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Simultaneous Optimization for Mass and Energy Networks in Biorefineries

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Abstract

This paper addresses the simultaneous optimization of mass and energy networks using systematic methods, while considering multiple components and alternative design options for regeneration and storage. The problem is formulated as a mixed integer linear programming model (MILP) to calculate targets for the capital (regeneration units, buffer tanks) and the operating cost (energy, water, raw materials use, and effluent treatment cost). The method has been applied to design the utility network of a real life biorefinery process. Compared to the initial design, optimized by sequential and heuristic approaches, our method managed to further reduce the energy consumption by 45%. Furthermore, the mass flow of the regenerated streams was significantly lower than that of the base case, resulting also in capital cost savings. Future work will incorporate options for the energy and treatment systems.

Keywords: Biorefinery, MILP, Energy Network, Mass Network, optimization

1. Introduction

For the concept of the biorefinery to spread out, it is necessary to keep the operational cost low. The optimal use of each utility is a complicated design problem that calls for a systematic approach. Different methods are proposed in the literature. The energy consumption problem is systematically addressed by pinch analysis (Linnhoff & Hindmarsh, 1983). For the systematic design of heat exchanger networks (HENs), most methods consider that the temperatures and the flowrates of the mass network are fixed. The same methods also include options for grassroots or retrofit design, continuous or batch operation, with or without area targeting (Morar & Agachi, 2010; Klemeš & Kravanja, 2013). More recently, the transhipment model (Papoulias & Grossmann, 1983) was extended to use variable inlet and outlet temperatures (Navarro-Amorós et al., 2013) and then this new model was further improved with variable flowrates (Kong et al., 2017; Quirante et al. 2017) and multiple thermal utilities with area targeting

The problem of water network synthesis can be divided into three subclasses: a) direct reuse/recycle network b) regeneration network, and c) total water network

(Bagajewicz 2000; Jeżowski, 2010; Khor et al., 2014). Existing models use evolutionary algorithms, stochastic optimization, and superstructures formulated as mixed integer nonlinear programming (MINLP) or as mixed integer linear programming (MILP) after linearization (Bagajewicz 2000; Yoo et al., 2007; Jeżowski, 2010). The combined problem of water and energy consumption was first addressed by a conceptual design method (Savulescu and Smith, 1998). Generally, conceptual design methods come with good graphical visualization and simple operability, but they cannot easily deal with multiple contaminants and trade-offs between capital and operational costs. Mathematical programming-based methods follow a simultaneous or sequential optimization approach (Yoo et al., 2007; Jeżowski, 2010; Ahmetović et al., 2015). Although sequential methods are easier to solve, they cannot fully consider the trade-offs among the freshwater cost, the energy cost, and the investment cost. Simultaneous approaches are based on complex superstructures, while a decomposition strategy is proposed to decompose the MINLP problem into two sub-problems: MILP and NLP, which were sequentially solved with an iterative procedure (Ahmetović et al., 2015; Zhao et al., 2019).

However, existing methods consider only the simultaneous use of water and energy (or one main component and energy), handling any other substance as contaminant. Moreover, multiple technological options can exist for the regeneration of a substance, which result in different network designs. This work aims at the optimization of the utility network (mass and energy) including design options for regeneration technologies and storage at different temperature levels, while considering the cost of capital investment. The problem is nonlinear by nature, but assumptions and piecewise linearization techniques are adopted to keep it linear. The method is applied for the utility network design of a real life biorefinery process. The results of sequential optimization with heuristics are compared to those generated by the proposed simultaneous framework.

2. Methodology

The utility network superstructure is a bipartite graph having N utility exchange locations as nodes, I as sources and J as sinks, and S streams as edges:

$$\boldsymbol{G} = (N, S) = (I \cup J, S)$$

The graph is actually a joint graph (Bretto, 2013; Diestel, 2018) accounting for two interacting superstructures:

- A superstructure of mass source (I^M) and sink (J^M) nodes:

$$\boldsymbol{G}^M = (I^M \cup J^M, S^M)$$

- A superstructure of energy source (I^E) and sink (J^E) nodes:

$$\boldsymbol{G}^E = (I^E \cup J^E, S^E)$$

The two networks interact with each other since the nodes of the energy exchange network (EEN) are the edges (streams) of the mass exchange network (MEN):

$$N^E = (I^M, J^M) = S^M_{ij}$$

Process units ($m \in M$) are associated with the utility exchange locations to keep information about the layout of the network (Fig.1). A process unit physically can be a piece of equipment or a whole process section, but, in this work, it is decided to use process sections, for clarity reasons. Five different types are introduced:

i. *Processing* units, which convert the raw materials to products
ii. *Supply* units, which supply make up streams of utilities

iii. *Storage* units, which store utilities
iv. *Upgrade* units, which upgrade the quality of the incoming utility streams
v. *Treatment* units, which treat the discharged streams

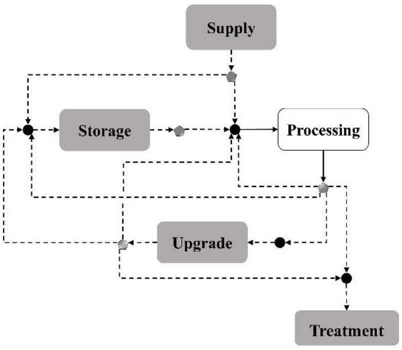

Fig.1 Connectivity among Process Units

3. Optimization Problem Formulation

The optimization problem is described below.

Given: Fixed number of utilities (mass and energy), mass and energy sinks, mass and energy sources, and process units related to the sinks and sources. Fixed operating temperatures and efficiencies of the process units.
Optimize: Mass flows between mass sources and sinks (F_{ij}), heat exchange between sources and sinks (Q_{ijk}), selected process units (Z_m).
Minimize: The total annual cost (TC).
Subject to: Any constraints.

The objective function is to minimize the total cost by taking into account the operating and the capital cost (Fig.2). The capital cost includes the annualized, piecewise linearized cost of the process units and the cost of the mass and energy matches. The operating cost includes the utility and treatment cost.

TC (Total Annual Cost) = $Cost^{C}$ +$Cost^{UM}$+$Cost^{UE}$+$Cost^{TR}$, where

$$Cost^{C} = \sum_{m\in M^{N}} Cost_{m} + \sum_{j\in J^{M}} \sum_{i\in I^{M}} ap_{ij} \cdot Y_{ij}^{M} + \sum_{j\in J^{E}} \sum_{i\in I^{E}} ap_{ij} \cdot Y_{ij}^{E}$$

$$Cost^{UM} = \sum_{n\in N^{M}} pp_{n} \sum_{m\in M^{S}} \widehat{F}_{nm}^{OUT}$$

$$Cost^{UE} = \sum_{n\in N^{E}} pp_{n} \sum_{m\in M^{S}} \left(\widehat{Q}_{nm}^{H} + \widehat{Q}_{nm}^{C}\right)$$

$$Cost^{TR} = \sum_{n\in N^{M}} tp_{n} \sum_{m\in M^{D}} \widehat{F}_{nm}^{IN}$$

Where ap_{ij}= cost of the match ij [M\$/yr]
pp_{n}= purchase cost of utility n [M\$/ktn or M\$/MW]
tp_{n}= Treatment cost of utility n [M\$/ktn]

Fig.2 Cost Functions (in M\$/year)

The degrees of freedom in MEN include the (i,j) matching and the splitting/mixing of the stream flows. The utilities are constrained by the availability on the source nodes and the demand on the sink nodes. The degrees of freedom in EEN include the (i,j) matching and the heat flows between (i,j).The energy balances are formulated according to the extended formulation of the transshipment model (Yee & Grossman, 1991), because, when necessary, constraints on the thermal matches can be specified. The equipment purchase cost is annualized with respect to the chosen depreciation factor and life of investment and is a function of the throughput of the process unit.

4. Case Study

The process of CIMV consists of eight processing units: 1) biomass handling 2) biomass extraction 3) delignification 4) de-acidification 5) washing of the cellulosic pulp 6) concentration of the extraction liquor 7) treatment of lignin, and 8) concentration of the sugar syrup. The raw materials (lignocellulosic biomass) are converted to products (C6, C5, and lignin) by following the sequence of the processing units. Mass utilities include water, acetic acid (AA), and formic acid (FA), while energy utilities include steam and cooling water. It is postulated that the process treats 300kt/yr dry poplar with bark, with 34.8% w/w humidity before drying and 15% w/w after drying.

It is postulated that the process operates 8,000 hr/yr and that the ΔTmin for the heat integration is 10K. The depreciation factor is set at 35%, and the life of investment at 15 years. Table 1 shows the costing data. The prices for the mass and energy utilities are provided by CIMV. The treatment cost for water and solids is an approximation based on Mountraki et al. (2016), while the treatment cost for AA and FA is postulated to be half of its buying price. Prices refer to $ in 2016 and are updated using inflation indicators from the chemical engineering plant cost index (CEPCI) (Compass International, 2018). Prices in euros (€) are converted into United States dollars (USD $) according to the 2016 year average exchange range (ECB, 2018).

Table 1. Costing data ($2016)

	Mass Utilities	
	Purchase Price [$/tn]	Treatment Cost [$/tn]
Water	0.53	0.31
AA	492.93	246.47
FA	793.18	396.59
solids		0.41

	Energy Utilities		
	Tin (°C)	Tout (°C)	Cost [$/kWh]
Steam	176	175	0.048
Cooling Water	15	25	0.018

The base case studies the sequential optimization of CIMV process, starting with the solvent, following with the water, and finishing with the energy consumption. The initially open mass network (no recycles) requires 191.8 tn/hr water, 75.3 tn/hr AA, and 138.0 tn/hr FA. The closed mass network of case 0 requires 82.50 tn/hr water, 1.14 tn/hr AA, and 1.33 tn/hr FA. Case 0 managed to save the 57% of water, the 98.5% of AA, and the 99.0% of FA. In total, 117.51 tn/hr go to treatment, 114.78 tn/hr go to upgrade, and 250.90 tn/hr are shortly stored in the buffer units. Before applying energy integration, CIMV requires 194.2 MW for cooling and 206.8 MW for heating. After energy integration, case 0 requires 65.4 MW for cooling and 71.4 MW for heating (Fig.3). Energy PINCH managed to reduce energy requirements by 66%. The cost of the energy utilities (C^{UE}) is the 82% of the total annual cost (Table 2).

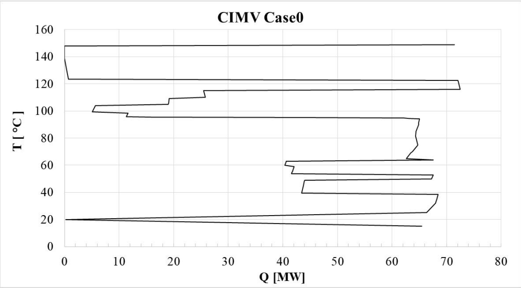

Fig.3 GCC– Case 0

Table 2. Cost Summary – Case 0

M$ 2016/yr					
TC	C^{UM}	C^{UE}	C^{T}	C^{IB}	C^{IU}
130,531.9	13,284.8	107,376.0	3,693.4	37.4	6,140.4
	10.2%	82.3%	2.8%	0.0%	4.7%

Simultaneous optimization has been applied to CIMV process. UNO model looks for the utility network configuration with the minimum annual cost, considering the mass and energy utility cost, the treatment cost of the effluents, and the annualized investment cost. The resulted network has 36 matches between splitters and mixers and requires 99.51 tn/hr water, 1.45 tn/hr AA, and 0.01tn/hr FA. In total, 131.33 tn/hr go to treatment and 64.91 tn/hr go to upgrade, while no intermediate storage is used. Fig.4 shows the GCC of the process with the resulted network. The integrated process requires 39.6 MW for heating and 33.4 MW for cooling. The energy requirements, after PINCH, is meant for the upgrade unit, which upgrades the quality of 64.91 tn/hr. The cost of the energy utilities is the 50% of the total annual cost (Table 3).

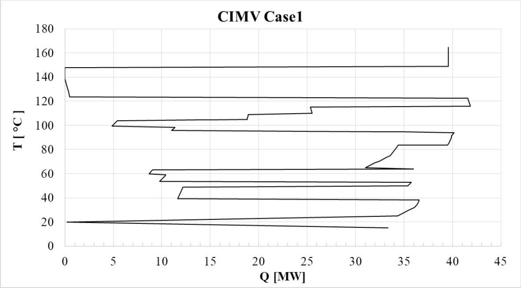

Fig.4 GCC– Case 1

Table 3. Cost Summary – Case 1

M$ 2016/yr					
TC	C^{UM}	C^{UE}	C^{T}	C^{IB}	C^{IU}
39,711.7	6,199.1	20,000.3	9,067.8	0.0	4,444.5
	15.6%	50.4%	22.8%	0.0%	11.2%

5. Conclusions

A method is devised to optimize utility networks, considering simultaneously the cost of mass and energy utilities and the capital investment in supporting units. The framework is applied in a real life biorefinery and managed to reduce up to 70% of the total annual cost, compared to the initial design, by reducing mainly the utility cost for both mass and energy. In the particular case study, 62% of the thermal flows were identified as a degree of freedom and UNO model managed to properly allocate mass and thermal flows. UNO finds practical application in grassroots and retrofit systems, exclusively for the design of the utility network but not for the optimization of the process or the supporting unit design. It can be used to analyze how the uncertainty of different costs affect the process and find flexible designs, able to absorb price fluctuations, simply by changing the mass flows. Future work may incorporate options for the energy system, including heat pumps and generation of different steam qualities. The integration of detailed treatment systems and the analysis of total site networks is also left as a future challenge.

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