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Reverse Logistics Network Design for a Biogas Plant: an Approach Based on MILP Optimization and Analytical Hierarchical Process (AHP)

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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.

Key words: Anaerobic co-digestion, biogas, reverse logistics, optimization, multicriteria analysis.

Introduction

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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 [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 [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 [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.

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 [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 modelled 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 travelling 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 CO₂ 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. [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].

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 modelled 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, [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. [17] develop a regional MILP-based model to supply bioethanol facilities. [18] Design of regional and sustainable bio-based networks for electricity generation using a multi-objective MILP approach. [19] focused on the logistics issue of biomass utilization, especially storage and supply chain optimization. [20] Develop a deterministic MILP model for reverse logistics and compare it to the stochastic counterpart to deal with data uncertainty.

Figure 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.

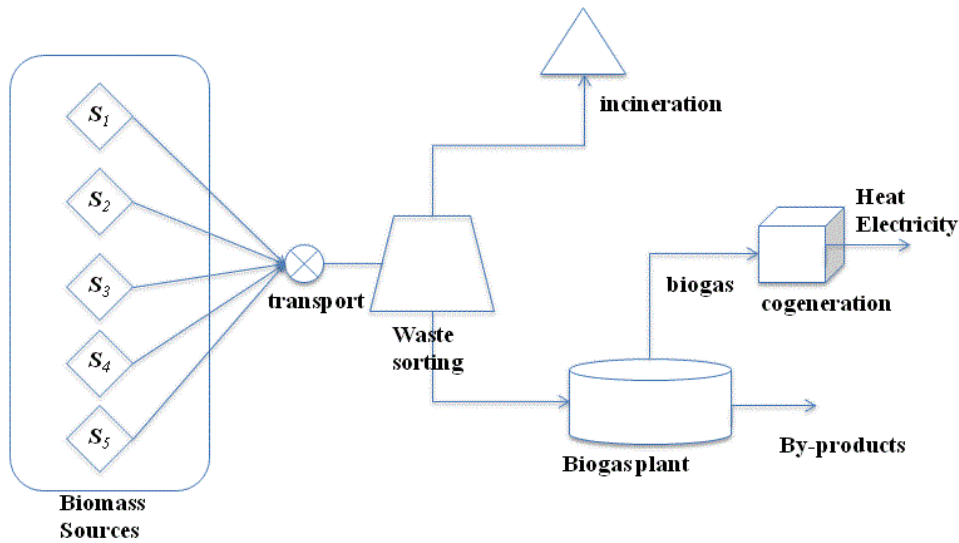


Figure 1. Logistic network of a digestion plant.

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 the 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.

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]. 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 [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 [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 [25] used by [31, 32] or AHP – Analytic Hierarchical Process [28] used by [29–31]. The second family of methods named partial aggregation (outranking) which are based on pairwise comparison, such as ELECTRE or PROMETHEE used by [32–34]. Although use of these methods is growing, future research should aim to address these issues in a more complete way to create a basis for implementing best practices in bioenergy projects.

3. Proposed methodology

The proposed methodology aims to determine the most appropriate logistics network, integrating both optimization and MCA according to the system to be modelled. For this, a four-step procedure is defined in Figure 2.

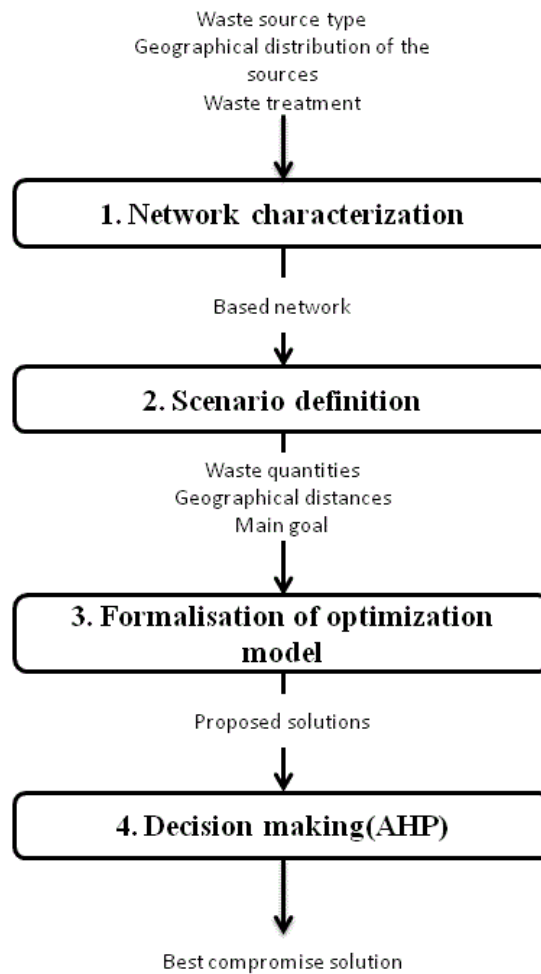


Figure 2 Steps of proposed methodology

3.1 Network characterization

Identifying the processes, actors and variables associated with the waste treatment chain is a key stage in the development of solutions to system problems. This step is based on a review of existing standards related to the method of waste treatment chosen. Identifying and characterizing local sources of waste production, the type of waste that can be processed, the treatment stages, and the form of energy generation, among other things, are some of the tasks to be performed at this stage. The network characterization will enable a better understanding of the advantages, disadvantages and limits, and therefore provides a better basis to develop system enhancements.

3.2 Scenario definition

The objective is to adapt to a given case the knowledge acquired in the previous step. This is the adaptation of the network to geographical, social and cultural characteristics of the area where the project is realized. One of the tasks is to study the cartography of the city to define the places where potentially the equipment will be located, in addition to defining routes to complete the logistics network. The analysis of the area where the network must be implemented makes it possible to strengthen the viability of the scenarios defined. The definition of each scenario seeks to provide a set of potential alternatives in implementing the network for waste treatment.

3.3 Formalization of the optimization model

At this step the proposed scenarios are translated into a mathematical language, based on linear equations. The proposition of optimization models makes it possible to quantify the resources used in each scenario. The goal is to find formal mathematical expressions of costs, times and distances involved within the network. Furthermore, the optimization model minimizes costs and distances travelled, and therefore delivers the optimal values for each scenario. Mathematical optimization techniques are currently used in the definition of a logistics network.

3.4 Decision-making (AHP)

The model proposed in the previous section makes it possible to determine the optimal logistics network for each scenario depending on cost and distance travelled. In order to make an assessment of the scenarios, a survey including the different actors involved in the project must be carried out in order to integrate their preferences into a set of criteria. To formalize this stage of the methodology, the method of Analytic Hierarchy Process (AHP) was used. This is a multicriteria method of decision support that makes it possible to solve complex decision problems. In particular, the AHP method uses a multi-level hierarchical structure constructed from a goal, criteria and evaluated alternatives, later to make a peer comparison of the alternatives depending on criteria generating evaluation matrices of double entry. These comparisons serve to determine the degree of importance (weight) of every criterion and then to prioritize the proposed alternatives [35,36].

The AHP method is defined by the following stages:

1. Decomposition of the problem in a hierarchical structure: a problem of decision-making is characterized by three factors: the expected objective, evaluation

criteria and possible alternatives. In AHP, these three factors are sorted in descending order, creating a structure with three hierarchical levels.

2. Peer comparison: AHP is based on expert opinion to determine the importance of criteria and a peer comparison is made between the criteria. This comparison determines the relative importance of a criterion over the others based on the scale proposed by Satty (Table 1).

Intensity importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong demonstrated importance
9	Extreme importance
2, 4, 6, 8	Intermediate values

Table 1. Satty scale

3. Definition of the importance of criteria: The information collected in the previous stage is synthesized in double-entry matrices to calculate a priority vector of criteria (weights). This importance of criteria is obtained from the eigenvector of the double-entry matrices normalized to 1.
4. Consistency of judgments: An additional feature of this methodology is to determine the consistency of expert opinion. Thus, a coherence index is calculated and it is considered a problem of inconsistency if this index value exceeds 0.1 (see [37,38]).
5. Prioritization of alternatives: once the importance of the criteria is defined and validated, the alternatives are evaluated. Therefore, the prioritization of the alternatives is obtained, giving consideration to the relative importance of each criterion.

4. Case study

This article was developed in the framework of a project to improve waste management in the city of Nancy, France.

4.1 Network characterization

The city produces a significant quantity of waste and the aim of this work is to treat the organic waste in order to produce energy in the form of electricity and heat. Figure 3

shows the named Greatest Nancy area which includes a network of urban and rural locations as potential sources of biomass to be considered.

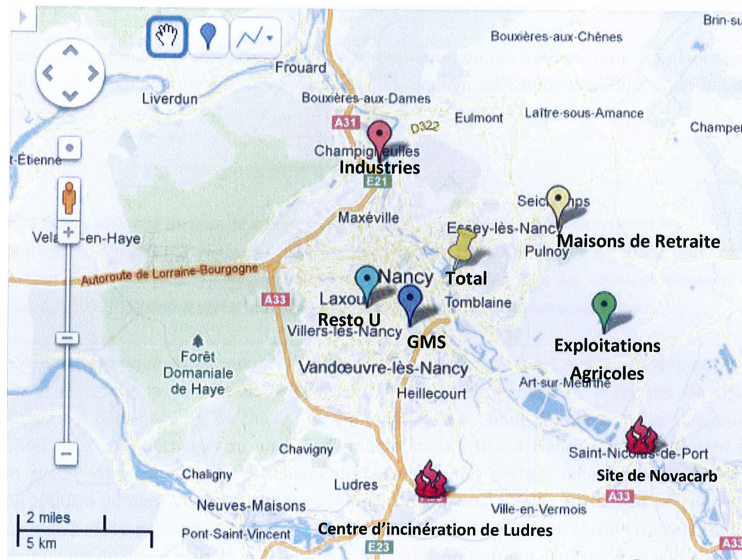


Figure 3 Greatest Nancy area

The types of waste and its energy potential are:

Type of waste	Source	Quantities (Ton/year)	Methane (Nm3/year)
non-domestic waste	industry	13374	927600
	canteens and restaurants	286	
	distribution centers	1500	
	retirement homes	300	
domestic waste	ordinary household	20000	1200000
green waste	green waste	1400	294000
Agriculture	chaff	600	1260000
livestock waste	manure	76000	2920000
	animal manure	72000	

Table 2. Waste characterization of evaluated system [39]

4.2 Scenario definition

Regarding the logistics system evaluated, three scenarios are proposed. Due to their homogeneous nature, S4 and S5 waste does not need to go through the selective sorting in any of the evaluated scenarios.

Scenario 1: This proposes to locate the digester in the same enclosure together with the incineration site. Concerning the waste sorting, in this scenario the selection is made *a*

priori during the waste collection process. Therefore, for this case the sorting selection is made simultaneously with the waste collection (Figure 4)

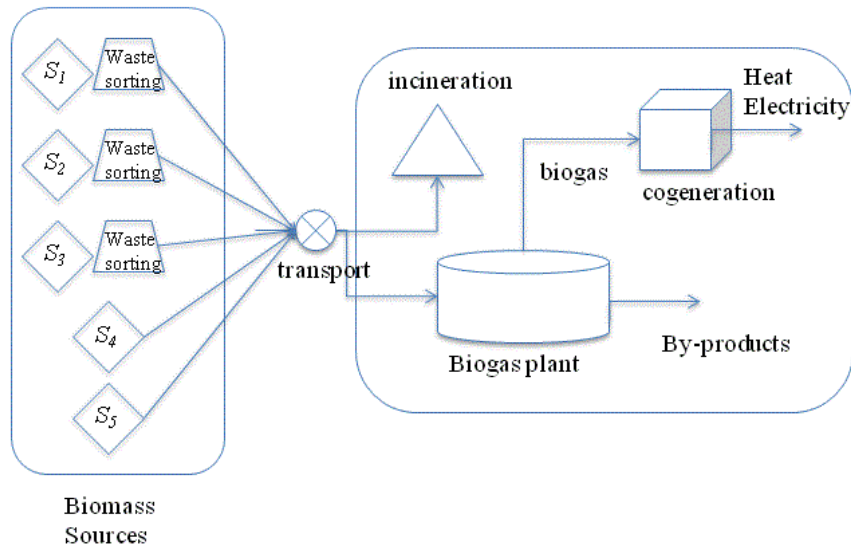


Figure 4. Scenario 1

Scenario 2: Proposes to construct an anaerobic co-digester in the same place where cogeneration of energy will be realized (Figure 5). Regarding the waste sorting, as in Scenario 1, it will be done simultaneously with the waste collection.

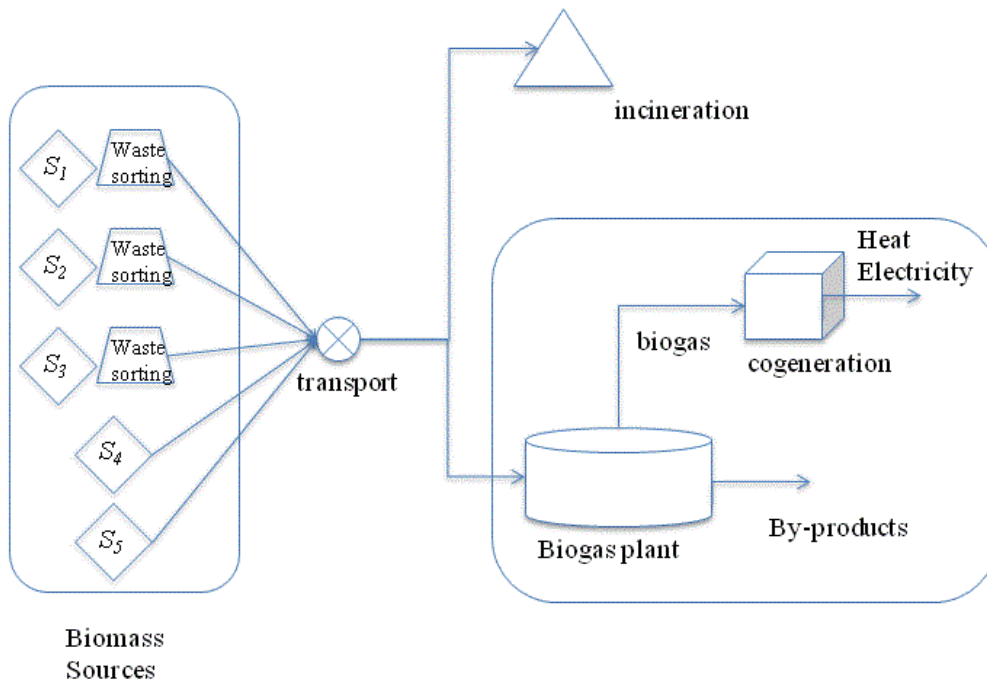


Figure 5. Scenario 2

Scenario 3: Proposes to locate the anaerobic co-digester in a place near the sources that produce a greater volume of organic matter: livestock waste (S_4) and agricultural waste (S_5) (Figure 6). Concerning the waste sorting, it is proposed that this be done at the same location where the co-digester is located.

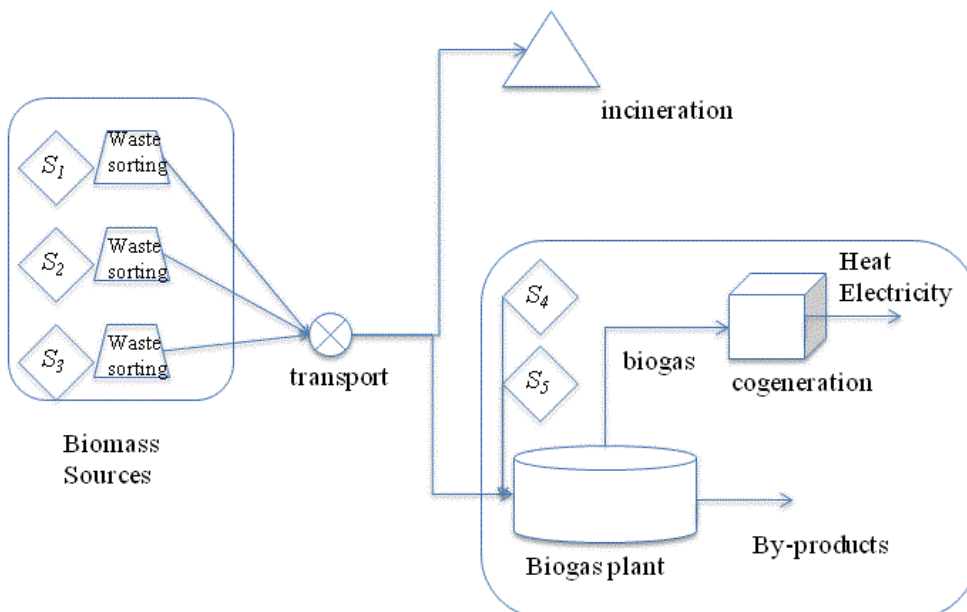


Figure 6. Scenario 3

Among the set of alternatives to locate each of the elements that constitute the reverse logistics network, the aim is to evaluate different scenarios based on associated costs, initial investment, transport and utilization of resources.

Each scenario is simulated and evaluated by the optimization model explained in section 4.2. First, some working hypotheses were defined:

- Waste collection will be weekly; considering that the year has 52 weeks, 3285.75 ton/week in total are transported in turn.
- Moreover, domestic waste (S_2) will be collected by external companies; therefore, it will not be considered inside the logistics network.
- Five days of work per week, in two turns per day, that is, 10 returns were held weekly.
- The biomass quantities transported in each turn are equivalent to 10% of the total transported during the week (Table 3).

Type of waste	Volume/week	Volume/turn
non-domestic waste	297.30	29.73
domestic waste	0	0
green waste	26.92	2.69
Agriculture	115.38	11.54
livestock waste	2846.15	284.61

Table 3. Waste transported weekly

- Trucks with a maximum capacity of 19 tons will be used.
- This implies transport of 328.575 tons each turn with a fleet of 18 trucks
- Any one of five waste collection points is considered as the starting point for the trucks
- It is considered as the waste collection point a central point of the production area of every type of waste
- The distances are determined by the cartography of the study area, and divided into three types of distances: short (7.5 Km), medium (15 km) and long (22.5 km).

- An annual production of waste is taken as a constant, that is, it does not consider the change in the stations.
- Processing times of waste are not considered because they affect the three scenarios proposed in the same way.

4.3 Formalization of the optimization model

Every scenario is simulated and evaluated by the MILP optimization model that makes it possible to determine the most suitable combination of distances between waste collection points and the different stages of treatment. The model seeks to obtain the lowest total cost; in addition, it assures as a result to cross the shortest distance and consequently produce lower CO₂ emissions for every scenario to be proposed.

The objective function (1) seeks to minimize all the costs associated with waste treatment. CT_k represents the costs of using transport trucks (depending on the number of trucks required and type of fuel used) and C_k is the cost of obtaining the trucks, taking into account that they can be purchased or leased.

$$\text{Min } \sum_{k=1}^{18} CT_k + C_k \quad (1)$$

The subsequent equations that simulate the paths that the waste material must follow according to its nature are described as follows:

$$D_k = \sum_{i=1}^7 \sum_{j=1}^8 b_{ijk} * d_{ij} \quad (2)$$

$$\sum_{i=1}^5 b_{i6k} + b_{47k} + b_{57k} = 1 \quad (3)$$

$$\sum_{i=1}^5 b_{i6k} = b_{67k} + b_{68k} \quad (4)$$

$$b_{ijk} + b_{jik} \leq 1 \quad (5)$$

The calculation of distances D_k that each truck must travel is by means defining a binary variable b_{ijk} that will be 1 if truck k travels between the starting point i and the arrival point j , zero otherwise (i and j represent 5 waste collection points and the locations of the waste sorting, the biomass plant and the incinerator). d_{ij} represents the actual distance

between points i and j , which is therefore multiplied by the binary variable only if added to the distances really travelled by the truck. Equations (3), (4) and (5) make it possible to assure that all obligatory paths will be realized; for example, equation (4) ensures that all waste that leaves the waste sorting facility should go to the co-digester or to the incinerator.

$$q_{ik} < \sum_{j=1}^7 b_{ijk} * M \quad \forall X = 1, 2, 3, 4, 5 \quad (6)$$

$$\sum_{k=1}^{18} q_{ik} = Q_i \quad (7)$$

$$\sum_{i=1}^5 q_{ik} \leq \text{Cap}_k \quad (8)$$

The next set of equations, (6), (7) and (8), assure the transport of all waste. The variable M ensures that the truck takes waste only from points i that it visits, that is to say, the quantity transported q_{ik} is activated only when the truck passes for i ($b_{ijk}=1$), otherwise q_{ik} is zero. Equation (7) makes the total waste of five types to be transported. In addition, the quantities transported by each truck cannot exceed the maximum capacity (equation 8). Equation 9 calculates the cost of using trucks depending on the type of fuel used: diesel (p_d) or natural gas (p_g). Equation 10 assures that only one fuel option is chosen.

$$C_{Tk} = \sum_{i=1}^8 \sum_{j=1}^8 \{ (d_{ij} * a_{ijk} * p_d) + (d_{ij} * e_{ijk} * p_g) \} \quad (9)$$

with $k \in (1, \dots, n)$

$$b_{ijk} = a_{ijk} + e_{ijk} \quad (10)$$

The acquisition cost of the truck C_k will be determined by an evaluation of four different alternatives. The first two options correspond to the purchase of the truck according to the two types of fuels: pd_k for diesel and pn_k for natural gas. The other two options correspond to the rent according to both fuels as well. If the truck is leased, the price is associated with the duration of use that will be calculated by the division between distance D_k and the truck's average speed V_k .

$$C_k = \sum_{k=1}^{18} pd_k * o_k + pn_k * r_k + Ld_k * T_k * u_k + Ln_k * T_k * s_k \quad (11)$$

$$T_k = D_k/V_k \quad (12)$$

$$o_k + u_k < M * \sum_{i=1}^8 \sum_{j=1}^8 a_{ijk} \quad (13)$$

$$r_k + s_k < M * \sum_{i=1}^8 \sum_{j=1}^8 e_{ijk} \quad (14)$$

$$o_k + u_k + r_k + s_k = 1 \quad (15)$$

Equations (13) and (14) assure the link between the acquisition of a truck that supports a type of fuel and the use of this (equation 9). For example, a diesel truck can only be acquired if diesel fuel was previously chosen as the type of fuel, and vice versa. Finally, equation (15) limits the choice to only one of four possible acquisition options.

4.4 Decision-making

The proposed methodology seeks to determine the most suitable scenario for the waste treatment in the Greater Nancy area. The scenarios will be evaluated by using four criteria and the determination of the best scenario will be obtained using the decision-making methodology of AHP. The four criteria to be evaluated are:

- Cost: Includes all costs associated with the implementation of every scenario, such as the cost of transport, cost of acquisition of trucks, cost of land etc.
- Distance Covered: This is the sum of the total distance travelled by all trucks to complete the provisioning network of each scenario.
- Durability: Represents the total emission of CO₂
- Feasibility: Is evaluated by an expert who determines the applicability of each scenario. Each scenario is evaluated on a scale of 1 to 9 in terms of technological complexity, where nine (9) represents the most feasible scenario to be implemented.

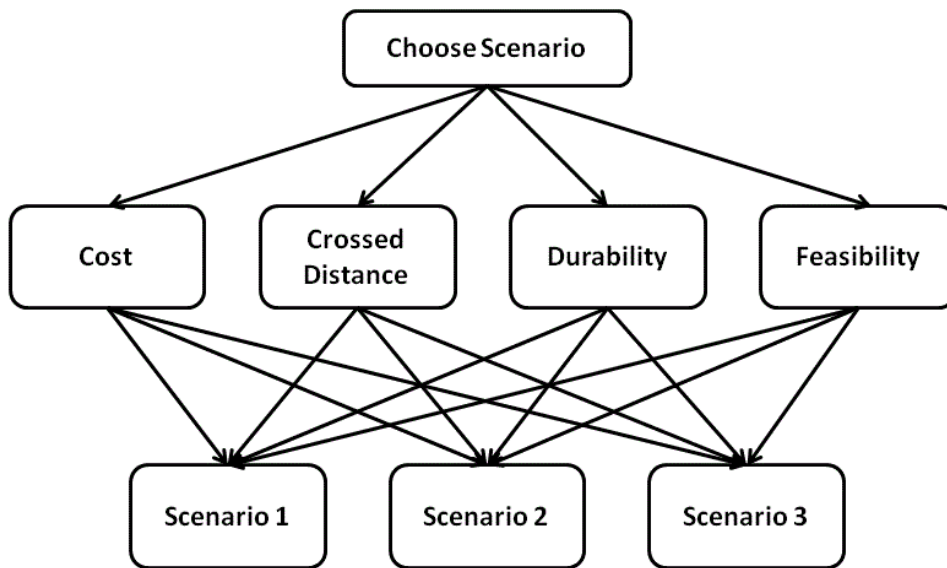


Figure 7. Hierarchical structure of case study

Figure 7 shows the hierarchical representation of the problem, aiming at choosing the most suitable scenario (top level), evaluated from four criteria (middle level) and three possible alternatives (low level) Table 5.

The double entry matrix obtained from pairwise comparisons among the criteria by experts graphs the relative importance of each criterion (Table 4).

	Costs	Distance	Durability	Feasibility
Costs	1	3	9	5
Distance	1/3	1	7	3
Durability	1/9	1/7	1	1/5
Feasibility	1/5	1/3	5	1

Table 4. Double entry matrix

Once computed as explained in Section 3.4, the weights of the criteria were: cost 55.77%, distance 26.75%, durability 4.16% and feasibility 13.30%.

The consistency of the expert opinion has been tested, obtaining an index of 0.066, which indicates that the calculated weights are consistent.

Results of costs, distance travelled and durability are calculated using the mathematical model in Section 3, therefore ensuring an optimal situation for each scenario.

	Cost	Crossed distance	Durability	Feasibility
Scenario 1	601 161	332.5	40.80	9
Scenario 2	560 378	357.5	43.87	7
Scenario 3	1 124 589	292.5	35.90	5

Table 5. Evaluation of each scenario according to the four evaluation criteria

Table 5 shows the summary of results for the four criteria. It is not simple to determine which scenario is better, since if focusing only on the cost, Scenario 2 is the most suitable. If the distance and durability are evaluated, Scenario 3 is the best. On the other hand, Scenario 1 is the most convenient as far as technological feasibility.

AHP methodology makes it possible to determine the most suitable scenario, taking into account the four criteria.

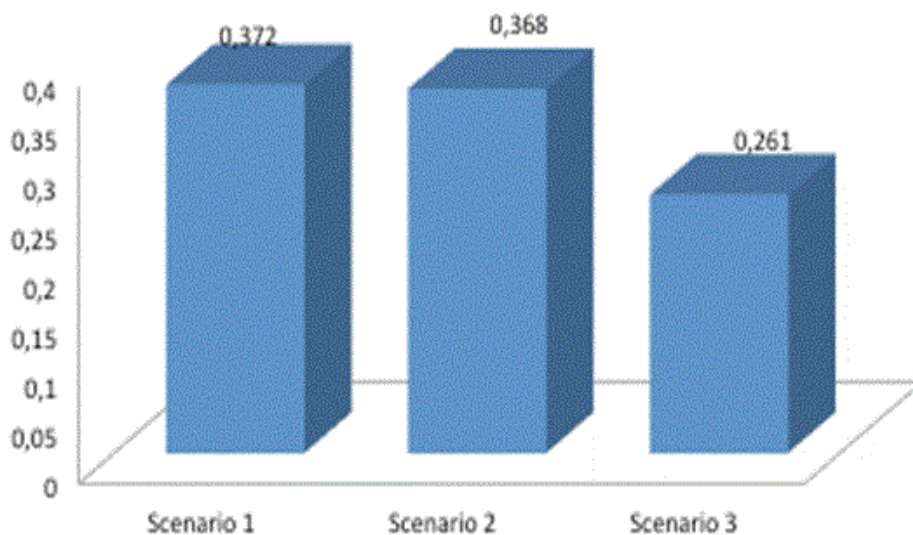


Figure 8. Prioritization of scenarios

In conclusion, the best scenario is proposition 1 with 37.2%, followed closely by proposition 2 with 36.8%. The determination of Scenario 1 can be explained because it presents best performances for the whole set of criteria.

5. Conclusion and perspectives

This work makes it possible to verify the complexity of the conception of a reverse logistics network due to the great quantity of associated factors and situations that can occur. This is verified by the large number of hypotheses that had to be defined for the optimization model. In addition, making the optimization model work together with multicriteria analysis allows us to take into account the opinion of all stakeholders in the system.

Each scenario presents, based on the biomass plant site, innovative solutions relating to the waste sorting, vehicle type and fuel used. The aim was to reduce both the use of resources (acquisition cost of trucks, fuel quantity etc.) and environmental impact (CO₂ emissions) from the implementation of every scenario. Choosing the most suitable scenario always depends on the point of view and preferences of the evaluator. For example, from the point of view of an economist, Scenario 2 best satisfies his expectations because it has the lowest global cost. In contrast, to an environmentalist Scenario 2 is the worst, because it generates a greater quantity of CO₂, so he would prefer Scenario 3 with the lowest CO₂ emissions. For this case the utilization of a multicriteria method is necessary to reach a compromise between all stakeholders (Scenario 1).

Waste producers' awareness to understand the importance of waste sorting and regrouping of waste in view of its energetic valuation constitutes the key success factor of this project. To consider giving a subsidy to producers in order to motivate the regrouping by type of waste can be an interesting solution; in addition, to ensure the commitment of the parties involved in this type of projects that are beneficial to both the people of Greater Nancy area and the environment.

This work opens up numerous future prospects. Improve the precision in the definition of scenarios proposed, doing one more in-depth study on the mapping of the area to determine the best paths in the logistics network. Besides gathering more data relating to waste production, especially in farms (agriculture and livestock) since they are contributing a greater quantity. Reflect on the type of vehicle used to transport liquid or solid waste. Add the stages of waste processing to improve the accuracy of the model. These and other types of improvements make it possible to increasingly adapt the proposed scenarios to reality and provide major robustness to the evaluation methodology proposed.

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