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Dynamic Waste Management (DWM): Towards an evolutionary decision-making approach

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Abstract

Due to the social, economical and environmental impacts associated with waste management, it is necessary to move towards decision-making approaches which integrate each one of these aspects. Currently, the recommended approaches are rather static and linear in their application; furthermore, they do not allow an optimal use of the available materials. Consequently, the choice for a waste management process is often based on fixed parameters, while the systems are in constant evolution. But actually, the validity of the prioritization of a waste treatment process is directly related to the impacts associated with the length of paths, means of transport and characteristics of the road chosen. The available tools however neglect this dynamic aspect, which is critical to reduce the load of the studied system. In order to guarantee a sustainable and dynamic waste management, DWM suggests an evolutionary new approach which maintains a constant flow towards the most favourable waste treatment processes (facilities) within a system. To do so, the DWM is based on the law of conservation of energy, which allows balancing a network while considering the constraints associated with transport. To demonstrate the scope of the DWM, the following article outlines the approach and then presents an example of its application.

Keywords: Waste management, decision-making tool, model simulation, systemic approach, integrated management, law of conservation of energy.

Introduction

Faced with problems associated with the exploitation of natural resources, industrialized countries now aim to achieve sustainable waste management. In spite of various tools developed to support the decision-making process of a waste management process, none combine the concepts of systemic analysis and impact minimization in a global and dynamic way (Woolridge *et al.,* 2005, Ishii *et al.*, 2010). Waste management must go beyond simply reducing the buried or incinerated volume; it must seek social acceptability, economical profitability and environmental compatibility, while supporting a responsible and equitable evolution of the society (Morrissey *et al.,* 2004, Ghinea *et al.*, 2012, Pires et al., 2011). In order to recommend the most adequate waste management processes, the specific needs of a society must be determined. To do so, decision makers require tools which will allow them to foresee the volume of waste, to warrant a constant and sufficient supply to the facilities and to determine the most appropriate site for the facilities (Gautam *et al.,* 2005, Eskandari *et al.*, 2012).

Having been criticized numerous times, the traditional "end of pipe" approach has been replaced by the waste hierarchy. In spite of the advantages of this new approach, its linear aspect can lead to erroneous or even inadequate decisions (Kirkeby *et al.,* 2006, Schmidt *et al.,* 2007). Although the current tools, such as life cycle analysis (LCA), allow comparing various scenarios by taking into account impacts associated with transport, the results obtained rely on a static evaluation of the parameters contributing to essentially environmental indicators (Winkler *et al.,* 2007, Liamsanguan *et al.*, 2008). Because of the dynamic and stochastic characteristics of the studied networks, waste management must be based on the global load exerted on the system rather than on a linear classification of the available options. Furthermore, the load is directly influenced by the impacts associated with transport (Bovea *et al.,* 2007, Salhofer *et al.,* 2007, Eisted *et al.*, 2009), such as the means of transport chosen, the distance traveled and the road type.

This article presents the Dynamic Waste Management approach (DWM), which combines the concepts of distribution in networks and conservation of energy. By integrating the intrinsic characteristics associated with transport during the decision-making process, DWM allows minimising the load applied to the waste management systems and ensures a constant supply to the available processes.

Dynamic Waste Management

Basic concepts

In addition to the evolution of the waste treatment processes and means of transport, the quantities of available waste (generated or in reserve) vary constantly. This type of network is similar to a water distribution network, where varying volumes of water enter the system, are stored and then redistributed according to the demand. Indeed, in a water distribution network, the law of conservation of energy sends the flow towards the lowest heads. Thus, rather than responding to the demand in a linear way according to an established hierarchy, the distribution is dynamic and can ensure a continuous supply towards the areas considered priority (lowest heads). The distribution of flows then becomes complementary rather than substituting.

In order to achieve acceptability, profitability and durability, waste management should follow the model of the law of conservation of energy, which allows a distribution of flows according to the global load (head) of the system. Unlike the waste hierarchy approach which loses its validity when unexpected events occur, DWM allows an optimal maintenance of a system’s load while seeking a steady state. Table 1 presents the analogy between DWM and hydraulic networks.

Table 1. Analogy: Water network vs. Waste management (Rojo *et al.,* 2008)

WATER DISTRIBUTION NETWORK	WASTE MANAGEMENT SYSTEM
Water treatment plant (source)	Source of generated waste
Water distribution network (pipes)	Transport network (route, train, etc.)
Reservoir	Storage of materials (Reserve)
Hydraulic head	Load attributed to processes impacts
Water demand (uses)	Capacity of the facilities (Landfill, recycling, energy recovery, etc.)

Influences of transport

By using mass balances, as the one used in the LCA, it was demonstrated that transport significantly influences the prioritization of a treatment process compared to the other options in a waste management system (Merrild *et al.*, 2012). By considering that the load in the system corresponds to the impacts associated with processes and transport, the distribution of flows and the balance of the system depend directly on available volumes and on the characteristics of the network.

Based on the law of conservation of energy, DWM allows studying the global behaviour of the systems by considering the impacts associated to transport as linear load losses. Thus, a higher linear load loss reduces the probability that the waste will follow those paths within the network.

Law of conservation of energy

As mentioned previously, DWM is based on the law of conservation of energy in order to ease the supply directed at the favoured process (the lowest load). However, this flow distribution is directly influenced by the impacts associated with means of transport and leans towards minimizing the global load of the system. By taking into account the analogy with the water distribution networks, DWM is based on the energy conservation equation according to Bernoulli (Equation 1), which compares the hydraulic balance between two points in a network.

$$\frac{v_1^2}{2\cdot g}+h_1+\frac{P_1}{\rho\ \cdot g}=\frac{v_2^2}{2\cdot g}+h_2+\frac{P_2}{\rho\ \cdot g}+\Delta H \tag{1}$$

The parameters of this energy conservation equation are: fluid speed ($\boldsymbol{\upsilon}$), gravitational acceleration ($\boldsymbol{g}$), elevation or head ($\boldsymbol{h}$), pipe pressure ($\boldsymbol{P}$), fluid density ($\boldsymbol{\rho}$) and head loss ($\boldsymbol{\Delta H}$).

When considering flows go through circular pipes entirely filled by fluid, the speed becomes :

$$v=\frac{Q}{S}=\frac{4\cdot Q}{\pi\cdot D^2} \tag{2}$$

and the head loss becomes :

$$\Delta H=\gamma\cdot\frac{L}{D}\cdot\frac{v^2}{2\cdot g}=8\gamma\cdot\frac{L}{D^5}\cdot\frac{Q^2}{g\cdot\pi^2} \tag{3}$$

The pipe parameters are represented by the head loss coefficient ($\boldsymbol{\gamma}$), the flow ($\boldsymbol{Q}$), the section ($\boldsymbol{S}$), the diameter ($\boldsymbol{D}$) and the length of the pipe ($\boldsymbol{L}$).

Knowing that the network undergoes no external influences, that the speed of the fluid is constant, the system is closed and full and the dynamic and static pressures both remain constant from one point to another, equations 1 and 3 become:

$$h_1=h_2+\Delta H=h_2+\left(8\gamma\cdot\frac{L}{D^5}\cdot\frac{Q^2}{g\cdot\pi^2}\right) \tag{4}$$

In other words, the head loss between two points is expressed only by the potential energy (hydraulic head). Equation 4 illustrates that the flows in such networks are directed towards the lowest head levels, which are themselves influenced by the head losses associated with the flows and the characteristics of the pipes (length, diameter and roughness).

The loads in DWM

Using the concepts of hydraulics, available treatment processes in a waste management system must be supplied according to their load (head) within the network, and not simply one after the other (Ang *et al.*, 2003). Besides optimizing the use of the available processes, this approach makes the impact analysis possible on the network as a whole. To study the behaviour of a network on the basis of potential energy, equation 4 is separated into three distinct segments:

- The load at the starting point ($\boldsymbol{h_1}$)
- The load at the arrival point ($\boldsymbol{h_2}$)
- The linear load loss between the 2 points ($\boldsymbol{\Delta H}$).

In DWM, the load at the arrival point ($\boldsymbol{h_2}$) is replaced by the load associated with the waste treatment involved. This load is called the global allocation index (***GAI***) and serves as a representation for every waste treatment process of the socioeconomic and environmental impacts associated with its use. Globally, the determination of the GAI stems from a multi-criteria approach, rating every potential process on multiple criteria. In a general manner, equation 5 expresses the GAI for a treatment process T as the pondered sum (w_i) of the grade of each process (C_{Ti}) with respect to the chosen criteria (i). These criteria allow the potential environmental, socioeconomic and technical impacts of the potential processes to be taken into account.

$$GAI_T=\sum_{i=1}^{n} w_i * C_{Ti} \tag{5}$$

A major aspect in DWM is the comparison of the processes and the means of transport first on a common base and then with respect to the desired parameters.

The load at the starting point (**h_1**) is shown by the prioritization index ***(PI)***, which represents the importance a waste generator (industries, municipalities, etc.) has in the system. This starting load influences the distribution of flows when the system is saturated and allows prioritizing the generators with the highest load. For example, when some waste is dangerous or cannot be kept in the generator, it will be characterized as a priority and redirected towards the available treatment processes.

As aforementioned, the linear load loss (**ΔH**) corresponds to the impacts associated with transport in the DWM and influences significantly the distribution of flows in the system. These impacts are called the index loss associated with transport (**ΔI_T**) and are explained in the following section.

Index loss associated with transport

Due to the impacts caused by the mean of transport, the distance traveled, the volumes transported and the characteristics of the road, a particular attention must be brought to **ΔI_T**. In spite of a favourable ***GAI*** for a specific treatment process, the influence of **ΔI_T** can result in the generators having a transport radius that is no longer relevant to send the waste to certain facilities. In other words, even if it is more suitable to recycle a material rather than bury it, the distances required to reach a recycling point might make a landfill more suitable. Taking this into consideration, the linear load in equation 3 now corresponds to the index loss **ΔI_T** as shown in equation 6:

$$\Delta I_T = \alpha \cdot \frac{L}{R^{\beta}} \cdot Q^{\delta} \tag{6}$$

The different numerical values and the load loss coefficient, length of the pipe (***L***), diameter (***D***) and flow (***Q***) from Equation 3 were respectively replaced by the index loss coefficient (**α**), the length of the path (***L***), the road characterization factor (***R***) and the amount of transport (***Q***). Variables **β** and **δ** represent respectively the coefficient associated with the parameters ***R*** and ***Q***. These variables influence the load loss (index loss) relative to the path and balance the equation's parameters in order to adjust the influence of the characterization factor and the flow in Equation 6.

General equation of DWM

In the general DWM equation (equation 7), which is based on the energy conservation equation, flow distribution is influenced by the generators prioritization index (***PI***), the global allocation index (***GAI***) attributed to available treatment processes and the characteristics of the transport within the network (**ΔI_T**).

$$PI = GAI + \Delta I_T = GAI + \left(\alpha \cdot \frac{L}{R^{\beta}} \cdot Q^{\delta} \right) \tag{7}$$

Once the parameters of equation 7 have been defined, it is possible to study the behaviour of the chosen system. As with Bernoulli's equation, it is also possible to measure the state of equilibrium of the network, to determine the optimal model of flow distribution, to identify the weaknesses of the system, to fix the maximum capacity of the reserves, to plan the capacity of available and foreseen processes, etc. Knowing the reserves are directly influenced by the behaviour of the network and can either be dynamically filled or emptied, the global load of the system is represented by the reserve index.

Example of applying DWM

To demonstrate the extent of DWM, the following section presents a study of a waste management scenario. For the purpose of this example, the suggested system is fictive although it was created using realistic conditions. The simulations were carried out using the hydraulic networks analysis software EPANET2. This tool allows analysing the behaviour of networks and relies on the law of conservation of energy (US EPA, 2008).

Characteristics of the studied system

The selected scenario deals with managing wooden waste in an area of approximately 30 000km^2. The system consists of three main waste generators, which can send the waste towards four waste treatment processes or one reserve (temporary storage). Transport is made by trucks with a 20 metric tons (t) capacity per shipment. Generated waste comes from three different sources of wood located on the territory (sources 1, 2 and 3 on Figure 1).

Once introduced into the network, the waste can be sent towards:

R.	A reserve	(Max. capacity : 10 000t and 200 shipments/month)
A.	Incineration	(Max. capacity : 70 shipments/month)
B.	Recycling	(Max. capacity : 45 shipments/month)
C.	Composting	(Max. capacity : 65 shipments/month)
D.	Landfill	(Max. capacity : 50 000t and 100 shipments/month)

The map of the system as well as its global diagram (modelled in EPANET2) is presented in figure 1. This figure also illustrates the characteristics of the possible paths and the values of ***PI*** and ***GAI*** from the generators, reserve and available processes. Furthermore, a link between a generator and a treatment process expresses their compatibility.

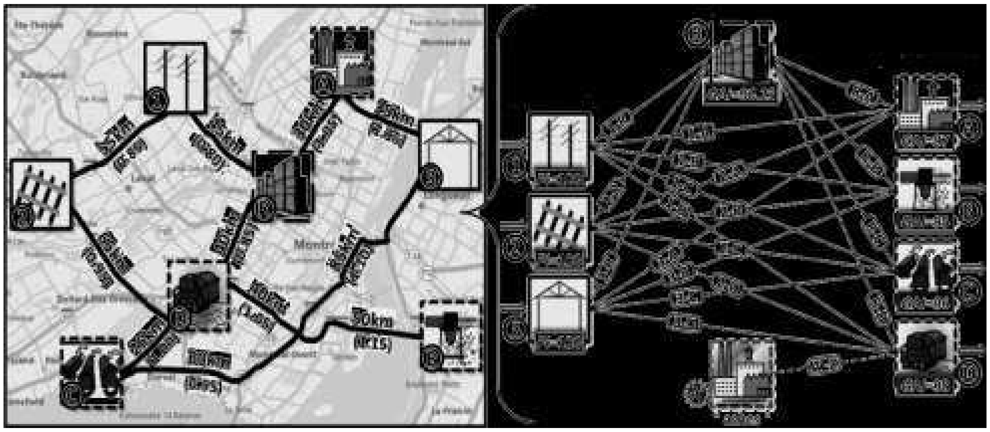

Figure 1. Map of the studied network and global diagram modeled in EPANET2

The values used for the simulation come from a logical distribution, but were attributed randomly. In this scenario, the generators have the same prioritization index (***PI***); the reserve and the treatment processes have global allocation index values (***GAI***, values between 90 and 100) according to their load within the network. The higher the index, the less likely the waste flow moves towards that treatment process. In addition to the volume of generated waste, ashes resulting from the incinerator are redirected towards the landfill and induce a supplementary load within the network. In this case, a 10% fixed volume of the incinerated mass is transformed into ashes.

The numbers in parenthesis on the map represent the congestion factor of the road (***R***). This congestion factor is influenced by traffic density, width and amount of lanes and road type. For the following example, the ***R*** values were based on the *Roadway Congestion Index* (***RCI***) developed by the *Federal Highway Administration* in Texas (Schrank *et al.,* 1996). In a city such as Detroit, where the level of congestion is high, the ***RCI*** measured is 1.24, while in a city with low congestion level such as Buffalo, the ***RCI*** is 0.73 (Schrank *et al.,* 2007). Since ***R*** is equivalent to the diameter of the pipe and that the pressure loss is inversely proportional to the pipe size, ***R*** becomes the reverse of the ***RCI*** (equation 8).

$$R = \frac{1}{RCI} \tag{8}$$

During simulations, two types of trucks were used: waste coming from generators ***1*** and ***2*** are transported by truck ***X*** and waste coming from generator ***3*** is transported by truck ***Y***. This second type leads to a higher index loss of 50%.

Simulation in EPANET2

Because of the differences between a waste management system and a hydraulic network, simulation in EPANET2 requires adjustments. In this network, valves and non-return valves were used to define facilities capacity and to avoid flows (transport) circulating in loops. With this approach, transport is considered independently and waste distribution can be carried out anywhere within the network. As shown in the global diagram (figure 1), the actors (generators, reserve and processes) represent the nodes of the network and are interrelated by the routes which separate them.

In EPANET2, ***PI*** and ***GAI*** values of the actors are converted into hydraulic loads (in meters). Furthermore, the reserve was set to guarantee that a lower level will lead to increased supply, while a higher one favours evacuation. The index of the emptied reserve was set so that at equal distances, technologies B and C are prioritized. Also its evacuation is ensured in the whole system when it is at full capacity. Thus, the global load of the system will allow maintaining an optimal level in the reserve. Due to the software, the shape which is privileged for the reserve in this simulation is a cylinder with an interval of index (height, H_r) of 3 and capacity of 10 000t. Therefore, the initial volume in the reserve was set at 4000t (200 shipments).

For this example, the time scale is ten months with time steps of one month. During the simulation, flow units are of one shipment per month and correspond to one cubic meter an hour measured in EPANET2. To establish the parameters in the ΔI_T equation (equation 5), table 2 presents the reference data used. For this example, these values were fixed in an empirical way.

Table 2. Index loss associated with transport (***ΔIT***)

ΔI_T	*L* (km)	*R* (1/RCI)	*Q* (ship./month)	Truck
1.00	100	1.00	100	Type X
1.50	100	1.00	100	Type Y
1.20	100	0.75	100	Type X
1.05	100	1.00	200	Type X

The values in this table lead to obtain parameters ***α***, ***β*** and ***δ*** associated with the index loss (I_t) equation. Considering the index loss values (***α***) calculated are of $2.2\text{x}10^{-6}$ for trucks of type ***X*** and $3.2\text{x}10^{-6}$ for trucks of type ***Y***, we get that:

$$\Delta I_T = \alpha \cdot \frac{L}{R^{0.6338}} \cdot Q^{0.0704} \tag{8}$$

Results

In order to show the behaviour of DWM under various constraints, each one of the input flows fixed for the three waste generators follow a particular tendency. Waste coming from the first generator is random, while the second is constant the third follows a seasonal variation. To show the behaviour of the system during the peak periods, the volume of waste during the 4th month are higher than usual, while no waste is generated during the 7th month. The volume of generated waste and flow distribution are presented in detail in Figure 2.

Figure 2 shows that the waste coming from each generator is distributed to the treatment processes or to the reserve with respect to the GAI. For example, wood waste coming from generator 1 during the first month (90 tonnes) is directed to processes A (31T), B (12T) and C (16T). Also, as previously stated, incineration produces waste (ashes) with a weight of 10% of the total waste sent to combustion. Thus, for the first month, the amount of waste sent to process D (reserve) corresponds to 10% of 70T (29T+31T+10T burnt in process A), i.e. 7T.

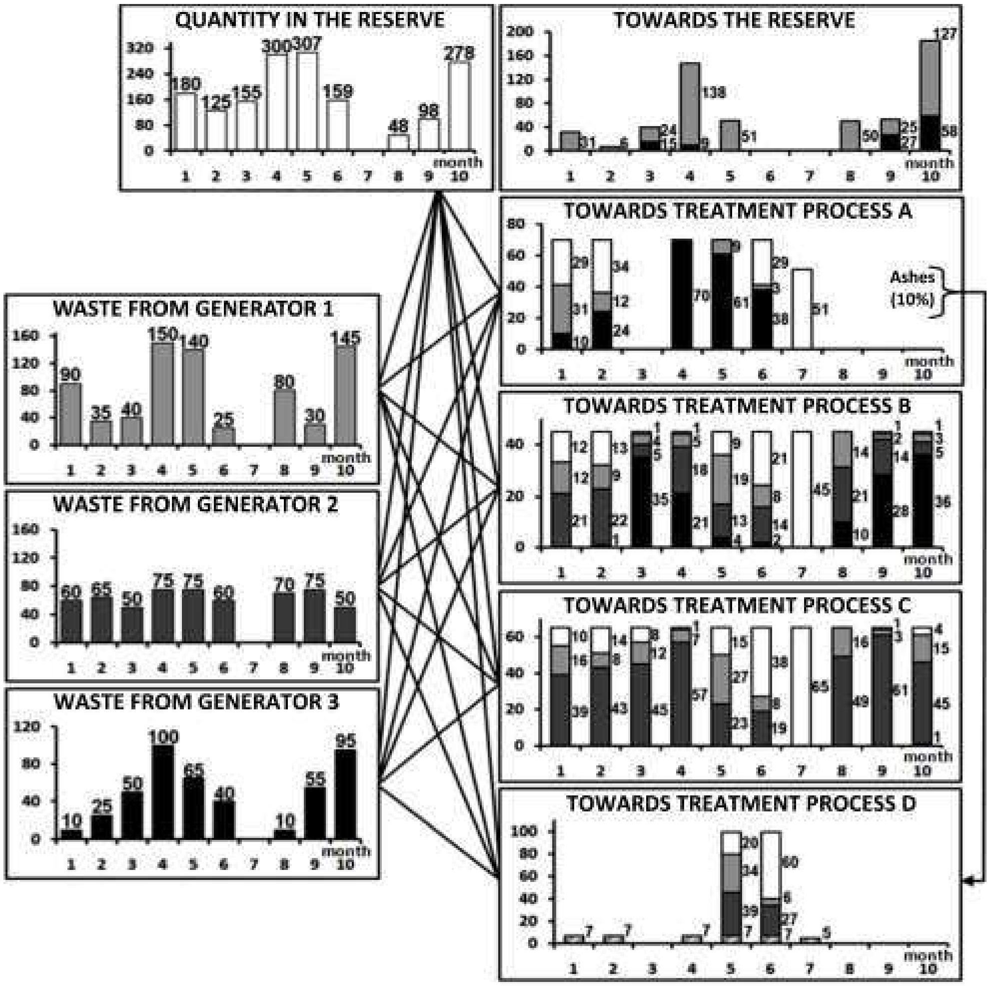

Figure 2. Network's flow distribution according to the global diagram (in shipments/month)

Several observations ensue from the simulation: on one hand, the fixed parameters lead to the reserve being supplied when its total index is lower than 97 (125 shipments). On the other hand, the more the reserve is filled up, the more likely the flow will move towards processes ***A*** and ***D***.

As for technologies ***B*** and C, which have favourable indexes (loads) in the system, their supply is constant throughout the simulation because of their reserve, which compensates when there is insufficient waste generated (e.g. 6th and 7th month). According to the allocation indexes, which are influenced by transport, it can occur that certain flows are more continuous than others. For example, the fraction of waste coming from generator 2 directed towards process ***C*** is relatively constant because of the short distance which separates them and the low ***GAI*** attributed to the composting facility.

Although the ashes produced in the incineration (process ***A***) are redirected towards the landfill (process ***D***), the high index of the landfill and the presence of a reserve in the system leads to a minimal supply moving towards the landfill. In other words, in an actual situation and according to the parameters initially adopted, the global flow distribution would allow a minimization of the impacts.

Sensitivity analysis

To analyse the influence of the main parameters of the network, various sensitivity analyses were realised. Through these analyses, it was noted that ***PI*** had practically no influence on flow distribution when the capacity of the waste treatment facilities was sufficient to accept all the generated waste. On the other hand, when the network was at its full capacity, high ***PI*** allowed prioritizing certain generators with regards to others.

To demonstrate the influence of the index interval fixed for the reserve during the simulations, an analysis was carried out according to three different heights (**H_R**) and by preserving the same maximum capacity and the same initial volume (200 shipments). The chosen intervals are:

- **H_{R-1}** = 1
- **H_{R-2}** = 3
- **H_{R-3}** = 5

It was observed that the lower the index interval (the height in the software), the more stable the influence of the reserve was and the more sensitive the network was to the fluctuations. Thus, as shown in figure 3, by reducing the index interval of the reserve, the global load of the network is in a better equilibrium. Consequently, it facilitates a constant supply to the processes whose index is lower than the average index of the reserve and to minimize the supply towards processes whose index is higher.

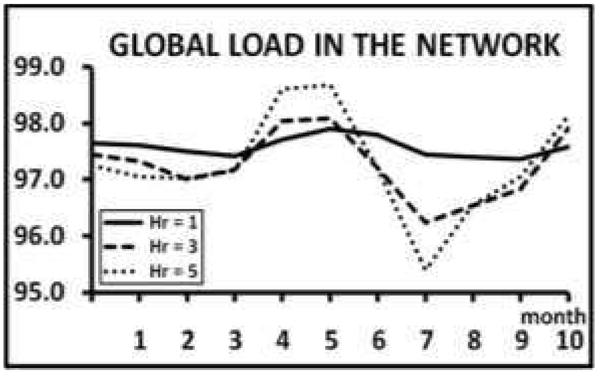

Figure 3. Sensitivity analyzes according to the interval of index of the reserve

With regard to the index loss associated with transport, a sensitivity analysis was carried out in order to analyze the effects associated with the type of truck used. For the analysis, transport coming from generator 3 was replaced by:

- Truck type *W* : $\Delta I_T = 0.5$ $\alpha = 1.1x10^{-6}$
- Truck type *X* : $\Delta I_T = 1.0$ $\alpha = 2.2x10^{-6}$
- Truck type *Y* : $\Delta I_T = 1.5$ $\alpha = 3.2x10^{-6}$

* For **L** = 100km, **R** = 1.0 and **Q** = 100 shipments/month

The results show that the index losses associated with transport exert a significant influence in the network and directly affect flow distribution. When transport has a high **ΔI_T**, flow distribution tends to follow the shortest paths. Thus, the most distant treatment processes in the system are rather supplied by the generators, because of its less constraining transport. Figure 4 presents the waste produced by generator 1 and directed towards process B. Finally, the more the trucks coming from generator 3 have a high **ΔI_T**, the more important the contribution of generator 1 is in minimizing the global load of the network.

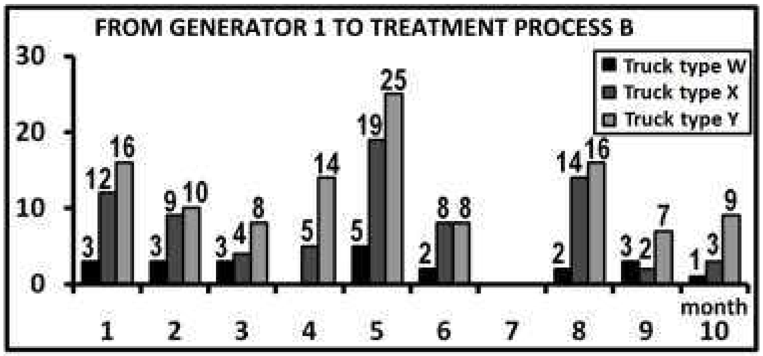

Figure 4. Sensitivity analyzes according to the type of truck

Discussion

The results obtained in the simulation and sensitivity analyses clearly confirm that DWM is a promising sustainable approach to waste management. Besides facilitating the constant supply of the most favourable processes within a system (low GAI), DWM ensures the minimization of the global load of the network. Being based on the law of conservation of energy (particularly on Bernoulli's theorem), the approach allows studying the general behaviour of a system as well as the influence of each of the actors and means of transporting. Rather than being based on a linear waste hierarchy, DWM offers a dynamic decision-making approach based on the systemic analysis of the network. Thus, in spite of the fluctuations in the generated waste, the approach facilitates the equilibrium of the network and the optimal use of the reserves. The results obtained during simulation also illustrate that the higher the global load of the system, the more it is favourable to direct flows towards the processes with high ***GAI***. Even though the global studied system takes into account the adequacy between the processes and the waste type, one of its weaknesses lies in the lack of consideration of the intrinsic composition of the produced waste during the distribution towards the process with the lowest GAI. Thus, one of the possible outlooks for this work would be to include some criteria judging of the compatibility of the waste produced with the processes and therefore take into account the inputs in the GAI.

Looking at the global load of the network, the reserves capacity and the processes supply, DWM helps to determine if reserves or processes in the system are ineffective and if new ones are necessary, but also to establish their optimal capacity. In addition, as DWM is based on a geographical modeling of the systems, it would be possible to optimize the positioning of the new facilities in order to reduce the global load even and to maximize the supply of favourable waste treatment processes (low GAI). Furthermore, the presented example highlights the fact that the economic viability of some treatment units could be questioned. Indeed, Figure 2 shows that the incinerator wouldn't be used all the time through the 10 months: this questions the role of incineration in a multi-process waste treatment scheme, especially in a perspective of reducing the global impacts of waste. It would thus be relevant to rethink the role of incineration on a territory scale in such a system so that its supply would be constant and, consequently, its economic viability assured. This would therefore justify, through co-incineration, its relevance in a waste treatment process.

To this point, the application of DWM relies on the development of better adapted tools. In spite of the possible use of EPANET2, this software requires a certain number of adjustments and is complicated when attempting to model the system. Besides the difficulties associated with the software, a particular attention is required during the determination of the parameters. Indeed, the methods chosen to calculate indexes values (***PI***, ***GAI***) and to obtain the variables for the ΔI_T equation must absolutely be validated, due to their significant influence on the results during simulations. In this process, it would be relevant to establish an index determination method that would be based on normalized parameters that are representative of the different environmental and socioeconomic spheres.

Conclusion

In the optics of achieving sustainable development, waste management must incorporate an integrated approach which administers flow distribution in a responsible way. The analysis tools must take into account the fluctuations and the evolutionary characteristics of the parameters which influence the validity of the prioritization of certain processes. Thus, it is essential to consider the characteristics associated with the paths, with the means of transport as well as with the types of roads taken. This measure stems from the fact that the general behaviour of a system is sensitive to flows, heads (loads), configurations and reserves, and that the constant supply of the favourable processes rests on a minimization of the global load and on the equilibrium of the network.

The results obtained during simulations demonstrate that DWM follows these criteria, while supporting a diversified waste management in agreement with the principles of social acceptability, economical profitability and environmental compatibility. Moreover, this dynamic new approach can also represent a new step towards *Industrial Ecology*. Due to the analogy with water distribution networks (where flow distribution within the network is influenced by the head losses in the pipes), the constraints associated with transport become a crucial factor in DWM. Being based on the law of conservation of energy (particularly on Bernoulli's theorem), DWM offers new perspectives to correct the lack of flexibility of other approaches. Hence, DWM is part of an innovative, simple, flexible and evolutionary approach and supports the objectives of sustainable development.

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