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SUSTAINABLE MULTIMODAL SUPPLY CHAIN DESIGN FOR RECYCLING WATERWAYS SEDIMENTS

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ABSTRACT: *Increasing regulatory legislations for carbon and waste management and the focus on corporate social responsibility are driving a major focus on supply chain sustainability, Sustainable Supply Chain Management involves different multiple objectives of social, economic and environmental sustainability. The current view is that there is a natural trade-off between the economic and the environmental dimensions. This paper proposes a strategic model for supply chain design with consideration of* CO_2 *emission, multimodality and total 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 location decisions of strategic design of a supply chain. Case Study is presented to illustrate the effectiveness of the formulation and solution strategy.*

KEYWORDS: *Facility location, Supply chain Design, Mixed Integer Programming,* CO_2 *Emissions, Multimodality.*

1 INTRODUCTION

The French waterway system consists of large navigable rivers and canals connecting many regions. Maintaining a safe navigation channel, in the NPDC (Nord Pas De Calais) region in France, requires the regular removal of accumulated sediments which are often contaminated with zinc, plumb, cadmium, and mercury.

New legislation, such as the European Water Framework Directive DCA. (2000), ensures that disposal should be reduced to minimal level and the fluvial sediment should be treated. Recently, the European Union (EU) has become à highly influential proponent of sustainability. The European Parliament views this concept as so critical to the future of the EU that current and future legislation must integrate sustainability into implementation orders (American Chamberof Commerce of Europe, 2004).

Such measures cause an increase on the research interest to find the potential costumers and create the need for establishing an efficient fluvial sediment sand network. Within SEDIBET. (2007) research project, financed by the French national research agency ANR (Agence Nationale de la Recherche) , a multidisciplinary research team aims to design a logistic network of recycling inland waterways sediments, and to evaluate the impact of environmental values of the neo-material option for various actors in NPDC region.

In this context, this paper deals with the design of a sustainable supply chain network in order to satisfy the demand of the treated sand 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. A multimodal transportation and environmental taxes are taken into consideration for environmental aspects.

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.

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2 LITERATURE REVIEW

For Drezner and Hamacher. (2004) a general facility location problem involves a set of spatially distributed customers and a set of facilities to serve customer demands. Moreover, distances, times or costs between customers and facilities are measured by a given metric. Possible questions to be answered are: (i) which facilities should be opened? (ii) which customers should be serviced from which facilities so as to minimize total costs? In addition to this generic setting, a number of constraints arise from the specific application domain. The interested reader is referred to some important reviews on facility location in (ReVelle et al, 2004; Daskin et al, 2005).

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 for instance carpet recycling, and Barros et al. (1998) in sand recycling, but without consideration of the environmental cost and multimodality.

The transport sector is the significant source of CO_2 emissions, this sector is naturally concerned by global warming. As a result, improving transport efficiency is among the foremost concerns of supply chain management initiatives. Several studies show that today the lack of satisfaction regarding transport efficiency is based both on the use of road transport and on green house emissions, see (Leonardi and Baumgartner, 2004; Mckinnon et al, 2003).

Few models have been proposed in which the choice of transportation modes as a decision is included. These articles can be divided into those that allow several transportation modes to be chosen for the same arc in the network and those that only allow one transportation mode in each link (Cordeau et al, 2006; Wilhelm et al, 2005; Bouzembrak et al, 2010).

Melo et al. (2009) highlighted that there was a lack of models integrating choice of transportation modes. They argued that multimodality should be considered, in particular on the strategic planning level, but they conceded that this integration leads to much more complex models due to the large size of the problems that may result.

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 cots and multimodality in supply chain design is completely absent in literature, the integration of price of environmental pollution is becoming critical.

3 CASE STUDY

This case concerned the treatment of the sand issue from the weeping of the fluvial channels of the NPDC region in France, see (Bouzembrak et al, 2010). These sediments have been stored along the waterways or in some agriculture lands bought by the French waterways VNF(Voies Navigable de France), which owns and manages 245km of navigable rivers in this region; to use them as depots. Although it could be polluted with zinc, plumb, cadmium, and mercury. These pollutions prevented the use of the sand which is considered as ultimate waste.

European legislation was adopted to find a solution to this problem and some cleaning processes were provided by some industrial laboratories. In order to achieve this challenge, the French national research agency is interested with the design of the supply chain network of the recycling sediments accumulated from canals. We consider only one type of product, 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 EUR are necessary to built a treatment facility developed by Solvay (Novosol, 2009). The treatment process is composed of two steps, phosphating and calcination. Heavy metals are stabilized by capturing them in calcium phosphate matrix, then the organic componds are destroyed by calcination to get clean sand that can be used by the customers. More informations about the process can be found in some report of Novosol. (2009). The treatment capacity of unit is limited to 150 000 tons/year (see Table 3).

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 sand is to the brickworks, requiring a minimum of 10 000 tons per year, the concrete facilities and stations, requiring a minimum of 26 000 tons per year, and the roads projects, requiring a minimum of 200 000 tons per years. Nevertheless, very limited information is available about the possible location of these projects Blanpain et al. (2009). The Table 1 resumes the demand of each customer per year.

The SEDIBET. (2007) project is only interested in strategic plan. Therefore, we will only consider the strategic sand problem and model it as a static problem. Accordingly, we consider a time period of one year, and suppose that the demand of fluvial sediment sand is known in advance over the year. A schematic representation of the network for a single period, single commodity, and multimodal transportation op-

Customers	Brikworks	Concrete facilities	Concrete satations	Roads projects
Quantity (tons)	10 000	6 000	20 000	200 000

Table 1: Demand of treated sand per year

tion is shown in Figure 1. The network has four layers (see Figure 1). The first level corresponds to the suppliers or fluvial canals 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 sediements. We call these layers suppliers, storage depots, treatment facilities, and customers, respectively. Transportation arcs connect the actors of the regional network. The transportation of the sand throughout the network yields transportation costs that are proportional to the amount of sand and distance. Notice that, in the NPDC region, sand can also be transported by train, and inland waterway, which are cleaner and cheaper than by road. The road transportation cost is more expensive than the waterway one, (see Table 2). 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.

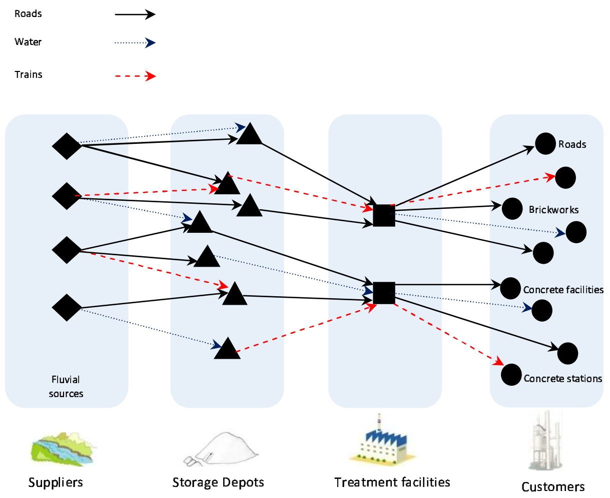

Figure 1: The supply chain network of the fluvial sand

For CO_2 emissions in France, we found in some reports of the ADEME (Agency of Environment and Energy Managment in France) the CO_2 emissions factors for the three transportation modes. The emissions factors are detailed in (Table 2). (Jancovinci, 2007; Ballot, 2009). The problem was to get insight into the logistical costs and environmental costs with setting up such a network and to decide with the location of the treatment facilities. A facility location model is developed using a mixed integer program and solved with branch-and-bound. The strategic plan we intend to elaborate should answer the following questions:
- What type and how many facilities should be installed?
- Where the new sites should be located?
- How much fluvial sediment sand should each plant handle?
- 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 (Chopra and Meindl, 2001).

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

Table 2: CO_2 Emissions factors (g/t.km)

Description	Value
Total available fluvial sediments* (Tons)	31 000 000
Capacity of the treatment facility* (Tons/Year)	150 000
Storing capacities of storage depots* (Tons)	10 000 000
Fixed costs for opening a treatment facility* (EUR)	15 000 000
Transportation costs by road** (EUR/Ton.km)	4.3 - 8.4
Transportation costs by water** (EUR/Ton.km)	4 - 13
Transportation costs by train** (EUR/Ton.km)	3.6 - 7.8
Handling costs at storage depots* (EUR/Ton)	15
Processing costs at cleaning facilities* (EUR/Ton)	59
Carbon Price (EUR/Ton)	170

Source : *VNF, Nord Pas DE Calais, **DRE Aquitaine 2004," les coûts du transport des matériaux de carrières par la route et le rail "

Table 3: Data used in implementation

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 of 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 (EUR)
C_{ikm}	The unit transportation costs of sand between fluvial source i and sediment depot k using transportation mode m (EUR/Ton)
C_{kjm}	The unit transportation costs of sand between sediment depot k and treatment facility j using transportation mode m (EUR/Ton)
C_{jlm}	The unit transportation costs of sand between treatment facility j and customer l using transportation mode m (EUR/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 (EUR/Ton)
CS_k	The storage costs at this depot k (EUR/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)
ω_1	Weight of economic dimension. (%)
ω_2	Weight of environmental dimension. (%)
γ	Carbon price (EUR/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 treatement 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)

With this notation, the treatment facility location problem can be formulated as follows:

Minimize ψ

$$\psi = OC + \omega_1 \cdot [TC + SC + RC] + \omega_2 \cdot EC \quad (1)$$

Where

- Opening costs:

$$OC = \sum_j (CO_j \cdot X_j) \quad (2)$$

- Transportation costs:

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

- Storage cots:

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

- Treatment costs:

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

- 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. The Environmental Costs EC function is formulated as:

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

Subject to

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

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

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

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

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

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

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

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

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

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

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

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

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. Constraint (7) guarantees that the demand of the customers will be satisfied. Constraint (8) imposes a capacity restriction for each storage depot, while constraint (9) limits the capacity of the treatment facilities. Constraints (10), (11) enforce the flow conservation of the product. Constraints (12), (13), (14) impose a capacity restriction of each mode of transport throughout the network. Constraint (15) enforces the binary nature of the configuration decisions for the facilities, and constraints (16), (17), (18) are standard integrality and non-negativity constraints.

5 COMPUTATIONAL RESULTS

The calculations were carried out on a Linux cluster, consisting of two 3 GHz Xeon processors and 4 GB RAM. We used ILOG OPL 6.1 as modeling language and the mixed integer solver from CPLEX 10.1 (ILOG, 2007) commercial software for all the variants of the problem. Details on the implemented models are given in (Table 3).
For our test case, the problem dimensions are: 50 fluvial sources, 30 storage depots, 5 potential treatment facilities $\{S_1, S_2, S_3, S_4, S_5\}$, and 60 customers. The mixed integer programming model contains 11 408 constraints and 4 876 decision variables. For this problem size, the computation time was negligible. If the problem size increases, the number of constraints will increase too. If this is the case, it is not sure that the problem can still be solved in reasonable time. According to the previous description, the following table 4 shows the impact of ω_1 and ω_2 on the facilities location decisions and on the transportation mode used.
Weight represents the values of the ω_1 and ω_2 used on the objective function. Potential facilities contain the set of the potential sites. % of sand transported throughout the network presents the mode of transport used en percentage. Finally the value of the objective function expressed in Euro.

As we can see on Table 4 , we have 4 types of facility location solutions, which are:
1. The Environmental location solution: we find this solution $\{S_1,S_4\}$ when ω_1 is between 0 and 0.2. This solution presents the location of two treatment facilities (Figure 3) from five potential facilities. The first site is located in the center north of the region, where we find the highest number of customers and the most important quantity of sediments to clean. The second treatment facility is located in the center of the region, in order to serve the demand of the customers of this region and the north west of the NPDC region, and to reduce the transportation costs. Most of the treated sand are transported using the trains with an average of 72.3%, 25.3% using the waterways, and only 2.4% of the sand are transported using the roads. (Figure 2)
2. The Economic-Environmental location solution: The solution $\{S_1,S_5\}$ presents the location of two treatment facilities (Figure 4) from five potential facilities when ω_1 is between 0.3 and 0.5. The first treatment facility is located in the center of the region, in order to serve the demand of the customers of this region and the north west of the NPDC region. The second site is located in the center north of the region, where we find the highest number of customers and the most important quantity of sediments to clean. Analysis of the mode of transport used shows that 63% of the treated sand are transported using the trains, 37% using the waterways and

N°	**Weight**		**Potential facilities**					**% of sand transported throughout the network**			**Values(EUR)**
	ω_1	ω_2	S_1	S_2	S_3	S_4	S_5	*Roads*	*Waters*	*Railways*	*Objectivefunction*
1	0	1	X			X		3%	24%	73%	30 039 950
2	0.1	0.9	X			X		3%	26%	71%	31 895 690
3	0.2	0.8	X			X		1%	26%	73%	33 750 860
4	0.3	0.7	X				X	1%	37%	63%	35 598 230
5	0.4	0.6	X				X	1%	36%	63%	37 445 080
6	0.5	0.5	X				X	0%	37%	63%	39 290 250
7	0.6	0.4				X	X	0%	37%	63%	41 134 900
8	0.7	0.3				X	X	0%	50%	50%	42 979 440
9	0.8	0.2				X	X	0%	53%	47%	44 823 850
10	0.9	0.1				X	X	0%	53%	47%	46 667 200
11	1	0				X	X	13%	73%	14%	48 509 520

Table 4: Experiments results

only 0% of the sand are transported using the roads. (Figure 2)

3. The Economic location solution: The solution $\{S_4, S_5\}$ is obtained when ω_1 is between 0.6 and 0.9. This solution presents the location of two treatment facilities (Figure 5) from five potential facilities. The first site is located in the center north of the region, the second one is located in the north west of the region, in order to serve the demand of the customers of each region, and to reduce the transportation costs. Analysis of the mode of transport used shows that 48% of the treated sand are transported using the railways, 52% using the waterways and only 0% of the sand are transported using the roads. (Figure 2)
4. The extremely economic location solution: The solution $\{S_4, S_5\}$ is obtained when ω_1 is equal to 1. (Figure 5) presents the solution. Most of the treated sand are transported using the waterways 73%, 14% using the railways, and only 13% of the sand are transported using the roads. (Bouzembrak et al, 2010).

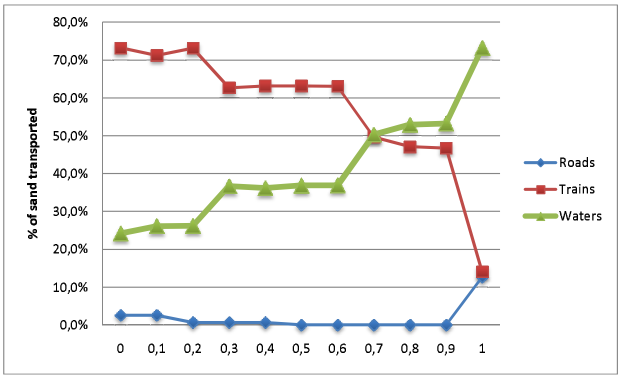

Figure 2: The transportation mode choose varying w_1

6 CONCLUSIONS

Although there is a wealth of literature and research on modeling of strategic supply chain design, there is an apparent lack of consideration of transportation mode and CO_2 taxes. It is the first model to our knowledge that integrates CO_2 emission taxes and multimodality in the supply chain network design phase. In this paper, we formulated a strategic supply chain design model which includes explicitly the carbon taxes and multimodality. 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 depends on the environmental policy of the company, if the managers are environmental they will take the first solution, if they are looking for the environmental and economic solution they should choose the second solution, and if they want the economic scenario they should adopt the third solution. This means that using the model, supply chain managers are now able to see the impact of integration of the CO_2 taxes and multimodality in the strategic decisions of location. That will help them to decide the best strategic design of the supply chain.

The second important result is the using of GIS in location of potential facilities for treatment in the design of sustainable supply chain, it provides a good way for integrating constraints as: noise reducing, location facilities far from the urban areas, emphasize the use of industrial wasteland for selection of potential facility locations.

Finally, another issue is the influence of the location of the demand points and their awaited demand in the establishment of the sand supply chain. We think that it will be useful to consider the uncertainty of data, for example, by generating scenarios that capture the request uncertainty of future custumer (location, demand).

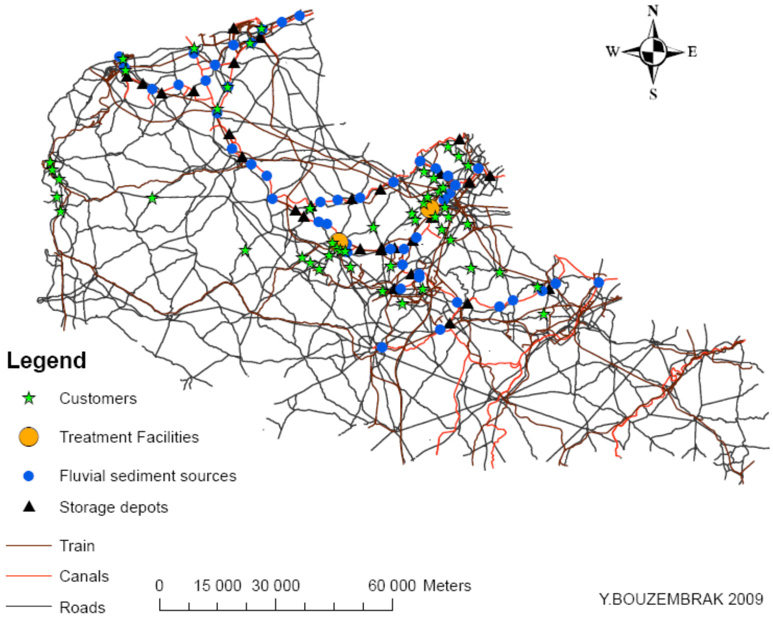

Figure 3: The presentation of the solution $\{S_1,S_4\}$: w_1 between 0 and 0.2

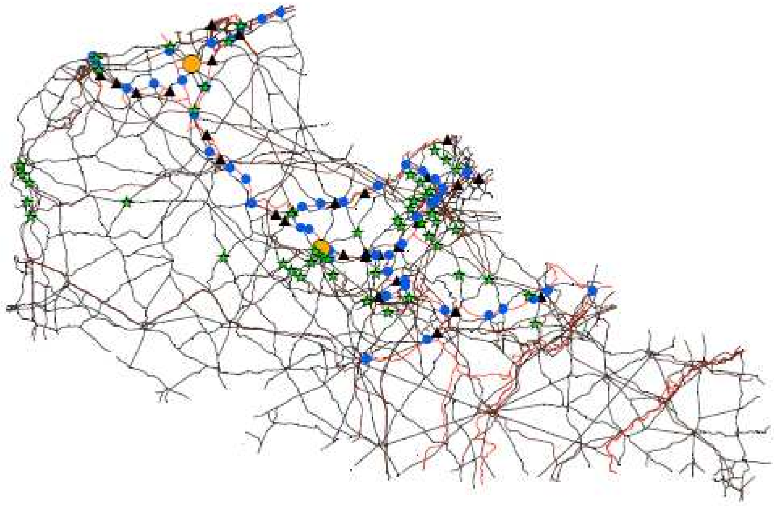

Figure 4: The presentation of the solution $\{S_1,S_5\}$: w_1 between 0.3 and 0.5

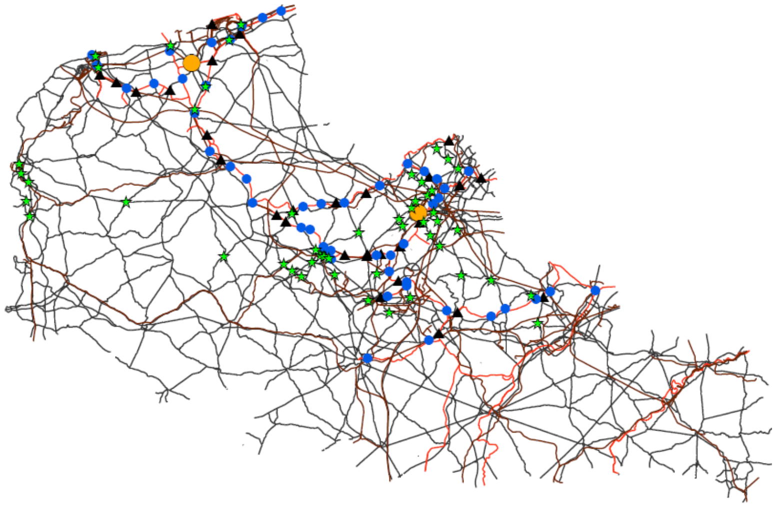

Figure 5: The presentation of the solution $\{S_4,S_5\}$: w_1 more than 0.6

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