Transport optimization of an anaerobic digestion co-product in a closed-loop supply chain

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Abstract— **This research explores the opportunities and challenges of integrated logistics, covering both the inbound (supply) and outbound (distribution) transportation to/from an anaerobic digestion plant involving several types of suppliers and customers in a region of Quebec (Canada). All participants supply organic residues (in liquid or solid form), and some are also customers who require to receive and use the co-product. The residues are transported to the plant by two types of truck (tanker and solid bulk) of different capacities, where they are transformed by anaerobic digestion. The resulting co-product, a digestate used as an organic fertilizer, must then be efficiently distributed to the customers. The main objective of this project is to size a fleet of trucks adapted to the needs and capacity of the plant under study and minimize transportation costs. After defining and modeling the problem by using mathematical optimization, several scenarios reflecting different transportation strategies (backhauling and heterogeneous truck fleet configuration) have been tested. This article presents and compares the results of the different scenarios, highlighting the economic benefits and suggesting future research avenues. The preliminary results show that substantial transportation cost savings can be obtained by using backhauling and a heterogeneous fleet, reaching up to 17% when both are combined while decreasing the traveled distance by up to 42%.**

Keywords— Circular economy, closed-loop supply chain, transportation, truck fleet configuration, backhauling, anaerobic digestion.

I. INTRODUCTION

Nowadays, energy and environmental issues are at the heart of many new territorial development projects. In particular, circular economy is being put forward as a means of alleviating these problems [1]. By reducing waste, reusing it when possible, and recycling what cannot be reused, financial, logistical and environmental benefits can be achieved.

Anaerobic digestion is a last-resort solution for all organic residues that cannot be recycled in any other way. Through this process, organic residues are decomposed, producing a biogas as well as a co-product, known as the raw digestate, which can be used as a fertilizer [2-3].

An anaerobic digestion plant located close to its suppliers can be a sustainable source of energy and an effective approach to waste management [3]. However, such an infrastructure represents a high investment cost and the supply of a large quantity of processed residues, which can deter individual players, like property owners and small cooperatives [2]. Agreements and an optimized closed-loop supply chain must be established between the suppliers and the plant as well as the clients to guarantee a steady supply of residues, continuous production of biogas and digestate, an efficient allocation and distribution of the digestate.

A number of challenges remain, notably in the collection of residues and the distribution of digestate. Many suppliers are needed to provide a sufficient level of residues which leads to a wide network thus and in turn is requiring a thorough and careful transportation planning [2]. This is also observed in other sectors with operations over a distributed network, e.g., in forestry, where it is common to have several collection points of biomass for supplying a single bioenergy production plant [4]. Numerous researchers have analyzed transportation problems, including questions of logistics optimization through backhauling (i.e., optimization of material flow aimed at reducing the number of empty trips by combining inbound and outbound trips) [5-6], collaborative strategies for inbound and outbounds logistics [7] and information sharing mechanisms [8]. The aim of this research is to study the advantages of applying some of these practices; namely using a heterogeneous truck fleet (as opposed to a homogeneous one) and using backhauling. To this end, we developed a mathematical optimization model that we applied to a regional case study in the province of Quebec (Canada), and

we analyzed different scenarios involving these two logistics practices.

The remainder of this article is as follows: the next section presents the case study and its characteristics. Next, we describe the model we developed and the scenarios. Then, we show the preliminary results and discuss the limitations of our study. Finally, we conclude with future research avenues for improving the model.

II. CASE STUDY

This research is based on the real case study of an anaerobic digestion plant to be implemented in the Mauricie region in the province of Quebec (Canada). In this case study, thirteen (13) emitters of organic residues joined forces to supply the future anaerobic digestion plant with residues. The anaerobic digestion process transforms these residues into renewable biogas and generates a co-product, raw digestate, that can be used as a fertilizer. The emitters fall into two categories; emitter-takers, who supply the anaerobic digestion plant with organic residues and expect to receive digestate in return, and non-taker emitters, who supply organic residues but do not require receiving digestate in return. Two different types of truck are needed as the emitters supply organic residues that can be either liquid or solid. Similarly, digestate can be distributed in either liquid or solid form. Due to the type of residue storage equipment already in place, an emitter of liquid organic residues will only accept liquid digestate, while an emitter of solid organic residues will only accept solid digestate. Following the anaerobic digestion process, the generated digestate is in liquid form only. It is therefore necessary to equip the plant with an industrial separator that enables the raw digestate to be converted into solid digestate and wastewater. As only the organic matter present in the digestate is of interest to the emitter-takers, the separation process enables a product containing the same amount of organic matter but less water to be transported. This separator is an expensive piece of equipment and must therefore be sized adequately to guarantee the production of sufficient quantities of solid digestate to meet the demand. Moreover, after visiting a supplier, each truck must return to the plant before visiting the net one due to bio-security concerns (i.e. cross-contamination issues). Figure 1 shows the material flow within the closed-loop supply chain network of the case study.
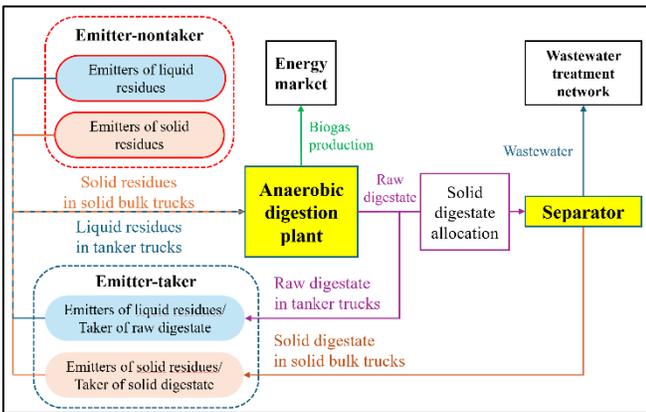

***Fig. 1**. Material flow in the closed-loop supply chain network*

The plant's managers want to optimize transportation in this closed-loop supply chain, specifically by determining the type and size of the required truck fleet (how many tanker trucks and solid bulk trucks to use, and their size), but also analyzing different strategies of allocating the digestate to each emitter-taker. In this work-in-progress article, we will consider the digestate allocation as known according to a well-known principle of proportionality, i.e., emitters-takers are allocated a quantity of digestate proportional to the quantity of organic residues they supply to the plant. This allocation strategy is the one currently considered by the plant's manager. Moreover, the size of the separator is not considered as a decision variable; it produces the exact quantity of required solid digestate.

III. MATHEMATICAL MODEL DEVELOPMENT

A. Assumptions

Our assumptions can be organized around two main themes: those related to the anaerobic digestion plant and those related to transportation.

Assumptions related to the anaerobic digestion plant
- The network contains only one anaerobic digestion plant.
- The anaerobic digestion plant is connected to the wastewater treatment network so that the wastewater leaving the separator can be discharged.
- The anaerobic digestion plant operates 24 hours a day, 7 days a week.
- The separator is adequately sized for the allocated quantity of digestate.

Assumption related to transportation
- The payback period for a truck (tractor and trailor) is 15 years.
- Trucks can only be in two states; either empty or in full truckload where the weight limit is reached before the volume limit.
- Tank trucks and solid bulk trucks of the same size have identical operating costs but different acquisition costs.
- All drivers have the same availability time; there is no transport during the weekends, and it is assumed that the drivers have a one-hour break per day, leading to a seven-hour working day.
- Trip times include transport times as well as loading/unloading times.
- All trucks start their trips from the plant.
- All parameters are assumed to be known; therefore uncertainties are not considered in the model (deterministic).

B. Mathematical model formulation

- *Sets*

The sets used in the model are defined in Table 1.

TABLE I. SETS

Notation	Definition
E_{pl}	Set of all emitter-takers of liquid residue / raw digestate.

Notation	Definition
E_p	Set of all emitter-takers.
E_{np}	Set of all emitter-nontakers.
E	Set of all emitters.
M	Set of all types of trucks (transporting liquid or solid bulk materials).
S	Set of all truck sizes.

- *Decision variables*

The decision variables are positive real numbers, they can depend on up to three different indices. The $e \in E$ index specifies which emitter the truck is heading for (i.e., delivery), the $m \in M$ index specifies which type of truck is used, and finally the $s \in S$ index specifies the size of the truck making the trip. The decision variables used in the model are defined in Table 2.

TABLE II.   DECISION VARIABLES

Notation	Definition
$AREC_{e,m,s}$	Number of "Backhauled (one way loaded and loaded return)" trips to emitter e with truck type m of size s.
$AEC_{e,m,s}$	Number of "one way loaded and empty return" trips to emitter e with truck type m of size s.
$REC_{e,m,s}$	Number of "one way empty and loaded return" trips to emitter e with truck type m of size s.
$N_{m,s}$	Numbers of trucks of type m and of size s.

- *Parameters*

The parameters used in the model are defined in Table 3:

TABLE III.   PARAMETERS

Notation	Characteristics	
	Units	*Definition*
T	year(s)	Planning horizon
$C_{m,s}$	WMg/truck	Maximum load for a truck of type m and of size s.
$D_{e,m}$	WMg/T	Requested quantity (demand) by the emitter e of the digestate transported by a truck of type m.
$R_{e,m}$	WMg/T	Quantity of residue sent by the emitter e and transported by a truck of type m.
$T_{AREC_{e,m,s}}$	Minutes (min) per trip	Duration of an "AREC" type trip to the emitter e of a truck of type m and of size s.
$T_{AEC_{e,m,s}}$	min per trip	Duration of an "AEC" type trip to the emitter e of a truck of type m and of size s.
$T_{REC_{e,m,s}}$	min per trip	Duration of an "REC" type trip to the emitter e of a truck of type m and of size s.

Notation	Characteristics	
	Units	*Definition*
T_{driver}	min per year	Driver's working time availability for one year.
$CAC_{m,s}$	Canadian dollars ($)/truck	Depreciated acquisition cost of a truck of type m and of size s.
COC_{AREC_s}	$/min	Operating cost of a truck of size s for an "AREC" type trip.
COC_{AEC_s}	$/min	Operating cost of a truck of size s for an "AEC" type trip.
COC_{REC_s}	$/min	Operating cost of a truck of size s for an "REC" type trip.
α_1		Coefficient that converts the total quantity of residues entering the plant into the total quantity of raw digestate distributed.
α_2		Coefficient that converts the total quantity of residues entering the plant into the total quantity of solid digestate distributed.

- *Objective function*

This model aims at minimizing the total transportation costs:

$$Total\ costs = \sum_m \sum_s (N_{m,s} * CAC_{m,s}) + \sum_e \sum_m \sum_s [(AREC_{e,m,s} * T_{AREC_{e,m,s}} * COC_{AREC_s}) + (AEC_{e,m,s} * T_{AEC_{e,m,s}} * COC_{AEC_s}) + (REC_{e,m,s} * T_{REC_{e,m,s}} * COC_{REC_s})] \quad (1)$$

- *Constraints*

C1: the demand must be satisfied; all emitter-takers must receive the predetermined allocated quantity of digestate.

$$\sum_s ((AREC_{e,tank,s} + AEC_{e,tank,s}) * C_{tank,s}) = D_{e,tank} \quad \forall e \in E_p \quad (2)$$

$$\sum_s ((AREC_{e,solid\ bulk,s} + AEC_{e,solid\ bulk,s}) * C_{solid\ bulk,s}) = D_{e,solid\ bulk} \quad \forall e \in E_p \quad (3)$$

C2: all emitters must supply the anaerobic digestion plant with their available quantity of organic residues.

$$\sum_s ((AREC_{e,m,s} + REC_{e,m,s}) * C_{m,s}) = R_{e,m} \quad \forall e \in E_p \forall m \in M \quad (4)$$

C3: the driver's working time availability must be respected.

$$\sum_e (AREC_{e,m,s} * T_{AREC_{e,m,s}} + AEC_{e,m,s} * T_{AEC_{e,m,s}} + REC_{e,m,s} * T_{REC_{e,m,s}}) \leq T * T_{driver} * N_{m,s} \quad \forall s \in S, \forall m \in M \quad (5)$$

C4: the model must respect the flow balance of the anaerobic digestion; part of the residues is consumed and transformed into biogas, leaving a liquid-solid mixture at the end of the process.

$$\sum_e \sum_m R_{e,m} * \alpha_1 = \sum_e D_{e,tank} \quad (6)$$
$$\sum_e \sum_m R_{e,m} * \alpha_2 = \sum_e D_{e,solid\ bulk} \quad (7)$$

C5: decision variables must be in their respective mathematical sets.

$$AREC_{e,m,s} \in \mathbb{R}^+, AEC_{e,m,s} \in \mathbb{R}^+, REC_{e,m,s} \in \mathbb{R}^+, N_{m,s} \in \mathbb{N}^+, D_{e,tank} \in \mathbb{R}^+, D_{e,solid\ bulk} \in \mathbb{R}^+ \quad (8)$$

IV. Numerical Experimenst and Preliminary Results

A. Scenarios

With this model, the aim is to study the impact of two main logistics practices, i.e., the type of the fleet, either homogeneous (all trucks are the same size) or heterogeneous (trucks can be one of three sizes), and the possibility of backhauling on 1) the transportation costs, 2) the traveled distances (loaded and unloaded), and 3) the usage rate of the trucks (of each type). For heterogeneous fleets, three truck sizes recommended by the Ministry of Transportation of Quebec have been retained in our model. The smallest (S) has a capacity of 35.5 Mg (i.e. 1 Mg = 1 tonne), the medium (M) has a capacity of 40.5 Mg and the largest (L) has a capacity of 46.5 Mg. In the case of a homogeneous fleet, all trucks are of size M. Four scenarios have been considered as shown in table IV where scenario S01 is the base-case scenario.

TABLE IV. Definition of each scenario

Scenario	Type of fleet	Backhauling allowed
S01	Homogeneous	No
S02	Heterogeneous	No
S03	Homogeneous	Yes
S04	Heterogeneous	Yes

Scenario S01 is considered as the base-case scenario. Moreover, it is expected that the possibility of backhauling will be more impactful on the overall transportation costs.

B. Data collection

To formulate and solve this model, we received information and data from our partner company regarding the organic residue emitters (location, type of emitter, quantity of residue supplied, etc.), the planned location of the anaerobic digestion plant and the types of trucks considered. From this data we were able to approximate the time taken for each trip, the acquisition costs depreciated over fifteen years, and the operating costs of the trucks, taking into account average fuel consumption loaded and unloaded, average speed, the cost of consumables (tires, brakes, etc.), the cost insurance and the drivers' salaries. Part of this data is confidential. We set the planning horizon for one year.

C. Preliminary results and discussion

Our model was solved by using IBM ILOG CPLEX Optimization studio v12.8.0.0 on a desktop computer equipped with an intel core i7-8700 @3.20 GHz and 64 GB RAM under Windows 10. All scenarios were solved in less than fifteen seconds each.

1) Transportation costs

As expected, the value of the objective function obtained for scenario S01 is the highest. The potential cost savings in terms of percentages obtained for S02, S03, and S04 are shown in table VI, showing a continuous increase as more logistics practices are mobilized.

TABLE V. Savings of each scenarios compared to base-case scenario (S01)

Scenario	S02	S03	S04
Cost-savings	10.33%	15.38%	17.38%

The cost savings of the most efficient scenario (S04) compared to the base-case scenario (S01) is around 17%. We note that the two logistics practices tested here (i.e. using a heterogeneous fleet, and allowing backhauling), do not have the same impact in terms of cost savings; when using a heterogeneous fleet and no backhauling (S02), the cost saving obtained is around 10%. When the fleet is homogeneous but backhauling is allowed (S03), this leads to a cost saving around 15%. S03 and S02 both improve the base case scenario by using two different practices. One can see that S03 leads to much higher cost savings than S02, showing that backhauling is more cost effective than using a heterogeneous fleet. Combining both practices leads to an improvement of 2% compared to S03, 7% compared to S02, and 17% compared to the base-case scenario. To conclude, backhauling has a greater impact on cost savings than using a heterogeneous fleet but mobilizing both practices is efficient in reducing the total cost of transportation.

The various fleet configurations selected by the model as being the most efficient for each scenario are shown in table VI.

TABLE VI. Selected fleet for each scenario

Scenario	Number of trucks					
	Tank trucks			Solid bulk trucks		
	S	M	L	S	M	L
S01	-	4	-	-	2	-
S02	0	0	3	0	0	2
S03	-	3	-	-	2	-
S04	0	2	1	0	1	1

In this model, the economy of scale offered by larger trucks offsets and even pays for the higher acquisition cost. In S02 and S04, where the fleets can be heterogeneous, large size trucks (56.5Mg) are favored over their lower-capacity counterparts. In S02, only L size trucks are selected and thanks to the larger capacity, the total number of the fleet is reduced from 6 trucks in S01 to 5 trucks in S02, thus lowering the acquisition cost of the fleet. S04 is the only scenario where multiple sizes are selected. Compared to S03, there is the same total number of trucks, but one M tank truck and one M solid bulk truck are discarded in favor of L-size ones. This configuration optimizes the number of backhauled trips and helps further reduce the unloaded travel distances.

2) Traveled distances

In addition to costs, an interesting performance metric to analyze is the total number of kilometers traveled for each scenario, as well as the number of kilometers traveled loaded and unloaded (see Figure 2).

Figure 2 shows that for scenarios S01 and S02, as backhauling is not allowed, trucks cover as much distance when loaded as when unloaded.

Compared to the base-case scenario, the number of kilometers in S02 is greater with a heterogeneous fleet. Looking in more detail at the truck fleet used in each scenario, we can see that in S02, only large trucks are used compared to the medium

trucks in S01. As large trucks have a higher transport capacity, there is no need to make as many trips as medium ones make to deliver the same quantity of digestate, and therefore the fleet cover less kilometers.
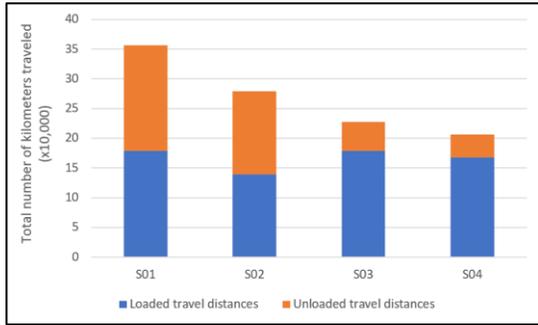

Fig. 2. *Total travel distances loaded and unloaded for each scenario*

In S03 and S01, we can see that the total number of loaded kilometers traveled is nearly identical. However, the total number of unloaded kilometers traveled is almost cut by four in S03 leading to an overall reduction of 130,000 km in traveled distance. S03 is an overall improvement compared to S02. In S03, loaded distance is greater while unloaded distance and total traveled distance are lower compared to S02. Finally, S04 is the scenario with the shortest unloaded traveled distance and the shortest total traveled distance, with nearly 42% less traveled distance compared to S01. This leads to carbon emission saving, which means that S04 is a more environmentally friendly scenario than the others.

3) Usage rate of the trucks

The measurement of usage rates is based on the truck driver's net working time. A usage rate close to 100% will create feasibility issue at the operational planning level where the trips must be scheduled on a daily basis. The results are shown in Table VII.

TABLE VII.   AVEGRAGE TRUCK'S USAGE RATE PER SCENARIO (S = 35.5MG, M = 40.5MG, L = 46.5MG)

Scenario	Average truck usage					
	Tank trucks			*Solid bulk trucks*		
	S	M	L	S	M	L
S01	-	87%	-	-	67%	-
S02	0%	0%	98%	0%	0%	59%
S03	-	85%	-	-	63%	-
S04	0%	95%	56%	0%	21%	93%

In all scenarios, but especially for tank trucks in S02, it would be more realistic to add one truck to the fleet to lower the average truck usage. However, this would lead to a higher total transportation cost, these decisions could be explored when going to an operational planification level.

V. CONCLUSION AND FUTURE WORK

The potential transportation cost savings are interesting when using a heterogeneous fleet combined with backhauling, since this leads to a saving of 17% as well as a 42% reduction in the traveled distances, contributing to the reduction of carbon emissions. Our model has some limitations. First, we do not

consider the seasonality of demand (fluctuations). However, the model could be easily modified to consider this aspect. Second, to ensure the reproducibility of our results and greater transparency, larger instances could be tested. By modifying the allocation strategy, it would be possible to achieve cost savings in several ways: one strategy could be to prioritize the closest players to the anaerobic digestion plant, even if this means leaving the players farthest away. By doing so, the trucks would travel fewer kilometers, thus reducing the total operating cost of the truck fleet. These savings could then be used to compensate financially for the emitter-takers left behind.

In addition, it is important to remember that in this article we're only interested in the total transportation cost. Savings can be made at other points in the supply chain, notably in plant sizing. As aforementioned, organic residues are transformed into raw digestate during the anaerobic digestion process. This raw digestate, in liquid form, must then be dewatered by a separator before it can be distributed to the solid digestate emitter-takers. However, the separator has a high acquisition and operating cost. Another strategy for saving total costs would be to modify solid digestate allocations. By reducing solid digestate allocations, it would be possible to save not only on the sizing of the separator, and therefore its acquisition and operating costs, but also on the sizing of the solid bulk truck fleet.

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