Process design, supply chain, economic and environmental analysis for chemical production in a glycerol biorefinery: Towards the sustainable design of biorefineries

Process design, supply chain, economic and environmental analysis for chemical production in a glycerol biorefinery: Towards the sustainable design of biorefineries

Drivers such as our deep dependence on fossil fuels availability and price volatility, global concern about climate change and social distress, are steering the economy to be more sustainable and based on a greater use of renewable resources. Therefore, the concept of integrated biorefineries has attracted much attention by aspiring at replacing fossil sources. However, as has been recently witnessed through multiple failures and the shutdown of biorefinery plants all over the world, a biobased economy that heavily depends on the production of biofuels, leads to unsatisfactory results. Thus, it seems that an economy based on the innovative and cost–efficient use of bio-resources for the production of both chemicals and biofuels/bioenergy, is in fact very promising regarding the three pillars of sustainability (economic, environmental and social). Notwithstanding, to be competitive in the long run and to present an advantage in the global markets, robust systems for the acquisition, production and distribution of these bioproducts must be in place.

Although considerable studies have been carried out on the analysis and optimization of biomass conversion to biofuels and bioenergy, up to date limited research has been done on the valorization of biorefinery by-products. This is especially noticeable concerning the valorization of glycerol, which is, as main by-product of the biodiesel industry, responsible for approximately 2/3 of the world supply of glycerol. Despite the many uses for pure glycerol, the exponential growth of biodiesel production in a recent past due to fossil-based energy insecurity and environmental concerns, has led to a significant surplus of glycerol, resulting in a significant drop of its market value. Then, how to deal with the large quantities of low price crude glycerol surplus may become an environmental problem. As a result, exploratory research being carried out along the years has been pointing to glycerol as a powerful starting material for the production of a plethora of value-added chemicals and biofuels. A significant challenge is that emerging technologies are accompanied by uncertain performance characteristics, as well as exogenous sources of uncertainty such as product price and demand. This leads to a significant number of possible options regarding the design, operation and product portfolio offered by biorefineries, from which the most suitable process configurations must be selected, with regards to economics, environmental constraints and overall sustainability. Therefore, uncertainties should not be overlooked. Furthermore, given the multiplicity of large (bio)chemical operations and the often-conflicting objectives among the several business divisions, such as planning, manufacturing, distribution and corresponding environmental consequences and concerns, it is therefore vital to model these activities and to develop comprehensive and systematic methods to capture the synergies and the trade-offs within this complex system. Therefore, the foremost aim of this thesis is to provide a roadmap for early-stage managerial decisions targeting at identifying feasible alternatives for the design and planning of sustainable glycerol biorefineries and corresponding value chains. In this way the thesis is contributing to the transition towards the sustainable development of and imports for the planning and execution of these concepts. To achieve this, significant effort is firstly invested into process understanding and into the development of data-driven process models ("gate-to-gate"). Secondly, detailed methodologies for the economic and environmental assessment are developed, where uncertainty and sensitivity analysis play a significant role. Nevertheless, in order to further advance the development and implementation of glycerol based biorefinery concepts, it is critical to analyze the glycerol conversion into high value-added products in a holistic manner, considering both production as well as the logistics aspects related to the supply chain structure. Therefore, the boundaries of analysis were extended to include all activities and operations involved in the glycerol-based biorefinery to bioproducts supply chain. To this end, the GlyThink model is proposed so as to identify operational decisions - including locations, capacity levels, technologies and product portfolio, as well as strategic decisions such as inventory levels, production amounts and transportation to the final markets. GlyThink is a multi-period, multi-stage and multi-product Mixed Integer Linear Programming optimization model based on the maximization of the associated Net Present Value (NPV).

Furthermore, strongly based upon the GlyThink model, alongside with detailed economic and environmental assessment, a multi-layered framework for the optimal design and planning of glycerol based biorefinery supply chains under uncertainties is developed in this thesis. The proposed integrated framework ultimately leads to the identification of the optimal design and planning decisions for the development of environmentally conscious biorefinery supply chains, where the consequences of external economic uncertainties on the environmental objective function are analyzed and the trade-offs identified. In summary, this thesis covers the development of methods and tools for the modeling and optimization at the strategic and tactical level, along with detailed economic and environmental assessment techniques, including the incorporation of multi-level uncertainties. All in all, despite the fact that all methods and tools derived in this thesis have been developed to address the optimal design and planning of the glycerol-based biorefinery, they are flexible and applicable to other biorefineries similar in nature.