The designs in terms of used raw materials are similar when the circular economy is considered or neglected.

b) Circularity is enabled: when $P^{Economic}$ is maximized there are smaller differences than when SP is maximized, but they are still noticeable. The circular design provides a higher number of employees (14,983 compared to 14,863). On the other hand, a design with maximization of $P^{Economic}$ depends on more ethanol than other products as a fuel substitute. With the maximization of SP, these differences are even higher. Ethanol is produced in an almost 21 % (3,425 Mt/y against 2,832 Mt/y) larger quantity than when circularity is disabled;

the same holds for the production of green gasoline and FT diesel. Almost 2,000 more employees are employed in the circular design and more miscanthus and less forest residue are used for the production of biofuels.

4. Conclusions

In this paper, the concept of SP as a sustainability criterion that promotes circular economies and closed loops of materials, energy, and waste is demonstrated. For circularity assessment, a fraction of reused and recycled materials as one of the sub-metrics of Material Circularity Indicator is used. From our results, a positive synergy between SP and circularity can be seen because when circularity is included, we gain better sustainability performance from all three pillars and the circularity is increased when SP is maximized. Even when only P^{Economic} is maximized, sustainability is improved when circularity is enabled.

Results from the case study show that technologies using renewable energy sources that incorporate circularity of material, energy, and waste are more sustainable from economic, environmental and social perspectives. The scope of circularity and closed loops with sustainability criteria should be among the main objectives of future research.

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