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Development and implementation of an optimisation model for biofuels supply chain

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ABSTRACT

Biofuels supply chain comprises a wide set of activities involving a rather complex set of parameters. Cultivation of the raw materials is closely related to the agricultural sector whereas the production of the final product presumes the operation of a conversion plant. The distribution network aims at delivering the final product close to the consumption. The extent of the involvement of each one of the previously mentioned sectors is the result of strategic and operational planning of the whole supply chain and, in the general case, determines the efficiency of the biofuels sector. Taking also into account the very rapidly changing opinions related to the environmental behaviour of the whole biofuels supply chain, it becomes very clear that the parameters in the sector are continuously changing. Therefore, the consideration of an integrated supply chain appropriately modelled is believed to be very critical and could result in the optimal solution per case, economically and/or environmentally speaking. In this paper the development of a mathematical model for the optimal design and operation of Biofuels Supply Chain is proposed as an integrated approach that can take into account both technical and economic parameters affecting the performance of the whole value chain. Model implementation would facilitate and support the decision taking in various planning and operational issues such as infrastructure investments, the quantities of raw materials to be cultivated, the quantities of biofuels to be produced in the domestic market or imported, identifying the best available solution for the optimal design and operation of the biofuels supply chain.

1. Introduction – scope and objectives of the work

Driven by the necessity to reduce oil dependence, address the imperative needs for energy security and mitigate the greenhouse effect and climate change on a global level, various promising ideas and activities for fuel substitution in the transportation sector have seriously been investigated during the last years. In that framework the use of biofuels and other alternative fuels i.e. biogas, hydrogen, natural gas, is being encouraged and promoted through various actions. Bioethanol and biodiesel present a competitive advantage compared to the other alternative fuels, since they have a large field of applicability in the existing car fleet, as many of their attributes and characteristics are similar to the respective ones of conventional fuels, i.e. diesel and gasoline.

Although offering a prosperous solution, at least in the energy supply part, biofuels deployment has undergone a rather slow progress [1] both at EU and national level. The majority of Member States failed to reach the targets initially set by the Directive 2003/30/EC [2], due to their relatively high production costs, in some cases reinforced by the different support schemes per country applied. Similarly in Greece, the use of a quota mechanism, allowing the Government to decide the amount of biofuel (biodiesel) that has to be supplied each year, resulted in a very small penetration rate and didn't set the fundamentals for the establishment of a free market for biofuels trade.

In any case, the technical and economic feasibility of biomass-derived fuels has been extensively examined [3–9] and many efforts have been made in order to identify and quantify all the interrelated parameters; however, no extended work has been done with regards to the evaluation of the entire biofuels' supply chain.

Additionally, the public opposition that has risen relative to biofuels' sustainability throughout their Life Cycle [10–15], reinforced

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by the food versus fuel debate [16,17] caused a major push back in biofuels policy and rendered a new challenge to face.

Biofuels' successful penetration in a country's energy fuel mix presupposes numerous strategic and operational level decisions, being currently reinforced by the new Renewable Energy Directive 2009/28/EC for an overall share of 10% energy from renewable sources in transportation by 2020 [1]. Biofuels environmental sustainability throughout their Life Cycle is a vague story, with the results of various Life Cycle Analyses (LCAs) appearing to be controversial [18,19]. Considering the above and taking into account the importance of the biofuels issues, this work aims to identify the structure of the entire biofuels supply chain and the various types of problems that emerge in strategic and operational level. The work also attempts to develop an integrated mathematical model for the appropriately defined optimisation of the biofuels supply chain. The value chain that has been defined in the context of the present work typically includes the feedstock production, the biofuel production, the blending (if applicable), the distribution and the consumption of biofuels. It is believed that the model can be very useful for the evaluation of the biofuels supply chain performance either at strategic or operational level.

2. Supply chain management considerations

Supply Chain Management (SCM) is the determination of the optimal material flow among vendors, facilities, warehouses and customers. It is an integrating environment which includes all the stages from the product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers and end-of-life management of the product after its useful life. A supply chain includes a network of retailers, distributors, transporters, storage facilities, and suppliers that participate in the production, delivery, and sale of a product to the consumer. The supply chain is typically made up of multiple companies who coordinate activities to set themselves apart from the competition. In parallel, the SCM involves the optimal coordination of the various operations included in the production of raw materials and final products, the storage, the importing and/or exporting raw materials, intermediate and final products. It usually implies the optimisation of a performance criterion financial and/or operational, either in a short or in a long time horizon.

SCM has been a widely applied approach for coordinating and controlling in an integrated manner all the stages that may seem independent in other considerations, recognising that any parameter affecting one specific point of the supply chain, in fact affects its entire behaviour and performance. It has been used extensively in solving classical production and operations management problems and organising the production and distribution of products in a global level. The main advantage of the early incorporation of the operational research tools into the classic SCM concept and visualisation is the optimisation approach, which may also integrate the spatial and temporal characteristics of the supply chain. The optimisation criterion, depending on the problem under consideration, may be the minimisation of the transportation cost or the total cost, the maximisation of the supply chain's efficiency and various others optimisation criteria [20].

Over the years the implementation fields and, consequently, the amount of literature on SCM has growing rapidly. The research community has developed global supply chain design and optimisation models. The business environment that surrounds the problem is continuously changing. First, firms are increasingly outsourcing to both domestic and global locations. Second, many companies that had viewed their sourcing problems as an enterprise-level concern, now strive to integrate decision processes across tiers in the supply chain. A third issue is the broadened definition of supply chain performance, as mission, strategy and objectives can vary considerably based on the value of the product offered to the customer. Supplier selection decisions change the global supply chain design problem in fundamental ways, in part because they are based on more broadly defined criteria [21].

The SCM concepts become more interesting not only because of the continuously changing characteristics of the main SCM actors but also due to their wide applicability. Recently the supply chain approach has been extended much further than the classical product/production consideration. During the last years research works have been developed that apply very successfully the SCM basic principles and approaches to other material and non-material flows. For example, novel supply chains have been introduced concerning biofuels, biomass, natural gas, hydrogen, energy in general and water. Representation and modeling of these new supply chains and the development of the optimisation models can be very essential to the identification of the problems characteristics, the integration of the various initially independent parameters and processes and the solution of various different level problems [22–26].

A challenging aspect of a great importance in the successful and efficient consideration of these novel supply chains, the ones of biofuels and alternative fuels in general, is their optimal design and operation. Following that, many models and solutions have been employed as Decision Support Tools, assisting at choice making in the level of strategic and/or operational planning.

More precisely in the biomass sector, mathematical models have been developed and applied into bioenergy systems planning [5], in decision support modeling methodologies for product and process design decisions under economic evaluation [27,28], in raw material supply estimations [8], in bio-fuel multi-stage activity modeling aiming at determining efficient public policy in uncertain agricultural markets [7], in integrated economic and environmental Life Cycle optimisation of biofuel production [6].

Additionally in the field, more innovative, State-Task-Network (STN) approaches have also been used in order to minimize total system cost whilst ensuring satisfaction of the prescribed energy demand load [29], whilst also, modeling principles have been applied to Waste to Biomass SCs, so as to minimize the total cost of the system throughout the entire planning horizon, identifying the more cost effective strategy of supplying end product from biomass waste over a planning horizon, under projected annual demands and available feedstock supply [30–32].

Thus, traditionally, mathematical modeling applications have been focussed on process models and simulation tools to facilitate the assessment of supply chain performance, in terms of raw material availability, energy supply demand satisfaction, logistics and geospatial- siting parameters of the production plants. However, no integrated mathematical model assessment, incorporating both the optimisation of raw materials- feedstock and end product selection in biofuels field, has been made. Acknowledging that, in the present work a Mixed-Integer Linear Programming model has been developed to determine the optimal exploitation of the appropriately defined BSC aiming at facilitating decision making in a nexus of complex contradictory issues like feedstock to be cultivated and/or imported, local biofuel production and/or imports, creation of a strategic plan for the associated sector or an operational level activity.

3. Biofuels supply chain characteristics

The Biofuels Supply Chain (BSC) is very interesting and complex, involving factors from various different fields. Typically, a biofuel production (chain) involves domains such as agriculture (energy crops, raw materials production), biofuel production (modification