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Environmental taxes in Supply Chain Design for recycling waterways sediments ⋆

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Abstract: Waterways sediments is an example of a valuable material that can be recycled. In this study, Design Chain Network of recycling waterways sediments is presented to determine a logistic strategy for real world recycling company in France, and to analyse the influence of integration of environmental taxes on supply chain design decisions. We propose a strategic model for supply chain design with consideration of CO_2 emission taxes, multi-modality and the different logistics costs. We show how these features are formulated in a mixed integer programming (MIP) model, thus capturing the role of the environmental taxes and the transportation modes in the strategic design of a supply chain. The models are solved by commercial software Cplex 10.1 and the computational results are compared. The study is followed by the analyses of the results.

Keywords: Supply Chain Network Design, Mixed Integer Programming, Environmental taxes, Multi-modality.

1. INTRODUCTION

Sediment is particulate material such as sand, silt, clay or organic matter that has been deposited on the bottom of a water body and is susceptible to being transported by water. In many regulated rivers, sediments are accumulated behind dams and reduce the sediment supply downstream, and are contaminated with many contaminants, such as heavy metals, nutrients pesticides and other organic micropollutants, threatens the good ecological status of waterways, which is the focal point of the European Water Framework Directive (EWFD) (Directive 2000/60/EC. (2000)). The removal of contaminated sediments from waterways, to ensure their navigability, imposes high costs for the regulatory and responsible authorities at the local level. Dredged material that is too contaminated, and cannot be used directly, is subject to treatment because many techniques for this have been tested. However, EWFD provides for a new, global and integrated approach to water protection, improvement and sustainable use.

Such measures cause an increase on the research interest to find the potential costumers and create the need for establishing an efficient inland waterways sediments network.

In this context, this paper deals with the design of a sustainable supply chain network in order to satisfy the demand of the treated sediments and to respect the environmental requirements. The objective is to minimize the sum of opening, storage, production, transportation costs, and CO_2 emissions taxes. We determine location of treatment facilities and their capacities to satisfy an estimated annual demand of potential customers, and the amount of sediments to transport throughout the supply chain network .

We propose a mixed integer linear model to specify the objective function and constraints of the studied problem. The problem is solved optimally for real size instance using Cplex 10.1 solver. This paper is organized as follows, in section 2, the literature on supply chain design is discussed. In section 3, the case study is presented. In section 4, the mixed integer program is introduced. The results obtained for the problem in the NPDC region are discussed in section 5. Finally, section 6 presents some conclusions and future researches for this study.

2. LITERATURE REVIEW

In general, Supply Chain Networks are composed of five main logistic actors, which are: (i) Suppliers, (ii) plants manufacturing/services, (iii) Distribution centers, (iv) Costumers, (v) transportation assets. Many strategic question are found in literature of supply chain design, the main questions are the following: How many manufacturing plants should be implemented? How many Distribution centers should be implemented? Where should they be implemented? How much capacity should we have? Which customer zones to target? Which production plant should be supplied by each supplier? Which customer should be supplied by each distribution center? How much goods

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should be transported between logistic actors? Which mode of transportation should be used? The interested reader can find these strategic questions in some important reviews on supply chain network design ReVelle and Eiselt. (2005), Arntzen et al. (1995), Daskin et al. (2005), Martel (2005), Klose and Drexl. (2005), Cordeau et al. (2006), Amiri (2006).

Our case falls into the field of the recovery networks as remarked by Fleischmann et al. (2000). It has many sources, high investments costs for the recycling installation with the implication that only few will be built, not yet tested recycling technology and unclear destinations of the recycled products. Similar product recovery networks presented by Ammons et al. (1999) concern carpet recycling, Barros et al. (1998) in sand recycling, Shih (2001) in electronic equipment recycling, but without consideration of the environmental cost and multi-modality.
Few models have been proposed in which the choice of transportation modes as a decision is included.(Cordeau et al. (2006); Wilhelm et al. (2005); Bouzembrak et al. (2010); Melo et al. (2009)). Recently Pan et al. (2009), show that the logistical mutualisation is an efficient approach to reducing CO_2 emissions, at the same time they claim that the rail transport is an aspect that should be taken into account in order to achieve the objective of reducing the CO_2 emissions. The disadvantage of this model is that the economic dimension is absent.

Incorporation of CO_2 costs and multi-modality in supply chain design is completely absent in literature. However, the integration of environmental taxes and multi-modality is becoming critical, as most literature suggests.

3. CASE STUDY

This case concerned the treatment of the sand issue from the weeping of the inland waterways of the NPDC region in France (Bouzembrak et al. (2010)). The French waterway system consists of large navigable rivers and canals connecting many regions. Maintaining a safe navigation waterways, in the NPDC region , requires the regular removal of accumulated sediments which are often contaminated with zinc, plumb, cadmium, and mercury. These sediments have been stored along the waterways or in some agriculture lands bought by the French waterways VNF (Voies Navigable de France), to use them as depots. These pollutions prevented the use of the sand which is considered as ultimate waste. We consider the polluted sand stored in storage depots, which needs to be cleaned. Next cleaning facilities are envisaged to clean the polluted sand. These involve high investments; more then 15 000 000(€) are necessary to built a treatment facility developed by Solvay, and the treatment capacity of unit is limited to 150 000 (Tons/year). More informations about the process can be found in some report of Novosol.(Novosol (2009)). The environmental damage is not allowed in the choice of technology of treatment. However, constraints related to efficient energy use, minimize liquid and solid waste, and air pollution reduction are added. The destination of the treated sediment is to brickworks, concrete facilities, concrete stations, and the roads projects. The Table 1 resumes the demand of each customer per year.

Table 1. Demand of treated sediments per year

Customers	Brickworks	Concrete facilities	Concrete stations	Roads projects
Quantity (tons)	10 000	6 000	20 000	200 000

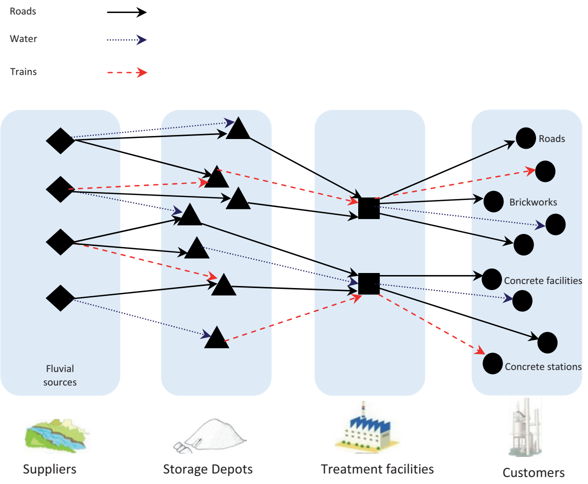

Fig. 1. The supply chain network of the fluvial sediments

We will only consider the strategic level of supply chain network design . Accordingly, we consider a time period of one year, and suppose that the demand of treated sediment is known in advance over the year. A schematic representation of the network for a single period, single commodity, and multi-modal transportation option is shown in Fig. 1. The network has four levels (see Fig. 1). The first level corresponds to the suppliers or inland waterways in our case study. The second one corresponds to the storage depots where sediments must be stored before treatment, and the third one corresponds to the treatment process. Finally, the fourth level corresponds to the customers: roads projects, brickworks, concrete facilities, and concrete stations. They use only treated sediments. The transportation of the sediments throughout the network yields transportation costs that are proportional to the amount of sediments. Notice that, in the NPDC region, sediments can also be transported by train, and inland waterway, which are cleaner and cheaper than by road. Hence, three matrices are considered: the first containing the distances between sites only reachable by road, the second containing the distances between sites reachable by train, and the third one containing the distances between sites reachable by waterway. These distance matrices were constructed using our GIS, ArcView 9.2 with network analysis package add in, which we built especially for this case. To select the best potential treatment locations in the NPDC region, we used spatial analyst package of Arcview.

For CO_2 emissions in France, we found in some reports of the ADEME (Agency of Environment and Energy Management in France) the CO_2 emissions factors for the three transportation modes. The emissions factors are detailed in (Table 2). (ADEME (2006)). The problem was to get insight the logistical costs and environmental costs with setting up such a network and to decide on the location of the treatment facilities. A facility location model is developed using a mixed integer program and

Table 2. CO_2 Emissions factors (g/ton.km)

Transportation Mode	Roads	Waterways	Railways
CO_2 Emissions (g/ton.km)	133.11	37.68	5.75

solved with branch-and-bound. The strategic plan we intend to elaborate should answer the following questions:
- How many facilities should be installed?
- Where the new facilities should be located?
- How much fluvial sediment should each plant handle?
- Which customer should be supplied by each treatment facility?
- How much sediments should be transported throughout the supply chain network?
- Which transportation mode should be used?

All location decisions influence each other. That is why it is not possible to take one decision apart from the others.

4. MATHEMATICAL FORMULATION

The proposed model is a mixed-integer linear programming model with multiple objectives with respect to economic and environmental criteria. The notations used for the formulation of the model are presented bellow.
The SC configuration decisions consist in deciding which of treatment centers to build, and the amount of sand shipped throughout the SC network using the different modes of transport.

- Sets and indexes:

S	set of fluvial sources, indexed by i
D	set of potential treatment facility locations, indexed by j
K	set of potential sediment depots locations, indexed by k
C	set of customer sites, indexed by l
M	set of transportation modes, indexed by m

- The inputs are:

CO_j	the fixed cost of opening treatment facility j (€)
C_{ikm}	the unit transportation costs of sand between fluvial source i and sediment depot k using transportation mode m (€/Ton)
C_{kjm}	the unit transportation costs of sand between sediment depot k and treatment facility j using transportation mode m (€/Ton)
C_{jlm}	the unit transportation costs of sand between treatment facility j and customer l using transportation mode m (€/Ton)
ϑ_{ikm}	the distance between fluvial source i and sediment depot k using transportation mode m (Km)
ϑ_{kjm}	the distance between sediment depot k and treatment facility j using transportation mode m (Km)
ϑ_{jlm}	the distance between treatment facility j and customer l using transportation mode m (Km)
CT_j	the processing costs at this treatment facility j (€/Ton)
CS_k	the storage costs at this depot k (€/Ton)
Q_j	the maximum processing treatment quantity at facility j (Tons/Year)
Q_k	the storage capacity of sediment depot k (Tons/Year)
β_m	the unit CO_2 emission using transportation mode m (Tons/Ton.Km)
γ	Environmental taxes (€/Ton)
Q_{ikm}	the transportation capacity between fluvial source i and sediment depot k using transportation mode m (Tons)
Q_{jlm}	the transportation capacity between treatment facility j and customer l using transportation mode m (Tons)
Q_{kjm}	the transportation capacity between sediment depot k and treatment facility j using transportation mode m (Tons)
D_l	the demand of sand of the costumer l (Tons)

- Decision variables:

X_j	=1 if treatment facility j is opened =0 otherwise
q_{ijm}	the amount of sand shipped from the fluvial source i to the treatment facility j using transportation mode m (Integer)
q_{jlm}	the amount of sand shipped from the treatment facility j to the customer l using transportation mode m (Integer)
q_{ikm}	the amount of sand shipped from the fluvial source i to the sediment depot k using transportation mode m (Integer)

The objective function (1) minimizes the sum of the fixed facility location costs, the transportation, storage, and CO_2 emissions costs from the supply points to the storage depots. The shipment, the processing, and CO_2 emissions costs from the storage depots to treatment facilities. The transportation and CO_2 emissions costs from treatment facilities to customers, and from storage depots to the customers.

Minimize ψ

$$\psi = OC + [TC + SC + RC] + EC \tag{1}$$

Where
- Opening costs:

$$OC = \sum_j (CO_j \cdot X_j) \tag{2}$$

- Transportation costs:

$$TC = \left[\sum_{i,k,m} C_{ikm} \cdot q_{ikm} + \sum_{k,j,m} C_{kjm} \cdot q_{kjm} + \sum_{j,l,m} C_{jlm} \cdot q_{jlm} \right] \tag{3}$$

- Storage cots:

$$SC = \sum_{i,k,m} CS_k \cdot q_{ikm} \tag{4}$$

- Treatment costs:

$$RC = \sum_{k,j,m} CT_j \cdot q_{kjm} \tag{5}$$

- Environmental costs:
The greenhouse gases include carbon dioxide CO_2, nitrous oxide NO_x, and carbon monoxide CO. The modes of transport are considered to be only the source of CO_2 in our case. To guarantee that the CO_2 emissions of each mean of transport in the way back are integrated, we added one ton to the quantities transported (6).

$$EC = \gamma \cdot \left[\sum_{i,k,m} \vartheta_{ikm} \cdot \beta_m \cdot (q_{ikm}+1) + \sum_{k,j,m} \vartheta_{kjm} \cdot \beta_m \cdot (q_{kjm}+1) + \sum_{j,l,m} \vartheta_{jlm} \cdot \beta_m \cdot (q_{jlm}+1) \right] \quad (6)$$

Subject to

Constraint (7) guarantees that the demand of the customers will be satisfied.

$$\sum_{j,m} q_{jlm} = D_l \qquad \forall l \in C \qquad (7)$$

Constraint (8) imposes a capacity restriction for each storage depot.

$$\sum_{i,m} q_{ikm} \leq Q_k \qquad \forall k \in K \qquad (8)$$

Constraint (9) limits the capacity of the treatment facilities.

$$\sum_{k,m} q_{kjm} \leq Q_j \cdot X_j \qquad \forall j \in D \qquad (9)$$

Constraints (10), (11) enforce the flow conservation of the product.

$$\sum_{j,m} q_{kjm} = \sum_{i,m} q_{ikm} \qquad \forall k \in K \qquad (10)$$

$$\sum_{k,m} q_{kjm} = \sum_{l,m} q_{jlm} \qquad \forall j \in D \qquad (11)$$

Constraints (12), (13), (14) impose a capacity restriction of each mode of transport throughout the network.

$$q_{ikm} \leq Q_{ikm} \qquad \forall i \in S, \forall k \in K, \forall m \in M \qquad (12)$$

$$q_{kjm} \leq Q_{kjm} \qquad \forall k \in K, \forall j \in D, \forall m \in M \qquad (13)$$

$$q_{jlm} \leq Q_{jlm} \qquad \forall j \in D, \forall l \in C, \forall m \in M \qquad (14)$$

Constraint (15) enforces the binary nature of the configuration decisions for the facilities.

$$X_j \in \{0,1\} \qquad \forall j \in D \qquad (15)$$

Constraints (16), (17), (18) are standard non-negativity constraints.

$$q_{ikm} \geq 0 \qquad \forall i \in S, \forall k \in K, \forall m \in M \qquad (16)$$

$$q_{kjm} \geq 0 \qquad \forall k \in K, \forall j \in D, \forall m \in M \qquad (17)$$

$$q_{jlm} \geq 0 \qquad \forall j \in D, \forall l \in C, \forall m \in M \qquad (18)$$

5. RESULTS

For our test case, the problem dimensions are: 50 fluvial sources, 30 storage depots, 5 potential treatment facilities, and 60 customers. The calculations were carried out on a Linux cluster, consisting of two 3 GHz Xeon processors and 4 GB RAM. We used ILOG OPL6.1 as modelling language and the mixed integer solver from CPLEX10.1 commercial software for all the variants of the problem. For this problem size, the computation time was negligible. According to the previous description, the following tables show the impact of the environmental taxes γ on the supply chain design decisions,the amount of CO_2 emissions, and the transportation mode used. We will increase the value of γ until we get a fix configuration supply chain, that do not change rising γ.

5.1 Supply chain configurations

In table 3, we present the optimal supply chain configurations obtained varying γ , and a comparison between the values of objective function of two cases (γ=0) and ($\gamma \neq 0$). For example, for γ=4000 the optimal configuration is { S_1,S_5 } and the optimal objective value is 48 606 223. Imposing γ=0 and the optimal configuration { S_1,S_5 } to the model, we find an objective value equal to 48 510 715.

Table 3. Experiments results

N°	γ	Solution	Objective function (€)		Difference
			$\gamma \neq 0$	γ=0	(%)
1	0	S_4, S_5	48 509 520	48 509 520	0.0%
2	10	S_4, S_5	48 509 822	48 509 520	0.0%
6	200	S_4, S_5	48 515 341	48 509 520	0.0%
7	300	S_4, S_5	48 518 166	48 509 520	0.0%
22	3000	S_4, S_5	48 583 363	48 509 520	0.2%
23	4000	S_1, S_5	48 606 223	48 510 715	0.2%
32	13000	S_1, S_5	48 792 915	48 510 715	0.6%
33	14000	S_1, S_4	48 809 384	48 563 111	0.6%

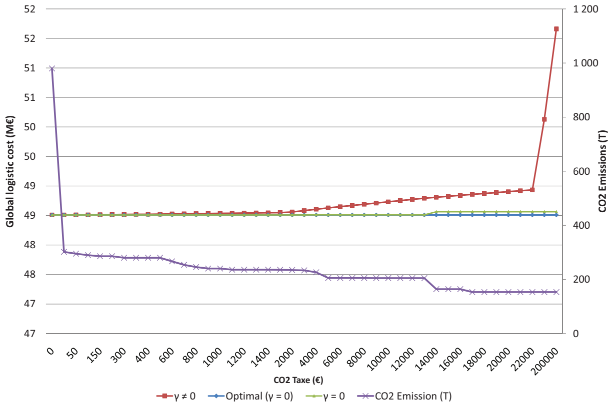

Fig. 2. Comparison of the global logistic cost for ($\gamma = 0$) and ($\gamma \neq 0$), and the corresponding CO_2 emissions for different values of γ

As we can see on the table 3 , we have 3 different solutions, { S_4,S_5 } , { S_1,S_5 } ,and { S_1,S_4 } . The first configuration is obtained when γ is between 0 and 3 000. The second network is obtained when γ is between 4 000 and 13 000. The last one is fond when γ is higher than 14 000. It can be observed, the optimal solution { S_4,S_5 } is approximately 0.2% cheaper than the second configuration { S_1,S_5 } and approximately 0.6% cheaper than the third solution.

Fig. 2 shows the optimal solution obtained for ($\gamma = 0$) and ($\gamma \neq 0$) which correspond to the different depicted points of γ. As occurred in the optimal case, reducing the CO_2 emission is not expensive until a certain level of $\gamma = 1000$. Above this level, an increment in the value of γ implies a significant increase in the global logistic cost. As can be also observed, solutions with higher carbon taxes imply networks with lower CO_2 emissions due to the need of reducing the global logistic costs. For instance, the design which corresponds to $\gamma = 0$ involves emission of 980 (tons) of CO_2 gazes while for γ= 10 the CO_2 emission is equal to 302 (tons). It is important to note that γ= 10 seems to be the best practical environmental taxes in our case, if the government want really to impose an environmental taxes in the real world.

5.2 CO_2 Emissions

Table 4 presents a comparison of quantity of CO_2 emissions obtained for ($\gamma = 0$) and ($\gamma \neq 0$). We observe that the integration of environmental taxes reduce the quantity of CO_2 emissions to at least 70%. For $\gamma = 10$, the amount of CO_2 emission decrease to approximately 70% less than the case with $\gamma = 0$. The best environmental result is obtained for $\gamma = 17\,000$, the % of reducing is approximately 84.4%.

Table 4. Experiments results

N°	γ	CO_2 Emissions (T)		
		$\gamma \neq 0$	γ=0	Difference (%)
1	0	980	980	0.0%
2	10	302	980	69.2%
6	200	286	980	70.8%
7	300	280	980	71.4%
22	3000	233	980	76.2%
23	4000	226	980	76.9%
32	13000	205	980	79.1%
33	14000	164	980	83.3%

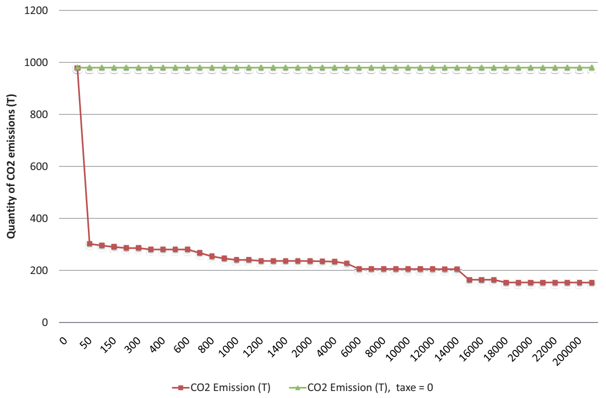

Fig. 3. Quantity of CO_2 emission varying γ.

Analysis of Fig. 3 shows that the most polluted configuration is the first one , without carbon taxes, in this case the quantity of CO_2 gazes is 980 (tons). This number go down to approximately 300 (tons) increasing γ to 10. As we can see also, we have four level of CO_2 emissions: the first level is obtained for γ between 10 and 600 , the average of CO_2 emissions is equal to 285 (tons). This average decrease to 238 (tons) in the second level when γ is between 600 and 4 000. In the third level for γ between 4 000 and 13 000, the average of CO_2 emissions is equal to 205 (tons). Finally, above 13 000 we obtained the fourth level where the average of CO_2 is about 156 (tons).

5.3 Transportation Modes

Table 5 shows the transportation modes used in carrying the sediment throughout the supply chain network en percentage.

Table 5. Experiments results

N°	γ	Transportation Modes		
		% Roads	% Waters	% Trains
1	0	9.3%	80.7%	10%
2	10	0.0%	78%	22%
6	200	0%	74.7%	25.3%
7	300	0%	54.7%	45.3%
22	3000	0%	52.0%	48.0%
23	4000	0%	36.7%	63.3%
32	13000	0.7%	36.7%	62.7%
33	14000	1.3%	25.3%	73.3%

As we can see on Table 5 and Fig. 4, we have 5 types of supply chain configurations, which are:

1. The extremely economic configuration: The solution { S_4,S_5 } is obtained when γ is equal to zero. Most of the treated sand are transported using the waterways 80.7%, 10% using the railways, and only 9.7% of the sand are transported using the roads(Bouzembrak et al, 2010).

2. The economic configuration: The solution { S_4,S_5 } is obtained when γ is between 10 and 200. Analysis of the mode of transport used shows that 24.3% of the treated sand are transported using the railways, 75.7% using the waterways and 0% of the sand are transported using the roads.

3. The economic-environmental configuration: The solution { S_4,S_5 } is obtained when γ is between 300 and 3 000. Analysis of the mode of transport used shows that 46.2% of the treated sand are carried using the railways, 53.8% using the waterways and 0% of the sand are transported using the roads.

4. The environmental configuration: The solution { S_1,S_5 } presents the location of two treatment facilities from five potential facilities when γ is between 4 000 and 13 000. Analysis of the mode of transport used shows that 62.7% of the treated sand are transported using the trains, 36.6% using the waterways and only 0.7% of the sand are carried using the roads.

5. The extremely environmental configuration: we find this solution { S_1,S_4 } when γ is above the value of 14 000. Most of the treated sand are transported using the trains with an average of 73%, 25% using the waterways, and only 2% of the sand are transmitted using the roads.

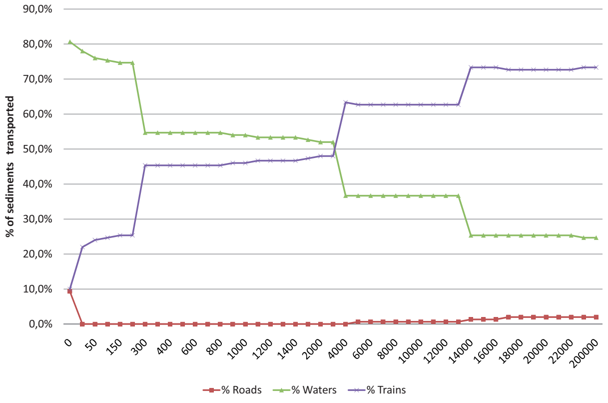

Fig. 4. The transportation mode choose varying γ

Fig. 4 shows that an increment in the value of γ implies a significant increase in the amount of sediments transported using the train as transportation mode, when γ was equal to zero the percentage of sediments transported using train was approximately 10% and rising γ to 14000 the percentage grow to approximately 72%. Or, when we increase the value of γ the percentage of sand transported using water transportation mode decrease, when γ go up from 10 to 200 000 the % of using waterways go down from 78% to 25%. The % of sediments transported using roads transportation fluctuate between 0% to 10%. From these results, it is clear that the integration of carbon taxes in the model efficient approach to reducing CO_2 emissions by choosing the best combination of the transportation mode. To achieve the objective of reduce the CO_2 emissions, we should take into account the multi-modality in the design of the supply chain especially the rail transport and the water transportation mode.

6. CONCLUSIONS

There is a wealth of literature and research on modelling of strategic supply chain design, but an apparent lack of consideration of transportation mode and CO_2 taxes. This research is the first model to our knowledge that integrates CO_2 emission taxes and multi-modality in the supply chain network design phase.

The results obtained point out, first, the impact of the integration of greenhouse gas emissions taxes in the design of the fluvial sediment recycling network; it changes the decisions of location. It is depend on the environmental policy of the company. This means that using the model, supply chain managers are now able to see the impact of integration of the CO_2 taxes and multi-modality in the strategic decisions of supply chain design. That will help them to select the best strategic supply chain network. Furthermore, if the government should imposes an environmental taxes, $\gamma = 10$ (€/ton) should be a reasonable solution in our case.

The second important result is the using of GIS in location of potential facilities of treatment in the design of sustainable supply chain. From these experiences we have learned that integration of environmental taxes in the model is an efficient way to achieve environmental goals, by choosing the best location and clean transportation modes. These results have also demonstrated that to reduce CO_2 emissions, we should take into account multi-modal network, in the design of the supply chain. We think that it will be useful to consider the uncertainty of data, for example, by generating scenarios that capture future uncertainty of the location (or the demand) of the customers. In this regard, the stochastic programming is an area of our future research.

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