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Life Cycle Assessment and Multi-Criteria Optimization of Regional Biomass and Bioenergy Supply Chains

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The presented research analyses the economical benefit, environmental burdens, and social impacts of biomass and bioenergy regional supply chains, through a multi-criteria optimization approach. The supply chains typically consist of four-layers and are comprised of agricultural, pre-processing, processing, and distribution layers (sectors). An integrated model for efficient biomass and bioenergy network optimisation is applied, as previously developed by Čuček et al. (2010), and now extended for explicit evaluation of the most relevant sustainability indicators and performance of life-cycle assessment (LCA). The synthesis of a biomass and bioenergy supply chain is accomplished by employing a mixed-integer nonlinear programming model (MINLP) incorporating mass and energy balances, feedstocks, heat and power integration, and the integration of different technologies into an overall network. LCA includes several environmental and social impacts from "cradle" to "grave". Besides the carbon footprint (CFP) as evaluated in the previous work by Čuček et al. (2010), additional footprints (De Benedetto and Klemeš, 2010) are also considered in this study. Economic, environmental, and social criteria are considered simultaneously during multi-objective optimization, in order to assess the trade-offs between the sustainability aspects.

1. Introduction

They are many important issues concerning sustainable agriculture, as well as biomass and energy supply chains. The important issues are energy, water, and chemicals usage, the economic situation, decreased availability of fossil resources, and climate change. The distributed availability of biomass resources, their low density and high moisture content could result in extensive requirements for transportation and pre-treatment, and have a significant influence on logistics. Another trade-off relating to the utilization of biomass for energy is the usage of food for energy. The previous work by Čuček et al. (2010) considered only a carbon footprint, which commonly stands for a certain amount of gaseous emissions that are relevant to climate change, and is associated with human production and consumption activities (Wiedmann et al., 2008). Although synonyms 'climate footprint' (Wiedmann et al., 2008) and 'GHG footprint' (Berners-Lee et al., 2010) are perhaps more appropriate than 'carbon footprint', where the usage of 'carbon footprint' stands for the amount of CO_2 and other greenhouse gases emitted over the full life-cycle of a process or product (POST, 2006). The term 'carbon footprint' is still used

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in this paper, mainly due to its widest acceptance so far. Besides greenhouse gas (GHG) emissions, several other negative impacts originate when using biomass for the production of bioenergy; as shortage of water, food, land, pollution of water etc. Other environmental footprints should also be considered:

- energy footprint (the demand for non-renewable energy resources, Schindler),
- water footprint (the total volume of direct and indirect freshwater used, Mekonnen and Hoekstra, 2010),
- agricultural land footprint (the agricultural land area used for growing biomass Kissinger and Gottllieb, 2010), and
- water pollution footprint (the amount of substances emitted to water, Sánchez-Chóliz, 2005).

Food vs fuel competition is very important issue relating to the usage of biomass for fuels, which should also be considered. This problem is emphasized by the head of Nestlé, saying "*If, as predicted, we look to use biofuels to satisfy 20 percent of the growing demand for oil products, there will be nothing left to eat.*" (Asch et al., 2009). For this reason, the food vs fuel issue is also included as a social footprint in this study.

2. Implementation of Sustainable Criteria Through Footprints

The model for bioenergy supply chain developed by Čuček et al. (2010) has been extended to include the consideration of different footprints. Environmental footprints are now evaluated for each layer, (i) raw material supplies, (ii) pretreatment, (iii) processing, and (iv) use of products, and also for transportation between the layers. 'Social footprint' is defined in order to consider the risk of diverting farmlands to the production of fuel rather than food (Čuček and Kravanja, 2010). The mathematical model developed by Čuček et al. (2010), has been slightly upgraded in order to include different direct footprints along the whole supply chain. LCA analysis has been extended to also include additional environmental footprints and social footprint for raw material supply and the product use layer. All environmental and social footprints are defined annually, and per unit of the supply-chain network's total area (A, km^2).

The environmental footprint is defined:

- for the supply layer, $ENVB_f^{\mathrm{L1}}$, as the production rate of biomass *pi*, $q_{i,pi}^{m,\mathrm{L1}}$, multiplied by environmental footprint for that biomass, $ei_{pi,f}^{\mathrm{L1}}$, caused by growing biomass:

$$ENVB_f^{\mathrm{L1}} = (\sum_{i\in I}\sum_{pi\in PI} q_{i,pi}^{m,\mathrm{L1}} \cdot ei_{pi,f}^{\mathrm{L1}})/\mathrm{A} \quad \forall f \in F \tag{1}$$

- for the pre-treatment layer, $ENVB_f^{\mathrm{L2}}$, as a mass-flow rate of biomass *pi* from the supply zone *i* in layer L1 to the pre-treatment centre *m* in layer L2, multiplied by environmental footprint for that biomass, $ei_{pi,f}^{\mathrm{L2}}$, caused by pre-processing:

$$ENVB_f^{\mathrm{L2}} = (\sum_{i\in I}\sum_{m\in M}\sum_{pi\in PI} q_{i,m,pi}^{m,\mathrm{L1,L2}} \cdot ei_{pi,f}^{\mathrm{L2}})/\mathrm{A} \quad \forall f \in F \tag{2}$$

- for the processing layer, $ENVB_f^{\mathrm{L3}}$, as a mass-flow rate of the intermediate product *pi* to the selected technology *t* at the process plant *n* in layer L3, multiplied by the environmental footprint for that product, $ei_{pi,t,f}^{\mathrm{L3}}$, caused by processing:

$$ENVB_f^{\mathrm{L3}} = (\sum_{n\in N}\sum_{pi\in PI}\sum_{t\in T}\sum_{(pi,t)\in PT} q_{n,pi,t}^{m,\mathrm{T,L2,L3}} \cdot ei_{pi,t,f}^{\mathrm{L3}})\ )/\mathrm{A} \quad \forall f \in F \tag{3}$$

- for the use layer, $ENVB_f^{\mathrm{L4}}$, as a mass flow rate of the directly used products *pd* and produced products from plants *pp*, each multiplied by the environmental footprint for that product, $ei_{pd,f}^{\mathrm{L4}}$ and $ei_{pp,f}^{\mathrm{L4}}$, caused by its usage:

$$ENVB_f^{\mathrm{L4}} = (\sum_{m\in M}\sum_{j\in J}\sum_{pd\in PD\subseteq P} q_{m,j^o,pd}^{m,\mathrm{L2,L4}} \cdot ei_{pd,f}^{\mathrm{L4}} + \sum_{n\in N}\sum_{j\in J}\sum_{pp\in PP\subseteq P} q_{n,j,pp}^{m,\mathrm{L3,L4}} \cdot ei_{pp,f}^{\mathrm{L4}})/\mathrm{A} \quad \forall f \in F \tag{4}$$

- for the transportation of materials between layers, $ENVB_f^{\mathrm{tr}}$, which depends on the density of biomass, distances, mode of transport, rate of biomass supply, and road conditions. Environmental footprint, $ei_{p,f}^{\mathrm{tr,L}a\mathrm{,L}b}$ is defined per t·km:

$$\begin{aligned} ENVB_f^{\mathrm{tr}} = (&\sum_{i\in I}\sum_{m\in M}\sum_{pi\in PI} D_{i,m}^{\mathrm{L1,L2}} \cdot f_{i,m}^{\mathrm{road,L1,L2}} \cdot ei_{pi,f}^{\mathrm{tr,L1,L2}} \cdot q_{i,m,pi}^{m,\mathrm{L1,L2}} + \sum_{m\in M}\sum_{n\in N}\sum_{pi\in PI} D_{m,n}^{\mathrm{L2,L3}} \cdot f_{m,n}^{\mathrm{road,L2,L3}} \cdot ei_{pi,f}^{\mathrm{tr,L2,L3}} \cdot q_{m,n,pi}^{m,\mathrm{L2,L3}} + \\ &\sum_{m\in M}\sum_{j\in J}\sum_{pd\in PD} D_{m,j}^{\mathrm{L2,L4}} \cdot f_{m,j}^{\mathrm{road,L2,L4}} \cdot ei_{pd,f}^{\mathrm{tr,L2,L4}} \cdot q_{m,j,pd}^{m,\mathrm{L2,L4}} + \sum_{n\in N}\sum_{j\in J}\sum_{pp\in PP} D_{n,j}^{\mathrm{L3,L4}} \cdot f_{n,j}^{\mathrm{road,L3,L4}} \cdot ei_{pp,f}^{\mathrm{tr,L3,L4}} \cdot q_{n,j,pp}^{m,\mathrm{L3,L4}})/\mathrm{A} \quad \forall f \in F \end{aligned} \tag{5}$$

The total environmental footprint of the supply chain network is defined:

$$ENVB_f = ENVB_f^{\mathrm{L1}} + ENVB_f^{\mathrm{L2}} + ENVB_f^{\mathrm{L3}} + ENVB_f^{\mathrm{L4}} + ENVB_f^{\mathrm{tr}} \tag{6}$$

The social footprint is defined only for multi-functional (multi-product) crops which can result in a supply of food, fodder, and/or energy. Social footprint is defined as a mass flow-rate of energy converted from food-intended crops:

$$SOCB_f = (\sum_{n\in N}\sum_{pi\in PI}\sum_{pp\in PP}\sum_{t\in T}\sum_{(pi,pp)\in PIP} q_{n,pi,pp,t}^{m,\mathrm{T,L2,L3}} / ((1-w_{H_2O}) \cdot f_{pi}^{conv,\mathrm{L2}} \cdot (\sum_{i\in I}\sum_{m\in M}\sum_{pi\in PI} q_{i,m,pi}^{m,\mathrm{L1,L2}})))/\mathrm{A} \quad \forall f \in F \tag{7}$$

A two-level MINLP approach was applied where at the first level (MINLP-1) different footprints are obtained by the maximization of profit ($ENVB_f^0$, $SOCB_f^0$).

At the second level (MINLP-2), the ε-constraint method is applied for each footprint *f*; *f* – set of footprints *F*. A sequence of (MINLP-2)$_\mathrm{i}$ problems is performed as the maximization of the profit *P* subjected to a footprint index (FPI)$_f$ which decreases sequentially from the maximal FPI$_f$ obtained at MINLP-1, by a suitable step size Δε, until FPI is zero.

$$\begin{aligned} &\max_{x,y}\ P = (c^{\mathrm{T}} y + f(x)) - \sum_f 10^{-6} \cdot ENVB_f - \sum_f 10^{-6} \cdot SOCB_f \\ &\text{s.t.} \quad h(x,y) = 0 \\ &\qquad\ \ y(x,y) \le 0 \qquad\qquad\qquad\qquad (\mathrm{MINLP}_i)_f \\ &\qquad\ \ \mathrm{FPI}(x,y)_f \le \varepsilon_{i,f} \\ &\qquad\ \ (x^{LO} x \le x^{UP}) \in X \subset \mathrm{R}^n, \ \ y = \{0,1\}^m \\ &\qquad\ \ \varepsilon_{i+1,f} = \varepsilon_{i,f} - \Delta\varepsilon_{i,f} \end{aligned}$$

When the profit is maximized vs each footprint *f*, all footprints $f \in F$ are minimized with a small weight (e.g. 10^{-6}) to provide solutions with the least values for footprints in those cases where multiple footprint solutions exist. Whenever a given footprint is decreased within a *f* sequence of (MINLP$_i$)$_f$ problem, all the profiles of footprints are obtained. Different sets of Pareto optimal solutions, one for each footprint, are generated at MINLP-2 as 2-dimensional projections of a multi-dimensional problem.

3. Demonstration Case Study

The above concept and developed model was extended to the bioenergy supply chain, Čuček et al. (2010). The data for various footprints were taken from many different sources, and are given in Table 1.

Table 1: Environmental footprints

	Water (t/t)*		Non-renewable energy consumption (GJ/t)		Emissions to water (t/t)		Emissions to air (t/t)	
RAW MATERIALS								
Corn grains	900		1.726		0.032		0.154	
Corn stover	900		1.726		0.032		0.154	
Organic manure	0.75		-		-		-	
Wood chips	2500		0.750		-		0.066	
MSW	0.229		-		-		-	
Timber	1500		0.5		-		0.044	
PRE-TREATMENT and PROCESSING								
DGP	3		2.5		-		0.147	
MSWINC	0.31		-		0.0016		0.415	
INC	-		-		-		-	
AD	0.091		-		-		-	
SAW	1.06		0.006		-		0.00125	
CScomp	0.005		0.01504		-		0.00134	
CGdry	0.5		1.251		-		0.09	
Tdry	0.004		0.0108		-		0.00078	
TRANSPORT (in t/tkm, and in GJ/tkm)								
	Road	Rail	Road	Rail	Road	Rail	Road	Rail
Corn grains	$1.36\cdot10^{-4}$	$7.3\cdot10^{-5}$	$3.89\cdot10^{-4}$	$2.08\cdot10^{-4}$	-	-	$5.3\cdot10^{-5}$	$8\cdot10^{-6}$
Corn stover	$2.33\cdot10^{-3}$	$1.25\cdot10^{-3}$	$6.67\cdot10^{-3}$	$3.57\cdot10^{-3}$	-	-	$1.1\cdot10^{-3}$	$8\cdot10^{-6}$
Manure, digestate, DDGS	$1\cdot10^{-4}$	-	$2.8\cdot10^{-4}$	-	-	-	$5.3\cdot10^{-5}$	-
Wood chips	$4.9\cdot10^{-4}$	$2.63\cdot10^{-4}$	$1.4\cdot10^{-3}$	$7.5\cdot10^{-4}$	-	-	$2.4\cdot10^{-4}$	$8\cdot10^{-6}$
MSW	$5.6\cdot10^{-4}$	-	$1.6\cdot10^{-3}$	-	-	-	$1.3\cdot10^{-4}$	-
Bioethanol	$1.24\cdot10^{-4}$	-	$3.5\cdot10^{-4}$	-	-	-	$2.7\cdot10^{-5}$	-
Boards, timber	$2.45\cdot10^{-4}$	$1.31\cdot10^{-4}$	$7\cdot10^{-4}$	$3.75\cdot10^{-3}$	-	-	$5.3\cdot10^{-5}$	$8\cdot10^{-6}$

*Since organic manure and MSW are waste, there is no available data on water footprint, and only raw materials moisture is taken as water footprint

DGP – Dry-grind process, MSWINC – MSW incineration, INC – Incineration, AD – Anaerobic digestion, SAW – Sawing, CScomp – corn stover compressing, CGdry – Corn grains drying, Tdry – timber drying

The environmental footprints for products are only assumed for digestate: carbon footprint 0.017 t/t and water pollution footprint 2.01 kg/t. The data in the literature vary significantly, environmental burdens are namely changed regarding the location, time, technology, composition etc., and, therefore, proper evaluation of LCA without measuring the footprints is impossible.

4. Results and Discussion

The optimal solution of 34 M€/y was obtained and footprints were calculated by the maximization of the profit in MINLP-1. Those values obtained were set as maximal footprints, and when normalized, set to 1. By maximizing the profit, for each footprint *f* out of six of them, a sequence of $(\mathrm{MINLP}_i)_f$ was performed where a footprint *f* was decreased from 1 to 0 whilst the other footprints *ff*, were minimized. Thus, a set of Pareto curves was obtained (Figure 1-6), where ε-constrained footprint *f* is given by bold black curve and other *ff* footprints by grey curves.

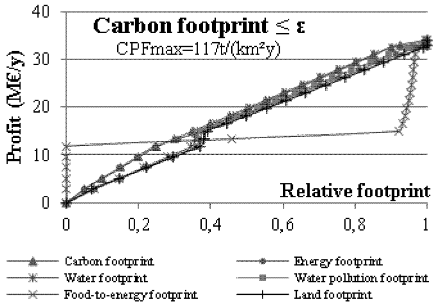

Figure 1: Carbon footprint vs profit

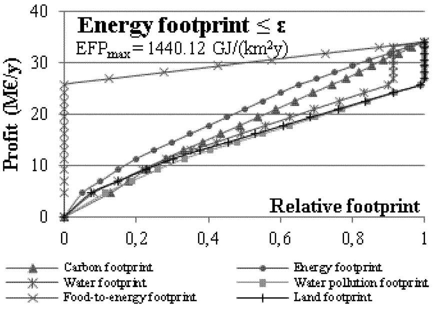

Figure 2: Energy footprint vs profit

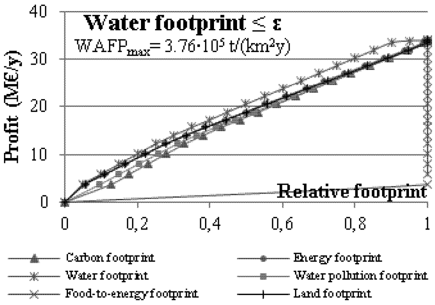

Figure 3: Water footprint vs profit

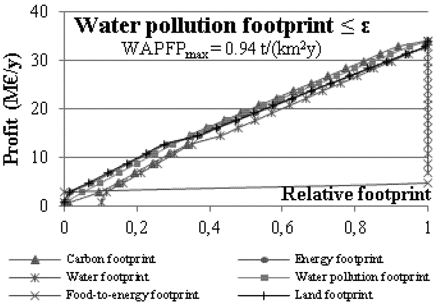

Figure 4: Water pollution footprint vs profit

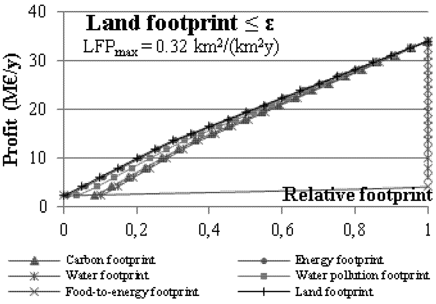

Figure 5: Land footprint vs profit

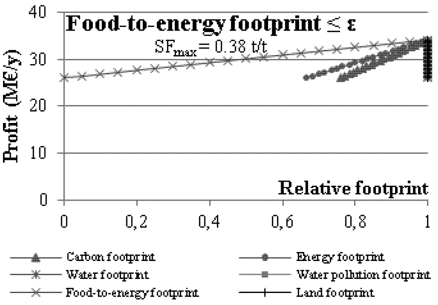

Figure 6: Food-to-energy footprint vs profit

It can be seen that the social footprint (SFP) especially differed from footprints. From the viewpoint of CO_2 emissions (CFP, Figure 1) it is preferable to produce food instead of energy. With the decreasing of energy footprint (EFP, Figure 2), the land footprint (LFP) decreased slower, the water footprint (WAFP) firstly decreased faster having by higher values of EFP, afterward it remained at the same values. From the energy viewpoint (non-renewable energy) it was preferable to produce food rather than bioenergy (already from the EFP of 0.7). From the viewpoint of water usage (WAFP, Figure 3), water pollution (WAPFP, Figure 4) and land use (LFP, Figure 5), all footprints decreased equally except SFP. It can be seen from Figure 6, that lower profit was obtained by lower SFPs, and this means that it is economically more preferable to produce energy rather than food. With the decreasing of SFP, EFP and CFP decreased linearly, whilst WFP, WAFP, and LFP did not change, and stayed at the maximal value.

Heat and electricity were generated by all ranges of different footprints; AD was selected within the whole range of EFPs, LPFs, WAFPs, and SFPs, and in the lower range of CFPs. Board-making was selected by the whole range of LPFs, WAPFPs, and SFPs.

5. Conclusions

When the regional biomass and bioenergy network is extended to different environmental and social impacts, different trade-offs are obtained between network alternatives. Each range on footprint is presented as a separate figure, which allows for a decision regarding the most appropriate criteria.

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