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A mixed-integer dynamic optimization approach for the optimal planning of distributed biorefineries

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ABSTRACT

The implementation of supply chains based on biomass conversion requires the exploration of various aspects, including the selection of processing technologies, configuration of the supply chain, portfolio of products as well as the feedstock selection. One important feature of this system is that the composition of the available biomass changes drastically through the year because this depends significantly on the climatic conditions; this way, the dynamic behavior of this process is an important issue that must be considered. This study presents a dynamic optimization model for the optimal planning of a distributed biorefinery system taking into account the time dependence of the involved variables and parameters. In addition, this paper incorporates a model predictive control methodology to obtain the behavior of the storages and orders of the supply chain; where the objective function is the difference between the required and satisfied demands in the markets. Therefore, this study considers relevant issues, which include the multiple available biomass feedstocks at various harvesting sites, the availability and seasonality of biomass resources, potential geographical locations for processing plants that produce multiple products using diverse production technologies, economies of scale for the production technologies, demands and prices of multiple products in each consumer, locations of storage facilities and a number of transportation modes between the supply chain components. The model was applied to a case study for a distributed biorefinery system in Mexico. Results show that is possible to get the configuration and the behavior of the supply chain considering its dynamic behavior in a rigorous way; furthermore, the solutions obtained by the model illustrate that the supply chains based on biomass conversion are seriously affected by the availability of bioresources over the time.

1. Introduction

Currently, the increasing demand of energy around the world and the problems related to the climate change caused by greenhouse gas emissions (GHGE) from burning fossil fuels have promoted the use of alternative energy sources such as biofuels (Clark et al., 2006). Biomass has gained considerable attention as feedstock for energy production because of its attractive characteristics, including its availability as a renewable resource, reduction of GHGE, creation of new infrastructure and the inherent flexibility of biomass to produce several products (biofuels, polymers, specialty chemicals, etc.). These reasons have motivated the research for synthesizing novel processing pathways or technologies associated to biorefineries.

Recently, the optimization of supply chains (SC) associated to biorefineries has gained a lot of attention (Shah, 2005). This way, Hosseini and Shah (2011) and Yue et al. (2014) described the key challenges and opportunities in modeling and optimization of biomass-to-bioenergy supply chains; they demonstrated that multi-scale modeling and optimization play an important role to address these challenges. Hosseini and Shah (2011) concluded that one of the key challenges in the field is to integrate the different components of supply chains without any prior assumption about the fundamental structure of the network.

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Nomenclature

Parameters

$\alpha_{m,k,r}^{conversion}$ conversion factor for the processing to get the product *k* through the route *r* and from the raw material *m*
C_m^{rm} unit transportation cost for the raw materials
C_k^p unit transportation cost for the products
C_k^{sale} unit price of the products
$C_{m,h}^{prod}$ unit production cost for the different raw materials in the suppliers
$Cs_{m,h}^{suppliers}$ unit raw material storage cost in suppliers
$Cs_{m,ph}^{rm-plants}$ unit raw material storage cost in secondary processing plants
$Cs_m^{rm-main}$ unit raw material storage cost in main processing plant
$Cs_{k,ph}^{pr-plants}$ unit product storage cost in secondary processing plants
$Cs_k^{pr-main}$ unit product storage cost in the main processing plant
$Cs_{k,dc}^{distr-centers}$ unit product storage cost in the distribution centers
${}^{OP}Cs_{m,h}^{suppliers}$ unit operational cost for the raw material stored in suppliers
${}^{OP}Cs_{m,ph}^{rm-plants}$ unit operational cost for the raw material stored in secondary processing plants
${}^{OP}Cs_m^{rm-main}$ unit operational cost for the raw material stored in main processing plant
${}^{OP}Cs_{k,ph}^{pr-plants}$ unit operational cost for the product stored in secondary processing plants
${}^{OP}Cs_k^{pr-main}$ unit operational cost for the product stored in the main processing plant
${}^{OP}Cs_{k,dc}^{distr-centers}$ unit operational cost for the product stored in the distribution centers
$C_{m,k,r,ph,q}^{FIX}$ unit fixed cost for the capital of secondary processing plants
$C_{m,k,r,ph,q}^{VAR}$ unit variable unitary cost for the capital of secondary processing plants
$C_{m,k,r,q}^{main-FIX}$ unit fixed cost for the capital of main processing plant
$C_{m,k,r,q}^{main-VAR}$ unit variable cost for the capital of main processing plant
$C_{m,k,r}^{processing\ plant}$ unit operational cost for the secondary processing facilities
$C_{m,k,r}^{processing\ main}$ unit operational cost for the main processing facility
$d_{h,ph}^{h-ph}$ distance between the supplier *s* and the secondary processing plant *ph*
$d_{h,main}^{h-main}$ distance between the supplier *s* and the main processing plant
$d_{ph,dc}^{ph-dc}$ distance between the secondary processing plant *ph* and the distribution center *dc*
$d_{main,dc}^{main-dc}$ distance between the main processing plant and the distribution center *dc*
${}^{UPP}I_{m,h}^{suppliers}$ upper limit for the raw material storage in suppliers
${}^{UPP}I_{m,ph}^{rm-plants}$ upper limit for the raw material storage in secondary processing plants
${}^{UPP}I_m^{rm-main}$ upper limit for the raw material storage in the main processing plant
${}^{UPP}I_{k,ph}^{pr-plants}$ upper limit for the product storage in the secondary processing plants
${}^{UPP}I_k^{pr-main}$ upper limit for the product storage in the main processing plant
${}^{UPP}I_{k,dc}^{distr-centers}$ upper limit for the product storage in the distribution centers
${}^{LOW}I_{m,h}^{suppliers}$ lower limit for the raw material storage in suppliers
${}^{LOW}I_{m,ph}^{rm-plants}$ lower limit for the raw material storage in secondary processing plants
${}^{LOW}I_m^{rm-main}$ lower limit for the raw material storage in the main processing plant
${}^{LOW}I_{k,ph}^{pr-plants}$ lower limit for the product storage in the secondary processing plants
${}^{LOW}I_k^{pr-main}$ lower limit for the product storage in the main processing plant
${}^{LOW}I_{k,dc}^{distr-centers}$ lower limit for the product storage in the distribution centers
K_F factor to annualize the capital cost
${}^{max}M_{m,h}^{prod}(t)$ maximum raw material production rate in the supplier *h*
$P_{k,dc}^{demand}(t)$ maximum required demand that can satisfy a distribution center *dc*
${}^{MAX}M_{m,h,ph}^{h-ph}$ upper limit for the transportation flow rate of raw material from the suppliers to the processing facilities
${}^{MAX}M_{m,h}^{h-main}$ upper limit for the transportation flow rate of raw material from the suppliers to the main processing facility
${}^{MAX}P_{k,ph,dc}^{ph-dc}$ upper limit for the transportation flow rate of product from the processing facilities to the distribution centers.
${}^{MAX}P_{k,dc}^{main-dc}$ upper limit for the transportation flow rate of product from the main processing facility