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A Mixed-Integer Linear Programming Approach for Simultaneous Ethanol Supply Chain and Involved Plants Design Considering Production Scheduling

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In this work, a mixed integer programming model for the optimal design and production scheduling of an integrated ethanol/yeast supply chain is proposed. The model simultaneously determines the structure of a three-echelon supply chain (raw material sites-production facilities-customer zones), material flows among network nodes, the design of each installed plant, and the corresponding production campaign. For the selected facilities, out of phase duplication is considered for batch stages, while for equipment design, the optimal sizes are selected from a set of discrete unit values. Also, the number of batches of each product in the campaign and its sequencing for each ethanol/yeast plant are obtained. From the mathematical point of view, a new challenge is posed in this problem: the appropriate production campaign composition for each plant cannot be easily determined since products to be produced in each plant, as well as their production levels, are results of the supply chain design problem which is simultaneously optimized. Therefore, the trade-offs among all these decisions are jointly evaluated in an integrated model. Several examples are considered in order to provide insights into the problem. The presented approach serves as a tool for guiding the decision making for designing and planning supply chain and involved production plants.

1. Introduction

Supply chain (SC) design has been traditionally defined by determining the number and location of production facilities and warehouses, their capacities, and the flows among the different nodes of the networks, pursuing economic objectives. Several decisions must be addressed in order to achieve an efficient SC coordination. They can be classified into three categories according to their importance and the length of the considered planning horizon. First, decisions regarding the location, capacity and technology of plants and warehouses are generally seen as strategic with a planning horizon of several years. Second, supplier selection, product assignment as well as distribution channel and transportation mode selection belong to the tactical level and can be revised every few months. Finally, raw material, semi-finished and finished product flows in the network are operational decisions that are easily modified in the short term. In general, previous works have addressed decision levels in hierarchical approaches in which SC design is first determined. Then, for each plant involved in the network, plant design decisions are after taken, and finally scheduling decisions are made using planning demand targets. However, these approaches do not consider any interactions between decision making levels and thus the SC design and planning decisions may result in suboptimal or even infeasible plant scheduling problems. Due to significant relations between decisions levels, it is necessary to consider the simultaneous optimization in order to determine the global optimal solution.

In the last years, there have been some attempts to combine decisions in SC optimization, particularly strategic and tactic decisions as Barbosa-Póvoa (2012) mentioned in her review.

Studies about ethanol SCs have been increased in the last decade, since its production is motivated by the use of renewable energy and, among biofuels, it is considered the most appropriate solution for short-term gasoline substitution (Giarola et al., 2011). Several authors have addressed the design of ethanol SC

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through mathematical modelling and optimization, and due to the environmental impact caused by this production, some of them have also considered sustainable aspects. Recently, Nikolopoulou and Ierapetritou (2012) have revised the major approaches for the sustainable design of supply chains.
Usually, when SC is designed, the performance of involved facilities are usually considered as “black boxes”, where only the production in each plant is determined, and neither plant design (configuration and unit sizes) nor production scheduling is obtained. However, the work presented by Corsano and Montagna (2011) address a mixed integer programming (MILP) model for the simultaneous optimization of SC and plants design. In that work, decisions regarding SC network, as nodes selection and materials distribution, are together considered with multiproduct batch plants design decisions in order to attain a more integrated perspective of the SC design problem. In a later work, Corsano et al. (2011) presented a MINLP optimization model for a sustainable design and operation analysis of sugar/ethanol SC. A detailed model for the ethanol plant design was embedded in the SC model, and therefore, plant and SC designs were simultaneously obtained. The advantage of that approach is that simultaneous optimization allows assessing the tradeoffs between different decision variables, evaluations that cannot be carried out when sequential methodologies are considered. However, this approach assumes that plants involved in the SC operate under single-product campaign mode. This is the simplest scheduling policy: each campaign is devoted to produce only one product until fulfill its demand. In this way, models are simplified, but from the commercial point of view, the production policy adopted is not realistic, since huge inventories should be kept to support this approach and may be impracticable when perishable products are considered.
In order to overcome this limitation and include a more realistic scheduling program in production plants, in this work a MILP model for the simultaneous SC design and multiproduct plants design and production planning is proposed. The main challenge of modeling this problem arises from the incorporation of the design and production planning through mixed product campaigns (MPCs) for each multiproduct semi-continuous batch ethanol plant considered in the network, for which the production of each product and their amounts are unknown a priori. The model involves the integration of SC decision levels and represents a tool for providing decision support for different scenarios. It will be shown through the examples that including detailed plant performance model, has influence in the overall SC design. Besides, residues from ethanol production are considered for producing two kind of yeast in order to reduce the environmental impact caused by ethanol residues. In order to carry out these productions, additional stages are considered for each ethanol plant in order to evaporate and dry the process disposals. Therefore, trade-offs between design and environmental decisions are assessed. The capabilities of the proposed formulation is highlighted through the examples, where different scenarios are evaluated and several trade-offs are analyzed.

2. Problem statement

The SC considered in this work comprises three echelons: raw material sites, ethanol/yeast production plants, and customer zones. Near to each raw material site s, a maximum amount of sugar cane, QSC_s^{UP}, is available for producing sugar and molasses. In this work, sugar production and distribution is not modeled, but it can be easily incorporated to the formulation. Molasses can be distributed from raw material sites s (s = 1,…, N_s) to plants f (f = 1,…, N_f) to produce ethanol. Each installed plant can produce the three products: torula yeast, ethanol and bakery yeast. The final products are transported from each facility to customer zones c (c = 1,…, N_c) in order to fulfill their demands. The minimum and maximum demands of each product at each customer zone, DM_{ic}^{LO} and DM_{ic}^{UP}, for i = torula yeast, ethanol and bakery yeast, are model parameters.
Ethanol and bakery yeast are simultaneously produced. The stages involved in ethanol production process are biomass fermentation, alcohol fermentation, centrifugation and distillation. For alcohol fermentation two units in series are considered. Bakery yeast is a by-product of ethanol production which is obtained through evaporation and drying of the centrifugation residue of this process. In other words, the ethanol fermented broth is centrifuged, separating solids and liquids. The solids are evaporated and dried for producing bakery yeast while the liquids are distillated for producing ethanol.
Torula yeast is used for cattle feed and is obtained through biomass fermentation, centrifugation, evaporation and drying stages.
The batch stages are biomass and alcohol fermentations, and distillation, while centrifugation, evaporation and drying make a semicontinuous subtrain. Distillation stage involves five items: the distiller feed vessel and distillate tank are batch units while the evaporator, condenser and the column are semicontinuous units. The number of out of phase parallel units for each batch stage is a decision variable, while only one unit is used for semicontinuous stages.

Molasses are fed to biomass fermentors of ethanol production, while torula biomass fermentors are fed with an ethanol distillated residue called vinasses. The considered technology for producing ethanol and yeasts is presented in Figure 1. The conversion factors were obtained from Mele et al. (2011) for ethanol production and Corsano et al. (2007) for yeast production. Due to vinasses degradation, a continuous supply of this residue must be assured. Therefore, MPC is the most convenient scheduling policy for planning these productions, in order to fulfill the demands in the time horizon of each installed plant H_f.

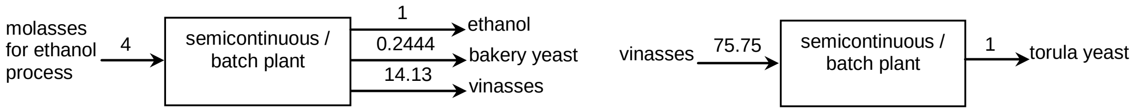

Figure 1: Schematic representation of the adopted technology

A maximum number of batches of each product in the campaign, NBC_{if}^{UP}, is allowed, and the number of campaign repetitions, NN_f, is uniformly discretized taking into account the minimum and maximum number of times that the campaign can be cyclically repeated over the time horizon, NN_f^{LO} and NN_f^{UP} respectively.

Then, the problem consists of simultaneously determining:

a) SC design: (i) plants location; (ii) molasses supply from each raw material site; (iii) product amount produced in each installed ethanol/yeasts plant; and, (iv) material flows among SC nodes.

b) Installed plants design: (i) the configuration of each plant (the number of in parallel units operating out of phase for batch stages); (ii) unit sizes; and, (iii) the number and size of the batches for each product in each plant.

c) Installed plants production scheduling: (i) the composition of the MPC (number of batches for each product in a campaign) for each installed plant; (ii) the assignment of batches to units in each stage; (iii) production sequence on each unit; (iv) initial and final processing times for the batches that compose the MPC in each processing unit; and (v) the number of times that each campaign is repeated over the time horizon.

The performance measure is maximizing the net profit calculated as the benefits by product sales minus the total annual cost, given by the cost associated to plants installation, equipment investment, production, and transportation between the SC nodes.

3. Mathematical modelling

The model basically considers: i) supply chain design constraints, which involve binary variables for plant location and products assignment and allow determining the flows among raw material sites, plants and customer zones; ii) design equation for each located ethanol/yeast plant, which involve binary variables for unit sizes selection, number of batches of each product in the campaign and number of times that the campaign is repeated through the time horizon; iii) scheduling constraints for located plants which assign batches to specific slots at each unit, timing constraints for determining the initial and final times of slots, equations for representing the ZW policy, and the campaign cycle time calculations.

The objective function is the maximization of the net profit given by the difference between income for sales and total costs. The total cost considers plants installation cost, semicontinuous and batch units cost for located plants, sugar cane cost, molasses transportation cost between raw material sites and production plants, and product transportation cost between plants and customer zones.

It is worth mentioning that constraints for plants design and scheduling are largely inspired from Fumero et al. (2012). Several adjustments were made considering that, in this new approach, the total production of each product in each selected plant is a model variable (in the previous model it was a model parameter). Also, several constraints reformulations and additional binary variables were necessary in order to keep the model linearity. Due to space reasons, the detailed formulation is not provided in this paper, but readers can request it to the authors.

4. Examples

The capabilities of the proposed approach is illustrated through an example involving five raw material sites, three possible locations for production plants and five customer zones which demand ethanol. It is assumed that if yeasts are produced, they are delivered to near customer zones because its degradation. Therefore, this example considers three extra customer zones next to the different production plants which

only demand yeasts. The maximum ethanol demand for each customer zone is 20,000 t, 30,000 t, 50,000 t, 40,000 t, and 40,000 t for c1-c5, while the maximum demands of torula and bakery yeasts (customer zones c6-c8) are calculated using relation given by Figure 1. For all products, the minimum demands are considered to be zero. The fuel cost is assumed to be 2 $/L, while sugar cane cost is adopted equal to 4 $/t. Product prices are 50 $/t for torula and bakery yeast, and 860 $/t for ethanol. The rest of the model parameters are not published but they are available for interesting readers.
Two cases are analyzed in this work: without and with process residual cost concerns. They were implemented and solved in GAMS (Brooke et al., 2005) in an Intel Core i7, 2.8 GHz processor. The number of binary variables, continuous variables and constraints is 2,200, 5,800 and 17,100. The time limit for solving the instances was 7,200 CPU s (2 h) and the final optimality gap was always under 1 %.

4.1 Case 1: without disposal cost

The optimal solution selects plants f1 and f3 for producing ethanol and both yeasts as it is shown in Figure 2. Molasses are transported from s1, s2 and s3 sites where sugar cane is processed. The maximum ethanol demand is supplied to customer c1-c5. Plant f1 produces 115,590 t/year of ethanol while f3 64,415 t/year, and both plants produce the maximum amount of bakery yeast according to the relation between ethanol and bakery yeast productions, i.e. 28,249 t and 15,743 t. However, produced vinasses are not totally used and therefore, torula demand is not fulfilled for neighbouring clients. Ethanol results profitable, so its maximum demand is produced. Produce bakery yeast is also profitable, i.e. it is convenient to add the evaporator and dryer for producing this yeast. However, torula production is not so profitable considering its selling price and the investment cost of the units involved in its process. Therefore, torula is produced in order to cover the idle times in semicontinuous subtrain in both selected plants and taking into account the trade-offs given by investment cost and selling prices. In this way, the production campaign in each plant is composed by two batches of ethanol and one batch of torula as it is shown in Figure 3. The campaign cycle time is equal to 24.54 h and the campaign is 305 times repeated over the time horizon.

4.2 Case 2: considering disposal cost in the objective function

In order to avoid process wastes, a process residue penalization is added to the objective function. This penalization considers the vinasses not used for torula production and the centrifuged cream not used for bakery yeast. Let $Vres_f$ be the discarded vinasses and $VCres_f$ the discarded centrifuged cream calculated according to the selected technology, then the term added to the objective function is:

$$\mathrm{ResC} = \sum_{\mathrm{f}} C_{vin}\, Vres_f + C_{cream}\, VCres_f \qquad (1)$$

where C_{vin} and C_{cream} represent the unit cost for vinasses and centrifuged cream disposals.
Considering both cost, C_{vin} and C_{cream}, equal to 5 $/t and the rest of parameters as in Case 1, the optimal solution selects again plants f1 and f3, but the material flows between SC nodes, plants design and production planning are very different to that obtained in the previous case. The produced amount of torula, ethanol and bakery yeast is 18,972 t, 109,620 t and 26,790 t respectively for plant f1, and 13,129 t, 70,380 t and 17,202 t for plant f2. Both plants have three biomass fermentors in parallel out of phase, two units out of phase for each item in distillation stage and one unit per stage for the remaining stages. Unit sizes for plant f1 are bigger than for f3. The production campaign in each plant involves two batches of torula and two batches ethanol, the campaign cycle time is equal to 24.54 h, and the campaign is repeated 305 times.
Plant f1 discards vinasses. The reason is that the available unit sizes do not allow producing more torula. In plant f3, the total possible amount of torula is produced according to the unit sizes selected for producing ethanol and bakery yeast, and the total produced vinasses are used for producing torula. The ethanol production is bigger in plant f1 since this plant has enough amounts of molasses from raw material site s1 (the nearest one). If more ethanol would be produced in plant f3, the molasses distribution cost would be increased. This means that is more convenient to discard vinasses in plant f1 than process them to produce a larger amount of torula increasing the unit sizes in plant f3 and the transportation costs.
It is worth to highlighting that this approach allows making all this analysis between different decisions involved in SC design and planning, and plants design and scheduling. This would not be possible in hierarchical approaches, where facilities are modeled considering only a maximum product capacity, a production rate, or yield coefficients.

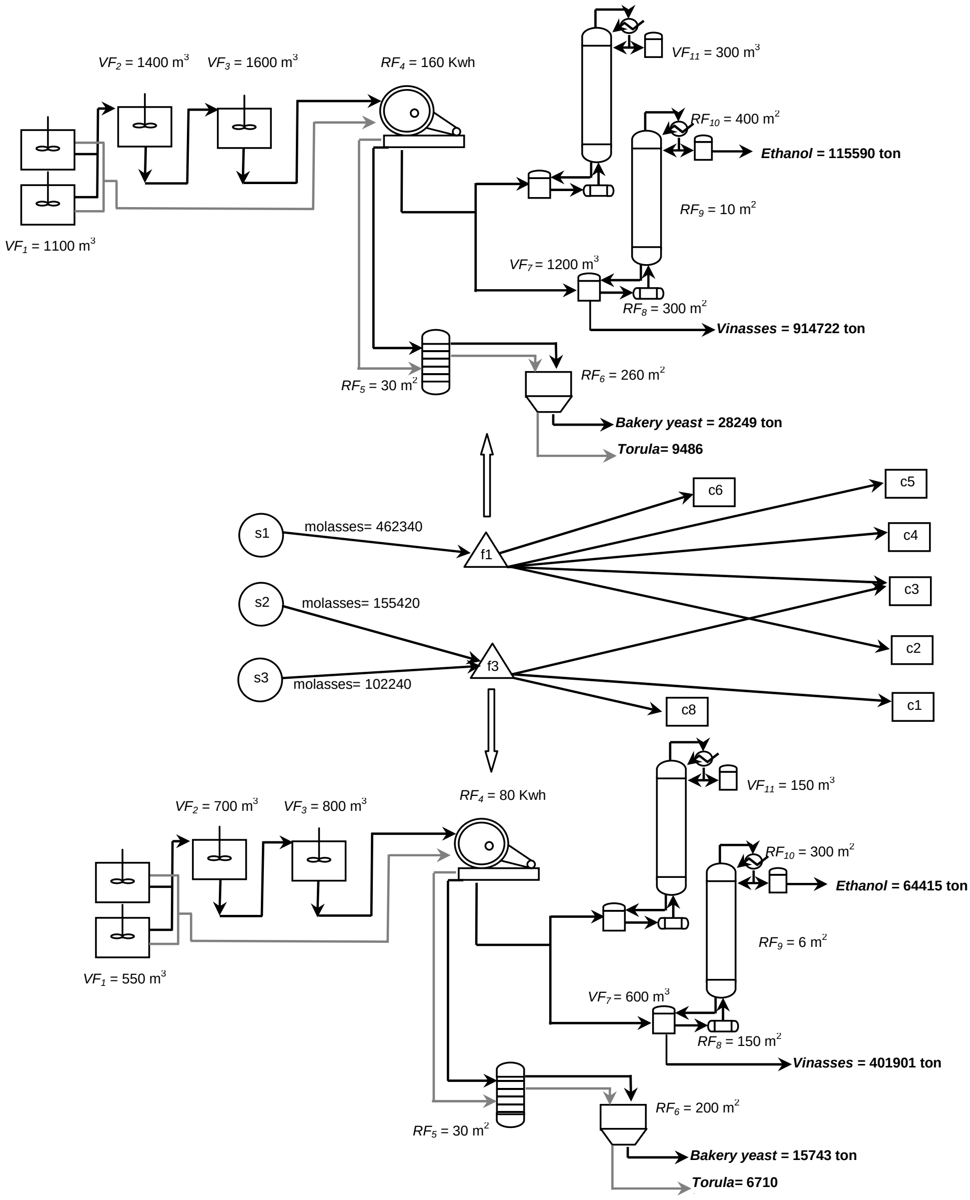

Figure 2: SC and plant design for Case 1.

5. Conclusion

In this work a MILP model for the optimal location of ethanol plants considering detailed formulation for plants design and production scheduling was presented. The production of yeasts for cattle feeding was incorporated to the model in order to evaluate the benefits of these productions using ethanol residues. Environmental concerns were also considered penalizing the process wastes in the objective function.

The capabilities of the proposed approach were illustrated through two instances and the model can be used for evaluating different scenarios. It represents a useful tool for decision making and provides valuable insight into the location, design and production planning problem for ethanol and derivative productions.

Numerical results show the importance of simultaneous optimization in this type of problem were several decisions are jointly taken into account and many tradeoffs are together evaluated. As can be observed through the different presented instances, plant design and planning decision may affect the network flows and product distributions.

The model size is large since several decisions are simultaneously considered. The proposed MILP becomes even more complex as the number of plants increases due to the presence of many binary variables for design and scheduling decisions. Hence, it should be appropriate to apply some decomposition methodology, like bi-level decomposition algorithm (Iyer and Grossmann, 1998), in order to improve the computational performance of the presented approach.

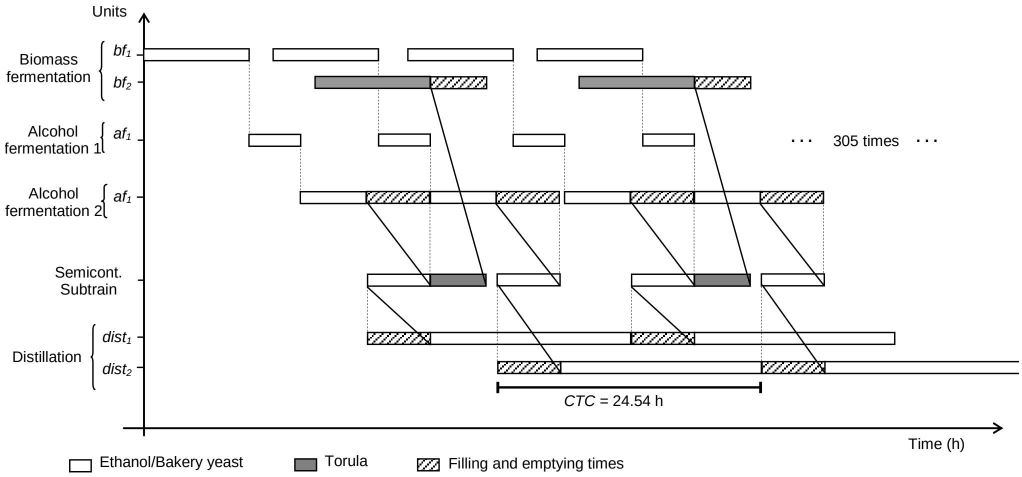

Figure 3: Gantt chart for production scheduling of both plants in Case 1.

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