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Multi-Objective Regional Total Site Integration

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This paper further develops a methodology for Regional Total Site Integration that is an extension of the Total Site Integration scope to the regional level. A previously developed general synthesis model by the authors has now been extended in this contribution for the purpose of Regional Total Site Integration applied within a demonstration case study of a regional biomass energy network. A multi-objective optimisation is performed as part of the synthesis for the evaluation of the maximal energy savings and footprint reduction within regional energy networks by accounting for the variability of demand and supply. The integration of renewable energy sources by maximising heat recovery within regional Total Sites clearly offers a significant contribution to regional energy savings, economic benefits, and footprint reduction.

1. Introduction

We are constantly faced by fast growing energy consumption that is still predominantly supplied by fossil fuels. Consequently, the environmental footprints have been rising considerably (Perry et al., 2008). “Green” solutions and environmental protection are becoming common issues of the twenty-first century (Čuček et al., 2012a), and energy saving and energy efficiency are becoming the top priority (European Commission, 2013). Consequently, significant efforts have been spent over recent years in increasing the share of renewables and to increasing energy efficiency.

Heat Integration (Linnhoff and Flower, 1978) and Total Site (TS) Integration (Dhole and Linnhoff, 1993) often shows the large potential for energy savings. It has been estimated that the majority of industrial plants throughout the world use up to 50 % more energy than necessary (Alfa Laval, 2011). TS Integration shows that in specific cases 20 – 25 % potential improvement can be made (Hackl et al., 2010); indeed even more in well-defined and structured cases. TS Analysis produces targets for the heat recovery, cogeneration potential and the utilisation of waste heat (Hackl et al., 2010). TS Integration offers opportunities for integrating heat via an intermediate carrier, from one site to another, which could be industrial sites, and even building complexes, offices and residential dwellings (Perry et al., 2008).

Regional TS Integration is an extension of the TS Integration scope to the regional level (Klemeš et al., 2013). It serves within a scope of regional energy supply and demand networks by integrating energy re-use and renewable resources. An important part of TS and regionally-integrated energy systems is also the evaluation of environmentally-related footprints.

This contribution firstly presents the concept of Regional TS Integration, and further the synthesis of optimally-integrated regional TSs. A mathematical programming framework was used for the synthesis. The multi-period synthesis model (Čuček, 2013) has been modified and extended to a multi-objective multi-period model. This enables a comparison between No Site Integration, Internal Site Integration and Regional TS Integration. Several total environmental footprints (Čuček et al., 2012c) are considered, such as carbon (CF), nitrogen (NF), water (WF) and energy footprints (EF). These footprints have been evaluated only on the heating and cooling sites based on the work of (Čuček et al., 2012b). The synthesis of sustainable Regional TS Integration is illustrated with a demonstration case study. The results and conclusions are presented, adding recommendations for future research.

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2. Regional Total Site Integration

Regional TSs integrate as many locally-available sources and sinks of energy as are feasible, including renewables (such as solar, wind, biomass, waste, etc.). The availability of renewable energy resources is usually lower and they are more distributed compared to fossil energy resources. There is a logistic challenge and the need for more extensive infrastructure networks. However, in many cases there are also chances for Regional Integration. The availability of most resource types can be, to some extent, predicted or at least forecasted, but it varies over the course of time. The certain variations of energy needs at demand sites should be accounted for and the dynamics of the TSs should be considered over time. There is a need for using a combination of non-renewables, renewable energy resource storage and/or energy storage, due to the time varying characteristics of the supply and demand sites.

The structure of Regional TS Integration is presented in Figure 1. The region is divided into a number of zones and within the region there could be several renewable energy sources available, such as biomass and some types of waste, energy from water, wind, the sun, geothermal sources, and ground heat or cold using heat pumps. If the demand within the region cannot be entirely satisfied by renewables, renewable resources' storage should be used together with non-renewables. The storage of biomass and waste is necessary due to the seasonal variation of their production, and can be a relatively cheap and uncomplicated option if the logistics are properly dealt with. Another option is to store energy (heat and/or electricity). However, this option is costly and despite recent research efforts is still waiting for a major breakthrough (Varbanov et al., 2010).

A wide range of technologies can be used to convert energy sources to heat and power depending on the availability of renewable energy sources within the region. Several technologies can be employed to generate heat only, such as burning organic materials (biomass and waste), heat pumps, and solar water heating. Hydropower plants, wind turbines, and photovoltaic panels generate electricity only. There are also several technologies that can produce combined heat and power, such as thermal processes (gasification, incineration, and pyrolysis), anaerobic digestion, concentrated solar thermal, etc. The generated power is fed into the electricity grid, and the remaining heat can be transferred to individual houses, greenhouses, building complexes, and industrial processes at another locations, etc. Additionally, heat can also be produced as a "waste" product within industrial plants, such as bio-refineries converting lignocellulosics into biofuels, oil refineries, glass factories, etc.

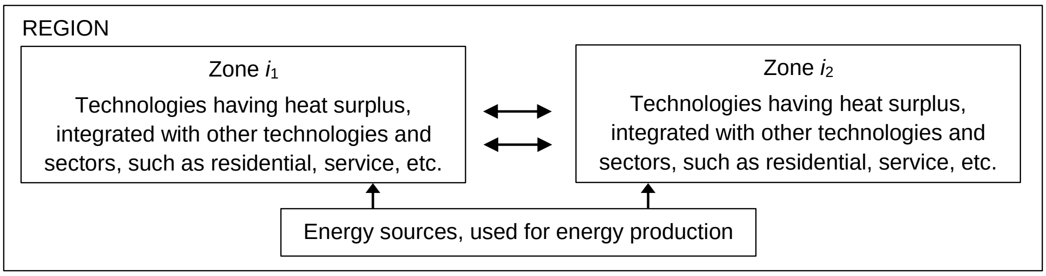

Figure 1: Regional Total Site Integration

3. Synthesis of Sustainable Regional Total Sites

The synthesis of a sustainable Regional TS has been tackled by a mathematical programming framework. A multi-period multi-objective optimisation is performed in order to evaluate the potential for improving profitability and reducing environmental footprints when applying TS Integration. Several renewable energy sources can be considered within a region. However, currently only biomass is considered, since unlike solar or wind, biomass can easily be accumulated and stored, thus ensuring a constant production of heat and power while available. Heat at different levels can be produced at power stations and also industrial plants, such as bio-refineries.

The generic simplified multi-period mixed-integer linear-programming (MILP) model (Čuček et al., 2013b), and the further improved version (Čuček, 2013), has now been further extended using multi-objective optimisation for considering several environmental footprints. It also enables optimisation in those cases concerning i) No Site Integration, ii) Internal Site Integration and iii) Regional TS Integration.

A four-layer (L1-L4) regional supply-chain superstructure has been formulated (Čuček et al., 2010), and contains sets of potential locations of a) harvesting sites at supply-zones – L1, b) collection, pre-processing, and storage – L2, c) main processing – L3, and d) usage – L4, including connections between and within these layers. The developed model consists of mass balance, production and conversion constraints, transportation, operating and capital cost, environmental footprints evaluation, and economic and environmental objective functions. The demand for products within the region is also defined.

4. Demonstration Case Study

The potential of Regional TS Integration for energy savings and footprints' reductions is demonstrated with a case study of regional biomass energy networks. The structure of the regional supply chain network is presented on Figure 2. The region covers ten zones ($i_1 - i_{10}$), six collection, storage and pre-processing centres ($m_1 - m_6$), three plant locations ($n_1 - n_3$), and three demand locations ($j_1 - j_3$). The regional plan is taken from (Čuček et al., 2010) after small modifications. Instead of two locations of local and once cross-regional demand, here three local demands are assumed close to the production plants.

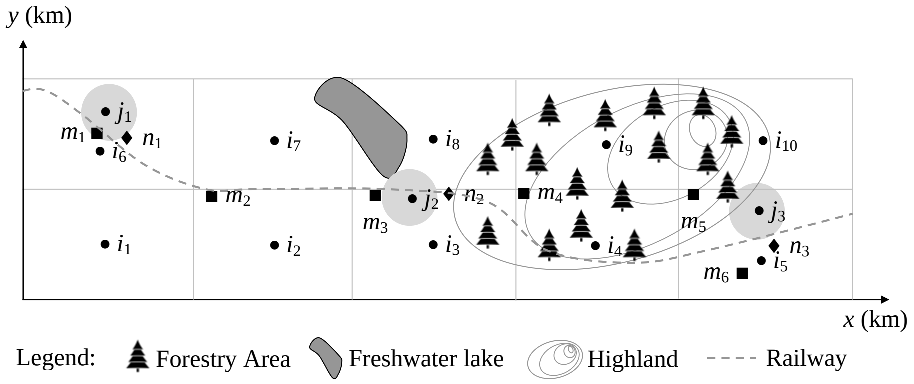

Figure 2: Regional plan for the illustrative example - modified from Čuček et al. (2010)

Only biomass was considered as a source of the region's renewable energy supply. At each zone there was harvesting of alternative biomass resources, corn grain and corn stover for the production of ethanol, and rapeseed for the production of biodiesel. The regional supply data for biomass resources are specified in Table 1. The data for corn grain and stover are taken from (Čuček et al., 2010). It was assumed that rapeseed contained 40 % of oil (Boland, 2012), and that the price of rapeseed oil was 1,200 $/t (IndexMundi, 2013).

Table 1: The availability of biomass resources within each zone, as % of the total area

Biomass/Zone	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}
Corn grain/stover	20	20	65	30	40	25	65	45	0	10
Rapeseed	45	45	10	0	20	45	25	20	5	20

At each plant location there were three alternative production technologies, the dry-grind process (Karuppiah et al., 2008), gasification and further catalytic mixed alcohol synthesis (Čuček et al., 2011), and transesterification of oil with methanol (Martín and Grossmann, 2012), rapeseed oil being assumed here. Gasification and catalytic mixed alcohol synthesis was the technology having energy surplus, and could be integrated within those processes having energy deficits, such as the dry-grind and transesterification processes. Additional heat energy, if not utilised within the process technologies, could be used for district heating. The demand is specified within the region. The demand for transportation fuels and very high pressure (VHP), medium pressure (MP) and low pressure (LP) steam is defined, and is shown in Table 2.

Table 2: The demand for biofuels (kt/y) and heat (TJ/y) at different pressure levels

Demand /Product	Ethanol and gasoline	Biodiesel and diesel	VHP steam*	MP steam*	LP steam*
j_1	230	0	0	0	0
j_2	0	250	600	7,000	1,200
j_3	150	0	0	0	0

5. Results and Discussion

Several optimisations were performed, both single and multi-objective ones. Maximisation of the profit before tax is performed by single-objective optimisation. In the multi-objective optimisation case, the profit is maximised versus minimising the environmental footprints, and is applied during TS Integration.

5.1 Single-objective optimisation

Single-objective optimisation was performed for the above mentioned three different cases of Site Integration in order to check on opportunities for energy savings and improvements in terms of economic prosperity and environmental footprints. The profit, different cost, environmental footprints and technologies at selected plant locations for all the cases are shown in Table 3. It should be noted that environmental footprints were only related to heating and cooling needs. Natural gas was assumed as a source of energy, and the closed-water cooling system is assumed (Čuček et al., 2012b).

Table 3: Results from the single-objective optimisation

	No Site Integration	Internal Site Integration	Total Site Integration	
Profit (M$/y)	406.2	415.1	440.2	
Utility cost (M$/y)	23.3	13.6	-20.2	
Investment cost (M$)	503.3	569.8	557.7	
Transportation cost (M$/y)	28.5	29.4	30.0	
Biomass cost (M$/y)	628.5	620.2	619.3	
Storage cost (M$/y)	23.2	26.8	27.6	
Direct | Total EF (TJ/y)	3,938	2,089	70	-7,900
Direct | Total CF (t/y)	81,095	43,023	1,444	-162,684
Direct | Total WF (kt/y)	10,259	8,982	3,637	2,634
Direct | Total NF (t/y)	60.3	32.0	1.1	-120.9
Technologies	n_1 The dry-grind process Gasification technology n_2 Transesterification	n_1 The dry-grind process Gasification technology n_2 Transesterification	n_2 The dry-grind process Gasification technology Transesterification	

It can be seen from Table 3 that the profit increased, and the utility cost and environmental footprints decreased from the left to the right; the lowest profit and the highest environmental footprints were for No-Site integrated case, and the highest profit and the lowest environmental footprints for the TS integrated case. The profit was significantly improved for the TS integrated case (for 34 M$/y), since the demand for VHP, MP, and LP steam could almost be satisfied with by-products from the bio-refinery, and thus less energy would need to be purchased. Also, the footprints were significantly reduced. EF, CF, and NF even became negative, and unburdened the environment (Čuček et al., 2012c), whilst WF was reduced by 74%. The utility cost was also significantly reduced in comparison when No Site Integration and they even turned into profit in the TS integrated case.

It can be seen that Internal Site Integration, Heat Integration within individual process technologies, enables the achieving of significant energy savings, improves the economics of regional networks, and enables significant reduction of environmental footprints. Even better Site Integration can be achieved through TS Heat Integration, Heat Integration between process technologies that are integrated through a utility system. TS Integration enables the achieving of maximum possible energy savings, and improves the sustainability (economics and environment) of regional networks.

On the other hand, the transportation and storage cost is increased when applying Heat Integration. It can be seen that there is a trade-off between transportation, investment, biomass, storage, and utility cost. When there was No TS Integration, there was a tendency towards decentralised processes, whilst when applying TS Heat Integration, centralised processes were preferred because TS Integration could only be efficiently performed between nearby processes.

5.2 Multi-objective optimisation of heat integrated Total Site applying total footprints

Multi-objective optimisation was performed in order to review the relationship between the economic profit and several environmental footprints. Total footprints (Čuček, 2012c) were applied in order to consider both burdening (direct) and unburdening (indirect) effects on the environment. Only the main Pareto curves are presented where relative footprints are decreased by suitable step-sizes from +1 to the point when zero profit is obtained (positive total footprint), and from -1 to even higher values than 0 when infeasible solutions were obtained (negative total footprint). Relative footprints were obtained so that all the total footprints obtained by optimisations were normalised by their absolute values of total footprints obtained by maximal profit solutions (see also the last column in Table 3). A set of Pareto optimal solutions is shown in Figure 3, where profit vs. relative environmental footprints is shown. It should be noted that only footprints on the heating and cooling side were evaluated (Čuček et al., 2012b). However, in order to achieve appropriate trade-offs, footprints related to the heat distribution system and equipment also need to be taken into account.

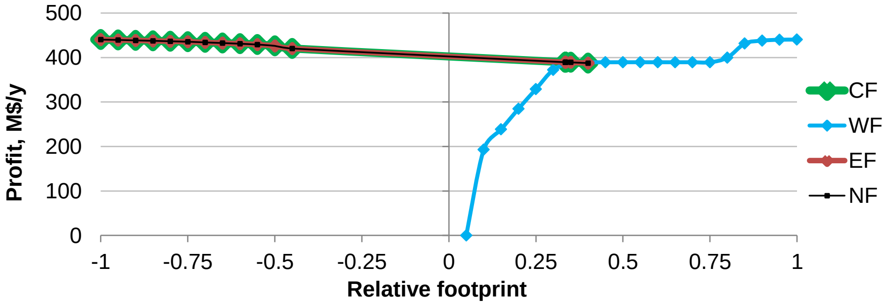

Figure 3: Profit vs. relative total environmental footprints

It can be seen from Figure 3 that feasible solutions were obtained by the whole range of total environmental footprints. CF, EF and NF were firstly negative, which indicated the net unburdening of the environment from the carbon, energy and nitrogen perspectives, whilst WF was always positive indicating the burdening of the environment with respect to the water consumption. CF, EF and NF were related to the consumed and sold energy (heating side), whilst WF was related to the heating and cooling sides. When increasing CF, EF and WF, the profit was reduced slightly. More bioethanol was produced at higher values of CF, EF and NF using the dry-grind technology and less by using gasification technology. In this way the required heating energy was increased and available heating energy decreased. When reducing WF towards zero, several technology changes occurred, first gasification technology was rejected and two dry-grind processes were employed, further one dry-grind and one transesterification process were selected, and finally nothing was produced at zero WF.

6. Conclusions and Future Work

This contribution presented multi-objective multi-period optimisation of Regional TS. A generic simplified synthesis model was used for this purpose. Several single - and multi-objective optimisations were performed for the cases of No Site Integration, Internal Site Integration and Regional TS Integration. The synthesis of sustainable Regional TS Integration was illustrated by demonstrating that the TS integrated case enables significantly higher profits when compared to internally-integrated and non-integrated cases. In addition utility costs and environmental footprints were significantly reduced. It was also demonstrated that centralised processes were preferred for TS Integration rather than No TS Integration's decentralised processes. The multi-period multi-objective synthesis enabled the identification of those solutions that were economically-efficient and environmentally benign. Advancing and optimising the designing of regional energy networks would contribute significantly to energy savings and footprint reduction, with the longer term of creating energy sustainable regions.

In the future the Regional TS model would also account for more detailed cost and footprint analysis regarding heat distribution networks' equipment, fouling, pumping cost and pressure drops (Chew et al, 2013). Even more footprints could be considered. – for instance toxicity to reduce local impacts in addition to global (Signor et al., 2010). However, the dimensionality of multi-objective optimisation accounting for a larger number of footprints would have to be reduced to a minimum number of footprints groups based on their similarities (Čuček et al., 2013a). Regional TS Integration would account for the different uncertainties inherent within data, fluctuations in supply and demands, and prices. Flexibility would be brought to regional energy supply and demand networks by including uncertainty into the design. Multi-objective multi-period optimisation under uncertainty would enable the identifications of those solutions that would be economically-efficient, environmentally-benign and flexible regarding uncertainties, thus being more realistic. It would evolve towards an efficient supportive tool for decision-making within regional energy planning and management.

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