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Reverse logistics network design for a biogas plant: An approach based on MILP optimization and Analytical Hierarchical Process (AHP)

Daniel Galvez[a], Auguste Rakotondranaivo[a], Laure Morel[a], Mauricio Camargo[a,*], Michel Fick[b]

[a] Université de Lorraine, Equipe de Recherche sur les Processus Innovatifs (ERPI), EA 3767, 8, rue Bastien Lepage, Nancy 54010, France
[b] Université de Lorraine, Laboratoire Réactions et Génie des Procédés (LRGP), UPR 3349, 1 rue Grandville, rue Bastien Lepage, Nancy 54010, France

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ABSTRACT

Among sustainable energy production processes, methanation (anaerobic co-digestion) has a high potential to valorize organic residual waste by exploiting its energetic capacities in the form of biogas. Nevertheless, at the early stage of the project, decisions must be made concerning the network used to supply biomass to the anaerobic co-digestion facility. However, these decisions involve complex hierarchical processes, taking into account the best compromise to be found among diverse factors and actors (economic, social, environmental, etc.). In this article a systematic approach integrating Mixed Integer Linear Programming (MILP) optimization and Analytical Hierarchical Process is proposed. It will allow project managers to evaluate possible scenarios for the implementation of an anaerobic co-digestion logistics network in order to facilitate the integration of the preferences of the stakeholders involved in the project. The approach proposed is then illustrated by the design of a municipal biogas facility in Nancy, France.
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1. Introduction

The volume of municipal solid waste has risen sharply in recent years. For example, for the period between 1980 and 2006, such waste increased in the OECD countries by 35%, whereas from 1960 to 2007, production in the United States increased by 72% [1]. This is the reason why the valorization of waste treatment has aroused great interest, in particular in the form of power generation. Indeed, during the last decade in European Union countries, waste treatment has significantly changed since landfill use has been continuously declining. This development in solid waste treatment aims to diminish the use of landfills because they produce a high volume of waste, generating pollution problems [2]. Alternatives to treatment using landfill reached 50% of waste treatment in the year 2010 [3].

Anaerobic co-digestion to produce biogas offers a new opportunity for the treatment of either biodegradable waste or residual organic waste as their energetic capacities can be used to create value in the form of biogas [4–6]. Anaerobic co-digestion is applicable to a high proportion of organic waste that can be of domestic, industrial, agricultural or livestock origin. From an environmental point of view, anaerobic co-digestion is not only useful in terms of waste management but is also a means of producing renewable power. According to Iakovou et al. [7] the two main problems limiting the further deployment of this type of processes are the cost and complexity of the associated logistics operations. This complexity mainly stems from a growing demand for biomass as well as its diverse sources and origins. Both Refs. [8] and [9] indicate that one of the principal problems facing anaerobic co-digestion development concerns the definition of the optimal location of a biogas plant and its associated logistics network.

A design and planning project to define the biogas plant logistics network is made up of a set of complex processes and hierarchical decisions associated with the multiple groups of stakeholders involved. A comprehensive check list of these decisions can be found in Iakovou et al. [7]. For example, strategic decisions include supply and demand contracts, network configurations, location and capacity of energy facilities, location of storage facilities, network design and sustainability of logistics operations, fleet management, vehicle scheduling and the selection of collection, storage and pre-treatment processes. At a very early stage, project managers must therefore deal with all these decisions that are very often contingent on a heterogeneous set of stakeholders. Moreover, the perishable, diverse and seasonal nature of the waste to be treated increases the uncertainty and complexity of the system definition process.

* Corresponding author.
E-mail address: mauricio.camargo@univ-lorraine.fr (M. Camargo).

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Having methods and tools to support decision-making in the early stages is therefore essential in reducing the probability of project failure. Some authors seek to compare different methods to determine the optimal process [10–12]. Nevertheless, as indicated by Iakovou et al. [13] most research focuses on the assessment of the energetic potential of biomass, or the selection of sites for waste collection and digester location, but few address this issue taking into account the decision makers point of view. That is, taking into account the aspects tied to the optimization of logistics networks but also considering the diverse points of view of all the actors and stakeholders.

To tackle the above-mentioned issues, this article proposes a methodology to evaluate different possible scenarios for the implementation of waste treatment by means of anaerobic co-digestion using MILP optimization and Analytical Hierarchical Process (AHP). To achieve this, each scenario is modeled using a mathematical programming tool based on "Mixed Integer Linear Programming" which optimizes a proposed logistics network, ensuring the lowest cost and the shortest possible traveling distance. Once the optimum projection for each scenario has been determined, multicriteria analysis is used to select the most suitable scenario, taking into account different aspects and decision makers' points of view represented by the evaluation of a set of criteria. In this case, four criteria are used to evaluate scenarios: the global costs associated with the running of the network, the total distance covered to transport the waste, the quantity of CO_2 emissions and the technical feasibility of implementing each scenario. The proposed model will be applied to the design of a reverse logistics network for producing biogas as renewable energy.

The article is structured as follows: In Section 2 we review different methods of waste treatment and focus on co-digestion. Section 3 describes the methodology, describing the definition of three scenarios, the proposition of the mathematical model and the multicriteria technique for evaluation. Section 4 explains the case study applied to Greater Nancy, France. Section 5 includes a discussion with conclusions and perspectives.

2. Overview of a biogas facility location and its associated reverse logistics network

As mentioned above, evaluation of bio-energy production needs a system perspective on biomass resources, transport, facility location and conversion technologies. For each particular system a wide variety of combinations are feasible, which makes it difficult to compare possible solutions. Gold and Seuring [14] carried out a comprehensive analysis of the different issues when defining the logistical systems for bio-energy. They conclude that even if it is obvious that providing the best solution needs an optimization of the logistics network, the current studies are mainly focused on the economical and environmental considerations. Integration of social and political aspects needs to take into account the preferences and priorities, sometimes subjective, of the set of stakeholders. The resulting complexity constitutes a major barrier to the implementation of bioenergy projects [15].

2.1. Biomass logistics network optimization

There are a number of challenges when designing logistical systems for dedicated biomass to energy. In addition to the complexity of the systems to be modeled and optimized, the uniqueness of the system to be implemented requires a customized approach to fit the requirements and constraints of the system to be represented.

Mathematical programming is often used to deal with this type of problems. For example, Zhu and Yao [16] proposed a conceptual Mixed Integer Linear Programming (MILP) model to design a logistical system to deal with multiple types of feedstock in the US state of Tennessee. Čuček et al. [17] developed a regional MILP-based model to supply bioethanol facilities. Pérez-Fortes et al. [18] designed a regional and sustainable bio-based networks for electricity generation using a multi-objective MILP approach. Rentizelas et al. [19] focused on the logistics issue of biomass utilization, especially storage and supply chain optimization. Pishvaee et al. [20] develop a deterministic MILP model for reverse logistics and compare it to the stochastic counterpart to deal with data uncertainty.

Fig. 1 shows a generic description of the principal logistics flows; first the diverse sources of biomass S_i, which are collected in urban and rural zones. Immediately, the waste treatment process begins with the transport of this organic matter to select and to be able to separate the matter that can actually be valued.

Different scenarios can be posed, depending on the geography of the supply network and the nature and volumes of biomass sources. The challenge is to find the best possible compromise in terms of cost and environmental impact. There are five possible types of waste available in the geographical zone:

S_1: non-domestic waste from private and public restaurants.
S_2: domestic origin.
S_3: municipal green biomass, mainly from maintenance of roadside verges.
S_4: agricultural origin.
S_5: livestock waste (manure).

Anaerobic co-digestion as a method of waste treatment presents a set of challenges to implementation:

- Transport distance plays a major role in energetic and environmental performance.
- The technological complexity of a bioprocess, due to the fact that a good conversion rate of the reaction strongly depends on supply and a balanced mix of biomass [21].
- The associated logistics network must be designed so as to ensure the best compromise between cost and environmental impact.

2.2. Multicriteria analysis (MCA) for bioenergy projects

However, in bioenergy projects the interest is not always exclusively in economic or environmental optimums from the analytical point of view of the system evaluated, but in the "most convenient" solution, which needs to be evaluated using several criteria. As a consequence, a decision-aid method must be applied [22–24]. Decision-making is a process in which the decision-maker chooses the input project parameters and variables to meet the best compromise solution of the "target" product or process, finding a reasonable compromise among the criteria [28,29]. However, identifying the best compromise requires eliciting the decision-maker's preferences: elicitation of the more important criteria, represented by weights; or establishing a description of the decision-maker's degree of satisfaction given by an appropriate set of values, represented by a utility function [25].

As stated by Buchholz et al. [15], interaction with decision-makers using MCA tools will facilitate and enhance the participation of the stakeholders in the bioenergy project.

Applications concerning bioenergy problems have been widely studied. Recently, an exhaustive literature review was provided by Scott et al. [22], showing that multicriteria approaches have been widely used at different stages of the project, in order to make decisions about biomass sources, location and technologies. Moreover, there are two main families of MCA Methods to rank options from best to worst. First, total aggregation, where a global score based is computed, methods such as MAUT – Multi-Utility Attribute Theory

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