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Synthesis of Networks for the Production and Supply of Renewable Energy from Biomass

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This paper presents a step towards an integrated approach when synthesizing self-sufficient food-and-energy regional networks and utilising multi-functional crops, which can then be used for food and energy production, dedicated energy crops and low-value agricultural co-products, and waste. For the purpose of analysis, the given region is divided into several zones, which are smaller administratively/economically/ geographically integrated areas within the region (Lam et al., 2010). The synthesis of energy production and consumption networks is performed using the superstructural approach, supported by mathematical programming methods. The synthesized networks are comprised of agricultural, pre-processing, processing, and distribution sectors. Economical and environmental evaluation is performed and discussed from optimisation, by employing a mixed-integer nonlinear programming MINLP process synthesizer MIPSYN (Kravanja, 2010).

1. Introduction

The generation of heat and electricity from renewable sources, especially biofuels, has significantly increased over recent years. Biomass is one of the key renewable resources, which offers the potential to reduce environmental impact and has a positive influence on energy security, the development of rural regions, and employment. Renewable resources are usually distributed over a specific area and their availability varies significantly according to time and location. The distributive nature of biomass resources and its low density requires a large transportation capacity and significant fuel consumption. For this reason an optimal synthesis of distributed processes, including pre-treatment, such as drying and densification of biomass and regional energy generation are needed (Halasz et al., 2005). Synthesis also has to cover optimum distribution to the location where the heat and electricity are consumed.

The goal of this current work was to develop an integrated MINLP model for efficient bioenergy network optimisation on a regional scale. The proposed model employs a

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four-layer structure and is capable of accounting for different biomass types, optimising the locations, types, and capacities of the processing plants, and the connecting logistics network. This model was tested within a case study, where the main intention was to achieve a self-sufficient renewable energy-and-food region, whilst surpluses were exported to external consumers.

2. Mathematical Model Formulation

A four-layer supply chain model is considered, the layers of which include supply, pre-processing, processing, and consumption (Figure 1). Transportation is another component taking place between the layers. Certain amounts of intermediate products are sent to the customer directly. Most of them are food crops for direct consumption.

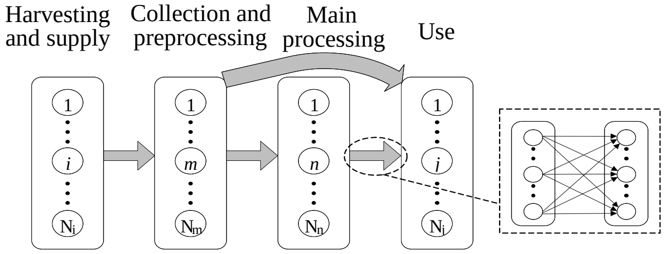

Figure 1: The generic structures of the networks for renewable production and supply

This model is formulated within a mixed-integer nonlinear programming (MINLP) form. It consists of mass balances, production and conversion constraints, cost functions, objective function, and carbon footprint (CFP). It follows the four-layer nature of the network's superstructure (Figure 1), starting from the harvesting and supply (L1) layer, collection and pre-processing (L2), main processing (L3); up to the use (L4) layer.

The main processing steps were first represented with detailed models and optimised by the process synthesizer MIPSYN in order to generate surrogate models based on conversion factors, investment and operating cost correlations, and released carbon footprint. These surrogate models were then inserted as black-boxes into the MINLP model for the synthesis of regional networks.

2.1 Mass balances, production and conversion constraints

The production rate of biomass type *pi* at supply zone *i*, subject to the hectare yield of *pi* and available area at zone *i*, is expressed via constraint (1):

$$q^{m,\mathrm{L1}}_{i,pi} = HY_{pi} \cdot A^{\mathrm{c}}_{i,pi} \qquad \forall pi \in PI, \forall i \in I \tag{1}$$

Biomass *pi* produced at zone *i*, is transported to pre-processing centres *m*:

$$q^{m,\mathrm{L1}}_{i,pi} = \sum_{m \in M} q^{m,\mathrm{L1,L2}}_{i,m,pi} \qquad \forall pi \in PI, \forall i \in I \tag{2}$$

Total available area for biomass competing for food and energy production (*pic*) must be within the total competing area for food and energy at zone *i*:

$$\sum_{pic \in PIC} A^{\mathrm{c}}_{i,pic} \le A^{\mathrm{UP}}_{i} \tag{3}$$

The collection and intermediate process centres *m* have to operate within the minimal and maximal product's mass flows:

$$q^{m,\mathrm{L2,LO}} \cdot y_m^{\mathrm{L2}} \le \sum_{i\in I} \sum_{pi\in PI} q_{i,m,pi}^{m,\mathrm{L1,L2}} \le q^{m,\mathrm{L2,UP}} \cdot y_m^{\mathrm{L2}} \qquad \forall m \in M \tag{4}$$

$$q_{pi}^{m,\mathrm{L1,L2,LO}} \cdot y_m^{\mathrm{L2}} \le \sum_{i\in I} q_{i,m,pi}^{m,\mathrm{L1,L2}} \le q_{pi}^{m,\mathrm{L1,L2,UP}} \cdot y_m^{\mathrm{L2}} \qquad \forall m \in M, \forall pi \in PI \tag{5}$$

Pre-treated intermediate product *pi* can be transported from the collection and intermediate process centre *m* to process plant *n* or directly to customer *j*:

$$\sum_{i\in I} q_{i,m,pi}^{m,\mathrm{L1,L2}} \cdot f_{pi}^{\mathrm{conv,L2}} = \sum_{n\in N} q_{m,n,pi}^{m,\mathrm{L2,L3}} + \sum_{j\in J} \sum_{pd\in PD\subseteq PI} q_{m,j,pd}^{m,\mathrm{L2,L4}} \qquad \forall m \in M, \forall pi \in PI \tag{6}$$

The intermediate product *pi* is sent to the selected technology *t*:

$$\sum_{m\in M} q_{m,n,pi}^{m,\mathrm{L2,L3}} = \sum_{(pi,t)\in PT} q_{n,pi,t}^{m,\mathrm{T,L2,L3}} \qquad \forall n \in N, \forall pi \in PI \tag{7}$$

The inlet flow to certain technology must not exceed its maximum capacity:

$$\sum_{(pi,t)\in PT} q_{n,pi,t}^{m,\mathrm{T,L2,L3}} \le q_t^{m,\mathrm{L3,UP}} \cdot y_{n,t}^{\mathrm{L3}} \qquad \forall n \in N, \forall t \in T \tag{8}$$

Intermediate product *pi* is converted into the product *pp* using corresponding conversion factor:

$$q_{n,pi,t}^{m,\mathrm{T,L2,L3}} \cdot f_{pi,pp,t}^{\mathrm{conv,L3}} = q_{n,pi,pp,t}^{m,\mathrm{T,L2,L3}} \qquad \forall (n \in N, pi \in PI, pp \in PP, t \in T, (pi,pp) \in PIP) \tag{9}$$

All of the produced product’s *pp* is sent to customers:

$$\sum_{(pi,t)\in PT} \sum_{(pi,pp)\in PIP} q_{n,pi,pp,t}^{m,\mathrm{T,L2,L3}} = \sum_{j\in J} q_{n,j,pp}^{m,\mathrm{L3,L4}} \qquad \forall n \in N, pp \in PP \tag{10}$$

All local demand is satisfied: the sum of the produced products from plants *pp*, and the directly used products *pd* must be greater than the demand for products *p*:

$$Dem_{j^o,p} \le \sum_{n\in N} \sum_{pp\in PP\subseteq P} q_{n,j^o,pp}^{m,\mathrm{L3,L4}} + \sum_{m\in M} \sum_{pd\in PD\subseteq P} q_{m,j^o,pd}^{m,\mathrm{L2,L4}} \qquad \forall j^o \in J, \forall p \in P \tag{11}$$

2.2 Cost functions

This model considers the cost functions for transportation, operating cost, and equipment cost. The transportation cost depends on the density of biomass, distances, mode of transport, rate of biomass supply, and road conditions. Total transportation cost is described by:

$$\begin{aligned} c^{\mathrm{tr}} = (&\sum_{i\in I} \sum_{m\in M} \sum_{pi\in PI} D_{i,m}^{\mathrm{L1,L2}} \cdot f_{i,m}^{\mathrm{road,L1,L2}} \cdot c_{pi}^{\mathrm{tr,L1,L2}} \cdot q_{i,m,pi}^{m,\mathrm{L1,L2}} + \sum_{m\in M} \sum_{n\in N} \sum_{pi\in PI} D_{m,n}^{\mathrm{L2,L3}} \cdot f_{m,n}^{\mathrm{road,L2,L3}} \cdot c_{pi}^{\mathrm{tr,L2,L3}} \cdot q_{m,n,pi}^{m,\mathrm{L2,L3}} + \\ &\sum_{m\in M} \sum_{j\in J} \sum_{pd\in PD} D_{m,j}^{\mathrm{L2,L4}} \cdot f_{m,j}^{\mathrm{road,L2,L4}} \cdot c_{pd}^{\mathrm{tr,L2,L4}} \cdot q_{m,j,pd}^{m,\mathrm{L2,L4}} + \sum_{n\in N} \sum_{j\in J} \sum_{pp\in PP} D_{n,j}^{\mathrm{L3,L4}} \cdot f_{n,j}^{\mathrm{road,L3,L4}} \cdot c_{pp}^{\mathrm{tr,L3,L4}} \cdot q_{n,j,pp}^{m,\mathrm{L3,L4}}) \cdot f^{\mathrm{yb}} \end{aligned} \tag{12}$$

The operating cost for the collection and intermediate process centres, which provide collecting, drying and compacting, and for the process plants is expressed as:

$$c^{\mathrm{op}} = (\sum_{i\in I} \sum_{m\in M} \sum_{pi\in PI} c_{pi}^{\mathrm{op,L2}} \cdot q_{i,m,pi}^{m,\mathrm{L1,L2}} + \sum_{n\in N} \sum_{pi\in PI} \sum_{t\in T} \sum_{(pi,t)\in PT} c_{pi,t}^{\mathrm{op,L3}} \cdot q_{n,pi,t}^{m,\mathrm{T,L2,L3}}) \cdot f^{\mathrm{yb}} \tag{13}$$

The process plant’s equipment cost is assumed to change nonlinearly with the selected size variable. Investment cost for the selected *m* centres and *n* plants is defined by:

$$c^{\mathrm{inv}} = (\sum_{m\in M} c_m^{\mathrm{fix,inv,L2}} \cdot y_m^{\mathrm{L2}} + \sum_{n\in N} \sum_{t\in T} (c_t^{\mathrm{fix,inv,L3}} \cdot y_{n,t}^{\mathrm{L3}} + \sum_{(pi,t)\in PT} (c_t^{\mathrm{var,inv,L3}} \cdot q_{n,pi,t}^{m,\mathrm{T,L2,L3}})^{c_t^{\mathrm{exp,inv,L3}}})) \cdot f^{\mathrm{yb}} \tag{14}$$

The objective function maximises the profit before taxation (P):

$$P = \sum_{n\in N}\sum_{j^o\in J}\sum_{pp\in PP} q_{n,j^o,pp}^{m,\mathrm{L3,L4}}\cdot c_{pp}^{\mathrm{price}} + \sum_{m\in M}\sum_{j^o\in J}\sum_{pd\in PD} q_{m,j^o,pd}^{m,\mathrm{L2,L4}}\cdot c_{pd}^{\mathrm{price}} + \sum_{n\in N}\sum_{j^e\in J}\sum_{pp\in PP} q_{n,j^e,pp}^{m,\mathrm{L3,L4}}\cdot 0.9\cdot c_{pp}^{\mathrm{price}} + \sum_{m\in M}\sum_{j^e\in J}\sum_{pd\in PD} q_{m,j^e,pd}^{m,\mathrm{L2,L4}}\cdot 0.9\cdot c_{pd}^{\mathrm{price}} - \sum_{i\in I}\sum_{pi\in PI} q_{i,pi}^{m,\mathrm{L1}}\cdot c_{pi} - c^{\mathrm{tr}} - c^{\mathrm{op}} - c^{\mathrm{inv}} \tag{15}$$

The income represents the revenue from selling products and from the tax imposed on waste. The expenses represent the raw materials cost (c_{pi}), the transport cost (c^{tr}), operating cost (c^{op}), and annualized network investments (c^{inv}).

2.3 Carbon footprint

The CFP (De Benedetto and Klemeš, 2010) is evaluated for the pre-processing, processing, and transportation activities. It only includes the net emissions caused by those operations which consume fossil fuels. The CFP per unit of the supply-chain network total area is defined using Eq. 16:

$$CFP = \Big(\sum_{i\in I}\sum_{m\in M}\sum_{pi\in PI} D_{i,m}^{\mathrm{L1,L2}}\cdot f_{i,m}^{\mathrm{road,L1,L2}}\cdot ei_{pi,e}^{\mathrm{tr,L1,L2}}\cdot q_{i,m,pi}^{m,\mathrm{L1,L2}} + \sum_{m\in M}\sum_{n\in N}\sum_{pi\in PI} D_{m,n}^{\mathrm{L2,L3}}\cdot f_{m,n}^{\mathrm{road,L2,L3}}\cdot ei_{pi,e}^{\mathrm{tr,L2,L3}}\cdot q_{m,n,pi}^{m,\mathrm{L2,L3}} + \sum_{m\in M}\sum_{j\in J}\sum_{pd\in PD} D_{m,j}^{\mathrm{L2,L4}}\cdot f_{m,j}^{\mathrm{road,L2,L4}}\cdot ei_{pd,e}^{\mathrm{tr,L2,L4}}\cdot q_{m,j,pd}^{m,\mathrm{L2,L4}} + \sum_{n\in N}\sum_{j\in J}\sum_{pp\in PP} D_{n,j}^{\mathrm{L3,L4}}\cdot f_{n,j}^{\mathrm{road,L3,L4}}\cdot ei_{pp,e}^{\mathrm{tr,L3,L4}}\cdot q_{n,j,pp}^{m,\mathrm{L3,L4}} + \sum_{i\in I}\sum_{m\in M}\sum_{pi\in PI}\big(q_{i,m,pi}^{m,\mathrm{L1,L2}}\cdot ei_{pi,e}^{\mathrm{L2}} + \sum_{n\in N}\sum_{pi\in PI}\sum_{t\in T}\sum_{(pi,t)\in PT} q_{n,pi,t}^{m,\mathrm{T,L2,L3}}\cdot ei_{pi,t,ei}^{\mathrm{L3}}\big)\Big)/\mathrm{A}\quad \forall e\in E \tag{16}$$

3. Demonstration Case Study

The data for this study were developed based on Central European conditions. The geographical features are illustrated in Figure 2 where set $I = \{i_1,..,i_{24}\}$ is used for the supply zones, set $M = \{m_1,..,m_{14}\}$ for the collection and pre-processing centres, set $N = \{n_1,..,n_{10}\}$ for the process plants, and set $J = \{j_1,..,j_7\}$ for demand locations, with subsets: $J^o = \{j_1,.,j_5\}$ for locations at local level, and $J^e = \{j_6, j_7\}$ for locations for export.

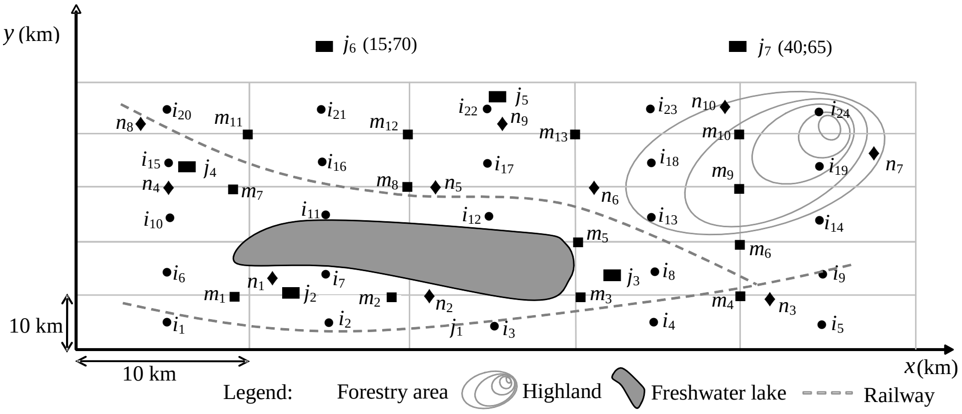

Figure 2: Regional plan for the demonstrated case study

Several technological options for raw material processing were considered in the synthesis: i) the dry-grind process for starchy crop-based ethanol plants from corn, wheat, and potatoes, ii) diluted acid from corn stover, and iii) alkaline pre-treatment for ethanol plants from wheat straw, iv) gasification/fermentation process from wood chips, v) anaerobic co-digestion of biomass waste, vi) incinerations of MSW, corn stover, wheat straw, hay, miscanthus, poplar and wood waste, and vii) the sawing of timber for manufacturing boards. Food demand was satisfied directly from the production of starchy crops, i.e. corn, wheat and potatoes. Besides the base case which included the pre-treatment of biomass at collection centres, four scenarios were considered in the synthesis of a self-sufficient regional network: a) without pre-treatment of biomass, b) tripled expense of transportation, c) ten times larger area, and d) the combination of expensive transportation, and a larger area. The objective was to maximise the profit while satisfying regional demand. Product surpluses can be exported. The resulted locations of the selected technologies and product surpluses are given in Table 1 and the effects of different scenarios can be studied from Table 2.

Table 1 The location of the plant and yearly amount of bioenergy and food for export

Scenarios	Plant location						Export			
	DG	IN	AD	GF	SAW	MSW	Heat (GWh/y)	Electricity (GWh/y)	Ethanol (kt/y)	Food (kt/y)
Base case	n_9	$n_{1,2,4,9}$	n_5	n_1	n_9	n_3	1,500.3	1,754.6	14.7	/
Excluded pre-processing of biomass	n_9	$n_{1,3,4,5,9}$	n_2	n_1	n_9	n_2	1,500.3	1,754.6	14.7	/
Transportation costs x 3	n_9	$n_{1,2,3,4,9}$	n_5	n_1	$n_{1,3,9}$	/	1,463,5	1,713,2	14.7	/
Area x 10	n_{10}	$n_{1,2,3,4,8,9,10}$	n_5	$n_{1,3,9,10}$	$n_{1,2,3,4,9,10}$	$n_{2,3,5}$	17,319.3	20,065.9	63.6	/
Transportation costs x 3 and area x 10	n_4	$n_{1,2,3,4,5,8,9,10}$	$n_{2,5}$	$n_{1,3,4,6,9,10}$	$n_{1,2,3,4,9}$	/	16,911.4	19,607.0	63.6	/

DG – the dry grind process, IN – incineration, AD – anaerobic digestion, GF – gasification/fermentation, SAW – sawing, MSW – MSW incineration

Table 2 Profit, cost and released carbon footprint for the scenarios

	Profit (M€/y)	Transportation costs (M€/y)	Production costs (M€/y)*	Carbon footprint (t/(y.km^2))
Base case with pre-processing	164.12	11.37	40.33	13.2
Without pre-processing	160.11	19.91	35.71	27.9
Transportation costs x 3	142.87	26.26	38.07	4.5
Area x 10	1,756.4	352.66	296.47	12.4
Transportation costs x 3 and area x 10	1,286.3	594.04	293.84	1.9

*Sum of investment and operating costs (with excluded raw materials costs)

It can be seen from Tables 1 and 2 that, for a relatively small-sized area (2400 km^2), only incineration was distributed in up to five plants, while all the other technologies were centralized. When compared to the base case, if the compressing of low-density biomass was excluded, the transportation costs and CFP would significantly increase, the production costs decrease, and one additional plant location would be selected. If transportation were more expensive, more sawing operations would have to be selected and MSW incineration plants rejected, which would considerably reduce the CFP. Highly-distributed energy production would be obtained if the area were 10 times larger. If the enlarged area were combined with 3 times more expensive transportation, an additional AD plant would have to be selected whilst, again, MSW incineration would not be economically viable. Also, centralized production would be preferable for ethanol production where only starchy crops are converted into ethanol; whilst lignocellulosic biomass should preferably be incinerated. CFP shows typical behaviour that, by increasing both the total area and transportation cost, much less CO_2 would released per unit of area.

The amount of resulting biomass would satisfy the entire demand for energy and food within the region. About 60 % of ethanol (demand for bioethanol is set at 20 % of petrol consumption), 90 % of electricity and 80 % of heat could be exported. Although all the demand for food would be satisfied, only corn need be selected for bioethanol production. The remaining area (40 % of the total area) would be better planted with miscanthus for heat and electricity generation.

4. Conclusions

An optimisation model for self-sufficient bioenergy production supply chain is presented, with a solution approach for designing and evaluating an integrated system at regional level. The model of the supply network shows high performance when solving problems with reasonably large numbers of different raw materials and processes. A self-sufficient energy-and-food region can be managed with relative high profits where most of energy can be exported, especially heat and electricity. When transportation is more expensive, and especially when the area is larger, the network becomes more distributive for the generation of heat and electricity, and more centralised for the production of bioethanol. From among the studied sources, miscanthus was confirmed as the most profitable biomass source for the generation of heat and electricity, and corn for the production of bioethanol. Solutions indicate that, by employing densification of biomass at collecting centres and by de-centralising plants over a larger area, the emission of CO_2 per unit of area can be significantly decreased. Research is under way to implement more footprints for obtaining multi-dimensional Pareto curves and to define more impacts along the bioenergy and food-supply chains.

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